

Hydraulic considerations in restoring boreal streams

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Abstract The physical habitat that controls ecosystem functioning is determined by local hydraulics and channel morphology. Hydraulic field studies were conducted in a boreal stream (1) to test the hypothesis that the local hydraulic conditions are determined by cross-sectional geometry and flow resistance in boreal conditions by analysing the relationship between flow velocities, cross-sectional geometry and flow resistance, and (2) to suggest success criteria for the restoration of local hydraulic conditions. Results suggest that, in the case of small channels, cross-sectional geometry and flow resistance are weakly interconnected and influenced by factors such as local roughness elements and channel forms. The study showed that both flow resistance and cross-sectional geometry are vital factors in determining local hydraulics. In stream restoration, a design based on consideration of only one of these two factors is inadequate and may result in a failure to replicate natural hydraulic conditions. Simple success criteria for the restoration of local hydraulics are developed.

Keywords Flow resistance; hydraulics; restoration; rivers; roughness; vegetation

Notation

A	cross-sectional area [m^2]
B	surface width [m]
f	Darcy–Weisbach friction factor [-]
g	acceleration due to gravity [m s^{-2}]
h	flow depth [m]
H_f	energy loss [m]
L	reach length [m]
n	Manning's roughness coefficient [$\text{s m}^{-1/3}$]
Q	discharge [$\text{m}^3 \text{s}^{-1}$]
R	hydraulic radius [m]
Re	Reynolds number [-]
s	sinuosity [-]
S	slope [-]
z	distance from the datum [m]
α	velocity distribution coefficient [-]
v	average flow velocity [m s^{-1}]
ν_k	kinematic viscosity [$\text{m}^2 \text{s}^{-1}$]

Introduction

The hydraulic analysis of flow in open channels provides the interface between discharge and the determinants commonly used by river scientists for assessing environmental flow requirements, including flow depth, bed shear stress, flow area and wetted perimeter (Jordanova *et al.* 2002). Local hydraulics and channel morphology are the primary determinants of the physical habitat, which control ecosystem functioning (Broadhurst *et al.* 1997).

The local hydraulic conditions are determined by flow resistance and geometry of a channel (Broadhurst *et al.* 1997). Non-uniform cross-sectional profiles, meanders, riffles and pools,

and natural vegetation increase the heterogeneity of depths and velocities and thus create variable habitats (Muhar 1996). However, the impacts of these features on channel hydraulics are significant though still not fully understood (Yen 2002). Channel–floodplain interaction is nowadays considered as a fundamental part of the fluvial system (e.g. Newson 1992; Brookes 1996; DVWK 1996; Ward *et al.* 2001). Traditional river engineering has focused mostly on flood conveyance. Environmentally sound hydraulic design must be effective at low and mean flows in addition to high flows to provide suitable habitat conditions.

Little is known about the hydraulic properties of small boreal streams, especially at low flows. A majority of studies in small channels have been restricted to flow resistance of irrigation canals and highway or field ditches of uniform cross section and longitudinal profile (e.g. Bakry *et al.* 1992; Maione *et al.* 2000). In natural rivers and streams channel topography, bank vegetation and in-stream woody debris may have a large influence on hydraulics (Rouvé 1987; Fisher 2001) and, further, the physical habitat (Broadhurst *et al.* 1997).

Under boreal conditions ecosystem response to stream management changes may need extra attention. Experiences gained and published on stream restoration are mostly from latitudes where climatic conditions are milder. Features such as ice and frost combined with a short growing season raise problems that have to be considered before applying any restoration measures, such as the removal of vegetation (Järvelä and Helmiö 1999).

In many restoration projects the design objectives and success criteria are not clearly stated. Ideally, the success of a restoration project should be based on several variables that can easily be measured in the field. These variables may relate to ecology (e.g. fish species presence and abundance), hydraulic conditions (e.g. depth, velocity or flow resistance) or physical habitat (e.g. conditions present in relation to the suitability for certain flora and fauna). This paper investigates the assessment of success of restoration using measurements of hydraulic conditions.

Broadhurst *et al.* (1997) stated that the local hydraulic conditions are determined by the flow resistance and geometry of the channel. The aim of this paper is to test this statement in boreal conditions. For this purpose, a field study including pristine, degraded and restored stream reaches was employed. The hydraulic conditions of the degraded and restored reaches are assessed against the conditions of the pristine reference reach. Secondly, success criteria for the restoration of local hydraulic conditions are suggested and a procedure for applying the success criteria in post-project evaluation is presented.

