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FLOW RESISTANCE IN ENVIRONMENTAL CHANNELS: FOCUS ON VEGETATION

Juha Järvelä

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Abstract

This thesis aims to improve the reliability of the determination of flow resistance in environmentally acceptable channels and floodplains. Special emphasis was placed on addressing the hydraulic effects of vegetation. For this reason, laboratory flume studies with living vegetation were employed. The most notable finding was that, when compared to leafless conditions, the presence of leaves increased the friction factor up to seven-fold. This was strongly dependent on the flow velocity. In addition, the linkage between flow resistance, channel properties, and physical habitat was investigated. For this purpose, field studies were conducted in degraded, restored, and natural channel reaches.

To determine friction factor *f* or Manning's *n* for non-submerged woody vegetation, a new procedure based on the measurable characteristics of vegetation and flow was developed. A major advantage of this procedure over the old methods was its ability to estimate the flow resistance of woody vegetation in both leafless and leafy conditions. In determining the velocity profile and flow resistance caused by submerged flexible vegetation, the approach developed by Stephan (2002) was found to be suitable. However, a new formulation was proposed for the shear velocity based on deflected plant height. This modification offered better practical applicability than the original formulation, which requires complicated turbulence measurements.

In the field studies, the experimental results for friction factors were, excluding those for low flows, in agreement with the values presented in the literature. Overall, the gathered field data from degraded, restored, and natural channel reaches formed a reference data set, which could be useful in other similar restoration or engineering projects. The field studies showed that both flow resistance and cross-sectional geometry were vital factors in determining local hydraulic conditions. The parameters defining these two factors were found to be simple but nonetheless valuable in evaluating the success of a project which aims to restore local hydraulics. A new procedure for applying the success criteria in the post-project evaluation of local hydraulics was developed.

Keywords	hydraulics, flow resistance, roughness, vegetation, rivers, floodplains

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Luonnonmukaisten uomien virtausvastus: erityistarkastelussa kasvillisuuden vaikutukset

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Tiivistelmä

Tämän työn päämääränä on parantaa virtausvastuksen määrittämisen luotettavuutta luonnonmukaisissa uomissa ja niiden tulvatasanteilla. Erityistä huomiota kiinnitettiin kasvillisuuden vaikutusten arviointiin. Tätä varten suoritettiin laboratoriokokeita elävillä kasveilla. Huomattavin koetulos oli, että kasvien lehdet kasvattivat yleistä kitkahäviökerrointa jopa seitsenkertaiseksi lehdettömään tilanteeseen verrattuna. Tähän vaikutti voimakkaasti virtausnopeus. Lisäksi työssä tutkittiin virtausvastuksen, uomaominaisuuksien ja fyysisen elinympäristön välistä riippuvaisuutta. Tätä varten tehtiin maastotutkimuksia peratuissa, ennallistetuissa ja luonnontilaisissa uomajaksoissa.

Yleisen kitkahäviökertoimen f ja Manningin kertoimen n määrittämiseksi vesisyvyyttä korkeammalle puuvartiselle kasvillisuudelle kehitettiin uusi menetelmä, joka perustuu kasvillisuuden ja virtauksen mitattavissa oleviin ominaisuuksiin. Tämän menetelmän huomattava etu aiempiin nähden on, että sillä voidaan määrittää sekä lehdellisen että lehdettömän puuvartisen kasvillisuuden virtausvastus. Vesisyvyyttä matalamman taipuisan kasvillisuuden virtausvastuksen määrittämiseksi Stephanin (2002) menetelmä todettiin sopivaksi. Kitkanopeuden määrittämiseksi esitettiin kuitenkin uusi keino kasvillisuuden taipuneen korkeuden perusteella. Tämä muutos paransi menetelmän käytännöllistä soveltamiskelpoisuutta alkuperäiseen versioon nähden, jonka käyttöön tarvitaan hankalia turbulenssimittauksia.

Maastotutkimuksista saadut kitkahäviökertoimien arvot olivat alivirtaamia lukuun ottamatta yhtäpitäviä kirjallisuudessa esitettyjen arvojen kanssa. Peratuista, ennallistetuista ja luonnontilaisista uomaosuuksista kerätty tieto muodosti vertailuaineiston, joka voi olla käyttökelpoinen samankaltaisissa luonnonmukaisissa vesirakentamishankkeissa. Maastotutkimukset osoittivat, että niin virtausvastus kuin uoman poikkileikkausgeometria olivat hyvin merkitseviä tekijöitä paikallisten hydraulisten olosuhteiden määrittämisessä. Poikkileikkausgeometrian ja virtausvastuksen kuvaamiseen käytettävät parametrit todettiin yksinkertaisiksi mutta hyviksi onnistumiskriteereiksi, joita voidaan käyttää paikallisten hydraulisten olojen ennallistamisessa. Onnistumiskriteerien soveltamiseksi ennallistamishankkeiden jälkiarvioinnissa kehitettiin uusi menetelmä.

Avainsanat	hydrauliikka, virtausvastus, karkeus, kasvillisuus, joet, tulvatasanteet

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LIST OF APPENDED PAPERS

This dissertation is based on the following papers:

I. Järvelä, J. 2002. Flow resistance of flexible and stiff vegetation: a flume study with natural plants. Journal of Hydrology 269(1-2): 44–54.

II. Järvelä, J. 2002. Determination of flow resistance of vegetated channel banks and floodplains. Bousmar, D. and Zech, Y. (eds.) 2002. River Flow 2002. Swets & Zeitlinger, Lisse. p. 311–318. ISBN 9058095096.

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IV. Järvelä, J. 2004. Determination of flow resistance caused by non-submerged woody vegetation. International Journal of River Basin Management 2(1): 1–10. [In press]

V. Järvelä, J. & Helmiö, T. 2004. Hydraulic considerations in restoring boreal streams. Nordic Hydrology 35. [In press]

VI. Helmiö, T. & Järvelä, J. 2004. Hydraulic aspects of environmental flood management in boreal conditions. Boreal Environment Research 9. [In press]

In papers I through IV, I was responsible for all phases of the study. In papers V and VI, I and Terhi Helmiö were equally responsible for the design of the study, data analysis and writing the manuscript. Uusimaa Regional Environment Centre carried out the field measurements in the Myllypuro Brook and the River Tuusulanjoki. The West Finland Regional Environment Centre conducted the field measurements in the River Päntäneenjoki.

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„Die Natur versteht gar keinen Spaß, sie ist immer wahr, immer Ernst, immer strenge, sie hat immer recht, und die Fehler und Irrtümer sind immer des Menschen.“
GOETHE: Gespräche mit Eckermann, 1829.

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1 INTRODUCTION

1.1 Background

As man has continued to exploit and tame rivers and floodplains with an ever increasing demand for technical effectiveness, it has become necessary to determine which factors affect the flow of water in a channel. Typically, the objective has been to convey flow efficiently, for example, to reclaim land, divert water for irrigation, protect housing and property from flooding, or improve navigation. For these purposes, channels made up of simple geometry and free of obstructions, such as vegetation, were desirable. Consequently, the determination of the flow resistance in such channels has become one of the key challenges in river engineering.

In the late 18th century, Chézy presented an equation which related mean flow velocity to channel and flow properties that could be measured or estimated across a wide range of design conditions. In the mid 19th century, Weisbach in Germany and Darcy in France developed resistance equations based on their work on pipe and open channel flows. Darcy's name is commonly associated with that of Weisbach in the development of the present-day resistance equation, which Weisbach first formulated (Rouse and Ince 1963). Some fifty years later, at the turn of the century, Manning and Strickler independently presented an empirical approach, which became a commonly used resistance equation among practising engineers. The equation relates mean flow velocity to hydraulic radius, slope, and to a roughness coefficient. Common to the approaches of Chézy, Manning and Strickler is the notion that flow resistance is described using an empirical or semi-empirical resistance coefficient, in which all sources of resistance are grouped. Details of all these approaches are presented in standard hydraulic texts (e.g. Chow 1959) and are not repeated here. Numerous attempts have been made to develop or replace the equations presented above but the basic ideas are still very much the same as they were more than a century ago. The problem is that a broadly applicable and reliable design method for complex hydraulic conditions is not available. The trend to prefer and promote natural river characteristics, including the preservation of riverbank and floodplain vegetation, has further complicated the hydraulic design process.

