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Original Research

Hydraulic Model Investigation of Flow Conditions for Floodplains with Coniferous and Deciduous Shrubs

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Abstract

This paper presents the results from a laboratory research project about water flow through and around coniferous and deciduous shrubs. These are the only two types of shrubs that were considered in this research project. The shrub obstruction consisted of natural branches fixed in the bed of the flume, transversly to the direction of the flow. Besides hydrodynamic parameters, shrub density, water swelling over them, and local drag coefficients of the shrubs was measured and calculated. The final measurement was influenced by the density of both shrub types mentioned above and the spatial orientation of their branches in specified shrub zones in the path of the flowing water. These were analyzed both quantitatively and qualitatively and the appropriate computational formulae were proposed.

Keywords: rivers, shrubs, flow resistance, water swelling, flood prevention

Introduction

The shrubs occurring in nature constitute a natural obstruction for water flow in which part of the energy is lost. In a channel the active flow cross-section is reduced. The flow resistance within the area populated by trees and shrubs increased, which caused a local rise of river water level. At a certain stage of calculations relating to either forecasting or designing, it is necessary to determine the hydraulic properties of this "natural flow resistance." In particular, quantitative hydraulic characteristics of shrubs are still missing. These types of shrubs are variable throughout the year depending on the season, which defines the number of leaves and branches, as well as their geometry. The shrubs grow spatially, which is significant to the value of the water swelling over the obstruction. The density of the shrubs can be measured by the so-called spatial concentration of the shrub ρ [1-3, 9], which is defined as the percentage share of the branches, leaves, and needles in the flow area (comparable to volume number ε_v [4]). This parameter and its measurement method are described in greater detail in the author's papers [2, 5]. The flow resistance resulting from the flow-through of local shrub patches can be characterized, among other factors, with local drag coefficients ζ [5-7, 9]. Apart from these parameters, which are quantitative, shrub obstructions are characterized by nonparametric elements such as the type of branches (deciduous or coniferous) and their orientation (vertical or horizontal) (Fig. 1). This paper attempts to tackle the question of to what extent modifying two variables would influence the flow conditions in an open channel. The first was the density of shrubs (regardless of their spatial orientation and type of branches), and second was increasing the shrub zone length in the direction of the flow.

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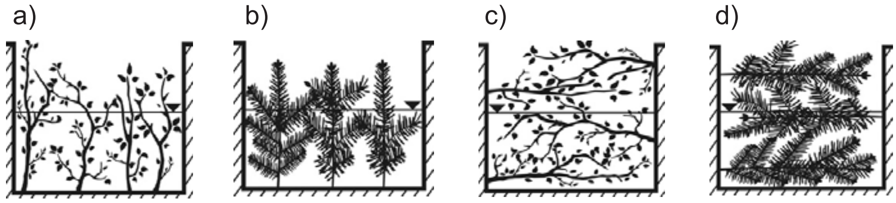

Fig. 1. Spatial orientation of shrub branches: a) – deciduous vertical, b) – coniferous vertical, c) – deciduous horizontal, d) – coniferous horizontal.

Modeling Research

Research Stand

The research model consisted of a straight, concrete, rectangular flume (5), 15 m in length, 1.0 m in width, with the flume bed at a constant 1.0% slope. A weir (8) was installed on the flume outlet wall to adjust the desired water level. The measurements of the flume filling ahead of and behind the shrubbery obstructions were carried out with piezometers (6) installed along the flume. A circular measuring overflow (4) was installed on the flume inlet wall and a measuring tank (9) located in the base of the model, were used to measure flow capacity. Fig. 1 shows a general schematic of the measurement set-up together with the supply installation.

The conifer and deciduous shrubs under investigation (scale 1:1) were mounted in the flume (5) in a specially designated shrub zone (7). The spatial concentration of the shrubs was done by means of using an external measuring cylinder and calibrated tank, each time installed directly in the flume. The shrubbery volume calculation is the difference between the volume of water poured into the tank with no shrubs, versus the volume of water poured into the tank without them [2, 5-6].

