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LOCAL VARIATIONS IN THE STAGE–DISCHARGE RELATIONSHIP FOR THE VISTULA RIVER IN THE SURROUNDINGS OF SANDOMIERZ DURING FLOOD EVENTS

LOKALNA ZMIENNOŚĆ RELACJI STAN–PRZEPŁYW NA RZECE WIŚLE W OKOLICY SANDOMIERZA W WARUNKACH WIELKIEJ WODY

Abstract

In this paper, the results of numerical simulations of the flow field in the compound channel of the Vistula river in the surroundings of Sandomierz are presented. Hydro_as-2d model was used for these calculations – this numerically solves so-called shallow water equations. Special attention was paid to local variations of the water surface level and velocity distribution due to river meandering, the split of the water stream between the main channel and the floodplain and also due to the removal of high vegetation. Additionally, results of the computations were interpreted in the context of the partly documented knowledge of flow behaviour in meandering compound channels.

Keywords: *stage–discharge relationship*, *floodplains*, *meander*, *shear stress*, *velocity field*, *high vegetation*, *turbulent flow*

Streszczenie

W artykule przedstawiono wyniki symulacji numerycznej pola przepływu w złożonym korycie rzeki Wisły w okolicy Sandomierza. W obliczeniach wykorzystano dwuwymiarowy model Hydro_as-2d stanowiący numeryczne rozwiązanie tzw. równań wody płytkiej. W artykule zwrócono szczególną uwagę na lokalne zmiany w układzie zwierciadła i w rozkładzie prędkości na skutek: meandrowania rzeki, rozdziału strug pomiędzy korytem głównym a terasą, a także na skutek hipotetycznej wycinki roślinności wysokiej porastającej terasy zalewowe. Ponadto podjęto próbę interpretacji otrzymanych wyników w świetle częściowo udokumentowanych w literaturze mechanizmów przepływu w meandrujących korytach wielodzielnych.

Słowa kluczowe: *relacja stan–przepływ*, *terasy zalewowe*, *meander*, *naprężenia ścinające*, *pole prędkości*, *roślinność wysoka*, *przepływ turbulentny*

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1. Introduction

The correct mapping of the stage-flow relationship is the basic information used by engineers for flood control purposes, especially for the proper determination of embankment elevations. This task is hampered in the case of rivers with compound channels with diverse vegetation cover on floodplains. The Vistula river in the surroundings of the city of Sandomierz is an example of such a case and this river section is the subject of the present analysis. The mapping of the hydraulic effects of vegetation spatial variation (Manning coefficient variation) is more effectively achieved through the application of two-dimensional models as opposed to one-dimensional models under the condition of proper database availability. Additionally, the geometric variation of high water channels in plan (meandering of river) and within cross-sections (variation of floodplain width) is another important reason for the application of two-dimensional models.

2. Morphological features of the modelled reach of the Vistula river and the range of numerical calculation

The analysed Vistula river reach is about 10 km in length and is placed between cross-section 65 and 79 (Fig. 1). The geometry of the reach varies rapidly along its route**.** There is a small left turn of the reach between cross-section 65 and 69. Within this sub-reach, the main channel is placed closer to the left centre line of the levee leaving the wide floodplain on the right side (Fig. 1). The main channel is shallow by wide point bars due to natural tendency of the main channel to meander. These point bars are a potential source of sediment which could be moved downstream during high flood events. Part of this sediment could be deposited downstream, mainly on floodplain areas where intense vegetation is present. Deposited sediment was observed on the vegetated floodplains after the flood event of May 2010.

There is a bend turning right in the reach between cross-section 70 and 72. Within this reach, the main channel is significantly narrowed (to a width of around 100 m) and the bed of this channel is deepened. The main channel is placed closer to the outer arc of the reach leaving the wide floodplain on the right-hand side of the reach. According to meander erosion/deposition theory [2], erosion of the main channel bed at the part lying closest to the outer arc of the bend, and also, some deposition in the part of the channel lying closest to the inner arc of the bend could be expected. Both floodplains within the discussed sub-reach are intensely vegetated by shrubs and trees.

There is a bridge located between cross-sections 74 and 75 in Sandomierz town. The floodplains within this sub-reach are significantly narrowed. The bed slope of the main channel between cross-sections 74 and 79 increases significantly (about 0.001) in comparison to upstream sub-reach (about 0.0006). This implies a significant increase in the velocity magnitude in the main channel.

