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Hydraulic aspects of environmental flood management in boreal conditions

Terhi Helmiö and Juha Järvelä

Helsinki University of Technology, Laboratory of Water Resources, P.O. Box 5300, FIN-02015 HUT, Finland

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In environmental flood management, an essential task is to improve channel conveyance using environmentally preferable methods, which aim to preserve natural morphological and hydraulic characteristics of a river. This requires a reliable channel design method that accounts for complex hydraulics, i.e. two-stage channel or considerable bank vegetation. Hydraulic field measurements were carried out in two rivers to find out how different factors affected flow resistance. In one of the study reaches, the effects of bioengineering on channel hydraulics were investigated under boreal climatic conditions. The Darcy-Weisbach friction factor, the Manning coefficient and the roughness height were related to the characteristics of channel geometry and flow. Comparison between the field data and the investigated channel design methods gave accurate results only in reaches having simple hydraulic properties. In reaches with complex hydraulics the results were poor.

Introduction

In many areas, natural flooding cannot be allowed because of intense land use, e.g. housing, industry or agriculture. Flood management aims at permanent reduction of floods or damage caused by floods by dredging river channels, constructing levees or regulating flows. The main task in flood management is to increase the conveyance capacity of a river channel, especially when flow regulation is not possible. Design and maintenance of channels having a simple geometry is relatively easy. While the interest in river restoration and rehabilitation has grown during the last years, the complexity of hydraulic design has also increased because of features like meanders, non-uniformity of cross sections and longitudinal plan, vegetation, turbulence, and momentum transfer between main channel and vegetation or floodplains. In flood management, a compromise between technical and environmental aspects is necessary (Fisher 1996).

Conveyance capacity of channels can be improved by removal of large woody debris and vegetation, enlargement of the channel, straightening, construction of bypass channels and diversions, construction of levees or a compound channel. Obviously too small a channel is inadequate to prevent damage , but oversizing a river channel may cause channel instabilities, erosion and sedimentation problems. It can isolate the channel flora and fauna from the surrounding environment and reduce the natural development of biodiversity (Darby and Thorne 1994). Dredging may cause reduction in the bottom roughness and the channel length, and thus, flow may be accelerated and retention time reduced. This can solve flooding problems locally, but the problems may move downstream. Construction of levees may increase peak discharges because of the elimination of overbank storage, cause erosion and deposition, and increase meander length and amplitude if the banks are not stabilized (Brookes and Shields 1996). Instead, construction of a two-stage i.e. a compound channel may be an effective solution with relatively low costs. It can provide effective flood management, but simultaneously allows for more natural morphological and hydraulic characteristics of the river during low flows (Darby and Thorne 1996). Construction of a compound channel can increase the flow resistance because of the momentum transfer between the high-velocity main-channel flow and the low-velocity floodplain flow (Pasche and Rouvé 1985, Nuding 1991). Similar momentum transfer effect is created between a non-vegetated and vegetated channel reach, e.g. between bank vegetation and mid-channel (Nuding 1991, Mertens 1989). The extra turbulence generated by the flow interaction introduces energy loss in addition to that associated with boundary resistance. This is not accounted for by the conventional resistance equations and their direct application may result in considerable error (Fisher 1996). Typically the effect of momentum transfer on total flow resistance is at its highest when the ratio of the floodplain depth to the main channel depth is 0.2 (Knight and Shiono 1996).

In-stream, bank and floodplain vegetation can have adverse effects on channel conveyance. The net impact of vegetation depends on many complex interacting factors, including the geomorphic setting of a channel, as well as the physical properties, extent, species, age, and health of the vegetation (Darby 1999). Masterman and Thorne (1992) considered bank vegetation to be a significant factor in reducing the discharge capacity of natural rivers and flood channels. Removal or thinning of bushes and trees can decrease the flow resistance as the momentum transfer between the high-velocity mid-channel flow and the near-bank flow diminishes (Mertens 1989). However, if a dense strip of bank vegetation separates the main channel and the floodplain, the total conveyance can decrease if the bank vegetation is partly removed creating longitudinal gaps. This is due to the fact that large turbulent eddies can better transfer momentum between the main channel and the floodplain. Vegetation promotes or suppresses turbulent motions and protects banks from erosion (Murota *et al.* 1984). Removal of protecting vegetation can lead to erosion and water turbidity (Kouwen and Unny 1973). Removing large woody debris may cause erosion (Brookes and Shields 1996) and reduce habitat diversity.

Environmental flood management can be divided into active and passive. When active management is used, bioengineering methods and natural materials should be preferred whenever possible. These include brush mattresses, dormant post plantings, vegetated gabions, live stakes and fascines, and revetments and deflectors made of logs, root wads or boulders (Begemann and Schiechtl 1994, Lachat 1994, FISRWG 1998, Patt *et al.* 1998). Application of bioengineering methods should not increase the flow resistance significantly as it would reduce the total conveyance capacity of the channel.

The objective of this research was to study how the flow resistance changes when environmental flood management including bioengineering is applied to a river reach in boreal conditions. The second objective was to validate the superposition approach of Einstein and Banks (1950) in combining components of friction factors in natural channels. Field measurements were carried out in two rivers over a five-year period. An analysis of the relationship between the parameters of geometry, flow and resistance is presented in this paper.

