Nauka Przyroda Technologie

2013
Tom 7
Zeszyt 4
#68

ISSN 1897-7820 http://www.npt.up-poznan.net

Dział: Melioracje i Inżynieria Środowiska

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APPLICATION OF SIAM FOR DETERMINATION OF TRENDS IN SEDIMENTATION OF THE STARE MIASTO RESERVOIR*

ZASTOSOWANIE SIAM DLA OKREŚLENIA TRENDÓW W ZAMULANIU ZBIORNIKA STARE MIASTO

Summary. The purpose of this paper is application of Sediment Impact Analysis Method (SIAM) on the basis of data from the Stare Miasto reservoir. The method is applied to determine trends in sedimentation of the reservoir. The object analysed, the Stare Miasto reservoir, is located in the Powa river in central part of Poland (Europe). The element splitting the object into main and upper part is a dam located in the upstream. The upper part is used as an element of sediment and water quality protection. In addition the highway A2 is narrowing the active flow cross-section in the central part of the reservoir. The methods used for the analysis include direct measurements of the reservoir geometry and computer model simulations. SIAM is utilized for the purposes of this research. The results obtained confirm proper performance of upper in the reservoir. The results also indicate that the highway bridge is the cause of sediment movement and redistribution in the main part.

Key words: reservoir sedimentation, flow simulation, SIAM, HEC-RAS

Introduction

In this paper the assessment of bottom aggradation and degradation conditions in the Stare Miasto reservoir has been made. The Sediment Impact Analysis Method (SIAM) implemented in HEC-RAS ver. 4.1.0 is used for this purpose. The reservoir is also split into two basic parts by an internal dam located in the upper zone. This should protect

*This work is a part of a scientific project "Initial sedimentation part in small lowland reservoirs: modeling and analysis of functionality" founded by National Science Centre in Poland, No. N N 305 296 740.

from fast accumulation of sediment from the area located near the main dam. One of the main problems related to the performance of reservoirs is protection from sediment deposition. Different methods have been applied for this purpose (YANG 1973, 1996). Very interesting and promising approach seems to be a construction of two-stage reservoir. The main idea of such a solution is to split the reservoir into two parts, namely the main part and the upper sedimentation zone. To achieve this goal, two dams have to be built. The first is the main dam working in the same conditions as in the ordinary single-part reservoir. The second is a smaller dam located in the upper part of the reservoir. The part of the reservoir upstream of this dam is expected to store sediments and pollutants. Such constructions may be found in Poland. An example of a more sophisticated solution is the Mściwojów reservoir (KASPEREK and WIATKOWSKI 2008, PIKUL and MOKWA 2008). But more direct approaches may also be found, e.g. Poraj reservoir, Kowalskie Lake (WICHER-DYSARZ and KANCLERZ 2012). New objects of this type are the Roszków reservoir and the Stare Miasto reservoir (WICHER-DYSARZ and KANCLERZ 2012, DYSARZ and WICHER-DYSARZ 2013).

The above described construction is based on the observation of natural sedimentation processes in reservoirs. The sediments are deposited first in the upper part of the reservoir near the inlet (YANG 1973, 1996). The main factor responsible for such distribution of solid particles is a decrease in transport capacity related to a decrease in stream velocity. The most prone to this process are coarser particles. Their deposition on the bottom changes the water levels and inundation frequencies of the floodplains in the backwater part of the inlet. The conditions for riparian vegetation growth in this area improve. An example illustrating such relations may be the Jeziorsko reservoir (DYSARZ et AL. 2006, DYSARZ and WICHER-DYSARZ 2011, HAMERLING et AL. 2013, WALCZAK et AL. 2013).

The finer particles are sediment slower and are transported along the reservoir. Some of them are stopped only at the dam. Only the finest are transported throughout the dam by culverts and spillways (YANG 1973, 1996). Hence, the idea of a two-stage reservoir with the small upper dam seems to be reasonable. However, the problem is more complex. The functioning of the internal dam located in the upper part of the object may also cause some problems with local erosion. The scour formation below the dams and weir has been a frequently observed phenomenon. In the reservoir analysed there is another element that may cause similar effects. This is the highway bridge narrowing the reservoir in the central zone. Hence, the sedimentation process in the Stare Miasto reservoir may have unexpected results.

