A HYDRAULIC MODEL OF DISCHARGE CAPACITY FOR RIVERS WITH FOREST VEGETATION ON FLOOD LOWLAND

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Abstract: A method for predicting river velocity and discharge in beds with forest vegetation on neighbouring lowland is presented. The Darcy-Weisbach formula was used at the calculation. The calculated discharge curve and distribution of velocities in cross-section are given.

Keywords: rivers discharge capacity, rivers with lowland vegetation

INTRODUCTION

River valleys are subject to be flooded by floodwater. Regular floods on valley areas by annual waters of average volume do not disturb site conditions. After retreating of the flood there more or less numerous different biotopes appear: water ponds and swamps creating a mosaic of a landscape. The habitat sites are parts of a system cross-linked within itself by various connections. A possibility of fauna migration is also a crucial condition of system existence and development. Forests, groups of trees, shrubs and separate trees located on flood areas create the sites of different kinds. Forests and shrubs on banks of a river and sides of the channel protect the land against erosion, crops and water against wind and create a biotope suitable for many species of fauna and flora, and they form even a winter shelter for some animals. They are also an element promoting prosperity of fauna and flora, playing an important role in the landscape. However, the growth of trees and shrubs does not seem to be an advantage for farmers. Flood waters assessed to be catastrophic with culmination tides of very small probability of occurrence, great volume and lingering water are very threatening for stability of life on flooded areas. Life in natural river valleys including forests and other biological formations

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presenting a shelter for rare species of plants and animals is negatively influenced by such an event.

DISCHARGE CALCULATION FOR CULMINATION WATER IN CHANNELS WITH LOWLAND VEGETATION

Hydraulic conditions of flow in open channel with compound cross-sections and high plants inside were the subject of studies mainly in European scientific centres throughout last few decades. Only the Union of Engineers of Water Management and Engineering Environment in Germany worked out the guidelines for hydraulics calculation of channel capacity, taking into consideration high vegetation inside it. The method of calculation recommended in this elaboration considers mutual influence of each part the section, that is, an exchange of mass and momentum between the area with and without vegetation, the flow in the main channel and through the floodplain. Coincidence of the results of this calculation with the results of laboratory measurements made in the Warsaw Agricultural University, Department of Hydraulic Engineering and Environmental Restoration was studied. Apart of specifying the size of channel and valley sections and of longitudinal slop, it is also necessary to make plant inventories in the area subject to flow in order to determine mean parameters of vegetation suitable for calculation of the discharge. The vegetation there consists of reed, grass, shrubs and trees. The discharge of water in the channel is considered to be quasi-steady and is described by parameters mean in time. Velocity of flow in the area with high vegetation is not subject to logarithmic law of distribution and does not actually change along with the depth. The assumption that the resistance of the flow bypassing different natural vegetation is the same as of flows bypassing evenly distributed plants at steady parameters, averaged by inventorying some of them, such as diameter of tree trunks or substitute shrub diameters, is the basis of hydraulic discharge calculations taking vegetation into account. Preparing hydraulic characteristics of vegetation, specific for its very diverse natural structures, is connected with problems of methodical nature. For the river channel shown on Fig. 1. overgrown with trees and shrubs, a study area (A_{pro}) 11 m long was chosen for inventorying. Then a calculation of all tree and shrub diameters was made, and there was their basal area $A_{o,p,i}$ determined. The mean basal area of plant stems was calculated by summing the plant stem basal areas according to the following relationship:

$$A_{o,p,n} = \frac{\sum A_{o,p,i}}{n} \tag{1}$$

where n - number of plant clumps found on the plot.
The equivalent basal diameter d_p of plant groups, and mean density a_y of plants along the flow and transversal a_x to it are defined with the assumption that both distances are equal, from the formulae:

$$d_p = \sqrt{\frac{4A_{o,p,n}}{\pi}} \tag{2}$$

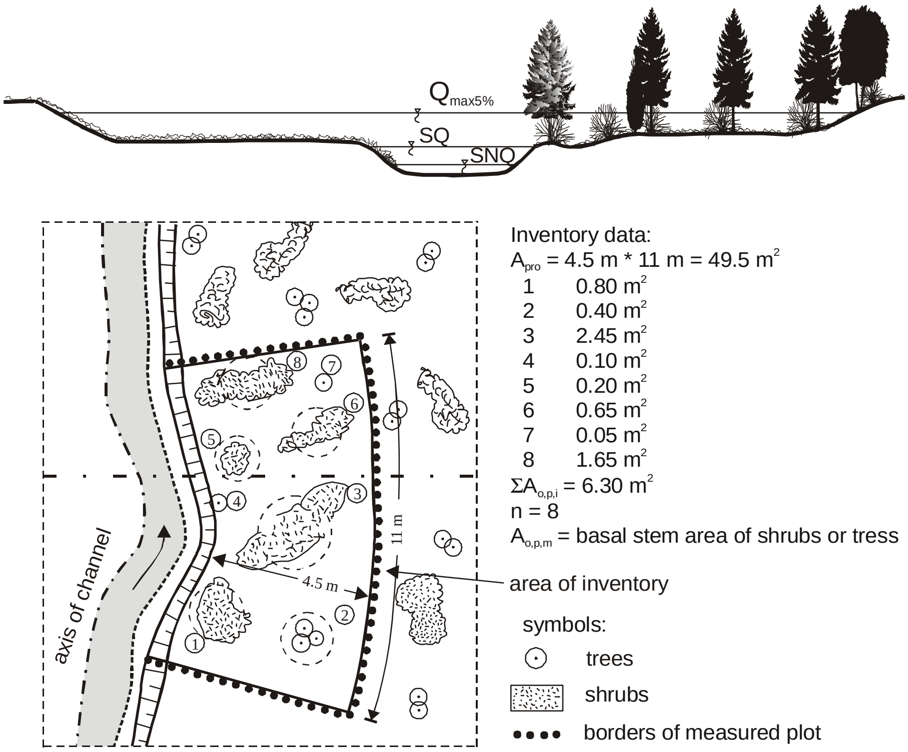

Figure 1. A scheme of the river channel and sample plot location

$$a_x = a_y = \sqrt{\frac{A_{pro}}{n}} \tag{3}$$

The grounds for the capacity calculation of channels with compound sections and floodplains overgrown with vegetation come from the analysis of flow conditions in the cross-section of the channel and delineation of flow areas influenced by dominating factors of roughness of the scarp and the bed of the channel (Fig. 2.), and the resistance in flow going through high vegetation areas and transitional areas between them. Compound cross-section of the channel is divided with vertical interfaces into the main channel and neighbouring floodplains. The heights of these interfaces are taken into consideration at calculation of wet perimeter of the main channel. Mean velocity of the flow in each area is calculated according to the Darcy-Weisbach equation:

$$V = \sqrt{\frac{8g}{\lambda} R_{hy} J} \tag{4}$$

where: λ - average dimensionless friction factor of flow in given part of section, g - gravitational acceleration [m/s^2], J - hydraulic slope [-], R_{hy} - hydraulic radius [m].
The resistance of flow caused by the roughness of the scarp and the channel bed is calculated from the formula given by Colebrook-White:

$$\frac{1}{\sqrt{\lambda_s}} = -2.03 \log\left(\frac{2.51}{Re\sqrt{\lambda_s}} + \frac{k_s}{14.84\, R_{hy}}\right) \tag{5}$$

where λ_s – friction factor not overgrown part of channel [-], k_s - roughness bed of channel [m].
As it results from the Colebrook-White law, the friction factors of flow depend on the Reynolds number and on relative roughness k_s/R. The influence of the Reynolds number on friction factors decreases along the increase of its value and of relative roughness of channel sides. In natural channels the relative roughness is so considerable that the influence of the Reynolds number may be neglected without any harm to the precision of calculations. Therefore Rickert recommends to apply the equation (5) for practical calculations in the following form:

$$\frac{1}{\sqrt{\lambda_s}} = -2.03 \log\left(\frac{k_s}{14.84\, R_{hy}}\right) \tag{6}$$