One of the first researchers to discuss the adverse environmental impacts of river engineering was a German professor, Alwin Seifert (1938), in a paper entitled "Naturnäherer Wasserbau" (literally "hydraulic engineering closer to nature"). Recent research has revealed that factors, such as 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). Moreover, channel-floodplain interaction is nowadays considered a fundamental part of the fluvial system (e.g. Newson 1992, Brookes 1996, DVWK 1996). More recently, channels that include features such as these have been referred to as environmental channels (e.g. Fisher 2001). Environmentally sustainable river engineering and flood management together with the application of bioengineering techniques have grown and have become routine tasks for river managers and engineers. In addition, particularly in industrialised countries, river restoration or rehabilitation is widely practised in order to 'revitalize' degraded aquatic ecosystems. Economic prosperity has made attempts to recover the lost biodiversity and ecological integrity of riverine landscapes possible. On the other hand, particularly in developing countries, increasing populations and emerging economies demand a more efficient utilisation of water resources, as was the situation in Europe and North America in the 20th century.

Vegetation along rivers and on floodplains was traditionally regarded as a nuisance, one that increases resistance and hinders flow capacity. Flow-vegetation interaction is a complex process, and research in this area has led to significant simplifications in practical applications. Conventional approaches use standard reference publications, such as Chow (1959) and Barnes (1967), to select a roughness coefficient or employ a simple semi-empirical method for their estimation. Recently, attempts have been made to develop physically based models and to relate resistance to the measurable characteristics of vegetation and flow. Though significant advances have been gained, the effects of vegetation on flow resistance are still not fully understood (e.g. Tsihrintzis 2001).

In Finland, the studies on open channel flow resistance are few and are principally oriented towards practical design problems. Kaitera (1934) was the first researcher to systematically investigate the magnitude and variation of resistance coefficients. Saari (1955) conducted field experiments in both a number of small natural channels and engineered channels to determine the resistance coefficients. For the most part, practising engineers have relied on these data and manuals published abroad. The academic research tradition in this field has been weak; the only previous related doctoral thesis was published some twenty years ago by Hosia (1983). Recently, a new approach to field studies was employed in three rivers and streams to support restoration and flood management efforts (Järvelä 1998, Helmiö and Järvelä 1998, Järvelä and Helmiö 1999).

In light of the comments made above, it is obvious that further research is needed to reduce uncertainty in determining flow resistance in environmental channels. In particular, this work is motivated by the new challenges and requirements arising from river restoration. Thus, this research falls into the framework of ecohydraulics. Here, special emphasis is placed on addressing the hydraulic effects of vegetation.

1.2 Hydraulic considerations

1.2.1 Introductory remarks

The need to estimate the open channel flow resistance has spurred a multitude of practical and theoretical studies to solve the (technical) flow problem. In the following four sections, these studies are first looked at through an "environmental lens" and thereafter focus is directed to issues dealing with vegetation. Firstly, local hydraulics, which affects the physical habitat, is discussed (section 1.2.2). Standard hydraulic texts or formulas are not repeated but briefly cited as appropriate, since there are excellent review papers available (e.g. Yen 2002). Secondly, hydraulic effects of vegetation are reviewed in more detail (sections 1.2.3–1.2.5). Herein, special regard is given to the research carried out in the German speaking Europe (Austria, Germany and Switzerland), as this research is often poorly acknowledged in English language publications. Flow-morphology interaction including sediment transport is for the most part beyond the scope of this review. Detailed reviews on this topic in environmental channels are given by Dittrich (1998) and Hunzinger (1998).

1.2.2 Local hydraulics: flow resistance – channel geometry – physical habitat

Rouse (1965) classified flow resistance into four components: 1) surface resistance, 2) form resistance, 3) wave resistance from free surface effects, and 4) resistance associated with local acceleration or flow unsteadiness. Factors affecting flow resistance in open-channels include substrate, flow depth, cross-sectional shape, vegetation, sinuosity, bed forms, sediment transport, and ice-cover. In addition, relevant to vegetated and compound channels is the flow interaction between the high-velocity main-channel flow and the low-velocity flow on floodplain or in vegetated zones (Sellin 1964, Pasche and Rouvé 1985, Knight and Shiono 1996, Thornton et al. 2000, Helmiö 2002). The extra turbulence generated by the momentum transfer introduces energy loss in addition to that associated with boundary resistance. This phenomenon is not accounted for by the conventional resistance equations. Worth noting is that the above-mentioned components and factors interact in a non-linear way so that any linear separation and combination is artificial. Nonetheless, different components can be combined to estimate the total resistance, for example, by the approach of linear superposition of friction factors (Einstein and Banks 1950). Several methods to estimate composite Manning's n have been developed, for example the Cowan method, in which separate Manning's 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). The conventional summation approaches (see e.g. Chow 1959) are strongly criticized by Indlekofer (1981), Ackers (1993) and Knight and Shiono (1996).

Routinely, hydraulic design of open channels has often focused on (flood) conveyance. Recently, analyses of environmental or in-stream flow requirements have underlined that ecologically sound hydraulic design must be effective at low and mean flows in addition to high flows to provide suitable habitat conditions (e.g. King et al. 2000, Dyson et al. 2003). Although the number and scope of river restoration projects are increasing, designs for these projects are often weak in hydraulic design for channel reconstructions (Shields et al. 2003). 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. 1999). 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.

Particularly in small rivers, natural channel topography, bank vegetation, and in-stream woody debris may have a great influence on hydraulics (e.g. Hydraulics Research 1988, Masterman and Thorne 1992, Huang and Nanson 1997), and further, the physical habitat (Broadhurst et al. 1997). 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). 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 woody debris cover of less than 2% of the streambed provided roughly half of the total flow resistance. Shields and Gippel (1993) 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.

Usually in river restoration and environmental engineering, natural river characteristics are sought after implying that the physical habitat and flow conditions should be as close as possible to a pristine reach. However, in many projects the design objectives and success criteria are not clearly stated (e.g. Brookes and Sear 1996). In many cases, ad-hoc approaches combined with subjective professional judgement, have formed the basis for the restoration (Brookes 1996). Restoration practitioners should start with an understanding of what ecosystem processes are operating in the watershed and how they have been affected by outside variables. The watershed approach prevents relying solely on site-level information, a common problem with historic restoration efforts (Bohn and Kershner 2002). Clearly defined assessment criteria are crucial for evaluating ecological integrity, especially in the pre- and post-restoration monitoring phases (Jungwirth et al. 2002).

1.2.3 Flow resistance caused by vegetation

Natural river floodplains and adjacent wetlands grow typically a diverse and heterogeneous combination of herbs, shrubs and trees, which play an essential role in determining water, sediment, nutrient, and pollutant transport (Nepf and Vivoni 2000). Vegetation is a key factor in the interrelated system of flow, sediment transport, and geomorphology in rivers (Tsujimoto 1999). Effects of vegetation on flow are significant and cause difficulties in hydraulic design. It has been generally agreed that vegetation increases flow resistance, changes backwater profiles, and modifies sediment transport and deposition (Yen 2002). 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). For comparison, in wetlands emergent vegetation frequently provides most of the resistance to surface water flow (Kadlec 1990). Masterman and Thorne (1992) considered bank vegetation to be a significant factor in reducing the discharge capacity of natural channels and related the reduction in channel capacity to the width-depth ratio. 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), Maione et al. (2000) and Sellin and van Beesten (2002).

Much of the earlier work on the hydraulic properties of riverine vegetation was conducted by agricultural engineers who concentrated on determining roughness coefficients or developing design methods, rather than on obtaining a better understanding of the physical processes (Wilson et al. 2003). Conventional approaches typically use reference publications, such as Chow (1959), Barnes (1967), Arcement and Schneider (1989), Coon (1998) and Hicks and Mason (1999), for selecting a roughness coefficient, which groups all sources of flow resistance, including vegetation, into Manning's *n*. Significant advances have been made to gain a better understanding of flow phenomena in floodplain and wetland flows. A considerable amount of research has been carried out in developing resistance laws for channels with rigid vegetation (e.g. Li and Shen 1973, Petryk and Bosmajian 1975, Lindner 1982, Pasche and Rouvé 1985), flexible vegetation (e.g. SCS 1954, Kouwen and Unny 1973, Temple et al. 1987, Kouwen and Fathi-Moghadam 2000), and various combinations (e.g. Sokolov 1980, Flippin-Dudley et al. 1998, Freeman et al. 2000). Recently, several studies have focused on velocity profiles and turbulent characteristics of vegetated channels (e.g. Shimizu and Tsujimoto 1994, Tsujimoto et al. 1996, Naot et al. 1996, Nepf 1999, López and García 2001, Stephan 2002). In addition, an increased interest in the application of various bioengineering techniques has prompted several studies covering the hydraulic aspects related to this activity (e.g. Oplatka 1998, Gerstgraser 2000). Overall, an abundance of studies, however, is based on laboratory experiments with simple artificial roughness (in uniform flow), whereas in reality natural vegetation exhibits a wide variety of forms and flexibility.

In hydraulic analysis, non-submerged and submerged conditions are typically distinguished, since flow phenomena become more complicated when flow depth exceeds the height of plants (Stone and Shen 2002). In addition, two types of vegetation are usually defined: rigid (normally woody or arborescent plants) and flexible (herbaceous plants). Following this categorization, an in-depth review is provided for submerged and non-submerged vegetation in separate sections below.

