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The analysis of factors inducing and inhibiting morphological changes of the Warta river reach downstream of the Jeziorsko reservoir (Poland)

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The main goal of the presented research is the analysis of morphological changes in the Warta river downstream of the Jeziorsko dam (Poland). The longitudinal erosion and local scours have been observed there since the dam was built in 1983. These processes were induced by the water management in the Jeziorsko reservoir and significant change of hydraulic and hydrologic conditions in the Warta river. The main factor determining the intensity of the erosion is type of soil in the river bottom and banks. However, other factors as local channel configurations or bottom armoring may accelerate or inhibit the process intensity. In the paper long series of the data collected since the reservoir was built are presented and discussed. The several factors influencing the intensity of erosion process in the Warta river reach under consideration are analyzed. Finally the prediction of the Warta river bottom is presented.

I. INTRODUCTION

The process of intensive longitudinal and local river bed erosion is often observed downstream of dams and weirs. The phenomenon is especially important in the case of large reservoirs. The main factor inducing the analyzed process is the change of hydraulic conditions in the river related to the dam performance. Since the dam is built the previous balance in sediment deposition and erosion is no longer kept. The particles are accumulated in the reservoir located upstream of the dam. The sediment transport continuity is interrupted. The main features of river stream flowing from stilling pool to river bed are very intensive turbulence and almost no load. The water starts to take the particles from the bottom just below the stilling pool or other bottom protecting structures.

The intensity of the river bed erosion depends on the factors mentioned above. In addition bottom and banks material characteristics as alluvium layer thickness and grain size play important role. The assessment and management of risk linked to local and longitudinal erosion of river bed downstream of the dams is crucial for the performance and safety of many hydraulic structures installed in the river including dams themselves.

The main purpose of the conducted research is to present and discuss the problem of local and longitudinal erosion of river bed observed in the Warta river reach downstream of the Jesiorsko Reservoir Dam. The paper consists of several sections. First the Jeziorsko Reservoir Dam and hydrological conditions in the water system are presented. Then the field measurements and bottom material characteristics are described and shortly discussed. The model used for the analyses is presented in section no. 5. Next section includes the analysis of simulation results and forecast of bed changed due to the erosion process. Last section includes summary and concluding remarks.

II. DESCRIPTION OF THE JEZIORSKO RESERVOIR

Jeziorsko reservoir was built in 1986 in central part of Poland. It is located in the Warta river, between the Sieradz (upstream) and Uniejow (downstream) gauge stations. The dam is located in the Warta river at km 484+090 (fig. 1). The Jeziorsko reservoir is relatively new object. First time it was filled up to the admissible maximum water level (121,50 m a.s.l.) in 1991. The hydropower plant was put into operation in 1995.

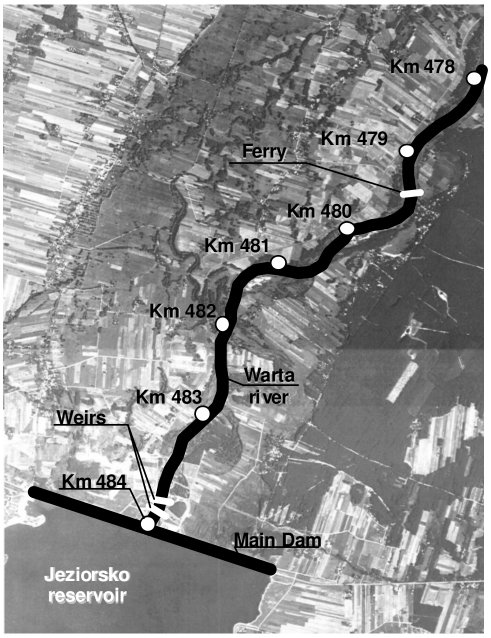

Figure 1 Map of the Warta river reach downstream of the Jeziorsko reservoir

The Jeziorsko reservoir is multipurpose reservoir performing in the annual working scheme. During the months from October to December the water stages are kept on the minimum level of 116 m a.s.l.. In spring months the reservoir is filled with water. The maximum water level 121.5 m a.s.l. is hold during April – June

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period. In the period from July to August the water stored at the reservoir is used and the reservoir water stages gradually come back to the minimum level. The main purpose of the reservoir performance is the flood protection during wet season. The reservoir is also the source of water for the big cities in Great-Poland province: Poznan, Kolo, Srem and Konin. The water stored is also used for irrigation purposes and to preserve biological life below the dam. The Patnow-Konin and Adamow power plants used the water from the reservoir for cooling. Other goal of the Jeziorsko performance is production of hydro-power, though, this is not significant due to the small difference between upper and lower water levels in the dam (about 10 m). The reservoir is also used for recreation and inland fishery.