Hydraulic considerations

Determination of resistance coefficients

The ASCE Task Force on Friction Factors (1963) recommended that the Darcy-Weisbach friction factor, f, should be used to express open-channel flow resistance as

$$f = \frac{8gRS}{v^2} \qquad (1)$$

where v is the average flow velocity, g is the gravitational acceleration, R is the hydraulic radius, and S is the bottom or energy slope for uniform and non-uniform flows, respectively. Although the friction factor f is dimensionless and, thus, should be preferred, Manning's n is more widely used in practical hydraulic engineering. This is mainly because values of n for different channel types and sizes have been widely presented in literature (e.g. Chow 1959, Barnes 1967, Coon 1998). Yen (2002) states it is appropriate to use the Darcy-Weisbach friction factor for point resistance, and to use the Manning coefficient for cross sectional and reach resistance, because in fluid mechanics f is usually associated with the shear momentum concept instead of the energy loss coefficient. In the present study, the friction factor f is defined as an energy loss coefficient, and the Manning coefficient is used only for comparison with literature values. Different factors affecting the flow resistance can be combined by the linear superposition approach to estimate the total friction factor (Einstein and Banks 1950). Although the friction factor is preferred in the present analysis, it can be easily related to Manning's n with the equation

$$f = 8gR^{-1/3}n^2 \tag{2}$$

Natural channels typically have asymmetric cross-sections with variable roughness along the wetted perimeter. Sinuosity and longitudinal undulations introduce additional resistance components. Approaches for computing the total conveyance can be categorised into two groups. First, separate resistance coefficients are assigned to different factors contributing to flow resistance, which are combined to deliver a composite roughness coefficient for the channel. Second, the cross-section can be subdivided into elements, and for each element a single resistance coefficient is determined. The discharge conveyed by each element is computed separately and summed up. The second approach can be used for both multi-stage channels and for channels without floodplains. The first approach can be used only for channels without floodplains.

The conventional summation approaches (*see* e.g. Chow 1959) are strongly criticized by Indlekofer (1981), Ackers (1993) and Knight and Shiono (1996). According to Garbrecht and Brown (1991), the simple summation approach leads to a significant overestimation of total conveyance for sections with width-depth ratios smaller than ten, regardless of shape. Several methods to estimate composite n have been developed, e.g. the Cowan's method in which separate Manning coefficients for bottom material, bottom irregularity, channel irregularity, flow obstructions, vegetation and sinuosity, respectively, are estimated from a table and combined (Cowan 1956, Chow 1959).

Analysis of friction factors

In the present study, the energy loss H_f for each reach between two consecutive cross sections was calculated backwards from Bernoulli's equation. For gradually varied flow, the equation can be written as (Chow 1959)

$$\frac{v_1^2}{2g} + h_1 + z_1 = \frac{v_2^2}{2g} + h_2 + z_2 + H_f \tag{3}$$

where $v^2/2g$ is the velocity head, h is the water depth and z is the bottom elevation. Darcy-Weisbach friction factor f or Manning coefficient n can be determined with the help of the energy loss H_f as

$$H_f = f\frac{L}{4R}\frac{v^2}{2g} = n^2\frac{Lv^2}{R^{4/3}} \tag{4}$$

where L is the length of the channel and R is the hydraulic radius.

For the analysis, Darcy-Weisbach friction factor f can be divided into sub-factors by the linear superposition approach (Einstein and Banks 1950) as

$$f = f_\mathrm{b} + f_\mathrm{s} + f_\mathrm{e} \tag{5}$$

where f_b is the friction factor taking into account the surface roughness and vegetal drag, f_s is the friction factor for sinuosity, and f_e is the friction factor that takes into account resistance caused by all other resistance factors, e.g. local losses, woody debris, and momentum transfer. Equation 5 is used for estimating f_e for the field data.

In Eq. 4, the friction factor f can be estimated from the Colebrook-White equation

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{c_1}{\mathrm{Re}\sqrt{f}} + \frac{k/R}{4c_2}\right) \quad (6)$$

where Re is Reynolds number, k is roughness height, and the term k/R describes the relative roughness. In the present study, the Reynolds number is defined based on the hydraulic radius as Re = vR/ν where ν is the kinematic viscosity. Hydraulic Research (1988) reported that the Colebrook-White equation is the most reliable over the whole range of flows, and recommended its use instead of the Manning equation in open-channel flow calculation. Equation 6 was originally developed for pipe flow, but its use has been extended for open-channel flow by adjusting parameters c_1 and c_2, which take into account the shape of the channel. Schröder (1990) and Yen (2002) compiled values for c_1 and c_2 in trapezoidal, wide and rectangular channels. Additionally, in Schröder (1990) the values are given as a function of bank slopes and bottom width for trapezoidal channels, and as a function of h/B for rectangular channels. Nuding (1991) developed similar functions for partly vegetated rectangular channels. For simplicity, values c_1 = 2.51 and c_2 = 3.71 determined for pipe flow are often used, which erroneously neglects the effects of the cross sectional shape of the channel. According to Graf (1998) c_1 can vary from 0 to 6 and c_2 from 3 to 3.75. For a rectangular channel with h/B = 0.25 the values c_1 = 3.17 and c_2 = 2.93 can be used, or for a wide channel the values c_1 = 3.22 and c_2 = 2.77 can be used (Yen 2002).

Values of roughness height k for different bottom materials and vegetation are available in literature. Chow (1959) gives values of about 30 to 900 mm for natural rivers. Schröder (1990) presents values of 6 mm for smooth soil bottom to 1500 mm for densely vegetated channels. Several other equations besides Eq. 6 have been developed to relate f and k, or n and k (*see* e.g. Bettess 1999, Duncan and Smart 1999).

The meandering of natural streams may increase flow resistance up to 30% (Chow 1959). A sinuous river is considered meandering when sinuosity s exceeds a certain value, i.e. 1.3 (FISRWG 1998) or 1.5 (Knighton 1984). Several methods have been developed to estimate the increase in friction factor due to sinuosity or meandering. The simplest and most widely used method is the SCS method that was later linearized to the LSCS method (James 1994). Several other methods have been listed by e.g. Fisher (1996) and James (1994), but in most of them sinuosity is related to flow depth and width, radius of bend curvature, and bend length or angle of curvature. The determination of these parameters in a natural channel with irregular meanders is complex. For simplicity, the LSCS method was used. Thus, the friction factor for sinuosity s in Eq. 5 can be estimated by equations (James 1994)

$$\begin{aligned} n_s &= (0.43s + 0.57)n \quad \text{when } 1 < s < 1.7 \\ n_s &= 1.30n \quad \text{when } s > 1.7 \end{aligned} \quad (7)$$

where n_s is the Manning coefficient for sinuous channel and n for straight channel. This implies that when sinuosity s increases in increments of 0.1, the friction factor f ($\sim n^2$) increases approximately 2%.