The paper consists of six 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 presented in fourth section. In the fifth one the results are discussed. The conclusions are presented in the last section.

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. The reservoir is a relatively new object, built in 2006. The main dam is 6.2 m high and 257 m long. The length of the reservoir 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 × 106 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 and ZGRABCZYŃSKI 2008). The depth in 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

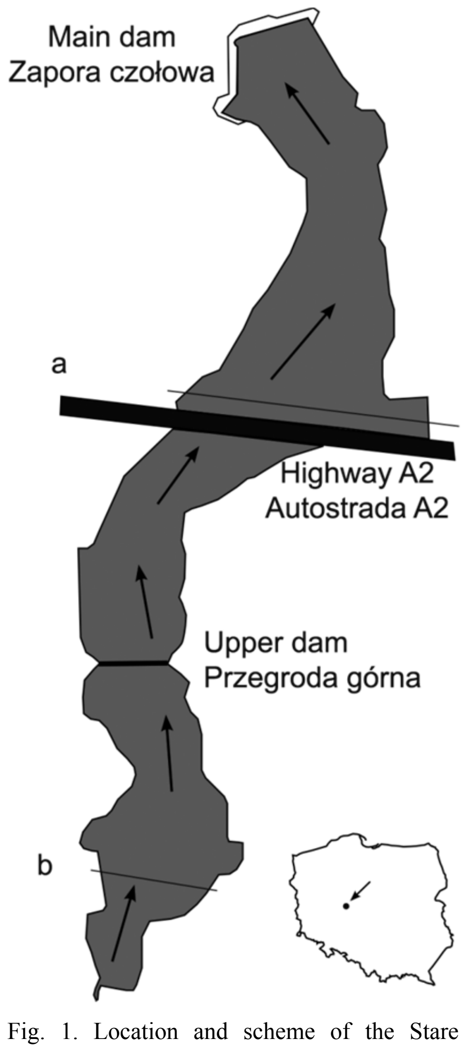

Fig. 1. Location and scheme of the Stare Miasto reservoir
Rys. 1. Lokalizacja i schemat zbiornika Stare Miasto

sediment and prevent from degradation of water quality. 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 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 and ZGRABCZYŃSKI 2008).

The average annual unit outflow from the watershed in the dam cross-section is 3.52 $dm^3/(km^2 \cdot s^{-1})$. The closest gauge station is Posoka. The data collected at this gauge station for the period 1984–2009 are available. The inflow varies from 0.04 to 16.3 m^3/s. This range is divided into 15 equal classes. The length of single class is 1.08 m^3/s. The total 9497 daily observations are used to construct discharge frequency curve according to standard procedures (e.g. CHOW et AL. 1988, OZGA-ZIELIŃSKA and BRZEZIŃSKI 1994).

The additional data used for our analyses include the geometry of the reservoir, water surface levels measured in 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 and ZGRABCZYŃSKI 2008). The maps are used for definition of 51 cross-sections from the main dam to Karsy town, where the inflow to the reservoir is located. The distances between the cross-sections vary from 30 to 200 m.

The direct measurements of the reservoir cross-sections are also used. Such a survey was made in August 2011. The measurements were made on the river reach along the length of 3.5 km from the main dam to the reservoir inlet in Karsy town. StreamPro ADCP (Acoustic Doppler Current Meter) produced by Teledyne RD Instruments was used for measurements of flow velocity as well as the reservoir depth. Measurements were made at 21 cross-sections at distances varying from 100 m to 200 m. The water surface elevation was also measured.

Two cross-sections shown in Figure 2 are used for comparisons with historical cross-sections. As it is visible the significant changes of bottom elevations are observed in the reservoir. The bottom downstream of the bridge is degrading. The accumulation of sediments is observed in the upper part of the reservoir. The location of the cross--sections is shown in Figure 1.