Before the dam started to perform the protecting elements had been installed in the tailwater to prevent from negative effect of erosion. The length of protecting structures were 90 m. The basic element of erosion protection is stilling pool. Downstream of the stilling pool the river banks and bottom were protected by the concrete slabs of the length 40 m and the thickness 1 m. The elevation of the concrete slab crest was 109.06 m a.s.l.. Below the slabs the fascine and stone mattresses protected the river bottom and banks. The mattress was 1 m thick and 50 m long.

III. RIVER HYDROLOGY

The Warta river catchment area in the dam cross-section is 9021.8 km^2. The hydrologic characteristics of the Warta river in this region may be assessed on the basis of records from the Sieradz gauge station. The gauge station is located upstream of the reservoir in the km 521. The catchment area ratio is $F_z/F_s = 1.108$, where F_s is catchment area in Sieradz and F_z – in the dam cross-section. The specific discharges in Sieradz gauge station determined for the period 1951-1998 were presented in ref. [5]. They are also shown in tab. I.

In the river reach downstream of the Jeziorsko reservoir there are four gauge stations. These are two gauge station located just below the dam: W.D. I in km 483+860 and W.D. II in km 483+330 and two gauge stations located near towns Ksieze Mlyny (in km 479+400) and Uniejow (km 465+850). Intensive longitudinal erosion of Warta river bed in the reach from weir no. 2 (km 483+710) to gauge station Ksieze Mlyny (km 479+400) caused large decrease of water surface elevation. It is especially visible for medium and low discharges. Due to that fact it is impossible to control water stages at gauge stations W.D. II and Ksieze Mlyny now. The mentioned gauge stations are used only during short period of time in the year when high water flow occur in the analyzed river reach. Because of the discussed river bed changes only two gauge stations installed in the system may be used to observe and control the discharges from the dam. These are W.D. I and Uniejow.

TABLE I.
CHARACTERISTIC FLOWS IN THE SIERADZ GAUGE STATION

Description	Notation	Value (m^3/s)
absolute observed maximum flow	*Max Q*	397.5
absolute observed minimum flow	*Min Q*	10.5
average flow	Q_a	48.9
median flow, flow related to probability of excedance 50 %	$Q_{50\%}$	187.0
flow related to probability of excedance 10 %	$Q_{10\%}$	353.0
flow related to probability of excedance 1 %	$Q_{1\%}$	557.0

IV. ANALYSIS OF DATA FROM FIELD MEASUREMENTS

Presented analyses of bottom and water surface elevations changes were done on the basis of field measurements made in period 1987-2004 (ref. [4], [6], [7], [8], [9], [11], [12]). A range of the observed river reach is from the dam tailwater to the Koscielnica village. This is the river reach from km 484 to km 465 (total distance is 19 km). The field measurements consist of longitudinal water surface leveling, the hydrometric measurements of 52 cross-sections and bed material sampling. During the field measurements the constant outflows from the reservoir were kept. The discharge intensity differs slightly between 31.5 and 33.0 m3/s.

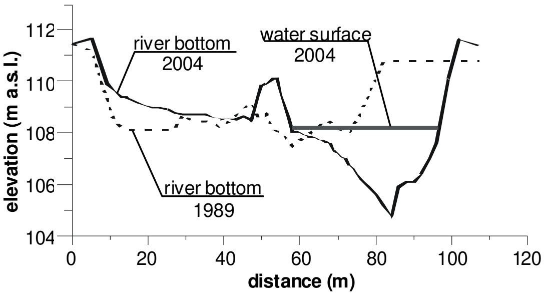

Figure 2. Observed bottom elevation in cross-section P5/1' (km 483+220)

The map of the system is presented in fig. 1. In the map there are denoted the main elements in the system as river reach kilometers, reservoir, dam, weirs and ferry rack. The river reach shown in the map includes the area of the most intensive bed morphology changes. The transverse contours of two selected cross-sections are drawn in fig. 2 and 3. In fig. 4 the longitudinal profile of the river is shown.

