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Flow resistance due to lateral momentum transfer in partially vegetated rivers

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[1] In the study of natural rivers, accurate conveyance estimation is challenging because of complex cross-sectional geometry and variable flow resistance. The aim of this study was to investigate the additional friction factor due to lateral momentum transfer at the interface of vegetated and nonvegetated channel parts in two rivers: (1) the Rhine River, a large dredged river with partially vegetated floodplains, and (2) the River Päntäneenjoki, a small boreal lowland river with dense bank vegetation and an undulating longitudinal profile. The friction factors of the interfaces were computed backward from the topographical field data, while the measured depth-flow regime data were computed with the help of an unsteady one-dimensional (1-D) flow model. Laboratory experiments were carried out to verify the effects of longitudinal spacing of plants on the friction factors. In the researched rivers the values of the friction factors at the interface were higher than the ones presented in the literature. *INDEX TERMS:* 1821 Hydrology: Floods; 9335 Information Related To Geographic Region: Europe; 1899 Hydrology: General or miscellaneous; *KEYWORDS:* apparent shear stress method, environmental hydraulics, flow resistance, lateral momentum transfer, river flow

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1. Introduction

[2] Areas near rivers were strongly utilized during the 20th century. Flood retention areas were drained and separated from the river channels for purposes like agriculture, housing and infrastructure, and the floodwater was moved downstream all the way to the sea as soon as possible. These measures reduced the natural retention capacity of rivers, raising flood peaks and reducing the duration of floods. Nowadays, the aim is to rehabilitate and restore channelized and otherwise engineered channels, floodplains and other flood retention areas. Many challenges are faced in channel hydraulics because of composite flow resistance. When overbank flow occurs, special consideration is required in, e.g., the interaction between main channel and floodplain flows, proportion of flow between subareas, differences in roughness between the main channel and the floodplains, significant variation of resistance parameters with depth & flow regimes, distribution of boundary shear stresses, the use of the hydraulic radius in calculations, effects of vegetation on retarding flow, sediment transport, and overbank flow in meandering channels [*Knight*, 2001].

[3] When a river rises above bank-full discharge the overbank flow reduces the conveyance of the main channel because of a strong vortex structure at the interface of the floodplain and the main channel [*Sellin*, 1964; *Shiono and Knight*, 1991]. Similar vortex structure exists also in partially vegetated channels [*Mertens*, 1989; *Naot et al.*, 1996; *Tsujimoto*, 1999]. The stream bank vegetation has a significant effect on channel conveyance if the channel width-depth ratio is low [*Masterman and Thorne*, 1992; *Coon*, 1998].

[4] Conveyance estimation methods of compound channels have been developed since the 1960s, including (1) the single-channel method, (2) the divided channel method, where the interfaces are included in the wetted perimeter of the main channel [*Posey*, 1967; *Myers*, 1987], and (3) the apparent shear stress (ASS) method, where the shear stress at the interface of the main channel and the floodplain is assumed significantly higher than the boundary shear stress of the main channel or the floodplain [*Wormleaton et al.*, 1982; *Knight and Demetriou*, 1983; *Pasche*, 1984]. The lateral momentum transfer could be satisfactorily modeled by turbulence models, but the use of complex models is not always justified in the solution of practical problems, and instead, the use of the ASS approach could be sufficient [*Pasche*, 1984]. *Knight* [2001] states that many authors have developed empirical equations for the ASS on specific division lines and most equations may fit particular experimental data sets well, but they are not generally applicable.

[5] In the early 1980s, several universities in Germany investigated the flow resistance of (1) vegetation, (2) the momentum transfer between the main channel and the floodplain, and (3) the momentum transfer between a vegetated zone and a nonvegetated zone of a channel [*Rouvé*, 1987]. On the basis of flume studies, three steady state ASS methods were developed [*Pasche*, 1984; *Mertens*, 1989; *Nuding*, 1991], in which the additional head loss caused by the momentum transfer was estimated as an interface friction factor (Figure 1). In these methods, a separate friction factor is computed for each floodplain, stream bank vegetation zone, nonvegetated channel part, and interface between these parts; they are then used to

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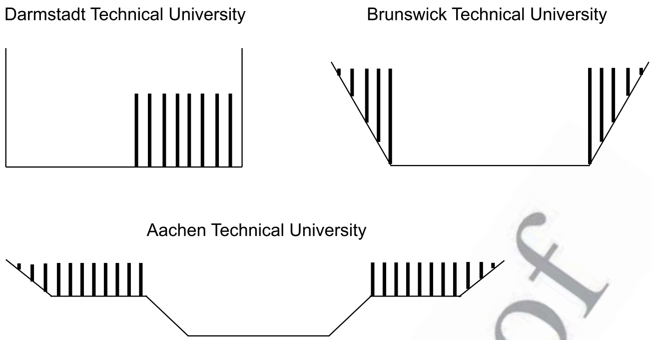

Figure 1. The laboratory studies on partly vegetated channels carried out in German universities in 1980s: Partly vegetated rectangular channel [*Nuding*, 1991], trapezoidal channel with bank vegetation [*Mertens*, 1989], and double-trapezoidal channel with floodplain vegetation [*Pasche*, 1984]

compute average flow velocities and discharges for each channel part.

