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Original Research Article

IMPACT OF MAINTENANCE METHODS OF AN OVERGROWN LOWLAND RIVER ON ITS HYDRAULIC CONDITIONS

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Abstract

The paper presents the results of numerical analyses carried out in the IRIC environment on the Nays2DH hydrodynamic model regarding the impact of plants in the riverbed and watercourse maintenance on hydraulic conditions. The research material was collected for the actual input variant in October 2018 on the Ślęza River in Wrocław. The constructed and calibrated model was reconfigured on basis of the existing vegetation in three possible variants related to river maintenance: W0 variant - leaving the vegetation in the riverbed, W1 variant - removing all vegetation in the riverbed, variant W2 - removing vegetation in the 2.0 m strip from the right bank, W3 - removing of vegetation in a strip of 2.0 m from the bank, alternately on the right and left bank. Hydrological boundary conditions were flows from 0,32 to 5 [m^3/s]. For four variants, the dependence of flows on the water table location, maximum and average velocities in the channel, and maximum and average shear stresses in the channel were analysed.

Keywords: river, vegetation, ecohydrology, maintenance river, nature-based solution

1. INTRODUCTION

Modern trends in water management are closely linked to the changing environment and the need for society to adapt to these changes. The era of socio-

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economic change in Central and Eastern Europe after World War II and lasting until the 1990s determined the development of technical solutions in river regulation. Thus, many river valleys were irrevocably transformed, built up and narrowed to a strictly regulated river bed. In addition, the development in the upper parts of the catchment area has influenced the increased outflow of water, which the narrowed valleys are unable to accommodate and cause damage to property. Noting this problem has become one of the key tenets of sustainable river management, an interdisciplinary approach that addresses the interplay between water flow, sediment, vegetation, nutrients and pollutants in the aquatic environment, often called "river health" [20] or "DNA of the river"[18].

Of great importance in shaping the river environment is the EU Water Framework Directive [5], which enforced the classification of water bodies into natural and artificial, i.e. transformed by man, and obliged, depending on the adopted characteristics, to maintain good ecological status or good ecological potential of waters. The introduction of the concept of ecological status, which is a determination of the structure and functioning of the aquatic ecosystem associated with surface waters, has become a binding determinant of the quality of a water body. Ecological status is influenced by biological, physicochemical and hydromorphological elements, the latter being linked to the presence of vegetation in the watercourse and its immediate surroundings.

At the same time, however, economic conditions do not allow rivers to be completely returned to nature. Human presence in the vicinity of rivers in the form of development, communication and technical infrastructure, valuable agricultural land is the reason for the protection of this property in the form of regulation of river sections. As the EU Flood Directive [4] indicates, floods are natural phenomena that cannot be prevented, and the proper way to counteract them is to minimize the risk of their negative effects, especially on human health and life, cultural heritage, economy and infrastructure.

The directive enforces the creation and updating of a series of documents describing flood hazards and risks on a basin-by-basin and river basin basis. Inventorying areas of special flood risk, and thus the combination of flood risk and possible flood damage caused by it, provides a path to action where it is necessary and expedient. The possibility, indicated in the EU Floods Directive, of deviating from the objectives of the EU Water Framework Directive of preserving or striving for good ecological status when it is necessary to meet the objectives associated with minimizing flood risk is where the two Directives are particularly coupled. Just as in the case of large investments the Directives indicate a relatively clear course of action, a greater problem arises in the case of smaller, local activities related to the day-to-day operation of the hydrographic system. The decision-making problem is maintenance work on watercourses and their valleys, mowing of banks, removal of trees and shrubs in valleys. On the one hand, the need to preserve the ecosystems associated with the waters and not to deteriorate the ecological condition, on the other hand, care for the hydraulic functioning of the watercourses and not to deteriorate the capacity of the channel , which could occur through uncontrolled development of vegetation [24]. How to reconcile these two aspects generates discussions among scientists and practitioners related to water management and nature conservation. A major challenge in this direction is also determining the forms and methods of restoration of watercourses. Among the 10 challenges posed to riparian habitats and their ecosystem services, there are pressing needs to show the public the essence of aquatic ecosystems in terms of promotion, define the legal framework for their protection, the need to improve methods and tools for assessing the effects of renaturalization [21].

Managing vegetation in the channel, or the entire river valley, requires an understanding of the characteristics and influence of plants on hydraulic conditions. Numerous studies conducted in this direction attempt to determine the effects of plant density and distribution [1, 2,13] on flow conditions under various external conditions. Determination of these characteristics is needed both for the most optimal conduct of maintenance work and the design and implementation of restoration projects.

