sustainability

MDPI

Article

Verification of Methods for Determining Flow Resistance Coefficients for Floodplains with Flexible Vegetation

Tomasz Tymiński [1,*], Tomasz Kałuża [2] and Mateusz Hämmerling [2]

[1] Institute of Environmental Engineering, Wrocław University of Environmental and Life Sciences, pl. Grunwaldzki 24, 50-363 Wrocław, Poland
[2] Department of Hydraulic and Sanitary Engineering, Poznan University of Life Sciences, 60-637 Poznan, Poland
* Correspondence: tomasz.tyminski@upwr.edu.pl

Abstract: In terms of the hydraulic effect of plant flexibility, of particular note is the calculation formula that was proposed by Kouwen, which combines the roughness of the riverbed with the plant community parameter *MEJ* (including the modulus of elasticity). Kouwen's method was developed on the basis of laboratory experiments with low vegetation (grasses). According to the authors of this work, the method can also be used to evaluate the resistance of medium vegetation (shrubs) deforming under the influence of water flow. The main objective of the presented research was to verify the application of Kouwen's method in order to calculate the flow resistance coefficient λ for quasi-regular formed plant obstructions (e.g., basket willow plantations). In a water laboratory, a comprehensive study of the biomechanical and hydraulic properties was carried out for flexible shrubs in floodplains. The results of the hydraulic measurements were compared with the results of the calculations that were made by four various methods using the Chezy-Manning, Garbrecht/Pasche, Lindner/Kaiser, and Kouwen formulas. For all of the flows through the vegetated zone that was tested, the best results were obtained when using the Kouwen calculation procedure and the worst were found for the Lindner formula, which did not include information on the plant flexibility.

Keywords: rivers; floodplains with plants; vegetation stiffness; flow resistance; drag coefficients

check for updates

Citation: Tymiński, T.; Kałuża, T.; Hämmerling, M. Verification of Methods for Determining Flow Resistance Coefficients for Floodplains with Flexible Vegetation. *Sustainability* **2022**, *14*, 16170. https://doi.org/10.3390/su142316170

Academic Editor: Ozgur Kisi

Received: 31 October 2022
Accepted: 1 December 2022
Published: 3 December 2022

1. Introduction

The quality of a hydrodynamic model that is used to analyze the transformations of a flood wave or for flood risk management may be affected by various parameters, such as the roughness coefficients included in a mathematical description of the flow, which is frequently assumed to be a priori based on respective tables [1,2]. It also plays an important role in the parametrization of the model, the calibration, the optimization, and the quantification of uncertainty [3,4]. Hydrodynamic models should consider not only the spatial variability of the parameters, but also their variability in time resulting from the river channel development [5,6]. For this reason, the provision of the most accurate description of the factors influencing flow resistance needs to be attempted. One of the most important factors shaping flood flow conditions in river valleys is the vegetation, especially the trees and shrubs growing on river banks and floodplains [7–9]. In the case of shrubs, flow disturbance depends mainly on the geometrical and biomechanical characteristics of the plants [10–22], among which the stiffness of the stems, branches, or trunks undoubtedly plays an important role. Its measure can be, for example, the elastic modulus of the plants [7,15–17,22,23]. It should be noted, however, that in the case of an area in a channel that is obstructed by plants, it is not about the flow of a single element, but about the flow of the stream through a whole set (community) of such elements that are appropriately distributed in the cross-section. Adjacent plants interact hydraulically with each other. The stiffness of the entire plant community is also different compared to that of a single stem [9,24–32].

The problem of the hydraulic influence of plants has been addressed by numerous scientific institutions worldwide for many years, and the results and reports of such studies can be found in the literature, such as in publications [7,9–14,18–20,22–45].

In 1985, Bretschneider and Schulz published a paper [46] on the application of computational formulas in order to determine the capacity of overgrown channels. In this paper, they presented a division of vegetation into low, medium, and tall (Figure 1). Low vegetation is vegetation whose height is much lower ($h_p << h$) than the flow depth (e.g., grasses). Medium vegetation has a height that is comparable ($h_p = h$) to the water depth (e.g., shrubs), while the height of tall vegetation always exceeds ($h_p > h$) the flow depth (e.g., trees).

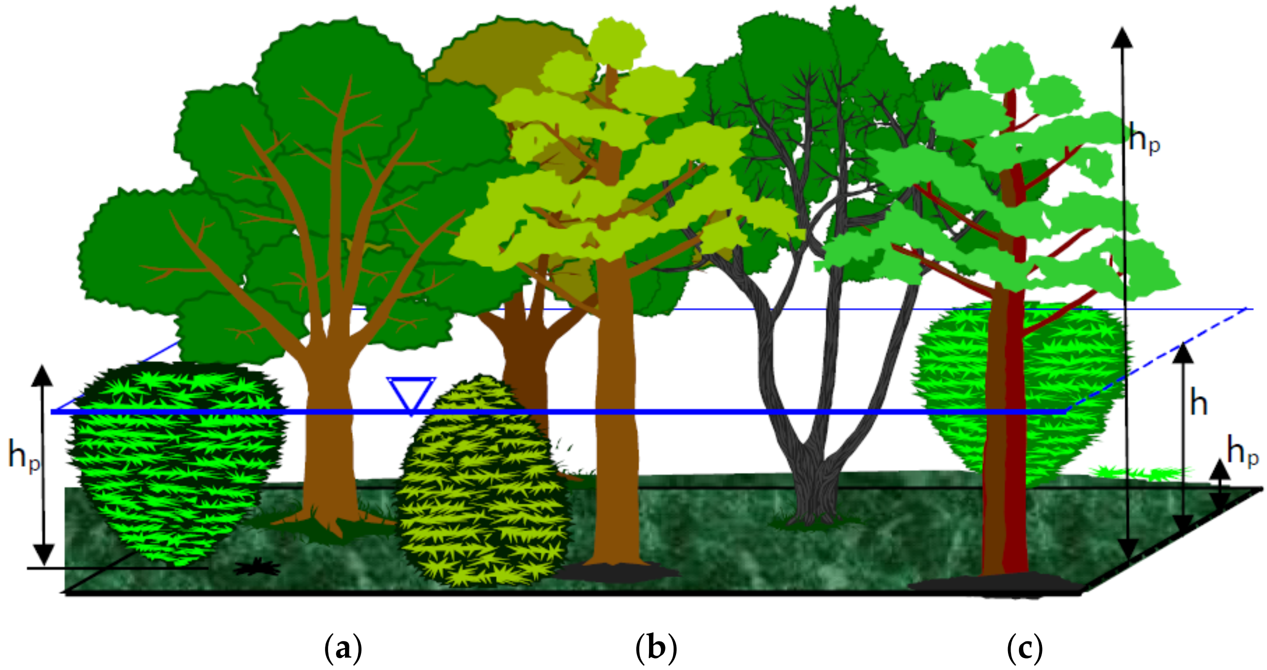

Figure 1. Bretschneider's division of plants: (**a**) medium ($h_p = h$; e.g., shrubs), (**b**) low ($h_p << h$; e.g., grasses), (**c**) tall ($h_p > h$; e.g., trees).

