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Natalia Mączka[1]
https://orcid.org/0009-0003-9982-6186

Paweł S. Hachaj[2]
https://orcid.org/0000-0001-5342-047X

Monika Szlapa[2]
https://orcid.org/0000-0001-5545-9036

IMPLEMENTATION OF THE NUMERICAL MODEL OF AN ACTIVE BED FOR THE WLOCLAWEK RESERVOIR

[1] student at Cracow University of Technology,
Faculty of Environmental and Energy Engineering, Poland
e-mail: maczka.natalia.klaudia@gmail.com
[2] Cracow University of Technology, Faculty of Environmental and Energy Engineering,
Department of Geoengineering and Water Management, Poland
e-mail: pawel.hachaj@pk.edu.pl, monika.szlapa@pk.edu.pl

Abstract

The article refers to the engineering thesis [1]. This study describes the behavior of bedload transport and bed morphology in the Wloclawek Reservoir, simulated with the PTM model. Through numerical simulations, the interaction between flow dynamics, material transport and deposition was investigated. This analysis was carried out based on two variables: the height of sediment bedforms and the change in the bed level. The results were obtained for medium to high Vistula River discharges: 780, 1143, 1630 and 2990 $m^3 \cdot s^{-1}$.

Keywords: dam reservoir, moving bed, sediment bedforms, bed elevation change

IMPLEMENTACJA NUMERYCZNEGO MODELU RUCHOMEGO DNA DLA ZBIORNIKA WŁOCŁAWSKIEGO

Abstrakt

Artykuł odnosi się do pracy inżynierskiej [1], w której opisano symulację zachowania osadów i zmian ukształtowania dna w Zbiorniku Włocławskim z wykorzystaniem modelu PTM. Za pomocą symulacji numerycznych zbadano wpływ dynamiki przepływu na transport i depozycję materiału dennego. Analizę przeprowadzono w oparciu o dwie zmienne: wysokość powstających form dennych i zmianę rzędnej dna. Porównano wyniki dla przepływów średnich i wysokich dla Wisły: 780, 1143, 1630 oraz 2990 $m^3 \cdot s^{-1}$.

Słowa kluczowe: zbiornik zaporowy, ruchome dno, struktury denne, zmiana poziomu dna

1. INTRODUCTION

The concept of "active bed" can be interpreted as the movement of sediment covering the bottom of the reservoir and constituting conglomerated organic and inorganic materials carried by water. The aim of this paper is to assess the spread of material that was previously deposited on the bottom.

Bed sediment transport can be explained as the movement of particles in the riverbed due to the shear stress imposed by the water flow (sufficient to pick up or carry away particles of a given diameter). These sediment layers can react differently based on factors like water flow speed, type of accumulated particles, exposure time [2]. In this way, particles susceptible to these activities can be detached from the bottom, transported and then deposited in a new area.

The considered sediment is formed by geological, geomorphological or organic factors. Sediments in the lowland reservoir are primarily: accumulated sediments from the soil, material transported downstream and decaying plants [3]. Hydrological factors also have a significant impact. These include, among others: water flow and water surface level.

The concept of "active bed" takes into account many processes that may be simulated by a numerical model. Such simulations are performed through iterative calculations to represent changes in bottom topography of reservoirs in time and space.

In this study, the case of an active bed was examined in the Wloclawek Reservoir. This simulation was intended to check how the model behaves under the influence of different boundary conditions (discharge values). Flow values for simulation are based on research [4]. There are the following characteristic flows:

- Q_1=780 $m^3 \cdot s^{-1}$ (median),
- Q_2=1143 $m^3 \cdot s^{-1}$ (75 percentile),
- Q_3=1630 $m^3 \cdot s^{-1}$ (the lowest of the highest flows).