Field studies

Hydraulic field measurements were carried out in two rivers in 1997–2001 to find out how different hydraulic characteristics affect resistance. The rivers were selected for the research based on their planned flood management or channel improvement works. Although one of the rivers is in an urban area and the other in a rural area, both catchment areas consist of one-third cultivated land and a majority of forests and other uncultivated areas. The largest differences are found in the area percentage of lakes and infrastructure.

The field measurement reaches were selected so that they had rather uniform hydraulic properties along the whole reach length (Fig. 1). Topography of several cross sections in each reach was surveyed. The sinuosity of each reach was determined from a map. Discharges were determined with the help of a propeller-type current meter from a minimum of five verticals and five depths in each vertical. Each discharge measurement was supplemented by a water surface level measurement in each of the previously surveyed cross-sections.

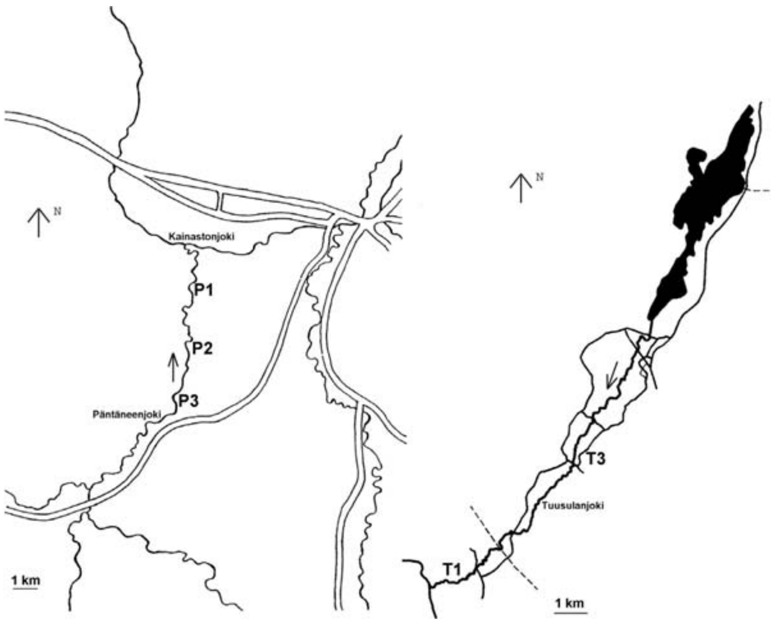

Fig. 1. The study reaches of the Päntäneenjoki (P) and Tuusulanjoki (T).

A sensitivity analysis was carried out for the measurements. An error of 10%–20% in discharge was estimated resulting from errors in the velocity measurement procedure (National Board of Waters 1984). Maximum errors in the cross-sectional coordinate measurements were considered Dx = Dy = 10 cm and in location of cross section DL = 2 m. The changes in the cross sections due to erosion and sedimentation were considered negligible in the limits of the sensitivity analysis, because the soil is mainly cohesive in both rivers. The very mild longitudinal slopes caused uncertainty in water surface slope measurements. The associated error in the water level measurement was considered to be Dh = 2 cm.

Coverage of in-stream and bank vegetation was mapped in the field in midsummer into four classes: 0 = no, 1 = sparse, 2 = moderate, and 3 = dense vegetation cover. The vegetation types were divided into three: H = flexible vegetation (herbs, grasses), S = stiff vegetation (shrubs, bushes) and T = stiff arborescent vegetation (trees). This relative classification allows comparison of the reaches with each other. Detailed descriptions of the rivers are given in the next sections. Banks are being referred to as the area above the mean water level.

Tuusulanjoki

The Tuusulanjoki is a river in a rather populated area in southern Finland. The mean discharge is 1.2 $m^3 s^{-1}$ and mean high discharge $HQ_{1/20}$ is 14–16 $m^3 s^{-1}$. The 125-km^2 catchment area is divided into lakes (6%), forest (55%), fields (28%) and infrastructure (11%) by its land use (Lempinen *et al*. 1999). The 15-km-long river begins from a regulating dam of a lake, Tuusulanjärvi. In the future, the present adjustable weir will be replaced by an overflow weir, causing greater peak flows with shorter duration. Main targets in the construction plan of the Tuusulanjoki are, firstly, improving the conveyance capacity and flood management during high flows to protect the infrastructure, and secondly, protecting biodiversity and recreational use during low flows. Two reaches of the Tuusulanjoki were selected for this study:

— T1: 1500–1978 metres from the downstream end (confluence with the Vantaanjoki); sinuosity s = 1.60; narrow channel with steep bank slopes, bottom material clay, silt and sand; no in-stream vegetation (vegetation coverage 0) but very dense willows on the banks (3, vegetation type T); some locally collapsed banks on the mid-reach.

Fig. 2. Reach P2 in the Päntäneenjoki with trees fallen into the channel before the construction works.

— T3: 8527–9085 m; $s = 1.06$; mild bank slopes, bottom material clay; sparse to moderately dense willows on the banks (1–2 S), and some sedges, reeds and other grassy type of vegetation below the mean water level (2 H).

The average longitudinal bottom slope S of these reaches is 0.0014 between the cross-sections 1500 m and 9085 m.

3.2. Päntäneenjoki

The land of the 210-km^2 catchment area of the Päntäneenjoki (MHQ 22 m^3 s^{-1}, HQ$_{1/20}$ 40 m^3 s^{-1}) is one-third under cultivation, and the rest is mainly forest and undeveloped fields and meadows. The catchment area has no lakes.