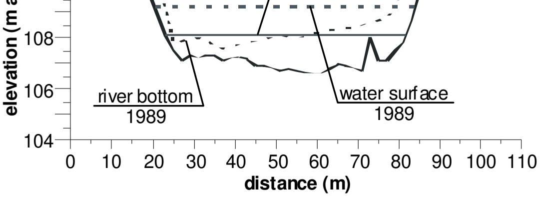

Figure 3. Observed bottom elevation in cross-section P6 (km 483+012)

The cross-sections presented in fig. 2 and 3 are denoted as P5/1' and P6. The field measurements done in July 12-17, 2004 are compared with the cross-section contours observed in July 17th, 1975. The thick continuous line

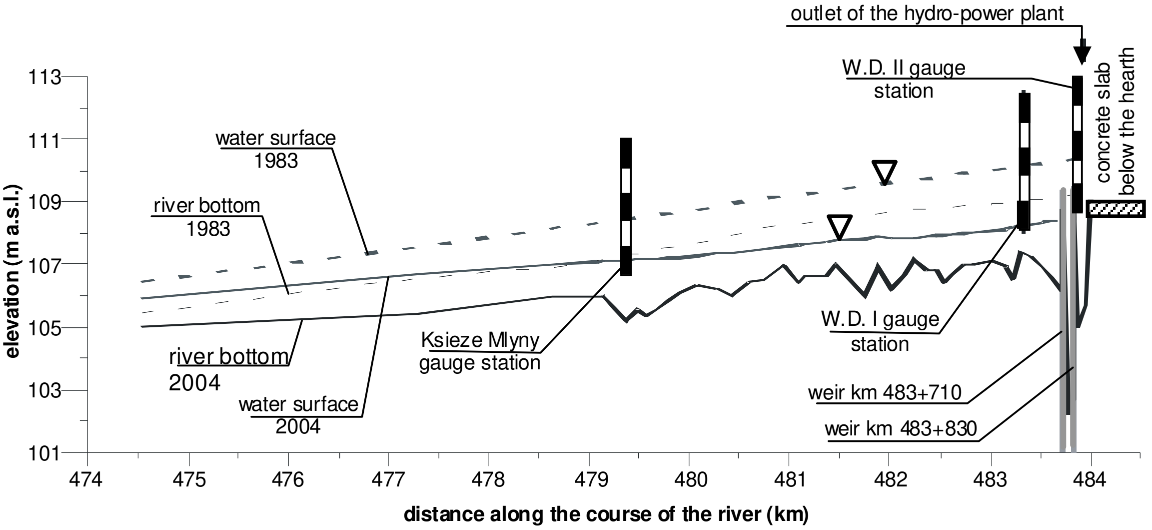

Figure 4. Water surface and bottom elevation changes in the Warta river downstream of the Jeziorsko Reservoir Dam

TABLE II.
Results of Field Measurements in Selected Warta River Cross-Sections (July 12-17, 2004, Discharge $Q = 32.5$ m^3/s)

cross-section	km	water surface (m a.s.l.)	bottom (m a.s.l.)
P4'	483+657	108.37	106.37
P5	483+514	108.35	106.92
P5/3	483+300	108.25	107.40
P6	483+012	108.11	107.11
P7	482+821	108.02	107.02
P7/5	482+358	107.90	106.81
P8	482+130	107.85	106.65
P8/3	481+656	107.80	106.01
P9'	481+169	107.65	106.65
P10	480+740	107.48	106.49
P11	480+080	107.27	106.35
P11/1	479+906	107.21	106.10
P12'	479+376	107.13	105.30
P13	478+630	107.01	105.96
P15	474+530	105.90	105.00
P17	470+140	104.33	103.14
P19	467+170	103.17	102.37
Uniejów	465+850	102.67	101.52

represents the data taken in 2004 for each cross-section. The past situation is denoted as thin dashes line. In addition the observed water surface elevations are also shown in fig. 2 and 3.

The longitudinal profiles of water surface and average bottom elevations in the reach range from km 484+000 to km 474+530 (fig. 4). The average bottom elevation are determined as the difference between the water surface level and the average depth measured along the bottom width. As it results from practical observations of natural river flows the later characteristic, average depth along bottom width, is almost always equal to depth evaluated in the channel axis. The thick continuous and dashed lines represent the river bottoms measured during July 12-17, 2004 and in July 17th, 1975, respectively. In the same figure there are corresponding water surface profiles denoted by thin lines. The measurements in the period July 12-17, 2004 were done during the discharge 32.5 m3/s. The historical data from July 17th, 1975 were taken during the discharge 33.0 m3/s. The thin and dashed gray lines represent maximum banks elevations.