1.2.4 Submerged (flexible) vegetation

Flexible, herbaceous type of vegetation is widely used as a protective liner in agricultural waterways, floodways, and emergency spillways (Ree 1949, Fenzl and Davis 1964, Haber 1982, Samani and Kouwen 2002). A significant amount of practical and theoretical research is available on such linings. For designing vegetated waterways, Palmer (1945) introduced the *n-UR* method relating Manning's n with the product of average velocity U and hydraulic radius R for various channel slopes and plant stands. The US Soil Conservation Service presented the method in a revised form (SCS 1954) making it popular in practise. Kouwen and Unny (1973) criticised the application of the method, since their experiments on flexible plastic roughness indicated that the resistance over such roughness is primarily a function of the relative roughness, defined as the ratio of the deflected plant height to the flow depth, h_p/h. They introduced a stiffness parameter MEI, flexural rigidity per unit area, which reflects the overall resistance to deformation of a plant stand as a result of a flow passing over it. Kouwen et al. (1981) stated that their stiffness-based method is capable of determining flow capacity when the *n-UR* method breaks down, namely when the slope is small and/or the vegetation is short and stiff. Ree and Crow (1977) provided, however, additional *n-UR* curves for small slopes. Temple et al. (1987) further developed the *n-UR* method. The retardance potential of the grass was represented using a retardance curve index that is primarily a function of stem length and density. Temple (1999) concluded that although alternate approaches for predicting vegetal flow resistance have been proposed, the *n-UR* method has remained the primary tool for practical application to grass-lined channel conditions. More recently, Escarameia et al. (2002) presented a design equation, which relates n to the grass height in addition to *UR*. Conventional empirical methods are widely used in practise, but it would be desirable to eventually replace them by less empirical relations.

In addition to early pipe flow investigations, atmospheric studies have significantly contributed to the understanding of mechanics of flow in and above rough and flexible boundaries (Raupach et al. 1980, Jacobs and Wang 2003). Among others, Plate and Quraishi (1965), Kouwen et al. (1969), Temple (1986), Watanabe and Kondo (1990) and El-Hakim and Salama (1992) have accepted the logarithmic velocity profile as the basis for defining flow relationships in the case of flexible roughness. It has been shown that when flexible roughness is sufficiently submerged, a log profile will develop in the non-vegetated layer. Recently, Stephan (2002) investigated three species of flexible aquatic vegetation under submerged conditions in a laboratory flume. Deflected plant height summarising all the flow and plant characteristics was found to be an appropriate parameter to describe the geometric roughness height. Subsequently, hydraulic roughness was defined based on the equivalent sand roughness using a modified log law approach. Based on the velocity measurements it was concluded that the computed equivalent sand roughness is directly proportional to the deflected plant height (Stephan 2002).

1.2.5 Non-submerged (rigid and flexible) vegetation

A majority of research on vegetative flow resistance is based on theory and experiments with rigid cylindrical elements. Li and Shen (1973) studied the effects of tall non-submerged vegetation on flow resistance by investigating the wake caused by various cylinder set-ups. Experimental results indicated that different patterns or groupings of cylinders significantly affect flow rates. This wake correction approach was incorporated into the methods of Thompson and Roberson (1976) and Jordanova and James (2003). Li and Shen (1973) identified four factors that need to be considered in determining the drag coefficient: 1) the effects of open-channel turbulence; 2) the effect of non-uniform velocity profile; 3) the free surface effects; and 4) the effect of blockage. Lindner (1982) concluded that, in densely vegetated channels, the first two of these are of minor importance and can be neglected. Petryk and Bosmajian (1975) presented a model to estimate Manning's n as a function of hydraulic radius and vegetation density for non-submerged rigid vegetation. In the case of vertically uniform dense vegetation, Manning's n increases in proportion to the 2/3 power of the hydraulic radius assuming that the channel boundary shear is negligible.

In the 1980's an extensive research programme on the hydraulic problems of environmental channels was undertaken by four German universities. The purpose of the programme was to develop methods for determining friction factor and calculating discharge in complex river sections with variable bank and floodplain vegetation. In the framework of the programme, several doctoral studies, including those by Lindner (1982), Evers (1983), Kaiser (1984), Pasche (1984), Bertram (1985), Rickert (1986), were conducted, and the findings were drawn together in a summary report (Rouvé 1987). Particular emphasis was placed on friction losses caused by momentum transfer between a main channel and vegetated zones. In addition, floodplain flow processes were investigated with scale models using rigid cylindrical roughness elements. Much of the research carried out in the 1980's in Germany was later incorporated in hydraulic design manuals published by two engineering associations (DVWK 1991, BWK 1999, BWK 2000). As a part of the research programme, various approaches for computing discharge in vegetated zones were developed. Lindner (1982) extended the work of Li and Shen (1973), resulting in a method to compute the drag coefficient C_d for a single plant in a group, and further the friction factor for vegetation. The governing equation for f utilises readily measurable physical properties in addition to C_d: longitudinal and lateral distances between the plants, and the plant diameter. Based on Lindner's approach and further experimental work, Pasche (1984) and Pasche and Rouvé (1985) presented a semi-empirical iterative process to determine C_d. Mertens (1989) and Nuding (1991) simplified Lindner's approach, assuming that a constant C_d value of 1.5 is valid for most practical cases. In addition, to relate the projected plant area more closely to the actual dimensions of the plant, Nuding (1991) suggested a simple method to account for the branches separately from the main stem. Recently, Schumacher (1995), Becker (1999) and Specht (2002) evaluated and presented some improvements to these methods. However, all these methods basically treat plants as cylinders.

The drag coefficient sums up pressure and friction drag. The ratio of form drag to surface drag depends on the shape of the element and the flow condition. In fully turbulent flow with a thin boundary layer, the pressure drag will drop substantially compared to laminar flow, caused by flow separation

(Schlichting and Gersten 2000). Furthermore, streamlining will sharply reduce the pressure drag. DVWK (1991) recommends C_d = 1.5 for practical computations. For comparison, Klaassen and Zwaard (1974) reported a mean drag coefficient of 1.5 for small, branched fruit trees. Meijer and van Velzen (1999) reported a drag coefficient of 1.8 for leafy reeds. Reed studies by James et al. (2001) revealed values ranging from 1.25 (stem only) to 1.75 (full foliage), corresponding the Reynolds number in the order of 5000.

A considerable number of flow resistance formulas or models has been developed treating plants simply as rigid cylinders. Branched and leafy flexible plants are far from this simplification. Vogel (1994) stated that the major contributor to the drag of most trees is the drag of the leaves, whether broad or needlelike. He found that reconfiguring or reshaping of the leaves is a critical process in generating drag. Kao and Barfield (1978) used the momentum principle in a slightly different way to that of Petryk and Bosmajian (1975) for determining flow resistance. Experimental results on simulated plants were used to determine the drag coefficient, and a nomographic solution of the flow problem was presented. The approach has difficulties associated with the determination of the projected area (derived from the “characteristic blade width”) and the drag coefficient for natural plants. The determination of the drag coefficient for plants is difficult, since streamlining affects both the frontal area and the wetted area. Because of a lack of information and despite very poor results, the effects of flexibility and depth on resistance for non-submerged vegetation are universally ignored in practice and in theoretical analysis (Fathi-Moghadam and Kouwen 1997).

Several researchers have used the stiffness of vegetation as a primary independent parameter to relate flow resistance to vegetation characteristics. Kouwen and Li (1980) related the flexural rigidity of vegetation per unit area (MEI) to the deflected plant height, and further, the flow resistance. Tsujimoto et al. (1996) and Kutija and Hong (1996) coupled a numerical model with a model describing bending of vegetation. Bending was related to the flexural rigidity of plants by using the cantilever beam theory. Fischenich (1996) argued that flow resistance cannot be directly related to MEI from physical reasoning and that this term is used simply as a surrogate for the vegetation area in an attempt to account for the deformation of vegetation. He additionally noted that MEI is difficult to measure in the field and has no meaning for large woody vegetation. Fathi-Moghadam and Kouwen (1997) concluded that for non-submerged cases, the vegetation density is always a dominant parameter regardless of tree species or foliage shape and distribution. Oplatka’s (1998) experiments on flow resistance of tall flexible willows in a towing tank showed that with increasing flow velocity the projected plant area perpendicular to flow rapidly decreases. For example, at the velocity of 1 m/s, the projected area was only about 1/4 of the initial value with no flow.