The goal of this study is to estimate the hydraulic conditions for four variants of lowland river maintenance treatment - removing plants completely from the riverbed, removing a 1.5m wide strip of plants, removing 1.5m wide strips of plants from the riverbed in alternating 5m sections, and leaving plants entirely in the watercourse. Numerical simulations were performed based on the actual conditions of a section of the Ślęza River near Wroclaw. The simulations were carried out to determine the distribution of velocities in the riverbed, evaluate average and maximum velocities, average and maximum shear stresses, and the water surface elevation at different flows.

2. STUDY AREA

The study area is a section of the Ślęza River near Wroclaw. The Ślęza is a left-bank tributary of the Odra River, is about 85.1km long and has a catchment area of 975 km^2. The analysed section encloses a catchment area of about 900 km^2 in 72.8 km of the river's course and is located in the geographical location 16°58'36" East longitude, and 51°04'53" North latitude. The location of the study area in the national scale and the catchment area is shown in Figure 1. The catchment area is dominated by agricultural land, accounting for 97.3% of the catchment area according to Corine Land Cover 2012. The large proportion of agricultural land influences the abundance of water in organic components - nitrogen and phosphorus, which, combined with the low gradient of the watercourse of 3.26‰

and the occurrence of low flows during much of the growing season, provide excellent conditions for the development of aquatic plants in the riverbed [25].

The modelled section is about 50 meters long and 11 meters wide, which is the width of the main river channel to the top of the bank. Figure 2 shows aerial photos over the modelled area taken in August 2019.

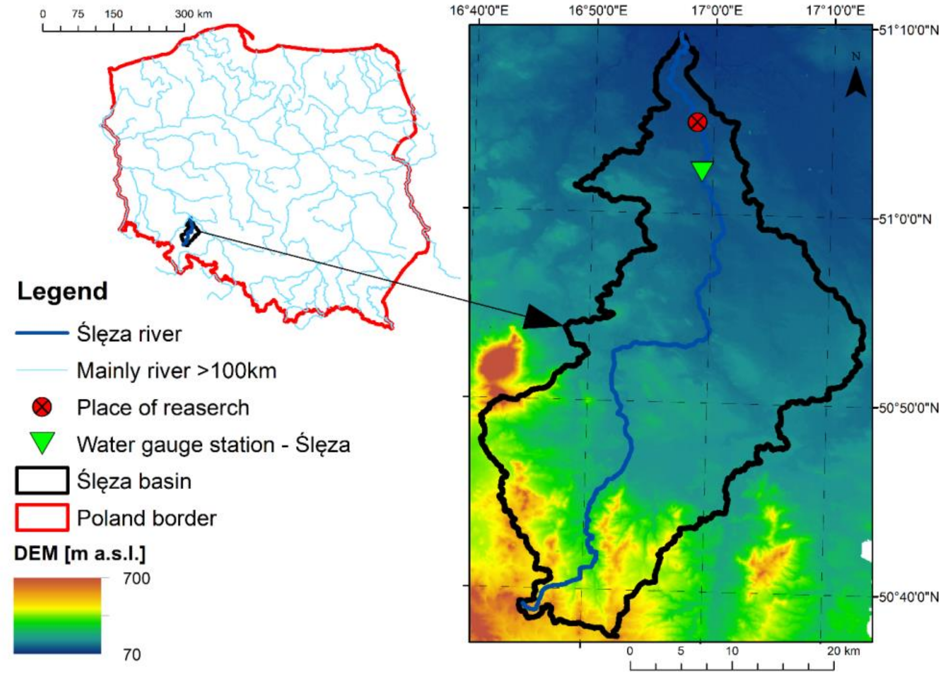

Fig. 1. The location of the study site in the catchment area (right) and the location of the catchment area in Poland (top left)

