



Master Thesis

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Spatio-temporal changes of Vistula riverbed below the Włocławek hydropower plant

by

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Abstract

Rivers are considered to be one of the most common and important factor of surface formation on earth. At the same time they are very sensitive to any forms of disruptions. Regardless of their size, course character and climate zone of location, construction of a dam is considered to be the strongest possible disturbance in a fluvial system. One of the phenomenon that most often occurs downstream the dam is erosion process characterized by the rate of riverbed incision. The objective of this thesis was determination of the state of the bottom of the part of Vistula River below Włocławek Barrage. The analyses were based on bathymetric data acquired during the measurements made in the period 2008-2011. To define spatio – temporal variations in a quantitative way, identification of spatial distribution of morphological processes and its dynamics over time was carried out by the means of volumetric analysis using DEMs. On the basis of the results it was stated that morphological processes below Włocławek hydropower plant represent the continuous trend of permanent riverbed degradation. Analysis conducted in the frames of this master thesis identify the mean riverbed incision at the level of about 0,1 m per year, which coincides with previous studies for 40 years period. On the basis of comparison of riverbed incision to another rivers in the world with characteristics of the zones below dams, it was stated that impact of activity of Włocławek hydropower plant on the precesses of erosion are considered to be on average level, and thus certainly not catastrophic.

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Abbreviations

USSR – Union of Soviet Socialist Republics

USA – United States of America

E/A - Erosion to Accumulation

GIS – Geographic Information Science

EOF - Empirical Orthogonal Eigenfunction

DEM - Digital Elevation Model

DoD - DEM of Difference

GPS – Global Positioning System

ASL - Above Sea Level

MW - megawatt

GWh – gigawatt hours

kV - kilovolt

RTK - Real Time Kinematic

IDW - Inverse Distance Weighted

TIN - Triangular Irregular Networks

SRTM – Shuttle Radar Topography Mission

1. Introduction

It's almost 5000 years since humans have begun to influence the transformation of rivers due to construction of dams and reservoirs. It is estimated that there are over 60 000 active reservoirs built around the world. Moreover, it is considered that nearly 77% of the total flow of 139 largest rivers in Europe, North America and Russia (former USSR) are affected by individual reservoirs, dams or cascades what is an evidence of the scale of changes in river morphological processes. Particularly important ones are sedimentation processes in reservoirs and erosion or erosion and accumulation ones below the barrages (Babiński 2007).

Development of erosion process below the dam is most often characterized by the rate of riverbed incision and the movement of erosion zone downstream. On the basis of analysed around the world sections of rivers below the barrages, it was stated that the process occurred most intensely in the first years of water damming and in the direct neighbourhood of the dams. Both, from the perspective of safety of dams as well as environmental conditions this phenomena can be dangerous. According to carried out studies, the riverbed decrease can reach locally such values as 20 m, whereas average level of general riverbed incision is estimated to up to 7 m (Raynov et al 1986).

There are numerous studies that documents how river's flow regulation may trigger the channel changes at different temporal and spatial scales (Wanguan et al 2007). In Poland, the most intensively studied part of the river is hydroelectric power plant in Włocławek on Vistula river, which is also the subject of the analysis in this master thesis.

1.1. Problem statement and study objectives

Włocławek Barrage, built on the Vistula river between 1963 and 1970, was designed with the premise that over the next 10 - 15 years a next facility will be built in the Ciechocinek region. It was supposed to be a part of the major plan predicting seven barrages in the lower part of Vistula river, which were expected to take the responsibility of the river regulation. The Włocławek dam construction was planned closely in relation to the forseen next object, which was presumed to guarantee maintenance of the water level at the lower part of Vistula river. Due to the lack of funds and change of the concept regarding dam security, the plan finally was not implemented (Geoland 2000).

Currently, it is 46 years since the Włocławek Barrage works as a single object without any support of a next facility. The object's working conditions much differ from those adopted in the project, therefore the dam does not meet the designed safety requirements and technical conditions both in reservoir exploitation as well as electricity production (TNZ 2006). The process of water damming in such circumstances, exceeds most of the technical parameters and contributes to many changes in the natural environment surrounding the river. Some of them have almost subsided, while the part associated with the transport of sediments is still in progress. On the one hand, there is accumulation of 90% of sediments in reservoir, whereas on the other hand, there is a permanent erosion of the riverbed below the barrage (Babiński 1982, 1992, 2002).

A hydropower plant, in accordance with the adopted pumped - intervention operational regime, is a reason of temporarily rapid changes in the movement of water in the stream channel below the barrage. It should be noticed that water discharge in the lower parts, during off – peak periods which is approximately $400 \text{ m}^3/\text{s}$, increases to more than $2000 \text{ m}^3/\text{s}$ during a peak operation. That increase occurs suddenly and causes within tens of minutes rise of the water level up to 2 m. These pulsed water impacts intensify the channel's erosion (Geoland 2000).

According to the previous studies, the erosion process leading to riverbed incision has covered a section of 9,2 km already within four years after hydroelectric facility inception. After 30 years of its operation, the riverbed in its neighbourhood decreased by almost 3,5 m, reaching its original level only on the distance of 33 km from the dam (Babiński 2007). The size of the existing erosion below the facility, has already overrun the project's assumptions several times. Lower water level exceed by approximately 2,5 m – 3 m conditions to which the barrage, buildings and devices located below it, have not been adapted to. Their stability is on the very edge of the limit values as the difference between the level of accumulated waters and level of the water in the channel below the dam is 14 m, which is 25% higher that it was previously assumed. The higher water pressure affecting the facilities along Vistula river increases possibility of the break-down virtually anytime. If it happens, a huge leakage of sediments accumulated over the years at the bottom of reservoir is predicted. (Geoland 2000).

The lowering of riverbed is intensified by creation of potholes with the depth up to 12 m during flood waves. This fact induced hydrotechnicians to build in 1998, at the distance of 520 m from the dam, a correction treshold resulting in micro reservoir. Its water was supposed to support the barrage, however after 7 years of its activity, a

decrease of elevation up to 16 m took place below it. Due to this fact, each time when flood wave passed, the process of erosion was accompanied by the destruction of the threshold. It is the sign indicating the change of the bottom from the stable so far to unstable one, what in the near future can significantly intensify the process of riverbed decrease (Babiński 2007).

In order to reduce phenomenon occurring in the region of the Włocławek Barrage, there were and still are all kinds of remedial actions conducted. Most of them, however, are ad hoc actions and do not solve the cause of all the problems. Only the construction of the next barrage in the Nieszawa district would provide in a sustainable manner a safe operational conditions both for objects of Włocławek Barrage as well as other facilities in the part currently being a subject of erosion processes. The lack of decision to proceed the implementation of this project could lead in the coming years to building disaster in the size threatening the lives of many people, causing huge economic losses and ecological catastrophe, both in the valley of Vistula river below Włocławek, as well as on the area from Włocławek to Płock. Until the next barrage will be build, the constant monitoring of morphological changes in the area of the dam is required. It will enable to determine the pace of the changes and its trends (Geoland 2000).

The objective of the thesis study is to determine the state of the bottom of the part of Vistula River below Włocławek Barrage. The analyses will be based on bathymetric data acquired during the measurements made in the period 2008-2011. The data from different time periods will determine the rate of change of the river bottom topography, which as a result will allow to plan further steps regarding the barrage exploitation.

1.2. Thesis structure

The thesis is divided into six chapters. The first one is the introduction to the subject of this work. It includes a detailed description of the problem regarding research area located in the neighbourhood of hydroelectric power plant in Włocławek and objectives of the master thesis.

The second chapter is devoted to literature review. It includes among others general information on the problem in the global scale as well as information on the model of riverbed degradation downstream the dam. Current studies of riverbed degradation below Włocławek dam are described in details as the most important part of this chapter. This section includes also description of so far analysis methods used while

examining riverbed changes and description of factors influencing dynamics of riverbed degradation downstream the dam.

Chapter number three includes methodology description. In the first section there is provided detailed characteristic of the study area, i.e. hydropower plant and Vistula river, whereas in the second part information regarding input data are discussed.

Chapter number four is the core of this thesis. It includes all conducted analysis like differential analysis of DEMs, cross – section and longitudinal profiles analysis as well as summary statistics and assessment of accuracy of DEMs derived from contour lines.

In the fifth chapter the discussion on obtained results was conducted. The outputs of the analysis were compared to general trends and current studies described in the second chapter of this thesis, as well as a general synthesis of the problem was described.

The thesis is finished by the general summary and conclusions presented in chapter six.

2. Literature review

2.1 General overview of the problem in the global scale

Rivers are considered to be one of the most common and important factor of surface formation on earth. At the same time they are very sensitive to any forms of disruptions (Klimaszewski 1978). Regardless of their size, course character and climate zone of location, construction of a dam is considered to be the strongest possible disturbance in a fluvial system. Researches conducted on a subject of hydrotechnical structures and their influence on natural environment of rivers and qualitative and quantitative characteristics of the events following dam construction are very extensive (Habel 2013).

Studies carried out (Williams et al. 1984, Raynov et al. 1986, Andrews 1986, Babiński 2002) on several rivers during last decades allowed to make a statement that erosion problem downstream of the dam is the problem of multiple hydrofacilities activity around the world. The exemplary values of riverbed decrease in cross-section profiles for the period up to 60 years of dams' activity in the world is presented in Table 1.

Table 1 Decrease of riverbed elevation downstream of the dam of part of selected rivers in the world

Nb	River, dam (reservoir), region (country)	Number of observation years	Riverbed decrease in cross-section profile (m)
1	Kolorado, Glen Canyon, Arizona	9	7,3
2	Kolorado, Hoover, Arizona	13	7,5
3	Kolorado, Davis, Arizona	26	5,8
4	Kolorado, Parker, Arizona	27	4,6
5	Kolorado, Imperial, Arizona	18	3,1
6	Jemez, Jemez Canyon, New Mexico	12	2,8
7	Arkansas, John Martin, Colorado	30	0,9
8	Missouri, Fort Peck, Montana	36	1,8
9	Missouri, Garrison, North Dakota	23	1,7
10	Missouri, Fort Randall, South Dakota	23	2,6
11	Missouri, Gavin's Point, South Dakota	19	2,5
12	Medicine Creek, Medicine Creek, Nebraska	3	0,6
13	Middle Loup, Milburn, Nebraska	16	2,4
14	Des Moines, Red Rock, Iowa	9	1,9
15	Smoky Hill, Kanopolis, Kansas	23	1,5
16	Republican, Milford, Kansas	7	0,9
17	Wolf Creek, Fort Supply, Oklahoma	27	3,4
18	North Canadian, Canton, Oklahoma	28	3,0
19	Canadian, Eufaula, Oklahoma	6	5,1
20	Red, Denison, Oklahoma-Texas	16	3,0
21	Neches, Town Bluff, Texas	14	0,9
22	Chattahoochee, Buford, Georgia	15	2,6
23	South Canadian, Conchas, Nev Mexico	7	3,0
24	Salt Fork, Arkansas, Great Salt Plains, Oklahoma	9	0,6
25	Rio Grande, Elephant Butte, Texas	15	1,8
26	An Sabee, Foote Sariyar (Turkey)	15	1,5
27	Saskatchewan, Squaw Rapids	13	1,2
28	Cheyenne, Angostura	16	1,5
29	South Saskatchewan, Dietenbaker	12	2,4
30	Huang He, Sanmenxia, China	4	4,0
31	Syr-Daria, Farchacka	7	1,3
32	Murgab, Hindukuska	60	4,0
33	Murgab, Tadhenska	7	5,6
34	Isar, Dingolfing	14	2,8
35	Lech, Forgensee	10	0,6
36	Saalach, Reichenhall	47	4,6
37	Wertach, Schwabmunchen	5	1,8
38	Dunaj, Faimingen	12	1,0
39	Dunaj, Ingolstadt	14	1,8
40	Rhein, Gerstheim	1,5	2,5
41	Wisła, Włocławek	27	3,5

Source: Babiński 2007

On the basis of analysis of American rivers it was calculated that riverbed decrease below dams may reach a range between 0,4 m to 38 m, with the most frequent (modal) depth of 2 m. For 98% of analyzed rivers, this value was less than 10 m (Williams et al. 1984). A simple regression of degradation of riverbed in time, calculated on the basis of analysed selected rivers in the world is presented in Figure 1.

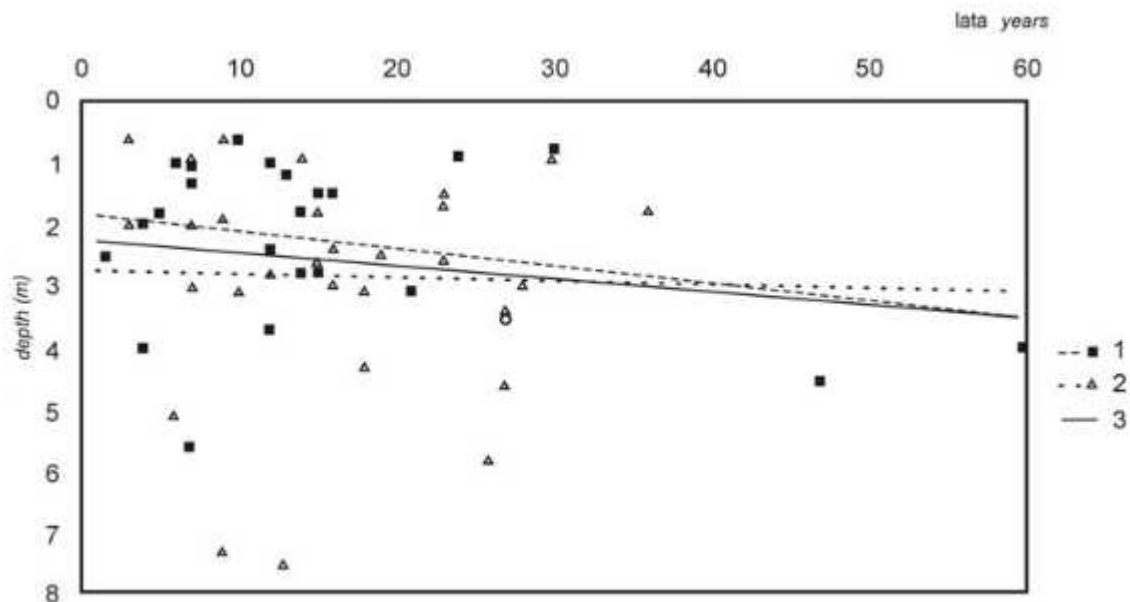


Figure 1 The rate of riverbed degradation below selected dams in the world (m) and it's straight regression (on the basis of data from Table 1)

1 – American rivers, 2 – other rivers of the northern hemisphere, 3 – all analysed rivers

Source: Babiński 2007

The large spread of measurement points and low coefficient of regression for three lines (less than 0,5), indicate a lack of correlation between these characteristics. Nevertheless, the general tendency of riverbed incision over time can be stated in all cases. It is found that erosion process occurred most intensively in the first years after damming period. The greatest decreases of riverbed were then noted. Moreover, erosion below dams usually took values within the range of 2 – 4 m (Babiński 2002).

An important element in determination the extent of riverbed erosion below dams, in addition to riverbed incision, is the study of the reach of erosion zone and the rate of its shifting. On the basis of the studies, it was found that in all analysed cases development of erosion zone was the most dynamic in the first years of dam operation as well (Figure 2). Record – holder is Colorado River (USA), where after 6 months of hydrofacility activity erosion zone has moved to a distance of 21 km, which gave the highest rate in the

world (42 km per year). After one year the distance reach was 28 km from the dam, after two years - 50 km and after 14 years - 111 km (Williams et al. 1984). The average annual rate of shifting is defined at the level from 0,4 km to almost 36 km in a few cases like e.g. Syr-Dyria river

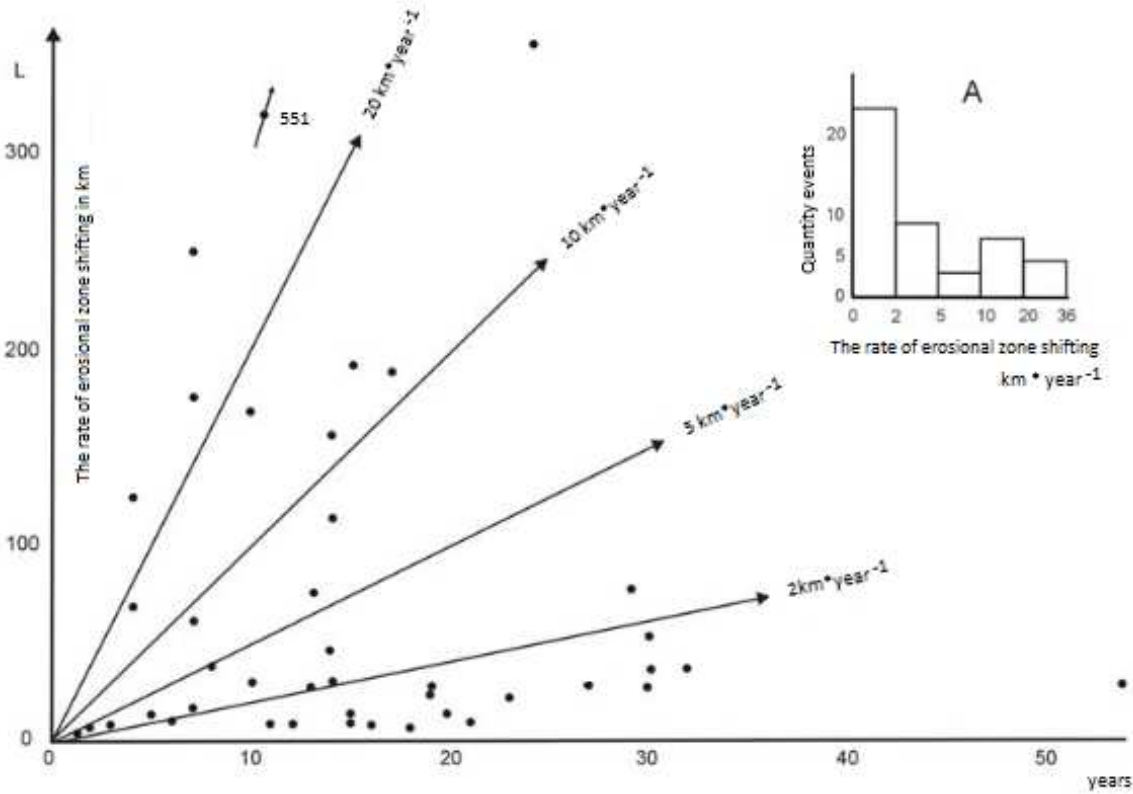


Figure 2 The rate of erosional shifting on the basis of selected rivers in the world

A – Quantity events in erosional zone shifting group

Source: Babiński 2002

below Farchatska dam (Raynovi et al. 1986) or Nile below the Nasser Reservoir with the rate of 30,6 km per year. Moreover, presented data indicates that the most numerous group are rivers in which the rate of erosion development range from 0,1 – 2 km per year, whereas with the increase of the rate of erosion zone shifting, the number of examined rivers in particular groups decreases.

Erosion of a riverbed below dams is a complex process, which appeared in each selected river, nevertheless of its location and characteristics. The process dynamics is difficult to predict, therefore this is still a large area of research. However, based on the research already conducted a general model of erosion was able to be developed. Its main assumptions are described further in this thesis.

2.1.1 General model of riverbed erosion downstream the dam

Construction of dams changes hydraulic and sediment transport characteristics of the river. It is generally stated that erosion occurring downstream the dam is so obvious that during each hydrofacility design on rivers, protection of riverbed against its influence is taken into account. However, based on the experiences, the reality looks a little bit different. Process of erosion is usually completely ignored as long as it does not create specific problems (Babiński 2007).

The factor that triggers erosion process below the dam is depletion of clastic debris in water. Conducted studies have shown that reservoirs catch from 80% to 99,5% of total amount of clastic material. When a significant proportion of such debris is accumulated in reservoir, the water flow released is relatively free of sediments. Consequently, the flow has excess energy due to transporting less sediment than it is capable. As a result, river aims to compensate the required sediment load through the erosion of riverbed followed by erosion of the banks (Kondolf 1997).