The purpose of this article is to underline local variations of the stage-flow relationship caused by two-dimensional geometric and vegetation cover features, such as:

– meandering of compound channel;

- different direction of the main channel center line in comparison to the direction of center line of whole compound channel;
- variation of vegetation cover within floodplains.

The numerical computation are done under steady flow condition for discharge magnitude equel to 5865 m^3/s This magnitude corresponds with the estimated historical flow peak discharge which was observed during the flood of May 2010 in Sandomierz.

There are two cases of numerical computations:

- **case 1 –** with consideration to the real vegetation cover on the floodplains
- **case 2 –** with the assumption of the total removal of high vegetation within floodplains in the sub-reach between cross-sections 69 and 73

Fig. 1. Vistula river reach in the surroundings of Sandomierz to be modelled

3. Description of the mathematical model and its boundary condition

Numerical calculation was realised with the Hydro_as-2d. This model constitutes a numerical representation of so-called shallow water equations with consideration of bed shear stress [7].

These equations have the following form:

$$\frac{\partial \mathbf{w}}{\partial t} + \frac{\partial \mathbf{f}}{\partial x} + \frac{\partial \mathbf{g}}{\partial y} + \mathbf{s} = 0 \qquad (1)$$

$$\mathbf{w}=\begin{bmatrix} H \\ uh \\ \upsilon h \end{bmatrix} \quad \mathbf{f}=\begin{bmatrix} uh \\ u^2h+0.5gh^2-vh\dfrac{\partial u}{\partial x} \\ u\upsilon h-vh\dfrac{\partial \upsilon}{\partial x} \end{bmatrix} \tag{2}$$

$$\mathbf{s}=\begin{bmatrix} 0 \\ gh(S_{fx}-S_{bx}) \\ gh(S_{fy}-S_{by}) \end{bmatrix} \quad \mathbf{g}=\begin{bmatrix} \upsilon h \\ u\upsilon h-vh\dfrac{\partial u}{\partial y} \\ \upsilon^2h+0.5gh^2-vh\dfrac{\partial \upsilon}{\partial y} \end{bmatrix} \tag{3}$$

where:

u – unit flow discharge in direction x,
υ – unit flow discharge in direction y,
v – kinematic viscosity coefficient,
H – water level,
h – depth,
S_{fx} – friction slop in direction x,
S_{by} – friction slop in direction y,

the friction slope is calculated by the Darcy-Weisbach formula:

$$S_{fy}=\frac{\lambda\upsilon\sqrt{\upsilon^2+u^2}}{8gR} \quad S_{fx}=\frac{\lambda u\sqrt{\upsilon^2+u^2}}{8gR} \tag{4}$$

$$\lambda=6.34\frac{2gn^2}{(4R)^{1/3}} \tag{5}$$

where:

n – manning coefficient,
R – hydraulic radius.

The turbulent viscosity coefficient (υ) is expressed as a product of the so-called shear velocity ej (v^*) and depth, enlarged by constant base value (υ_0):

$$\upsilon=\upsilon_0+c_\mu v^*h \tag{6}$$

3.1. Boundary condition

The upstream boundary condition is located at cross-section 65 of the Vistula river reach (Fig. 1) in the form of the discharge hydrograph [7]. The downstream boundary condition is located at cross-section 79 of the Vistula river reach in the form of a rating curve.

4. Determination of Manning coefficient values

Value of Manning coefficient on the floodplains was determined basing on the density and type of vegetation. This determination was supported by orthophotomap analysis. The value of the Manning coefficient for the main channel was assumed to be in the range 0.025–0.035 depending on the bed materials. Due to the compound channel structure, it should be mentioned that turbulent effects on the interface of floodplains and the main channel influence energy dissipation and should sometimes be taken into consideration for Manning coefficient fixing. The interchange of mass and momentum may cause complex secondary flow patterns [1, 4]. Importance of this effect depends on the ratio of floodplain and main channel depths [5]. According to much empirical research, the largest turbulent energy dissipation may occur when the depth ratio mentioned above reaches values not larger then 0.25 [3] [6]. Because the analysed Vistula river reach varies in the geometry of the cross-sections and also in plan geometry, it is hard to strictly apply rules implied from the results of the mentioned empirical experiments; nevertheless, the discussed depth ratio value is contained in the range of 0.4–0.5 in the case of the Vistula reach at a flow discharge equal to 5865 m^3/s. In this range of values, large scale turbulent effects are replaced by small scale effects. Dissipations of turbulent energy due to small scale effects are considered in the Hydro_as_2d model (eq. 1). It was assumed that the constant base value (υ_0) is equal to 0.001 m^2/s.