The river is meandering and erosion-prone. Floods are a result of the low conveyance capacity and obstructions caused by collapsed riverbanks. Three reaches of the Päntäneenjoki were selected for the study:

— P1: 2483–3450 metres from the downstream end (confluence with the Kainastonjoki); $s = 1.38$; bottom material clayey silt; sparse grassy in-stream vegetation (1 H), sparse willows and dense grassy vegetation on the banks (1 S&T, 3 H).

— P2: 6485–7706 m; $s = 1.70$; bottom material silt and clayey silt; sparse grassy in-stream vegetation (1 H), sparse willows on the banks (1 T); several small woody debris dams before and after the construction works; some locally collapsed banks on the mid-reach.

— P3: 10 290–11 300 m; $s = 1.89$; bottom material clayey silt; moderately grassy vegetation in the channel, dense shrubs on the banks below the mean water level (2 H, 3 S), dense willows and trees on the banks (3 S&T); woody debris and collapsed bank material in the channel.

The average longitudinal bottom slope S is 0.0002 between the cross-sections 2483 m and 11 300 m.

In the Päntäneenjoki, flood management was designed to reduce the damage for both agriculture and infrastructure caused by spring and summer floods. The design and construction was made by West Finland Regional Environment Centre. Passive and active flood protection works were carried out in the pilot reach P2 in 1998. Field measurements were done before and after the construction, denoted with P2 old and P2 new, respectively. Figure 2 shows a typical view from P2 before the construction works. It was desirable to reduce the frequency of overbank flows. Conveyance during high flows was improved by increasing the cross-sectional area above the mean water level. To protect the substrate diversity, most woody debris below the mean water level was left as it was. Meandering and variation of cross-sectional profiles was enhanced. In addition, various bioengineering methods were tested

Fig. 3. Example of applying brush mattresses in reach P2 of the Päntäneenjoki.

along the pilot reach P2 to stabilize the banks and reduce erosion. The tested methods were brush mattresses (Fig. 3), live and dead fascines, log revetments, and bank shaping and planting using primarily live grasses and stakes. Wetland biotopes were constructed onto adjacent fields to detain non-point source pollution, improve habitat diversity and improve flood retention.

The following measures were carried out along reach P2:

— 6485–6700 m: The riverbanks were dredged above the mean water (MW) level. Rock riprap and live fascines were applied locally for erosion control on the right bank (when looking upstream), and willow mattress, live fascines and willow stakes were applied on the left bank. A deflector was constructed in sub-reach 6678–6690 m.
— 6700–6820 m: A few brush mattresses were applied for erosion control in outer bends, and grass-type vegetation was planted on banks. From 6600 m to 6770 m, a flood channel was constructed 1.9–2.6 m below the bankfull level, shortening the river course by about 100 m.
— 6820–6950 m: Parts of the riverbanks were dredged above the MW level. Live willow (*Salix* sp.) stakes were planted on the right bank, and live fascines and black alder (*Alnus glutinosa*) saplings were planted on the left bank, where also a deflector was placed in sub-reach 6840–6860 m.
— 6950–7126 m: The right bank was dredged above the MW level, and willow stakes were planted. A low stone weir will later be constructed in location 7075–7100 m.
— 7126–7300 m: The left bank was dredged and saplings of black alder (*Alnus glutinosa*), birch (*Betula pendula*), rowan (*Sorbus aucuparia*) and grey alder (*Alnus incana*) were planted with live willow stakes. On the right bank rock riprap was applied to a 50-m-long reach for erosion control with willow stakes.
— 7300–7475 m: Only minor parts of the left riverbank were dredged and saplings of birch, grey alder, willow and bird cherry (*Prunus padus*) were moved here from the dredged banks.

Results and analysis

Spatial and temporal variations in resistance of different river reaches were investigated to get an insight into the relationships between flow variations and different factors causing resistance.

In the Tuusulanjoki, discharge varied from 0.27 to 7.43 $m^3 s^{-1}$ i.e. from very low discharge to about mean high discharge (MHQ). The surface width varied from 3 m to 18 m. In reach T1, Darcy-Weisbach friction factor f was on average higher than in reach T3, although overall, vegetation was denser in reach T3. This was partly due to higher sinuosity, larger bottom material