Studies of shrubs—whether in nature or on models in a laboratory—are difficult to carry out and do not guarantee the obtainment of the general characteristics. The high variability in this type of vegetation would suggest the use of statistical methods in the computational methods. In engineering applications, this can be cumbersome. New ways of incorporating the effects of shrub flexibility on flow are constantly being sought, opting for multiple simplifications. In the existing calculation methods, one specific plant state is assumed. This state is appropriately characterized, for example, by the means of the vegetation cluster parameters that are included in the flow calculation formulas. However, medium-height vegetation in particular has a variable amount of leaves, branches, and geometry over time (e.g., depending on the season). The hydraulics of such vegetation obstructions change over time, as the density and the size of the vegetation changes, since shrubs increase in volume when they are growing.

The lack of such general characteristics for plants on floodplains has already been pointed out in publications by Petryk and Bosmajian [34], Kaiser [29], and especially by Dalton et al. [36] and Klaassen's research team in the Netherlands [37,38]. The latter, admittedly, attempted to take into account the variable density of hedgerows, but their study only dealt with the following two extreme cases: "hedges obstructed by hay" and "hedges not obstructed by hay", which should only be regarded as an attempt to recognize the problem; the essence of their method being to treat the clusters of bush vegetation as plant obstacles where local energy loss occurs and to assign to them hydraulically characterized plant obstacles and dimensionless local loss coefficients ζ.

The procedures for hydraulic calculations [25,26,29,30], which are popular not only in Germany, but also elsewhere, have been established primarily for tall vegetation, as it is easier to describe. Such procedures are usually simulated by regularly spaced stakes (cylinders) in the laboratory channel. Their essential hydraulic parameter is the coefficient of frictional resistance λ. Much emphasis in these methods is placed on the phenomenon of stream interaction in adjacent parts of the flow cross-section [28,30–32,35]. These methods are also used in the case of medium vegetation, with some modifications in order to take into account the specificity of the shrubs, e.g., [29,30]. This approach to the problem means that, for shrubs, the methods of Pasche [27,28], Mertens [35], and Rickert [31] are often limited by the range of applicability or give slightly underestimated values for the resistance coefficients λ [9].

There are only a few research reports for the roughness coefficients of shrubs in the subject literature. In macro-structural methods, the plant communities with different concentrations can be determined from the mean or the extreme values of coefficient n, which is given in tables. However, this requires some experience and is not without the charge of subjectivity. An example of such utility tables, which was based on V.T. Chow [47], was included in the work by Franzini et al. [48], among others.

Water flow involving both rigid and elastic vegetation is a highly complicated process [49]. Any mathematical description of this phenomenon requires different methods, including vegetation parameters (trunk diameter, trunk spacing, modulus of elasticity) [50,51]. This also has an impact on many factors that are related to the morphology of the floodplains, the slopes, and the relief, as well as the following vegetation-related hydraulic properties: the vegetation type, the size of the plants, the plant growth, the water depth, and the flow velocity etc., [5,52–54]. Many of those factors are temporary or local in character [55]. They may change in space and time. Additionally, they may change cyclically in time (e.g., plant growth stages) or continuously during the growth period [56]. This variability may also be natural [19], caused by climate change (e.g., due to water temperature), or result from anthropopressure.

In analyzing the literature on the subject, it can be observed that low vegetation (e.g., [9,22,23,42,45]) and tall vegetation (e.g., [18,26–31,34]) are well described, whereas there is relatively less information concerning studies of the flow through communities of flexible bushy vegetation and, above all, quantitative and qualitative hydraulic characteristics of medium vegetation containing a parameter describing the plant flexibility. Taking into account the hydraulic effects of this vegetation is important, for example, when calculating the flow resistance, the capacity of the river channel, and the local damming of the water level upstream of the vegetation zone. In engineering practice, vegetation is characterized by hydraulic parameters in commonly used calculation formulas, which are presented in detail in the next chapter of this paper.

2. Hydraulic Calculation Formulas

The effect of flexible rush and shrub vegetation on river banks and floodplains (Figure 2) on the flow conditions depends not only on the geometry and the density of the plant structure, but also on the biomechanical properties (e.g., modulus of elasticity) [1,7,10–16]. In the hydraulic calculation for steady flow in open channels using the popular Chezy-Manning Formula (1), the "plant flow resistances" are taken into account by assigning them the subjectively chosen roughness coefficients "n" as follows:

$$Q = v \cdot F = \frac{F}{n} \cdot R_h^{2/3} \cdot \sqrt{I_E} \tag{1}$$

where Q—flow [m^3/s], v—flow velocity [m/s], F—flow area [m^2], n—Manning roughness coefficient [$m^{-1/3} \cdot s$], R_h—hydraulic radius [m], and I_E—energy line slope [-].

Figure 2. Flexible plants on river banks and floodplains. (**a**) Flood on the Vistula River (**b**) The Biała Ladecka River [7].

The calculation methods for estimating the flow resistance and the discharge capacity of overgrown channels may also be based on the so-called general flow law (which is given below as the Darcy–Weisbach Equation (2)) $v = f(\lambda, R_h, I_E)$, where: v—flow velocity [m/s], g—earth acceleration [m/s^2], R_h—hydraulic radius [m], I_E—energy line slope [-], and λ—dimensionless resistance coefficient (friction factor) [-] as follows:

$$Q = v \cdot F \; where \; v = \frac{1}{\sqrt{\lambda}} \cdot \sqrt{8 \cdot g \cdot R_h \cdot I_E} \tag{2}$$

and modifications of the Colebrook–White Equation (3) for open channels [25] are as follows:

$$\frac{1}{\sqrt{\lambda}} = -2.03 \cdot \log\left(\frac{2.51}{Re \cdot \sqrt{\lambda}} + \frac{k_s}{14.84 \cdot R_h}\right) \tag{3}$$

e.g., the simplified Equation (4) of Powell [39] (after Pasche [27,28]):

$$\frac{1}{\sqrt{\lambda}} = -2 \cdot \log\left(\frac{k_s}{14.84 \cdot R_h}\right) \tag{4}$$

where k_s—equivalent roughness [m] and Re—Reynolds number [-], or more generally after Kouwen [10–14,40] (5):

$$\frac{1}{\sqrt{\lambda}} = a + b \cdot \log\left(\frac{R_h}{k_s}\right) \tag{5}$$

where a, b—empirical parameters [-].