[6] *Pasche* [1984] expressed the interface friction factor in a compound channel with rough floodplains as a function of (1) the ratio of the plant diameter to the product of longitudinal and lateral plant distances, (2) the ratios of the wake length and the wake width to plant distances, and (3) the contributing width of the floodplain that has influence in the interaction process. *Mertens* [1989] suggested the computation of the interface friction factor in a trapezoidal flume with bank vegetation as $f_J = F\ (k_J, b_M)$, where the roughness height $k_J = F\ (a_x, a_y, d_P, b_{eff})$. In Darmstadt Technical University, the interface friction factor was expressed as the interface friction factor in a partially vegetated rectangular flume as $f_J = F\ (v_{M,ideal}/v_F,\ R_F/h_J,\ b_{eff}/b_m)$ [*Nuding*, 1991].

[7] The common problem with each method is that they were developed with stiff cylinders. The friction factors for natural vegetation have been investigated by, e.g., *Freeman et al.* [2000] and *Järvelä* [2002]. Some theoretical differences are found between the methods (Table 1). *Stephan* [1993] compared the methods to measurements in a compound channel having a single floodplain, finding that the method of Mertens overestimated the interface friction factor in most conditions when having a rough floodplain, but methods of Pasche and Nuding were relatively accurate. *Schumacher* [1995] compared the methods with independent compound channel data and stated that the method of *Nuding* [1991] significantly underestimates the interface friction factor. *Nuding* [1998], however, corrected that Schumacher did not realize that the computational width must not exceed the physical width of the main channel in the computation.

[8] Newer approaches developed for the conveyance estimation of compound channels are (1) the coherence method (COHM), which provides simple estimates of discharge within a few percent of measurements for most flow cases in compound channels with deviations of up to 10° between main channel and floodplain alignment [*Ackers*, 1993; *Samuels et al.*, 2002], (2) the Shiono and Knight method (SKM), and (3) and the lateral division method (LDM) [*Knight*, 2001]. COHM requires simplification of the cross-sectional geometry to a double trapezoidal shape, and it does not predict the discharge components in the main channel and the floodplains. SKM and LDM are relatively complex 2-D methods developed to improve the coherence method [*Knight*, 2001].

[9] An unsteady 1-D flow model using the method of *Nuding* [1991] was developed to improve the computation in conditions such as those where the limitations of COHM are met [*Helmiö*, 2002]. A preprocessing program was developed to convert complex channel topography and resistance into parameters needed in the flow model [*Helmiö and Jolma*, 2003]. The model (1) computes separate friction factors for the main channel, the floodplains, the vegetation zones, and each interface between the main channel and floodplain; (2) predicts the individual components of discharge in the main channel and the

t1.1 **Table 1.** Differences Between the Methods of *Pasche* [1991], *Nuding* [1991], and *Mertens* [1989]

	Property	Pasche	Mertens	Nuding
t1.2				
t1.3	Applicable to simple concave channels with bank vegetation	no	yes	yes
t1.4	Applicable to compound channels with floodplain vegetation	yes	no	yes
t1.5	Wake width and length affect the friction factor of the floodplain and the interface	yes	no	no
t1.6	Plant diameter affects the interface friction factor	no	yes	yes
t1.7	Iteration of the contributing main channel width	yes	yes	no
t1.8	Computation of submerged vegetation	no	no	yes
t1.9	Contributing floodplain width related to the vegetation distances	yes	no	yes

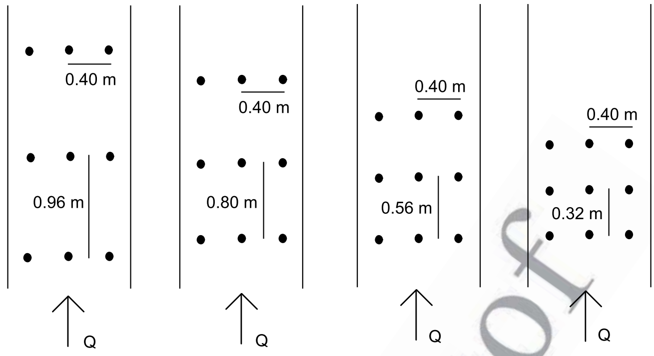

Figure 2. Measured spruce patterns in the flume experiments at HUT Laboratory of Water Resources.

floodplains; and (3) allows for significant variation in the channel geometry and the flow resistance parameters along the depth and flow regime. Thus it covers a significant part of *Knight*'s [2001] list for issues under special consideration for overbank flow.

[10] The first aim of this paper was to investigate the differences of the interface friction factors between non-vegetated and vegetated channel parts in rivers of different types and sizes. The interface friction factors were calculated backward from measured topographical field data and discharge water level relationships with the help of the unsteady 1-D flow model developed by *Helmiö* [2002]. The model was earlier applied to a reach of the Rhine River having wide floodplains, with relatively good accuracy [*Helmiö*, 2004]. For this paper, the model was applied to the River Päntäneenjoki, a small natural lowland river with bank vegetation. The interface friction factors in these rivers are compared to each other and to the values presented in the literature.

[11] The second aim was to evaluate the usefulness of the theories of computing the interface friction factors, and to investigate the limitations of the unsteady flow model combined with Nuding's method. For this purpose, laboratory flume measurements were carried out to investigate the influence of the longitudinal spacing of plants on the friction factors of the interface, floodplains and vegetation zones. The friction factors for tree rows having variable longitudinal distances between each other were studied.