Hydraulic considerations

Factors affecting the flow resistance in open channels include substrate, flow depth, cross-section shape, vegetation, sinuosity, bed forms, sediment transport and ice cover. Important advances have been made to address the effects of these factors, as summarised in a comprehensive review by Yen (2002). Flow analysis is often based on empirical or semi-empirical models or equations because of the complex nature of the flow system and the diversity of the channel conditions. Professional judgement is often needed at some stage of the hydraulic design process. Stream restoration with complicated hydraulic features has further confused the process, since the hydraulic design methods developed for regular channels are generally not valid for natural channels (Rouvé 1987; Fisher 2001).

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

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

where v = average flow velocity, g = acceleration due to gravity, R = hydraulic radius and S = bottom or energy slope for uniform and non-uniform flows, respectively. In practical

river management, reference publications (e.g. Chow 1959; Barnes 1967; Hicks and Mason 1999; Coon 1998) are often used for selecting a roughness coefficient, which lumps all the flow resistance processes into Manning's coefficient, n . In the present study the friction factor is preferred in the analysis, but it can be related to Manning's n by the equation

$$f = 8gR^{-1/3}n^2. \quad (2)$$

The friction factor can be partitioned into grain and form components (Einstein and Banks 1950; Millar 1999). The resistance associated with the solid boundary of a gravel-bed channel can be divided into three parts: a component caused by friction created by individual grains; a component of form resistance associated with flow separation over small-scale structures and a component of form resistance associated with large-scale bed undulations such as pools and riffles (Lawless and Robert 2001). The last component is often included in river restoration schemes, where it could have a significant effect on flood levels (Millar 1999). Different factors affecting the flow resistance can be combined by the linear superposition approach to estimate the total friction factor (Einstein and Banks 1950). For small channels, this may not be possible in practise, because the influence of individual roughness elements and local roughness extremes on flow resistance may be of great importance.

Vegetation is a key part of the interrelated system of flow, sediment transport and geomorphology in rivers (Tsujimoto 1999). Masterman and Thorne (1992) considered bank vegetation to be a significant factor in reducing the discharge capacity of natural rivers and flood channels. They related the reduction in channel capacity to the width–depth ratio, suggesting that vegetation effects are significant if the ratio is less than 16. Over the years, a significant amount of research has been carried out in developing resistance laws for channels with flexible vegetation (e.g. Kouwen and Unny 1973; Kouwen and Fathi-Moghadam 2000), stiff vegetation (e.g. Petryk and Bosmajian 1975; Pasche and Rouvé 1985) and a combination of both (e.g. Järvelä 2002). In addition, some studies have focused on velocity profiles and turbulent characteristics of vegetated channels (e.g. Shimizu and Tsujimoto 1994; Nepf 1999; López and García 2001).

McKenney *et al.* (1995) argued that the effect of woody debris on sedimentation, scour and flow damming has not been adequately addressed for low-gradient streams. Field studies by Manga and Kirchner (2000) revealed that a woody debris cover of less than 2% of the streambed provided roughly half of the total flow resistance. Shields and Gippel (1995) reported, based on field studies on two 20–50 m wide rivers, that removal of debris decreased the friction factor for near-bankfull conditions by roughly 20–30%. Huang and Nanson (1997) reported that in small forested rivers log and debris dams and large protruding roots can dominate channel morphology, obscuring hydraulic geometry relations.

Field studies

Background: restoration project

Restoration of Myllypuro Brook in southern Finland was selected to illustrate the challenges in hydraulic design of small boreal streams. Myllypuro Brook is situated in Nuuksio National Park in southern Finland. It is a small boreal stream with a forested catchment area of 24.5 km² and a mean discharge of 0.24 m³ s⁻¹. The stream is 8.8 km long and has a surface width range of 1–5 m. In the early 20th century, parts of the catchment were in agricultural use as fields and pastures and the brook was partly straightened and deepened for land drainage. Before these modifications, the brook flooded frequently during snowmelt. Under the current land management scheme ecological aspects are of primary concern. For this reason, the channel–floodplain interaction with frequent flooding is desired for restoration.

The restoration project included design challenges, such as the reconstruction of meanders, cohesive sediments, mild slopes, diverse vegetation and harsh climatic conditions (Figure 1).