Scope of Study

Our research into the effect of shrubs in the flow conditions was conducted within the following measurement ranges:

- variable channel flow capacity ranging from 10.0 and 100.0 l/s
- variable measuring flume filling, within the interval of 8.8÷70.1 cm
- variable local flow velocity ranging from 5 and 45 cm/s
- variable length of the shrub obstructions: 1/3, 2/3, 3/3 m
- shrub obstruction width of 1 m
- spatial orientation of branches: vertical and horizontal (Fig. 1)
- type of branches: deciduous and coniferous (Fig. 1)
- variable spatial concentration of the shrubs: 10.0÷85.0%.

Research Findings and Discussion

The computational formula of the local drag coefficient ζ solves the Bernoulli equation for cross-sections in front of and behind the shrub obstruction and the local loss equation with respect to the unknown parameter ζ [5-9]:

$$\zeta = \frac{2g\left(H_g - H_d\right) + \alpha\left(v_g^2 - v_d^2\right)}{v_d^2} \quad (1)$$

...where:

α – the St. Venant's coefficient [-]

H_g and H_d – water depth ahead of and behind the obstruction [m]

g – acceleration due to gravity [m/s²]

v_g and v_d – mean flow velocity ahead of and behind the obstruction [m/s].

From the point of view of flood prevention, the so-called vegetative rise is of particular interest. Here, by vegetative rise we understand the difference between the max-

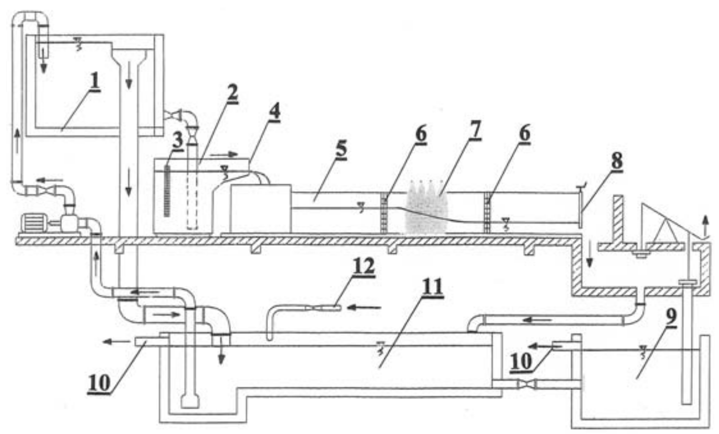

Fig. 2. Schematic view of the measurement set-up (1 – higher tank, 2 – measuring tank, 3 – gauge, 4 – circular measuring weir, 5 – flume, 6 – piezometers, 7 – shrubs, 8 – weir, 9 – measuring tank, 10 – to sewers, 11 – main tank, 12 – supply pipeline).

imum depth H_g of upstream water, resulting from the rising influence of vegetation, and the depth H_d downstream of the obstruction:

$$\Delta H = H_g - H_d \tag{2}$$

The measurements of water depth and flow velocity ahead of (H_g; v_g) and behind (H_d; v_d) the shrub obstruction allowed the calculation of local drag coefficient ζ and the counting of water rise ΔH due to the shrubbery. The relationships: H_g = f(q), ΔH = f(q), ΔH = f(L), ΔH = f(ρ), ζ = f(ρ), ζ = f(L), ζ = f(Fr), ζ = f(Re), and ζ = f(q) have been established. In this regard the power function as below is optimal:

$$y = a\, x^n \tag{3}$$

...where: y – denotes the depth above (H_g), the swelling (ΔH) or the drag coefficient (ζ), x – concentration of vegetation (ρ), length of the shrub obstruction in the flow direction (L), Froude number (Fr), Reynolds number (Re) or specific discharge (q= Q/B) by flow capacity (Q), and shrub obstruction width (B); a, n – power function parameters established empirically [5].

These relationships are discussed in detail in the author's paper [5]. Some of the sample curves: ΔH = f(q), ζ = f(Re), ΔH = f(L), ζ = f(Fr), are shown in Figs. 3, 4, and 6-8.