The data set is completed with bed sediment samples. There are 36 samples used. They have been used in previous research on the Stare Miasto reservoir (DYSARZ et AL. 2013). The sieve analysis is used to determine the mass ratio in classes of diameters compatible with Polish regulation. In general the sediments analysed should be classified as fine or very fine sands.

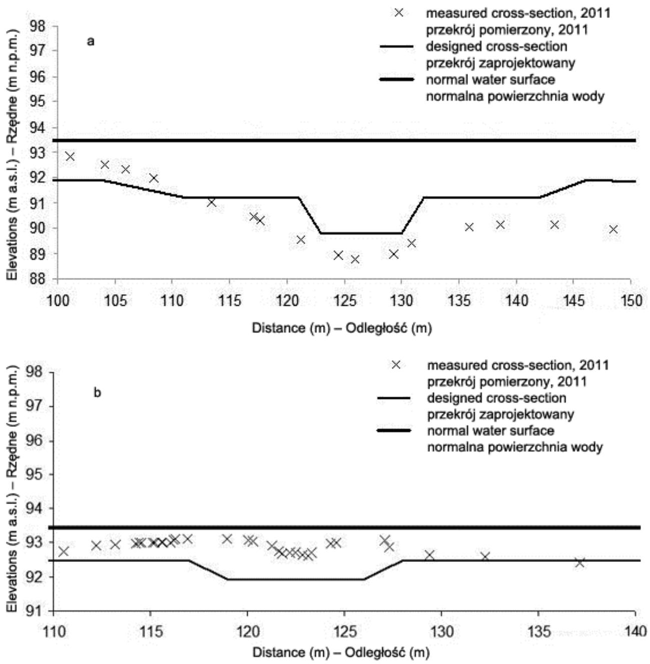

Fig. 2. Comparison of measured and designed cross-section shapes: a – downstream of the bridge, b – in the upper part of the reservoir (localization – in Fig. 1)
Rys. 2. Porównanie pomierzonych i zaprojektowanych przekrojów poprzecznych: a – poniżej mostu, b – w górnej części zbiornika (lokalizacja – na rys. 1)

Methods

Steady flow computations

The computations have been made by application of the well known HEC-RAS package, version 4.1.0. The software consists of several computational modules. For preliminary computations the steady flow module is used. Its basis is well know Bernoulli equation modified for implementation in compound channels (BRUNNER 2010). The computations require: (1) reservoir geometry, (2) estimation of roughness, (3) construction of structures, (4) discharge and (5) evaluation of downstream boundary conditions. The last element is implemented as water head at the main dam.

The hydraulic computations are performed for each class of discharges according to frequency curve. The mean of each class is chosen as representative value. The hydraulic parameters are then used in the SIAM procedure described below.

Sediment Impact Analysis Method (SIAM)

The Sediment Impact Analysis Method (SIAM) is one dimensional sediment budget tool. It is not a sediment routing model. It may be used for preliminary assessment of river or reservoir reaches prone to aggradation or degradation due to sediment transport. The method was developed as part of the Mississippi Delta Headwaters project. This project was a joint effort of the Engineering Research and Development Center (ERDC) and Colorado State University (LITTLE and JONAS 2010). The first implementation of SIAM was done by MOONEY (2006). SIAM is also available in HEC-RAS package since version 4.1.0 (BRUNNER 2010, LITTLE and JONAS 2010).

HEC-RAS implementation of SIAM enables direct import of results from hydraulic computations module. The additional data required are (1) flow frequency curve, (2) bed sediment samples, (3) sediment sources. The basic properties of sediment particles, e.g. specific gravity, also have to be determined. The important element of SIAM is implemented transport formula. In HEC-RAS there are six available equations for evaluation of sediment transport potential. These are (1) Ackers-White, (2) Engelund-Hansen, (3) Laursen (Copeland), (4) Meyer-Peter and Müller (MPM), (5) Toffaleti, (6) Yang. The results obtained are aggradation and degradation of particular reaches of river or reservoir. It is expressed in tonns per year. Such values may be easily recalculated into average increase/decrease of bottom elevation. The mass is transformed into volume for known sediment density of particular fractions. Then the volume is divided by the area of bottom. It gives the average height of sediment deposits in case of aggradation or depth of sediment removal in case of degradation.