The studies conducted by Schumm 1969, Gregory et al. 1974, Emmett 1974, Knox 1977, Williams et al. 1984, Hooke 1997, Grams et al. 2002, Downs et al. 2004, Gregory 2006 allowed for identification a general model of riverbed degradation downstream from the dam (Chien 1985). Its characteristics was developed on the basis of exemplary 150 river sections around the world (Figure 3) (Babiński 2007).

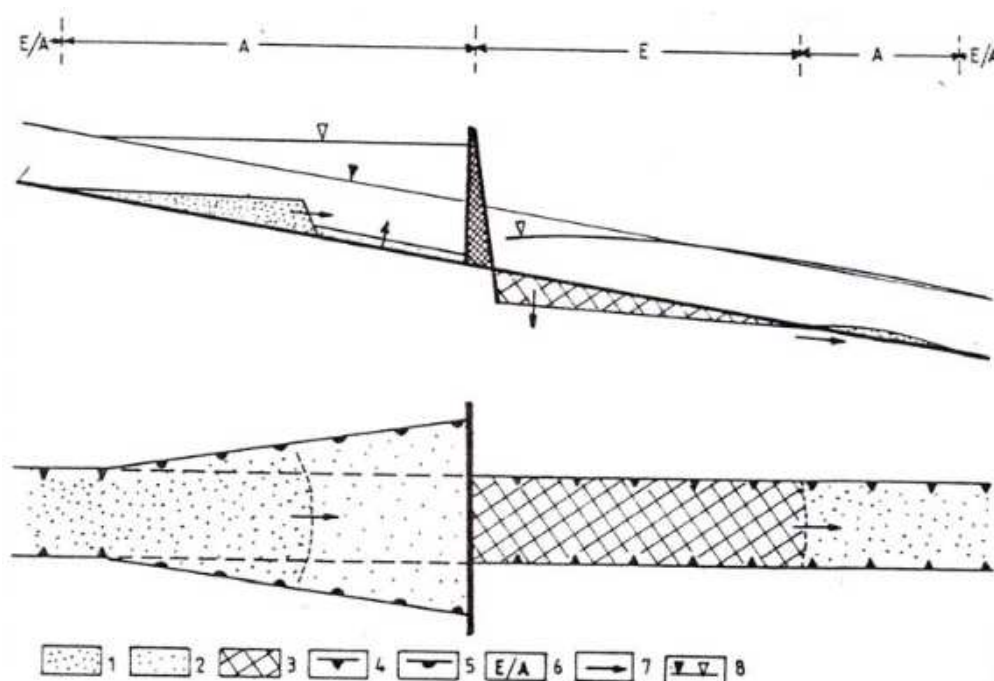


Figure 3 Influence of a dam on fluvial processes in alluvial rivers

1 – zone of bed load accumulation; 2 – zone of suspended load accumulation; 3 – erosional zone; 4 – side erosion; 5 – abrasion; 6 – segments of different degree of channel development (E/A – transit, A – accumulation, E – erosion); 7 – direction of fluvial processes; 8 – water level before and after dam construction

Source: Babiński 2002

It is stated that riverbed erosion in regulated rivers occurs at much higher rate than it does in natural rivers (Knighton 1998). However, the extent to which riverbed degradation occurs is primarily dependent on the extent to which the flow has been regulated. Development of erosion process below the dams is most often characterized by the rate at which the riverbed decrease and the front of erosion zone is moving down the river (Childs 2010). In the analyzed sections of rivers, it was found that the process occurred most intensively in the first years after damming period and in the direct neighbourhood of barrage (Babiński 2007). However this process may extend to hundreds of kilometers. Due to the fact that huge distances may be required to regain sediment load by the water, the front of erosion zone can progress up to ten of kilometers per year (Childs 2010). Although, there is stated a general tendency to erosion distinguish in time, more detailed analysis represent this process more complex. It was founded that after a period of rapid riverbed transformations during the construction of thresholds, partial suppression of erosion occurs as a result of filling the reservoirs with water. Only after that period, lasting from several months to several years, the process becomes active again, being modified due to geological and morphological conditions and human activity in time (Babiński 2007).

Analyzing the process of erosion in a period longer than few years, it is concluded that it is characterized by high irregularity, but with a general tendency to expiration. However American research has shown that the period of 20-40 years of activity of water thresholds does not always permit to state the tendency of decreasing dynamics of this process in time. It even indicates its almost straight-line development. A similar trend was observed in case of many Russian dams (without support from lower-located reservoirs) and also on the Vistula below the dam in Włocławek (Williams et al. 1984). Nevertheless, these situations may only indicate a still unstable riverbed and lack of resistance for the erosion process.

Based on the above it can be stated that erosion process is the phenomenon that causes significant changes of riverbed over time, both in short and long term periods. To

fully understand the processes occurring in a given area and to prevent such changes, riverbed analysis are of a great importance. They not only allow to constantly monitor all changes, but first of all they can predict the future tendencies and provide a possibility to react on time.

2.1.2 Factors influencing dynamics of riverbed degradation downstream the dam

The process of erosion below dams depends mainly on three factors: water flow, topography and geological structure of the channel (Kondolf 1997). However, the geology aspect is considered to be the most important one.

Erosion process is a hydraulic action derived from the energy of flowing water. It can be compared to a situation when riverbed materials lose their shear strength and its particles disconnect from each other. The particles are eroded when water flow velocity equals a certain value that is called critical velocity. This value is defined on the basis of diameters of grains (Zieliński 2014). These two parameters (grain size and critical velocity) were frequently used for erosion process interpretation from many years. However, currently other parameters start to be included as well. Among them are parameters describing geotechnical conditions of materials building the river floor. Soils strength parameters and physical parameters connected with them (e.g. relative density or plasticity index) are thought to have one of the biggest impact on erosion rate (Smaga 2015).

Resistance for erosion is dependent on the type of soils. We distinguish here cohesion and cohesionless ones. Cohesion soils mean high clay content, which don't crumble and can be excavated with vertical slideslopes. They are hard to break up when dry and are plastic when moist. This type of soils include among others sandy clay, silty clay, clay and organic clay (Blasio 2011). Their erosion resistance usually depends on such parameters like critical shear stress caused by the flow, critical shear stress for erosion, density of sediment particles, median particle diameter and sediment consolidation coefficient (Smaga 2015). Regarding cohesionless soils, they include any free-running materials like sand or gravel whose strength depends on friction between particles (Blasio 2011). In case of cohesionless soils, erosion resistance is correlated with particle shape and size, density and porosity. They are usually eroded when critical shear stress amounts to $0,1 - 5 \text{ N/m}^2$ (Briaud et al. 2003).

Apart from geological factors, the intensity of erosion might be increased also by daily fluctuations of water levels related to the operation of hydropower plants. Water levels exceeding the level of the flood plains contribute to increase of share of clastic materials in channel processes. Small flows, in turn, limit them to the regulation zone of the channel. In this process, however the main role is played by daily fluctuations of water levels, exceeding the level of so-called full – load water (Babinski 1997).

2.2 Review of current studies on riverbed below Włocławek hydropower plant

Works related to construction of a dam on Vistula river in Włocławek began in May 1962. It was also the time when regulation activities of adjusting river channel to new hydraulic conditions were started. During implementation of these works it was necessary to consider first of all changes in the future course as well as the effects of increased erosion process (Babiński 1982). In this case, both mechanical composition of the material building the river bottom and its thickness have a huge impact on the course of erosive and accumulative processes below dams. In case of Vistula, the riverbed consists mainly of sandy formations with a grain diameter ranging from 0,37 to 0,57 mm (Babiński 1992). It means that Vistula channel, due to its geomorphological structure, is susceptible for riverbed erosion itself.

The main aspects of development of riverbed erosion below dams include the rate of channel bed incision and movement of the front of erosion zone downstream (Williams et al. 1984). Frequently these phenomena are studied on the basis of observation of changes in the cross – sections and longitudinal profiles of a riverbed. Comparison of profiles of morphometric parameters at various periods allows for determination of the changes, however in order to provide reliable results, they should be based on several decades of observations (Klimek 1983).

The section of Vistula riverbed below hydropower plant in Włocławek was the subject of many studies. Most of them were conducted by Babiński (1982, 1992, 1997, 2002, 2007, 2014) and Habel (2013). Majority of them is focused on quantitative descriptions of riverbed evolution on the basis of analysis of cross – sections and longitudinal profiles. Based on its results it can be stated that a phenomenon of erosion process has become visible already from the moment of complete crossing of riverbed with a dam, i.e. from October 1968.

First detailed research (Babiński 1982) on changes of Vistula riverbed below hydropower plant was taken soon after start of its operation. First two years of damming was the time of creation of a new morphodynamic riverbed system. Already in this period, an extensive pothole with a depth of over 10 m in the vicinity of the dam was created (Babiński 1997). Based on the analysis of 45 cross – sections for the period of 1967 – 1972 and its results presented in Table 2, it is stated that in the timeframes from August 1967 to October 1969, on the section from the dam to first cross – section profile (670 m), there was over 1,1 mln m³ material eroded, whereas only 0,3 mln m³ accumulated. The calculated ratio of erosion to accumulation (E/A) for this section was at the level 3,83, which means almost 4 times higher erosion in comparison to accumulation. On the profiles from 1 to 10 and from 10 to 20, a slight dominance of erosion is noted either, as the E/A ratio was equal to 1,28. On further sections of Vistula, the ratio was smaller than 1 and range from 0,21 to 0,79. It means that further downstream, the process of material accumulation took place. In general, within first two years, over the distance of 10 km (to section 33) about 3,74 million m³ was eroded, whereas about 3,24 mln m³ accumulated giving the comparison ratio at the level of 1,15 (Babiński 1982, 1992).

Table 2 Amount of eroded (E) and accumulated (A) material between particulat cross – section profiles in the period from 25 August 1967 to 23 November 1972 in m3

Cross-sections	Distance (m)	25 Aug 1967 – 1 Oct 1969				1 Oct 1969 – 6 Nov 1970				6 Nov 1970 – 11 Jun 1971			
		E (m ³)	A (m ³)	A-E (m ³)	Ratio (E to A)	E (m ³)	A (m ³)	A-E (m ³)	Ratio (E to A)	E (m ³)	A (m ³)	A-E (m ³)	Ratio (E to A)
0 – 1	670	1 116 220	291 450	- 824 770	3,83	529 300	162 140	- 367 160	3,26	546 050	312 890	- 233 160	1,75
1 – 10	1800	1 051 956	823 233	- 228 723	1,28	250 110	465 456	215 346	2,04	948 033	318 096	- 629 937	2,27
10 - 20	2060	724 972	565 980	- 158 992	1,28	674 403	309 585	- 364 821	2,18	483 052	301 488	- 181 564	1,60
20 - 26	2100	299 145	430 288	131 143	0,70	797 173	353 072	- 444 101	2,26	340 045	729 650	389 605	0,47
26 - 29	1415	128 193	601 130	472 937	0,21	733 507	150 835	- 582 672	4,86	112 303	523 865	511 562	0,18
29 - 33	2260	418 580	532 690	114 110	0,79	606 558	229 463	- 377 095	2,64	356 360	727 825	371 465	0,49
0 – 33	10305	3 739 066	3 244 771	- 494 295	1,15	4 291 051	1 670 548	- 2 620 503	2,57	2 785 843	3 113 814	327 971	0,89
33 - 45	8305	2 635 640	1 554 563	- 1 081 077	1,70	2 264 475	4 489 600	2 225 125	0,50	3 185 225	2 106 652	- 1 078 573	1,51

Cross – sections	Distance (m)	11 Jun 1971 – 26 Oct 1971				26 Oct 1971 – 23 Nov 1972			
		E (m ³)	A (m ³)	A-E (m ³)	Ratio (E to A)	E (m ³)	A (m ³)	A-E (m ³)	Ratio (E to A)
0 – 1	670	67 000	122 610	56 510	0,55	251 920	259 290	7 370	0,97
1 – 10	1 800	223 510	201 423	- 22 087	1,11	349 737	293 573	- 56 164	1,19
10 – 20	2 060	176 360	420 493	245 133	0,42	678 913	232 050	- 446 863	2,93
20 – 26	2 100	475 037	251 363	- 223 674	1,89	401 043	250 087	- 150 956	1,60
26 – 29	1 415	495 467	89 855	- 405 612	5,51	410 448	158 490	- 251 958	2,59
29 – 33	2 260	265 837	291 673	26 836	0,90	511 963	532 389	20 426	0,96
0 – 33	10 305	1 702 211	1 378 417	- 323 794	1,23	2 604 024	1 725 879	- 878 145	1,51
33 – 45	8 305	1 970 595	1 254 265	- 716 330	1,57	287 300	2 505 210	2 217 910	0,11

Source: Babiński 1982

Analysing the next period, from October 1969 to November 1970, for the entire analysed sections, erosion outweighed accumulation processes. The level of ratio was always greater than 1 and ranged from 2,04 to 4,86. At that time, the amount of eroded material from riverbed was equal to over 4,29 mln m³, whereas accumulated one only to 1,67 mln m³. However, material that was eroded has been partially deposited downstream, between sections 33 – 45, at a distance from 10 km to over 18 km from the dam. The proof for that is the level of calculated ratio at the level of 0,5.

During two following periods, i.e. November 1970 – June 1971 and June 1971 – October 1971, a suppression of erosion was noted. Average erosion to accumulation ratio amounts from 0,89 to 1,23. Predominance of erosion over accumulation occurred in the zone located in the direct vicinity of the dam (cross section 1-10) and from section 33 to 35, where E/A ratio was 1,51 and 1,57 respectively.

As for the previous analysed period the process of riverbed erosion decreased, in the period from October 1971 to November 1972 increased erosion is noted again. The E/A ratio was over 1,5 for almost entire section. The exception were the first and last sections (sections 29-33), where the ratio didn't exceed the value of 1. In turn, accumulation zone included area between cross – sections 33 – 45, with the E/A ratio of 0,11 (Babiński 1982, 1992).

On the basis of further studies (Babiński 1997) carried out for the period to 1987, it is noted that the process of erosion didn't progress, as it was initially supposed. On the contrary, erosive zone at that time was characterized by a varied pace of movement downstream with different loss of riverbed material dependent on time (Table 3).

Table 3 Dynamics of erosion process below Włocławek dam

Years	Riverbed loss		Movement of the front of erosion zone	
	mln m ³ /year	mln m ³ in total	km/year	km in total
1968 – 1969	0,8	0,8	2,0	2,0
1969 – 1972	1,1	3,2	2,4	7,0
1972 – 1984	0,5	5,9	0,6	6,8
1984 - 1987	1,6	4,7	2,7	8,0

Source: Babiński 1997

Already after four years of activity of hydropower plant, erosion zone moved over 9 km from water threshold, with loss of material at the level of over 4 mln m³. These values give the average speed of front of erosive section movement of 2 km per year, with the loss of material of about 1,0 mln m³ per year. A slight decrease in the erosion zone movement in the

first year of research was related to damming and filling reservoir. In the next 12 years, the rate of movement of erosion decreased to 0,6 km per year, with average riverbed loss at the level of 0,5 mln m³. It meant movement of erosion zone at the distance of 15,8 km, with a negative balance of eroded material amounted to 9,9 mln m³ (Babiński 1992).

From the comparison of the data from the first four years (1968 – 1972) and the next twelve (1972 – 1984), it might be assumed that erosion process below the dam has adopted a curvilinear dependency with tendency to expire in time (Babiński 1982). Meanwhile, the next three – year research period (1984 – 1987) showed another increase in the dynamics of the erosion zone. Its intensity even exceeded the value from the initial period. The rate of movement of the front of erosion zone increased to 2,7 km per year with the average amount of material eroded of 1,6 mln m³ per year. Till that time, since the beginning of hydrofacility operation, erosion zone has already moved to a distance of 23,7 km from the dam, while the balance of riverbed loss was closed to the value of 14,6 mln m³. These data, assuming a relatively constant distribution of erosive process in longitudinal profile of the 400 m wide channel, indicates a lowering of the bottom of the river floor from 2 to 3 m on the 3 km section below the dam, 1 – 2 m on the further 10 km to 0 - 1 m on the final 10 km (Babiński 1982, 1992).

Analysing erosion process in 1970 – 1987 in terms of mean values, it can be noticed that on average there was a loss of riverbed material in the amount of 0,7 mln m³ per year, while the front zone of erosion zone moved at 1,1 km (Babiński 1997).

Comparison of the studies conducted (Habel 2013) for decadal perspective, i.e. 1969 – 2009 represent a constant trend of channel incision (Figure 4).

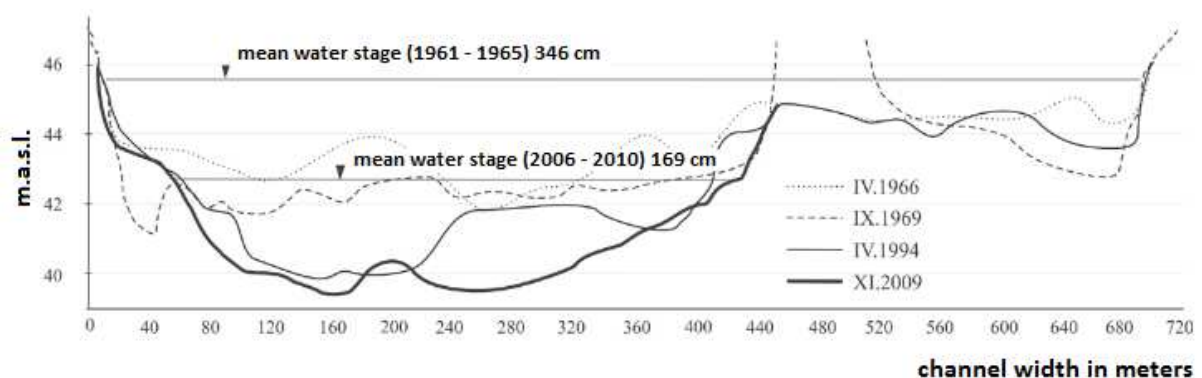


Figure 4 Changes in cross – section of Vistula river at the gauging profile in Włocławek

Source: Habel 2013

Variations in depths with tendency to decrease downstream from the dam, confirm a general trend of riverbed erosion process below dams (Chalov et al. 2001, Wang et al. 2004). Comparison of mean depths, which were calculated for cross sections of 1969 and 2009, indicates increase of a mean depth of the channel on average by 3,5 m in the vicinity of the dam (Figure 5) (Habel 2013).

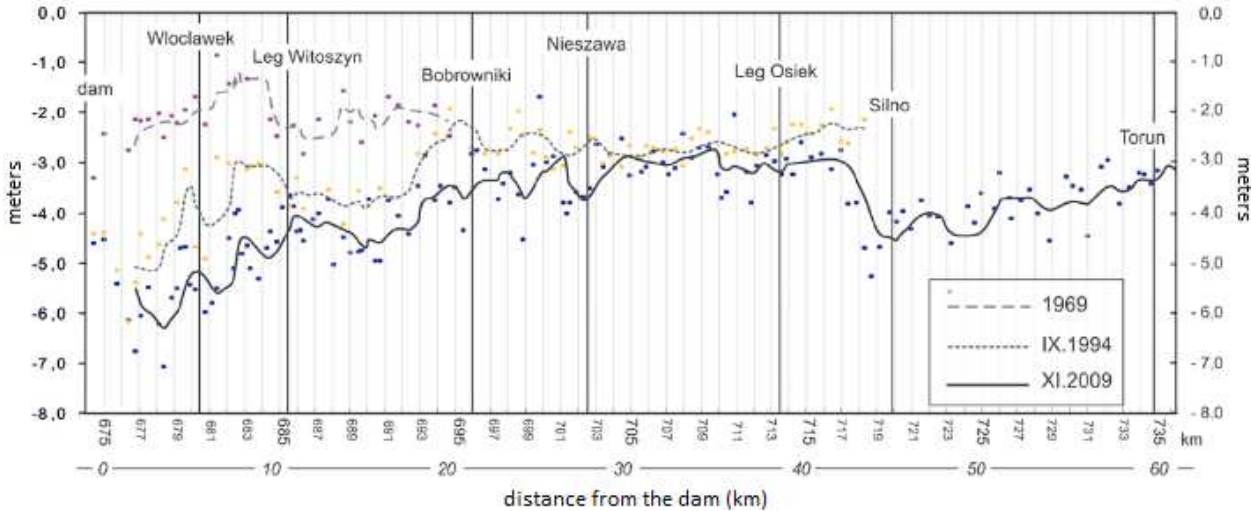


Figure 5 Change of hydraulic mean riverbed depths in time (points on chart). Continuous line denote moving average

Source: Habel 2013

At the distance of 10 – 20 km away from the hydro facility, the variation in the mean depths at the defined lowest reach, rised on average by 2,1 m. Comparison of variations in depths for the distance of above 20 km was carried out only for the period of 1994 – 2009, due to the lack of data available for the proceeding years. For this time, at the reach from 20 to 30 km, the riverbed incised on average by about 0,6 m.