In the shrub-covered river floodplain, the total flow resistance is exposed as follows:

1. The friction resistance on the surface of the bottom and the banks of the channel—λ_b (λ_0);
2. The flow resistance of the plants (shape resistance)—λ_R

The total flow resistance coefficient λ is then calculated according to Formula (6):

$$\lambda = \lambda_b + \lambda_R \tag{6}$$

The Kouwen Formula

The calculation Formulae (3)–(5), which are shown above, include the dependence of the resistance coefficient λ (friction factor), among others on k_s—the equivalent roughness of the riverbed. Taking into account the influence of plant flexibility on the flow conditions, special consideration should be given to the studies and the calculation formula of Kouwen [10–14]. Based on the measurements of the flow resistance over flexible plastic cylinders, he expressed k_s—equivalent (absolute) roughness as a function of the shear stress that was induced by flow. The Kouwen analyses that were based on studies of low height artificial vegetation were tested under flow conditions in channels with natural vegetation (grass). This effect was the dependency $k_s = f(h_p, R_h, I_E, MEJ)$ with the following equation:

$$k_s = 0.14 \cdot h_p \cdot \left(\frac{\left(\frac{M \cdot E \cdot J}{\rho \cdot g \cdot R_h \cdot I_E} \right)^{0.25}}{h_p} \right)^{1.59} \tag{7}$$

which combines the roughness of the channel k_s [m] with the plant height h_p [m], the hydraulic radius R_h [m], the slope of the energy line I_E (or I) [-], and, above all, the plant parameter MEJ [Nm^2] (where: M—relative planting density [-] and EJ refers to the "rigidity" (flexibility) of a plant community. The moment of inertia of the cross-section J [m^4] depends on the geometry of the plants, and the modulus of elasticity E [Pa] is a characteristic that specifies their elastic properties).

The Kouwen method was developed on the basis of laboratory studies using low-height vegetation (grass) and plastic elements. According to Tymiński and Kałuża [7,15], this method can also be used in order to determine the flow resistance of medium-height vegetation (rush and shrubs) that is deformed by the water flow. This paper assesses this problem.

3. Materials and Methods

3.1. Modelling Research

The correct determination of the flow resistance coefficient has a significant impact on the results of the calculation of the discharge capacity of overgrown channels and is a prerequisite for the development of a reliable mathematical flow model. Which calculation method should be selected: the method of Chezy-Manning [47,57,58], Garbrecht/Pasche [25,42], Lindner/Kaiser [25,26,29], or Kouwen [10–14]? The answer to this question was the main objective of the presented research. The laboratory test aimed to verify the applicability of the Kouwen method for shrubs, in particular by calculating drag coefficient λ for quasi-regular formed plant obstructions, e.g., basket willow plantations (Figure 2). Within the framework of the research grant, comprehensive investigations of the biomechanical (MEJ) and hydraulic properties of flexible plants growing on a river floodplain were carried out in the water laboratory. Laboratory experiments were required for such a vegetation type. The modulus of elasticity and MEJ had to be determined for basket willows, in view of the insufficient literature data. Vegetation with established elastic properties was tested hydraulically in an experimental channel because experimental data were used as empirical reference data to assess and verify the analyzed computational formulas. A detailed description of the studies and results can be found in the publications of Tymiński and Kałuża [7,15]. The hydraulic and biomechanical test stand is shown in Figures 3 and 4.

3.1.1. Research Stand

The research model (Figure 3) was a rectilinear symmetrical flume with a tripartite cross-section. The length of the flume was 13 m, the total width of the cross-section was B = 2.10 m, with a slope gradient of 1:1, and the width of each floodplain b = 0.60 m. The maximum flow depth in the flume was H = 0.30 m. The longitudinal slope of the bottom of the main flume and floodplains was constantly at 0.0003. A weir was built at the outlet of the flume to regulate the water level.

The hydraulic experiments that were carried out in the lab consisted in the measurements of depth and flow velocity for a given flow rate q. The water depth measurements upstream and downstream of the plant zone on the floodplain were carried out using piezometers installed along the study flume, additionally controlling the measurement with water gauge needles. A circular measuring overflow (D = 379 mm) at the inlet to the flume and a measuring tank in the basement of the building were used for flow rate measurements (Figure 4). The multidirectional measurements of the local velocity were carried out by means of a programmable electromagnetic probe PEMS-E30 (with an accuracy of ±0.001 m/s). Each series of measurements was repeated, and the results were averaged.