The first step in the preparation of data for SIAM is splitting of analysed river of reservoir into a number of sediment reaches. The Stare Miasto reservoir is divided into 14 reaches as it is presented in Table 1. Denotation RS means "River Station" as it is understood in HEC-RAS. The distance of upstream and downstream River Stations is measured from the main dam. In the right column specific elements included in particular reaches are listed. Hence, the upper dam located in RS 2.190 is in reach-07 ranging from 2.224 to 2.170. The bridge is located inside reach-10.

Table 1. Splitting of the Stare Miasto reservoir into sediment reaches with constant parameters
Tabela 1. Podział zbiornika Stare Miasto na odcinki o stałych parametrach rumowiska

No. Nr	Reach Odcinek	Upstream RS Dopływ RS (km)	Downstream RS Odpływ RS (km)	Remarks Uwagi
1	2	3	4	5
1	Reach-00 Odcinek-00	3.474	3.164	Posoka river Rzeka Posoka
2	Reach-01 Odcinek-01	3.144	3.051	Reservoir inlet Wlot do zbiornika
3	Reach-02 Odcinek-02	3.033	2.995	
4	Reach-03 Odcinek-03	2.976	2.893	

Table 1 – cont. / Tabela 1 – cd.

1	2	3	4	5
5	Reach-04 Odcinek-04	2.878	2.68	
6	Reach-05 Odcinek-05	2.663	2.517	
7	Reach-06 Odcinek-06	2.501	2.241	
8	Reach-07 Odcinek-07	2.224	2.170	Upper dam Przegroda górna
9	Reach-08 Odcinek-08	2.151	1.947	
10	Reach-09 Odcinek-09	1.929	1.471	
11	Reach-10 Odcinek-10	1.453	1.399	Bridge – highway Most – autostrada
12	Reach-11 Odcinek-11	1.385	0.811	
13	Reach-12 Odcinek-12	0.791	0.183	
14	Reach-13 Odcinek-13	0.169	0.000	Main dam Zapora czołowa

The last element prepared for SIAM is sediment source evaluation. Only upstream sources are taken into account. The annual inflow of sediments into the Stare Miasto is evaluated on the basis of three formula: (1) Ackers-White, (2) MPM and (3) van Rijn. All three formula are implemented for uniform flow conditions in the upper cross-section. The final results are presented in Table 2. There are some not verified differences between computed values.

Table 2. Estimated total annual inflow of sediment (t)
Tabela 2. Oszacowany całkowity roczny dopływ rumowiska (t)

No. Nr	Class Klasa	Max d (mm)	Ackers-White equation Równanie Ackersa-White'a	MPM equation Równanie MPM	van Rijn equation Równanie van Rijna
1	2	3	4	5	6
1	Clay	0.002		191	5 238
2	FM	0.005		479	5 729
3	MM	0.02		382	1 655
4	CM	0.05		189	363

Table 2 – cont. / Tabela 2 – cd.

1	2	3	4	5	6
5	VFS	0.1		846	960
6	FS	0.25	43 966	4 609	449
7	MS	0.5	2 395	665	49
8	CS	1	502	139	8
9	VCS	2	26	6	

Results

Hydraulic computations

The fundamental results analysed are water surface profiles and hydraulic conditions along the reservoir. It is noticed that the main factor determining the water table is the water head the main dam. For that reason, only one example of profile is presented here (Fig. 3), though all of them are implemented in SIAM.