Table 1

Manning coefficient values assigned for the sub-reaches in two cases of computation

Sub-reach	Left floodplains		Main channel	Right floodplains	
	case1	case2		case1	case2
65–66	0.04	0.04	0.025	0.04	0.04
66–67	0.04	0.04	0.025	0.04	0.04
67–68	0.04	0.04	0.025	0.04	0.04
68–69	0.04	0.04	0.025	0.1	0.1
69–70	**0.1**	**0.04**	**0.025**	**0.06**	**0.04**
70–71	**0.09**	**0.04**	**0.035**	**0.1**	**0.04**
71–72	**0.09**	**0.04**	**0.035**	**0.1**	**0.04**
72–73	**0.04**	**0.04**	**0.035**	**0.075**	**0.04**
73–79	0.08	0.08	0.035	0.087	0.087

5. Analysis of numerical calculation results

5.1. Compound channel meandering hydraulic implication

Between cross-section 71 and 72 (Fig. 2a) the average water level surplus on the outer arc of the sub-reach is about 5 cm. Additionally, the increase of shear stress is observed close to the outer arc of the sub-reach (from 10 to 40 Pa). Even such a small water level centrifugal surplus could initiate a helicoidal secondary flow [8] which could be the potential cause of erosion on the outer bank of the main channel in the middle of the sub-reach. This effect could be confirmed by geodesic measurements of the main channel bed local deepening reaching 0.6 m. A stronger centrifugal effect is more visible due to intense vegetation cover (Fig. 2a).

5.2. The hydraulic implications of the main channel center line and the center line of the whole compound channel having different directions

At cross-section 70, there is an interesting two-dimensional hydraulic features which could be observed. One may observe the local variation of flow direction on the right floodplains in comparison with the flow direction in the main channel according to the maximum energy grade-line slope. The implication of this phenomena is the local hydrodynamic shear stress increase acting on part of the bank of the right floodplain (Fig. 4). The maximum value of shear stress acting on the right bank is about 120 Pa. This effect of the strong shear stress gradient is magnified by intense vegetation cover on the right bank of main channel and on the right floodplain in the vicinity of cross-section 70 (Fig. 4).