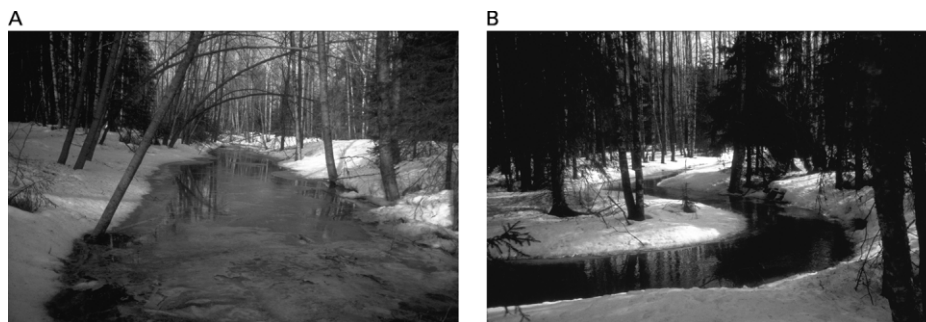


Figure 1 Before and after the restoration: the brook was restored to its historical meandering channel (right) from the channelized reach, which was dredged in the 1960s (left)

Because of the relatively low stream power and cohesive sediments, natural geomorphological processes can be slow. Thus, channel instabilities may not be a problem, but neither are the defects in channel design adjusted by changes in the channel morphology. The boreal climate with a short growing season and a cold winter restricts both bioengineering and the natural recovery of vegetation. In addition, privately owned land in the brook valley sets spatial boundary conditions for the hydraulic and geomorphic design. The brook provides several interesting field study sites as both pristine and engineered reaches of various levels of disturbance or degradation can be found.

Hydraulic investigations

The hydraulic studies were conducted in eight reaches of the Myllypuro Brook over a five-year period, 1997–2001. The field study included pristine, restored and degraded and straightened reaches. It was assumed that the conditions found in the pristine reach may be regarded as a reference for the degraded and restored reaches. Herein, it is however recognised that the magnitude of the flow resistance coefficient, which can be used to describe the hydraulic conditions, depends strongly on the physical scale of analysis as reach estimates average several different local environments (Broadhurst *et al.* 1997).

The study reaches were delimited so that the cross-sectional geometry was relatively homogeneous within the individual reaches. This approach was based on the available longitudinal and cross-sectional profiles, topographic maps and professional judgement. For each study reach three to six representative cross sections were surveyed to characterize the reach. Datum marks were installed in each surveyed cross section in order to reliably monitor cross-sectional geometry and water stage. A sub-reach was delimited to be between two surveyed cross sections so that, for example, three surveyed cross sections made two sub-reaches. Lengths of the sub-reaches varied from 36–79 m. Flow velocities were measured using a minipropeller-type current meter. Velocity measurements were taken from 1–6 depths in 1–8 verticals at such cross sections where the disturbing effects of the channel form and vegetation were at a minimum.

Coverage of in-stream and bank vegetation was mapped in the field in midsummer into four classes as follows: 0 = no, 1 = sparse, 2 = moderate and 3 = dense vegetation cover. Four types of vegetation were distinguished: short herbs (SH) (<20 cm), tall herbs (TH) (>20 cm), shrubs (S) and trees (T). SH and TH represent flexible grassy vegetation whereas S and T represent arborescent stiff vegetation.

The properties of the reaches are described in the following text beginning from the upper reaches and continuing downstream. Selected physical, geomorphic and vegetation parameters are compiled in Table 1. The longitudinal slopes were calculated from the lowest point of each cross section. Reach M1 (6000–6303 m upstream from Lake Pitkäjärvi) was in

Table 1 Physical, geomorphic and vegetative properties of the field study reaches

Reach	Reach length L (m)	No. of sub-reaches	Sinuosity s	Bottom slope S	Bank-full depth (m)	Bank-full width (m)	In-stream vegetation cover*	Bank vegetation cover*	Bank vegetation type*
M1	250	6	1.3	0.0004	0.6	3.5	3	2	TH + SH
M2	213	4	1.0	0.0028	1.1	4.0	1	2	TH + S
M3	179	4	1.05	-0.0007	1.6	6.7	0	2	TH
M5	213	4	1.0	0.0020	1.6	7.1	1	2	TH + S
M6	475	5	1.8	0.0048	0.9	3.1	0	2	TH + S
M7	179	4/5	2.0	-0.0002	1.4	5.2	0	1	SH + TH
M8	135	2	1.3	0.0061	1.2	5.5	0	1-2	TH + SH
K9	35	2	1.3	0.0077	1.4	6.3	0	1-2	TH + SH

* See text for definitions.