The longitudinal profiles of water surface and average bottom elevations measured in 1975 are taken as the description of initial conditions in the system. In the fig. 2, 3 and 4 one may notice that the changes of the river bottom elevation are significant.

The basic cross-sections hydraulic properties with water surface and average bottom elevations measured in July 12-17, 2004 are presented also in tab. 2

The specific grain sizes of bed sediment were determined on the basis of sieve analysis. The samples of bottom material taken from Warta river bed were used. The results of the analysis are shown in tab. 4. This table presents the data measured in July 12-17, 2004. The presented specific grain sizes are D_{10}, D_{35}, D_{90} and D_{95}. These factors are frequently used for the description of bottom material characteristics.

Although, the tab. 3 presents only current measurements, the grain sizes in the analyzed river reach have been controlled since the dam was built. In the natural conditions before the dam was built the largest specific grain sizes (D_{95}) varied between 0.60 and 1.00 mm. After 14 years of reservoir performance, in 1997 the same indicators increased to the range from 1.20 to 10.0 mm. The values presented in the table are related to the conditions in 2004, after 21 years since the reservoir started to perform. Now the specific grain size is varying from 3.80 to 36.0 mm.

TABLE III.
GRAIN SIZES OF BOTTOM MATERIAL IN THE WARTA RIVER BED
(JULY 12-17, 2004)

cross-sect.	km	specific grain sizes (mm)				
		D_{10}	D_{35}	D_{50}	D_{90}	D_{95}
P5	483+514	0.29	0.65	3.80	20.0	28.0
P5/2	483+390	0.27	0.44	6.70	32.0	36.0
P6	483+012	0.34	0.49	1.25	15.0	18.5
P7	482+821	0.32	0.48	0.73	8.40	15.5
P8/1	482+019	0.34	0.58	0.78	2.30	3.80
P8/2	481+887	0.32	0.49	0.63	6.50	9.40
P8/3	481+656	0.21	0.36	0.54	10.0	18.5
P8/4	481+369	0.30	0.50	0.70	12.0	20.0
P9'	481+169	0.34	0.60	0.73	1.35	1.90
P10	480+740	0.21	0.27	0.34	0.70	1.50
P10/2	480+425	0.32	0.48	0.56	3.00	8.00
P11	480+080	0.30	0.53	0.74	11.5	19.0
P12'	479+376	0.26	0.37	0.42	0.79	0.90
P13	478+630	0.32	0.47	0.50	0.93	1.30
P16	472+190	0.33	0.47	0.53	1.10	1.35
P17	470+140	0.34	0.57	0.73	2.10	3.90
P18	468+280	0.30	0.33	0.48	0.90	1.25
P22	465+920	0.37	0.52	0.60	1.35	1.75

The changes in time of the specific grain sizes for the selected cross-sections are also presented in fig. 5. The increase of the bottom material grain sizes is especially visible in the period 1997-2004. The largest changes were observed in the river reach ranging from weir no. 2 (km 483+700) to Ksieze Mlyny gauge station (km 479+400). In this period the specific grain sizes D95 increased almost 4 times, from 10.0 to 36.0 mm.

Although the increasing tendency is clearly visible in the grain sizes changes in time, several factors may inhibit this process. Two of them are the most important namely bank erosion and earth works performed to install the weirs (fig. 1). However, the temporary inflow of smaller material is not able to stop intensive bottom material segregation caused by the bed erosion. The substantial increase of the largest grain sizes caused so called bottom armouring in the Warta river. In the cross-sections where the increase of grain sizes is largest the decrease of average bottom elevations is small during the last 3 years. It varies from 3 to 15 cm in the reach from weir no. 2 to Ksiezę Mlyny gauge station. The result of bottom armouring is increase of river bed resistance to outwash.

The analysis of field measurements data shows the significant longitudinal bed erosion with local bed and banks washouts. The changes of bottom and water surface elevations in time for the selected cross-sections are presented in fig. 6 and 7. During the period of first 4 years since the dam was built (1983-1987) the erosion process occurred in the reach ranging from km 484+000 to km 481+500 (length 3.5 km). The intensive bed erosion was observed just below the stilling pool in the reach of length 300 m. In 1987 the maximum depth of local scour was 1.70 m.