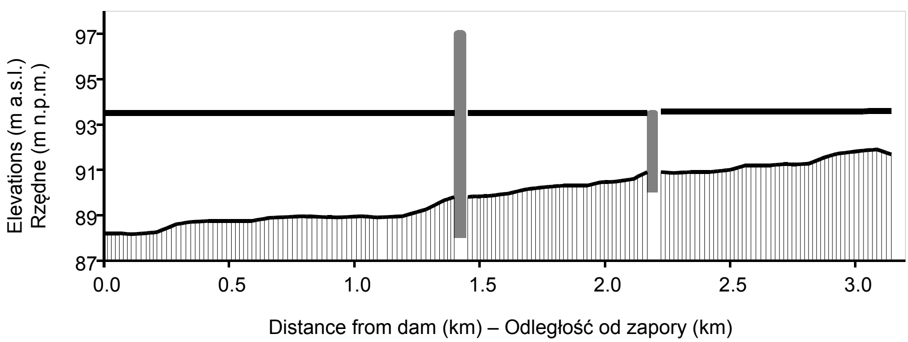

Fig. 3. Water table profiles for Q = 15.76 m^3/s with normal (93.50 m a.s.l.) water surface elevation at the dam
Rys. 3. Układ zwierciadła wody dla Q = 15,76 m^3/s przy normalnym (93,50 m n.p.m.) poziomie piętrzenia na zaporze

The results presented in Figure 4 are calculated for discharge Q = 15.76 m^3/s. Horizontal axis represents the distance measured from the main dam. The elevations of water surface and bottom are shown on the vertical axis. The ground is the area below bottom line drawn as vertical sections reaching the bottom line. The bridge and the upper dam are also marked in the figure.

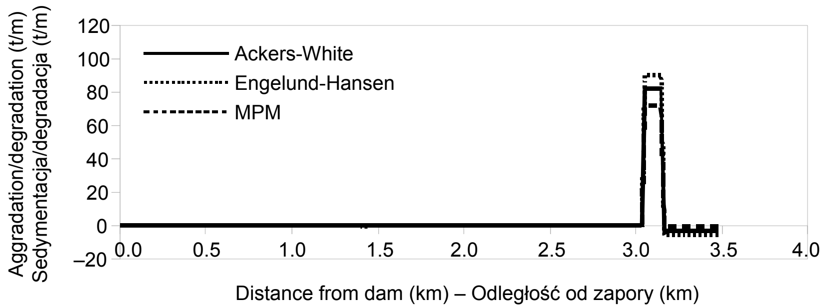

Fig. 4. Yearly aggradation and degradation along the Stare Miasto reservoir calculated by means of different transport formula with source sediment inflow estimated from Meyer-Peter and Müller formula
Rys. 4. Roczna sedymentacja i degradacja na długości zbiornika Stare Miasto liczone za pomocą różnych formuł transportowych ze źródłowym dopływem rumowiska szacowanym formułą Meyera-Petera i Müllera

SIAM results

The results of SIAM implementation are presented as graphs and tables. The Figures 4-7 show the distribution of aggradation and degradation zones along the reservoir. The graphs presented in Figures 4 and 5 are prepared for the simulations with upstream source estimated by MPM formulae. The next figures are constructed on the basis of simulations with sources calculated from van Rijn. The effect of calculations with Ackers-White sources is not presented here, because the results are considered not reliable. This fact is presented in Table 3, and explained below.

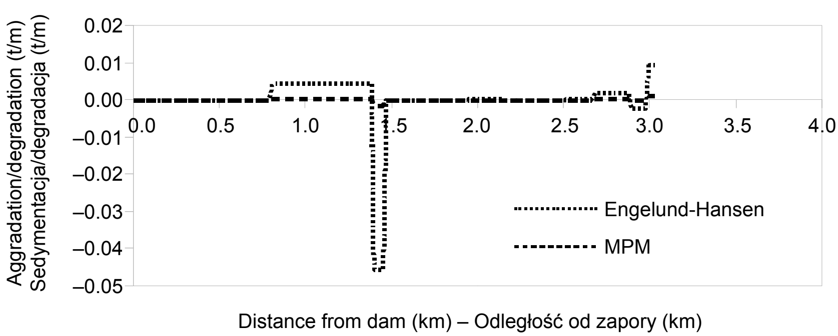

Fig. 5. Yearly aggradation and degradation along the Stare Miasto reservoir without inlet reach calculated by means of different transport formula with source sediment inflow estimated from Meyer-Peter and Müller formula
Rys. 5. Roczna sedymentacja i degradacja na długości zbiornika Stare Miasto bez odcinka dopływowego liczone za pomocą różnych formuł transportowych ze źródłowym dopływem rumowiska szacowanym formułą Meyera-Petera i Müllera