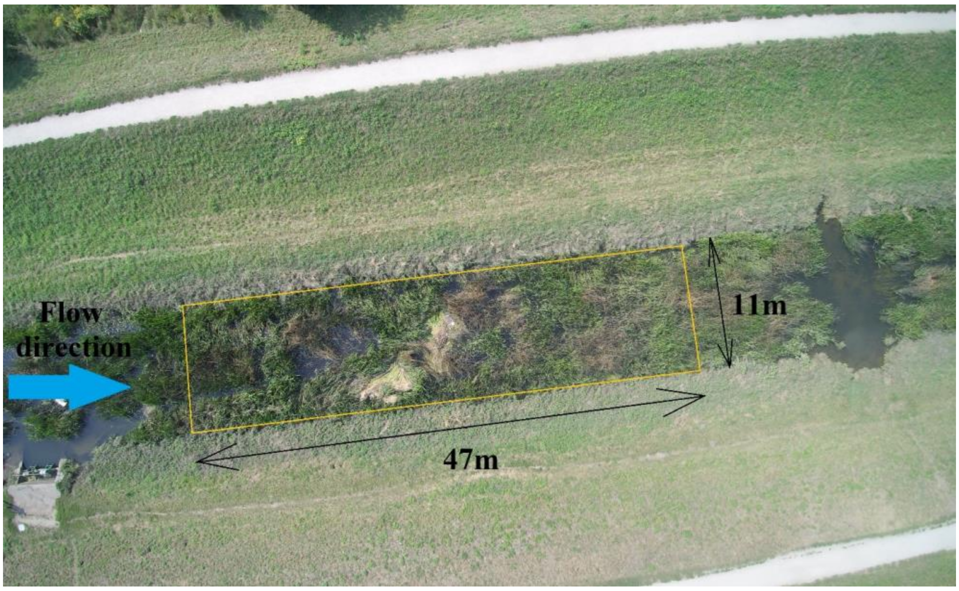

Fig. 2. The study site of the bird's-eye view photo (yellow colour indicates the exact contours of the modelled section of the Ślęza River bed

3. HYDROLOGICAL CONDITIONS

The analysis of hydrological conditions was conducted for the Ślęza water gauge, located about 5 km above the study area (at 68.5 km of the river's course). The characteristic flows for the water gauge are given in the report on the mapping of flood hazard and risk and are at the level of SNQ=0.46, SSQ=2.75 and SWQ=22.3 for the multiannual period 1956-2010. Based on the data of average daily flows provided by IMGW-PIB, it was determined that the Ślęza River is characterized by relatively long-lasting low flows on an annual basis. In addition, during the growing season from April to October, this phenomenon is further intensified. As evidenced by Wolski [26], in the shorter multi-year period of 2005-2016, the average flows per year are SSQ=2.6 m^3/s, and during the growing season they even drop to the value of SSQ=2.2m^3/s. The frequency distribution of flows for the whole year and the growing season is shown in the figure 3 [26]. Since it is the low and medium flows that make up the majority of flows during the growing season, they are very important for assessing the impact of plants on hydraulic conditions.

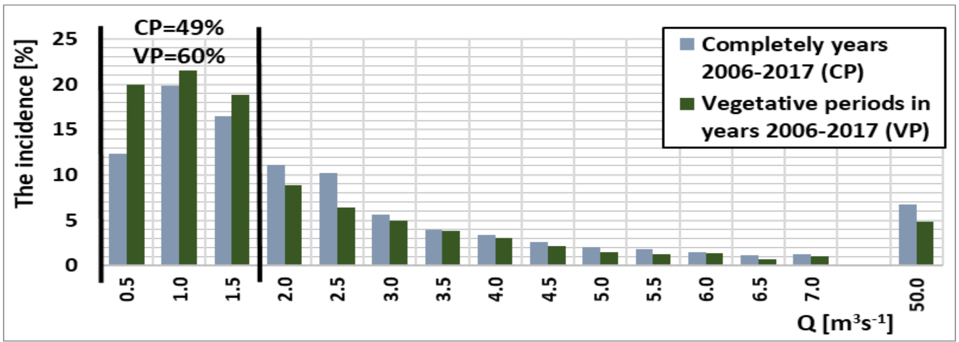

Fig. 3. Histogram of the frequency of flows at the Ślęza River gauge for the 1995-2016 multi-year period in terms of the whole year and the growing season

4. METHODOLOGY

The numerical study was based on a real section of the Ślęza River. For this purpose, a thorough field survey was carried out, in which the bathymetry of the bottom and the distribution of vegetation and, consequently, roughness in the modelled channel plan were determined. The survey was conducted in early October 2018, when vegetation from the entire growing season could be distinguished. Adoption of vegetation from the entire season made it possible to define the most unfavourable conditions in terms of channel capacity, when the largest part of the cross-section actively guiding water is occupied by plants. Mapping in a 1m x 1m grid of the entire modelled area was carried out, thus obtaining a bathymetric map of the trough. At the same time, the number and density of plants present in the area were mapped at the same scale, obtaining a plant matrix, which, after a calibration process, translated into the spatial distribution of the Manning roughness coefficient n in the riverbed. The study made two main theoretical assumptions about the measured site conditions. It was assumed that the removal of plants does not interfere with the bathymetry of the riverbed - the bathymetry is constant for all modelled variants of riverbed maintenance, and the removal of plants occurs permanently - the removed vegetation does not grow back throughout the growing season or is removed regularly.

The two-dimensional Nays2DH model in the IRIC environment (https://i-ric.org) was used for numerical modelling. Nays2DH is a computational model for simulating unsteady horizontal two-dimensional (2D) flow, sediment transport, and morphological changes of bed and banks in rivers which was developed by Shimizu et al. [9,10].