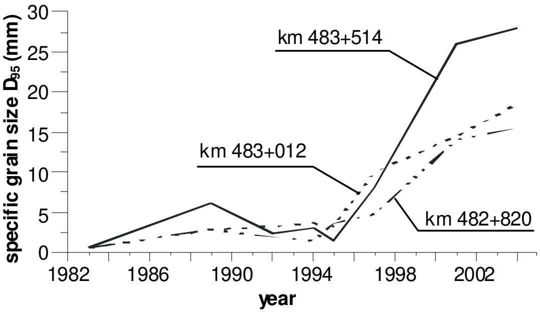

Figure 5. Changes of particles specific diameter during the observation period

In 1991, after the 8 years of sediment transport continuity interruption, the longitudinal erosion was observed in the reach of length 7.0 km. The maximum local scour depths occurred below the concrete protection elements of stilling pool. The scours depths were 3.0 m and 3.2 m. They occurred in the river reach of length 100 m. The secondary effect of erosion was the significant decrease of water surface elevation. The observed decrease of water surface elevation was 1.3 m in the cross-section located just below the concrete protection elements of stilling pool during the discharge 30 m3/s.

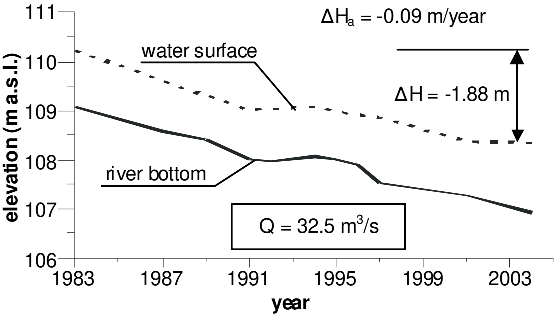

Figure 6. Bottom and water surface elevation changes at cross-section P5 (km 483+574)

In order to restore initial water surface elevations, conditions of hydraulic jump inundation and protection elements stability below the stilling pool two weirs were built in the period 1993-1994 (fig. 1 and 4):

- weir no. 1 located in km 483+830, the overfall crest 109.50 m a.s.l.
- weir no. 2 located in km 483+710, the overfall crest 109.40 m a.s.l.

The construction and earth works related to the installation of weirs caused local increase of bottom elevation below weir no. 2 (fig. 6). The secondary effect of this activity was temporary decrease of bed sediment grain sizes.

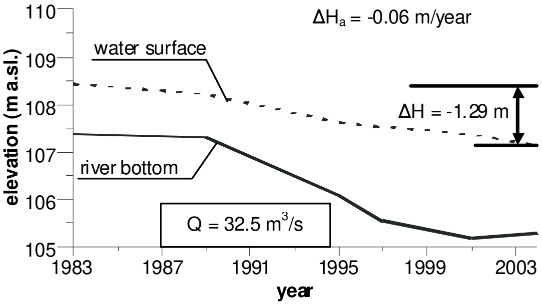

Figure 7. Bottom and water surface elevation changes at cross-section P12 (km 479+400)

V. WATER AND SEDIMENT TRANSPORT MODEL

Due to the complex cross-sections geometry in the analyzed Warta river reach, the basis for the simulation model are St. Venant equations in conservative form. For the sake of sediment transport simulation the equations may be written in the form explicitly indicating the changes of cross-section area related to river bed elevation variations.

$$dA = Bdh - Pdz_b , \tag{1}$$

where A is cross-section area, B – surface width, P – wetted perimeter. dh and dz_b are infinite changes of water depth and bed elevation, respectively. Taking into account (1) the mass balance equation is written in the following form

$$B\frac{\partial h}{\partial t} - P\frac{\partial z_b}{\partial t} + \frac{\partial Q}{\partial x} = q , \tag{2}$$

where t is time and x indicates the distance measured along the river reach. Q is discharge and q is lateral inflow to the reach.

The assumed momentum equation form is as follows

$$\begin{aligned} &\frac{\partial Q}{\partial t} + 2\frac{Q}{A}\frac{\partial Q}{\partial x} - B\frac{Q^2}{A^2}\frac{\partial h}{\partial x} + gA\frac{\partial h}{\partial x} = \\ &= gA\left(i_b - I_f\right) + q\left(u_q - \frac{Q}{A}\right) + \frac{Q^2}{A^2}\frac{\partial A_h}{\partial x} \end{aligned} , \tag{3}$$

where i_b and I_f are bottom and energy slopes, respectively. u_q is component of the lateral inflow velocity in the channel direction. The term $\partial A_h/\partial x$ describes the changes of cross-section related to the changes of river bed geometry. This term is important only in the case of large geometry changes along the open channel.