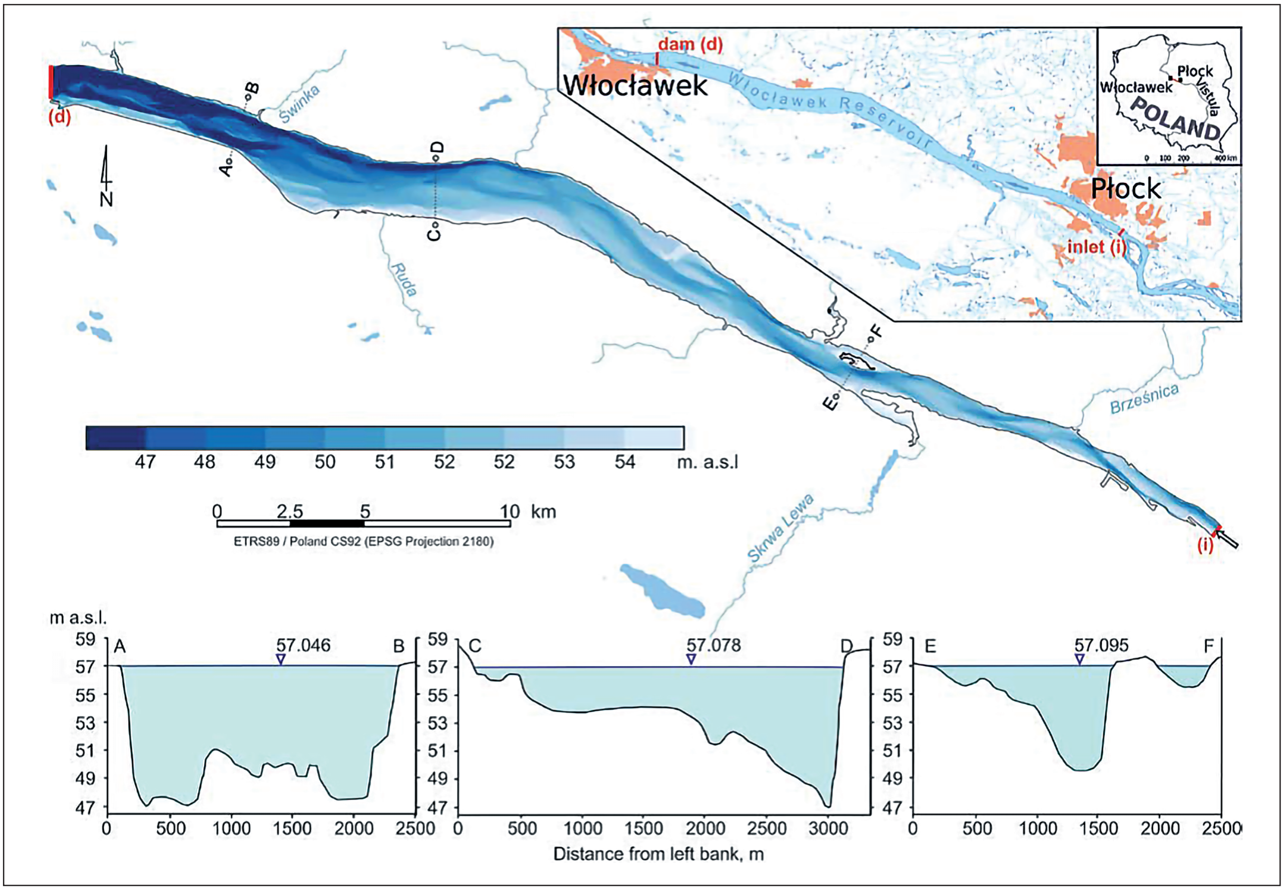

Fig. 1. Bathymetric map of the Wloclawek Reservoir [4]
Ryc. 1. Mapa batymetryczna Zbiornika Włocławskiego [4]

Furthermore, there is one observed flow:

- Q_4=2990 $m^3 \cdot s^{-1}$ (20.04.2013).

As a result, it is possible to determine what approximations this particular numerical analysis can provide.

2. STUDY AREA

The Wloclawek Reservoir is the largest dam reservoir in Poland in terms of the area, which is 70.4 km² [5]. This artificial reservoir (Fig. 1) was created in 1970 by damming the waters of the lower Vistula, which increased the average water surface elevation by 14 m at the dam cross-section. It extends from Plock to Wloclawek, which is the section from 632 to 675 km of the river course.

The dam has a total length of 1200 m and the normal water damming level is 57.3 m above mean sea level. Generally, this hydrotechnical construction consists of the ground dam, weir, hydroelectric power plant, fish passage and side dam on the left bank of the Vistula [6]. After years of exploitation of the reservoir its capacity decreased from 408 million m^3 (initial capaity) to 370 million m^3 in 2013 [3]. The reason was the accumulation of material at its bottom. The reservoir has a typical form of a ribbon lake: a narrow and long profile (Fig. 1). It is caused by the fact that the reservoir area was a part of the previous natural riverbed of the Vistula. The results of this fact are now visible in the form of changes in the depth caused by geomorphological processes, like deposition of gravel with an admixture of sand carried by the Vistula and abrasive processes caused by high flows [7]. All these phenomena involve the transport of solid material, which is related to the issue of the moving bottom.