Freeman et al. (2000) argued that the equations, parameters, and methods developed by other researchers (e.g. Ree and Crow 1977, Kouwen and Li 1980) for a combined density and blockage of heavy ground cover and grasses do not produce satisfactory results. Freeman et al. (2000) presented a methodology to determine flow resistance coefficients in cases of submerged and partially submerged shrubs and woody vegetation. Data for developing the method were extracted from the study of Werth (1997), in which twenty natural plant species with both homogenous and mixed plant spacings were investigated with and without leaves. Unfortunately, a density measure such as leaf area was not recorded. Separate empirical regression equations were developed for the submerged and partially submerged cases revealing the modulus of elasticity to be a critical parameter. This can be estimated from the ratio of the undeflected plant height to the stem diameter H/d, though field measurements were recommended (Freeman et al. 2000). The approach does not directly take into consideration the deformation of foliage, as the stiffness modulus is a property of the stem(s). It appears not to be reasonable to assume that E can be related to only H/d, which implies that the differences in flexibility between species are neglected.

Kouwen and Fathi-Moghadam (2000) used coniferous tree saplings in flume experiments and large coniferous trees in air experiments to demonstrate that the friction factor varies greatly with the mean flow velocity caused by bending of the vegetation and with flow depth caused by an increase in the submerged momentum absorbing area. The proposed model for estimating the friction factor for non-submerged roughness relates friction factor to flow velocity and a species-specific vegetation index ξE, which accounts for the effects of shape, flexibility, and biomass. The determination of ξE requires measuring of the natural frequency of a tree. This is very difficult to perform in the field, and therefore the method has limited practical applicability until values of ξE become available for typical species of bushes and trees.

1.3 Objectives and scope of the study

This thesis aims to improve the reliability of the determination of flow resistance in environmental channels and floodplains. The specific objectives fall into two main topic areas. Firstly, special focus is directed to addressing the effects of vegetation in contributing to flow resistance (points 1, 2 and 3 below). Secondly, this research addresses the linkage between flow resistance, channel properties, and physical habitat (points 4 and 5). The specific objectives are as follows:

1. Identify and assess key processes and mechanisms that control vegetation-induced flow resistance by conducting laboratory experiments on living vegetation; in particular, assess how type, density and distribution of vegetation affect resistance under different flow conditions. (I, III)
2. Evaluate selected methods that are available for predicting flow resistance caused by natural flexible and rigid vegetation under submerged and non-submerged conditions, and report issues for further development and suggest potential improvements. (II, III)
3. Develop a procedure which is capable of predicting flow resistance caused by leafless and leafy woody vegetation in non-submerged flow. (IV)

4. Gather field data on flow resistance in degraded, restored, and natural channel reaches, and assess the factors causing resistance to support hydraulic design and modelling efforts in river restoration and environmental engineering projects. (V, VI)
5. Test the hypothesis that local hydraulic conditions are determined by cross-sectional geometry and flow resistance by analysing the relationship between flow velocity, cross-sectional geometry, and flow resistance. Suggest success criteria for the restoration of local hydraulic conditions, and develop a simple procedure for applying the success criteria in post-project evaluation. (V)

This research is not intended to address the effects of sediment transport, nor does it focus on refined turbulence theories or on the scaling of vegetation. The laboratory studies provide detailed studies on vegetation as opposed to the field studies, where flow resistance is investigated in a broader context.

2 METHODS

2.1 Laboratory flume studies

2.1.1 Experimental set-up

Experiments were conducted in a 50-m long by 1.1-m wide re-circulating glass-walled flume. The studied plants covered a 6-m long section in the midway of the 36-m long section designed for these experiments (Figure 1). Living willows, wheat, sedges and mixed grasses were used in the study, as such plants are often found on riverbanks and floodplains. 15-m long sections before and after the test area were covered with a 10-cm thick layer of crushed rock (diameter 16–32 mm), except the last 2.5 m before the test area. This section was covered with smoother crushed rock (diameter 3–5 mm). Vegetation was installed in the flume in metal boxes with thin walls. The dimensions of the boxes were 100 cm × 27.5 cm × 10 cm (length, width and height in the principal flow direction, respectively).

Flow was released from a head tank to the flume through a stilling basin and a flow straightener. Desired flow depth was gained adjusting an overflow weir at the downstream end of the flume. A set of seven flow depths at the beginning of the test area, called the entrance flow depth h_0 (25, 30, 40, 50, 60, 70, 80 cm) and six discharges Q (40, 70, 100, 143, 201, 292 l/s) were adopted for the study. The selected Q–h_0 combinations produced average velocities between 0.1–0.5 m/s, which were capable of causing significant bending and streamlining of the vegetation. Flow was non-uniform in all test runs. Water surface slope along the test section was measured using a differential pressure transducer in 3–7 longitudinal locations averaging over a period of 30–60 seconds. The entrance flow depth was recorded with a pressure transducer. Deflected plant height was determined visually using a ruler or a measuring tape fixed to the flume wall and verified with digital images or video recordings. Up to three levels of deflection were determined: minimum $h_{p,low}$, mean $h_{p,m}$ and maximum $h_{p,up}$.

Flow velocities were measured using a 3-D acoustic Doppler velocimeter (ADV) manufactured by Nortek. Mean velocity components (u, v, w) correspond to the stream-wise (x), lateral (y), and vertical (z) directions, respectively. Velocities were recorded for 1–2 minutes for each point with a sampling frequency of 25 Hz. The sampling volume of the downward-looking ADV is cylindrical in shape (height = 9.0 mm and diameter = 6.0 mm) and is located approximately 55 mm below the tip of the instrument. Filtering of the raw data was performed with WinADV (Wahl 2000). Special care is essential when interpreting ADV measurements. The Doppler noise can change the true turbulence characteristics significantly, even for high-level turbulence flows (Nikora and Goring 1998). Other sources of error include low signal-to-noise ratio, probe orientation and measuring time (Babaeyean-Koopaei et al. 2002).

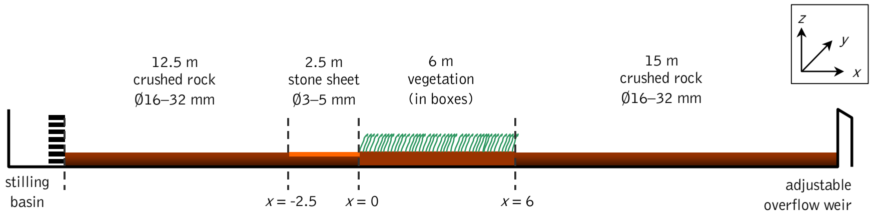

Figure 1. Experimental set-up and definition for the coordinate axes (not to scale).

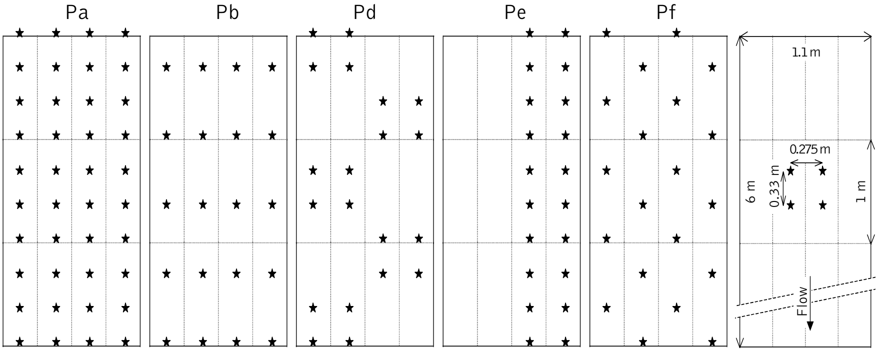

Figure 2. Spacing of willows in patterns Pa, Pb, Pd, Pe and Pf. Only half of the 6-m long test section is shown (not to scale).

2.1.2 Test series descriptions

Experiments consist of three groups, each of which includes one to nine test series. Series groups R2* and S3* were employed mainly for the head loss measurements, whereas series R4 served the velocity measurements (ADV), as described below:

Series group R2* (grasses–willows): The vegetation boxes were filled in the field with a 10-cm thick natural floodplain topsoil layer growing mixed grasses. The length of the grasses was in average 30 cm with the individual stem length ranging between 20 and 40 cm. When visually observed, the grass cover was relatively homogeneous, but spatial analysis of dry biomass in the vegetation boxes revealed up to 35% variations from the average (130 g/m^2, dried 1.5 hours in 105 °C). In series group R2*, only leafless willows were used. The willows were installed in five various patterns with the grasses (Figure 2). The main stems of the willows were approximately 70 cm in length with several small branches. The average diameter of the stems at a height of 10 cm from the bottom was 8.3 mm.