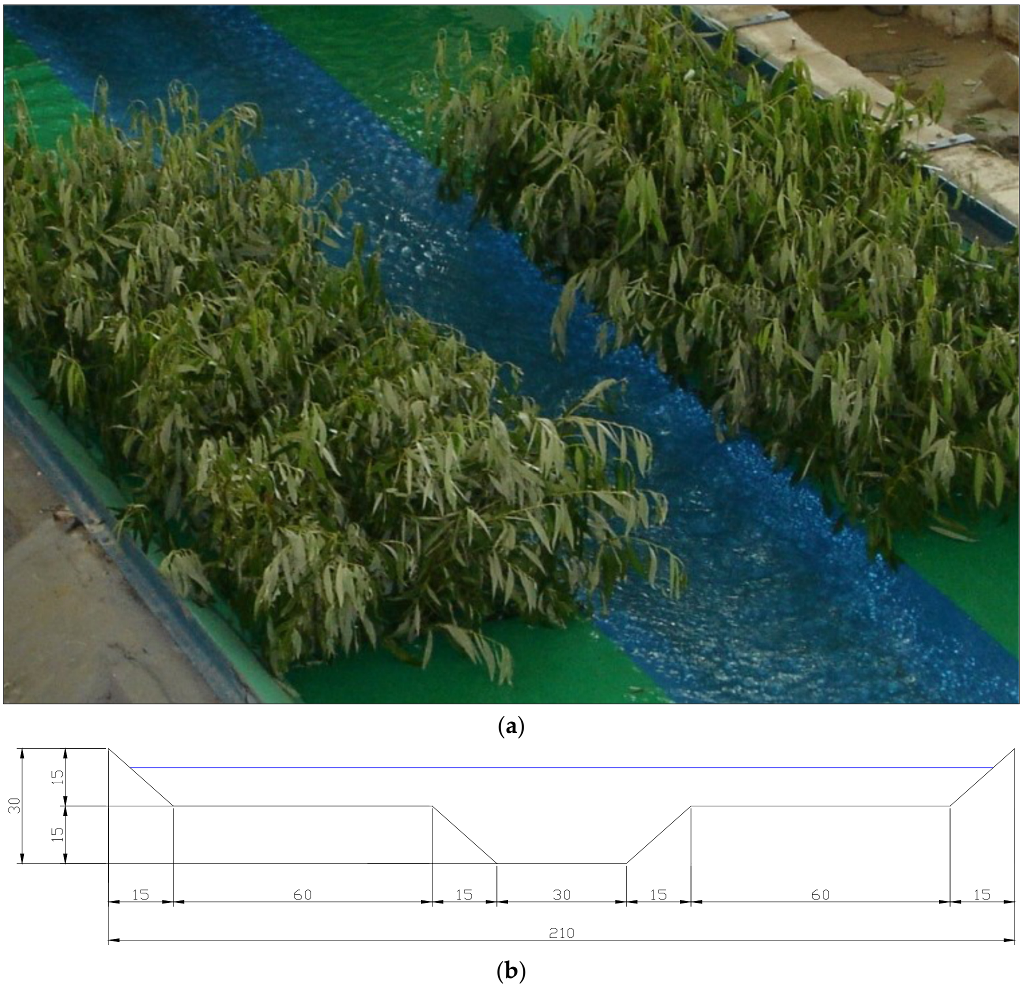

Figure 3. Research stand in water laboratory. (**a**) Plant zones in the laboratory flume. (**b**) Scheme of the laboratory flume cross-section.

In the planned experiment, due to the feasibility of the specific testing conditions, only the variants in which the plant height was approximately equivalent to the channel depth were tested. In order to obtain variants with tall- and low-height vegetation, complete submergence of vegetation ($h >> h_p$) would be required to obtain the effect of low vegetation or very shallow channel filling would be needed to simulate the role of tall vegetation. Nevertheless, this was not the subject of this study, which instead focused on the elastic effect of medium-height vegetation.

3.1.2. Hydraulic Parameters in the Plant Zone

In addition to measuring the total flow q_{total} for the entire flow cross-section (Figure 4: circular measuring weir), the flow value q_K was also determined in the central part of the flume, where there were no plants (Figure 3). In this case, the point velocity was measured with the PEMS probe. The measuring verticals were located every 5 cm. In each vertical there were 4–6 measuring points between the bottom of the flume and the water surface. In total, the local velocity was measured at 72 points in 13 verticals. The discharge q_K was calculated using the graphical Harlacher method, according to [59]. The value of flow through the plant zones on the left and right floodplains was calculated as the difference between the total flow and the flow in the part of the channel without plants ($2q_R = q_{total} - q_K$).

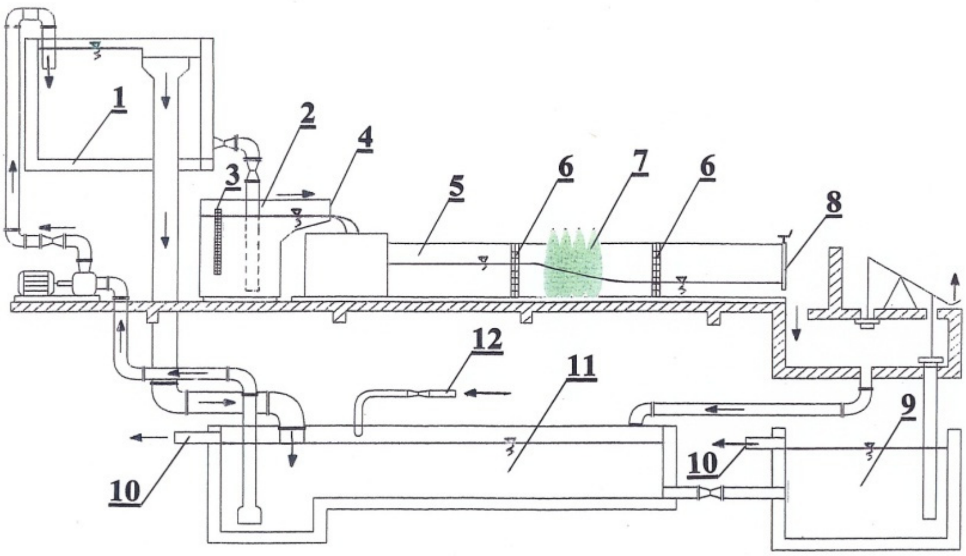

Figure 4. Schematic view of the measurement set-up (1—higher tank, 2—measuring tank, 3—gauge, 4—circular measuring weir, 5—flume, 6—piezometers, 7—shrubs, 8—weir, 9—measuring tank, 10—to sewers, 11—main tank, and 12—supply pipeline).

The methods used to calculate the drag coefficients were verified for 3 different flow rates q_R in the plant zone in the left floodplain (Figure 3; Table 1). As an example, detailed calculations are presented below for only one selected specific flow rate q_R = 0.0095 $m^3/(s{\cdot}m)$.

Table 1. Summary of flume conditions to verify laboratory tests.

Hydraulic Parameters				
q_R	$m^3/(s{\cdot}m)$	0.0072	0.0095	0.0105
$h = f(q)$	m	0.072	0.092	0.099
$F = f(q)$	m^2	0.0460	0.0594	0.0650
$R_h = f(q)$	m	0.0655	0.0765	0.0878
I_E	-	0.0003	0.0003	0.0003
n_b	$m^{-1/3}{\cdot}s$	0.012	0.012	0.012
n_{total}	$m^{-1/3}{\cdot}s$	0.050	0.050	0.050

All required values for the hydraulic parameters are given in Table 1, where: $h = f(q)$—water depth, $F = f(q)$—flow area, $R_h = f(q)$—hydraulic radius, n_b—roughness coefficient of the bottom and banks of the channel, $n = 1/k_{St}$—replacement roughness coefficient for channel and vegetation (k_{St}—Strickler coefficient), and I_E—slope.

3.1.3. Parameters of the Vegetation Zone

The vegetation cover zone (Figure 3) was formed over a length of 2.0 m and width of 0.6 m by natural willow branches with a diameter of 5 mm, spacing $a_x = a_y = 0.05$ m (“chessboard”), and stem height of 0.30 m. The form drag coefficient of 1.1 is taken from the literature [25,32]. The planting density was 239 stems/m^2 (M), and the representative modulus of elasticity was 3139 MPa. The flexibility of the vegetation zone was described with parameter MEJ = 23.0 Nm^2 [7,15].