The reservoir currently serves mainly energy purposes. The Wloclawek power plant is a run-of-river one. It has a capacity of 160 MW. In 1971–2001, it produced yearly 550 GWh to 1043 GWh of electricity.

3. MATERIALS AND METHODS

3.1. Data sources

The numerical solution was performed based on actual values for the Wloclawek Reservoir. Data on the physical properties of the reservoir were received from the Institute of Geography and Spatial Development of the Polish Academy of Sciences in Torun. The obtained parameters of bottom sediments are as follows:

- D_{35} = 0.003 mm,
- D_{50} = 0.022 mm,
- D_{90} = 0.033 mm,
- Bed porosity: 50%,
- Bed density: 2650 $kg \cdot m^{-3}$,
- Salinity: 0.45 ppt.

3.2. Numerical simulation tool

In order to examine processes connected with moving bottom, SMS (Surface-water Modeling System) package [8] distributed by the AQUAVEO company was used. For the purposes of visualization, analysis and manipulation of numerical data, two models were used within this platform: AdH [9] and PTM [10].

3.2.1. The ADH model

To perform a proper PTM simulations, velocity fields obtained from AdH model calculations are necessary. The AdH model (Adaptive Hydraulics Model) is a numerical model used to simulate water flow and related phenomena in the aquatic environment [11]. The results of AdH are used as part of the inputs used in the operation of the PTM model. The PTM modeling shown in this paper re-utilized previously made AdH simulations [4] as their hydrodynamical base.

3.2.2. Active bed in the PTM model

The PTM model tracks sediments particles flowing from a given source. Their motion is calculated both in Lagrangian and Euler frameworks depending on the origin of the particles [12]. Sediment that enters the simulation area as suspended is treated in a Lagrangian way: their movement is described as tracking the trajectories of selected "representative" particles. For the sediment already present in the domain, Eulerian calculations (local, grid-based) are performed. Fluid movement is considered in specific places in space [13]. Local acceleration is described using the derivative migratory.

The Eulerian framework is responsible for the calculations moving bed – as it considers sediment already present there when the simulation starts. There are two methods for calculating: van Rijn or Soulsby-van Rijn. For the second method, the empirical equation of the sediment transport rate per 1 meter of cross-section [14] is presented (1):

$$A_s\bar{v}_h\left(\left(\bar{u}^2+\frac{0.018}{C_w}\bar{v}_w^2\right)^{\frac{1}{2}}-v_{kr}\right)^{2.4} \tag{1}$$

where:

q_t [$m^2 \cdot s^{-1}$] – unit load of debris transport
A_s [-] – transport coefficient (depending on grain size)
$\bar{v}_h$ [$m \cdot s^{-1}$] – depth-averaged horizontal velocity component
$\bar{v}_w$ [$m \cdot s^{-1}$] – average circulation speed in the wave
$\bar{u}$ [$m \cdot s^{-1}$] – depth-averaged velocity
c_w [-] – wave influence factor
v_{kr} [$m \cdot s^{-1}$] – critical speed of movement

The coefficients $A_s = A_{sb} + A_{ss}$ are defined by equations (2, 3).

$$A_{sb}=\frac{0.005H(d_{50}/H)^{1.2}}{(g(s-1)d_{50})^{1.2}} \tag{2}$$

$$A_{ss}=\frac{0.012d_{50}d_{gr}^{-0.6}}{(g(s-1)d_{50})^{1.2}} \tag{3}$$

where:

H [m] – local depth,
d_{50} [m] – median of the sediment grain size distribution,
d_{gr} [-] – dimensionless grain size,
g [$m \cdot s^{-2}$] – gravity acceleration,
s [-] – relative density of the sediment grain to the density of water (ρ_1/ρ_w).

3.2.3. Simulation parameters

Calculation results for the Wloclawek Reservoir are obtained for the following settings: AdH model simulation time: 10 days; PTM simulation time: 7 days; PTM start time: 12 hours after AdH start time; resulting map data file written every 1 hour. The algorithm parameters were set to: Numerical Scheme 2; Shear, Bedforms, and Mobility Updates every 30 time steps.