Series group S3* (sedges–willows): Natural yet nursery-grown slender tufted-sedges (*Carex acuta*) were placed in the natural floodplain topsoil layer by boring holes for planting pots (diameter 4 cm). Otherwise, the natural root structure and soil compaction were left intact. The plant pots were positioned in a staggered pattern averaging 512 stems/m^2. In each pot there were several stems of 3 mm in average diameter. In the pots, the stems were randomly distributed in clusters or apart; usually the diameter of the stems as a group was ~20 mm. The lower part of the stems up to the height of ~5 cm was more or less stiff. Average stem length was kept at 30 cm by cutting. Willows were installed without roots in the boxes in two different patterns with the sedges (Figure 2, Pa and Pf). One example is presented in Figure 3. The willows (*Salix sp.*) averaged 70 cm in length and 8.6 mm in diameter at a height of 10 cm from the bottom. The willows were investigated first with leaves and in the next phase without leaves. In the last phase the sedges were removed, and the leafless willows on bare bottom soil were investigated. The leaf area index (LAI) corresponding the pattern Pa was estimated to 3.2. Conventionally LAI refers to the ratio of the area of the upper side of the leaves in a canopy projected onto a flat surface to the area of the surface under the canopy. This definition of LAI as the one-sided area of foliage per unit area of ground or A_l/A_b was adopted for this study.

Series R4 (wheat): Young wheat was used as a vegetative cover in the experiments. Seeds of wheat were planted in a 10-cm thick layer of topsoil and covered with a jute cloth. The flume was first used as a greenhouse with a plastic cover. The wheat covered the test area with an average of 12000 stems/m^2, though the cover was sparser close to the seams of the boxes. The average length and width of the stems were approximately 28 cm and 2.8 mm, respectively.

Figure 3. Test run 010607-21 of series S3Pa with leafy willows and sedges. The average flow velocity was 38.7 cm/s.

2.2 Field studies

Field studies were performed at two rivers and one brook. The study reaches were delimitated so that the cross-sectional geometry was relatively homogenous 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, several 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. Flow velocities were measured using propeller-type current meters.

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 the minimum. Coverage of in-stream and bank vegetation was mapped in the field in midsummer conditions into four classes as follows: 0 = no; 1 = sparse; 2 = moderate; and 3 = dense vegetation cover. This relative classification allowed comparing the reaches within each other. The field sites are briefly described below; further details are presented in papers V and VI.

Myllypuro Brook is located in Nuuksio national park in southern Finland. It is a small boreal stream with a forested catchment area of 24.5 km^2. The stream is 8.8 km long and has a surface width range of one to five meters. 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. Eight reaches of the Myllypuro Brook were selected for this study. The brook provided pristine, restored, and degraded and straightened reaches of various levels of disturbance for the investigations. 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.

River Päntäneenjoki in western Finland is fed by a 210-km^2 catchment, which has no lakes. Approximately 30% of the area is under cultivation and the rest is mainly forest and undeveloped fields and meadows. The river is meandering and prone to erosion. Flooding is typical and is intensified by obstructions caused by collapsed riverbanks. The river meandered in relatively natural state until the autumn of 1998, when first flood management measures were implemented on a 1-km long reach. Three reaches of the River Päntäneenjoki were selected for this study. In one reach, environmental flood management including bioengineering was applied. Three types of vegetation were distinguished: H = flexible vegetation (herbs, grasses), S = stiff vegetation (shrubs, bushes) and T = stiff arborescent vegetation (trees).

River Tuusulanjoki is situated in southern Finland and has been partially modified to enhance conveyance capacity. The land use of the 125-km^2 catchment area consists of lakes (6%), forest (55%), agricultural fields (28%) and infrastructure (11%). The 15-km long river originates from a regulating dam of the Lake Tuusulanjärvi. Two reaches of the River Tuusulanjoki were selected for this study. Vegetation was investigated similarly to the River Päntäneenjoki.

A sensitivity analysis was carried out for the field 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 to be 10 cm and in location of the cross-section 2 m. The very mild longitudinal slopes caused uncertainty in water surface slope measurements. The error associated with the water level measurement was estimated to be 2 cm. The alterations in the cross-sections caused by erosion and sedimentation were considered negligible in the limits of the sensitivity analysis. Unsteadiness of the flow was not of particular concern during the field measurements.

2.3 Quantification of flow resistance

According to standard hydraulics texts, flow resistance can be determined by measuring head loss and then calculating the friction factor f from the energy loss H_f using Bernoulli's equation (Equation 1) and the Darcy-Weisbach equation (Equation 2). For gradually varied flow, the equations can be written as (Chow 1959)

$$\beta \frac{U_1^2}{2g} + h_1 = \beta \frac{U_2^2}{2g} + h_2 + H_f \tag{1}$$

$$f = \frac{H_f}{L} \frac{8gR}{U^2} \tag{2}$$

where U = average flow velocity, g = acceleration due to gravity, R = hydraulic radius (~ flow depth h for wide channels); and β = a velocity distribution coefficient assumed often unity in open channel flow. Subscripts 1 and 2 refer to the upstream and downstream sections, respectively, and L is the distance between the sections. As recommended by the ASCE Task Force on Friction Factors (1963), the friction factor is preferred in this analysis but it can be related to Manning's n with the equation

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

Friction factors or drags can be superimposed using the approach developed by Einstein and Banks (1950), which has been confirmed in several studies covering a wide variety of roughness and flow conditions (Wessels and Strelkoff 1968, Indlekofer 1981, Rauws 1988, Fathi-Moghadam 1996).

In fluid mechanics, the drag F_d, which acts on a reference area A_p (typically projected area), may be defined as

$$F_d = \frac{1}{2} \rho C_d A_p U^2 \tag{4}$$

where ρ = density of the fluid, C_d = drag coefficient, A_p = reference (projected) area, and U = average velocity. It should be noted that there are other alternatives to define the reference area (e.g. wetted area, plan area), which can significantly influence the computed drag coefficient. Therefore, Vogel (1994) regards Equation 4 as only a definitional equation that converts drag to drag coefficient and vice versa. Furthermore, he stated that no published figure for drag coefficient is of any value unless the reference area is indicated. Defining the reference area or the momentum absorbing area (MAA) for natural vegetation is difficult. Among others, Wu et al. (1999) couple the drag coefficient with the reference area into a bulk drag coefficient C'_d, which is a lumped parameter based on the total frontal area of vegetation in a channel reach L, i.e. projected plant area per unit volume (= $A_p/(AL)$). The disadvantage of this formulation is that the vegetal drag coefficient C'_d has a unit of 1/m.

To estimate flow resistance caused by natural vegetation, the force balance for uniform flow can be extended for gradually varied flow by applying the momentum principle. The gravitational force is defined as $F_g = \rho g(A_b h)S$, where

S = energy slope, A_b = bottom area, and h = flow depth. Assuming that the drag exerted on the boundaries of a densely vegetated channel is not significant compared to the drag on vegetal elements implies that $F_d = F_g$. By equating Equation 4 to the gravitational force and using the definitions $u_* = (ghS)^{1/2}$ and $U/u_* = (8/f)^{1/2}$ the friction factor can be formulated as

$$f = 4C_d \frac{A_p}{A_b} \tag{5}$$

For determining C_d for a single plant in a group, Lindner (1982) presented an equation based on the work by Li and Shen (1973) as

$$C_d = C_{dw}\left(\frac{u_i}{U}\right)^2 + \Delta C_{dw} \tag{6}$$

where C_{dw} = the drag coefficient of a cylinder in a 2-D laterally limited flow and ΔC_{dw} = the drag coefficient due to the free surface effects. The two terms in RHS of Equation 6 represent the blockage and free surface effects, respectively. The Lindner method for computing f uses, in addition to C_d, readily measurable physical properties: longitudinal and lateral distances between the plants, and the plant diameter

$$f = \frac{4dh}{a_x a_y} C_d \tag{7}$$

where d = diameter of the element, h = flow depth, and a_x and a_y = the longitudinal and lateral distances, respectively, between the plants.

A common approach to determine flow resistance is based on relating friction factor f to mean cross-sectional velocity U and shear velocity u_* as

$$\frac{U}{u_*} = \sqrt{\frac{8}{f}} \tag{8}$$

The velocity profile is given by Prandtl's log law modified by Nikuradse

$$\frac{u}{u_*} = \frac{1}{\kappa}\ln\frac{z}{k_s} + C \tag{9}$$

where κ = von Karman constant, z = vertical ordinate, k_s = equivalent sand roughness, and C = integration constant. Integration of Equation 9 yields the mean velocity U. Stephan (2002) modified the log law and derived an equation for velocity profile above aquatic vegetation

$$\frac{u}{u_*} = \frac{1}{\kappa}\ln\frac{z - h_{p,m}}{h_{p,m}} + 8.5 \tag{10}$$

where κ = 0.4 and $h_{p,m}$ = mean deflected height of vegetation (definitions in Figure 4). To be able to compute the velocity profile, the shear velocity u_* must be estimated. This parameter is the most fundamental velocity scale with which to normalise mean velocity and turbulence (Nezu and Nakagawa 1993). For the present study, four different definitions of u_* were introduced:

$$u_{*1} = \sqrt{ghS} \tag{11}$$

$$u_{*2} = \sqrt{g(h - h_{p,m})S} \tag{12}$$

$$u_{*3} = \sqrt{g(h - h^{*})S} \tag{13}$$

$$u_{*4} = \sqrt{-\left(\overline{u'w'}\right)_{\max}} \tag{14}$$

where S = energy slope and h^{*} = flow depth corresponding to the maximum measured value of the Reynolds stress $-\overline{u'w'}$. The definition of u_{*1} does not include any plant parameters, whereas the reduced flow cross section caused by the vegetation is included into the definition of u_{*2} by means of $h\text{–}h_{p,m}$. From a practical point of view, u_{*2} is a convenient definition as $h_{p,m}$ can be easily measured. The definitions of u_{*3} and u_{*4} are based on both turbulence characteristics and influences of vegetation.