natural condition with no engineering works. The substrate was of organic type: peat and mud. Aquatic plants (dominant species: *Nuphar lutea*, *Iris pseudacorus*, *Lysimachia thyrsiflora*) were abundant and stream banks were dominated by grassy vegetation. Flow velocities were small because of a very mild slope. Further downstream, reach M2 (4651–4849 m) was a straightened channel with a clay and silt bottom. Aquatic vegetation (*Potamogeton sp.*, *Sparganium sp.*) was sparse, but banks grew moderate cover of herbs, bushes (*Salix sp.*) and trees. Reach M6 (3655–4130 m) was pristine and strongly meandering. Cross sections were narrow with steep side slopes. There was moderate vegetation cover on the banks (*Deschampsia caespitosa*, *Equisetum sylvaticum*, *Dryopteris carthusiana*, *Salix sp.*), but in-stream woody debris caused damming. Reach M3 (2713–2894 m), which had been dredged in the 1960s, was straight and had uniform, wide cross sections. Vegetation cover in the bottom was almost non-existent, but moderate on the banks (*Equisetum sylvaticum*, *Dryopteris carthusiana*, *Filipendula ulmaria*, *Alnus incana*). Reach M7 (53–232 m along the new channel, numbering started from cross section 1443 m) had been restored by excavating its historical meandering alignment in 1997. The restored channel was strongly meandering with only sparse bank vegetation (*Equisetum sylvaticum*, *Ranunculus repens*, *Anemone nemorosa*) as a result of slow natural succession. Reach M5 (885–1098 m) had quite a similar history and properties as reach M3; after the second restoration phase the reach was partially filled and partially left as a backwater. As a part of the restoration project, reach M8 (625–760 m) was excavated to replace the straightened channel in December 1999. There was no in-stream vegetation, and sparse to moderate cover of grassy vegetation (*Epilobium angustifolium*, *Filipendula ulmaria*, *Angelica sylvestris*) on the banks. In July 2000 woody debris was installed into the reach to enhance the diversity and flooding. Reach K9 was located in Antiaanpuro-Koivulanoja, a small tributary of Myllypuro (102–137 m from the confluence with Myllypuro Brook). This reach was shorter because of the smaller size of the cross sections. The reach was restored in late 1999 by excavating a meandering planform to substitute for the former ditch-like channel. Soil was mostly clay, but sands and gravels were found sporadically. Grassy vegetation of sparse to moderate cover and small trees were present on the banks. Woody debris and protruding roots contributed to the spatial variability.

Results and analysis

Friction factors were calculated from the field data with Eq. (1) using the energy slope, $S_e = H_f/L$, which was determined from Bernoulli's equation

$$z_1 + h_1 + \alpha \frac{v_1^2}{2g} = z_2 + h_2 + \alpha \frac{v_2^2}{2g} + H_f \quad (3)$$

where H_f = energy loss, L = reach length, z = distance between the channel bottom and the datum, h = flow depth, α = velocity distribution coefficient assumed here as unity and subscripts 1 and 2 refer to upstream and downstream sections, respectively.

An often-used approach is to relate flow resistance to the cross-sectional geometry or the discharge. For this paper, hydraulic radius, R and depth–width ratio, h/B , were selected to represent the cross-sectional geometry. Friction factors were investigated against the flow velocity, v , the Reynolds number $Re = vR/\nu_k$, where ν_k is the kinematic viscosity, and the cross-sectional geometry. Furthermore, the parameters of the cross-sectional geometry were investigated against the flow velocity and Reynolds number. These investigations were made both at reach and sub-reach scale. The analysis is not limited to the bankfull stage or the dominant discharge and the data are biased towards small discharges. Variation of discharges can be seen in Figure 2, where reaches M3, M6 and M7 represent degraded, pristine and restored reaches, respectively.

In Figure 3, reach-averaged friction factors are presented as functions of the corresponding Reynolds numbers. Power functions were fitted to the data with R^2 values presented in Figure 3. The fitting was not carried out for reaches M1, M2 and M5 because of the limited number of measurement points. The friction factors decreased with increasing Reynolds numbers for reaches M6 and M8. The friction factor decreased with increasing flow velocity, but there was substantial variation between the reaches.

The geomorphic and vegetative characteristics of reaches M3, M6, M7 and M8 differed markedly from each other (Table 1). Reach M6 had a significantly steeper bottom slope than reaches M3 and M7. Nonetheless, the differences in the friction factors were small. Reaches M6 and M7 were highly sinuous, but the f values were in the same range as those of the almost straight reach M3. This observation is explained by the low flow velocities and the effects of vegetation and woody debris at the straight reach. Reach M3 had accumulated debris and vegetation, which seemed to compensate for the effect of straightening. The reference reach M6 meandered in pristine condition and therefore higher f values than in the other reaches were expected.