The analysis of partial relationships for a single variable (3) has derived a general empirical equation (4). This can be used to calculate the water swelling ΔH or the local flow drag coefficient ζ for shrubs of given density, within a given shrub zone length in the flow direction and also as a function of the specific discharge and shrub type (conifer or deciduous) and their branch configuration (Fig. 1). Similarly as for the single variable function (3), also in this case the power function (4) is optimal with respect to the correlation with the measurement data, which is a superposition of partial functions (3). For a given slope of the laboratory flume it takes the form of the following equation:

$$y = f\,(L; q; \rho) = \alpha\, L^A\, q^B\, \rho^C \tag{4}$$

...where:
y – vegetative swelling ΔH or drag coefficient ζ;
A, B, C – empirical exponents of the power function;
L, q, ρ – variables under investigation;
α – empirical equation coefficient.

Our analysis leads to equations that hydraulically characterize the four types of shrub obstructions under study (Fig. 1). In the case of obstructions with vertically fixed shrubs these equations have three variables: flow rate, length, and density. In the case of the shrubs being fixed horizontally, due to the scope of our study, vegetative swelling ΔH and drag coefficient ζ are functions of only two variables: density of shrubs and flow rate. The following equations have been obtained:

- for the vertically fixed deciduous shrubs (Fig. 1a)

$$\Delta H = 1.3\cdot 10^{-5}\, L^{0.6}\, q^{0.9}\, \rho^{1.5} \tag{5}$$

$$\zeta = 0.071\, L^{2/3}\, q^{1/3}\, \rho^{3/2} \tag{6}$$

- for the vertically fixed coniferous shrubs (Fig. 1b)

$$\Delta H = 0.1\cdot 10^{-5}\, L^{0.6}\, q^{0.9}\, \rho^{2.0} \tag{7}$$

$$\zeta = 0.0053\, L^{2/3}\, q^{1/3}\, \rho^{2.0} \tag{8}$$

- for the horizontally fixed deciduous shrubs (Fig. 1c)

$$\Delta H = 2\cdot 10^{-5}\, q^{0.40}\, \rho^{2.0} \tag{9}$$

$$\zeta = 0.130\, q^{-0.212}\, \rho^{2.0} \tag{10}$$

- for the horizontally fixed coniferous shrubs (Fig. 1d)

$$\Delta H = 5\cdot 10^{-5}\, q^{0.43}\, \rho^{1.5} \tag{11}$$

$$\zeta = 0.304\, q^{-0.175}\, \rho^{1.5} \tag{12}$$

...where:
ΔH – water swelling [m],
ζ – drag coefficient [-],
L – shrub zone length [m],
q – specific discharge [l/(s·m)],
ρ – spatial concentration (density) of shrub [%].

Influence of Shrub Parameters on Flow Conditions

Density of Shrubbery

For each investigated shrub, obstruction discharge rating curves and vegetative rise functions were analyzed (Fig. 3). It can be clearly seen that the depths and water levels in the channel grow with the flow rate as a power function. Quantitatively, the phenomenon heavily depends on the density of the shrubs. Its presence drastically cuts the flow capacity of the channel (by as much as from 4 to 70%),

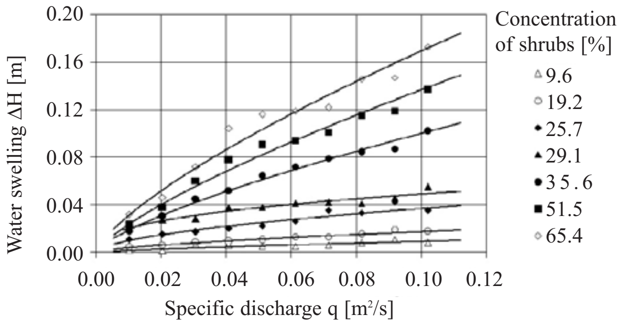

Fig. 3. Water swelling vs. specific discharge from the vertically placed deciduous branches (Fig. 1a).