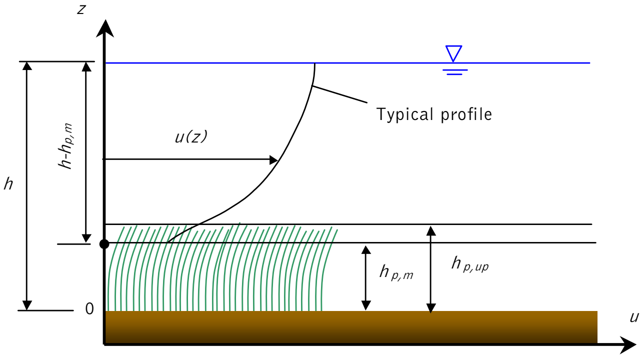

Figure 4. Definition sketch for the used parameters.

3 RESULTS

3.1 Influence of type, combination, distribution, and density of vegetation on flow resistance (I, II, III)

3.1.1 Experimental data (I, II, III)

Data were available for analysis from 18 test series. Depending on the vegetation set-up, 18 to 32 depth-velocity combinations were studied for each test series totalling about 400 test runs (Table 1). First, the validity of the approach for deriving friction factors (Equations 1 and 2) was checked by applying a momentum equation including pressure, velocity, and drag terms for channel bottom soil, glass walls, and vegetation. The drag contributed by the glass walls was negligible. Thus, in Equation 2 the hydraulic radius was replaced with the flow depth. By conducting experiments without any vegetation the average base friction factor for the test section (bottom and walls) was determined to be 0.061 for series R2* and 0.055 for series S3* and R4. The base friction factor of the bottom and walls was subtracted from the results given by Equation 2. Next, following the grouping introduced in section 2.1.2, an overall description of the experimental series is given.

Series group R2* (grasses–willows): The range of the Reynolds number, $Re = Uh/\nu$, was 24200–178000 indicating that all the test runs were above the laminar-flow range. The average flow velocity, $U = Q/A$, varied between 6.1 and 45.7 cm/s. The energy slope ranged between 0.0001 and 0.0065, and the Froude number was 0.21 at its maximum. The grasses were submerged in each test run but conditions for the leafless willows ranged from through-flow to a full overflow of 10–20 cm. In most test runs, the willows did not bend but oscillated slightly. However, in a few test runs the willows bent at high discharges with large inundation resulting in a maximum reduction of willow height by 10 cm. The grasses were very flexible and formed a wavy surface, when exposed to a flow. (I)

Series group S3* (sedges–willows): The range of the Reynolds number was 24200–177000 and the average flow velocity 7.2–46.8 cm/s. The energy slope ranged between 0.0001 and 0.0127, and the Froude number was 0.25 at the maximum. Willows were erect in all test runs with minor bending in a few experiments resulting in a 5–10-cm reduction in the height of the tips. More important than the bending of the main stems was the streamlining of the small branches and leaves at higher velocities. Bending of the sedges was dependent on the velocity and depth showing a wider range of deflected height than the grasses (R2). At low velocities, the sedges formed roughly an erect layer, but at higher velocities a 12–15-cm thick waving layer was produced. (I)

Series R4 (wheat): The range of the Reynolds number was 24200–86700 and the average flow velocity 7.2–33.0 cm/s. The energy slope ranged between 0.0002 and 0.0036, and the Froude number was 0.18 at its maximum. At the time of the experiments, the wheat showed flexibility comparable to grass. Relative submergence $h/h_{p,m}$ ranged from 1.5 to 3.3 for this series of measurements. For the cases of small relative submergence with low velocity, unambiguous determination of the deflected plant height was difficult. The amplitude of the waving plant tips was approximately 3–6 cm. (III)

Table 1. Summary of the experiments. Willow patterns Pa through Pf described in Figure 2.

Series[#]	Description	Number of test runs	Range of f	Range of Re ($=Uh/\nu$)	Range of energy slope S
R2	Grasses (mixed natural growth)	23	0.18–1.93	24400–176700	0.0001–0.0033
R2b Pa_x	Leafless willows	26	0.24–0.57	24200–177000	0.0001–0.0022
R2b Pf_x	Leafless willows	25	0.13–0.31	24200–177000	0.0001–0.0012
R2 Pa_x	Grasses with leafless willows	26	0.65–1.78	24400–176700	0.0003–0.0065
R2 Pb_x	Grasses with leafless willows	18	0.29–1.04	24500–176400	0.0001–0.0037
R2 Pd_x	Grasses with leafless willows	18	0.36–1.28	24300–177900	0.0001–0.0042
R2 Pe_x	Grasses with leafless willows	18	0.23–1.09	24500–176700	0.0001–0.004
R2 Pf_x	Grasses with leafless willows	26	0.34–1.92	24300–176700	0.0002–0.0056
S3	Sedges (*Carex acuta*)	32	0.26–2.43	24200–177000	0.0001–0.0059
S3b Pa_x	Leafless willows	23	0.26–0.83	24200–177000	0.0001–0.0036
S3b Pf_x	Leafless willows	23	0.12–0.38	24200–177000	0.0001–0.0016
S3 Pa_L	Leafy willows	23	0.90–5.86	24300–178700	0.0007–0.0114
S3 Pf_L	Leafy willows	23	0.33–2.71	24200–178500	0.0003–0.0046
S3 Pa	Sedges with leafy willows	23	2.07–6.78	24200–177000	0.0009–0.0127
S3 Pf	Sedges with leafy willows	23	1.27–4.29	24200–177000	0.0005–0.0069
S3 Pa_x	Sedges with leafless willows	23	1.21–2.27	24200–177000	0.0003–0.0063
S3 Pf_x	Sedges with leafless willows	23	0.67–1.75	24200–177000	0.0002–0.004
R4	Wheat	23	0.23–3.21	24200–86667	0.0002–0.0036

[#] Note: S3* and R2* refer to the series as a group of nine and eight series, respectively.

3.1.2 Influence of type and combination of vegetation (I, II)

In this section, the influence of type and combination of vegetation on flow resistance is highlighted using four series (willow pattern Pa) from group S3*. The friction factor f was examined by plotting it against the corresponding Reynolds number, flow velocity, flow depth, and relative roughness (I). In Figure 5, the friction factor is shown against the Reynolds number; note the vertical scale.

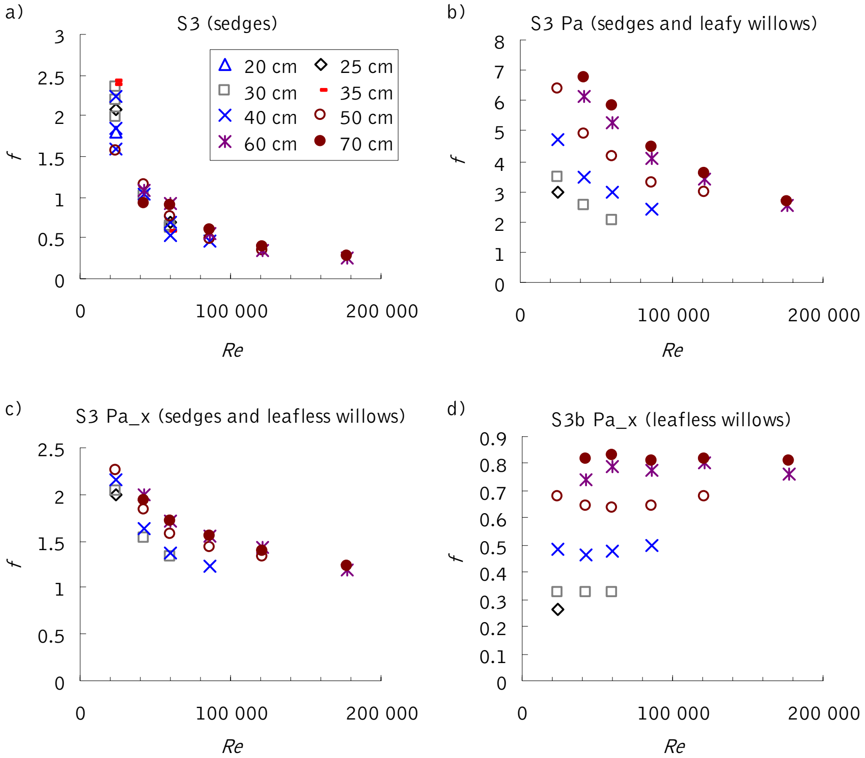

Figure 5. Friction factor vs. Reynolds number for four series from group S3; note the vertical scale. Data were classified according to the entrance flow depth (see Table 1 for series description).*