The friction factor was plotted against the hydraulic radius and depth–width ratio. Because of the similarity of the plots, only the friction factor vs the depth–width ratio is

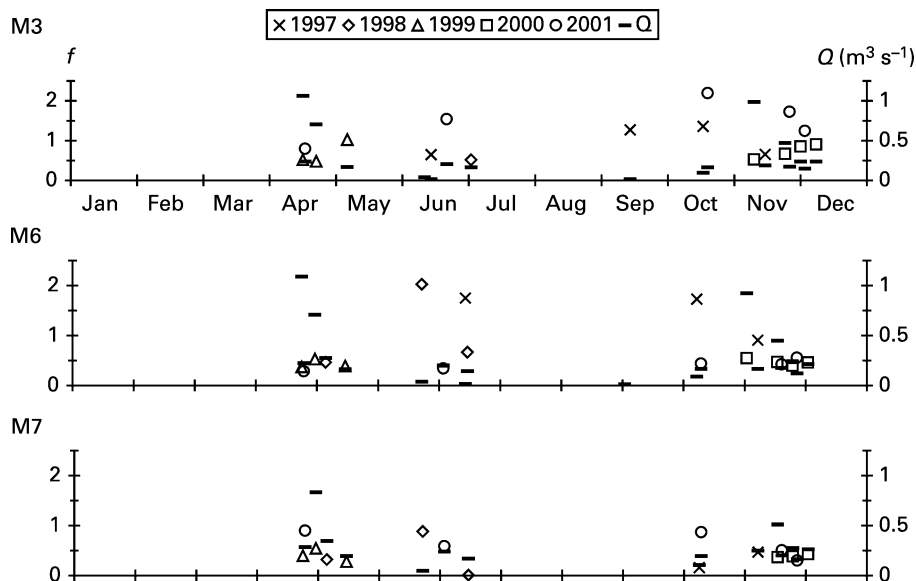


Figure 2 Variation of friction factor and discharge in different years and seasons in reaches M3, M6 and M7

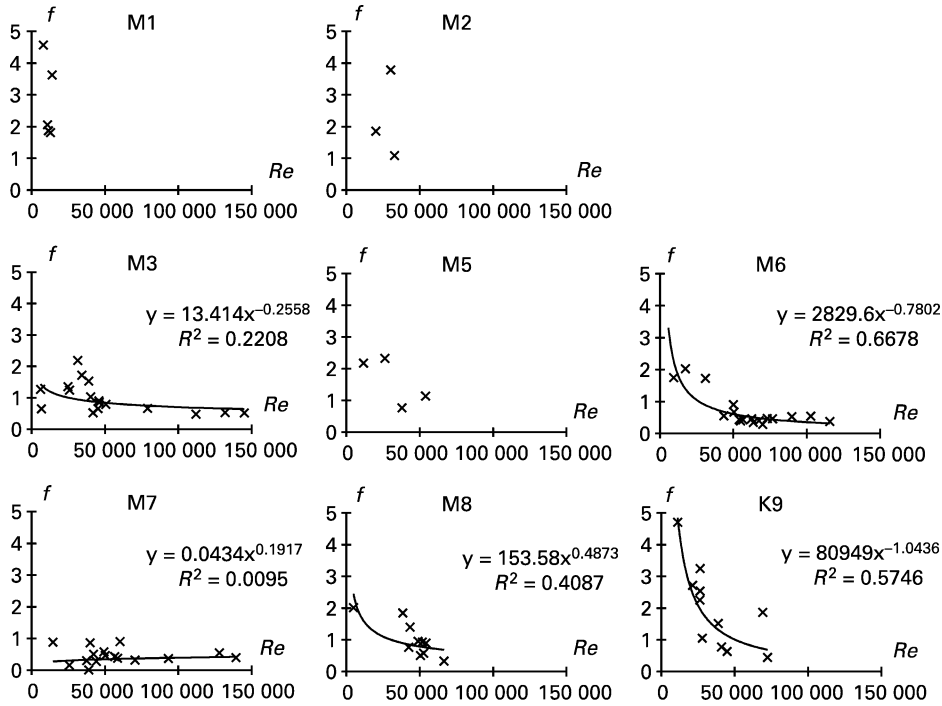


Figure 3 Reach-averaged friction factor, f , as a function of the corresponding Reynolds number. Because of the scaling, f values greater than five are not shown