2. Modeling

2.1. Flume Study on Plant Distances

[12] Laboratory flume study was carried out at the Helsinki University of Technology (HUT) to verify and quantify the dependence of the longitudinal spacing of plants, a_x, on the friction factor of floodplain or vegetation zone f_F. *Pasche* [1984] assumed that when the vegetation density at the interface of the main channel and the floodplain increases, the interface friction factor increases as well, until a certain density, after which the vegetation begins to dampen the momentum exchange. Both the longitudinal and the lateral spacing affect the floodplain friction factor, but the longitudinal spacing is especially significant, because it controls the size of the eddies at the interface. Large turbulent eddies can better transfer momentum between the main channel and the floodplain. Vegetation promotes or suppresses turbulent motions and protects stream banks from erosion [*Murota et al.*, 1984]. *Pasche* [1984] carried out the flume studies with rigid cylinders, and the experiments and analysis in this paper may not be as accurate for flexible vegetation as it is for the more rigid types (i.e., trees) of vegetation.

[13] In the methods of *Pasche* [1984], *Mertens* [1989], and *Nuding* [1991] the longitudinal spacing of plants affects the interface friction factor in two ways: through the vegetation density parameter and through the contributing width of the floodplain that has influence in the interaction process. These methods designate the effects of longitudinal and lateral spacing separately, both in a different way. *Pasche* [1984] relates both the floodplain friction factor and the interface friction factor to the ratio of the wake length to the longitudinal spacing of plants, and the ratio of the wake width to the lateral plant distance. According to *Mertens* [1989] and *Nuding* [1991], the vegetation density can be determined as

$$\omega_P = \frac{d_P}{a_x a_y} \tag{1}$$

where d_P is the average diameter, and a_x and a_y are the longitudinal and lateral spacing of plants, respectively. *Pasche* [1984] and *Nuding* [1991] relate the contributing width of the floodplain that has influence in the interaction process to the longitudinal spacing of plants. In the method of *Mertens* [1989] the interface friction factor is dependent on a vegetation parameter that deals differently with the longitudinal and lateral spacing of plants, and on a contributing width that depends only on the width of the vegetation zone and not the plant spacing.

[14] The experiments were conducted with three rows of three living spruce saplings (height h_P = 0.56–0.72 m, longitudinal spacing a_x = 0.32–0.96 m, lateral spacing a_y = 0.40 m, diameter d_P = 0.096–0.135 m) in a 50 m long, 1.1 m wide, and 1.3 m high, nontilting glass flume (Figure 2). The average diameter d_{Paver} = 0.116 m was computed as the ratio of the cross-sectional area of each spruce to the height of the spruce, determined from digital photographs. The corresponding vegetation density parameters ω_P at different row distances were 0.91 m^{-1}, 0.52 m^{-1}, 0.36 m^{-1} and 0.30 m^{-1}.

Figure 3. The laboratory flume experiments: (left) a_x = 0.56 m, a_y = 0.40 m, Q = 0.059 m^3/s, and h_{av} = 0.495 m, from above, looking upstream; (right) a_x = 0.96 m, a_y = 0.40 m, Q = 0.0128 m^3/s, and h_{av} = 0.132 m, flow from left to right.

[15] The spruce saplings were thrust to a level screen plate (thickness 55 mm, length 3.35 m, hole diameter 35 mm) and 1.45 m long screen plates were laid before and after the level plate to stabilize the flow and cause turbulence (Figure 3). A vertical screen plate was fixed in the beginning of the flume to create mixing. The first screen plate was placed at 11.5 m from the beginning of the flume, and a weir was used to adjust the water level at 28 m. The water surface levels were measured manually by gauging rods in front of and behind the vegetation zone to compute the head loss and the friction factor caused by the vegetation, assuming a gradually varied flow with a steady water surface slope in the measurement reach of the flume. To confirm the assumption of a steady slope, the water levels were also measured between the trees at a number of selected discharge rates. A Thompson V notch weir was used to determine the discharge in the flume. The vegetation was sparse, ω_P < 1 m^{-1} [*Nuding*, 1991], and hence the measured head loss included components of the flume bottom roughness and the resistance caused by spruces. The friction factor of the flume bottom was measured separately and subtracted from computed total friction factors to separate the friction factor of the spruces.

[16] An error analysis was carried out for the measurements. A measurement error of Δh = 0.01 m for each water level measurement was assumed, including the methodological error and the errors due to the waving of the water surface. For discharges from 7 l/s to 166 l/s, an error of ΔQ = 6% was computed from the calibration data of the weir. The cross-sectional area covered by vegetation and the volume of vegetation between the measurement points both remained constant at the same water levels during the study.

2.2. Computation of the Interface Friction Factors

[17] Using the method of *Nuding* [1991], the 1-D unsteady flow model developed by *Helmiö* [2002] takes into account both the flow resistance of a floodplain or a vegetated stream bank and the flow resistance of the interface based on the momentum transfer between the main channel and the floodplain or the vegetated zone. The model and the equations used are described in detail by *Helmiö* [2002].