4. Results

Based on the results of the laboratory measurements, the flow resistance coefficient λ was calculated. For the flume and vegetation zone conditions that are described in Section 3.1, the Chezy-Manning, Garbrecht/Pasche, Lindner/Kaiser, and Kouwen methods were used. Example calculations are provided below, and a summary of the calculation results is shown in table in Section 4.4.

4.1. The Method of Garbrecht/Pasche (GP)

According to Garbrecht [42], the Strickler coefficient k_{St} [$m^{1/3} \cdot s^{-1}$] can be calculated from Formula (8):

$$k_{St} = \frac{1}{n} = \frac{26}{k_s^{1/6}} \tag{8}$$

Hence, the equivalent roughness k_s [m] is as follows:

$$k_s = (26 \cdot n)^6 \tag{9}$$

Formula (9) makes it possible to determine the equivalent roughness k_s, knowing the Manning coefficient n, and thus to use a calculation procedure for the flow conditions based on friction coefficient λ (Equations (4)–(6)) as follows:

$$\frac{1}{\sqrt{\lambda}} = 2 \cdot \log\left(\frac{14.84 \cdot R_h}{(26/k_{St})^6}\right) \leftarrow k_{St} = \frac{1}{n} \tag{10}$$

$$\frac{1}{\sqrt{\lambda}} = 2 \cdot \log\left(\frac{14.84 \cdot 0.0765}{(26/20)^6}\right) \rightarrow \lambda = 0.633$$

4.2. The Method of Chezy-Manning (CM)—Using Equation (1)

By comparing Formulas (1) and (2), we can apply the Manning coefficient of roughness n that is used in the Chezy-Manning method in order to determine friction coefficient λ as follows:

$$\frac{1}{n} \cdot R_h^{2/3} \cdot \sqrt{I_E} = \frac{1}{\sqrt{\lambda}} \cdot \sqrt{8 \cdot g \cdot R_h \cdot I_E} \tag{11}$$

$$\frac{1}{\sqrt{\lambda}} = \frac{R_h^{1/6}}{n \cdot \sqrt{8g}} = \frac{0.0765^{1/6}}{0.050 \cdot \sqrt{8 \cdot 9.81}} \rightarrow \lambda = 0.463$$

4.3. The Method of Lindner/Kaiser (LK)

This method (Equations (12)–(14)) has been described in detail in publications [25,26,29–32]. It is popular and widely used in Europe, especially in Germany. The following points are the main steps of this calculation procedure:

(a) The relative flow round the velocity (v_i/v_R):

$$\left(\frac{v_i}{v_R}\right)^2 = 0.6 + 0.5 \cdot \log\left(\frac{a_x}{a_y}\right) = 0.6 + 0.5 \cdot \log\left(\frac{0.05}{0.05}\right) = 0.6 \tag{12}$$

where a_x and a_y—plant spacing (x—along and y—across the flow direction) [m].

(b) The drag coefficient of the plant community c_{WR} ($c_{W\infty}$ = 1.1 according to [25,31,32]):

$$c_{WR} = c_{W\infty} \cdot \left(1 + 1.9 \cdot c_{W\infty} \cdot \frac{d_p}{a_y}\right) \cdot \left(\frac{v_i}{v_R}\right)^2 + 2 \cdot \left[\frac{1}{1 - \frac{d_p}{a_y}} - 1\right] \tag{13}$$

$$c_{WR} = 1.1 \cdot \left(1 + 1.9 \cdot 1.1 \cdot \frac{0.005}{0.05}\right) \cdot 0.6 + 2 \cdot \left[\frac{1}{1 - \frac{0.005}{0.05}} - 1\right] = 1.02$$

(c) The drag coefficient of the vegetation zone (friction factor):

$$\lambda_R = 4 \cdot c_{WR} \cdot \omega \cdot R_h = 4 \cdot c_{WR} \frac{d_p}{a_x \cdot a_y} \cdot R_h \tag{14}$$

$$\lambda_R = 4 \cdot 1.02 \cdot \frac{0.005}{0.05 \cdot 0.05} \cdot 0.0765 = 0.623$$

4.4. The Method of Kouwen (K)—Using Equation (7)

The equivalent roughness k_s of the vegetation that was studied here was calculated using Formula (7). The so-called dynamic velocity v^* [m/s] is determined by applying Equation (15), and the dynamic critical velocity v_k [m/s] (i.e., the minimum velocity of the stream, at which the plants bend) is derived from the Kouwen empirical Formula (16) as follows:

$$v^* = \sqrt{g \cdot R_h \cdot I_E} = \sqrt{9.81 \cdot 0.0765 \cdot 0.0003} = 0.015 \tag{15}$$

$$v_k = \min.\begin{cases} 0.028 + 6.33 \cdot (MEJ)^2 \\ 0.23 \cdot (MEJ)^{0.106} \end{cases} = \min.\begin{cases} 0.028 + 6.33 \cdot (23.0)^2 \\ 0.23 \cdot (23.0)^{0.106} \end{cases} = 0.321 \tag{16}$$

The parameter $\Omega = v^*/v_k = 0.015/0.321 = 0.047 < 1.0$, hence, in Equation (5): $a = 0.15$ and $b = 1.85$ (selected based on Table 2).

Table 2. Empirical coefficients a and b for Equation (5) (after [40]).

$\Omega = (v^*/v_k)$	Parameter	
	a	b
$\Omega < 1.0$	0.15	1.85
$1.0 < \Omega < 1.5$	0.20	2.70
$1.5 < \Omega < 2.5$	0.28	3.08
$2.5 < \Omega$	0.29	3.50

Table 3 shows a comparison between the values of the drag coefficients and the specific discharge that were either measured or calculated from the Formulae (1), (2), (5)–(7), and/or (10)–(14).

Table 3. Results of the study.