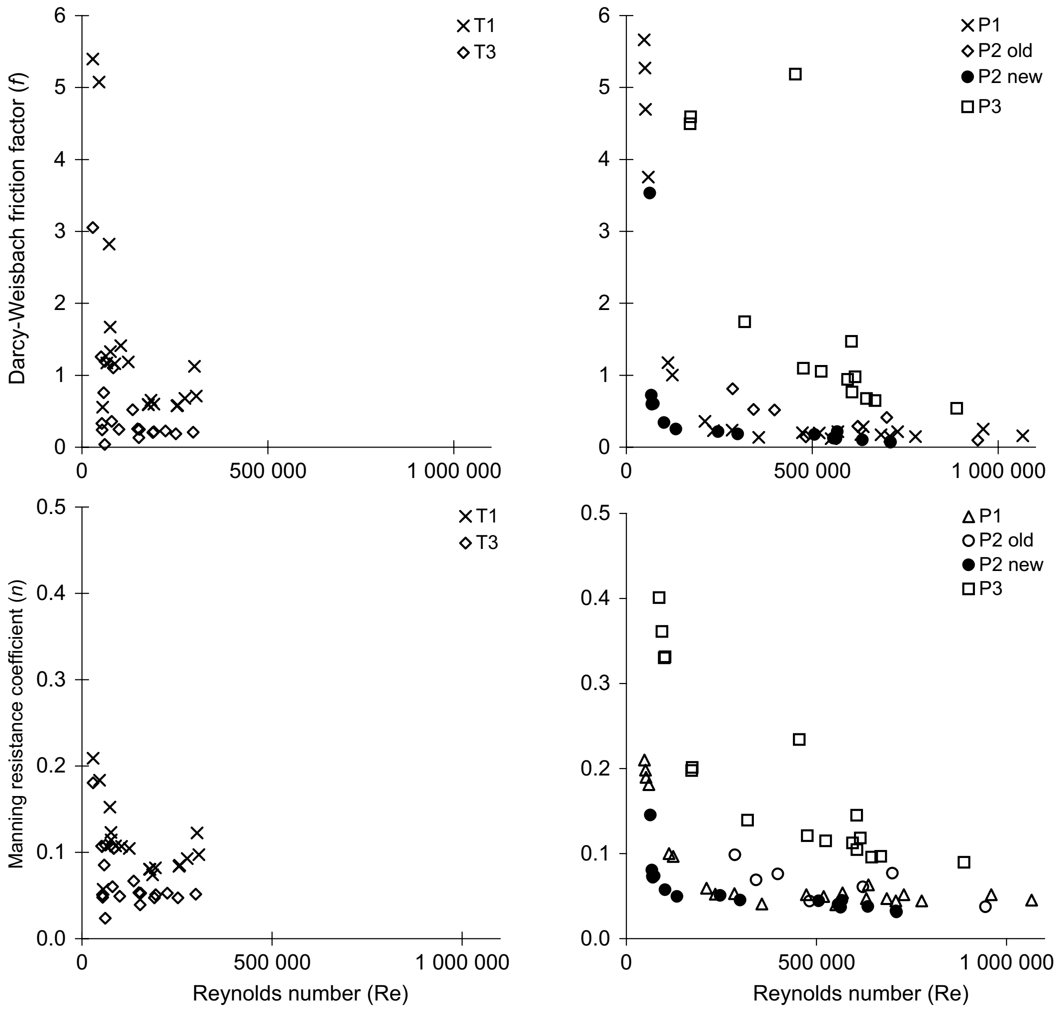

Fig. 4. Darcy-Weisbach friction factor f and Manning resistance coefficient n as a function of Reynolds number Re in the Tuusulanjoki (T) and Päntäneenjoki (P); reach-averaged results.

and some local losses caused by collapsed banks in the mid-reach. The summary of the results is presented in Table 1 and in Fig. 4. Significant changes in friction factors caused by vegetation growth were not detected during the growing season, whereas some yearly differences were found. The seasonal and yearly variation and the dates of measurements are given in Fig. 5. For

Table 1. Summary of the field data of the Tuusulanjoki (T) and Päntäneenjoki (P); reach-averaged values.

River reach	s	Q ($m^3 s^{-1}$)	v ($m s^{-1}$)	h (m)	Re	Fr	f	n
T1	1.60	0.27–7.02	0.15–0.43	0.65–2.79	29000–307600	0.05–0.14	0.56–5.40	0.057–0.209
T3	1.06	0.28–7.43	0.08–0.40	0.89–2.39	29100–299300	0.03–0.12	0.04–3.05	0.024–0.181
P1	1.38	0.35–20.6	0.08–0.67	0.99–3.51	47900–1065900	0.04–0.16	0.12–5.66	0.040–0.210
P2 old	1.70	0.35–10.2	0.38–0.62	2.36–3.92	285600–945100	0.11–0.16	0.10–0.81	0.038–0.099
P2 new	1.70	2.59-19.0	0.12–0.48	0.77–3.58	63500–710700	0.05–0.12	0.07–3.53	0.031–0.145
P3	1.89	0.31–16.9	0.18–0.49	0.80–4.07	86200–888400	0.05–0.11	0.54–20.3	0.090–0.401