[18] The method of *Nuding* [1991, 1998] was chosen for the model, because of its applicability both to compound channels and to partially vegetated simple concave channels. It uses fewer iterative parameters than the methods of *Mertens* [1989] and *Pasche* [1984] and is therefore more useful for practical purposes. To compute the total hydraulic radius and the total friction factor, a procedure was developed for the model. Now it was further adjusted, to include the losses caused by the changes in the velocity heads, as well as the assumption of the same water level and the same water surface slope in every part of each cross section. This is essential in smaller rivers having significant variation in the cross section size and shape, and the longitudinal profile. Thus the total losses can be determined as

$$S_f + S_v = \frac{H_f + H_v}{L} = \frac{f_{tot} Q|Q|}{8gA^2R} + \frac{v_1^2 - v_2^2}{2gL} \quad (2)$$

where H_f is the loss due to friction, H_v is the loss due to the difference between the velocity heads and f is the total resistance coefficient. An effective hydraulic radius for each component i = M, L1, L2, R1, R2 was calculated as

$$R_i = \frac{f_i Q_i |Q_i| L}{8gA_i^2\left(\left(H_{f,i} + H_{v,i}\right) - \left(v_{1,i}^2 - v_{2,i}^2\right)/2g\right)} \quad (3)$$

based on the assumption that the losses in each part of the cross section were the same. The losses of the main channel can be computed from equation (2) by replacing the parameters of the whole channel by ones of the main channel. The composite hydraulic radius is then

$$R_{TOT} = \sum_{i=1}^{5} R_i Q_i^2 \Bigg/ \sum_{i=1}^{5} Q_i^2 \quad (4)$$

and the composite friction factor

$$f_{TOT} = \frac{8gA_{TOT}^2 R_{TOT}\left(\left(H_{f,M} + H_{v,M}\right) - \left(v_1^2 - v_2^2\right)/2g\right)}{Q_{TOT}|Q_{TOT}|L}. \quad (5)$$

The model was earlier applied to a 28-km-long reach on the Upper Rhine with partially vegetated floodplains [*Helmiö*, 2004]. The computed results correlated well with the measured values. The vegetation density ω_P was

Table 2. Some Properties of the Modeled Rivers

	Rhine River	River Päntäneenjoki
Mean discharge, m^3/s	2300	1.4–1.8
Mean high discharge, m^3/s	–	19–22
Length, km	1320	22.6
Catchment area, km^2	185,000	210
Longitudinal slope	0.00093	0.00091
Cross-sectional profile	compound	simple concave

0.062 m^{-1} on the right floodplain and 0.017 m^{-1} on the left floodplain.

[19] The method of *Nuding* [1991] does not take into account that the density of vegetation dampens the momentum exchange after reaching a certain density, but allows the interface friction factor to increase infinitely. Therefore a maximum limit of the interface friction factor was set to f_{Jmax} = 0.40 in the application of the Rhine River, based on the maximum values determined in flume studies [e.g., *Pasche*, 1984; *Nuding*, 1991; *Becker*, 1999]. Without the limitation, the water levels were overestimated significantly, and it was assumed that the values of the friction factors of the interface were overestimated.

[20] For this paper, the flow model was further applied to the River Päntäneenjoki, a small boreal river in Western Finland with very complex topography: high composite friction factors, dense stream bank vegetation, variable shapes of cross sections and an undulating longitudinal profile. Its bed material is mainly clay and clayey silt. Parameters to describe the Rhine River and the River Päntäneenjoki are presented in Table 2. The model was applied to a 8.8-km-long reach of the River Päntäneenjoki, divided into 96 cross sections 15–100 m apart, from cross section 11300 m to cross section 20117 m from the upstream end. The confluence of the River Kainastonjoki is located in 22600 m. In three reaches, 13–23 different discharges and water levels were measured during 1997–2001. The lowest research reach (P1) had sparse grassy vegetation in the channel and sparse willows on the stream banks. The 1.2-km-long middle reach (P2) was widened above the mean water level to increase flood conveyance, and protected from erosion with several bioengineering measures, and thus has a mildly two-stage-shaped cross section. The upstream end reach (P3) had very dense stiff vegetation on the stream banks. For a more detailed reach description, see *Helmiö and Järvelä* [2003].

[21] The measured discharges varied from low discharge of less than 1 m^3/s to mean high discharge of 20.55 m^3/s. The measured discharge and water level data were used to compute discharges as the functions of water levels, $h = F(Q)$, for each cross section having discharge measurements. The roughness height k_M of the main channel bed was calibrated with several low discharge rates of 1.0 m^3/s, 1.5 m^3/s and 2.0 m^3/s at which the water levels were so low that the additional losses due to the momentum transfer were negligible in most cross sections. The lowest values of k_M in all low discharges were used as bottom roughness of the main channel.

[22] The discharge rate of 12 m^3/s and the vegetation classification of the River Päntäneenjoki were used for the calibration of the stream bank vegetation resistance parameters (Table 3). They were calibrated with the help of the water level discharge functions and validated with photographs, a videotape and maps of the river. The same vegetation density parameters were applied to both stream banks, because no clear trend of differences was seen in the photographs and the videotape. The vegetation density parameter ω_P was 0.3 m^{-1} in the upper reach (J = 1–45) and 0.032 m^{-1} in the lower reach (J = 46–96).