The sediment transport continuity equation is taken in the below form

$$P\left(1-p\right)\frac{\partial z_b}{\partial t} + \frac{\partial\left(AC_s\right)}{\partial t} + \frac{\partial S_t}{\partial x} = 0 , \tag{4}$$

where p is the bed porosity, S_t is total sediment transport intensity and C_s is the average volumetric concentration of sediment over a cross-section. The last two variables are linked according to the relationship

$$S_t = C_s Q , \tag{5}$$

The initial conditions for the system of partial differential equations (2) – (4) are written below

$$\begin{aligned} Q(x,t=0) &= Q_P(x), \\ h(x,t=0) &= h_P(x), \ , \\ z_b(x,t=0) &= z_{bP}(x), \end{aligned} \tag{6}$$

where Q_P, h_P and z_{bP} are the scalar functions determined along the river reach $0 \le x \le L$ (L – the length of the reach). Assuming that the Froude number along the analyzed river reach is much lower than 1 the boundary conditions are as follows

$$\begin{aligned} Q(x=0,t) &= Q_0(t), \\ h(x=L,t) &= h_L(t), \ , \\ z_b(x=0,t) &= z_{b0}(t). \end{aligned} \tag{7}$$

The functions Q_0, h_L and z_{b0} are determined for time $t \ge 0$.

The energy slope I_f in the case of flow with movable bed is linked to the variables describing water flow (Q, h, A, etc.) as well as to the features of bed material (ρ_s, D_{35}, etc.) and bed forms. According to the analyses presented in [3] the bed forms identification is related to the Shields' parameter and additional variable defined as follows

$$\theta = \frac{RI_f}{\left(\frac{\rho_s}{\rho} - 1\right)D_{35}}, \qquad Z = \frac{R}{D_{35}}, \tag{8}$$

where R is hydraulic radius, D_{35} is characteristic sediment particles diameter, ρ and ρ_s are water and sediment particles densities, respectively. The energy slope is calculated as

$$I_f = C \cdot Z^m \cdot Fr^{2n} , \tag{9}$$

where Fr is Froude number and C, m and n are parameters determined on the basis of (8). The procedure is described in details in [3].

For the evaluation of the volumetric concentration of sediment Ackers and White formula ([1]) is used. The formula describes the total concentration of suspended and bed load. Its basis is the set of two dimensionless parameters, mobility number F_{gr} and sediment transport relationship G_{gr}, defined as follows

$$F_{gr}=\frac{u_*^{N_1}}{\sqrt{gD_{32}\frac{\rho_s-\rho}{\rho}}}\left[\frac{u}{\sqrt{35}\log\left(\frac{10h}{D_{35}}\right)}\right]^{1-N_1}, \tag{10}$$

$$G_{gr}=C_w\left(\frac{F_{gr}}{A_1}-1\right)^{M_1},$$

where u_* is shear velocity

$$u_*=\sqrt{gRI_f}\ . \tag{11}$$

The coefficients N_1, A_1, M_1 and C_w depend on the water flow around the particles and they are defined on the basis of so called dimensionless particle diameter

$$D_{gr}=D_{35}\left(\frac{\rho_s-\rho}{\rho}\frac{g}{\nu^2}\right)^{1/3}, \tag{12}$$

where ν is kinematic viscosity coefficient. The total volumetric concentration of sediment in the cross-section is evaluated as follows

$$C_s=\frac{G_{gr}D_{35}}{h\left(\frac{u_*}{u}\right)^{N_1}}. \tag{13}$$

The presented model consists of partial differential equations (PDEs) (2) – (4), the additional formulae (5), (9), (13) and initial and boundary conditions (6), (7). This is the system of nonlinear hyperbolic PDEs. The domain of the problem is $0 \le x \le L$ and $t \ge 0$. If the formulae (5), (9), (13) are substituted into equations (2) – (4) the system consists of three PDEs with three dependent variables: $Q(x, t)$, $h(x, t)$, $z_b(x, t)$. The application of the accurate analytical methods to solve the problem is practically impossible due to the complex nature of the presented mathematical model. The approximate numerical methods have been used for the simulation of many physical processes for long time. In the analyzed case the decomposition of the PDEs' system and application of a few different numerical methods is forced by the complexity of the problem. The first step is the separation of the water flow and sediment transport equations. Such approach is consistent with different dynamic of these two processes. The changes of the water flow parameters as discharge and depth are much more faster than changes of bed elevations.