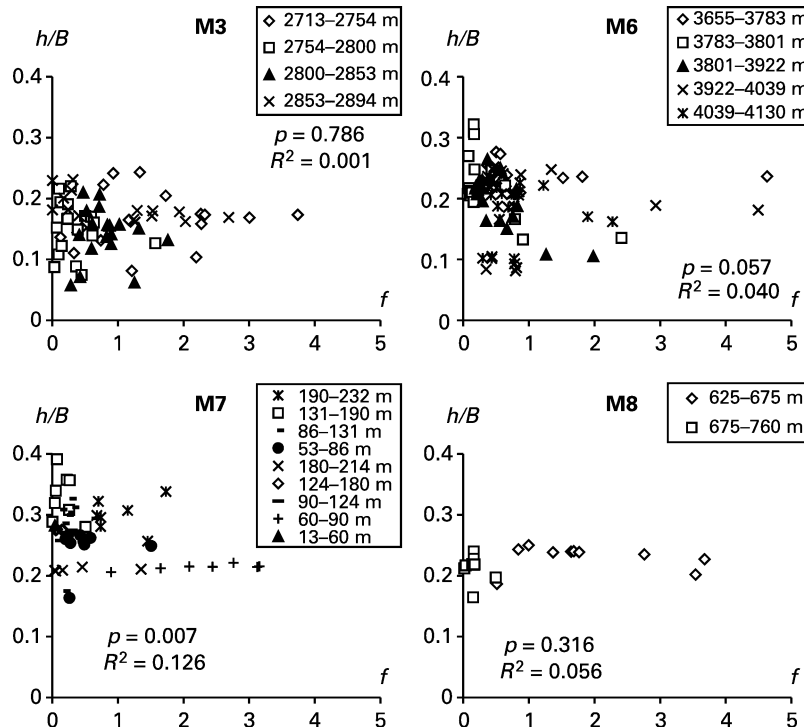


Figure 4 Depth-width ratio vs friction factor for sub-reaches of M3, M6, M7 and M8. See the text for the statistical parameters R^2 and p

presented (Figure 4). In this figure, the sub-reaches are referred to by their start and end points as a distance along the centre line of the channel from a selected zero point downstream. A linear regression analysis was carried out using the least-squares method. R^2 values and p values determined using the t -test with a 95% confidence level are shown in Figure 4. Based on the statistical analysis, both R^2 and p values were small and therefore no clear dependence between the parameters was found either at reach or sub-reach scale. The effects of individual roughness elements, e.g. logs and boulders, overlaid the effects of the cross-sectional geometry. Therefore, the length of reach analysed can strongly affect the magnitude of the flow resistance coefficient. When investigating the relationship between the flow velocities and cross-sectional geometry, the statistical analysis showed no clear dependence between the parameters (Figure 5). However, clear differences were detected between the reaches. With equal values of v , the depth–width ratio was clearly higher in reach M7 than in reaches M6 and M8.

Vegetation can be a major source of temporal variation in flow resistance. Dense vegetation can also alter the effective area of a cross section that conveys the flow. Considerable seasonal variation caused by the growth of vegetation has been reported by several authors including Bakry *et al.* (1992), Fisher (1995), Sellin and van Beesten (2002) and Maione *et al.* (2000). Vegetative characteristics in boreal streams can be expected to be different compared to warmer climates. In the present study, temporal variation in flow resistance was investigated in reaches with the greatest number of measurements: M3, M6 and M7. Data available for the analysis covered the years 1997–2001, but measurements were taken mostly in April–June and October–December. The temporal variation of the observed friction factors with corresponding discharges is presented in Figure 2. In the figure, the friction factors for discharges of the same magnitude can be compared. It appears

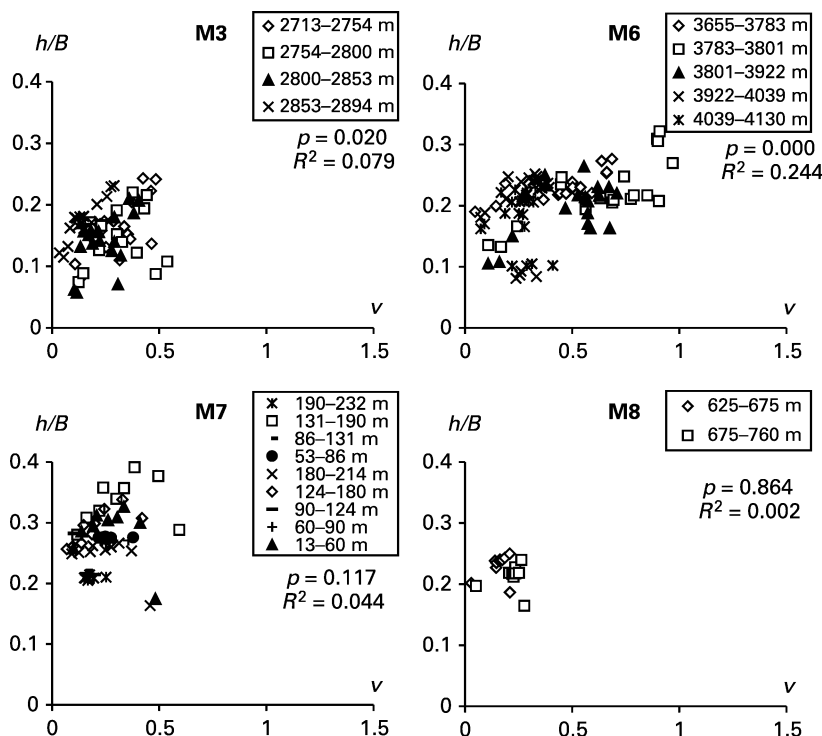


Figure 5 Depth–width ratio vs average velocity for sub-reaches of M3, M6, M7 and M8. See the text for the statistical parameters R^2 and p

that there was no distinct pattern in variation either between the seasons or the years. The discharge significantly influences the amount of vegetation and woody debris that is exposed to the flow, and therefore friction factors related to different discharges should not be compared with each other.