The model is based on the basic equation of continuity in an orthogonal coordinate system (x, y) are as follows:

Equation of Continuity

$$\frac{\partial h}{\partial t}+\frac{\partial(hu)}{\partial x}+\frac{\delta(hv)}{\delta y}=0$$

Equations of Motion

$$\frac{\partial(uh)}{\partial t}+\frac{\partial(hu^2)}{\partial x}+\frac{\partial(huv)}{\partial y}=-hg\frac{\partial H}{\partial x}-\frac{\tau_x}{\rho}+D^x$$

$$\frac{\partial(vh)}{\partial t}+\frac{\partial(huv)}{\partial x}+\frac{\partial(hv^2)}{\partial y}=-hg\frac{\partial H}{\partial y}-\frac{\tau_y}{\rho}+D^y$$

where h is water depth, t is time, u is velocity in the x direction, V is velocity in the y direction, g is gravitational acceleration, and H is the total water depth. Here, the bed shear stresses in x and y directions (τx and τy) are expressed by using coefficient of riverbed shearing force Cf as

$$\frac{\tau_x}{\rho}=C_f u\sqrt{u^2+v^2}$$
$$\frac{\tau_y}{\rho}=C_f v\sqrt{u^2+v^2}$$

In the model, the bottom friction is set using Manning's roughness parameter. The coefficient of riverbed shearing force Cf is estimated by Manning's roughness parameter nm as follows:

$$C_f=\frac{gn_m^2}{\sqrt[3]{h}}$$

The model, with a spatial resolution of 0.2m x 0.2m, was built for a section of the channel 11m wide and 47m long. Simulations were performed for steady-state flows and were characterized by a time step of Δt = 0.02s and a simulation time of 660s. The upper boundary condition for the model was a steady-state inflow with a specified intensity equal in successive 8 steps to Q1=0.32, Q2=0.65, Q3=1.00, Q4=1.29, Q5=1.78, Q6=2.79, Q7=3.44, Q8=5.00 [m3/s] while the lower boundary condition was free outflow. The channel bottom conditions and roughness distribution were implemented into the model based on values measured in the field.

Calibration of the model was carried out for existing vegetation (variant W0) for flows of Q=1.29 m^3/s , according to the scheme in Figure 4. The calibration methodology [16] assumes the definition of the roughness coefficient by optimizing the water table position and velocities measured in the field and obtained in the model. The calibration consisted of selecting the factor of roughness (N) in such a way that, when multiplied by the field-obtained Plants matrix (Pi,j), Manning's roughness coefficient matrix (ni,j) is obtained, which, when entered into the model, will yield the results of the velocity and surface water elevation as close to the field measurements as possible.

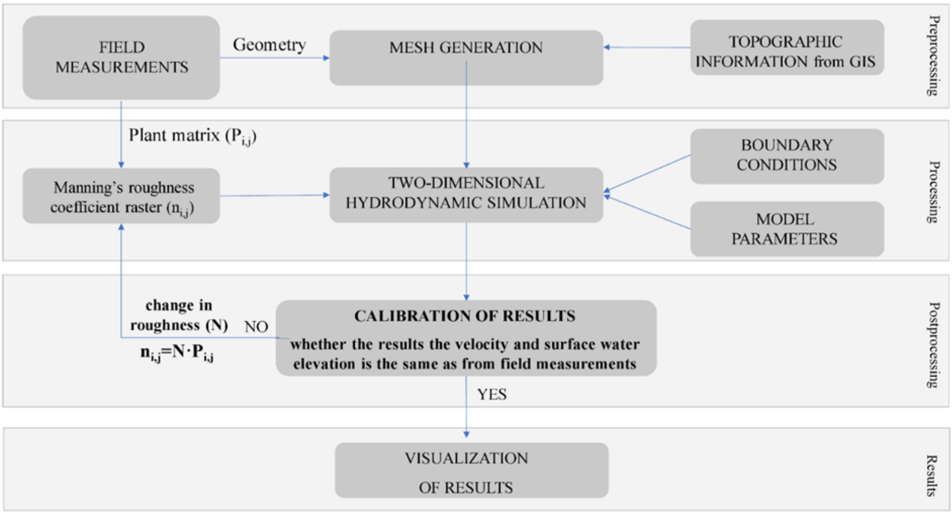

Fig. 4. Model calibration scheme

5. RESULTS AND DISCUSSION

The roughness calibrations carried out for variant W0 yielded Manning's roughness coefficient values throughout the modelled field in the range of n = 0.025-0.090. For the other variants, the spatial distribution of Manning's roughness was defined by assuming minimum values of n = 0.025 for the area where plants were removed while using the actual roughness in areas where vegetation remained. The distribution of Manning's coefficient of roughness for the 4 maintenance alternatives analysed is shown in Fig.5