In the analysis of an active bed, two result variables were taken into account: *native sediment bedforms* (short: Bedforms) and *bed elevation change* (short: dz/dt).

4. RESULTS

4.1. Native sediment Bedforms

The Bedforms map shows the location and height of native sediment structures on the bottom. These are forms that arise as a result of the interaction of flowing water and native sediments. The Bedforms variable is interpreted as an average height (or double amplitude) of such forms in each location.

At the beginning of the simulation no bedforms are present. They develop in time in the region where the water velocity is high enough to form them (Fig. 2). As the discharges for all the simulation runs are constant, the bedforms reach their final shape after some time (from 11 hours of the simulated time for 780 $m^3 \cdot s^{-1}$, to 30 hours for 2990 $m^3 \cdot s^{-1}$) and then no further evolution of them occurs. Figure 2 shows the maps of the bedforms variable at the end of the simulations (day 10). Indication are as follows:

- A – 780 $m^3 \cdot s^{-1}$,
- B – 1143 $m^3 \cdot s^{-1}$,
- C – 1630 $m^3 \cdot s^{-1}$,
- D – 2990 $m^3 \cdot s^{-1}$.

The value of the bedforms variable is correlated with the shear stress value. This is a function of flow conditions and sediment bed parameters. It is defined as shear stress, i.e. the force that the water flow exerts on the bottom. The dependency between these two parameters can be illustrated using the shear rate formula (4).

$$u_*=\sqrt{g\,h\,S} \tag{4}$$

where:

u_* [$m \cdot s^{-1}$] – shear velocity
g [$m \cdot s^{-2}$] – gravitational constant
h [m] – river depth
S [rad] – river slope

It follows the intuition that the biggest bedforms appear in the regions where the main current of the Vistula River flows and that the range of their appearance grows with the discharge. However, for the highest simulated flow, Q_4 = 2990 $m^3 \cdot s^{-1}$ the bedforms seem to diminish in the upper part of the reservoir (Fig. 2 – D). This is due to the fact that for such a high discharge the shear stress at the bottom is high enough to erode and level up the emerging bedforms.

In order to better present the dependence between the bedforms height and the total discharge, differential maps were created; they are shown as sub-figures B–A, C–B, and D–C of Figure 2. The bedform height difference was calculated by the equation (5).

$$\Delta_{\text{bedforms}} = \text{bedforms}_w - \text{bedforms}_m \tag{5}$$

where:

bedforms_w [m] – size of vertical bedforms for greater flow,

bedforms_m [m] – size of vertical bedforms for smaller flow.

Color scale interpretation on the differential bedforms maps (Fig. 2) goes as follows: increase of the height along with the discharge increase is shown in warm colors (positive values), whereas, smoothing of the bottom as the flow increases is presented by cold colors (negative values). No change in the bedforms height leaves the appropriate fragment white.

The difference maps show that the bedforms change usually in the upper part of the reservoir. For the two smallest flows (780 and 1143 $m^3 \cdot s^{-1}$), the difference in values is visible up to the point where the reservoir is narrowed. This indicates the formation of bottom forms larger by approximately 0.2 m for the flow of 1143 $m^3 \cdot s^{-1}$ than for 780 $m^3 \cdot s^{-1}$. The difference in the further flows (1143 $m^3 \cdot s^{-1}$ and 1630 $m^3 \cdot s^{-1}$) indicates a similar accumulation of material (0.2 m), but occurring over a larger area of the reservoir.

Differential maps for the two highest flows (2990 $m^3 \cdot s^{-1}$ and 1630 $m^3 \cdot s^{-1}$) show characteristic differences that can be divided into two parts: an area of negative values at the inflow and an area of positive values in the middle section of the reservoir. Values within –0.2 m indicate greater smoothing of the bottom at higher speed.

Considering the discussed flow values and their differential maps, it can be concluded that there is a certain tendency in the formation of vertical bottom forms. Greater flow means greater force influencing on the bottom. Water carries material from the top of the reservoir, depositing it in further places.

Around the inflow high velocity of water smooths the bottom. However, for lower flows, the upper part of the reservoir is characterized by velocities low enough not to wash out the material, but at the same time high enough to enable the transport and accumulation process. As a result, bottom forms are formed.