Method of Calculation	Hydraulic Parameter										
	$q = 0.0072$ m^3/(s·m)			$q = 0.0095$ m^3/(s·m)			$q = 0.0105$ m^3/(s·m)			Relative Error	Remarks
	Drag Coefficient (Plants)	Drag Coefficient (Total)	Specific Discharge	Drag Coefficient (Plants)	Drag Coefficient (Total)	Specific Discharge	Drag Coefficient (Plants)	Drag Coefficient (Total)	Specific Discharge		
	λ_R	λ	$q \cdot 100$	λ_R	λ	$q \cdot 100$	λ_R	λ	$q \cdot 100$	$\delta q/q$	$\lambda_b = 0.026$
	-	-	m^3/(sm)	-	-	m^3/(sm)	-	-	m^3/(sm)	%	
Lindner/Kaiser	0.534	0.560	0.40	0.623	0.649	0.52	0.716	0.742	0.58	~40	$c_w = 1.1$
Garbrecht/Pasche	-	0.516	0.42	-	0.633	0.53	-	0.773	0.57	~40	$n = 0.050$
Chezy-Manning	-	0.486	0.43	-	0.463	0.62	-	0.441	0.75	~30	$n = 0.050$
Kouwen	0.153	0.179	0.70	0.176	0.202	0.93	0.201	0.227	0.103	~2%	$MEJ = 23.0$
Measured	-	0.176	0.72	-	0.196	0.95	-	0.220	0.105	0	-

5. Discussion and Conclusions

The main criterion when evaluating the accuracy of each calculation method that was tested (*GP*, *CM*, *LK*, and *K*) consisted in a comparison of the measured value of the flow through the plant zone in the floodplain (q_R) with the value of flow obtained from the calculations (Table 3).

In the case that was studied here, the value of flow was determined primarily by the flow velocity ($Q = v \cdot F$), which in turn depends highly significantly on the flow resistance, which is characterized in hydraulic calculations by the roughness coefficients. For the water laboratory measurement, the coefficient of friction λ was determined by regression calculus.

By analyzing the test results in Table 3, it was therefore possible to compare not only the flow values, but also the values of the resistance coefficients.

Hence, it is clear that for all of the flows through the vegetated zone q_R that were tested, the best results were obtained when using the Kouwen calculation procedure and the worst results were obtained for the Lindner/Kaiser formula (*LK*). For example, for the flow for q_R = 0.0095 $m^3/(s \cdot m)$, the coefficient of friction that was calculated from the Kouwen formula was $\lambda_{calculated}$ = 0.202, and this was the closest to the value that was obtained from measurements $\lambda_{measured}$ = 0.196. The reason for the poor results for the Lindner/Kaiser method is likely that in practice the parameter c_w for flexible plants takes on values that are much lower than those for rigid cylinders c_w < 1.1.

The publications by Petryk and Bosmajian [34], similarly to those by Klaassen [37,38], also point out the extensive role that the adoption of a suitable value for a plant drag coefficient c_w plays and what discrepancies in its values can occur here. Lindner [26] also indicated this problem for in situ measurements in fields with wheat. The resistance coefficients c_w for wheat are clearly smaller than the value of c_w = 1.0 that were recommended by Petryk and Bosmajian [34].

In contrast, the effectiveness of the Chezy-Manning (Strickler) method depends significantly on the subjective determination of roughness *n*, which requires a certain amount of skill and engineering experience. Of course, also in the case of this method, some modifications are known that improve the result, e.g., the interesting proposal of Indlekofer that was described in [57], which concerns the correction of the Strickler coefficient ($k_{St} = 1/n$) for mixed vegetation, i.e., flexible and rigid.

When comparing the computational methods, it should also be noted that Lindner's formula was derived for simulating rigid cylinder plants and, unlike Kouwen's formula, it does not include information on the flexibility of the community (*MEJ*) or the inclination of the plants under the hydrodynamic pressure of the water flow. Hence, Kouwen's method more accurately reflects the actual flow conditions through the resilient plant zone.

Another, equally important, hydraulic parameter is the energy grade line, which, in laboratory measurements, is frequently replaced by the channel bottom slope. In a study by Kouwen [12], the longitudinal slope of the channel assumed various values (I = 0–0.030), and this parameter was also included in Formula (7). The results of our investigations that are presented in this paper refer to one, constant value of the longitudinal channel slope. Still, laboratory and field tests were also conducted for other values of channel slope [1,44]. Comparable results and conclusions were obtained, which indicates the applicability of the Kouwen method for other slopes.

Unfortunately, Kouwen's procedure has some shortcomings. Among others, there is no experimental characterization of plant deflection velocity (dynamic critical velocity) as a function of the community elasticity (*MEJ*) for individual shrub species. Kouwen developed such relationships only for grasses, while for shrubs they can possibly be used (as in the above paper) in the case of comparable values of the *MEJ* parameter, the h_p heights, the d_p stem diameters (of the shrubs and grasses that Kouwen studied). There is also still limited literature on the modulus of elasticity for typical intercropped plant species (especially shrubs). This implies a need for further research, especially regarding the empirical relationships (11): $v_k = f(MEJ)$.

Taking into account the new ecological perspective on the presence of trees and shrubs in floodplain areas and the requirements that are related to flood protection, it is reasonable to strive to learn as much as possible about the phenomenon of the influence of plants on the flow and to take it into account in engineering practice, especially in hydraulic calculations where flow resistance coefficients play a fundamental role. Efforts should, therefore, be made in order to determine the values of these coefficients in an optimal way at all times, and the Kouwen calculation method that has been presented above is one possible proposal for the calculation of these friction coefficients for flexible plants in floodplains.