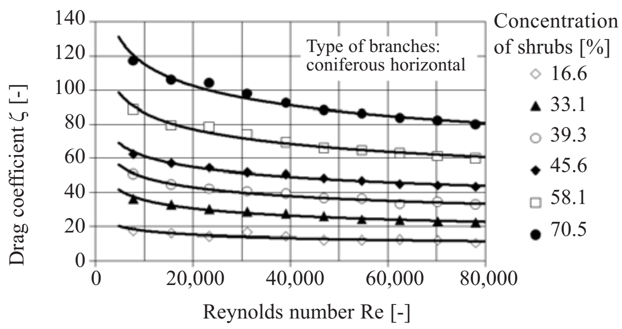

Fig. 4. Drag coefficient vs. spatial concentration of the shrubs as it relates to the Reynolds number.

Table 1. Effect of density and of shrub zone length on discharge reduction.

Type of shrub obstruction	Spatial orientation	Length	Density	Threshold density	Discharge reduction
Deciduous	Vertical	L = 1/3 m	10-85%	60%	4-50%
Deciduous	Vertical	L = 2/3 m	20-75%	60%	8-52%
Deciduous	Vertical	L = 3/3 m	20-75%	60%	12-60%
Deciduous	Horizontal	L = 1/3 m	25-55%	50%	21-69%
Coniferous	Vertical	L = 1/3 m	30-70%	60%	5-32%
Coniferous	Vertical	L = 3/3 m	30-60%	60%	10-41%
Coniferous	Horizontal	L = 1/3 m	15-70%	65%	10-51%

which is shown in Table 1. Initially the local drag coefficient changes with flow rate (or the Froude`s number or the Reynolds's number). However, eventually it mainly depends on the density of shrubs (Fig. 4).

Fig. 4 shows a comparison between the values of drag coefficients ζ either measured or calculated from the formulae (6-8). Although the analysis produced high correlation coefficients (R>0.99), the hydraulic study results obtained for the case of very dense shrubs cannot be generalized (to a more satisfactory degree) together with those obtained for the case of medium or low concentrations ρ.

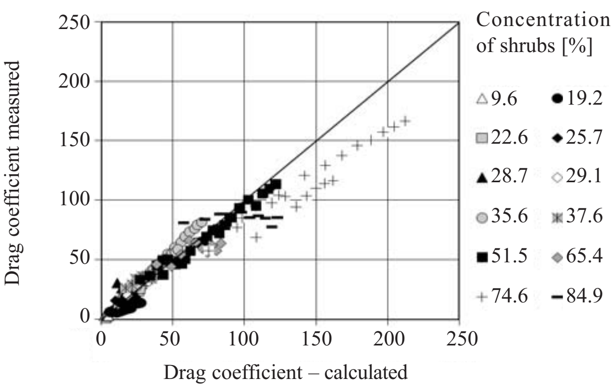

Fig. 5. Measured vs. calculated (by formula 6) local drag coefficients.

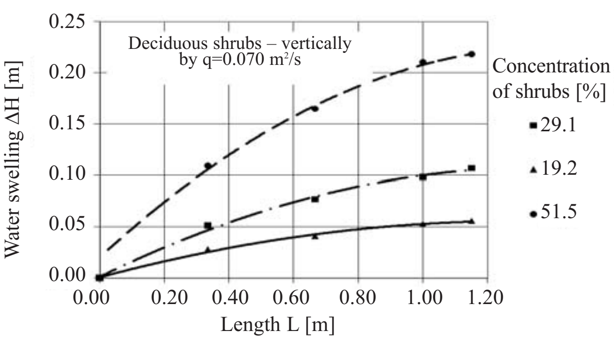

Fig. 6. Water swelling vs. shrub zone length and density of shrubs.

It is noticeable that the results were relatively good for shrubs with density below a certain threshold value ρ_G, determined for a particular type of shrub (approximately 60%). This threshold concentration value establishes the scope of applicability of all the formulae (5-12). For each type of shrub obstruction a threshold value of the spatial concentration ρ_R was determined (Table 1).

Length of Shrub Zone

Hydraulic impact of the length of the shrub zone can be analyzed using the example of an obstruction made up of vertically placed deciduous shrubs (Fig. 1a). The vegetative rise and the drag coefficient grow proportionally to the increase in the shrub zone length in the flow direction.