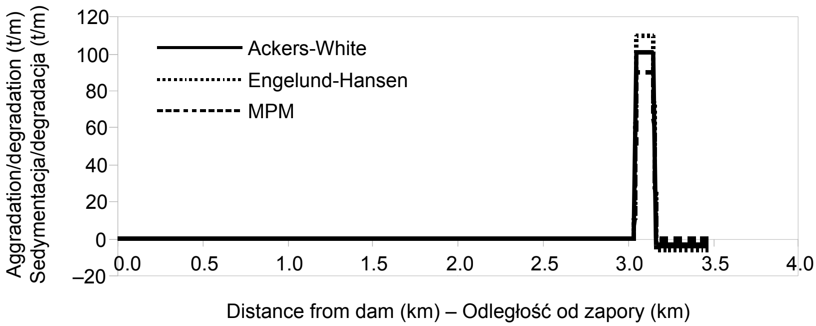

Fig. 6. Yearly aggradation and degradation along the Stare Miasto reservoir calculated by means of different transport formula with source sediment inflow estimated from van Rijn formula
Rys. 6. Roczna sedymentacja i degradacja na długości zbiornika Stare Miasto liczone za pomocą różnych formuł transportowych ze źródłowym dopływem rumowiska szacowanym formułą van Rijna

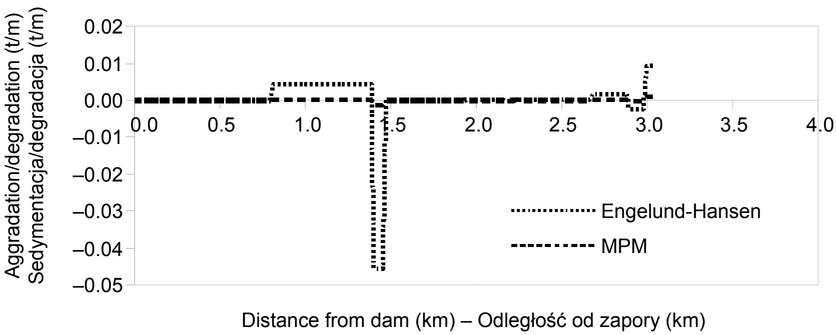

Fig. 7. Yearly aggradation and degradation along the Stare Miasto reservoir without inlet reach calculated by means of different transport formula with source sediment inflow estimated from van Rijn formula
Rys. 7. Roczna sedymentacja i degradacja na długości zbiornika Stare Miasto bez odcinka dopływowego liczone za pomocą różnych formuł transportowych ze źródłowym dopływem rumowiska szacowanym formułą van Rijna

In all figures horizontal axis represents the distance from the main dam. The vertical axes show the estimated values of aggradation and degradation in tonns per 1 m for single year. The upper dam and the bridge are also marked there. The Figures 4 and 6 are composed for the whole reservoir. The inlet part of the reservoir is not present in Figures 5 and 7 to indicate the changes near the upper dam and the bridge.

In Figures 4 and 6 three transport formula are used. These are Ackers-White, Engelund Hansen and MPM. The rest is not presented due to their unreliability. The Ackers--White formulae is omitted in Figures 5 and 7, because this method showed no results for the parts of the reservoir different than the inlet.

Table 3. Average yearly increases of bottom elevations in the inlet reach (cm)
Tabela 3. Średnie roczne przyrosty rzędnych dna na odcinku wlotowym (cm)

Source Źródło	Transport Przenoszenie	Value Wartość
Ackers-White	Ackers-White	115.15
	Engelund-Hansen	117.27
	MPM	112.77
MPM	Ackers-White	20.21
	Engelund-Hansen	22.36
	MPM	17.73
van Rijn	Ackers-White	24.77
	Engelund-Hansen	27.00
	MPM	22.29

The estimated average increase of the bottom elevations in the reach-01 as centimeters per year are presented in Table 3. The results for the simulations with sources calculated by Ackers-White formulae are overestimated. But, the rest of the results seems to be consistent with observations.