The friction factor of scarps and of channel bed with k_s roughness is then calculated from transformed formula (6).
The resistance of flow in parts of channel sections overgrown by vegetation depends on both vegetation and bed roughness. The friction factor for this area, according to the concept issued by Einstein and Banks, is the following sum:

$$\lambda = \lambda_s + \lambda_v \tag{7}$$

where λ - average friction factor in part of cross-section [-], λ_s - friction factor caused by channel bed roughness [-], λ_v - friction factor for submerged vegetation [-].
Signs and symbols were adopted from the reference studies. The friction factors for high vegetation λ_v were the object of investigations by Kaiser (1984), Lindner (1982) and Pasche (1984). For areas with trees the λ_v factor is calculated on the basis of resistances caused by submerged vegetation and is related to the area of the whole floodplain:

$$\lambda_v = \frac{4 h_p d_p}{a_x a_y} C_{WR} \cos\alpha \tag{8}$$

where h_p - height of submerged part of trees [m], d_p - trees diameter [m], α - the angle of slope the bed in transverse direction to direction of flow, C_{WR} - dimensionless drag coefficient for submerged part of the trees.
The drag coefficient C_{WR} depends on the ratio of the V_i flowing velocity to the average velocity V_v of the flow going through tree-overgrown areas, and to the height of waves formed on the surface of the water flowing around the trees:

$$C_{WR} = \left(1.1 + 2.3\frac{d_p}{a_y}\right)\left(\frac{V_i}{V_v}\right)^2 + 2\left(\frac{1}{1 - d_p / a_y} - 1\right) \tag{9}$$

Pasche (1984) gave an empirical formula on the relative velocity of water flowing against the tree, and Rickert reduced it to the following form:

$$\left(\frac{V_i}{V_v}\right)^2 = 0.6 + 0.5 log\left(\frac{a_x}{a_z}\right) \tag{10}$$

The way of calculation of flow intensity in the floodplain with trees (Fig. 2.) is exemplified below. Calculation of the flow rate in a floodplain requires definition of the width of this area. For this aim we need calculation of the length a_{NL} and the width a_{NB} of the Karmann path of the round-the-tree flow.

$$a_{NL} = 128.87 C_{W\infty} d_p \left(1 + \frac{g\, a_{NL}\, J}{V_T^2 / 2}\right)^{-2.143} \tag{11}$$

$$a_{NB} = 0.24\, a_{NL}^{0.59} (C_{W\infty} d_p)^{0.41} \tag{12}$$

where a_{NL} - the length of the Karmann path formed at a single plant submerged [m], a_{NB} - the width of the Karmann path formed at a single plant submerged [m].
The drag coefficient $C_{W\infty}$ is determined for single tree at ideal two-dimensional flow. Its variability for different forms of the turbulent flow was given by Lindner (1982) in the equations:

$$C_{W\infty} = 3.07 Re_p^{-0.1680} \quad \text{for} \quad Re_p = \frac{V_v d_p}{\nu} < 800 \tag{13}$$

$$C_{W\infty} = 1.0 \quad \text{for} \quad 800 \le Re_p \le 8000 \tag{14}$$

$$C_{W\infty} = 1.2 \quad \text{for} \quad 8000 < Re_p < 10^5 \tag{15}$$

where Re_p – the Reynolds number for a single plant [-], ν - viscosity [m^2/s].
The calculations are conducted at the assumption of the V_T value, and of $V_T > V_v$, due to the occurrence of velocity V_T in the formula (11) for cross-section interfaces. Then the coefficient of overgrowing is calculated:

$$\Omega = \left(0.07\frac{a_{NL}}{a_x}\right)^{3.29} + \left(\frac{a_{NB}}{a_y}\right)^{0.95} \tag{16}$$