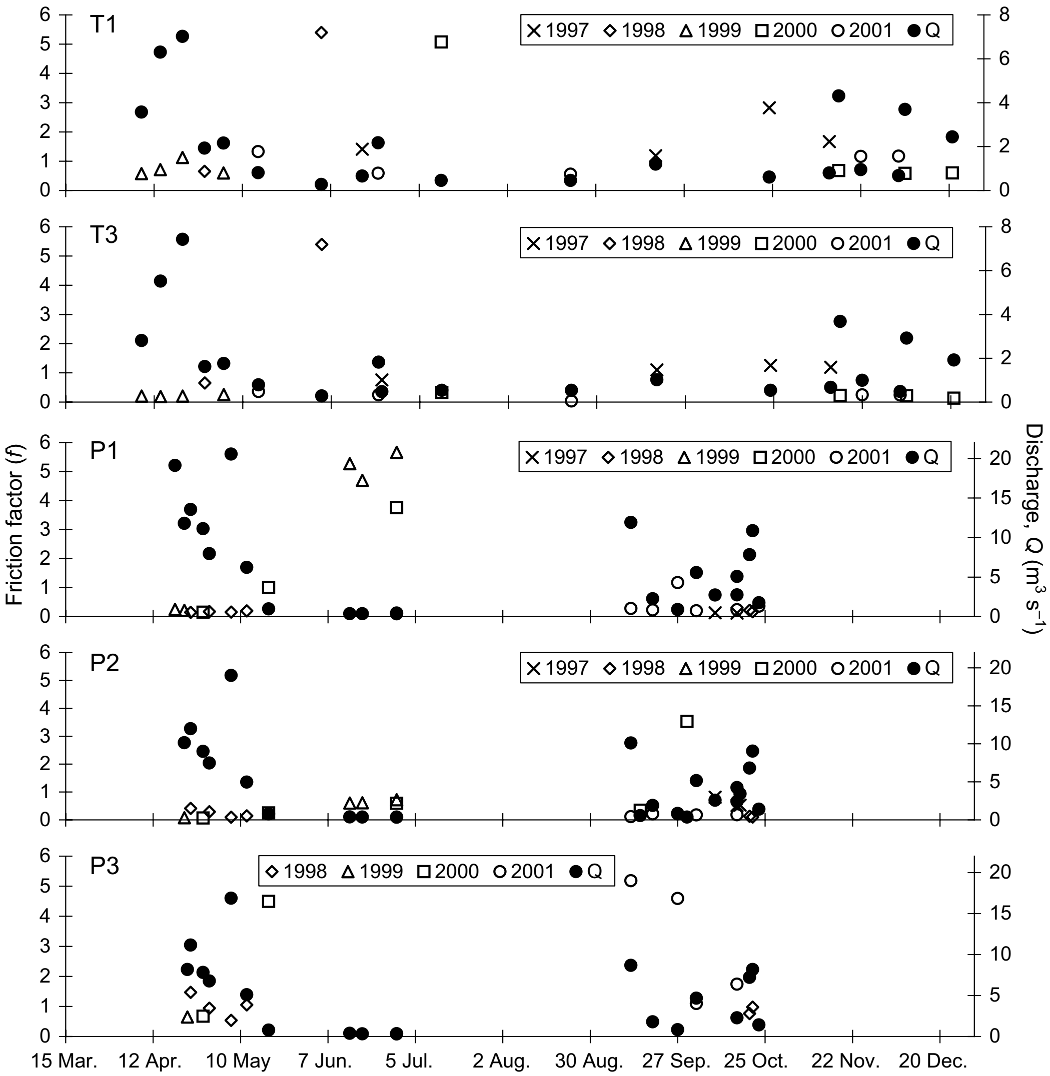

Fig. 5. Yearly and seasonal variation of friction factor and discharge in the Tuusulanjoki (T) and Päntäneenjoki (P).

example, in late autumn 1997, friction factors were somewhat greater with the same discharge as in autumn 2001 in both reaches. Furthermore, in reach T3, the discharges in the end of 2000 were much greater than in the end of 2001 because of the exceptionally rainy period of October–December 2000, but the friction factors were approximately of the same magnitude.

The resistance coefficients were similar to or somewhat greater than the literature values (Chow 1959) and values computed with Cowan's (1956) method (Fig. 6). Chow's and Cowan's values are based on mean flow. The relative roughness, k/R, is larger during low flow, which increases the friction factor f according to Eq. 6. Thus, high values were mainly caused by large relative roughness, i.e. large roughness elements and low flow, but some larger values were also found in reach T1 during high flow. Based on the results, Cowan's and Chow's methods well predict resistance coefficients for mean flow, but not for low flow.

In the measurements of the Päntäneenjoki, discharges varied from mean low discharge

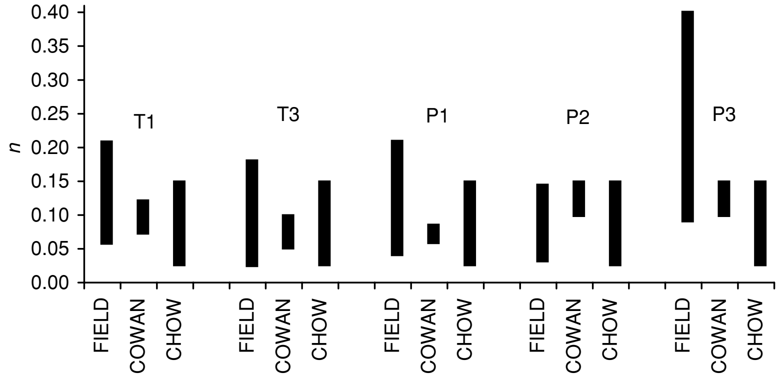

Fig. 6. Comparison of Manning coefficients from the field data, Cowan's method and Chow's classification in the Tuusulanjoki (T) and Päntäneenjoki (P); reach-averaged results.

(NQ) to mean high discharge (MHQ). The surface width varied from 3 m to about 25 m. In the approach to compute *f*, it was assumed that reach P2 after the construction can be treated similarly to the other reaches despite the narrow floodplains constructed above the mean water level. At the same water levels, the ratio of the wetted perimeter to the cross-sectional area did not significantly change from the pre-construction state. Therefore, the channel was not treated as a typical two-stage channel. The introduced error is expected to be small for high flows, which are important for flood conveyance.

Before the construction of the pilot reach in summer 1998, the friction factors in reach P2 were slightly higher than in reach P1, mainly because of higher sinuosity, except on very low discharges. Friction factors were clearly highest in reach P3, partly because of high sinuosity and dense vegetation, especially on the banks. During low water level, woody debris and local bank collapses increase the flow resistance. The summary of the results is presented in Table 1 and Fig. 4. Seasonal or yearly variation in *Q*–*f* relationships could not be detected in the Päntäneenjoki (Fig. 5). After the construction works, the friction factors in the whole reach P2 decreased to about the same as in reach P1. This was because the channel was not left totally untouched below the mean water level, but woody debris was locally removed. However, the resistance increased in those sub-reaches where no major dredging was carried out (Fig. 7). This could be because of two reasons. Firstly, altering the channel into a two-stage shape could increase the flow resistance because of momentum exchange between the mid-channel and the newly constructed floodplain. Secondly, the friction factor of the vegetation used for bioengineering could be higher than that of the original vegetation.

The sub-reaches 7300–7706 m and 6485–6700 m had relatively low friction factors on all discharges. The mid-reach between these sub-reaches had collapsed banks in cross sections 6825 m, 6900 m, 7050 m and 7188 m. This may increase the friction factors especially on low discharges because of increased longitudinal variation on the sub-reaches between 6700 m and 7300 m.

The resistance coefficients in reaches P1 and P2 were similar to or somewhat higher than the literature values (Chow 1959) and those calculated with Cowan's method (Fig. 6), but in reach P3 they exceeded the literature values clearly. This may be partly because of dense vegetation especially on the banks. There are dense willows on the banks of reach P3, which can cause considerable momentum exchange between the mid-channel and the vegetated zone and thus, increase the friction factor. Presumably, Cowan's and Chow's methods are not able to give proper resistance coefficient values for a low flow situation, but neither for flow in a channel with floodplains or densely vegetated banks.