Plotting *f* against *Re* for the sedges produced a declining curve, but there was considerable deviation in the friction factor corresponding the equivalent Reynolds number (e.g., for *Re* ~ 24200, *f* ~ 1.6–2.4; Figure 5a). The same type of plot for leafless willows on bare bottom soil indicated that *f* was more or less independent of *Re* (Figure 5d). Combinations of sedges and leafless willows behaved approximately in the same way as only sedges; the values were simply shifted upwards (Figure 5c). Combinations of sedges and leafy willows exhibited the highest *f* values (Figure 5b). When the different vegetative covers were compared, the series of leafless willows without sedges differed from the rest (Figure 5d). For the leafless willows, the friction factor increased with the depth almost linearly despite the fact that velocity varied by a factor of up to four between the various test runs (I).

Presence of leaves on willows affected significantly the flow resistance. Leaves up to tripled the friction factor compared to the leafless case, even when the bottom was growing sedges (cf. plots b and c in Figure 5). In a similar comparison without any bottom vegetation, the differences were even more pronounced showing up to a seven-fold difference (Figure 6). Streamlining of the leaves and smaller branches explained the strong dependency on flow velocity (II).

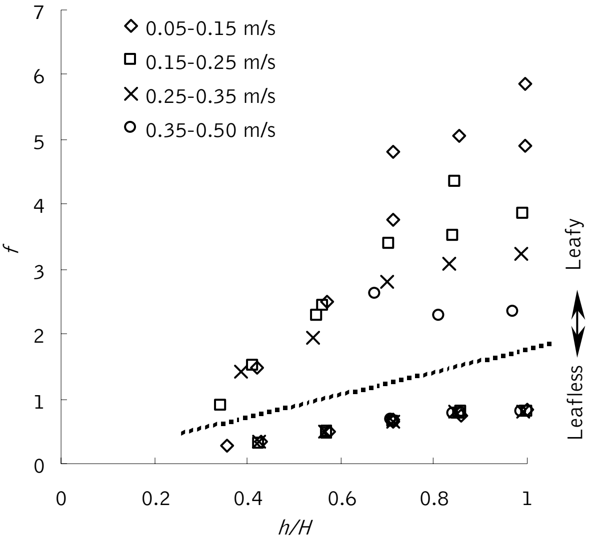

Figure 6. Friction factor vs. the relative submergence for leafy and leafless willows (pattern Pa). Data were classified into four velocity classes. The dashed line separates the leafless and leafy cases.

3.1.3 Influence of distribution and density of vegetation (I, II)

In this section, firstly, the influence of horizontal distribution, and secondly, the influence of density on vegetal flow resistance are reported. For the first purpose, data for four patterns of leafless willows with grasses of series group R2* were used. The selected patterns (Pb, Pd, Pe and Pf; Figure 2) had the same number of willows with grasses per unit area. The different spacing of the willows had a small or even negligible effect on f (Figure 7). This was explained by the branched structure of the willows and the small values of projected willow area per unit volume (I, II).

For the second purpose, data for two densities of leafless and leafy willows of series group S3* were used. Effect of density was investigated by comparing friction factors for patterns Pa and Pf. In pattern Pa, the willow density was double compared to pattern Pf. For the leafless willows, doubling the willow density resulted in approximately doubled f values (Figure 8). Similar density effect was observed for the leafy willows, where doubling the willow density approximately doubled also the f values for comparable flow conditions (Figure 9).

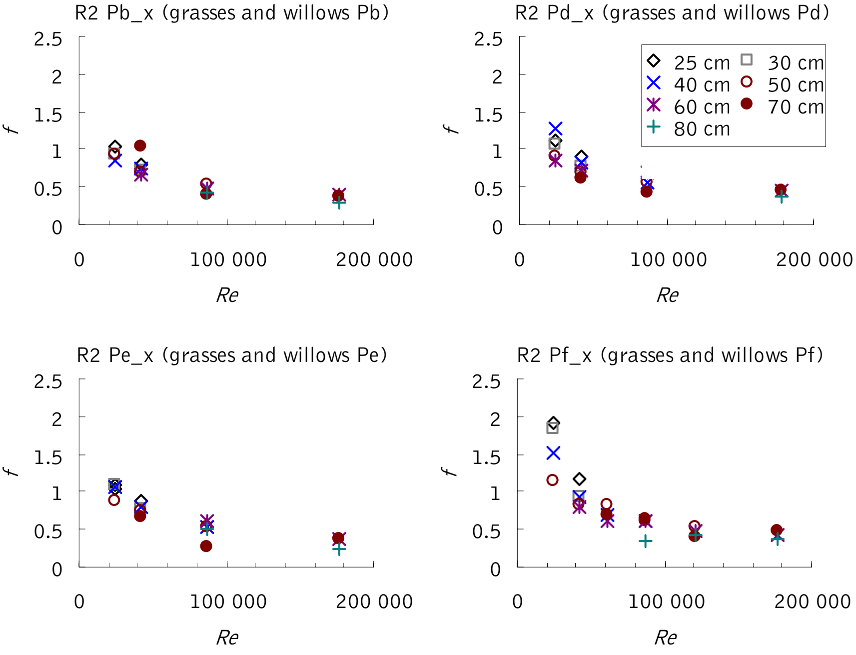

Figure 7. Friction factor vs. Reynolds number for four patterns of leafless willows from series group R2. Data were classified according to the entrance flow depth (see Figure 2 for willow pattern description).*

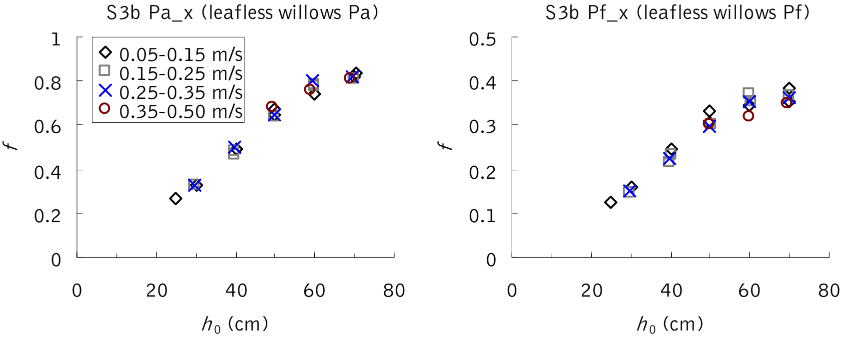

Figure 8. Friction factor vs. entrance flow depth for leafless willows; in pattern Pa (left) plant density was double to pattern Pf (right). Data were classified according to the average flow velocity.

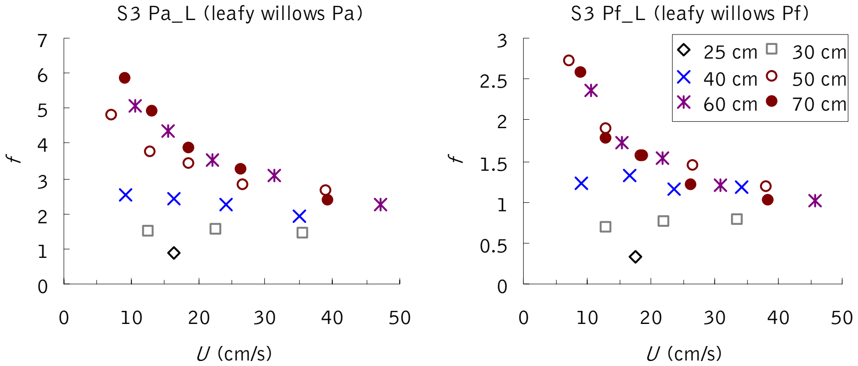

Figure 9. Friction factor vs. average flow velocity for leafy willows; in pattern Pa (left) plant density was double to pattern Pf (right). Data were classified according to the entrance flow depth.