The analysis of mean depths measured on cross – sections enable to asses the vertical erosion below the dam. On the basis of data from three different periods: 1969 – 1994, 1994 – 2009 and 1696 – 2009, the annual rate of mean increase of channel depth was estimated (Table 4). During the 40 years of hydropower plant operation, the mean rate of riverbed decrease in the neighbourhood of the dam at the reach from 0 to 5 km, was estimated to 8,6 cm per year. On the other hand, during the first 25 years of the dam operation, the level of riverbed incision amounted to 9,2 cm per year, whereas in the period of 1969 – 2009 a small decrease was recorded at the rate of 7,5 cm per year (Habel 2013, Babiński 2007).

Table 4 Mean annual rate of channel decrease at the 45 km long reach below Włocławek dam in the period of 1969 - 2009

River kilometre River reach	Distance from the dam in km	Increase rate of mean depths observed in given periods (in cm-year ⁻¹)		
		1969-1994	1994-2009	1969-2009
675-680 Dam – Włocławek city	0 to 5	9.2	7.5	8.6
680-685 Włocławek – Łęg Witoszyn	5 to 10	8.2	11.1	8.6
685-696 Łęg Witoszyn – Bobrowniki	10 to 21	4.4	5.7	5.3
696-702 Bobrowniki – Nieszawa	21 to 27	-	4.0	-
702-713 Nieszawa – Łęg Osiek	27 to 38	-	1.5	-
713-720 Łęg Osiek – Silno	38 to 45	-	2.3	-

Source: Habel 2013

At the distance of 5 – 10 km further down the river, in the period of 1994 – 2009, the mean value was estimated to 11,1 cm per year, which meant that erosion process has been intensified in comparison to previous years. Despite it is often assumed that riverbed erosion below hydro facilities tends to diminish in time (Williams et al. 1984), the channel incision of Vistula has shown clearly intensified erosion at that time. Such situation may arise from the fact of geological structure of the channel, which represents favourable conditions for selective erosion (Babiński 2007, Habel 2013).

Another element that needs to be considered while studying the morphodynamics of river floor are longitudinal profiles. Analysis of its variations in time enable to assess the erosion zone and debris accumulation zone movement rate on the analysed river section (Babiński 2002). Based on the research conducted (Table 4), the scale of erosion appears to decrease progressively with distance. The greatest decrease of riverbed in the thalweg zone was noted at the reach of 10 - 21 km away from the dam, on average by 1,62 m, while the smallest one was determined at the distance of 45 – 60 km from the dam, with the mean rate of 0,52 m. Additionally, analysis of dynamics of riverbed changes in longitudinal profiles, stated development of deposition zone both in terms of its length as well as the thickness of the sediments layer covering the bed in the thalweg (Table 5) (Habel 2013).

Table 5 Vertical changes in the Vistula riverbed of the selected reaches below
Włocławek dam

River kilometre River reach	Distance from the dam in km	Vertical changes in thalweg zone in given periods of time (in cm)			
		1978-1980	1978-1990	1978-1995	1978-2009
685-696 Łęg Witoszyn – Bobrowniki	10 to 20	-22	-33 ↓	-34 ↔	-162 ↓
696-702 Bobrowniki – Nieszawa	20 to 26	-4	-18 ↓	-48 ↓	-131 ↓
702-713 Nieszawa – Łęg Osiek	26 to 37	+18	+7 ↓	-49 ↓	-47 ↔
713-720 Łęg Osiek – Silno	37 to 45	-4	+31 ↑	+57 ↑	-55 ↓
720-735 Silno-Toruń	45 to 60	-2	+62 ↑	+51 ↓	-52 ↓

Tendency regarding bed changes in comparison to the preceding period: ↓ – erosion, ↑ – deposition, ↔ – stabilization (transportation).

Source: Habel 2013

According to Habel (2013), the rate of movement variations dependent on deposition and erosion zones arose not only because of geological structures of the bottom and geometric features, but also due to water flow conditions dominant in the analysed period.

It is officially stated that damming a river contributes to radical changes in fluvial processes. Particularly, it disrupts the transport of bed load and its renewal below dams. Above results of current studies regarding riverbed of Vistula below Włocławek hydropower plant, confirm that erosion process on this river section is still the problem as the development of the phenomenon is still progressive in time. Due to this fact further studies are required to monitor subsequent erosion expansion.

2.3 Methods of riverbed dynamics analysis

In most rivers worldwide, activities such as dam construction have disturbed continuity of sedimentary transport causing accelerated erosion. In large scale systems, the effects of continuous human-induced perturbations usually become visible over a spatial stretch of tens of kilometers and over a time span of decades. This indicates the importance of synthetic examination of how anthropogenic activities in rivers affect sediment processes and corresponding morphological responses. Better understanding on the relations between river

evolution and human alterations can make a crucial improvement on rational management of the watershed (Yuhi et al. 2013).

Diverse human-induced morphological changes have been already widely studied during last decades (e.g. Kondolf 1997, Yuhi 2008, Dang et al. 2011). However, it is usually difficult to completely understand the temporal and spatial variations that take place in the river channel and to evaluate combined effects of human interferences on them. Therefore, analysis of the long-term and large-scale morphological changes over time requires comprehensive approach. There are numerous methods currently used as the mean for riverbed examination. Sometimes they are used one at a time, while another time as a combination giving extensive source of knowledge about processes occurring. The most common approaches are described further in this chapter.

2.3.1 Planimetric analysis

One of the simplest approach for characterization of river's morphological changes is measurement and analysis of planimetric parameters. The features that are considered to be planimetric are those elements that are non dependent on elevation and are represented on two - dimensional maps (Hart 1998).

Analysis of river's planimetric parameters include such features as valley width, sinuosity, confinement, meander belt width, meander amplitude and wavelength, as well as radius of curvature. Despite these factors are not directly related to riverbed processes, from its measurements different kind of parameters related to e.g. erosion or sediment routing can be calculated (Leopold et al. 1957, Brice 1975, Thorne et al. 1997).

Planimetric morphological datasets are usually generated from maps, multi-temporal satellite images and other remotely sensed data which can provide precise estimation of physical processes variability and relevant information for possible rates and magnitude of expected channel changes being response to human activities and bed evolution (Zahedul Islam et al. 2017). Maps and aerial photographs are mostly used for this purpose. Historical maps ensure valuable information in regard to channel position, complexity and simplification previously to the appearance of aerial photography. Although old maps can only provide qualitative information, they are often used for assessing river morphology prior to the human pressures and to better understand the characters and locations of human interventions (Kondolf et al. 2016).

Aerial photographs are generally better than maps. With its decadal intervals they are best for determination of planform changes over time. Rivers and its characteristics represented on photos with different scales, can be digitized and then overlain in GIS-based framework allowing for direct comparison and analysis. The use of satellite images to study of morphological changes has continuously increased with improvement of images resolution (Thorne et al. 1993), however in planimetric analysis their application is still reserved to sufficiently wide rivers due to precision of measurements.

Regarding bed elevation data, there are two types of representation that can be generally used for planimetric features. The first one is representation of spatio-temporal distributions by plotting particular parameter versus distance downstream within the timeframe of different years, and the second one – representation of temporal trend by plotting mean value of a parameter along a given reach versus time. First type of representation enable visualisation of spatial variation of specific planimetric parameter and compare its values at the same point for different years (Figure 6), whereas the second type of representation gives information on the temporal trend (or trajectory) of the parameter (Figure 7) (Kondolf et al. 2016).

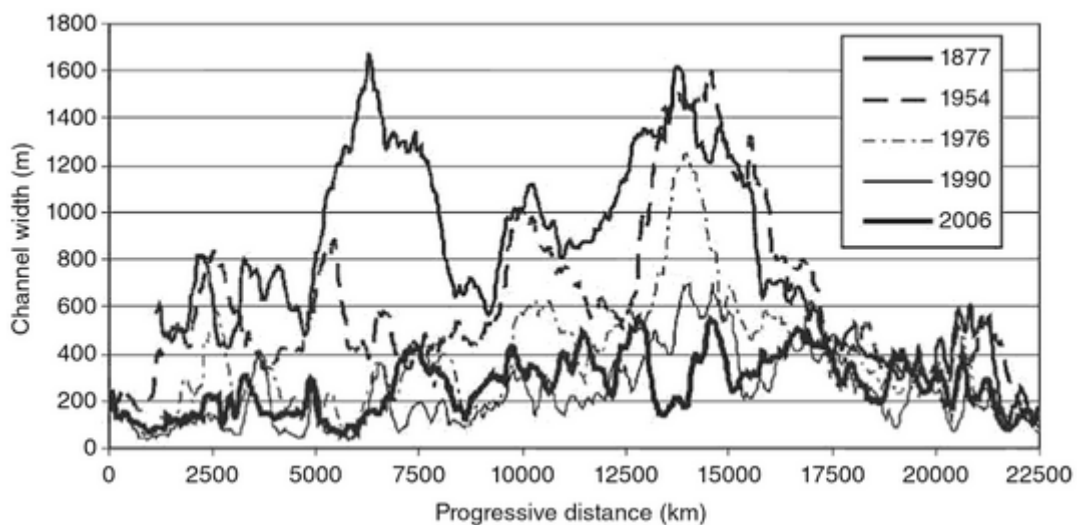


Figure 6 Example of spatio-temporal changes regarding channel width of Trebbia River (Italy)

Source: Pellegrini et al. 2008

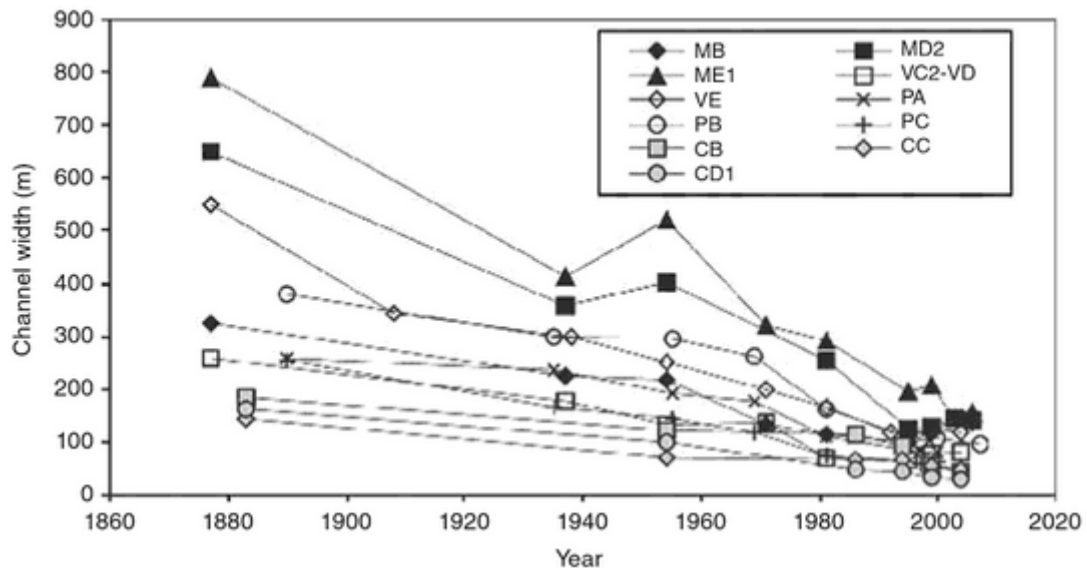


Figure 7 Example of temporal trends regarding channel width along defined reaches of four Apenninic rivers (Italy)

Source: Rinaldi et al. 2008

Planimetric analysis are useful in many fields. However due to their planform characteristics its values are often combined with other parameters or analytical methods further described in this chapter.

2.3.2 Volumetric analysis

Determination of spatial distribution and magnitude of morphological processes over time within rivers is notoriously difficult. However, volumetric analysis is a mean that makes it possible. As its name implies, volumetric analysis is a quantitative approach which involves measurement of the volume of specific factors. Dependent on source data, there are several methods that allow determination of riverbed changes over time. The most common ones are:

- empirical orthogonal analysis,
- measurement profiles analysis (cross-section and longitudinal),
- digital elevation model analysis.

2.3.2.1 Empirical orthogonal analysis

The empirical orthogonal eigenfunction (EOF) is a widely used statistical tool that can be applied among others to analyze riverbed changes in order to determine their variations over time or along a river. Variations are examined in a compact fashion, where data

determine significance of changes. Despite analytical character of the approach, EOF is only a descriptive tool and doesn't provide any information related to processes taking place around riverbed profile (Dean et al. 2002).

Based on riverbed analysis, the main objective of the EOF is description of riverbed changes by the smallest number of functions called eigenfunctions. Eigenfunctions can be generated on the basis of multiple riverbed profiles (Hsu et al. 2006). Data that is required for the analysis include cross-section profiles either over time at defined location or over distance at a defined time. The advantage of this method is the fact that the first eigenfunction is selected in such a way that it represents the eigenvalue that accounts for the highest possible variation in bed level changes. Following eigenfunctions are chosen in turn such that they represent the highest possible amount of the remaining variance. Thanks to such approach, it is possible to account for a high percentage of the variance with a low number of terms (Yuhi et al. 2013).

The EOF method is based on the assumption that elevations (h_{ik}) measured in (k) surveys at the same (i) locations are explained by the summation of eigenfunctions multiplied by constants. Presentation of this assumption in the form of formula for i^{th} profile and k^{th} survey is as follow (Dean 2002):

$$h_{ik} = \sum_{n=1}^N C_{nk} e_{ni}$$

where:

C_{nk} – a coefficient for k^{th} survey and n^{th} eigenfunction

e_{ni} – n^{th} empirical eigenfunction varying spatially evaluated at i^{th} location long a profile

Outputs of the EOF analysis are usually represented in graphs. Figure 8 is exemplary description of spatial and temporal eigenfunctions for a segment of Teodori river in Japan. The first spatial function $e_{1(x)}$ (graph from the left) corresponds to the mean riverbed profile during defined period of time, whereas temporal function $c_{1(t)}$ is related to the curve representing temporal variation in volume of sediments/erosion.

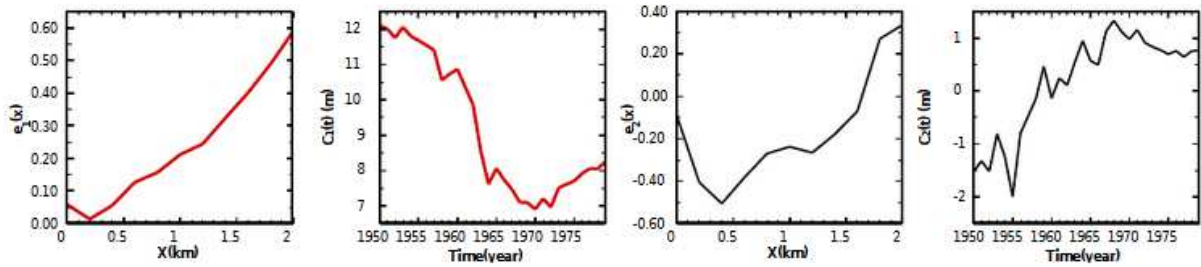


Figure 8 Exemplary outputs of temporal and spatial eigenfunctions for 1st and 2nd modes of the riverbed variation (on the basis of Teodori River, Japan)

Source: Yuhi et al. 2013

EOF analysis is used to highlight the variation trends of a phenomenon. To represent best its characteristics, the input data should concern periods in decadal scales. The approach can be used individually or as a supplement to another analytical methods.

2.3.2.2 Measurement profiles analysis

The phenomena of erosion is most frequently studied in relation to observations of changes in surveyed profiles of a river channel. Measurement profiles analysis is approach that is applied for morphological riverbed studies for ages. The analysis can be made in a form of cross – section or longitudinal profiles. The term cross – section is related to graphical representation of river morphology in aspect perpendicular to a flow direction. This kind of perspective provide a long – term knowledge on riverbed level trends and help to identify morphodynamic zones. However, it has limitations in estimation of sediment transport/erosion rates (Fuller et al. 2003). Data is provided for the individual cross – sections that have been measured, therefore information for the areas between cross – sections need to be interpolated from the survey data. Even though it can ensure general information on the trends, it can not constantly provide accurate information about specific areas of riverbed, particularly in those rivers where cross – sections are far away from each other (Basher 2006).

The main objective of cross - section measurement and analysis is provision of among others input data for hydrodynamic modeling and basic information on morphological characteristics of the channel (Rinaldi 2003). The analysis is carried out through the superimposition of cross sectional topographic surveys (Figure 9). The frequency of surveys in cross – section profiles differs depended on the river. It may range from couple of years to decadal scales. Historical series of measurements provide additional information, as they enable the examination of changes of such parameters as depth, width, width – to – depth and

net deposition or erosion (Murphey et al. 1985, Simon 1992). Monitoring of riverbed using cross – sections usually covers the sections in gauging profiles.

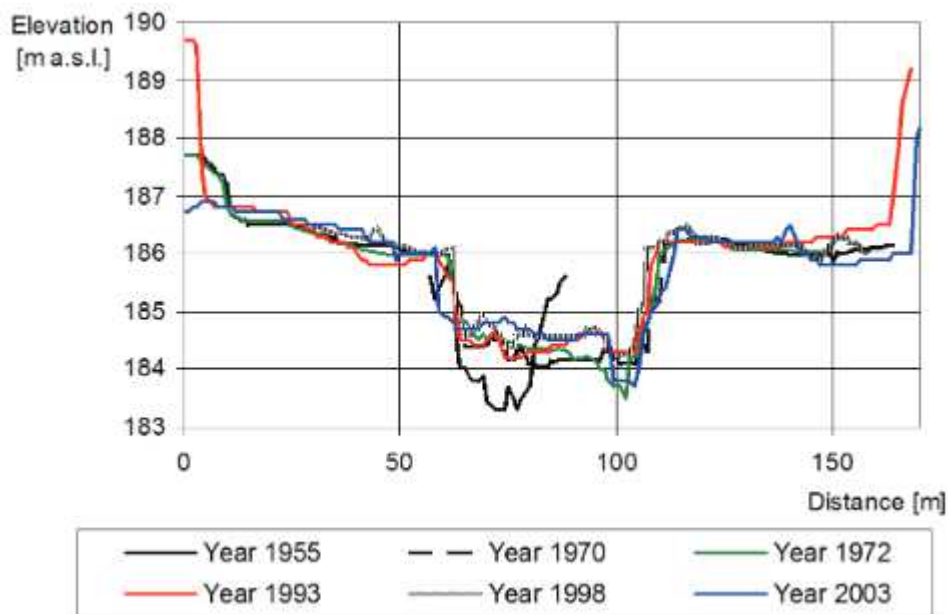


Figure 9 Exemplary visualisation of analysis of changes in geometry of riverbed on the basis of cross – section of Nida river

Source: Łapuszek et al. 2015

The second form of a measurement profile analysis are longitudinal profiles. Longitudinal profile is graphical representation of riverbed morphology in the aspect of longitudinal distances downstream along the river. The main objective of measurement and analysis of river channel in longitudinal profiles is provision of information on stream energy by the river slope and determination of inundation relationship between terraces, floodplain and channel. Monitoring changes in that perspective enable to distinguish morphodynamic and morphostatic sections of a river (Krzemień 2008).

Similarly as in case of cross – sections, longitudinal profiles can be analysed on the basis of short and long - term periods. Analysis of multi – temporal profiles ensure direct information on spatio – temporal propagation of changes. Plotting the variations in riverbed elevation for different time periods versus distances downstream ensures an effective way to make visualisation of the spatial distribution and amount of riverbed elevation changes (Figure 10) (Rinaldi 1998).