[23] Computations were made in the steady state to investigate the changes in the interface friction factor. In the model, the discharge was used as the upper boundary condition, and the stage discharge curve as the lower boundary condition. The River Päntäneenjoki has an average sinuosity of s = 1.6. On the basis of the linearized Soil Conservation Service method [*James*, 1994], the friction factor $f\ (\sim n^2)$ increases approximately 2% with the increase of sinuosity in increments of 0.1. Therefore the compound friction factors computed by the model were multiplied by 1.12 to include the additional resistance caused by sinuosity.

3. Results and Analysis

3.1. Laboratory Study on Plant Distances

[24] The friction factors of different setups are classified by Reynolds numbers, velocities and water depths in Figure 4 and Table 4. The results are also presented as Manning n values. The f values were not plotted against Re number because different setups have different relative submergences. As the plants are not vertically homogeneous, different water levels cause different momentum absorbing areas, and thus different average velocities. Two of the measurement cases are shown in Figure 3.

[25] The results showed that a maximum value of the friction factors was found between the spacing of 0.56 m and 0.96 m (Figure 4). The assumption of *Pasche* [1984] that a maximum flow resistance is reached at a certain longitudinal spacing of plants, after which the flow resistance is reduced, should also be taken into account when computing the interface friction factor.

[26] Despite the low value of Re = 6000 during one measurement, the flow could be assumed to be fully turbulent, as the flume roughness was very high and the water was well mixed. For Re = 19000, the variation of the friction factor was not consistent when compared to the friction factors of other Re values (Figure 4). On the basis of the errors estimated in the measurements, the errors of the

Table 3. Used Roughness and Vegetation Coefficients for the Flow Model of the River Päntäneenjoki: Main Channel Roughness k_M, Floodplain Roughness k_{FB}, Vegetation Distances a_x and a_y, Plant Diameters d_P, and Heights h_F in Cross Section J[a]

J	Length, m	k_M, m	k_{FB}, m	a_x, m	a_y, m	d_P, m	h_F, m
1–3	11,300–11,700	0.82	0.5	1.0	1.0	0.30	2.5
4–7	11,700–12,050	0.95	0.5	1.0	1.0	0.30	2.5
8–11	12,050–12,310	0.40	0.5	1.0	1.0	0.30	2.5
12–18	12,310–13,000	0.30	0.5	1.0	1.0	0.30	2.5
19–45	13,000–15,600	0.70	0.5	1.0	1.0	0.30	2.5
46–51	15,600–16,000	0.40	0.5	2.5	2.5	0.20	1.5
52–53	16,000–16,115	0.70	0.5	2.5	2.5	0.20	1.5
54–84	16,115–19,150	0.95	0.5	2.5	2.5	0.20	1.5
85–94	19,150–20,000	0.40	0.5	2.5	2.5	0.20	1.5
95–96	20,000–20,117	0.70	0.5	2.5	2.5	0.20	1.5

[a]Same values were used on both stream banks.

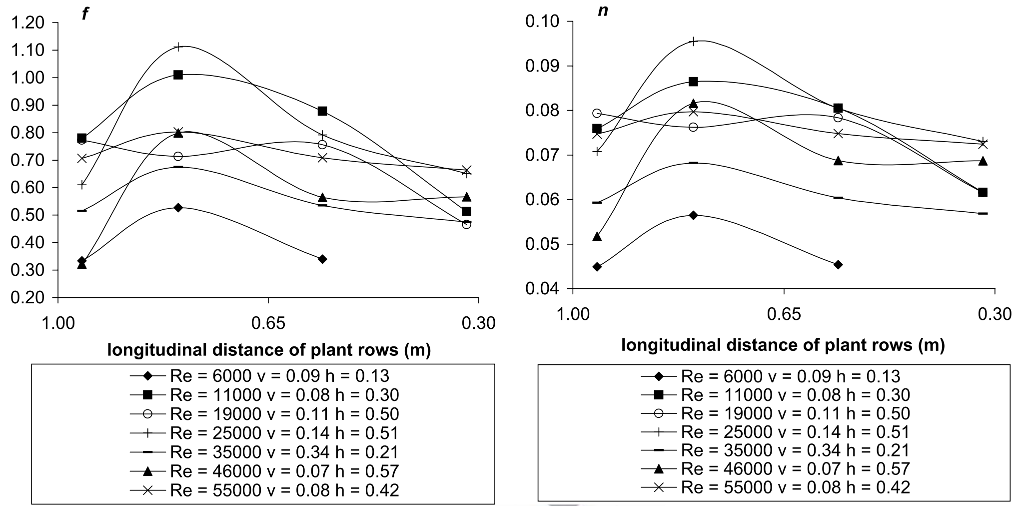

Figure 4. The friction factors and Manning coefficients of the different spruce setups.

computed friction factors were, on average, 8%, being a maximum of 10.5% in the case of highest flow velocity. The variation of friction factors for *Re* = 19000 is within the limits of the sensitivity analysis and can be considered as a measurement error.