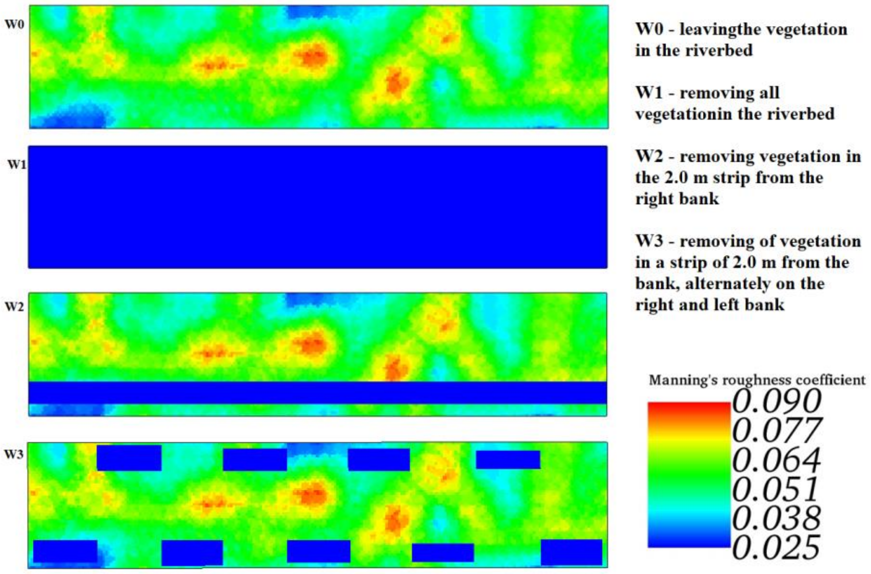

Fig. 5. Spatial distribution of Manning's roughness n for the analyzed variants

For each of the specified variants of vegetation maintenance in the river, simulation was carried out for successively increasing flows. Five main parameters characterizing the hydraulic conditions in the analysed section of the riverbed were analysed: average velocities, maximum velocities, average shear stresses, maximum shear stresses and the average water surface elevation in relation to the magnitude of the flow. Tables and graphs showing the obtained values of each parameter are presented below.

The water surface elevation for all variants increases with the amount of flow, which follows directly from the basic principles of open channel hydraulics. Similarly, the differences between the variants also increase with the magnitude of the flow. The different variants indicate the great importance of the maintenance work carried out on the ordinate of the water surface. For variant W1 with complete removal of vegetation, there is a significant reduction in roughness and, consequently, also in the depth and the water surface elevation. The curve of the dependence of the water surface elevation on the flow rate in this variant significantly deviates not only in the range of values, but also in shape, significantly flattening with increasing flows, indicating a significantly higher capacity of the riverbed itself, as it is capable of carrying more water at a shallower depth. The link that the presence of plants in a riverbed reduces its capacity by increasing resistance and reducing the effective flow field has been repeatedly proven in various studies [17]. From the point of view of flood protection, this is an important feature, which, however, is not beneficial from the point of view of the retention of the riverbed and the ability of the river to naturally dam and thus recharge neighbouring areas. Variant W2 with the removal of vegetation in a strip on one side of the river shows an indirect effect on the relationship in question. The average ordinate of the water surface in the riverbed is significantly lower than with full vegetation, but it is also significantly higher than in Variant W1 without vegetation. Very interesting in this context is the comparison of variants W2 and W3, which are similar in terms of the area of vegetation removed, but in the case of variant W3 with the removal of plants alternately on the right and left bank, we do not observe any lowering of the average water level in the analysed section of the riverbed compared to variant W0 with vegetation. This way of carrying out maintenance work preserves the natural damming and retention of water in the riverbed, without producing large yields in terms of capacity. The results obtained are in principle consistent with those previously obtained by other researchers. Errico et al. [2] for the variants of total plant removal and mid-channel plant removal obtained water ordinate changes of 0.03 to 0.05m, while conducting the study in a much smaller river with a flow range of 0.31-1.22 m3/s, which, when translated to the channel scale in the present study, yields similar values.

Table 1. Table of dependence of water surface elevation on flow rate

Q [m^3/s]	Water surface elevation [m]			
	mean			
	W0	W1	W2	W3
0.32	1.1	1.02	1.07	1.1
0.65	1.2	1.08	1.16	1.2
1	1.29	1.13	1.24	1.29
1.29	1.36	1.17	1.29	1.36
1.78	1.46	1.23	1.38	1.46
2.79	1.63	1.34	1.53	1.63
3.44	1.73	1.4	1.62	1.73
5	1.95	1.52	1.8	1.95

The analysis of the results of average and maximum velocities for the section of the studied channel, is partly similar to the relationship of the water surface elevation. First, both mean and maximum velocities increase similarly with increasing flow, with the increase for mean velocity being most similar to a linear curve, while for maximum velocity it is definitely more like a logarithmic curve. Secondly, there is a convergence of results for the variant with existing vegetation and with alternate removal of plants from the right and left banks (W0 and W3). Both mean velocities and maximum velocities are lowest in these variants.