The dimensionless velocity in interfaces is calculated from the formula:

$$C_T = -3.27 \log \Omega + 2.85 \tag{17}$$

The width of the area of main channel flow influence on flows in floodplains is calculated from the formula:

$$b_m = \frac{h_T}{\lambda_v (0.068 e^{0.56 C_T} - 0.056)} \tag{18}$$

where h_T - depth of interfaces between main channel and floodplain [m], c_T - dimensionless velocity in interfaces.
At calculation of the discharge in the main channel, the interface of the floodplain from the main channel is treated as the rough wall with roughness of channel k_T and friction factor λ_T. In reality these resistances are made by intensive cyclical impulses of mass and momentum in transverse direction to the main flow, as well as by associated high turbulence strains and whirls on the surface of water in round-the-tree flows. The roughness in the interfaces is calculated from the formula:

$$k_T = 0.854\, R_{hy,T}\, \Omega \left(1.7\frac{2b_m}{b_k}\right)^{1.07} \tag{19}$$

where $R_{hy,T}$ - hydraulic radius concerning the resistance by the interface [m], b_m width of the zone of influence of the area with trees on the area without trees [m], b_k - main channel width [m].
The occurrence of different roughness and friction factors in the main channel requires calculation of the average friction factor and the distribution of the hydraulic radius of the main channel according to the concept by Einstein assuming the equity of average velocity in every sub-domain of the main channel:

$$R_{hy,i} = \frac{\lambda_i}{\lambda} R_{hy,F} \tag{20}$$

where λ_i - friction factor of part-section with hydraulic radius R_i, $R_{hy,F}$ - hydraulic radius of the main channel calculated with account of the length of interfaces h_T.
The calculation of the hydraulic radius for different roughness in cross-sections is conducted using the iterative method. The hydraulic radius in the interface $R_{hy,T}$ is calculated from the formula (20), then the equivalent height of roughness in the interface k_T from the formula (19) and the friction factor λ_T from the formula (6).

The average friction factor in the whole main channel λ is calculated with consideration to the friction factors in the flow bed λ_S and λ_T in the interface cross-section:

$$\lambda = \frac{2\lambda_T h_T + 2\lambda_S l_S}{2h_T + l_S} \tag{21}$$

The average velocity of main channel flow is calculated from the Darcy - Weisbach formula (4), and the velocity V_T in the interface between the main channel and its floodplain from the formula:

$$V_T = C_T \sqrt{\frac{\lambda_v}{8}} V_F \tag{22}$$

The velocity V_T calculated from the equation (22) is usually different from the one assumed at the beginning of a_{nl} calculation (11); therefore the wholeness of calculations should be repeated, accepting the calculated value V_T according to formula (22) as the next approximation.

THE CALCULATION RESULTS

For the channel shown on Fig. 1., overgrown with trees and shrubs, a surface was chosen immediately adjacent to the main channel A_{pro}= 49.5 m^2, where measurements of tree and shrub diameters were made. The results of measurements were shown on Fig. 1. Longitudinal slope of main channel and floodplains J = 1 ‰ was adopted in calculations of the discharge. The variability of roughness of surfaces of individual parts of the channel was taken into account as characterised by absolute roughness k_S. The calculated velocities of the flow in individual areas of compound intersections of the channel were presented on Fig. 2. The curves of flow capacity of individual parts and of the whole channel were shown on Fig. 3.