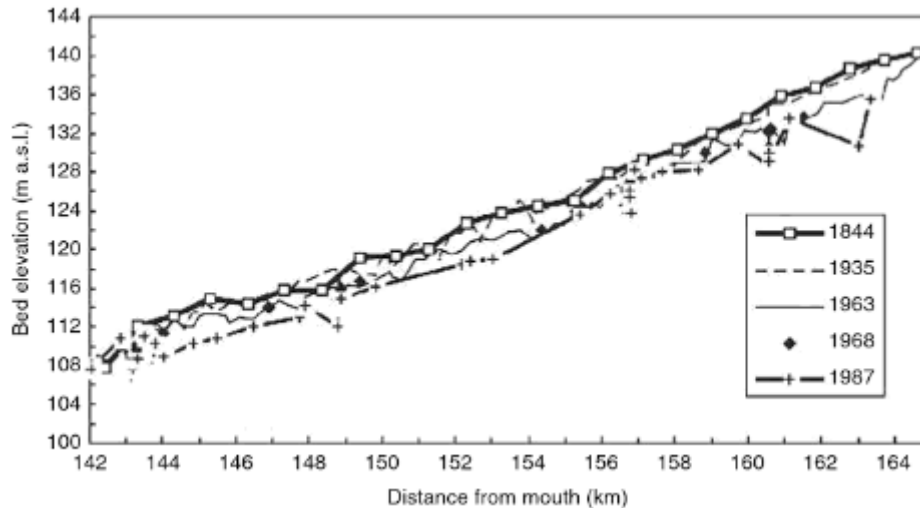


Figure 10 Exemplary visualisation of multi – temporal longitudinal profiles on the basis of Arno River (Italy)

Source: Rinaldi et al. 1998

Riverbed elevation adjustment at a specific site, achieved by plotting bed level versus time, ensures precise information on temporal trajectory of change or trend in a single location of the river (Figure 11) (Kondolf et al. 2016).

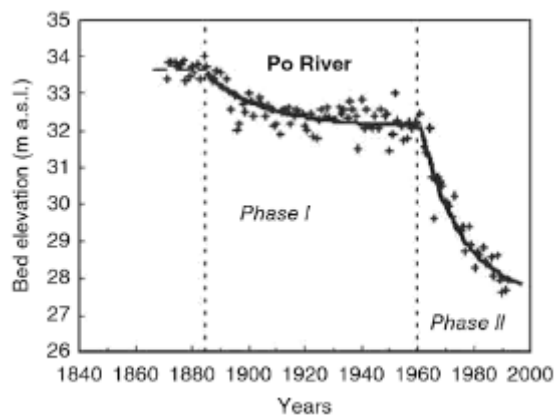


Figure 11 Exemplary visualisation of trends of riverbed level adjustments at a site and with identification of phases of bed changes on the basis of Po River (Italy)

Source: Surian et al. 2003

Analysis of surveyed profiles – both in cross – sectional and longitudinal aspect are considered to be one of the primary tool used to monitor riverbed level. Despite the fact that areas between specific profiles need to be interpolated from surveys, the method is often supplemented by site inspections and aerial photo analysis to ensure an indicator of river behaviour.

2.3.2.3 Digital Elevation Models analysis

Digital elevation model (DEM) is a digital representation of terrain's surface based on points of known elevation. As it is created on the basis of various data sources like satellite and radar images, aerial laser scanning, field surveys, topographic maps or other existing cartographic surveys, DEM is considered to be a reliable and accurate mean of landform projection. For this reason, DEMs are usually used to derive detailed information on topographic attributes, geomorphometric parameters or terrain information in general. Due to recent developments in remote sensing and GIS techniques, they appeared to be particularly crucial for numerical modeling of riverbed's surface processes for quantitative evaluation of morphological changes (Blanchard et al. 2010).

Application of DEMs into assessment of riverbed's topographical variations provide insight on elevation changes due to erosion or deposition processes indicating past and present morphological structural response to human alterations and riverbed processes over time (Lane et al. 2003, Schwendel et al. 2012). To detect such changes, volumetric analysis using DEMs are based on comparison of two DEM data sets collected for two different time periods, as only data sets captured for two different periods can result in estimation of land loss or gain for a vast area (Dawson et al. 2010). Regarding analysis in GIS framework, there are two approaches commonly used for DEMs volumetric analysis. First one is related to creation of DEM of Difference (DoD), whereas the second one is a comparison of cross-section profiles created on the basis of developed DEMs.

DoD approach is based on mathematical algorithm for assessment volumetric changes of landforms on two different time periods (Wheaton et al. 2010). The timeframes of analysis can be extended to decades if only accurate historical DEMs can be generated. Creation of DoDs usually is related to subtraction of one elevation model from another to disclose a mosaic of morphological change. Typical path is to subtract DEM that was surveyed earlier by the DEM that was measured later (Figure 12).

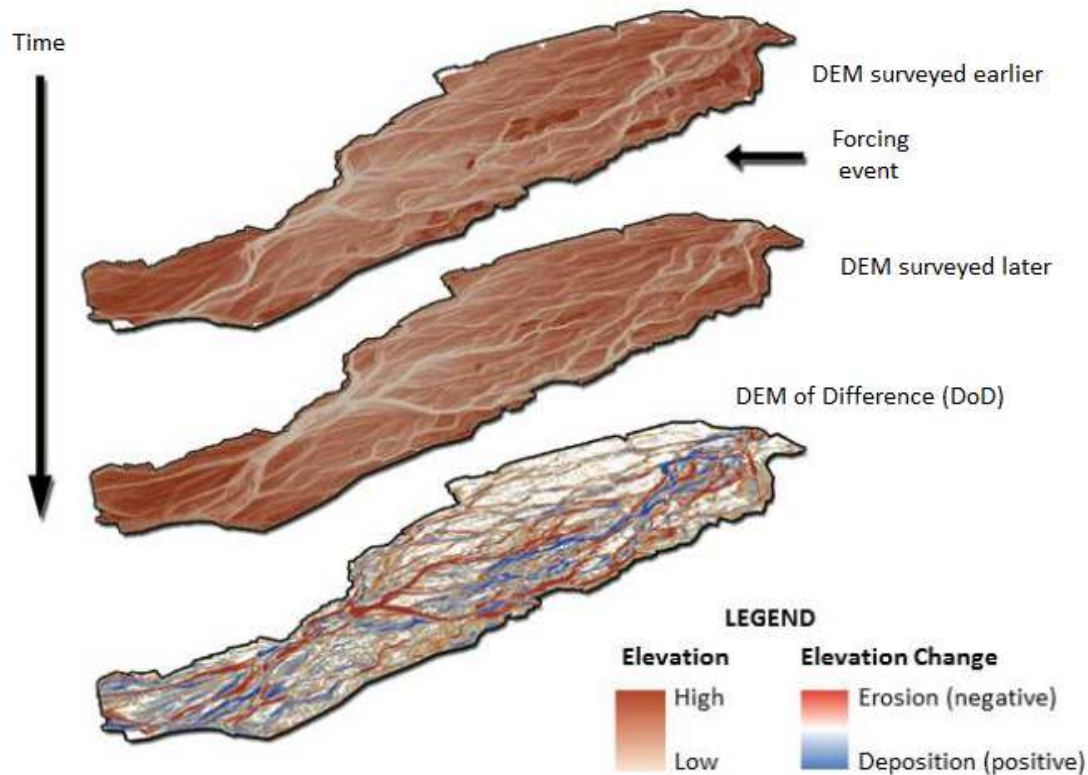


Figure 12 Example of generation of DEM of Difference of Rees River (New Zealand)

Source: Williams et al. 2011

As a result, the output DEM provides summarized total variation across DEMs which quantifies total volumetric change. Positive and negative values on the above example, show deposition and erosion respectively (Wheaton et al. 2010).

The second approach of volumetric analysis regarding DEMs is cross – section profiles analysis. The main principles of the method are similar to that one described in the previous subchapter, however profiles are extracted from developed DEMs. Profiles comparison shows the variations in elevation in vertical scale along a 3D line created on the surface of particular DEM (Zandbergen 2008, Hicks 2012). Similarly like in case of DoDs, the time scale of conducted research can be extended to long periods, dependent on the availability of archive DEMs. The outputs of exemplary cross-section profile analysis are presented in Figure 13.

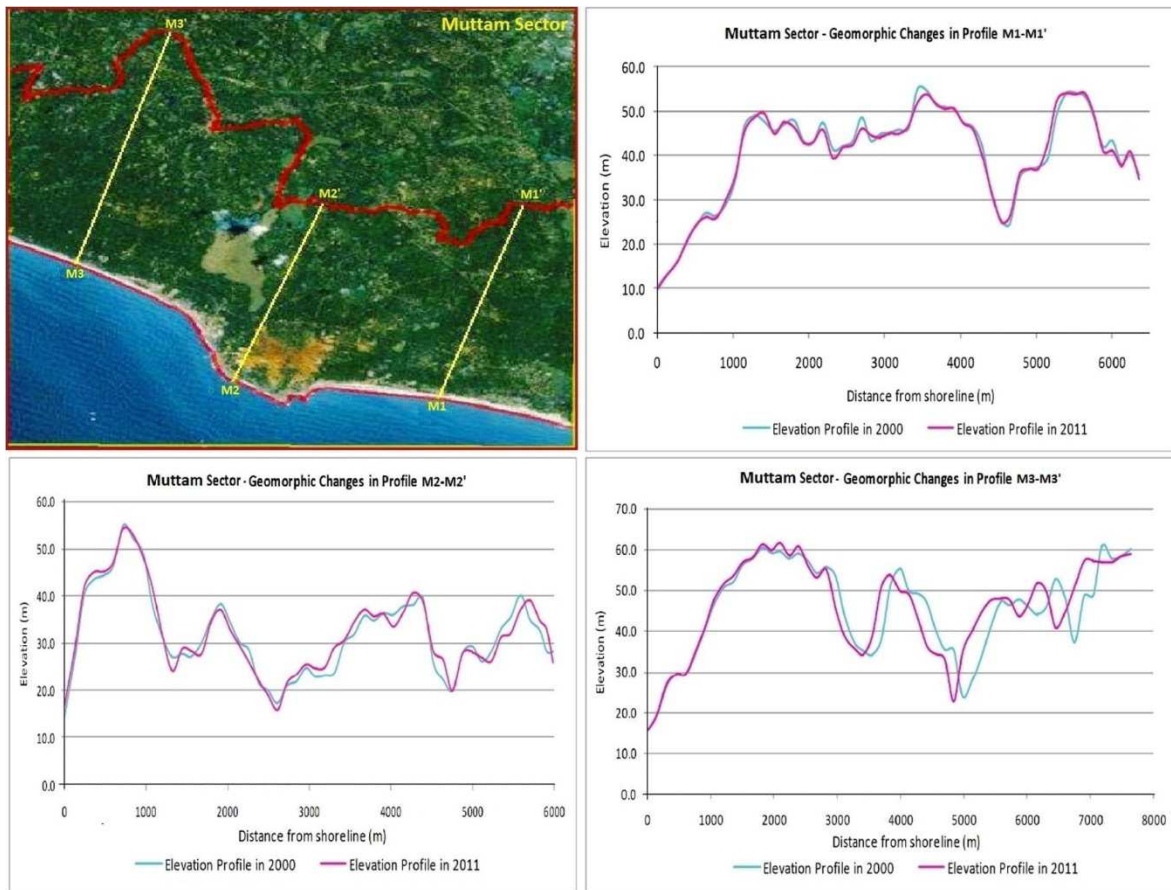


Figure 13 Example of cross – section profile analysis on the basis of change assessment of sediment load across Muttam area (India)

Source: Kaliraj et al. 2017

There are many methods that have been proposed for assessment of geomorphological changes of riverbeds. As time and budget are usually limited, efficient and accurate assessments are essential. Constant advances in technology both for data acquisition and analysis generate opportunities to understand riverbed morphological changes with better precision and at larger spatial scales.

Accuracy of described analysis methods is dependent mostly on the survey accuracy of source data. Dependent of the technology of data acquisition it can range from subcentimeters values regarding best application of GPS surveys to submeters values regarding aerial images. In some methods like DEM analysis the accuracy of analysis is also affected by another factors like resolution, method of interpolation, terrain topography etc. Despite this fact, DEMs are considered to be one of the most precise approach for volumetric analysis of morphodynamics of river systems.

3. Methodology

3.1. Study area

3.1.2 Location of hydropower plant and specific study area

Włocławek is a city located in the south – eastern part of the Kujawsko – Pomorskie voivodeship with a population of almost 115 000. The main river flowing through the city is the Vistula, dividing Włocławek on two parts – the right bank (northern part of the city) and the left bank (southern part). The river section flowing through the town amounts to 18 km. In the eastern part of the city, water of Vistula is raised by the dam, creating the Włocławek reservoir.

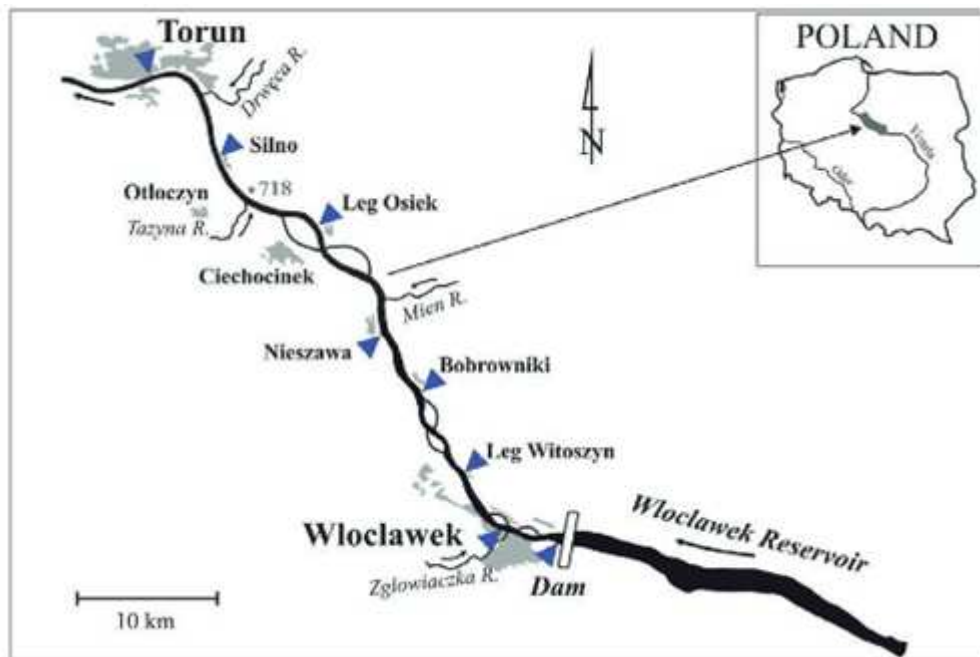


Figure 14 Location of Włocławek dam

Source: Habel 2013

The study area contained the lower part of the Vistula river in direct vicinity of the power station. The size of the area covered by surveys amounts to 300 x 400 m. Its location is presented in the Figure 15. Decision on the location and the extent of study area was made on the basis of occurrence of accelerated erosion of the riverbed below the dam caused directly by the operation of hydroelectric facility.



Figure 15 Study area of the lower Vistula river

Source: Dariusz Popielarczyk

3.1.2 Hydrological characteristics of the Vistula river

The Vistula is the largest river in Poland. It flows from the south to the north throughout the whole country to finally debouched into the Baltic Sea. It is the second largest river of the Baltic Sea drainage area. Vistula's length amounts to 1047 km from its source in the south in the Beskid Śląski, up to the north to the Baltic Sea at Bay of Gdańsk. The river's basin covers almost entire eastern part of the country. The whole basin is 194 thousand km². 87% of this area, that is 169 thousand km², is on the territory of Poland, whereas the remaining part in Belarus, Ukraine and Slovakia (Majewski 2013).

Hydrological conditions of the Vistula river basin can be presented as characteristic discharges and runoff units from particular basin areas. River discharge can be defined as the volume of water going by a measurement point or gauging station located along a waterway in a given time, whereas runoff is the unit related to the mean specific discharge and referes to the whole amount of water that comes into a river water system from such sources as rainfall, snowmelt and groundwater (Habel 2013). For the whole Vistula basin, the average level of runoff amounts to 5,34 l/(s*km²), whereas for lower part of Vistula including Włocławek dam 5,18 l/(s*km²) (Majewski 2013).

Regarding water flows and discharges, summer floods seems to dominate in the drainage of the upper Vistula. The lower section, including Włocławek and the part of river below Włocławek dam, shows a tendency to meltwater floods. The annual precipitation of river basin oscillates between 1000 – 1300 mm in the upper part at its source, decreasing to 450 mm in Toruń, on the section below the dam (Sobolewski 2000). Concerning lower Vistula valley, in the past occurred flood waves resulted among others from ice and its jams, with the average time span of ice phenomena at the level of 60 – 65 days (Glazik et al. 1999). Currently, the most common forms of icing are movement of ice and ice floats resealed by the dam. In the period from start of dam operation, i.e. 1970 to 2000, ice cover on the lower part of Vistula appeared once in five years (Pawłowski 2003).

Water flows are of a great importance in the process of riverbed erosion. Their influence is more visible in conditions of high variability caused by peak – intervention operation of hydro facilities. High water levels exceeding the flood plain contribute to increase of clastic sediments in the channel processes, whilst low flows limit them in turn only to regulatory part of the river. In this process, however the main role is played by daily fluctuations of water levels exceeding the level of so – called full – load water (Babiński 1992). In case of peak – intervention work of Włocławek dam, daily fluctuations on water levels reach up to 3 m (Babiński 1982, 1992). During these sudden water discharges, temporary water level increase occur, however this phenomena is often associated with the average flows on Vistula. During the low – level periods as well as during flood waves, small daily variations of the water level are recorded. Therefore the most intense riverbed incision below dam take place in the period of average levels (Babiński 1992).

3.1.2 Geomorphology and geological structure of lower Vistula

Lower Vistula is compound of a complex of river terraces and its valley is characterized by a series of widenings and narrowings. The alternating nature of its ‘shape’ was conditioned first by the influence of last glaciation and the geological structure of the basin itself. The predominant geomorphological parts consists of Kujawy Moraine Plateau and Dobrzyń Moraine Plateau on the both sides of the river (Wisniewski 1976). The eastern line of the Kujawy Moraine Plateau located in the neighbourhood of Nieszawa town is of a great interest of the scientists due to vicinity of Włocławek dam, therefore its geological structure is well defined (Habel 2013).

The geological structure of the lower Vistula is shown in the Figure 16. At one of the exposed fragment of a gravel pit (right side of the channel), ice – marginal, gravel and sand layer are overlaid by the layer of moraine clay. They are isolated from each other by a thick layer of fine sands (Babiński 1982). The part of fluvial sand sediments, with the upper section that reach the elevation up to 60 – 66 m a.s.l., at some fragments can be found at the top of moraine clay, which may constitute a proof for multiple glaciations. The opposite Dobrzyń Moraine Plateau, presents a similar geological structure. The drillings made in that cross – section indicated geological structure of three layers of moraine clay, separated with the layers of sand formations or Pliocene clays (Habel 2013).

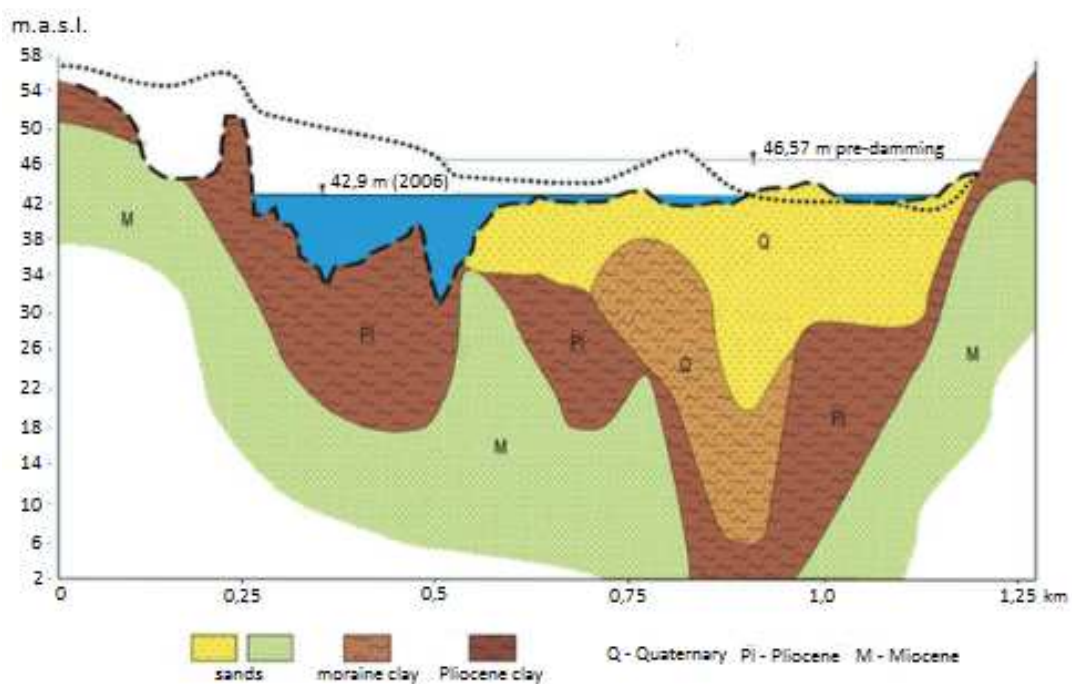


Figure 16 Geological structure of lower Vistula in cross – section in the vicinity of Włocławek dam

Source: Habel 2013

Dotted line in the above figure indicates the state of cross – sectional profile prior to the construction of dam, whereas dashed line the course of the cross – sectional profile 500 m below the dam in 2010.