Further into the reservoir, the water velocity decreases. For low flows, these values are so small that they do not affect the bottom morphology. Due to the lack of sufficient conditions, neither erosion nor accumulation of material occurs. In turn, for high flows, conditions arise in which bottom forms are formed. These are water velocities that do not cause bottom erosion and are sufficient to transport material.

4.2. Bed level change

The bed level change dataset (dz/dt) means changes in bottom height over time. The variable dz/dt is a vector value in one dimension. Taking it mathematically, bed level change is the partial derivative of the bed evolution variable with respect to time. Results of calculation present the evolution of the bed (Fig. 3).

The simulation results have to be stabilized in space. There is a “spatial warm-up section” for this purpose (to 3 km below the inflow).

The part of the mesh marked with a blue circle on the C–B difference map (Fig. 3) shows numerical artifacts. This conclusion results from the lack of a reasonable physical explanation – there is no increase in speed and no shallowing occurs. Which means the results at this point are not interpretable. To get rid of this numerical effect in the future, it is needed to modify the mesh.

Therefore, two places should be ignored during interpreting the results, i.e. the initial area of the reservoir at the inflow (stabilization in space) and the place of narrowing (numerical artifact).

For the bed level change velocity maps, the dark blue color on the map indicates washing out (about 1 $cm \cdot h^{-1}$), while pink shows the overfilling of material (about 1 $cm \cdot h^{-1}$). These changes occur up to a certain part (middle of the reservoir for the flow 2990 $m^3 \cdot s^{-1}$). Values stabilize after approximately 7 hours of simulation.

The largest differences dz/dt occur in the upper part of the reservoir ($dz/dt \approx 1$ $cm \cdot h^{-1}$), in its further section there are no clear differences ($dz/dt \approx 0$ $cm \cdot h^{-1}$). This means that the water velocity decreases until it drops below the velocity at which the bottom can no longer be moved. This also means that high flows (2990 $m^3 \cdot s^{-1}$, 1630 $m^3 \cdot s^{-1}$) have the greatest impact on visible changes