The basis of the numerical solution is digitizing of the domain in time and space with integrations steps Δt and Δx, respectively. The domain is covered by the grid with $L/\Delta x + 1$ nodes is $0x$ direction and a number of nodes in $0t$ direction. Next the terms in the equations are approximated by the algebraic formulae. In this way the system of three PDEs is replaced by the number of algebraic equations, which is the discreet form of the considered mathematical model. The choice of the digitizing method and numerical scheme is of the crucial importance. In the case of unsteady flow modeling the Preissmann scheme is recommended for many researchers (e.g. ref. [2], [14], [10], [13]). This is one of the finite difference method approximations. The Preissmann scheme is relatively simple, but the accuracy of the results is huge. Due to above reasons the mentioned scheme is used for the implementation of the mathematical model presented earlier.

VI. SIMULATION RESULTS

The field measurement data are used to prepare the mathematical model described in the previous part of the paper. The unsteady flow and longitudinal erosion process occurring downstream of the weir no. 2 (km 483+650) is analyzed. The river reach length is 17.807 km. The river reach is divided into several cross-sections. The average distance between cross-sections is $\Delta x = 500$ m.

The initial condition is the current stage of the analyzed system. Two elements are used as boundary conditions. The average annual scheme of the Jeziorsko reservoir performance is imposed in the inlet of the river reach. The second boundary condition is the rating curve determined for the Uniejow gauge station located in the outlet.

The chosen time step is $\Delta t = 24$ h. This value guarantee the stability of computations and prevents from too long time of simulation.

On this basis the forecast of river bottom changes is elaborated. The unsteady flow and sediment transport in the analyzed river reach is simulated. The simulation begins in current stage, what means year 2004. The time horizon is year 2010. The final results of the simulation are presented in fig. 8.

The forecast is not restful. The river reach vulnerable to erosion changes will be longer. In fig. 8 one may notice that bottom and water decrease will be greater in the future. The flow conditions will degrade. This will result in greater difficulties with inland sailing and water use. The actions preventing from longitudinal erosion are necessary.

VII. CONCLUSIONS

The longitudinal and local erosion process in Warta river reach ranging from the dam tailwater to the Uniejów gauge station was analyzed. The presented investigations were done on the basis of field measurements done in the period 1987-2004 and numerical forecast for the period 2004-2010. The measurements were compared with the initial conditions in the system which were changed in 1983. The main features of the investigated process is significant variability in time and along the reach. The main factors influencing the process are the outflows from the reservoir and the bed material segregation resulting in the increase of grain sizes.

The reservoir started to perform 21 years ago (in 1983). The process of Warta river bed erosion occurred in the reach ranging form the tailwater of weir no. 2 (km 483+650) to the ferry rack in Kościelnica town (km 465+000). The most intensive bed erosion is observed in the 9.0 km reach located downstream of the dam. In this area the decrease of the bottom elevations is varying from 2.60 m in the tailwater of weir no. 2 to 0.5 m in km 474+530. In downstream of this reach the bottom elevations decrease is varying from 0.50 m to 0.25 m. The