Nonetheless, both the single variable partial functions (eq. 3) as well as the general formulas of several variables (eqs. 5-8) do not show any linear dependence. When adding a second shrub zone to the initial zone, the water level rose only slightly and there is not a linear relationship to water swelling (Fig. 6). Table 2 presents the sample results of effects of shrub zone length on water swelling for three selected types of shrub obstruction of different densities.

Spatial Orientation of Branches

Fig. 7 shows the swelling function $\Delta H = f(q)$ for the two types of branches and two types of various spatial orientations. For comparable density of shrubs the hydraulic influence of horizontal branches (curves c and d) was considerably greater (up to 40% for q = 0.10 m²/s). Vertical branches, both deciduous and coniferous (curves *a* and *b*), were characterized with hydraulically smaller rises and smaller drag coefficient values.

Also, the variability of the local drag coefficient from the shrubs depends on the spatial orientation of the branches (Fig. 8). For the vertically fixed shrubs the value of this coefficient decreases with the increase of the Froude number and eventually stabilizes. For horizontally fixed shrubs an opposite trend is observed, which means that the local drag coefficient becomes greater with an increase of the Froude number.

Table 2. Results of measurements of the relationships ΔH = f(L).

Type of shrub obstruction			Length of shrub zone					
			L = 1/3 m		L = 2/3 m		L = 1 m	
Density of shrubs	Specific discharge	Depth downstream	Depth upstream (H_g) and water swelling (ΔH) [m]					
ρ [%]	q [m²/s]	H_d [m]	H_g	ΔH	H_g	ΔH	H_g	ΔH
Shrubs No. 1			$\Delta H = 0.0392\ L^{0.6}$ [m]					
20	0.050	0.274	0.294	0.020	0.305	0.031	0.313	0.039
Shrubs No. 2			$\Delta H = 0.0849\ L^{0.6}$ [m]					
30	0.060	0.311	0.355	0.044	0.378	0.067	0.396	0.085
Shrubs No. 3			$\Delta H = 0.2099\ L^{0.6}$ [m]					
50	0.070	0.347	0.456	0.109	0.512	0.165	0.557	0.210

Type of Branches

Laboratory experiments reveal that the type of branches (shape of leaves) in the shrubbery obstruction influences the flow conditions. This is illustrated in Fig. 7 for four different types of shrub obstructions with comparable spatial concentration (density). Deciduous shrubs demonstrate greater drag to the stream and produce a higher rise of the water level than the coniferous shrubs with comparable density and length in the direction of flow and a similar branch pattern. As an example, for shrubs with approximately 35% density and vertically oriented branches, the rise produced by the coniferous shrubs amounts to only 30-35% of that produced by deciduous shrubs.

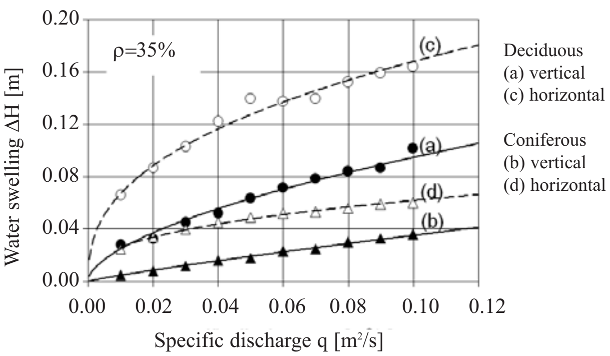

Fig. 7. Water swelling vs. specific discharge for given type and spatial orientation of branches (Fig. 1).

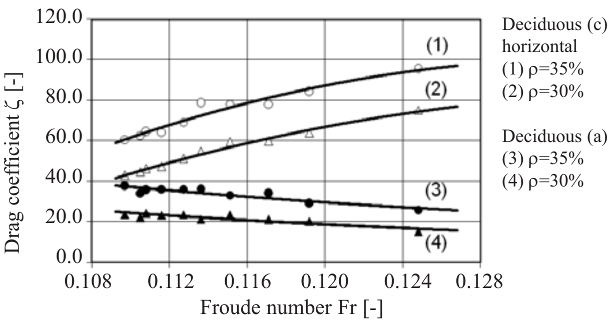

Fig. 8. Drag coefficient vs. Froude number using vertical and horizontal orientation of branches (Fig. 1).