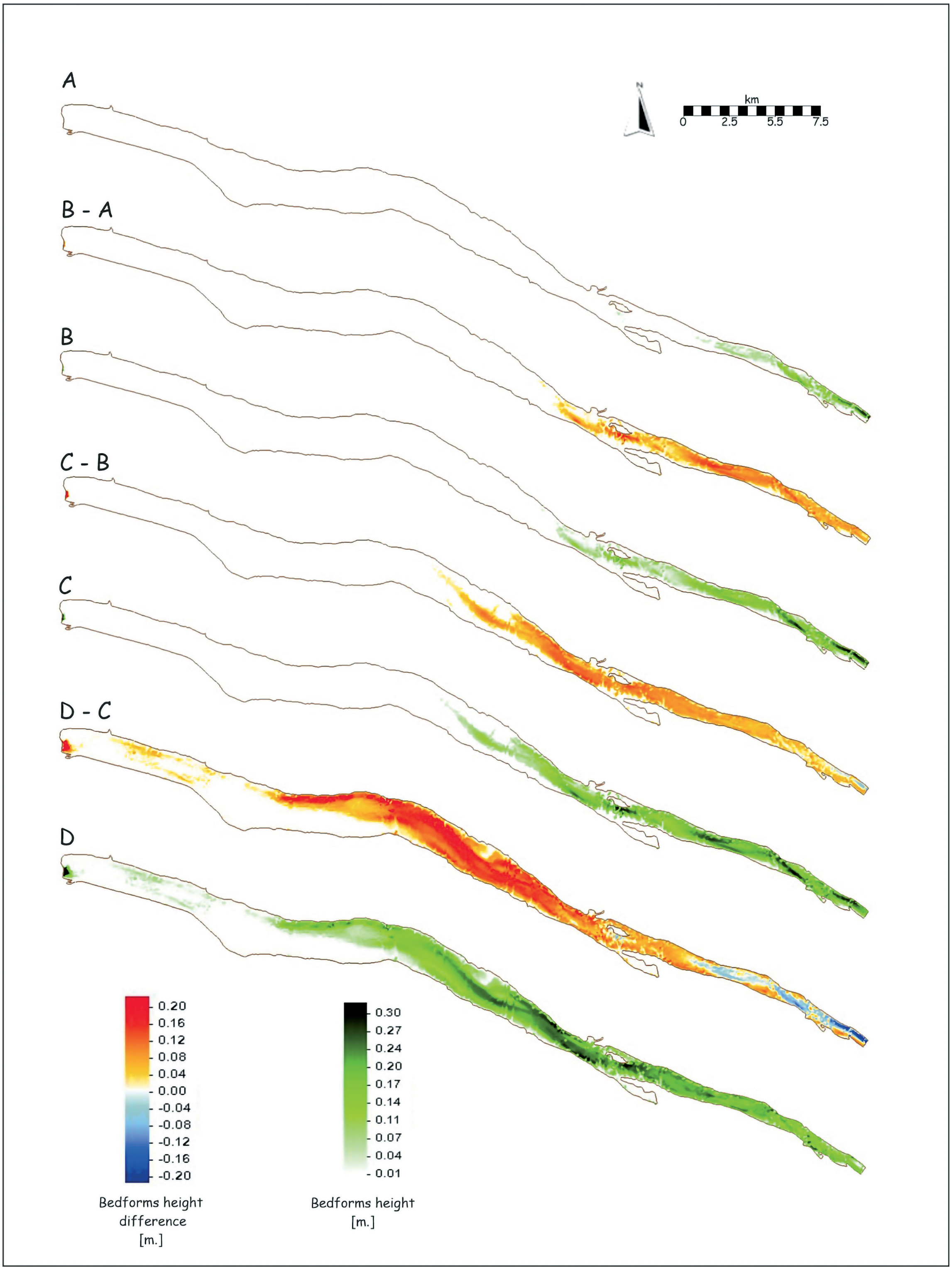

Fig. 2. Bedforms maps for the proper flow / Bedforms differential map between flow (A – 780, B – 1143, C – 1630, D – 2990 [$m^3 \cdot s^{-1}$]) in 10th day

Ryc 2. Mapy form dennych dla odpowiedniego przepływu / Mapy różnicowe form dennych pomiędzy przepływami (A – 780, B – 1143, C – 1630, D – 2990 [$m^3 \cdot s^{-1}$]) w 10 dniu