3.2. Interface Friction Factors

[27] At the discharge rates used for calibration, relatively accurate water level values were calculated by the flow model in the steady state in the River Päntäneenjoki (Figure 5). Calculations were additionally made at discharge rates of 3 m^3/s and 7 m^3/s. At these discharges, the results were poorer (Figure 6). The water levels were overestimated by 10–30 cm in reach P2, which had a moderate compound channel form, causing an overestimation in reach P3, which had dense stream bank vegetation, as well. Thus the composite friction factors were overestimated by the model. This was not improved by changing the method to estimate the compound hydraulic radius and the compound friction factor (equations (2)–(5)) to an estimation of the hydraulic

Table 4. Measured and Computed Parameters From the Flume Experiments With Spruce Saplings

Row Distribution, m	Date	Q, m^3/s	dh, mm	L, m	Average h, m	Average A, m^2	Average v, m/s	n	f	Re	Fr	Weir h, m
0.56	26 Nov. 1999	0.0143	1.00	2.62	0.134	0.147	0.10	0.045	0.340	6973	0.085	0.15
0.80	3 Nov. 1999	0.0128	1.25	2.62	0.133	0.147	0.09	0.056	0.527	6245	0.076	0.15
0.96	30 Nov. 1999	0.0128	0.90	2.90	0.132	0.145	0.09	0.045	0.334	6256	0.077	0.15
0.32	26 Nov. 1999	0.0274	0.60	2.62	0.302	0.332	0.08	0.062	0.513	10724	0.048	0.30
0.56	24 Nov. 1999	0.0277	1.05	2.62	0.301	0.332	0.08	0.081	0.878	10844	0.049	0.30
0.80	3 Nov. 1999	0.0273	1.15	2.62	0.304	0.334	0.08	0.086	1.009	10659	0.047	0.30
0.96	30 Nov. 1999	0.0273	1.00	2.90	0.302	0.332	0.08	0.076	0.779	10684	0.048	0.30
0.32	26 Nov. 1999	0.0586	0.70	2.62	0.493	0.542	0.11	0.062	0.466	18737	0.049	0.45
0.56	24 Nov. 1999	0.0589	1.15	2.62	0.492	0.541	0.11	0.078	0.756	18840	0.050	0.45
0.80	3 Nov. 1999	0.0584	1.05	2.62	0.495	0.545	0.11	0.076	0.714	18622	0.049	0.45
0.96	30 Nov. 1999	0.0591	1.30	2.90	0.494	0.543	0.11	0.079	0.773	18873	0.049	0.45
0.32	29 Nov. 1999	0.0815	1.70	2.62	0.514	0.565	0.14	0.073	0.651	25535	0.064	0.45
0.56	24 Nov. 1999	0.0810	2.05	2.62	0.513	0.564	0.14	0.081	0.792	25396	0.064	0.45
0.80	3 Nov. 1999	0.0814	2.85	2.62	0.517	0.569	0.14	0.095	1.112	25424	0.064	0.45
0.96	30 Nov. 1999	0.0855	1.90	2.90	0.519	0.570	0.15	0.071	0.611	26673	0.066	0.45
0.32	26 Nov. 1999	0.0807	12.50	2.62	0.211	0.232	0.35	0.057	0.474	35334	0.241	0.15
0.56	24 Nov. 1999	0.0807	13.95	2.62	0.212	0.233	0.35	0.060	0.535	35297	0.240	0.15
0.80	03 Nov. 1999	0.0810	15.65	2.62	0.222	0.244	0.33	0.068	0.675	34967	0.225	0.15
0.96	30 Nov. 1999	0.0811	14.90	2.90	0.213	0.234	0.35	0.059	0.515	35444	0.240	0.15
0.32	29 Nov. 1999	0.1538	4.20	2.62	0.563	0.619	0.25	0.069	0.567	46068	0.106	0.45
0.56	24 Nov. 1999	0.1585	4.15	2.62	0.579	0.636	0.25	0.069	0.565	46813	0.105	0.45
0.80	04 Nov. 1999	0.1555	5.85	2.62	0.570	0.627	0.25	0.082	0.799	46261	0.105	0.45
0.96	30 Nov. 1999	0.1590	2.80	2.90	0.564	0.621	0.26	0.052	0.321	47570	0.109	0.45
0.32	29 Nov. 1999	0.1585	11.00	2.62	0.419	0.461	0.34	0.072	0.664	54504	0.169	0.30
0.56	24 Nov. 1999	0.1585	11.75	2.62	0.419	0.461	0.34	0.075	0.708	54518	0.170	0.30
0.80	04 Nov. 1999	0.1520	11.85	2.62	0.424	0.467	0.33	0.080	0.802	51995	0.160	0.30
0.96	30 Nov. 1999	0.1590	13.10	2.90	0.419	0.460	0.35	0.075	0.706	54724	0.170	0.30