In 1986, the mapping of geological structure along the river bank near Włocławek revealed several exposures of soils. Some of them, like silt and clay or gravel and pebbles considered as fluvio-glacial deposits, were categorized as erosion – resilient formations that occurred mainly along the left bank (Falkowski et al. 1987). However, Vistula valley below

Włocławek dam represents high morphodynamics due to its geological structure. At the top of deposits of the Miocene and Pliocene, a number of landslides and slumps weathered material can be found and in some parts Miocene deposits are going to enter into a direct contact with Quaternary sediments. It means that the structure of Vistula channel is currently developing into Pliocene clays and to a certain extent sand deposits (Habel 2013).

3.1.3 Characteristics of Włocławek hydropower plant

Włocławek hydroelectric power plant is located on the cross section of Vistula river on 674,85 km. It was constructed in 1970 and till now is one of the biggest hydropower plants in Poland. The dam was designed as the first part of the contemporarily planned Lower Vistula Cascade. The ordinate of 44,50 m ASL was designed for the water on the next station supposed to be constructed, whereas changed slope influenced the calculations of safe filtration of the dam and substrate of all facilities and its stability. The basic measurements and ordinates of the Włocławek dam are presented in Figure 17 (Habel 2013).

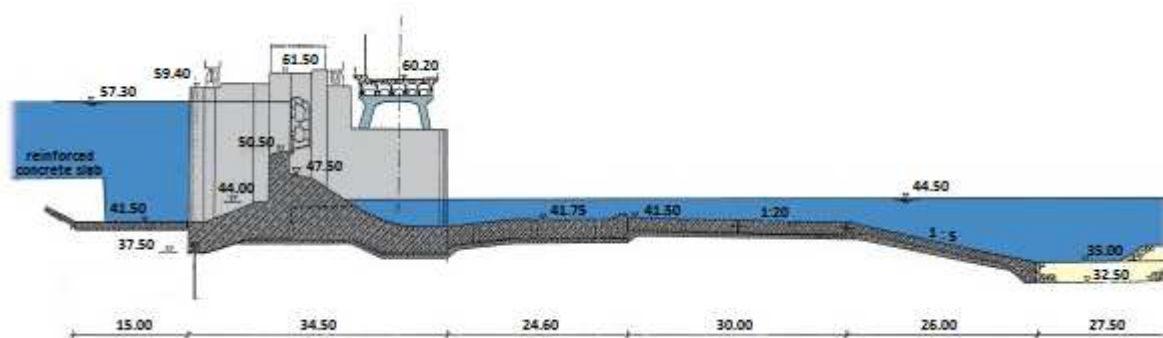


Figure 17 Long section of the weir and its fortifications

Source: Depczyński 2009

Włocławek hydropower with installed power capacity of 162 MW and average annual power generation of 739 GWh, produce over 20% of the electricity generated in the domestic hydropower plants. The most important parts of the facility include such structures as:

- hydropower plant
- earth dam
- 10 weirs locked with sluice gates
- navigation lock with chamber and the designed water head 12,8 m

- fish – pass containing 30 concrete chambers in the dividing pillar and 3 rest – chambers with lure – water pipeline.



Figure 18 Hydroelectric power plant in Włocławek

1 – earth dam, 2 – weirs, 3 – power plant, 4 – navigation dock, 5 – fish ladder, 6 – check dam (artificial sill) stabilizing the lower part of the dam

Source: Habel 2013

Due to facility's unfavorable working conditions, increased erosion and degradation of the structures and adverse effects in the dam foundation, some treatments have been forced:

- construction of the temporary threshold damming up lower water below the barrage
- increase the minimum flow from initial 300 to more than 450 m³/s
- installation of hydroelectric breaks due to the lack of proper immersion of turbine rotors
- repeatedly renovations and repairs of embankments and bottom (Energia 2017).

Due to water storage, the reservoir with an area of 70 km² was created. Its capacity is 370 million m³. From the left side, it is limited by the 26,7 km long side dams, whereas from the right side, by the high river bank and almost 2,2 km embankments in the neighborhood of Borowiczki village. The water from the areas outside the embankments is drained by eight pumping stations and network of drainage ditches (Hydroprojekt 2017).

Technical parameters of particular elements of the facility are presented in Table 6.

Table 6 Characteristics of particular elements of Włocławek dam

Parameters of particular elements of Włocławek dam	
Earth dam	
Lenght	670 m
Width	13 m
Maximum height	20 m
Ordinate of barrage crest	60,2 m ASL
Ordinate of emergency level of water damming	58,5 m ASL
Ordinate of maximal level of water damming	57,3 m ASL
Ordinate of minimal level of water damming	56,0 m ASL
Barrage cubature	1,1 min m ³
10 weirs locked with sluice gates	
Lenght	200 m
Ordinate of weir crest	60,2 m ASL
Height	34,0 m
Ordinate of spillway threshold	50,50 m ASL
Width of the substructure	34,8 m
Flow capacity	11,150 m ³ /s
Hydroelectric power plant	
Lenght	162,0 m
Width of the substructure	60,0 m
Ordinate of cres	60,2 m
Height	33,9 m
Turbine type	Kaplan
Water flow rate through the turbines	2190 m ³ /s
Connection	three 110 kV lines
Navigation lock	
Length	158,0 m

Usable length of the chamber	115,0 m
Usable width of the chamber	12,0 m
Height of chamber's walls	17,0 m
Ordinate of lock bottom	41,8 m ASL
Ordinate of upper threshold	50,0 m ASL
Dividing pillar, separating the lower substrate of weir and hydroelectric power plant	
Maximal height with the fish – pass	34 m
Reservoir	
Total capacity	370,0 m ³
Usable capacity	52,7 m ³
Forced capacity	80,0 m ³
Forced total capacity	450,0 m ³
Area	70,4 km ²

Source: Hydroprojekt 2017

3.2 Input data

Data underlying the analysis in this master thesis were shared by the Chair of Satellite Geodesy and Navigation of the University of Warmia and Mazury in Olsztyn, Poland. Obtained data were already in the form of digital contours. The dataset covered the surface of 0,12 km² in the direct vicinity of the hydropower plant. To detect the physical and environmental dynamics of the river below Włocławek power plant, the bathymetric measurements were conducted in the time period of 2008 – 2011.

To achieve high accuracy in riverbed representation, the Integrated Bathymetric System developed by the team of researchers of the Chair of Satellite Geodesy and Navigation of the University of Warmia and Mazury in Olsztyn, was used. The system includes measurement techniques associated with Real Time Kinematic (RTK) observations, conventional measurement surveys with Total Station as well as echo sounding. The surveys were conducted on board of a small hydrographic boat combining system components.

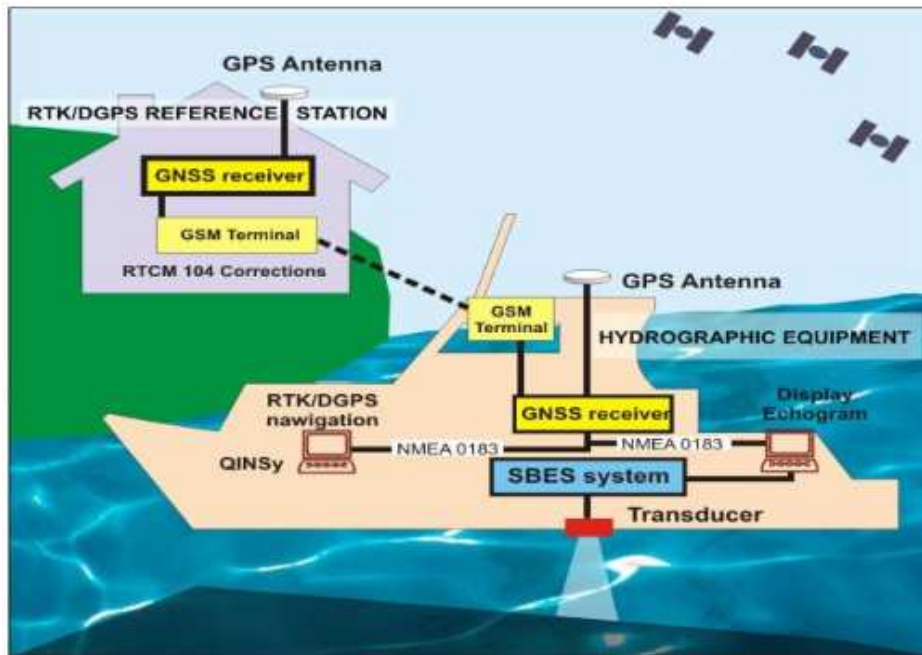


Figure 19 Integrated Bathymetric System components

Source: Popielarczyk 2012

The basic measurement profiles were designed at intervals of 5 m. Due to boat position determined in real time, precise navigation along the profiles was allowed together with recording of position and bathymetric data. Different conditions during measurements campaigns in particular years, forced to put the main focus on reliability of the water surface model acquired on the basis of cross-validation of data from RTK and RTS when measuring boat height or water level. Conducted RTK and RTS surveys were confirmed by digital readings from the hydroelectric power plant water level indicators. The mean value of vertical difference between surveys was estimated to 0,03 m. As final processing of points, echograms from echosounding were used for position and depth verification, whereas the bathymetric data were corrected in post – processing mode with the values of estimated water level (Popielarczyk 2012). The finally corrected points were the base for development of the obtained contours of Vistula riverbed.

4. Data Analysis

4.1 Methodological approach

The objective of the study is determination of Vistula riverbed changes in the vicinity of Włocławek barrage as a result of progressive erosion and operation of hydroelectric power plant. To define spatio – temporal variations in a quantitative way, identification of spatial distribution of morphological processes and its dynamics over time was carried out by the means of volumetric analysis. The input data were acquired from the Chair of Satellite Geodesy and Navigation of the University of Warmia and Mazury in Olsztyn, Poland already in the form of contour lines. Contour lines, in general are considered to be one of the most commonly used approach to provide information about elevation to map readers (Robinson et al. 1995). However, due to their coarse topological structure, they are not suitable for spatial analysis of ground morphology as even slope or shaded relief maps derived from contour lines are a rather cumbersome operation (Carrara et al. 2010). Despite that fact it was decided to use acquired contour lines in the master thesis, as for the reason of confidentiality of original source survey data - they were not possible to obtain. Because shared data were already in the form of digital contours, DEM was considered to be an accurate mean to visualisation of riverbed surface and to conduct detailed spatio – temporal analysis. The general scheme of the workflow and its particular steps is presented in Figure 20.

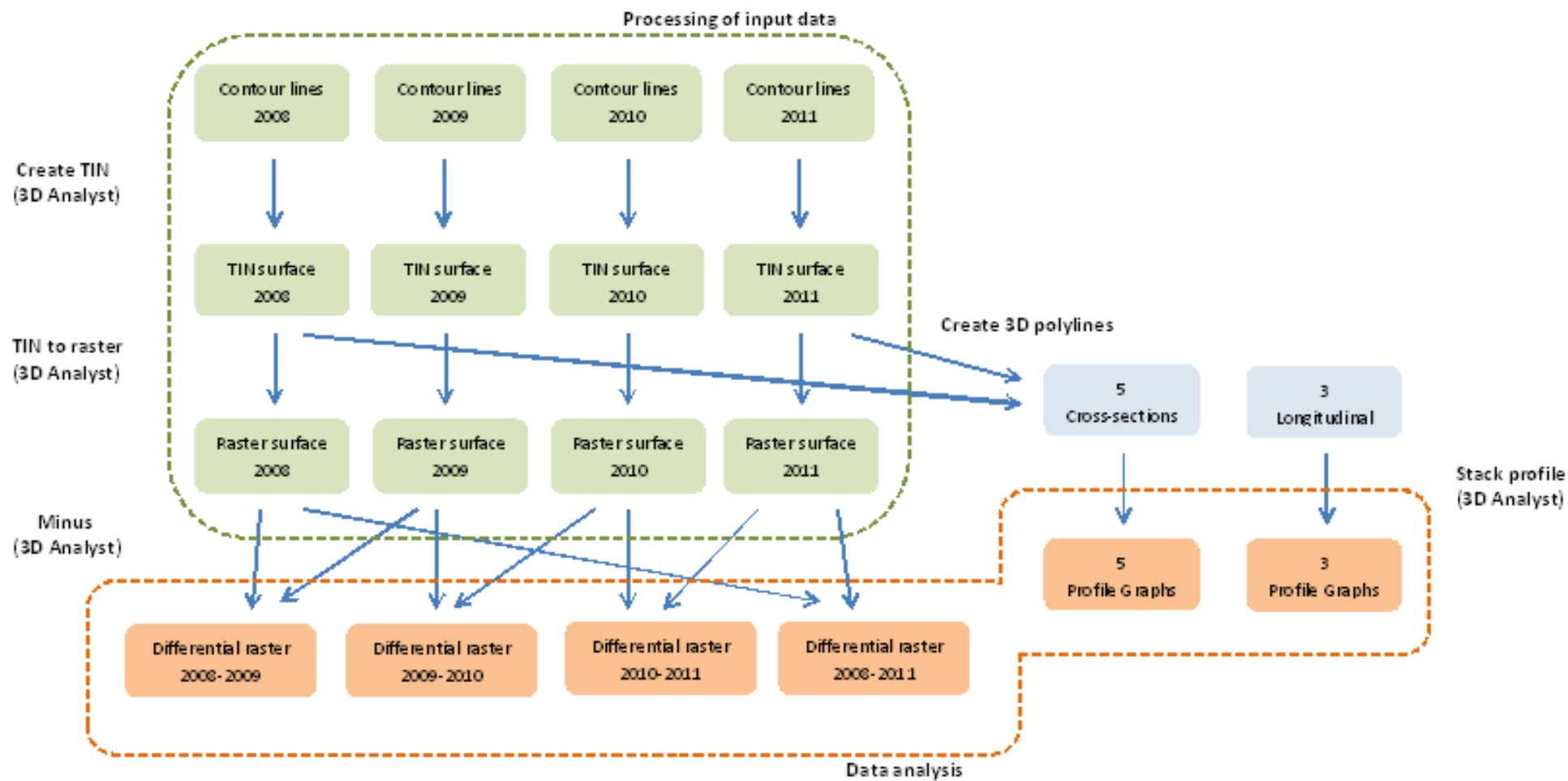


Figure 20 Scheme of workflow overview

According to information provided by scientists from Chair of Satellite Geodesy and Navigation of the University of Warmia and Mazury in Olsztyn, due to a large set of points and interest in the spatial variation over the smoothness of the overall surface, Inverse Distance Weighted (IDW) interpolation method was applied into creation of provided contour lines. Generated contour lines for particular measurement campaigns are presented in Figures 21 - 24.



Figure 21 Contour lines generated from the measurement data points for the year 2008

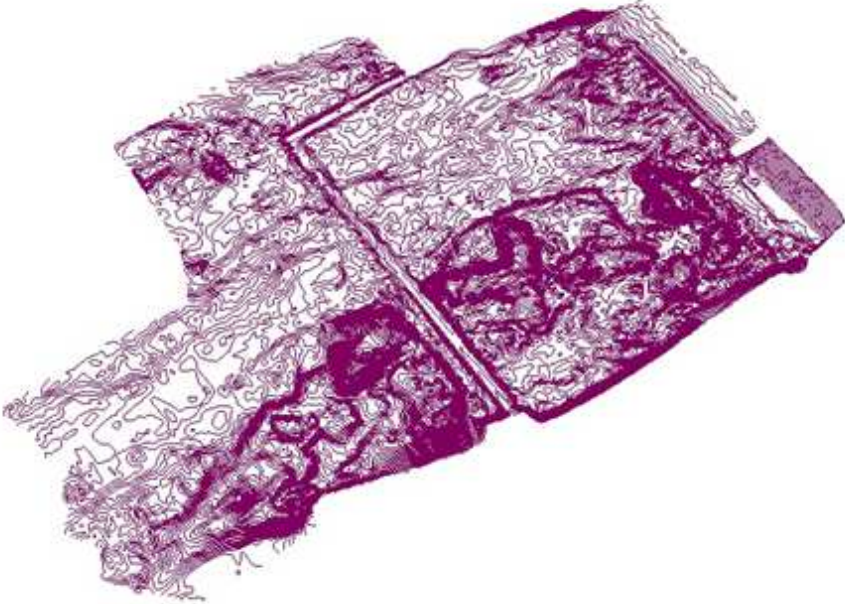


Figure 22 Contour lines generated from the measurement data points for the year 2009

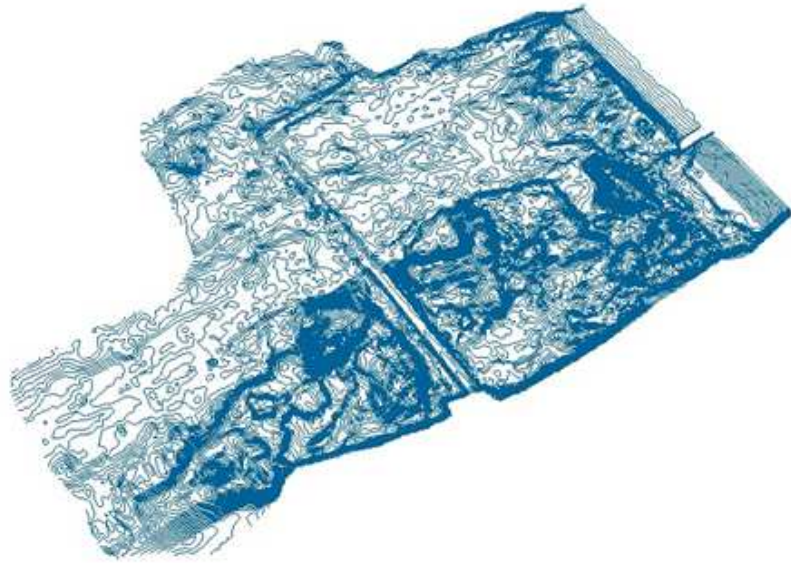


Figure 23 Contour lines generated from the measurement data points for the year 2010



Figure 24 Contour lines generated from the measurement data points for the year 2011

On the basis of the contour lines, 3D Triangular Irregular Networks (TIN) models were created for particular measurement years (Figure 25 - 28). In order to represent the shape of riverbed best, elevation values were divided into 16 classes with the interval of 1m. To emphasize changes in the surface elevation a vertical exaggeration was implemented at the level of 3. Generated models were the basis for further spatial analysis.