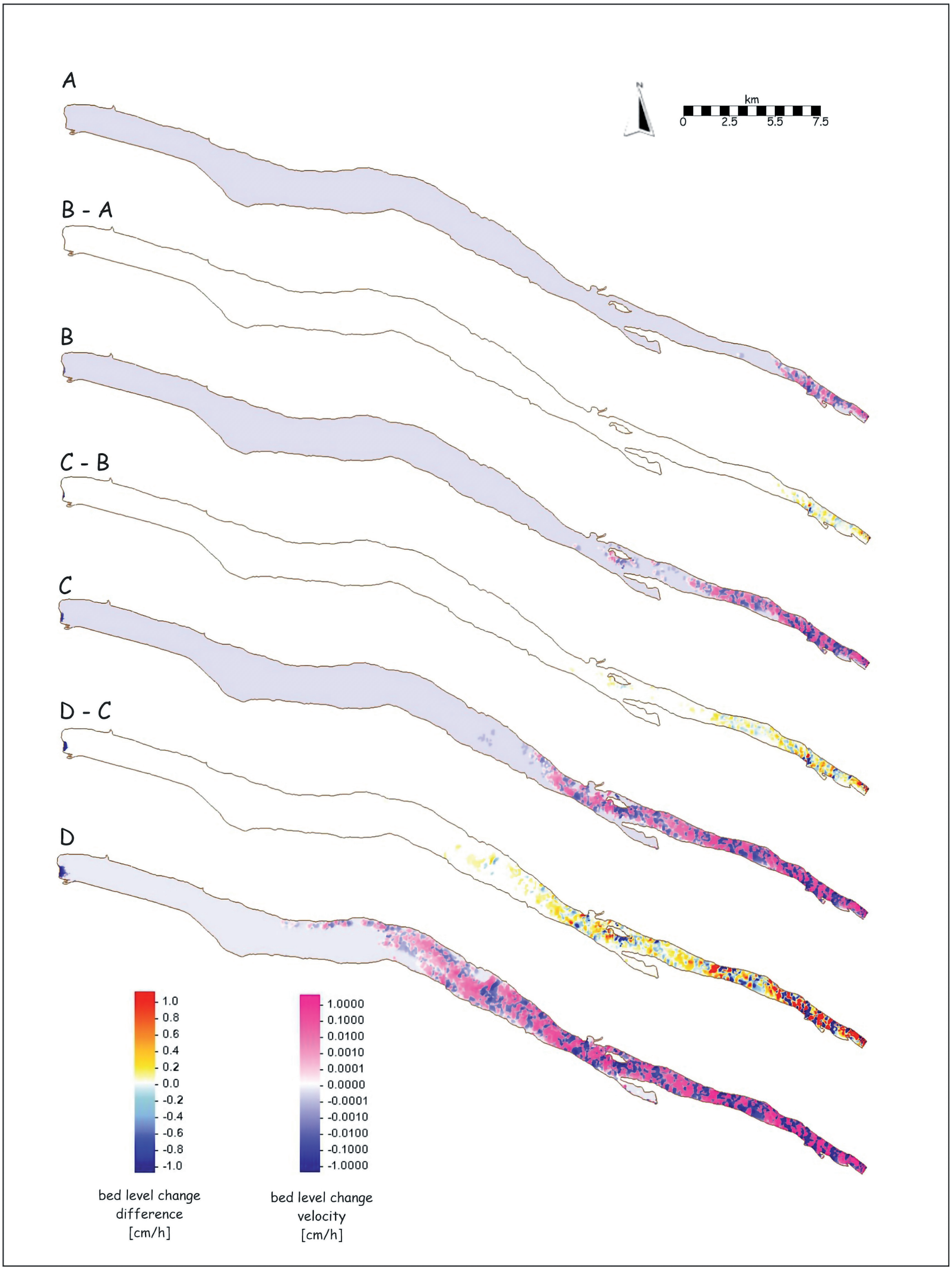

Fig. 3. dz/dt velocity maps for the proper flow / differential map dz/dt between flow (A – 780, B – 1143, C – 1630, D – 2990 [$m^3 \cdot s^{-1}$]) in 10 day(Values: positive – deposition; negative – removal)

Ryc 3. Mapy prędkość dz/dt dla odpowiedniego przepływu / Mapy różnicowe dz/dt pomiędzy przepływami (A – 780, B – 1143, C – 1630, D – 2990 [$m^3 \cdot s^{-1}$]) w 10 dniu (Wartości: dodatnie – osadzanie; ujemne – wymywanie) in bottom morphology. These are called course-forming flows. The smaller flows (780 $m^3 \cdot s^{-1}$, 1143 $m^3 \cdot s^{-1}$) do not significantly affect the shape of the bottom.

5. SUMMARY AND CONCLUSIONS

Changes of the bed morphology of Wloclawek Reservoir were simulated by implementing an active bed in the PTM model. Based on bed level change and bedforms maps, it is possible to indicate the locations of activity of geomorphological processes on the bottom.

The bottom carving processes depend on the flow rate. It is more intense for higher water velocity values. Lower discharges (Q_1 = 780 $m^3 \cdot s^{-1}$ and Q_2 = 1143 $m^3 \cdot s^{-1}$) do not significantly affect the bed. If the water velocity is too low, there is no sufficient shear for sedimented material transport. Higher discharges (1630 $m^3 \cdot s^{-1}$ and 2990 $m^3 \cdot s^{-1}$) have a visible impact on the bottom. For most area of the reservoir the higher the discharge (and – consequently – the flow velocity) the higher bedforms appear. However, for the highest discharge analyzed (Q_4=2990 $m^3 \cdot s^{-1}$) the bedforms start to flatten again in the upper part of the reservoir where the water velocity is the highest.

In the reservoir, there are some areas where material is washed out from a given place and then accumulated in its close neighborhood. That happens most in places where the water velocity increases, like the narrowing of the reservoir, the vicinity of the northern tributary, the vicinity of the island on the Vistula. Both erosion and sedimentation processes occur there. There is a certain tendency in the formation of vertical bottom forms. This effect grows with the total discharge which fits the intuition.

The research presented in this paper was the first approach to simulate the changes of the bed of the Wloclawek Reservoir using a numerical model that utilizes both Lagrange and Euler frameworks to emulate the movement of the bed sediment. The results fit the observations on the qualitative level. The desired next step of research involves making field measurements to compare with model predations on the quantitative level (model validation).

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