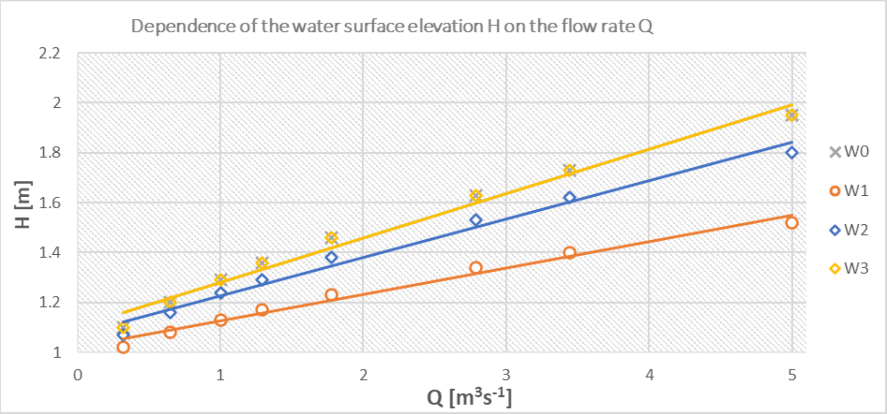

Fig. 6. Dependence of the water surface elevation H on the flow rate Q

In the case of average velocities, the highest values by far prevail in variant W1, which takes into account the removal of all vegetation from the channel. The values of maximum velocities are for flows of more than 0.5 m^3/s the highest in variant W2. The removal of vegetation on one of the banks creates a trough at this location, where the flow is concentrated and the highest velocities are obtained. The presence of such a form in the channel can be of great importance. This place concentrates most of the flow, causing water to stagnate in the rest of the channel. This leads, firstly, to a disruption of the debris transport system - erosion and deepening can occur in the trough, while debris material is deposited in vegetated zones. In addition, the self-purification capacity of water is disturbed [6,11,22] Some organic material (nitrogen and phosphorus compounds) is taken up by plants in a slow-flowing river. When most of the water flows through the trough at high velocity, plants do not have the opportunity to use these substances, which flow unused downstream. The obtained trends in velocity distribution are in line with similar past studies [3,8,14]. However, it is difficult to compare the velocity values themselves, as they usually depend on the individual characteristics of the study area (geometric characteristics of the channel, flow volume, plant density).

Table 2. Table of dependence of mean and maximum velocities on flow rate

Q [m^3/s]	Velocity [m/s]							
	maximum				mean			
	W0	W1	W2	W3	W0	W1	W2	W3
0.32	0.23	0.5	0.43	0.28	0.11	0.16	0.12	0.11
0.65	0.31	0.55	0.54	0.33	0.16	0.24	0.17	0.18
1	0.37	0.6	0.63	0.38	0.19	0.3	0.21	0.19
1.29	0.4	0.64	0.68	0.41	0.22	0.34	0.24	0.22
1.78	0.45	0.7	0.76	0.46	0.25	0.39	0.28	0.25

Q [m^3/s]	Velocity [m/s]							
	maximum				mean			
	W0	W1	W2	W3	W0	W1	W2	W3
2.79	0.53	0.79	0.9	0.54	0.31	0.49	0.34	0.31
3.44	0.57	0.84	0.97	0.58	0.34	0.53	0.38	0.34
5	0.67	0.95	1.11	0.68	0.4	0.63	0.45	0.4