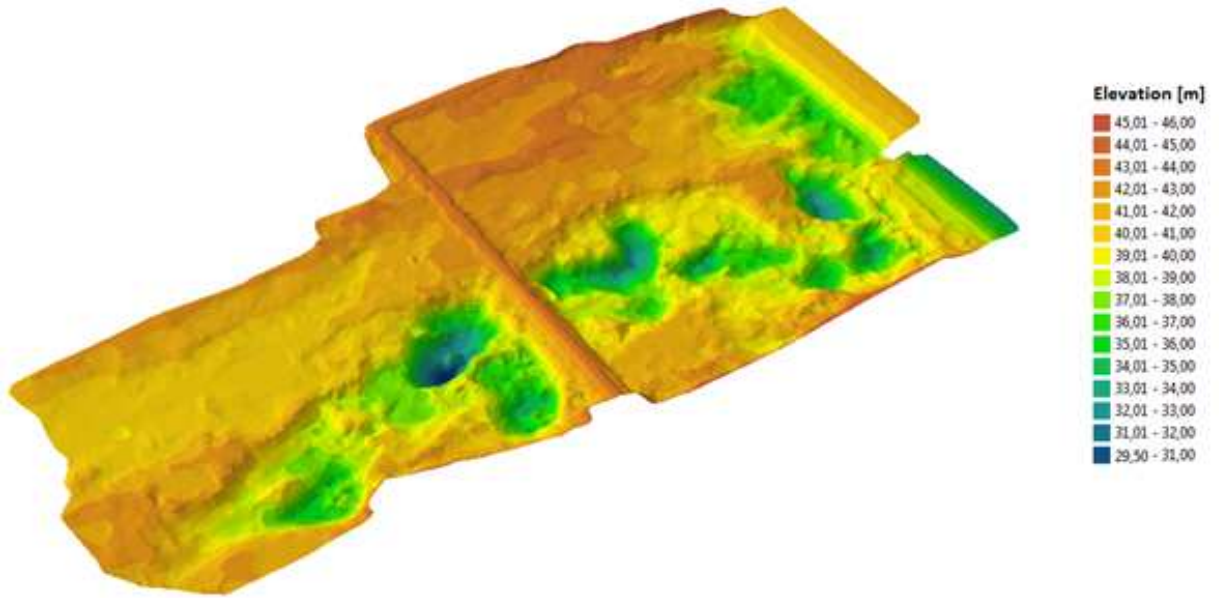


Figure 25 DEM generated for survey campaign from 2008

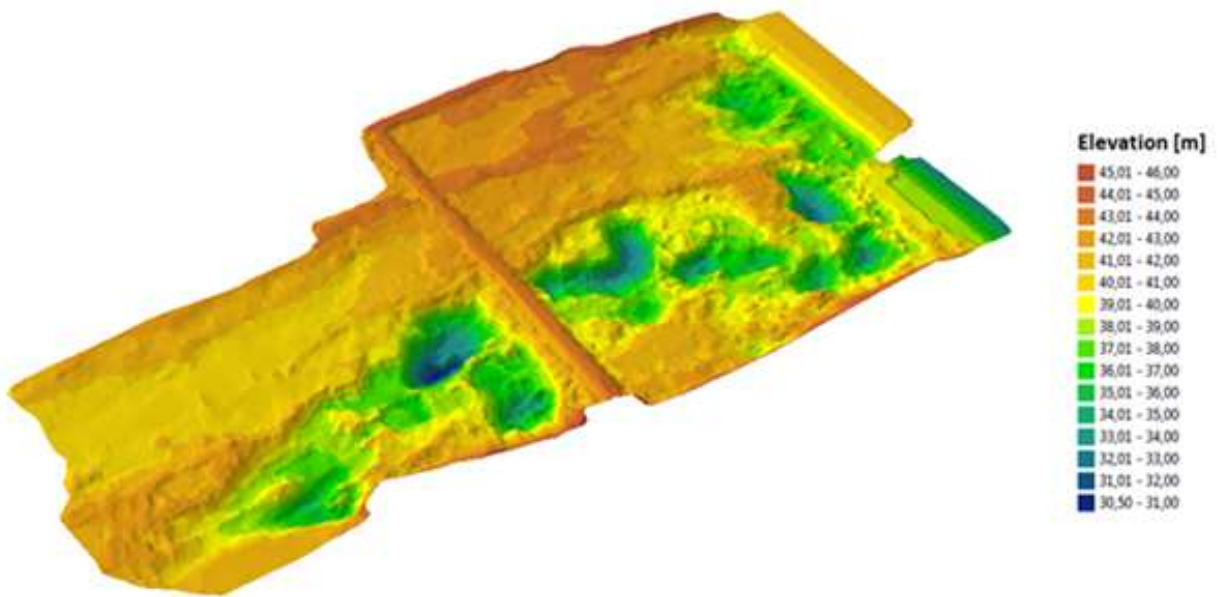


Figure 26 DEM generated for survey campaign from 2009

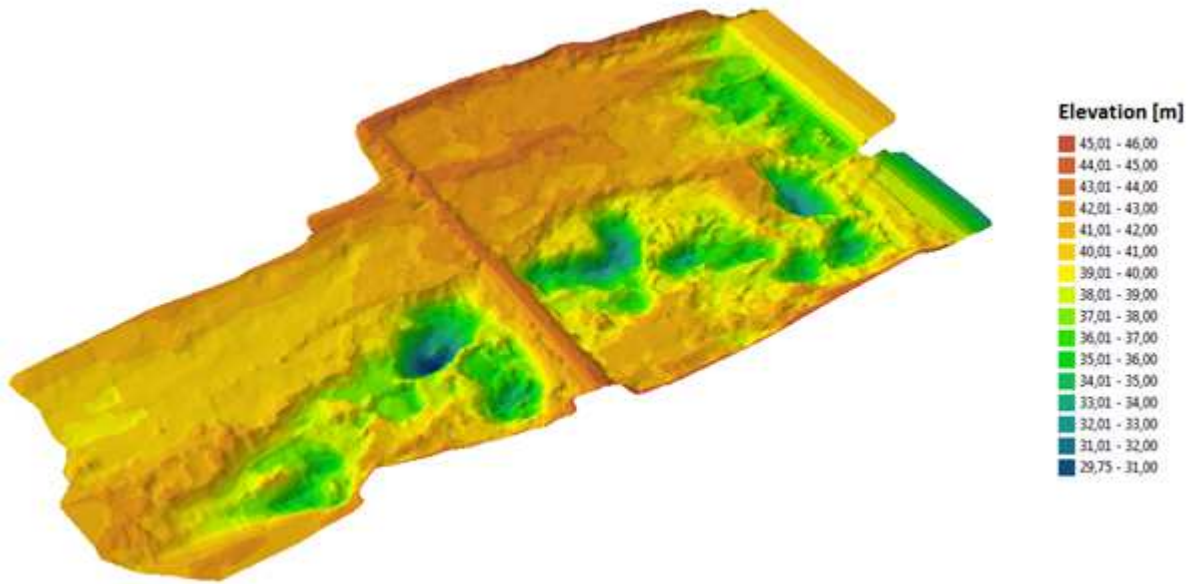


Figure 27 DEM generated for survey campaign from 2010

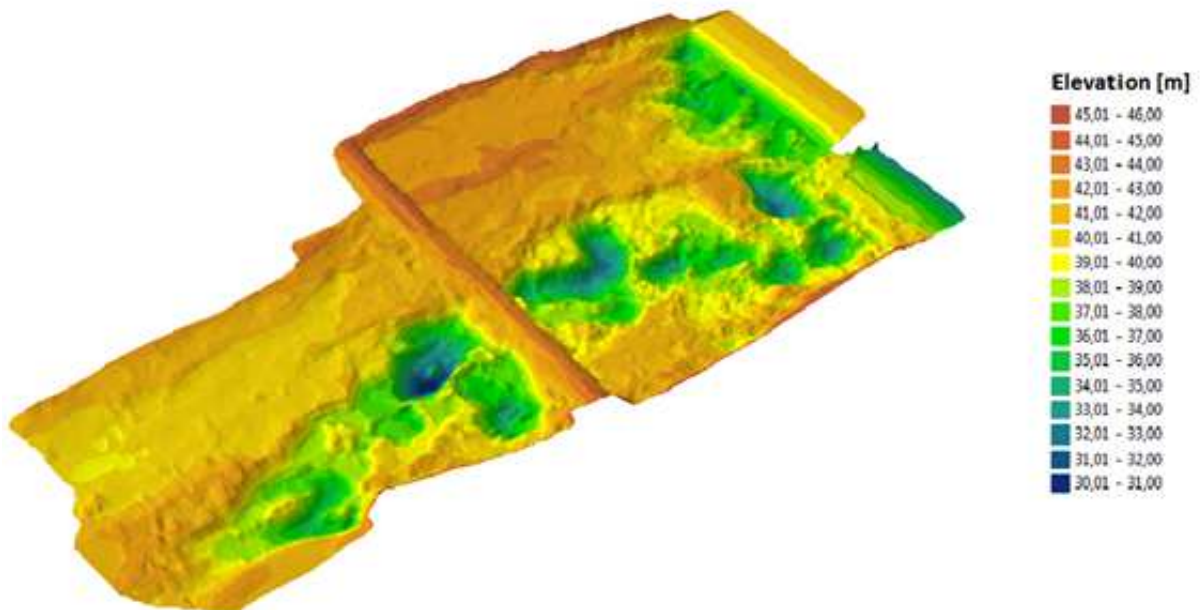


Figure 28 DEM generated for survey campaign from 2011

Spatial analysis are the process of analytical techniques examining relationships between geographic features. Due to limited hardware capabilities, further steps regarding spatial analysis were conducted on DEMs in raster formats generated from created TINs. The appropriate resolution for the rasters for analysis was assessed at the level of 3 m. With the

higher rate of resolution there is a better variation in the spatial context of analysed surfaces, particularly in terms of extreme values, which are of a great importance in case of analysis of morphodynamic changes.

Due to the form of acquired input data, the workflow of data processing was not appropriate regarding the order of particular steps. Generally for best performance of terrain variation, TIN surfaces should be provided directly from elevation points, not contour lines, as contour lines, as it was mentioned above, are not suitable for spatial analysis of ground morphology. In spite of this fact it was assumed that generated DEMs might be biased by elevation error. To determine the accuracy of DEMs derived from contour lines, the whole workflow was reproduced with an existing DEM of similar topography. The workflow of the analysis and its results are presented in 4.2.4 subchapter and in Figure 45.

Regarding spatial analysis, application of DEMs into assessment of riverbed's topographical variations provide the insight on elevation changes. To detect them, comparison of at least two datasets collected for different time periods should be enabled. In case of Vistula riverbed, the bathymetric survey campaigns took place in the period of 2008 – 2011. To estimate the changes in Vistula's riverbed elevation values, particular DEMs were compared to each other according to the scheme: 2008 – 2009, 2009 – 2010, 2010 – 2011 and 2008 – 2011 (Figures 30 - 33). Comparison of data in this way, enable to determine ranges of actual elevation differences and their distribution in annual perspective.

The differential analysis were based on DoD method, using 3D Analyst tool called Minus. The tool subtracts the values of the second input raster – in this case the older DEM, from the values of the first input raster – the newer DEM, on the cell-by-cell basis. Additionally, based on the results of the differential analysis, it was decided to analyse more precisely the riverbed elevation by means of longitudinal profiles and cross - sections. Eight profiles have been designed – 5 cross sections marked with letter 'A' and 3 longitudinal ones marked with letter 'B' (Figure 29). Their location was chosen in such a way, that the profiles pass through the most significant areas regarding elevation changes. In order to represent the general tendencies of morphological processes, the profiles were analysed in the timeframes of 4 years.

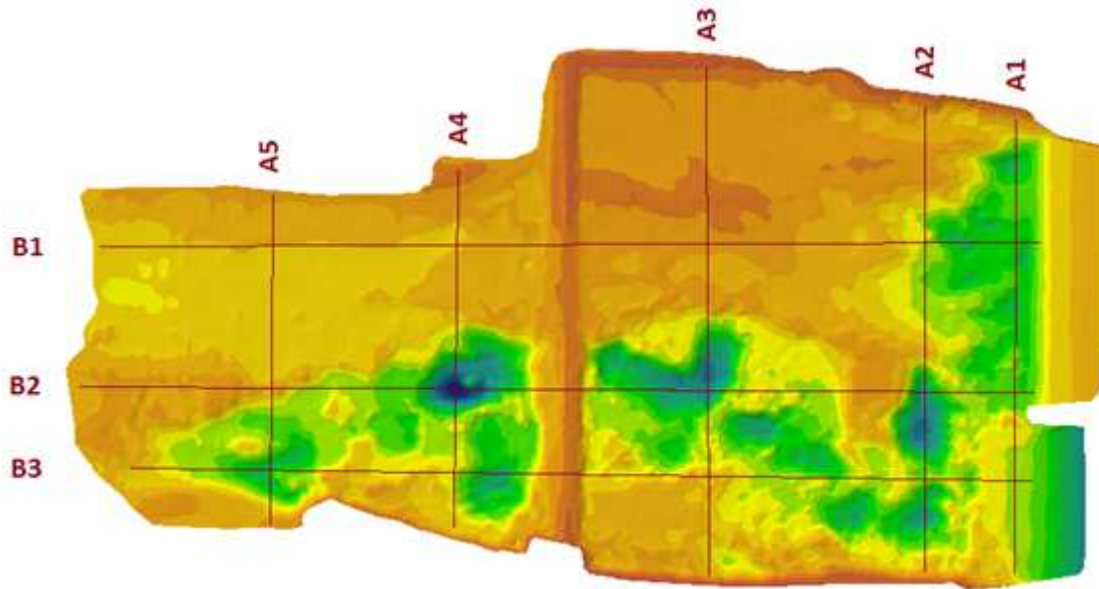


Figure 29 Designed profile lines distributed over the survey area

As the summary of all performed analysis, the general analysis of the volume of gained and loss material have been conducted using Cut Fill tool. By taking surfaces of particular locations at two different time periods, the tool identifies areas of surface material addition, surface material removal and areas where the surface has not changed (Figure 42). Additionally, to define the trend of changes, linear regression of particular cross – sections and longitudinal profiles have been calculated. The results are presented in Figures 43 - 44.

All spatial analysis were performed using ArcScene 10.4 software, whereas calculation of linear regression was carried out using MS Excel.

4.2 Analysis Results

Figures 25 - 28 represents created TINs describing variations in riverbed elevations. From the first look there can be noticed a number of deep pits formed in the riverbed of Vistula in the central part and along the left bank. Elevation values of particular models include within the range from 29,50 m to almost 46,00 m. Regarding classes with minimum values, there is a difference between particular models reaching up to 0,50 m. The significant changes in the surface occur in the direct neighborhood of the dam and further downstream in the vicinity of the temporary threshold damming up lower water.

4.2.1 DEM of Difference analysis

Regarding DoD approach, comparison of 2008 and 2009 models shows the distinct changes in the elevation over the whole surveyed area. A vast surface of the riverbed is characterized by bed incision within the range reaching up to 0,50 m. On some part of other areas a tendency to accumulation of sediments is represented. There is also a number of small spots scattered throughout the whole area with a structure loss reaching 1,0 m – 2,0 m dependent on the location. The biggest ones are identified in the north – east part of analysed area, in the neighborhood of the dam with the values up to 2,0 m. There are also located areas with the significant increase in the elevation of the riverbed.

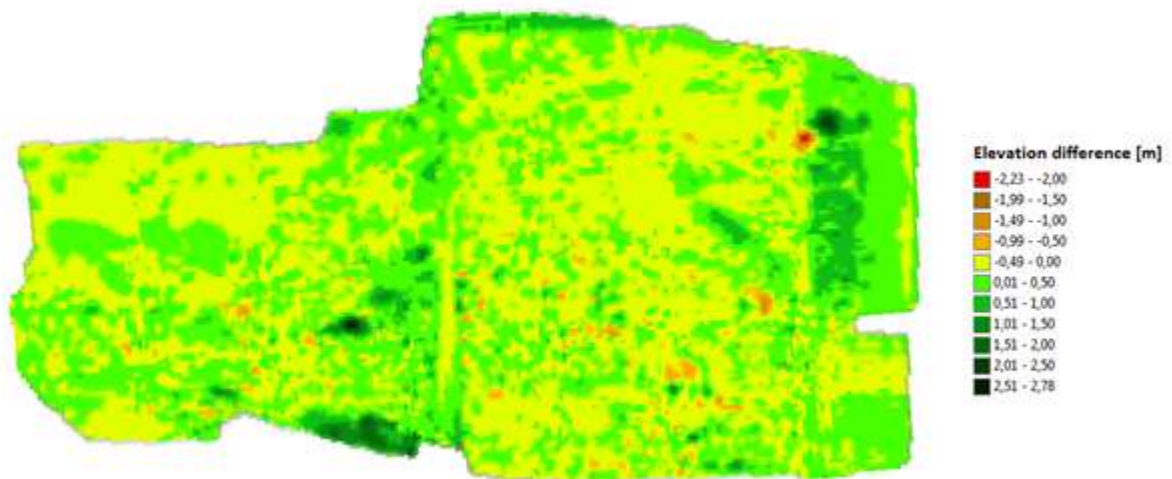


Figure 30 Comparison of elevations of 2009 to 2008 model

Surveys carried out in 2010 showed a further tendency of riverbed degradation of Vistula. The vast majority of the analysed area decreased up to 0,50 m. The biggest loss in the structure amounted to more than 3,0 m is noticed again in the north – east part of the analysed area, in direct neighborhood of the dam. There are also located the biggest areas of lowered riverbed in the range from 0,50 m to 2,0 m. The elevation changes occurred in the period of one year difference are significant.

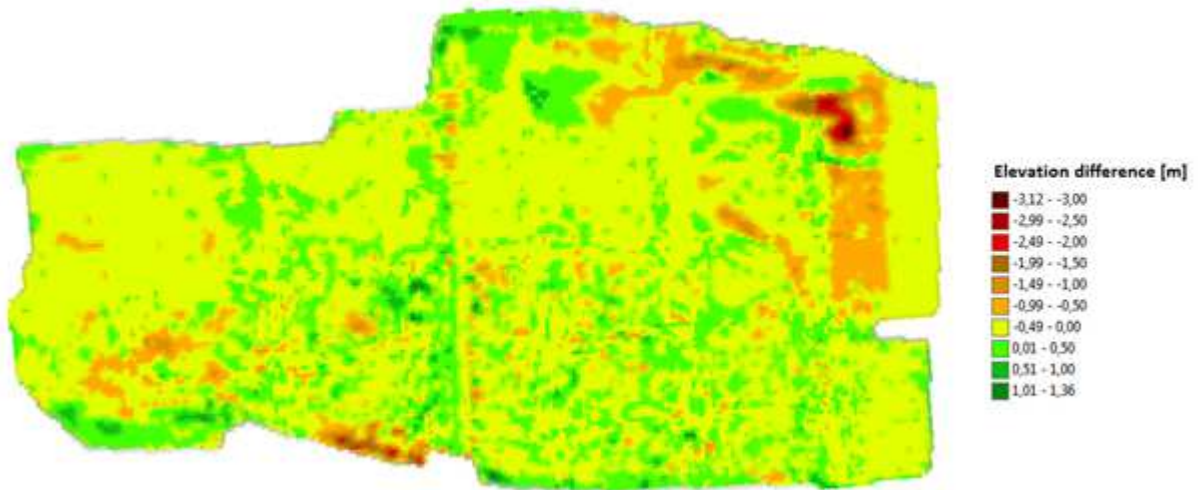


Figure 31 Comparison of elevations of 2010 to 2009 model

In contrast to comparison of 2009 - 2010 models, the analysis of elevation difference between 2010 and 2011 models showed a little bit different tendency.

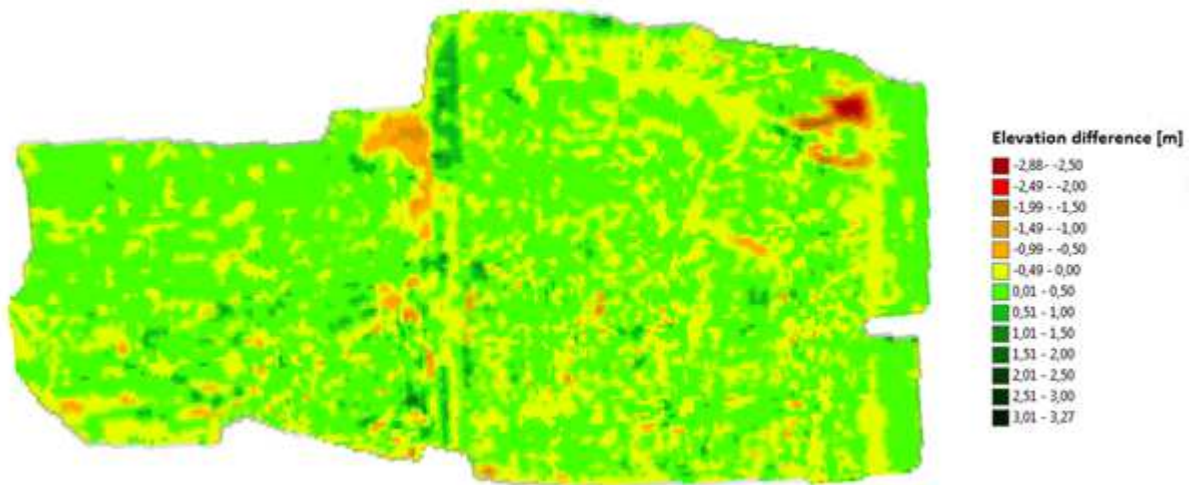


Figure 32 Comparison of elevations of 2011 to 2010 model

On the basis of presented raster, it can be noticed that the riverbed on majority of the area has increased within the range of 0,01 m – 0,50 m. Still, the largest structure loss occurred in the north – east part of analysed area in the neighborhood of the dam. It covers with the area of previous models comparison and is the evidence of the intensified erosion process which took place in this part of the river. Below temporary threshold, there are spots with riverbed decrease reaching the values between 0,50 m and 1,50 m.