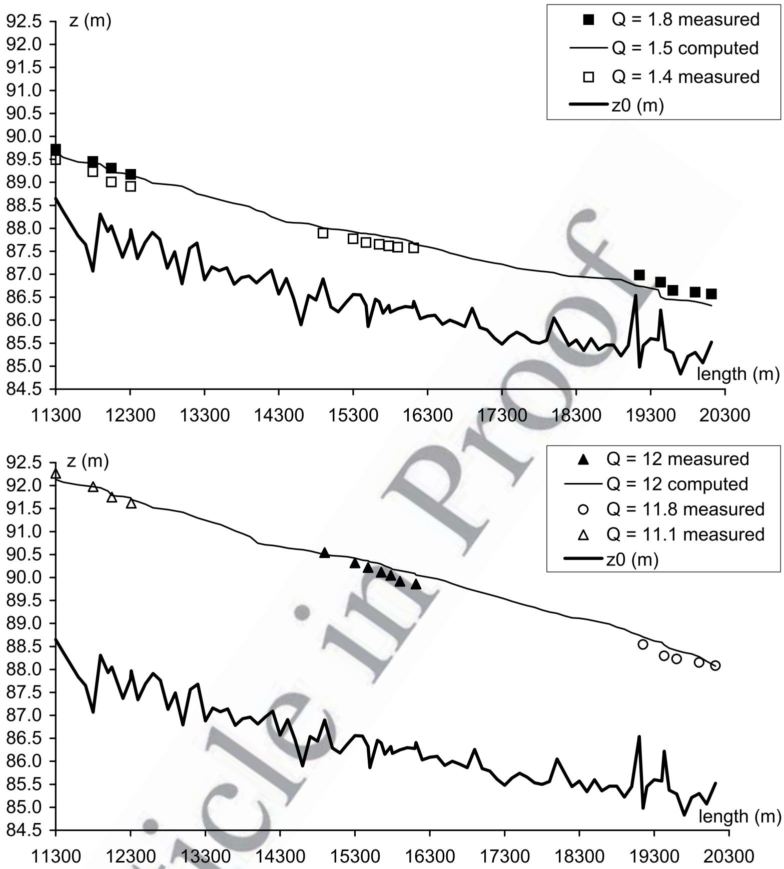

Figure 5. Simulation of water levels for steady discharges 1.5 m^3/s and 12 m^3/s. These discharges were used for calibration.

radius in a traditional way for a simple concave channel as $R = A_{TOT}/p_{TOT}$. Instead, in a compound channel, the differences were significant: the computational procedure was unstable when using the total hydraulic radius assuming a simple concave channel.

[28] A reason for a high overall friction factor may be that a single component of f used in the computation of the compound friction factor f_{TOT} is significantly overestimated. However, this is improbable, because the results at discharge rates of 1.5 m^3/s and 12 m^3/s were quite accurate, and thus support the assumption of correct estimations of roughness and vegetation parameters. In addition, the limitation of the friction factor in the same way as with the Rhine River reduced the friction factors insignificantly at reach P2. It seems that the method of Nuding is not well suited to a P2-type compound channel without dense vegetation.

[29] The components of the friction factors of the River Päntäneenjoki are compared with those of the Rhine River for steady discharge rates of 680 m^3/s (below bank-full), 1430 m^3/s and 3040 m^3/s. In the River Päntäneenjoki, a maximum of 36% of the discharge was conveyed through vegetation zones. In the Rhine River, having wide floodplains, up to 26% of the high discharge was conveyed on floodplains. These are strongly dependent on the division of the channel into the main channel and floodplains or vegetation zones.

[30] The composite friction factors f_{TOT} for the River Päntäneenjoki were at the discharge rate of 1.5 m^3/s from 0.12 to 0.52 (average 0.23) and at the higher discharge rates from 0.02 to 0.22 (average 0.14). The composite friction factors in the River Päntäneenjoki were about seven times the ones in the Rhine River, while the discharges in the Rhine River are about 250–450 times higher than in the River Päntäneenjoki.

[31] In the Rhine River, the friction factors of the interfaces were the highest at the lowest discharge and decreased along the increase of the discharge. In the River Päntäneenjoki, the mean value of the interface friction factor, f_J, was about 0.39 at a discharge rate of 3 m^3/s, at 7 m^3/s up to 2.35 and at 12 m^3/s about 0.63. *Becker* [1999] gives values of friction factors $f_J \approx 0.2$ for the main channel and $f_J \approx 0.2$–0.3 for the floodplain side of the interface. The highest measured values in the laboratory studies of *Nuding* [1991] were about $f_J = 0.23$. The values presented by *Becker* [1999] and *Nuding* [1991] are well in line with the flume measure-