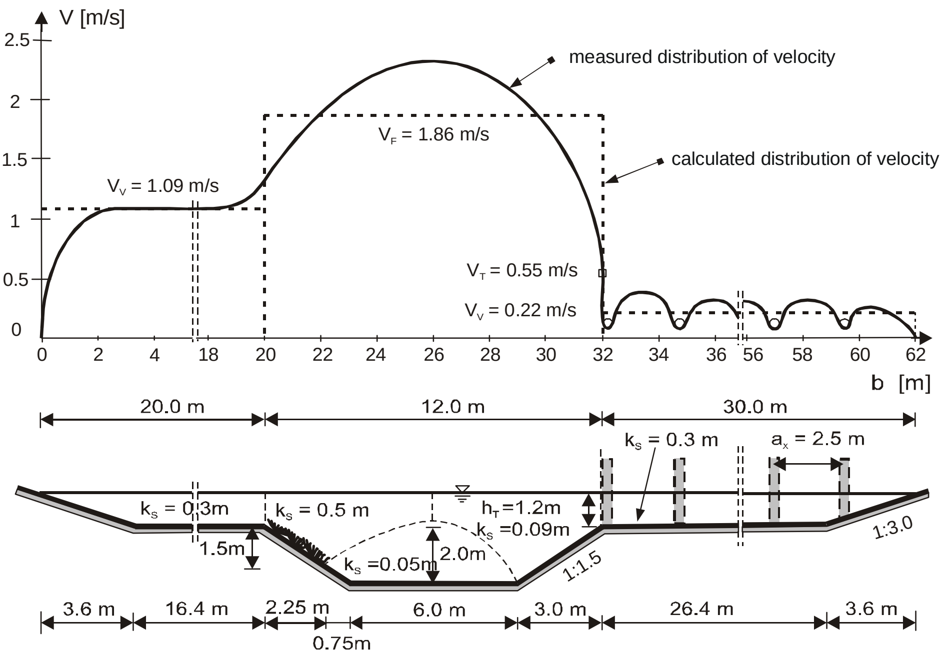

Figure 2. Calculated mean velocities for compound channel with account on vegetation and trees

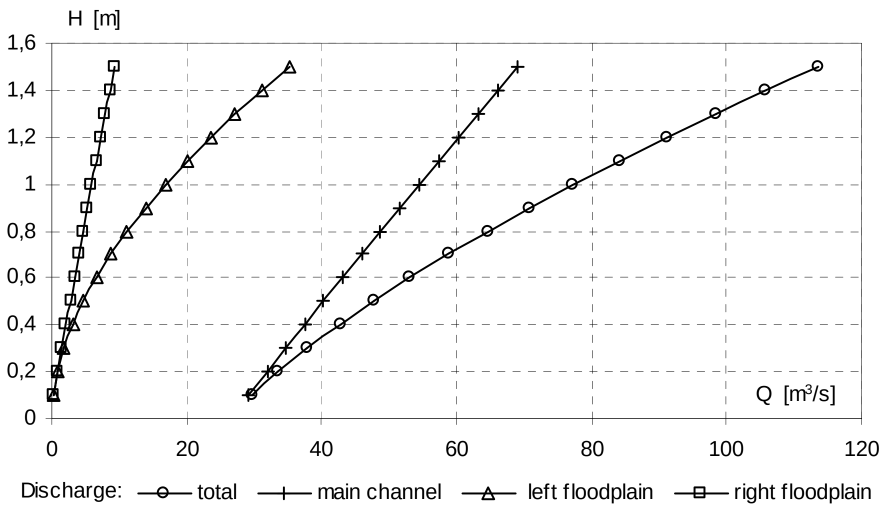

Figure 3. Calculated discharge curve for specified parts of compound channel with vegetation and trees

SUMMARY

The calculations made illustrate the possibility of analysing the flow capacity of channels and valleys in conditions of various densities of the plant cover consisting of trees, shrubs and low vegetation. Calculations as above should precede all decision-making concerning the removal of vegetation from floodplains, and they should make possible predicting of the behaviour of existing vegetation in response to new projects of engineering development of river channels and valley areas.

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