Comparison of 2008 – 2011 models, represent the total elevation differences over the 4 years.

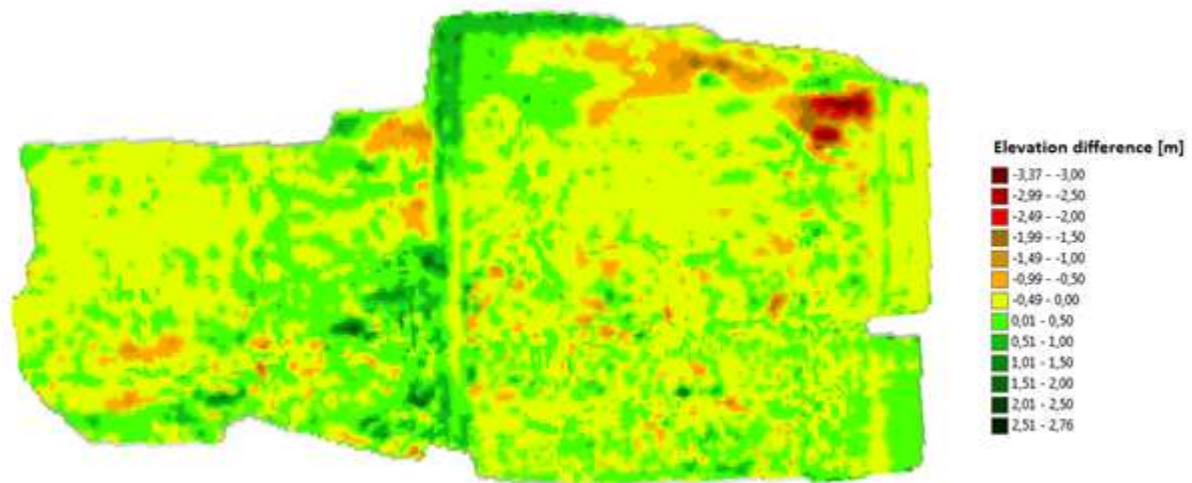


Figure 33 Comparison of elevations of 2008 and 2011 models

An overall trend of considerable erosion during the period of 2008 – 2011 is evident. As it was shown on previous rasters, the intensified erosion process is present on the north - east part of the analysed area. The maximum loss of the bottom structure reached there 3,37 m. Over the whole area there are vast surfaces with a structure loss which amounts to 0,50 m and a number of scattered pits with the lowered elevation within the range from 0,50 m to 1,50 m. Below the temporary threshold, there is the area characterized by tendency to accumulation of sediments.

4.2.2 Cross sections and longitudinal profiles analysis

The analysis of cross – sectional and longitudinal profiles show the general information on the trends regarding morphodynamic processes occurring in the riverbed. Results for cross – section analysis are presented in Figures 34 – 38.

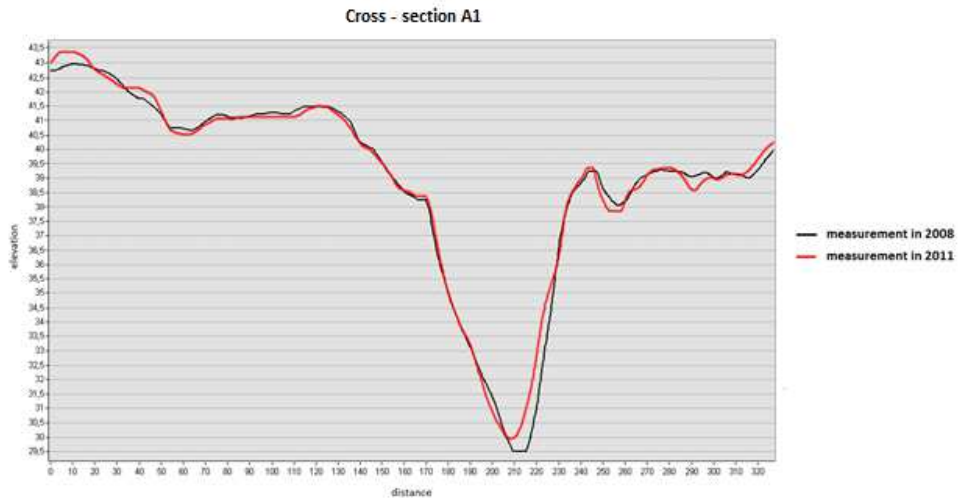


Figure 34 Elevation difference on cross – section A1

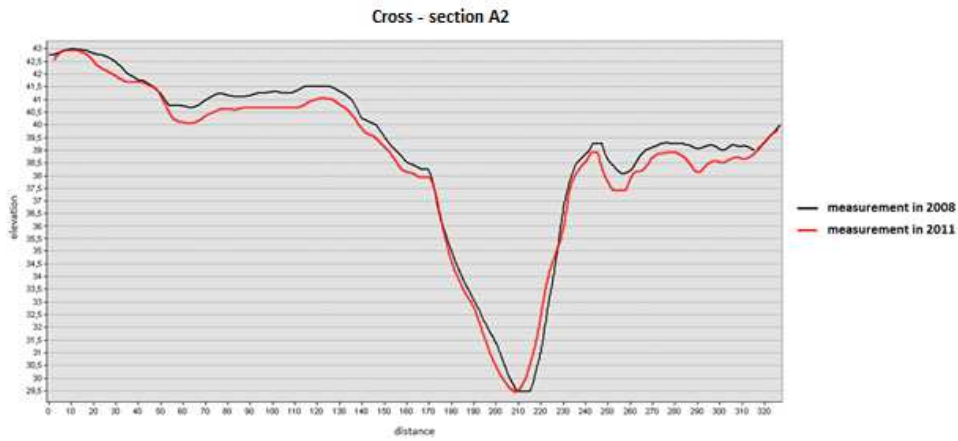


Figure 35 Elevation difference on cross – section A2

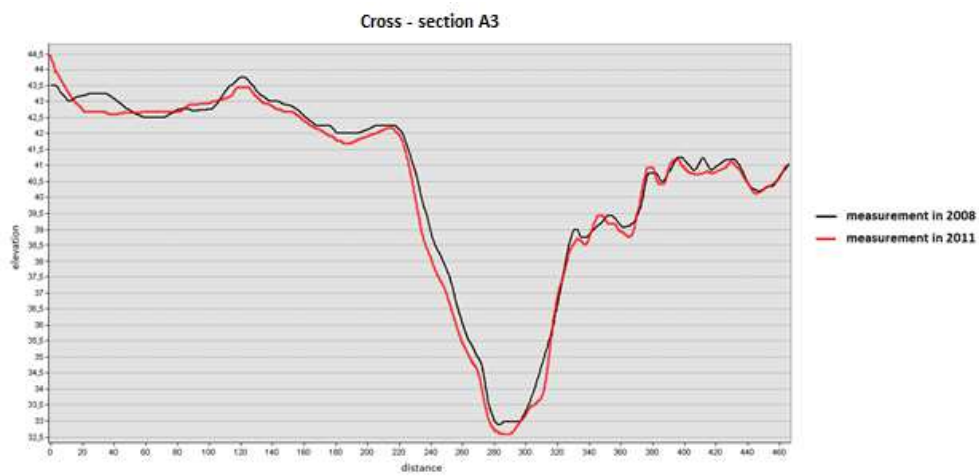


Figure 36 Elevation difference on cross – section A3

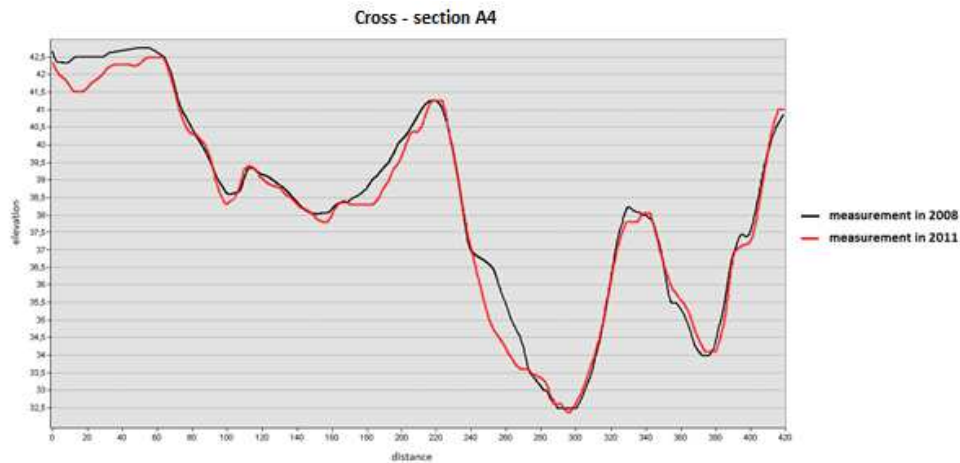


Figure 37 Elevation difference on cross – section A4

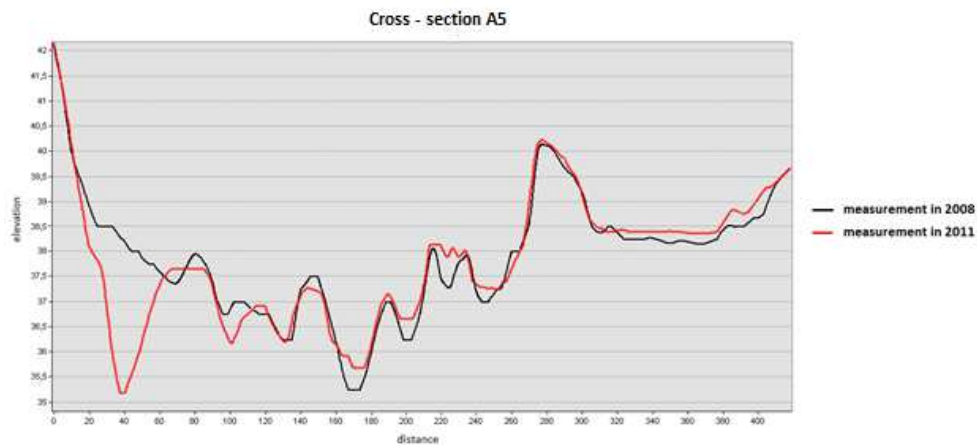


Figure 38 Elevation difference on cross – section A5

Vistula is characterized by the great diversity of the riverbed surface. Cross sections perfectly depicts elevation changes and their distributions over the profile lines. The most significant diversion is presented on the graphs related to profiles ‘A2’, ‘A4’ and ‘A5’. ‘A2’ line is located below the temporary treshold and the riverbed decrease can be noticed over the whole profile line. The riverbed lowering along the entire profile line amounts to approximately 0,50 m within 4 year period. Profiles ‘A4’ and ‘A5’ are located in the neighborhood of the dam. The biggest lowering in the riverbed structure occured on profile ‘A5’ where the elevation difference on the right part of the line reached almost 3,0 m. There are also parts with increased elevation values due to sediments accumulation. Depending on location, elevation differences of the remaining parts of these two profiles range from 0,10 m to more than 0,50 m. Cross section ‘A1’ and ‘A3’ are characterized with the lowest elevation differences. Their values amounts to less than 0,50 m rates.

Regarding longitudinal profiles, they do not demonstrate such big elevation changes as cross sections (Figures 39 - 41).

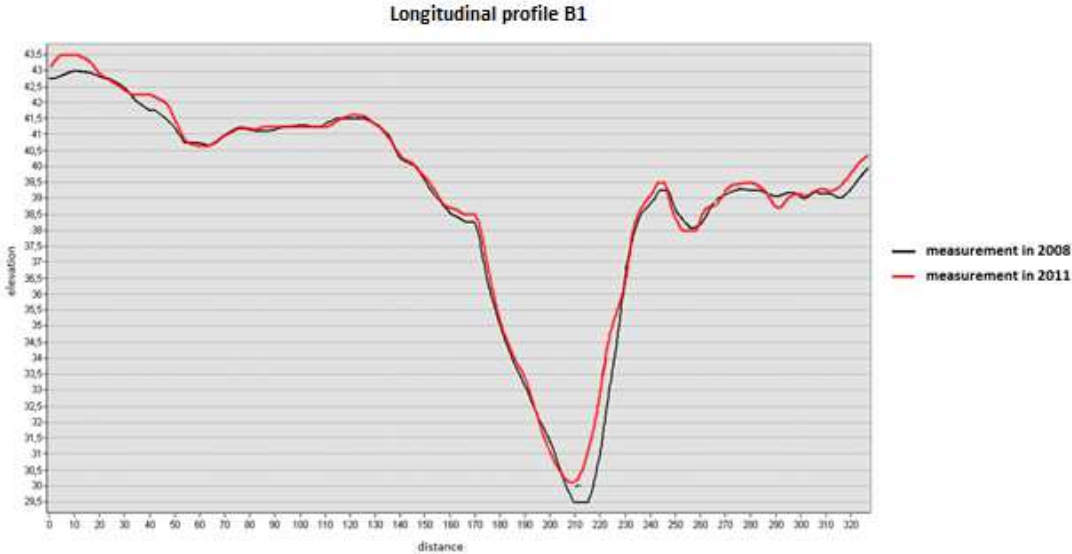


Figure 39 Elevation difference on longitudinal profile B1

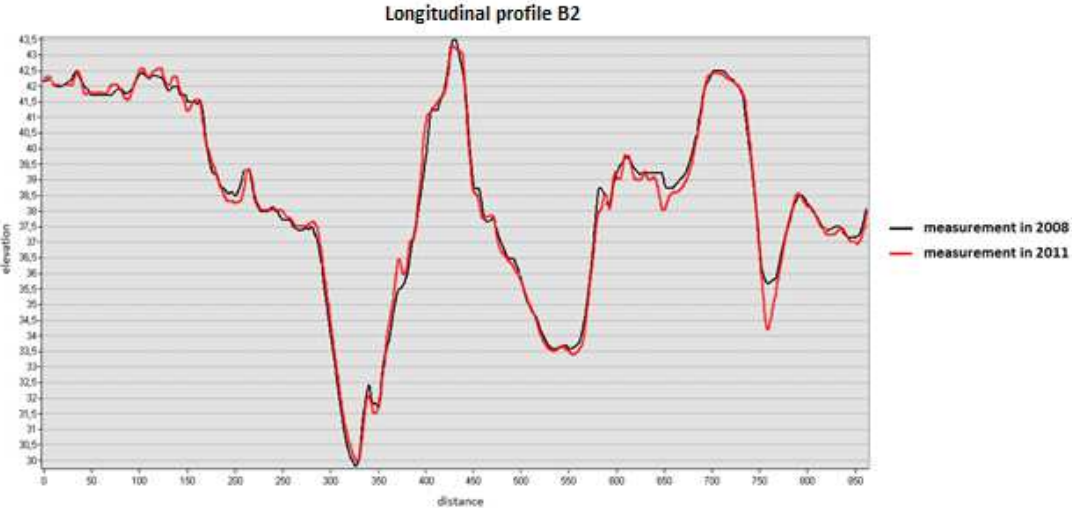


Figure 40 Elevation difference on longitudinal profile B2

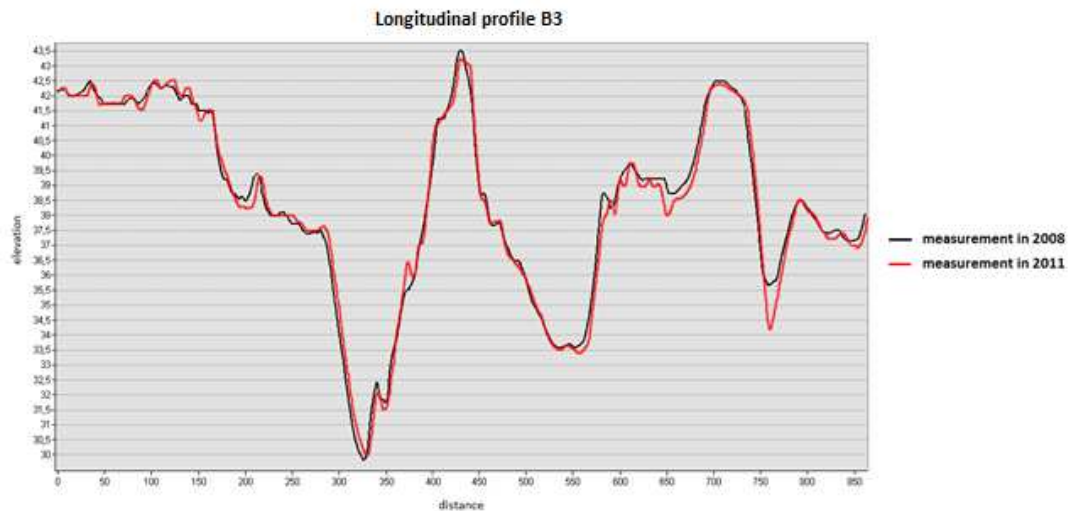


Figure 41 Elevation difference on longitudinal profile B3

The largest diversity between elevations with decreased riverbed occurred on left side of the profiles 'B2' and 'B3', which corresponds to location in direct neighborhood of the dam. The structure loss here reached up to 1,50 m. The other parts of the profiles show moderate changes in the range from several centimeters to about 0,50 m. On the graph of profile 'B1' there are places with noticeable elevation increase – at the bottom of the pit and on the profile edges. Its value amounts to about 0,50 m.

4.2.3. Summary analysis

To summarize all performed analysis, general evaluation of the volume of gained and lost material was considered to be best. On the basis of rasters from 2008 and 2011 the comparison of surface shape was conducted.

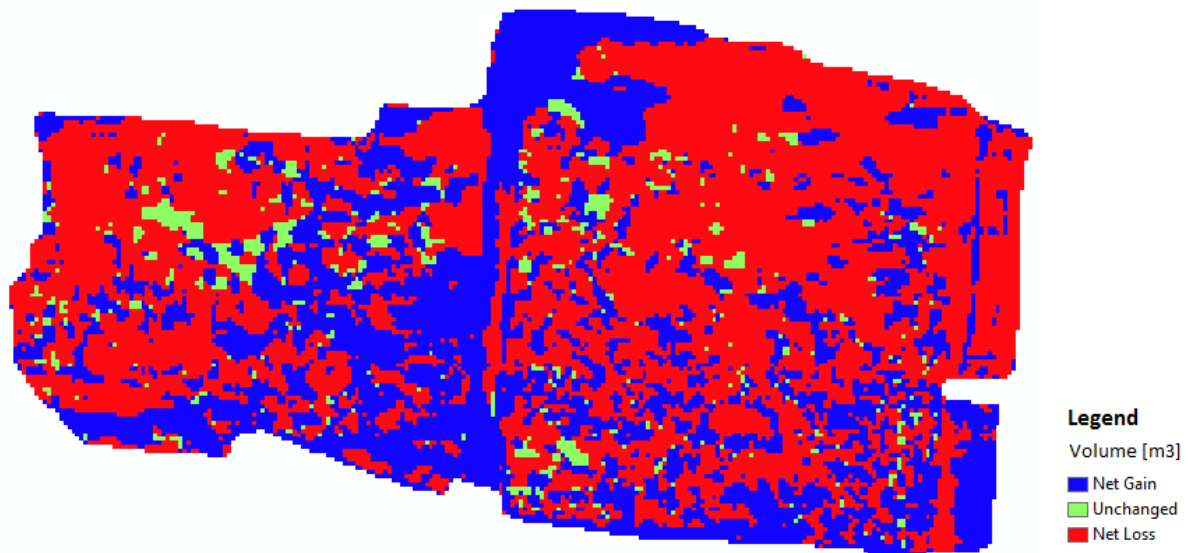


Figure 42 Evaluation of the volume of gained and lost material

In Figure 42 it can be seen that significant majority of the area is characterized by the loss of material. Most of the losses are located directly downstream the dam and further below the temporary threshold, whereas regions with gained material are located mainly below the temporary threshold in its direct neighbourhood. There are also some small spots with the unchanged volume values. These kind of spots are scattered around the whole analysed area. The actual numbers of material volume loss and gain are presented in Table 7.