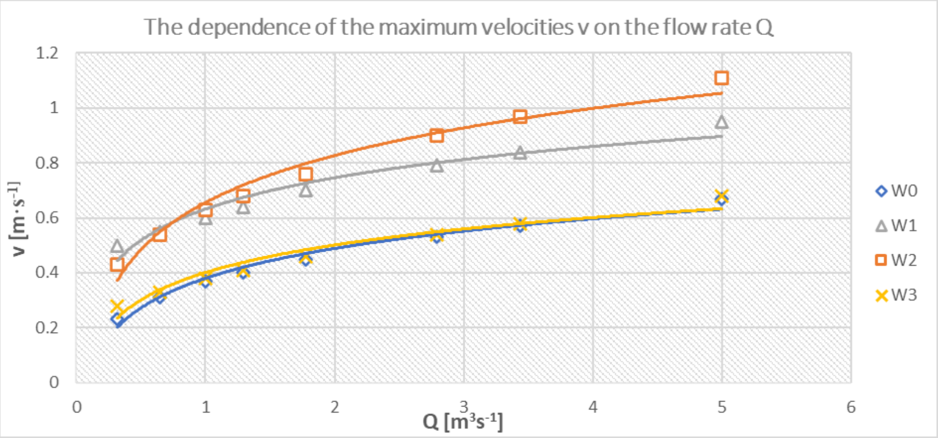

Fig. 7. The dependence of the maximum velocities v on the flow rate Q

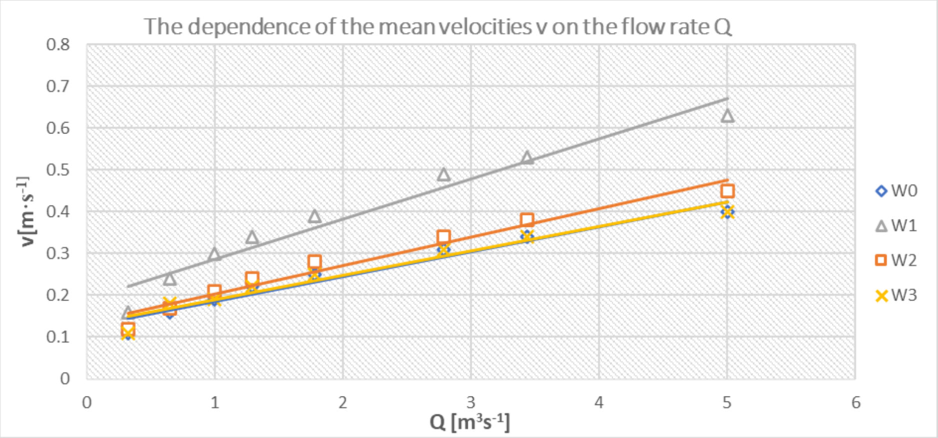

Fig. 8. The dependence of the mean velocities v on the flow rate Q

The interpretation of the obtained shear stress values is also very interesting. In this case, as for velocity, the increase in values for increasing flows occurs for average values in a linear manner, while for maximum values in a logarithmic manner. The average values of shear stress are the highest for the existing condition W0. The occurrence of different forms of vegetation throughout the flow field and the resulting changing roughness leads to a very different flow distribution affecting turbulence throughout the channel. Importantly, these values are relatively low, with little potential for erosion. In the case of variant W1 with vegetation removed from the channel, the average shear stresses are the lowest, as there are no major forms of turbulence in the obstacle-free flow field. Such a phenomenon adversely affects the river's self-purification processes while depleting various microhabitats of higher ecological value [2]. The average values in variants W2 and W3 are similar to each other, which is due to the fact that, in general, the area of removed plants is similar to each other.

In the case of maximum shear stresses, the smallest values are obtained for variant W1 with vegetation removed from the channel, which is due to the lack of turbulence throughout the flow field. On the other hand, the highest values of maximum shear stresses are observed for variant W2 with the created trough with increased velocity, which also has local maximum stresses. Similar values of maximum shear stresses were shown for variants W0 and W3.

In the case of shear stress, similarly to velocity, the trends are similar to other studies. Most of the stress studies are conducted on laboratory models rather than natural riverbeds, making numerical comparisons difficult [3, 7,15,16].

Table 3. Table of dependence of mean and maximum shear stress on flow rate

Q [m^3/s]	Shear stress [N/m^2]							
	maximum				mean			
	W0	W1	W2	W3	W0	W1	W2	W3
0.32	3.3	3.9	6.8	3.3	0.9	0.5	0.7	0.8
0.65	4.6	4.2	10	4.8	1.5	0.8	1.2	1.3
1	6	3.6	12.1	6.1	2	1.1	1.6	1.8
1.29	7.1	3.9	13.3	7	2.4	1.3	2	2.1
1.78	8.5	4.4	15.3	8.4	2.9	1.6	2.5	2.6
2.79	10.8	4.9	19	10.8	3.8	2.2	3.4	3.5
3.44	12	5.3	21.1	12.1	4.5	2.5	4	4
5	14.6	6.1	26.1	14.9	5.8	3.2	5.1	5.1