The effects of bank vegetation on reduction of channel capacity are significant when the ratio between surface width and water depth of the channel, B/h, is smaller than 16 (Masterman and Thorne 1992). The B/h ratio along the river reaches varied in the Tuusulanjoki from 3.2 to 10.5 and in the Päntäneenjoki from 3.3 to 17.4. Variations inside and between the reaches are

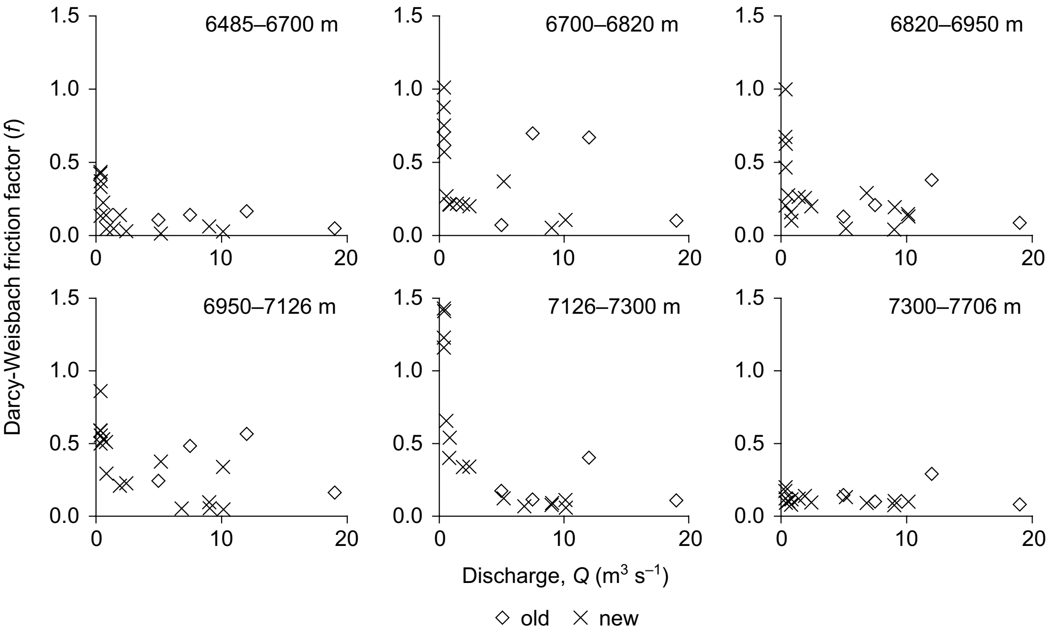

Fig. 7. Darcy-Weisbach friction factor *f* as a function of discharge *Q* ($m^3 s^{-1}$) in sub-reaches of reach P2 of the Päntäneenjoki; results are presented for each sub-reach between two cross sections.

shown in Fig. 8 as values for each cross section instead of an averaged value for the whole reach. In reach P2, the variation of both *f* and *B*/*h* between the sub-reaches of reach P2 increased significantly after the construction. No general dependence was found between the width-depth ratio and the friction factor *f* in either of the rivers. However, it is reasonable to assume that in reaches T1 and P3, the friction factors were increased because of the momentum transfer between the vegetated banks and the mid-channel.

Relatively high friction factors, especially for reaches T1 and P3, indicate that besides the bottom roughness height, also other resistance factors have a significant effect on the flow resistance in the Tuusulanjoki and Päntäneenjoki. Therefore, a detailed analysis of friction factors was carried out to determine which characteristics affect the friction factors the most along each reach and to separate other resistance factors from the bottom roughness height *k*. The friction factor *f* for each reach was divided into parts by Eq. 5. The roughness height values *k* were estimated for each reach based on the values of Schröder (1990), and values for f_b were computed with Eq. 6 using parameters c_1 and c_2 for a rectangular channel. The friction factors f_s were estimated based on Eq. 7 and the values for f_e were computed with Eq. 5 by subtracting other parameters from the measured value of *f*. The values for each factor are presented in Table 2.

Friction factors *f* in reaches T3, P1, and P2 both before and after the construction were well explained by the division approach, as f_e was almost negligible. Thus, it was assumed that no other resistance factors significantly affect the resistance. However, in reaches T1 and P3, values of f_e were much greater. During the low discharge, it could be explained by local bank collapses increasing the relative roughness. However its effect was decreased with increased water level. During the high discharge, the high flow resistance could be explained by the additional resistance caused by the momentum transfer between the mid-channel and the bank vegetation. To estimate the additional friction factor caused by the momentum exchange, some methods have been developed, e.g. Mertens 1989, Pasche and Rouvé 1985, but more detailed data on vegetation density and location would be necessary for the estimation. The negative values shown in Table

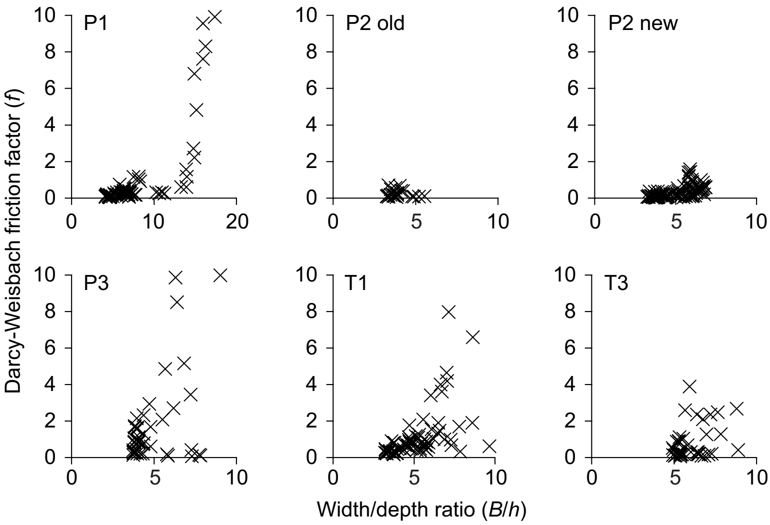

Fig. 8. Darcy-Weisbach friction factors f as functions of width-depth ratios B/h in the Tuusulanjoki (T) and Päntäneenjoki (P); results are presented for each sub-reach between two cross sections.