Table 7 Changes in volume of the material and size of the area in numbers

	Volume [m ³]	Area [m ²]
Net Gain	34 062	136 801
Unchanged	-	15 422
Net Loss	53 455	214 746

To define trend of spatio – temporal changes in the timeframes of 2008 - 2011, linear regression of particular cross – sections and longitudinal profiles have been calculated. Results are presented in Figure 43 and 44.

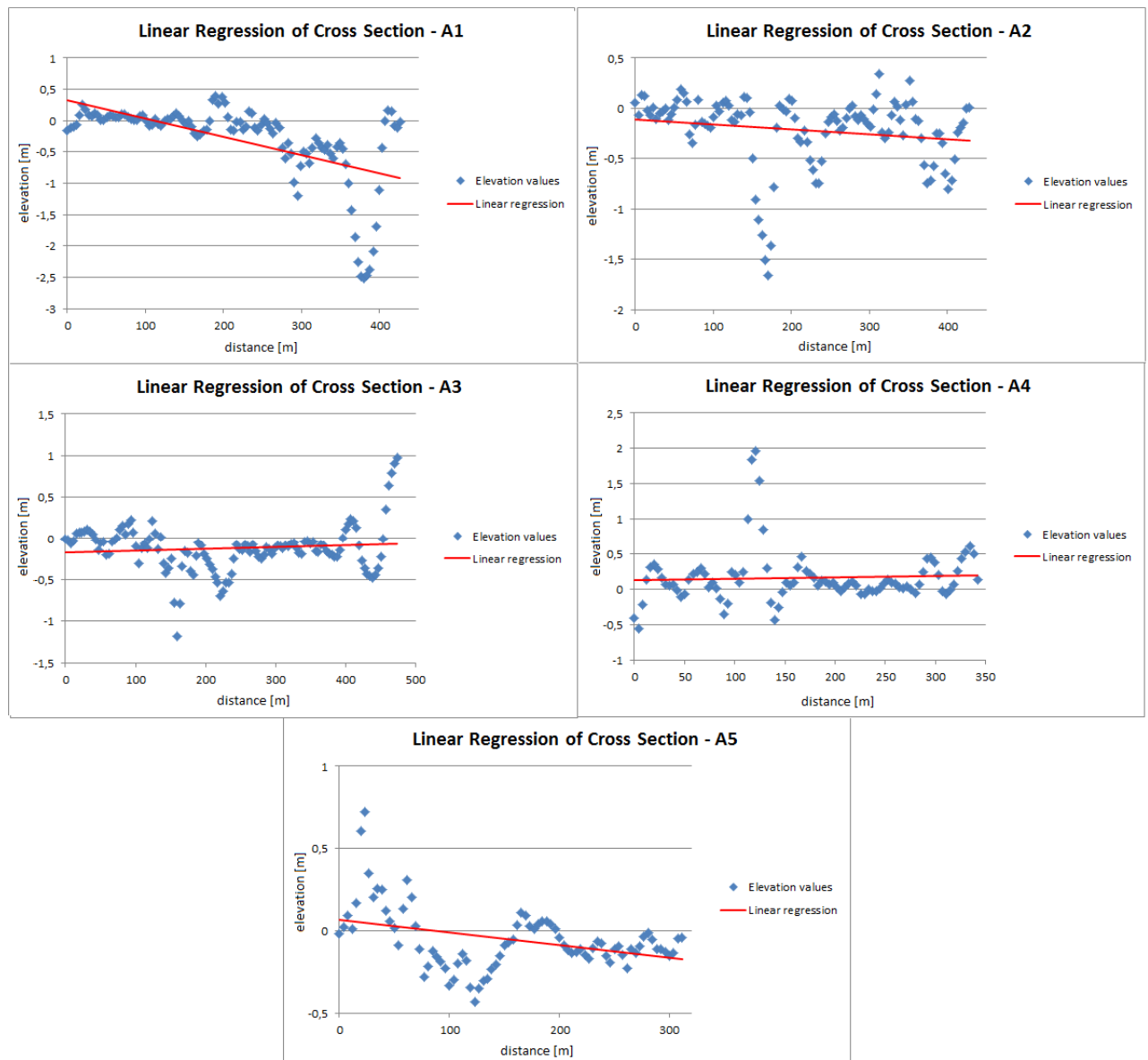


Figure 43 Linear regression of cross – sections A1 – A5

Based on the above diagrams it can be stated that linear regression represents different trends dependent on the cross – section. Cross – sections A1, A2 and A5 located in the direct neighbourhood of the dam and below temporary threshold are characterised by the decreasing trend, whereas A3 and A4 in contrast – slightly increasing one. Decreasing trend over time corresponds to incision of the riverbed, while increasing one to accumulation.

To be able to determine the trend of morphological processes dependent on the distance from the dam, linear regression of longitudinal profiles have been conducted. Results of the calculations are presented in Figure 44.

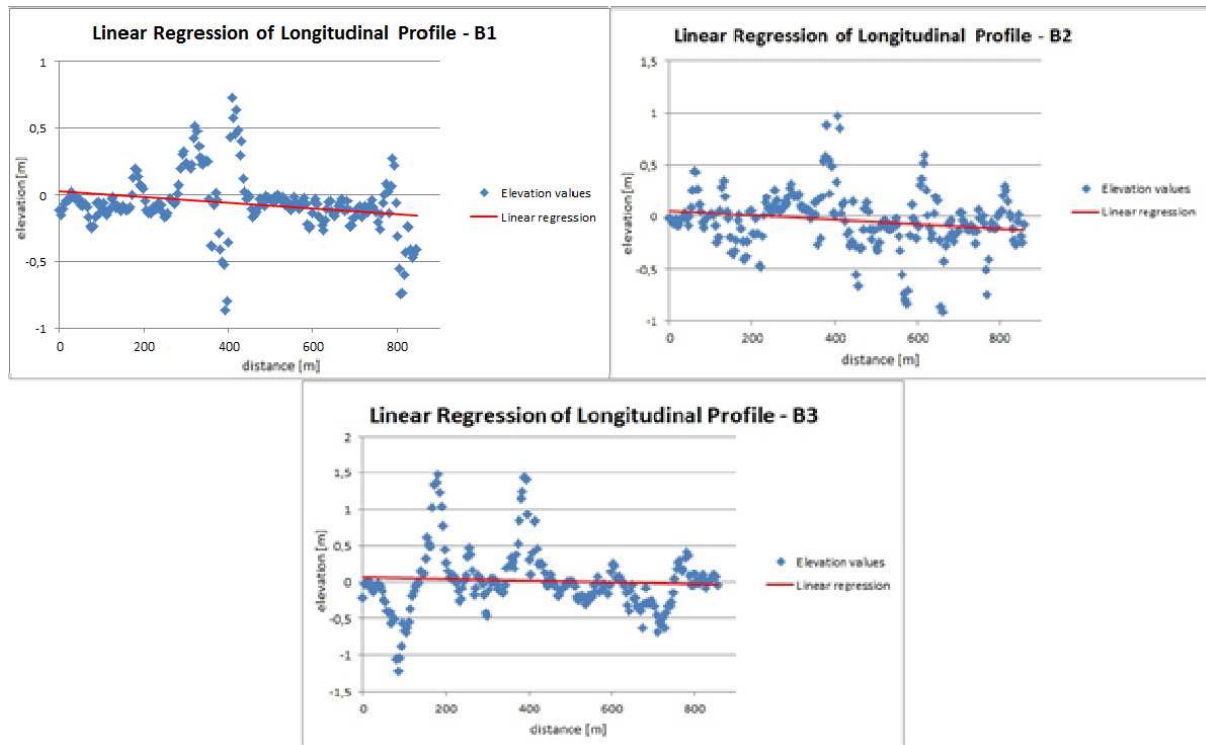


Figure 44 Linear regression of longitudinal profiles B1 – B3

The trend of morphological changes over time with the growth of the distance from the dam is showing decreasing tendency. However the further the distance the lower decrease of the trend. It means that the general incision of the riverbed decreases with the distance downstream the dam.

4.2.4 Assessment of the accuracy of DEMs derived from contour lines

To determine the magnitude of the error introduced to DEMs derived from contour lines, the workflow of its generation was reproduced on the basis of existing DEM of a similar topography. The diagram with particular steps is presented in Figure 45.

Existing DEM for the analysis was acquired from the earthexplorer.usgs.gov portal. The part of SRTM arc 1 covering the landform with the elevation variance in the range up to 12 m was chosen as a reference surface for the analysis. On the area covering selected part of the DEM, a number of points with the same density as in the project has been created with elevation values extracted from the selected DEM. On their basis, interpolation with IDW approach has been conducted. Created contour lines were the basis for creation TIN surface, which were converted at the end to raster format.

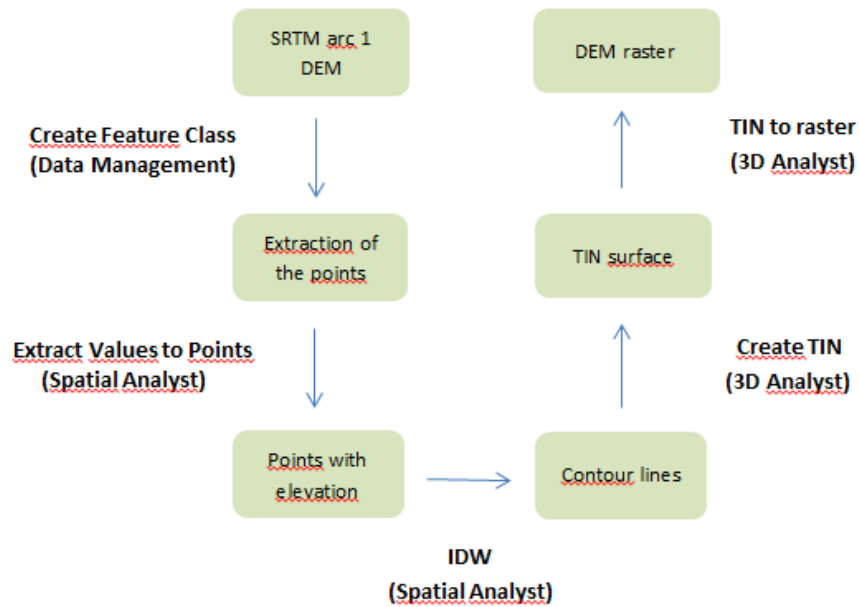


Figure 45 The workflow of accuracy assessment

To define the magnitude of the error introduced to DEM derived from contour lines, the newly computed raster surface was compared to reference one using *Minus* tool. The results of that comparison are presented in Figure 46.

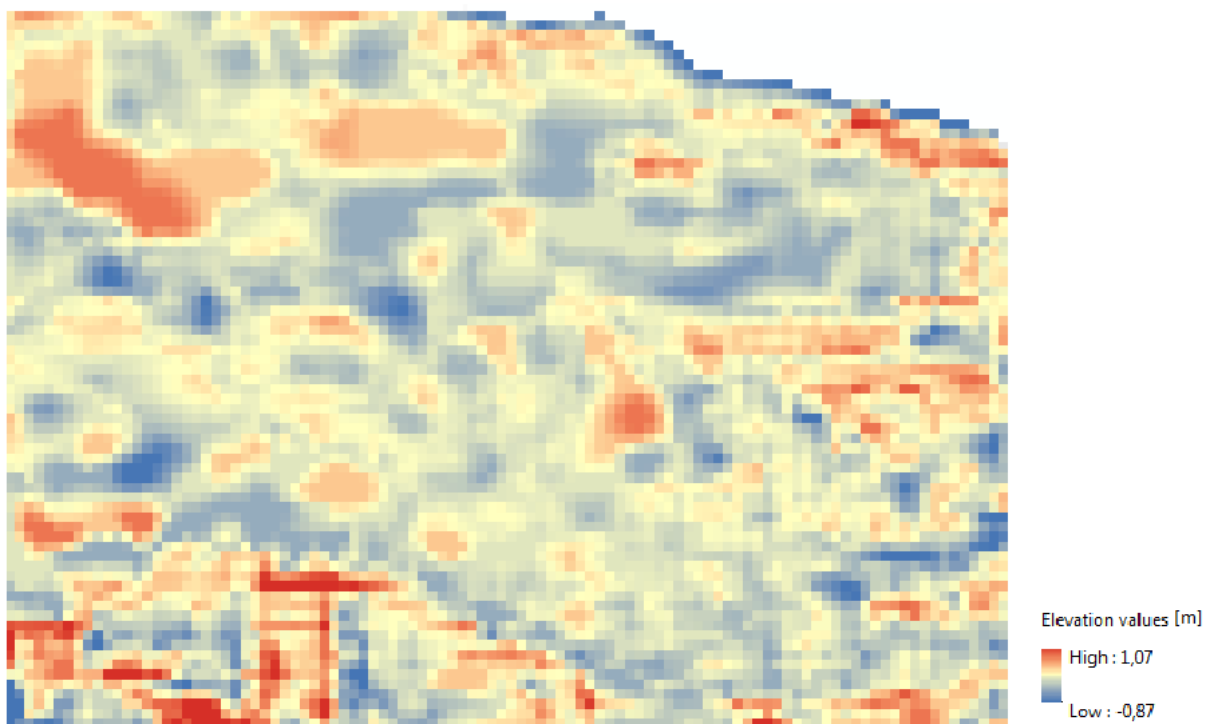


Figure 46 Assesment of elevation error magnitude

Comparison of DEM derived from contour lines with reference surface has shown the differences in elevation values. According to Figure 46 the magnitude of the error range from -0,87 m to 1,07 m. Regarding the fact that contour interval was set to 2 m, the range of estimated errors confirm the statement that the accuracy of DEMs derived from contour lines is about the half of the contour interval (Tyner 1992).

Presented and discussed results in this chapter form the basis for further discussion in chapter 5.

5. Discussion

The datasets collected during survey campaigns on Vistula below Włocławek dam, made it possible to study the dynamics of morphological processes of riverbed. Created DEMs representing the most current sculpture of riverbed, shows that the potholes created as a result of morphological processes are located mostly in the central part of the channel and along the left riverbank. Probably, in these areas erosion – resilient formations like silt and clay, have already been destroyed, reaching the layer of prone to erosion tertiary sand deposits. It means the change of the bottom from the stable so far to unstable one, what can significantly intensify the process of riverbed decrease.

The analysis of spatial variations during the whole 4 years period show a general tendency of riverbed degradation. The volume of eroded material over the analysed area equals to 53 455 m³ and cover the region of 214 746 m² which is 36% more than accumulated one (34 062 m³ on the area of 136 801 m²). Despite of this general trend, year – to – year analysis demonstrates various tendencies. Comparison of surveys 2008 – 2011 (Figure 33) indicates that analysed part of riverbed is very dynamic, particularly in the north – east part of the channel in direct vicinity of the dam and below the threshold. There have been noticed the biggest elevation changes both due to erosion and accumulation processes. Over the vast part of analysed area, there is a tendency of riverbed degradation reaching the values up to 0,50 m within the period of 4 years. Considering year – to – year analysis, a special attention should be paid to analysis of 2010 model. In comparison to 2009, the model 2010 shows a great trend of riverbed erosion. Apart from 'regular' riverbed incision at the level of 0,50 m over almost entire analysed area, there are also extensive areas with riverbed decrease at the rates from 0,50 m to almost 3 m. In contrast, comparison of 2010 and 2011 models show completely opposite tendency. The elevation variation over almost entire area represents sediment

accumulation trend reaching the level up to 0,5 m. There are some exceptions in the north - east part of the analysed area and below the threshold, where constant erosional processes are visible. The first case of intensified erosion is considered to be the result of the huge flood wave that took place in May 2010. Large water discharges washed out with increased flow rate the riverbed almost around the entire area. Whereas, one year later sediment accumulation is considered to be the result of the drought, which took place in Poland and the whole Europe for couple of months in 2011. High temperatures and lack of precipitation caused drastic decrease of water level in Vistula. The water discharge in hydropower plant was limited to the minimum one. Decreased water flow resulted in sediment accumulation below the dam. These phenomena confirm the statement of water flow influence of the dynamics of morphological processes downstream from the barrages.

Analysis of linear regression over time represents tendency of permanent incision of riverbed. Due to the fact that research area was located in the direct neighbourhood of the dam, it was not possible to refer to the issues of forehead of erosion moving downstream, however erosion process below the dam corresponds to general scheme developed on the basis of other rivers around the world. According to erosion model (Figure 3) the greatest degradation appeared in the direct vicinity of the dam. This assumption is supported by conducted volumetric analysis where the biggest area of eroded riverbed is located directly in the vicinity of the dam. In addition, linear regression analysis over time represent mostly decreasing trends, i.e. indicating riverbed degradation in particular on cross – section A1 and A5, whilst linear regression of longitudinal profiles enable to determine dynamics of morphological processes with the distance from the dam. The trend of morphological changes over time with the growth of the distance from the dam is showing decreasing tendency as well. However the further the distance the lower decrease of the trend. It means that the general incision of the riverbed decreases with the distance downstream the dam what coincides with the general model of erosion as well.

Comparing Vistula riverbed development trends with previously conducted studies, year – to - year analyses confirm the irregular nature of this phenomenon. However, whilst in case of the area of several dozen kilometers downstream the river the diversity of the phenomenon is caused only by natural factors and activity of the hydropower plant, in the analysed area additional human activity might contribute to such state. According to information provided, there were some ‘repair’ works carried out in the analysed area. They consists in most cases of deliberate filling of potholes with materials like hard stone rubbles in the places where depths have reached extreme values. Such situation took place for example

in the potholes below the threshold, which is confirmed by the increasing trend of linear regression on the cross – sections A3 and A4. Moreover, analysis of cross – sections and longitudinal profiles, indicates that general riverbed incision over the majority of analysed area in the period of 4 years, haven't reached the value of 0,50 m. It is estimated that in most cases the rate of riverbed degradation was at the range from 0,10 – 0,40 m. On the basis of this statement, it can be assumed that mean riverbed decrease is at the level of about 0,10 m per year. That assumption coincides with the previous studies, which stated the riverbed incision at the range from 7,5 cm to 9,6 cm, dependent on the analysed period. Referring these values to other dams in the world, it can be stated that impact of Włocławek barrage on the process of erosion is considered to be average and thus definitely not catastrophic.

Accuracy is the factor influencing the general quality of a data set and describes similarity of the data to the true values. In case of analysed data, the accuracy of data has been questioned due to incorrect workflow. On the basis of the accuracy analysis it was stated that DEMs derived from contour lines are biased by the elevation error at the range from -0,87 m to 1,07 m. Despite error propagation on the surface of analysed area was not possible to be determined, it was assumed that the error may affect certain extreme elevation values, but does not affect the general trend of morphological processes of the analyzed area.

6. Conclusions

Riverbed erosion downstream the dam is virtually impossible to stop, therefore several adverse consequences are to be expected. In case of Włocławek hydroelectric power plant morphological processes represent the continuous trend of permanent riverbed degradation. Despite general conclusion on erosion expiration with time, Vistula below Włocławek dam is the example where after more than 40 years of activity of water threshold, riverbed degradation is still in progress. Analysis conducted in the frames of this master thesis identify the mean riverbed incision at the level of about 0,1 m per year, which coincides with previous studies for 40 years period. On the basis of comparison of riverbed incision to another rivers in the world with characteristics of the zones below dams, it is stated that impact of activity of Włocławek hydropower plant on the precesses of erosion are considered to be on average level, and thus certainly not catastrophic. Therefore the only explanation for the threat of washing out of the dam as a result of riverbed incision is its lonely functioning, as the dam was designed closely in relation to the foreseen next object.

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