Verification of Results

Laboratory experiments by the author correspond with those carried out in Holland by Klaassen and van der Zwaard [1, 10], which were concerned, among others, with the conditions of flow through flooded areas of the Maas river. There was just one type of hedge on the floodplain of the Maas (the Hawthorn shrub), which was used as a means of partitioning plots of agricultural land. The shrubs (max. 3 m in height) mostly consisted of vertically deciduous branches. During the flood, shrubs were capturing "organic rubbish" that was generated by the surging river Maas, which increased the density over time. As the shrubs became more dense with flood rubbish, the water swelling also increased over the top of the obstruction. The density before the increase was estimated by the author to not be greater than 10% (see plots 1 and 3 in Fig. 9). Klaassen and van der Zwaard conducted experiments in hydraulic research of the Hawthorn shrubs in real world and laboratory settings. The laboratory experiment used a full-sized shrub (1:1). A detailed description of the investigation is given in the paper [10]. The shrubs on the floodplain of the Maas were hydraulically characterized

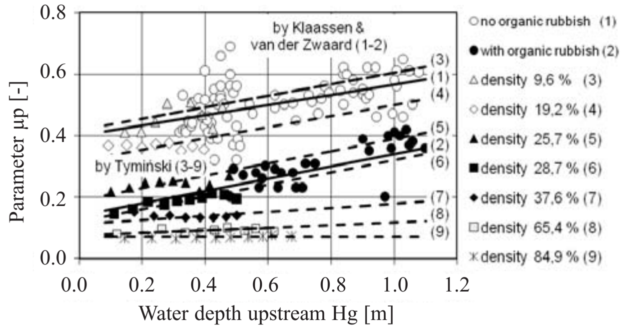

Fig. 9. Results of author's experiments compared to those obtained by Klaassen's team.

by the formula $\mu p = f(H_g)$, in the form of a nomogram (Fig. 9). The parameter µp carries information on the porosity of the obstruction p and the discharge coefficient μ for a given vegetative cluster; H_g is the water depth upstream of the shrubs.

In Fig. 9 curves 1 and 2 are the results by Klaassen and van der Zwaard. These results refer only to the two extreme cases of the density of shrubs, namely the "no organic rubbish" and the "with organic rubbish" case.

Results of our own laboratory measurements have been recalculated using the method of Klaassen and van der Zwaard [10] and put on their nomogram. In Fig. 9 these are plots 3 through 9.

A very good "laboratory-nature" correlation has been obtained. The research by the author confirms the trends observed by Klaassen and van der Zwaard, and complements and expands the hydraulic characteristics of shrubs presented by the researchers from Holland both in qualitative and quantitative terms.

Conclusions

1. The presence of shrubs has significant influence on the reduction of flow capacity of a channel. Dense, deciduous, vertical obstructions can reduce the flow capacity by approximately 50%, whereas the horizontal ones, with comparable density – by even up to approximately 70%. Vertical obstructions lead to a significantly smaller rise than the horizontal ones with a similar concentration and branch type. For comparable density of shrub mass in obstruction volume, and identical spatial orientation of branches, deciduous branches produce greater flow drag and higher rise in water level than coniferous branches.
2. The parameter that determines the flow resistance and the swelling of the water in front of a shrub obstruction is its spatial concentration (density). An increase in the obstruction's density results in an increase in drag and water swelling. In most cases this is a square or power relationship with an exponent greater than 1. For each type of shrub obstruction a threshold value of the spatial concentration of shrub branches exist, which, when exceeded, changes the phenomenon's character. The flow of water through very dense shrubs should be, it seems, analyzed as filtration through a porous medium.
3. Next to the density of the shrubs, the longitudinal dimension of the shrub obstruction must be seen as one of the dominant parameters. The modification in length of the shrub zone implies the change of flow resistance, causing an increase in water level ahead of new obstructions. However, it is important to emphasize that the relationship is not linear, the increase of flow resistance and the rise of the water level is not proportional to the lengthening of the shrub zone, which means a power relationship with an exponent less than 1.

Acknowledgements

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