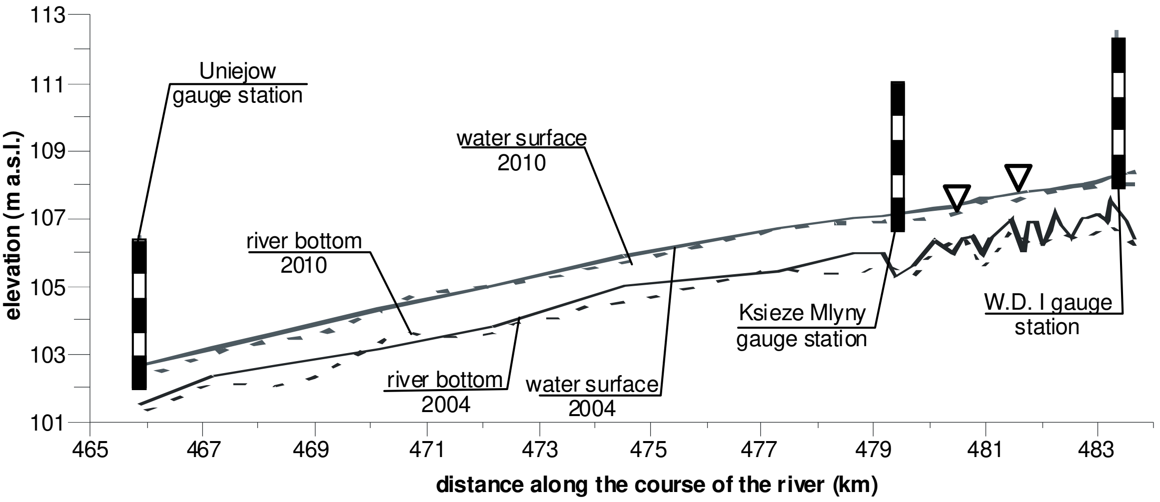

Figure 8. Current (2004) and forecasted (2010) water surface and bottom elevation changes in the Warta river downstream of the Jeziorsko Reservoir Dam

simulation performed indicated that the process of longitudinal erosion is moving further. It is expected that the bed changes reach the Uniejow gauge station until 2010.

Especially intensive bed erosion occurred in the river reach located downstream of the dam in the distance 4.2 km. The water surface elevations measured during the discharge 32.5 m^3/s in 2004 were lower than the average bottom elevations in 1989.

The increase of bed material grain sizes was observed. The effect of this process is the increase of bottom resistance to outwashes. The most intensive increase of grain sizes occurred in the river reach located just below the weir no. 2 (fig. 4 and 8).

The secondary effect of erosion process is the decrease of water surface elevations. After the period of 21 years since the reservoir started to perform the decrease of water surface elevations is varying from 1.88 m (km 483+510) to 0.56 m (km 474+530). These values were determined during the discharge 32.5 m3/s. The average annual decrease of water surface elevation is changing from 9.0 cm/year in km 483+510 to 6.1 cm/year in km 479+400.

Due to the erosion process in years 1983-1992, the water surface elevations in the tailwater of the dam was decreased to the elevation 109.06 m a.s.l.. This elevation is equal to the elevation of the concrete slab crest installed below the dam stilling pool. In order to restore the water surface elevations in the dam tailwater two weirs were built in km 483+860 and km 483+710.

NOTATION

Δt	time step of numerical simulation, (s) or (min, hours)
Δx	step of spatial integration in numerical computations, (m)
ρ	water density, (kg/m^3),
ρ_s	sediment particles density, (kg/m^3),
ν	kinematics viscosity coefficient, (m^2/s),
$\partial A_h/\partial x$	changes of cross-section related to the changes of river bed geometry, (m^2/m),
A	cross-section area, (m^2),
A_1	parameter,
B	surface width, (m),
C	parameter,
C_s	average volumetric concentration of sediment over a cross-section, (-)
C_w	parameter,
D_{35}	characteristic sediment particles diameter, (m) or (mm),
dh	increment of water depth, (m),
dz_b	increment of bed elevation, (m),
G_{gr}	sediment transport relationship, dimensionless,
F_{gr}	mobility number, (-),
Fr	Froude number, (-),
h_L	depth changes in the outlet cross-section imposed as boundary condition, (m),
h_P	initial depth in the river reach varying along the channel, (m),
i_b	bottom slope, (-),
I_f	energy slope, (-),
L	the length of the river reach, (m),
m	parameter,
M_1	parameter,
$Max\ Q$	maximum observed flow, (m^3/s),
$Min\ Q$	minimum observed flow, (m^3/s),
n	parameter,
N_1	parameter,
q	lateral inflow to the reach, ($m^3/(ms)$),
Q	discharge, (m^3/s),
Q_0	flow changes in the inlet cross-section imposed as boundary condition, (m^3/s),
$Q_{1\%}$	flow related to probability of excedance 1 %, (m^3/s),

$Q_{10\%}$	flow related to probability of excedance 10 %, (m^3/s),
$Q_{50\%}$	median flow, probability of excedance 50 %, (m^3/s),
Q_a	average flow, (m^3/s),
Q_P	initial flow in the river reach varying along the channel, (m^3/s),
p	bed porosity, (-),
P	wetted perimeter, (m),
R	hydraulic radius, (m),
S_t	total sediment transport intensity, (m^3/s)
t	time, (s) or (min, hours),
x	distance measured along the river reach, (m),
u_q	component of the lateral inflow velocity in the channel direction, (m/s),
u_*	shear velocity, (m/s)
z_{b0}	bottom elevation changes in the inlet cross-section imposed as boundary condition, (m),
z_{bP}	initial bottom elevation in the river reach varying along the channel, (m),

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