Author Contributions: Conceptualization, T.T. and T.K.; methodology, T.T. and T.K.; validation, T.T. and T.K.; formal analysis, T.T. and T.K.; investigation, T.T. and T.K.; resources, T.T., T.K. and M.H.; writing—original draft preparation, T.T., T.K. and M.H.; writing—review and editing, T.T., T.K. and M.H.; visualization, T.T., T.K. and M.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Tymiński, T. Hydraulic Model Investigation of Flow Conditions for Floodplains with Coniferous and Deciduous Shrubs. *Pol. J. Environ. Stud.* **2012**, *21*, 1047–1052.
2. Kałuża, T.; Sojka, M.; Strzeliński, P.; Wróżyński, R. Application of Terrestrial Laser Scanning to Tree Trunk Bark Structure Characteristics Evaluation and Analysis of Their Effect on the Flow Resistance Coefficient. *Water* **2018**, *10*, 753. [CrossRef]
3. Song, X.; Zhang, J.; Zhan, C.; Xuan, Y.; Ye, M.; Xu, C. Global Sensitivity Analysis in Hydrological Modeling: Review of Concepts, Methods, Theoretical Framework, and Applications. *J. Hydrol.* **2015**, *523*, 739–757. [CrossRef]
4. Castaings, W.; Dartus, D.; Le Dimet, F.-X.; Saulnier, G.-M. Sensitivity Analysis and Parameter Estimation for Distributed Hydrological Modeling: Potential of Variational Methods. *Hydrol. Earth Syst. Sci.* **2009**, *13*, 503–517. [CrossRef]
5. Laks, I.; Kałuża, T.; Sojka, M.; Walczak, Z.; Wróżyński, R. Problems with Modelling Water Distribution in Open Channels with Hydraulic Engineering Structures. *Rocz. Ochr. Srodowiska* **2013**, *15*, 245–257.
6. Szałkiewicz, E.; Dysarz, T.; Kałuża, T.; Malinger, A.; Radecki-Pawlik, A. Analysis of in-stream restoration structures impact on hydraulic condition and sedimentation in the Flinta river, Poland. *Carpath. J. Earth Environ. Sci.* **2019**, *14*, 275–286. [CrossRef]
7. Tymiński, T. (Ed.) *Analysis of Impact of Flexible Vegetation on Hydraulic Conditions of Flow in Vegetated Channels. Part 1: Mechanical Properties of Elastic Plants*; Monograph; Wrocław University of Environmental and Life Sciences: Wrocław, Poland, 2007; p. 82. (In Polish)
8. Kastrup, J.; Kröbl, P.; Kuckelsberg, I. 2D-HN Model of the Danube between Straubing and Vilshofen. Flow Simulation in Hydraulic Engineering. In *Dresdner Wasserbauliche Mitteilungen*; TU Dresden: Dresden, Germany, 2006; Volume 32. (In German)
9. Popek, Z. Calculating the Capacity of Flood Waters. In *The Scientific Review*; Warsaw University of Life Sciences: Warsaw, Poland, 1995; Volume 7. (In Polish)
10. Kouwen, N.; Unny, T.E.; Hill, H.M. Flow Retardance in Vegetated Channels. *J. Irrig. and Drain. Div.* **1969**, *95*, 329–342. [CrossRef]
11. Kouwen, N.; Unny, T.E. Flexible Roughness in Open Channels. *J. Hydraul. Div.* **1973**, *99*, 713–728. [CrossRef]
12. Kouwen, N.; Li, R.-M. Biomechanics of Vegetative Channel Linings. *J. Hydraul. Div.* **1980**, *106*, 1085–1103. [CrossRef]
13. Kouwen, N. Modern Approach to Design of Grassed Channels. *J. Irrig. Drain Eng.* **1992**, *118*, 733–743. [CrossRef]
14. Kouwen, N. Field Estimation of the Biomechanical Properties of Grass. *J. Hydraul. Res.* **1988**, *26*, 559–568. [CrossRef]
15. Tymiński, T.; Kałuża, T. Investigation of Mechanical Properties and Flow Resistance of Flexible Riverbank Vegetation. *Pol. J. Environ. Stud.* **2012**, *21*, 201–207.
16. Walczak, N.; Walczak, Z.; Ficner, T. Determination of the Variation of the Geometric and Dynamic Parameters of the Floodplain Vegetation. *Water* **2022**, *14*, 1274. [CrossRef]
17. Kubrak, E.; Marciszewska, K.; Dohojda, M. Low deflection of flexible elements after dynamic water pressure. *Acta Sci. Pol. Archit.* **2005**, *4*, 27–35. (In Polish)
18. Kubrak, E.; Kubrak, J.; Rowiński, P.M. Vertical Velocity Distributions through and above Submerged, Flexible Vegetation. *Hydrol. Sci. J.* **2008**, *53*, 905–920. [CrossRef]
19. Järvelä, J. Flow Resistance of Flexible and Stiff Vegetation: A Flume Study with Natural Plants. *J. Hydrol.* **2002**, *269*, 44–54. [CrossRef]
20. Järvelä, J. Determination of Flow Resistance Caused by Non-submerged Woody Vegetation. *Int. J. River Basin Manag.* **2004**, *2*, 61–70. [CrossRef]
21. Järvelä, J. *Flow Resistance in Environmental Channels: Focus on Vegetation*; Helsinki University of Technology Water Resources Publications: Espoo, Finland, 2004; ISBN 978-951-22-7074-3.
22. Łoboda, A.; Karpiński, M.; Bialik, R. On the Relationship between Aquatic Plant Stem Characteristics and Drag Force: Is a Modeling Application Possible? *Water* **2018**, *10*, 540. [CrossRef]
23. Qi, Y.; Bai, Y.; Cao, X.; Li, E. The Deformation and Shear Vortex Width of Flexible Vegetation Roots in an Artificial Floating Bed Channel. *Sustainability* **2022**, *14*, 11661. [CrossRef]
24. Tsujimoto, T.; Kitamura, T. *Flow over Flexible Vegetation and Formation of Honami Motion*; Monograph of 9th APD-IAHR: Singapore, 1994.