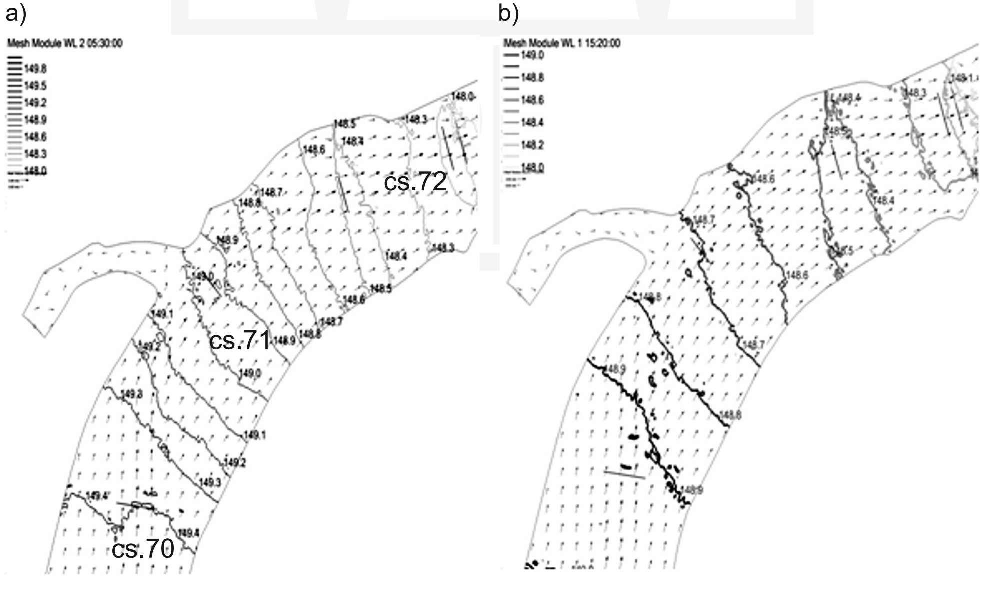

Fig. 2. Water surface: a) in real conditions, b) without any high vegetation

Removal of high vegetation in this area would cause a significant reduction of shear stress value in the above mentioned area (Fig. 5). In practice, this means a 10 cm reduction in the water level (Fig. 2b). Potentially, an additional effect of high water stream division is the generation of secondary flows in the form of strong eddies which are another source of increase in hydraulic resistance [9]. Other consequences of the increase in hydraulic resistance are erosion/sedimentation processes [4]. Within the sub-reach between cross-sections 70 and 71, a sudden local decrease of velocity on the right bank and the entrance