The friction factors of reach M7 were close to the values of the pristine reference, despite differences in cross-sectional geometry. Five years after restoration no considerable changes in flow resistance were observed (Figure 2). Field observations suggest that stream–floodplain interaction, with frequent flooding typical for the reference reach, was not gained. For the later restored reach M8, smaller cross sections were designed and woody debris was later introduced into the stream to retard the flow and to increase the substrate diversity. The adjusted design proved to be successful as both flow resistance and cross-sectional geometry were close to the values of the pristine reference. Field observations show flooding was more frequent in reach M8 than in reach M7 and thus closer to the reference.

Practical implications: success criteria and limitations

Based on the results at reach and sub-reach scales, interconnection between cross-sectional geometry and flow resistance was weaker than expected. However, it is essential that both factors meet the conditions set by the reference reach. Restoration of reach M7 showed that meeting only one of the two criteria was inadequate. In reach M8 both criteria were met and the restoration proved to be successful. In these reaches, the cross-sectional geometry and flow resistance could be used as simple success criteria for the restoration of local hydraulic conditions.

These criteria can be used as an assessment tool in post-project evaluation. Application of this procedure is presented in Figure 6. For both the reference reach and the restored reach, the flow velocity is plotted against (1) the friction factor and (2) the parameter(s) of cross-sectional geometry. The plots are compared to investigate if the relationships are similar for the reference reach and the restored reach. An example of applying the procedure is shown in Figure 7.

When comparing the experimental data with other studies, it should be noted that a majority of data in the literature were collected at higher flows and either from larger rivers

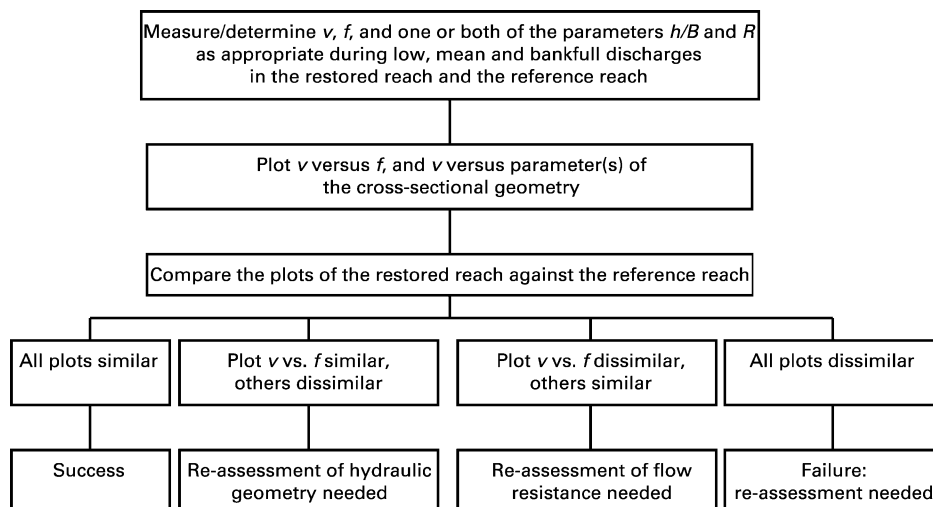


Figure 6 Procedure for applying the success criteria in post-project evaluation of local hydraulics