2 may be due to over-estimation of the values of roughness height k and inaccuracy of the other parts of the summation procedure.

After the construction of reach P2, friction factors were still relatively high during low flows because only minor clearing was performed in the lower part of the cross-section. The tested bioengineering methods had no significant effect on the flow resistance, and therefore their use did not reduce the conveyance capacity of the channel. The application of bioengineering methods in the Päntäneenjoki proved to be relatively successful. However, some of the tested bioengineering methods were unsuccessful, as many live stakes and fascines died during the first winter because of extreme winter conditions with up to 1.6-metre-thick ice cover. Success of bioengineering methods is highly dependent on weather conditions during the first couple of years. Re-installation and re-planting may be needed during the first years after the construction works.

A sensitivity analysis was carried out for the computation procedure. Partial derivatives of Eq. 3 were determined to get the error in f due to errors in the measured parameters of cross section, velocity and water level. Unsteadiness of the flow was not of particular concern during the measurements as the catchment is mostly forest and fields, and the slopes are mild. Based on

Table 2. Darcy-Weisbach friction factor f partitioned by Eq. 5; f_b includes the effects of the channel shape. Reach-averaged values for two discharges.

River reach	Q (m^3 s^{-1})	B (m)	A (m^2)	h (m)	R (m)	Re	f	n	k (m)	f_b	s	f_s	$f_e = f - f_b - f_s$
T1	1.20	6.03	4.47	1.09	0.66	124300	1.19	0.10	0.80	0.26	1.60	0.15	0.78
T1	7.02	13.14	19.65	2.79	1.30	307900	1.13	0.12	0.80	0.15	1.60	0.09	0.88
T3	1.76	7.31	6.14	1.24	0.76	149400	0.25	0.05	0.90	0.25	1.06	0.01	–0.01
T3	7.43	14.91	18.83	2.39	1.17	299300	0.21	0.05	0.90	0.18	1.06	0.01	0.02
P1	2.26	8.86	8.81	1.50	0.92	234200	0.23	0.05	0.60	0.16	1.38	0.06	0.01
P1	11.12	13.44	21.70	2.73	1.41	708600	0.15	0.04	0.60	0.12	1.38	0.04	–0.01
P2 old	4.97	8.56	13.29	2.36	1.28	482200	0.15	0.04	0.50	0.11	1.70	0.03	0.00
P2 old	12.00	14.46	27.58	3.69	1.63	700000	0.41	0.08	0.50	0.10	1.70	0.03	0.28
P2 new	2.41	6.97	7.36	1.60	0.91	300000	0.18	0.05	0.45	0.13	1.70	0.04	0.01
P2 new	9.01	10.45	19.51	3.02	1.53	711000	0.07	0.03	0.50	0.10	1.70	0.03	–0.07
P3	2.28	8.06	10.41	1.62	0.99	319000	1.74	0.14	0.90	0.20	1.89	0.06	1.48
P3	11.16	17.55	37.80	3.97	1.81	606000	1.47	0.15	0.90	0.13	1.89	0.04	1.30

the analysis, a maximum error of 10%–30% in the roughness coefficient was found realistic for most cases (Helmiö 1997).

Conclusions and recommendations

Environmental flood management includes engineering, ecological, geomorphic and hydrological aspects. In hydraulic design, a detailed understanding of complex river channels is needed. In general, the friction factors determined from the field measurements in the Tuusulanjoki and Päntäneenjoki were well in line with the values presented by Cowan (1956) and Chow (1959). However, the results differed significantly from these values in reaches with considerable bank vegetation.

The friction factors of reaches T3, P1 and P2 could be explained by the superposition approach of Einstein and Banks (1950). This was not the case in reaches T1 and P3, in which the momentum exchange between the mid-channel and dense bank vegetation affected considerably the friction factors. The resistance effects of woody debris, local bank collapses, and momentum exchange increased the friction factor more than 50% in reaches T1 and P3. The results of the field study assist practising engineers to assess the effects of environmental flood management on channel conveyance in similar conditions.

The superposition approach proved to be applicable in partitioning the friction factor into components. It was accurate in the channel reaches with simple hydraulic properties, but an adjustment of the method is necessary in complex channel reaches. The friction factor of the additional resistance caused by the momentum exchange should be determined using e.g. the method of Mertens (1989) or Pasche and Rouvé (1985), but it would require detailed quantitative data on vegetation spacing that was not available for this study. Therefore, more detailed vegetation mapping should be carried out along the hydraulic field measurements. The significance of the momentum transfer due to vegetation in the Päntäneenjoki will be investigated in more detail in a subsequent paper.

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Appendix. Used symbols.

B	surface width
c_1, c_2	constants dependent on the shape of channel cross section
f	Darcy-Weisbach friction factor
f_b	D-W friction factor for the surface roughness and vegetal drag
f_e	D-W friction factor for all the other factors causing resistance
f_s	D-W friction factor for sinuosity
Fr	Froude number ($= v/(gh)^{1/2}$)
g	acceleration due to gravity
h	average water depth of cross section
H_f	energy loss
k	roughness height
L	characteristic length
n	Manning resistance coefficient
n_s	Manning resistance coefficient for sinuous channel
Q	discharge
R	hydraulic radius
Re	Reynolds number
s	sinuosity
S	longitudinal bottom or energy slope for uniform and non-uniform flows, respectively
v	average flow velocity
z	bottom elevation
ν	kinematic viscosity