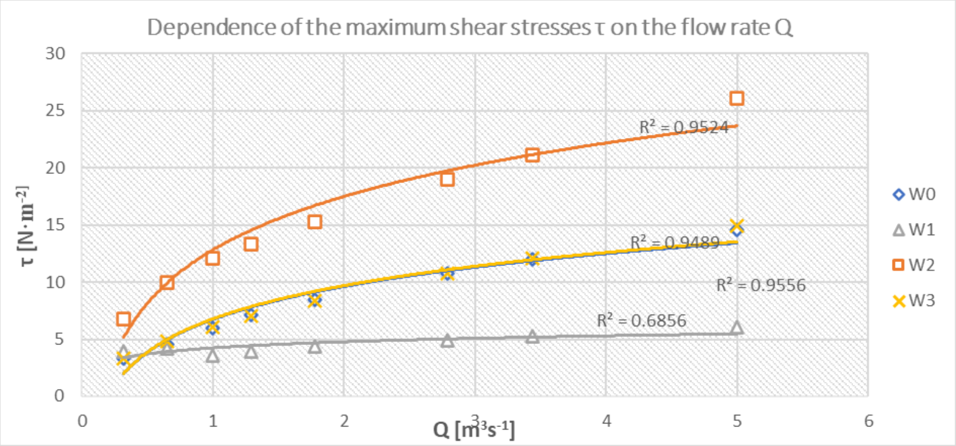

Fig. 9. The dependence of the maximum shear stress τ on the flow rate Q

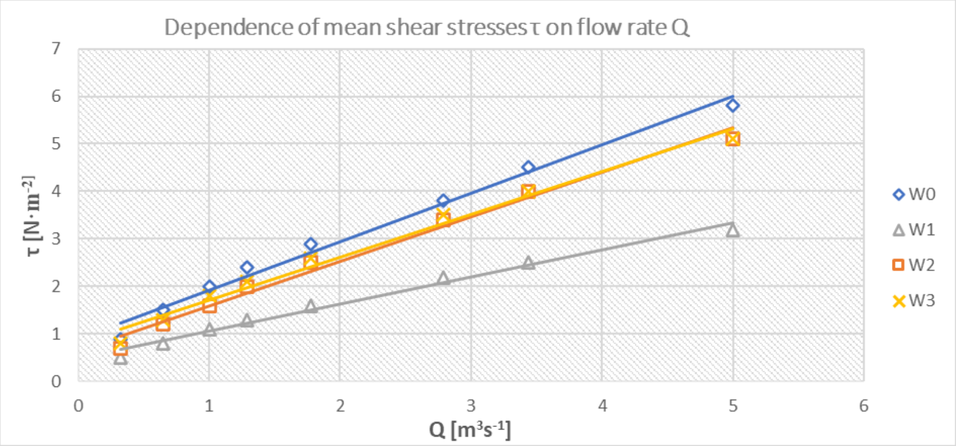

Fig. 10. The dependence of the mean shear stress τ on the flow rate Q

Solutions carried out in terms of maintenance work on watercourses can, where possible, be well integrated into nature-based sulutions (NBS) type activities. The implementation of restoration processes is often associated with the introduction of obstructions into the watercourse to increase the diversity of hydraulic conditions, the creation of zones of reduced and increased velocity, the creation of streamside structures, etc. [12,19,23]. As has been shown, different forms of maintenance work carried out can cause variable hydraulic conditions in the riverbed. It seems reasonable that maintenance works should be carried out not according to the scheme adopted for the entire watercourse, but according to certain features of the watercourse fragments. Such proceedings should be planned and map the main needs of a particular fragment of the watercourse. The basis for complete removal of plants can only be the overriding need to achieve increased channel capacity in a given section. Where possible, plant removal should be limited or minimized to parts of the riverbed. Adopting multiple and varied forms of maintenance work along a longer stretch of a watercourse can be the basis for increasing the biodiversity of a given watercourse.

6. CONCLUSIONS

Although the studies conducted do not completely exhaust the topic related to these processes, they do indicate the positive and negative impacts of certain forms of river maintenance on hydraulic conditions:

1. Complete removal of plants from the channel (variant W1) leads to a significant increase in the river's capacity. Water depths decrease at the same flow rate relative to the flume with vegetation. There is an increase in velocity throughout the channel, but the flow is fairly uniform and does not cause a significant increase in shear stress.
2. Removal of plants from one side of the flume (W2), leads to a significant concentration of flow in the resulting trough, the formation of a zone of increased velocity in it and increased maximum shear stresses. On the one hand, a partial increase in throughput is achieved, but on the other hand, this can lead to a deterioration of the river's self-cleaning processes and the formation of erosion and accumulation zones in the channel.
3. Removal of plants in alternating sections on both sides of the riverbed (W3) is a measure that affects the diversification of hydraulic conditions in the riverbed, but does not bring the achievement of increased throughput for low and medium flows. This form of maintenance increases local maximum velocities and maximum shear stresses.
4. It seems reasonable to carry out maintenance work on watercourses with knowledge of the basic impacts of the work carried out with adjustment on individual sections of the work to the main needs of the site.
5. The choosen methodology of the research allowed to optimally determine the hydraulic characteristics of the verified methods of channel maintenance. The use of numerical modeling calibrated with field studies allows for relatively low-cost verification of the designed restoration solutions.

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