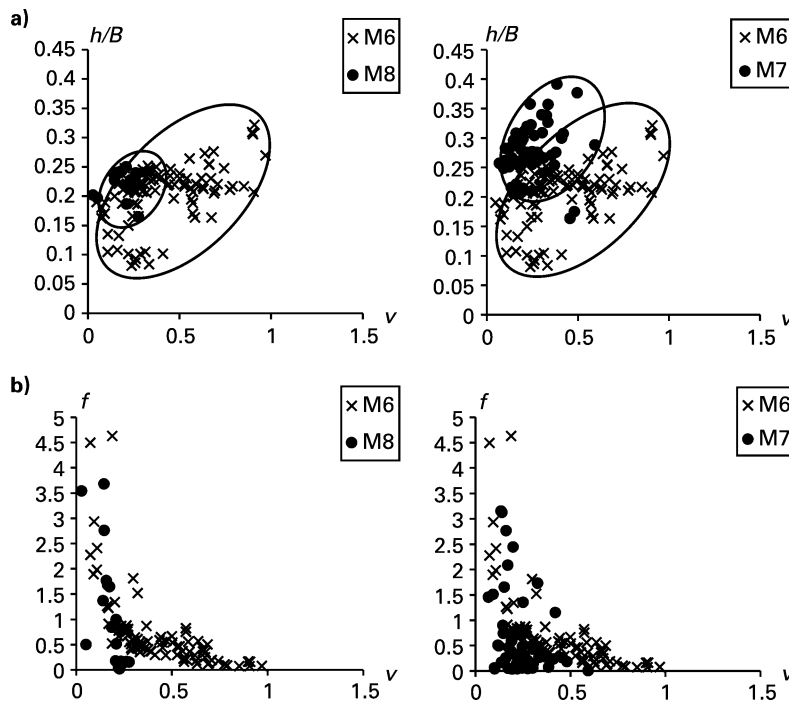


Figure 7 An example application of the procedure. (a) Depth–width ratio vs flow velocity differs in reach M7 from reference reach M6. (b) Friction factors vs flow velocities match relatively well

or engineered channels. Overall, the experimental results are in agreement with the values presented in the literature. Because of similar discharge and climatic conditions the results fit well with the study by Hosia (1980), although it was limited to low and mean flows, and in most cases only one or two measurements were taken at each location. The present data represent a wider range of flow and vegetative conditions. Barnes' (1967) roughness coefficient data for natural channels represent near-bankfull flows in larger rivers, and the greatest resistance coefficients are of the same magnitude as the minimum and mean values of the present study reaches. Excluding the low flows, the experimental values lie in the range presented in Chow (1959; Table 5-6 and Figure 5-5).

For a reliable computation of the friction factors from field data, the fundamental question is the quality of the discharge and stage measurements. Thus, a detailed sensitivity analysis was carried out for the measurement and computation procedure. An error of 10–20% was estimated for the discharge data, resulting from errors in the velocity measurement procedure (National Board of Waters 1984). Maximum errors in the cross-sectional coordinate measurements were estimated to be $\Delta x = \Delta y = 10$ cm and in location of the cross section $\Delta L = 2$ m. It is also recognised that there is uncertainty in water surface slope measurements because of the mild longitudinal slopes. Thus, in water level measurement, the error was estimated to be a maximum of $\Delta h = 2$ cm between two consecutive cross sections. Partial derivatives of Eq. (3) were determined to estimate the error in f due to errors in 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, slopes are mild and lakes attenuate run-off extremes. Based on the analysis, a maximum error of 20–30% in the roughness coefficient was estimated realistic for most cases (Helmiö 1997). One significant limitation of the research is that the quantification of in-stream vegetation over a long period of time is very difficult.

Conclusions

River and stream restoration has grown to be a common activity practised under a wide variety of circumstances. A variety of complex hydraulic problems, such as the effects of irregular profiles and vegetation, must be considered for this activity to succeed.

In the field study, the differences in the friction factors were surprisingly small between the pristine, restored and degraded stream reaches despite the fact that the geomorphic and vegetative characteristics of the reaches were markedly different. The parameters describing the cross-sectional geometry (width–depth ratio and hydraulic radius) correlated weakly with the observed flow resistance. The sinuosity or longitudinal bed slope were not able to explain the results. Spatial variations (e.g. positioning of vegetation and woody debris) were far more important than temporal variations. It is evident that in small channels site-specific factors, such as individual logs, may significantly contribute to flow resistance. Thus, particular emphasis is needed in the delimitation of field study reaches.

The results suggested that the hypothesis of flow resistance and cross-sectional geometry determining local hydraulic conditions is relevant in boreal streams. In the case of small channels cross-sectional geometry and flow resistance are weakly interconnected and are influenced by factors such as local roughness elements and channel forms. The differences in meeting the design objectives between the restored reaches show that, to achieve a sound restoration design that provides similar hydraulic conditions to those found at a natural site, both cross-sectional geometry and flow resistance need to be considered.

Parameters of cross-sectional geometry and flow resistance offer simple but valuable success criteria for the restoration of local hydraulic conditions. Fulfilling only one of these criteria would result in the failure of the design to fulfil the desired hydraulic conditions. In addition to fulfilling both criteria at reach-averaged scale, the natural variability of local hydraulics must be considered. A procedure for applying the success criteria in the post-project evaluation of local hydraulics was developed.

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