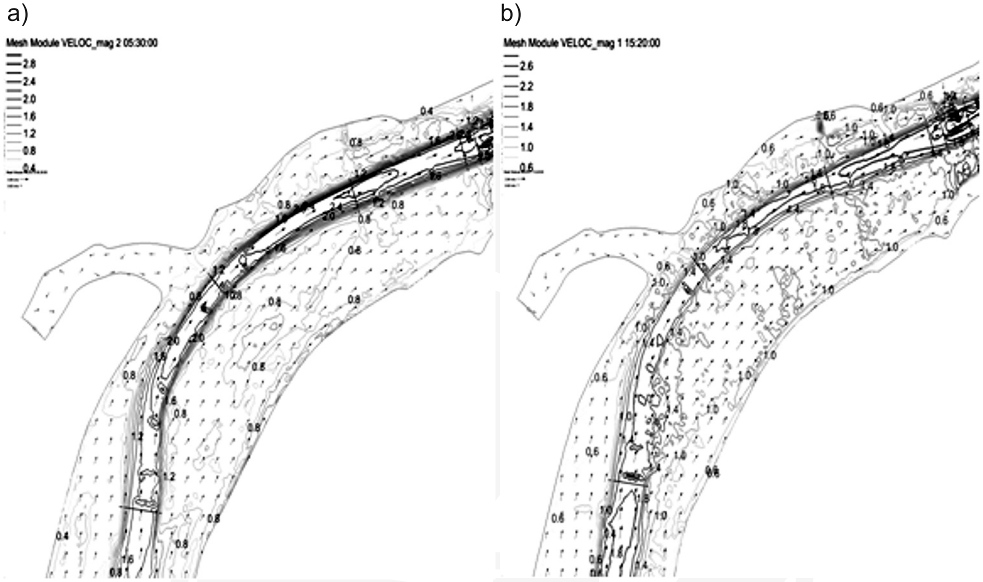

Fig. 3. Velocities field: a) in real conditions, b) without any high vegetation

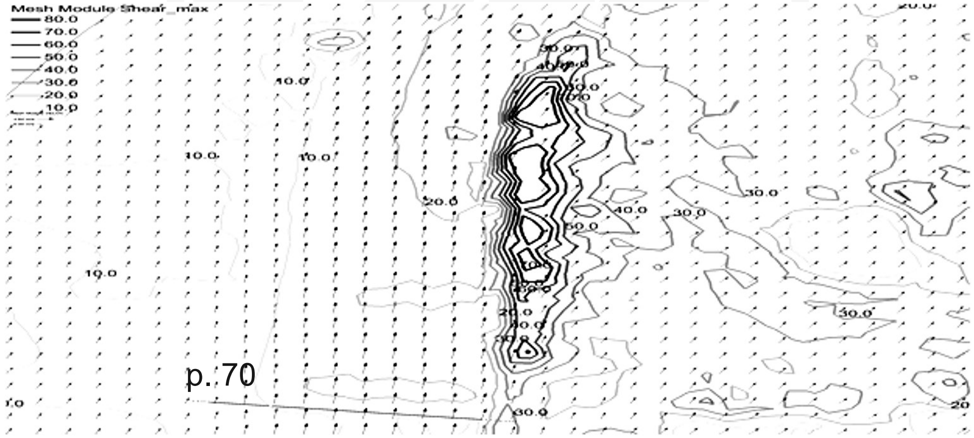

Fig. 4. Local shear stress field in real conditions, discharge: $Q = 5865$ m^3/s

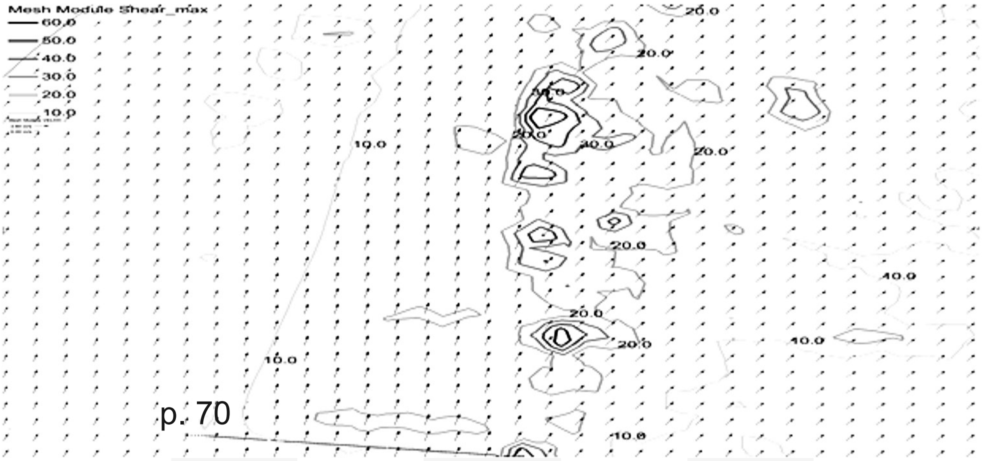

Fig. 5. Local shear stress field after removal of high vegetation, discharge: Q = 5865 m^3/s

of the right floodplains (due to water stream division), is observed (Figs. 3a, 3b). The large local negative gradient of shear stress and velocities are the conducive factors provoking sedimentation of suspended sediment taken from the main channel and deposited. The confirmation of this hypothesis requires more advanced hydrodynamic modelling with sediment transport model analysis – this is beyond of the range of this article.

5.3. Hydraulic implication of the high water channel contraction at the cross-section of the bridge in the city of Sandomierz

At the cross-section of the bridge (Fig. 1), the floodplain width is substantially reduced. Because 70% of the flow discharge is conducted by the main channel, high water channel narrowing is insignificant for water level elevation above cross-section 72. The contraction of the water flow due to the wings of the bridge is the cause of local water level increase by a few centimeters downstream of the bridge.

5.4. Hydraulic implication of the hypothetical high vegetation removal covering floodplains

The back water effect due to high vegetation removal between cross-section 69 and 72 is observed specially between cross-section 65 and 69 (Fig. 1). The decrease of the water level (due to hypothetical high vegetation removal) gradually changes from 0.5m at cross-section 69 to 0.41m at cross-section 65.

The maximal velocity magnitude in the main channel is not larger than 1.9 m/s. The right floodplain is relatively wide and the velocity magnitude in the sub-reach is about 0.6 m/s.

Within the sub-reach between cross-sections 69 and 72, the rapid decrease of the water level due to hypothetical high vegetation removal is changing from 0 m at cross-section 72 to 0.5 m at cross-section 69 (Fig. 2a, 2b). An additional implication of vegetation removal is also a decrease in the maximum flow magnitude velocity at the main channel from about 3 m/s to smaller than 2 m/s; however, the flow magnitude velocity on the floodplains slightly increases (Fig. 2a, 2b). In general, it could be said that the high vegetating removal implies a tendency to make the velocity field smoother during high water flow events and significantly reduce the water level within the sub-reach.

6. Conclusions

The results of 2D numerical hydraulic modelling for the analysed Vistula river reach in the surroundings of Sandomierz allow the capture of some relevant two-dimensional features of meandering compound channel, which influence local variation of the stage-flow variation within the river reach. These features include: inclined water level at the cross-sections within the bend; interaction between flow in the main channel and the floodplains (large gradient of velocities and shear stress in the bank zones); division of the water stream between the main channel and the floodplains due to complicated plane geometry; the effects of high vegetation covering the floodplains. The latter effect is the most significant from the practical point of view, especially regarding support for decisions associated with flood protection policy including the design/modification of levees or partial high vegetation removal.

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