25. DVWK. *Hydraulic Calculation of Watercourses*; DVWK-Merkblätter; Verlag Paul Parey: Hamburg/Berlin, Germany, 1991. (In German)
26. Lindner, K. The Flow Resistance of Plant Communities. In *Mitteilungen des Leichtweiss-Instituts für Wasserbau*; TU Braunschweig: Braunschweig, Germany, 1985; Volume 75. (In German)
27. Pasche, E.; Rouvé, G. Overbank Flow with Vegetatively Roughened Flood Plains. *J. Hydraul. Eng.* **1985**, *111*, 1262–1278. [CrossRef]
28. Pasche, E. Turbulence Mechanism in Natural Streams and the Possibility of Its Mechanical Representation. In *Mitteilungen des Instituts für Wasserbau und Wasserwirtschaft*; TU Aachen: Aachen, Germany, 1984; Volume 52. (In German)
29. Kaiser, W. Flow Resistance Conditions in Channels with Riparian Vegetation. In *Wasserbau-Mitteilungen des Instituts für Wasserbau, Konstruktiver Wasserbau und Wasserwirtschaft*; TH Darmstadt: Darmstadt, Germany, 1984; Volume 23. (In German)
30. Nuding, A. Flow Resistance Behaviour in Channels with Riparian Shrubbery, Development of a Flow Law for Watercourses with and without Woody Vegetation, with Special Consideration of Riparian Shrubbery. Ph.D. Dissertation, Wasserbau-Mitteilungen des Instituts für Wasserbau, Konstruktiver Wasserbau und Wasserwirtschaft, TH Darmstadt, Darmstadt, Germany, 1991. (In German).
31. Rickert, K. The Influence of Woody Plants on Light Conditions and Runoff Behaviour in Watercourses. Ph.D. Thesis, Mitteilungen des Instituts für Wasserwirtschaft, Hydrologie und Landwirtschaftlichen Wasserbau, Universität Hannover, Hannover, Germany, 1986. (In German).
32. Rouvé, G. *Hydraulic Problems in Near-Natural Watercourse Development*; DFG, Forschungsbericht, VCH Verlabsgesellschaft: Weinheim, Germany, 1987. (In German)
33. Vischer, D.; Oplatka, M. The flow resistance of a flexible riparian and foreshore vegetation. *Wasserwirtschaft* **1998**, *88*, 284–288. (In German)
34. Petryk, S.; Bosmajian, G. Analysis of Flow through Vegetation. *J. Hydrual. Div.* **1975**, *101*, 871–884. [CrossRef]
35. Mertens, W. On the hydraulic calculation of near-natural watercourses. *Wasserwirtschaft* **1989**, *79*, 170–179. (In German)
36. Dalton, P.A.; Smith, R.J.; Truong, P.N.V. Vetiver Grass Hedges for Erosion Control on a Cropped Flood Plain: Hedge Hydraulics. *Agric. Water Manag.* **1996**, *31*, 91–104. [CrossRef]
37. Klaassen, G.J.; Van Der Zwaard, J.J. Roughness Coefficients Of Vegetated Flood Plains. *J. Hydraul. Res.* **1974**, *12*, 43–63. [CrossRef]
38. Klaassen, G.J.; van Urk, A. *Resistance to Flow of Floodplains with Grasses and Hedges*; 21-st IAHR Congress: Melbourne, Australia, 1985.
39. Powell, R.W. Resistance to Flow in Rough Channels. *Trans. Am.Geophys. Union* **1950**, *31*, 575–582. [CrossRef]
40. Lehmann, B. Recommendations for Near-Natural Watercourse Development in Urban Areas. In *Mitteilungen des Instituts für Wasser und Gewässerentwicklung*; University Karlsruhe (TH): Karlsruhe, Germany, 2005; p. 230. (In German)
41. Fathi-Maghadam, M.; Kouwen, N. Nonrigid, Nonsubmerged, Vegetative Roughness on Floodplains. *J. Hydraul. Eng.* **1997**, *123*, 51–57. [CrossRef]
42. Garbrecht, G. Discharge Calculations for Rivers and Canals. *Wasserwirtschaft* **1961**, *51*, 40–45. (In German)
43. Västilä, K.; Järvelä, J.; Koivusalo, H. Flow–Vegetation–Sediment Interaction in a Cohesive Compound Channel. *J. Hydraul. Eng.* **2016**, *142*, 04015034. [CrossRef]
44. Wolski, K.; Tymiński, T. Studies on the Threshold Density of Phragmites Australis Plant Concentration as a Factor of Hydraulic Interactions in the Riverbed. *Ecol. Eng.* **2020**, *151*, 105822. [CrossRef]
45. Wu, F.-C.; Shen, H.W.; Chou, Y.-J. Variation of Roughness Coefficients for Unsubmerged and Submerged Vegetation. *J. Hydraul. Eng.* **1999**, *125*, 934–942. [CrossRef]
46. Bretschneider, H.; Schulz, A. *Application of Flow Formulas for Near-Natural Watercourse Development*; DVWK-Schriften; Verlag Paul Parey: Hamburg/Berlin, Germany, 1985; Volume 72. (In German)
47. Chow, V.T. *Open-Channel Hydraulics*; McGraw-Hill Book: New York, NY, USA, 1959.
48. Finnemore, E.J.; Franzini, J.B. *Fluid Mechanics with Engineering Applications*, 10th ed.; The McGraw-Hill Series in Civil and Environmental Engineering; McGraw-Hill: Boston, MA, USA, 2002; ISBN 978-0-07-243202-2.
49. Caroppi, G.; Västilä, K.; Järvelä, J.; Lee, C.; Ji, U.; Kim, H.S.; Kim, S. Flow and Wake Characteristics Associated with Riparian Vegetation Patches: Results from Field-scale Experiments. *Hydrol. Process.* **2022**, *36*, e14506. [CrossRef]
50. Västilä, K.; Järvelä, J.; Aberle, J. Characteristic Reference Areas for Estimating Flow Resistance of Natural Foliated Vegetation. *J. Hydrol.* **2013**, *492*, 49–60. [CrossRef]
51. Armanini, A.; Righetti, M.; Grisenti, P. Direct Measurement of Vegetation Resistance in Prototype Scale. *J. Hydraul. Res.* **2005**, *43*, 481–487. [CrossRef]
52. Comiti, F.; Da Canal, M.; Surian, N.; Mao, L.; Picco, L.; Lenzi, M.A. Channel Adjustments and Vegetation Cover Dynamics in a Large Gravel Bed River over the Last 200 years. *Geomorphology* **2011**, *125*, 147–159. [CrossRef]
53. Tabacchi, E.; Lambs, L.; Guilloy, H.; Planty-Tabacchi, A.-M.; Muller, E.; Dcamps, H. Impacts of Riparian Vegetation on Hydrological Processes. *Hydrol. Process.* **2000**, *14*, 2959–2976. [CrossRef]
54. Kałuża, T.; Sojka, M.; Wróżyński, R.; Jaskuła, J.; Zaborowski, S.; Hämmerling, M. Modeling of River Channel Shading as a Factor for Changes in Hydromorphological Conditions of Small Lowland Rivers. *Water* **2020**, *12*, 527. [CrossRef]
55. Posthumus, H.; Rouquette, J.R.; Morris, J.; Gowing, D.J.G.; Hess, T.M. A Framework for the Assessment of Ecosystem Goods and Services; a Case Study on Lowland Floodplains in England. *Ecol. Econ.* **2010**, *69*, 1510–1523. [CrossRef]

56. Walczak, N.; Walczak, Z.; Kałuża, T.; Hämmerling, M.; Stachowski, P. The Impact of Shrubby Floodplain Vegetation Growth on the Discharge Capacity of River Valleys. *Water* **2018**, *10*, 556. [CrossRef]
57. Indlekofer, H.M.F. Use of the Strickler formula for flowing water with profile division and vegetation stocking. *Wasserwirtschaft* **2004**, *11*, 15–22. (In German) [CrossRef]
58. Lecher, K.; Lühr, H.-P.; Zanke, U. Pocketbook of water management. In *Taschenbuch der Wasserwirtschaft*; Springer Verlag: Berlin/Heidelberg, Germany, 2021; ISBN 978-3-658-31287-9.
59. *ISO 748: 2021 (En)*; Hydrometry—Measurement of Liquid Flow in Open Channels—Velocity Area Methods Using Point Velocity Measurements. ISO: Geneva, Switzerland, 2021.