Discussion and conclusions

The analyses presented here are carried out within the whole range of discharge variability in the Stare Miasto reservoir. The flow frequency curve is the best representation of this range. Also the reconstruction of the Stare Miasto geometry seems to be accurate enough. The estimation of roughness is the only uncertain element in the calculation of hydraulic conditions in the reservoir. Due to the fact that the water table elevation is determined by water head at the dam, this uncertainty is not important.

Basic comparison of geometry reconstructed from maps and cross-sections measured indicated significant changes in the bed morphology. Significant accumulation of sediments is observed in the upper part of the reservoir (Fig. 2 b). The erosion process is noticed close to the bridge.

The results are shown in Figures 4-7. The main accumulation is kept in the upper part of the reservoir. The expected increase of the bottom elevation is about 20 cm per year (Table 3). The results also indicate possibility for degradation of bottom close to the bridge. The differences between computed values are too large to comment on them uniquely. However, the tendency for removal of sediments seems to be common for all reliable simulations.

The main purpose of this paper is analysis of sediment process in the Stare Miasto reservoir. The analysis has been made taking into account the potential sediment deposition and erosion along the reservoir. The importance of the presented consideration is related to the specific construction of the reservoir. This is a two-stage object with the main dam and the upper dam constraining the upper sedimentation zone. The problem becomes more complex because of the highway bridge, which has narrowed the central part of the reservoir.

The main tool used for the assessment is HEC-RAS package. Two elements of this software are used. The first is steady flow module. The second element used is a module based on Sediment Impact Analysis Method (SIAM). The calculated aggradation and degradation along the reservoir seem to assess the general tendencies observed. However, such simulations are prone to uncertainties. The disturbances in the obtained results depend mainly on the sediment transport formulae used for sediment budged calculation or assessment of sediment sources.

The calculations showed that the two-stage construction of the reservoir seems to perform well. The sediment particles are settled in the upper part of the reservoir as expected. However, the flow conditions presented indicate also some problems which were not predicted earlier. There are some sites at which local erosion may occur. The most important one is located close to the highway bridge.

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ZASTOSOWANIE SIAM DLA OKREŚLENIA TRENDÓW W ZAMULANIU ZBIORNIKA STARE MIASTO

Streszczenie. Podstawowym celem prezentowanego artykułu jest zastosowanie metody SIAM na bazie danych ze zbiornika Stare Miasto. Celem aplikacji jest określenie trendów w zamulaniu zbiornika. Analizowany obiekt, zbiornik Stare Miasto, jest zlokalizowany na rzece Powie w centralnej części Polski (Europa). Elementem dzielącym obiekt na części główną i wstępną jest przegroda zlokalizowana w górnej części. Część wstępna jest wykorzystywana jako element ochrony przed zamuleniem i degradacją jakości wody. Dodatkowo autostrada A2 przewęża aktywny przekrój poprzeczny zbiornika w jego centralnej części. Metody wykorzystane w analizach obejmują pomiary bezpośrednie geometrii oraz symulacje komputerowe. Metoda nazywana SIAM (ang. Sediment Impact Analysis Method) jest zaadaptowana do potrzeb prezentowanych badań. Uzyskane wyniki potwierdzają właściwe działania części wstępnej zbiornika. Wykazują również, że most pod autostradą jest źródłem wtórnego przemieszczania się rumowiska w zbiorniku.

Słowa kluczowe: akumulacja w zbiorniku, symulacja przepływu, SIAM, HEC-RAS

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Accepted for publication – Zaakceptowano do opublikowania:
13.11.2013

For citation – Do cytowania:
Dysarz T., Wicher-Dysarz J., 2013. Application of SIAM for determination of trends in sedimentation of the Stare Miasto reservoir. Nauka Przyr. Technol. 7, 4, #68.