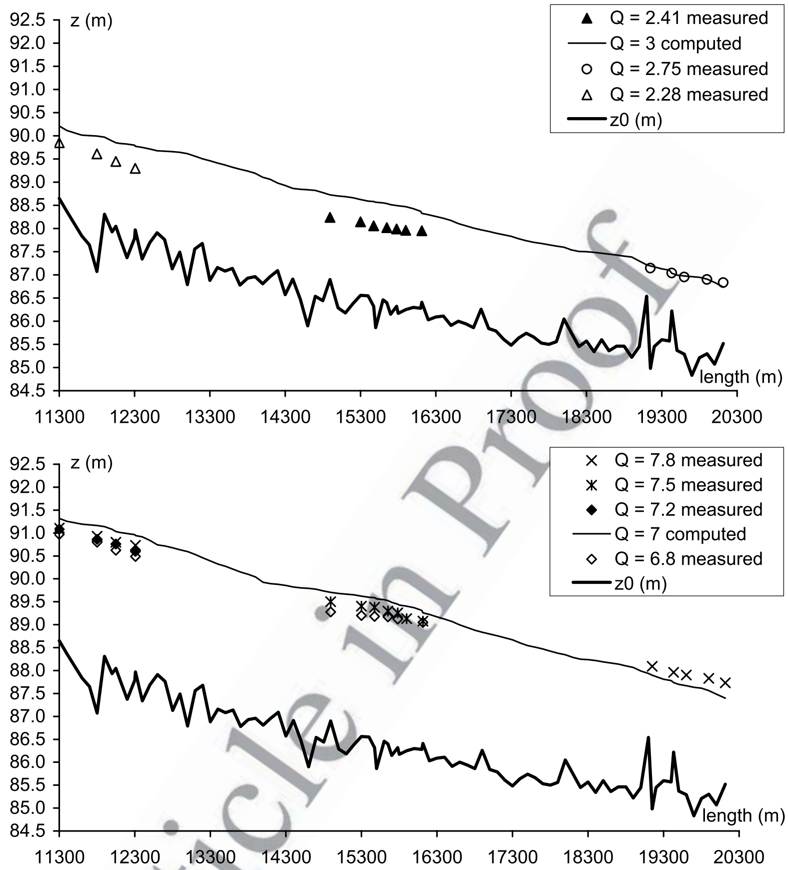

Figure 6. Simulation of water levels for steady discharges 3 m^3/s and 7 m^3/s.

ment results of *Pasche* [1984]. In the Rhine River a limitation of the maximum value of the interface friction factor to f_J = 0.40 was required to get the computed values of the water levels match the measured values. In the River Päntäneenjoki, the limitation of the interface friction factor did not significantly improve the results as it did in the Rhine River. The highest composite friction factors of the River Päntäneenjoki were about the same magnitude as, or higher than, the values of the interface friction factor presented in the literature [e.g., *Becker*, 1999].

[32] The method of Nuding that was used in the flow model was originally developed for partially vegetated channels, and it gave relatively good results in the River Päntäneenjoki, a river with bank vegetation, without any changes in the method. However, when using the method of Nuding in the Rhine River, a wide compound channel, the limitation of the maximum value from the method of Pasche was needed to make the computation more reliable.

4. Discussion and Conclusions

[33] The computed interface friction factors for the Rhine River and the River Päntäneenjoki were higher than the values presented in the literature. The main reason for this is that the values presented in the literature are determined in longitudinally uniform laboratory flumes and are therefore lower than the values determined for irregular rivers.

[34] The model of *Helmiö* [2002] including the method of *Nuding* [1991] was found to be relatively accurate in quantifying the discharges and the composite friction factors in a river with wide floodplains, i.e., the Rhine River, when a maximum value for the interface friction factor is determined. This is necessary because, in a wide compound channel, the effect of the momentum transfer does not affect the longitudinal flow velocities over the whole main channel width or over the whole floodplain width in a channel with floodplains, i.e., the estimation of the contributing width of the floodplain is not accurate.

[35] In a river with dense bank vegetation, the model was not as accurate. In the River Päntäneenjoki, the used computational procedure overestimated the composite friction factors, and thus the water levels, compared to the measured values. The division of the components of velocities and discharges in the main channel and vegetated stream banks may have been improper and they should be evaluated by additional field measurements.

[36] In the method of Nuding, other factors causing flow resistance could possibly also be implicitly included in the interface friction factor. In the River Päntäneenjoki, no additional resistance coefficient was included in the model to include the longitudinal channel variation, and therefore the relative roughness, *k/R*, was very high compared to the Rhine River, which has significantly larger cross sections that are no longer in natural conditions.

[37] The method of Pasche might produce more accurate results for compound channels with floodplain vegetation. However, the method of Nuding is much simpler to apply in practice, so its use can be recommended in cases when approximate results are needed for practical cases where no detailed multidimensional modeling is needed.

[38] *Pasche* [1984] assumed that when the vegetation density at the interface of the main channel and the floodplain increases, the interface friction factor increases as well, until it reaches a certain density, after which the vegetation begins to dampen the momentum exchange. The effect was verified in a laboratory flume study. This supports the approach made in the case of the Rhine River, in which the maximum value of the interface friction factor was limited.

Notation

A	cross-sectional area, m^2.
a_x,a_y	longitudinal and lateral distance of the vegetation elements, respectively, m.
b_{eff}	contributing width of the floodplain that has influence in the interaction process, m.
b_m	computational main channel width, m.
d_p	diameter of a vegetation element, m.
f	Darcy – Weisbach friction factor.
H_f	friction loss, m.
H_v	loss due to difference between the velocity heads, m.
h	water depth, m.
h_P	height of floodplain vegetation, m.
k	roughness height, m.
k_{FB}	roughness height of the floodplain bed, m.
L	reach length, m.
n	Manning resistance coefficient, s m$^{-1/3}$.
Q	discharge, m^3 s^{-1}.
p	wetted perimeter, m.
Re	Reynolds number.
R	hydraulic radius, m.
s	sinuosity.
v	average flow velocity, m s^{-1}.
$v_{M,ideal}$	ideal flow velocity in the main channel without the interaction process, m s^{-1}.
ω_P	vegetation density parameter, m^{-1}.

subscripts:

F	a whole floodplain.
J	the interface between nonvegetated and vegetated channel parts.
M	the main channel.
TOT	composite or compound parameter for the whole cross section.
1	upper of two consecutive cross sections.
2	lower of two consecutive cross sections.

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