3.2 Determination of flow resistance caused by submerged flexible vegetation (I, III)

3.2.1 Flow structure and resistance (I, III)

Using data for three different flexible plants, namely grasses (R2), sedges (S3) and wheat (R4), flow resistance caused by submerged vegetation was investigated. Flow structure above flexible roughness was studied by conducting velocity and turbulence measurements for nine test runs in series R4 (Table 2).

Table 2. Experimental conditions for test runs 1–9 in series R4 (wheat).

Test run	Q (l/s)	h (cm)	U (cm/s)	Re	Fr	S	$u_{*1}^{\#}$ (cm/s)	$u_{*2}^{\#}$ (cm/s)	$u_{*3}^{\#}$ (cm/s)	$u_{*4}^{\#}$ (cm/s)	$h_{p,m}$ (cm)
R4-1	40	30.60	11.88	24242	0.069	0.0015	6.75	3.88	2.89	0.82	20.5
R4-2	100	30.84	29.48	60606	0.169	0.0036	10.43	7.35	5.58	4.66	15.5
R4-3	40	40.65	8.95	24242	0.045	0.0005	4.35	2.87	2.43	2.05	23.0
R4-4	100	40.41	22.50	60606	0.113	0.0013	7.16	5.21	3.97	3.91	19.0
R4-5	143	40.70	31.94	86667	0.160	0.0020	8.94	6.96	6.06	5.00	16.0
R4-6	40	50.44	7.21	24242	0.032	0.0002	2.94	2.11	1.68	1.50	24.5
R4-7	100	49.50	18.36	60606	0.083	0.0006	5.58	4.16	3.68	3.09	22.0
R4-8	100	70.65	12.87	60606	0.049	0.0002	3.40	2.70	2.61	1.93	26.0
R4-9	143	70.37	18.47	86667	0.070	0.0003	4.61	3.84	3.58	2.72	21.5

$^{\#}$ See Equations 11–14 for definitions

It was expected that in the case of submerged flexible prone or waving vegetation f was a function of the relative roughness h_p/h. The results of series R2 and R4 agreed well with this, but series S3 behaved somewhat differently (Figure 10). As opposed to the grasses and wheat, the sedges were in a staggered pattern not fully covering the bottom. The flexural rigidity of the sedges was not constant over the height, and there was a considerable difference in the flexibility of the individual stems, which caused difficulties in determining the deflected plant height. The experiments on series S3 showed that the maximum value of the friction factor was achieved, when the sedges were just submerged (I).

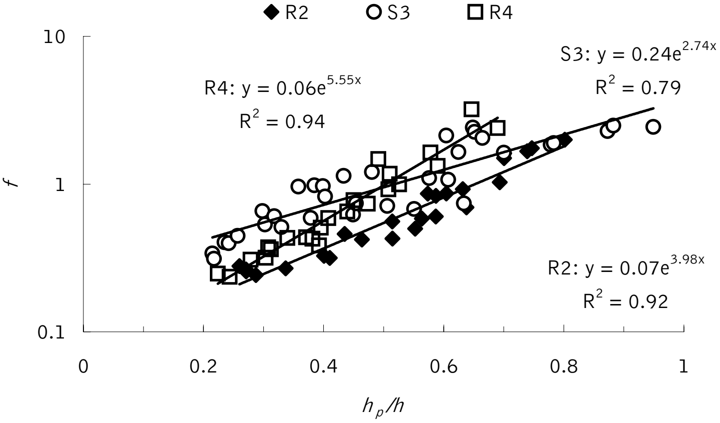

Figure 10. Friction factor vs. the relative roughness for grasses (R2), sedges (S3) and wheat (R4). The solid lines represent best fits using exponential functions.

For series R4 (wheat), the observed velocity profiles were comparable to typical profiles above flexible plants (Figure 11) exhibiting a reasonably logarithmic shape (III). In Figure 11, velocity was normalised with the shear velocity definition of u_{*2} (Equation 12). Because of the ADV limitations, measurements could not be taken in the region of ~6 cm below the water surface. In the region between $h_{p,low}$ and $h_{p,up}$, which denote the minimum and maximum observed deflected plant height, respectively, the flow velocity altered rapidly. Flow characteristics in this region were further investigated by plotting the vertical ordinate z against the corresponding ratio of standard deviation of velocity fluctuations u_{rms} to average velocity u. The value of this ratio was small and almost constant in the non-vegetated cross-section, but increased significantly at the level of the plant tips (III). The maximum values of the turbulence intensity u_{rms} and Reynolds stress $-\overline{u'w'}$ were recorded at approximately $h_{p,up}$, i.e. slightly above the mean deflected height (Figure 12).

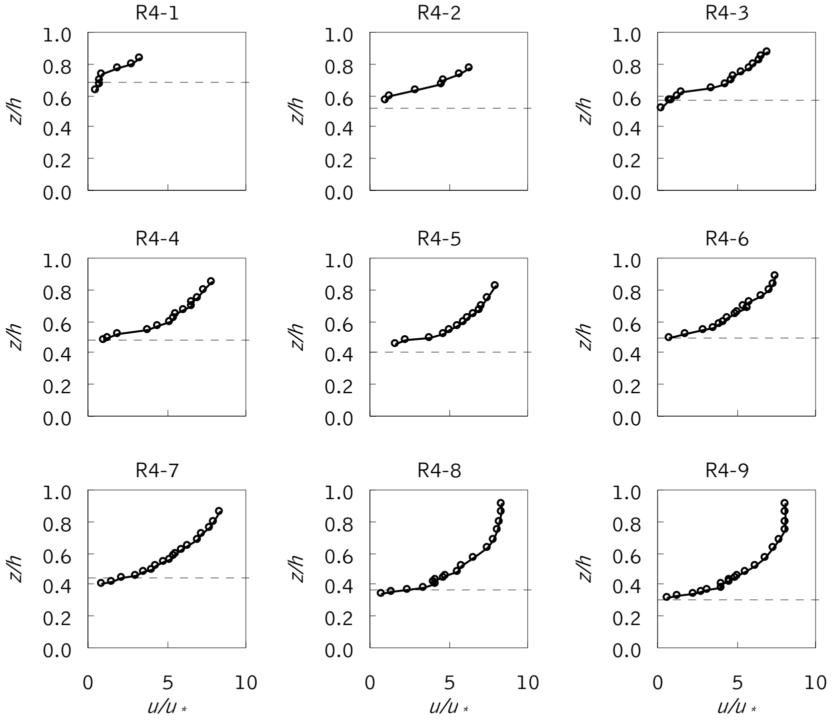

Figure 11. Averaged profiles for velocity normalised with the shear velocity u_{*2} *and flow depth h for wheat (R4). The dashed line denotes the mean deflected plant height. See Table 2 for test run description.*

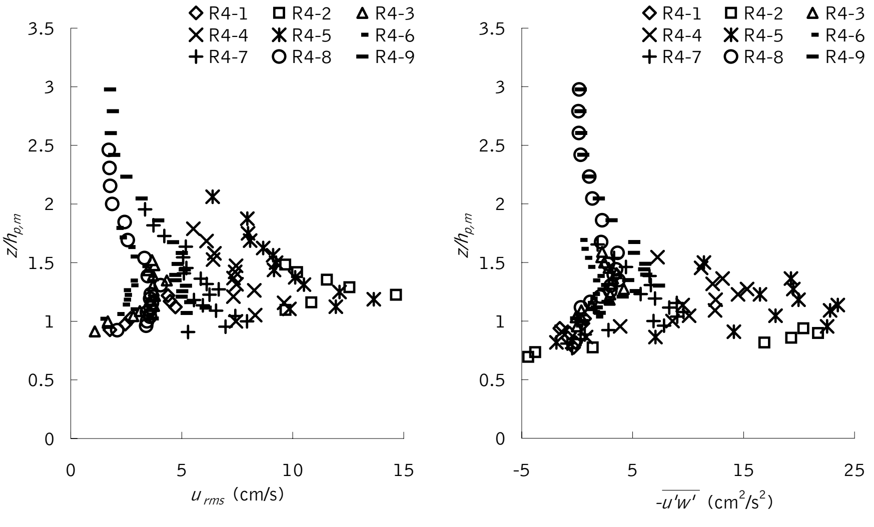

Figure 12. Averaged profiles for turbulence intensity (left) and Reynolds stress (right) for wheat (R4). The vertical ordinate was normalised with the mean deflected plant height.

3.2.2 Modification of an earlier computational approach (III)

The experiments reported in the previous section indicated that the prediction of velocity profile, and further, the flow resistance for submerged vegetation, could be based on the foundation incorporated in Equations 8–9. Here, the formulation in Equation 10 (Stephan 2002, Stephan and Gutknecht 2002) was selected for further analysis, and a new modification was suggested (III). Suitable velocity data were available for one series (R4) to test the approach by predicting the measured velocity profiles. Stephan and Gutknecht (2002) used the definition of u_{*4} (Equation 14) but did not discuss other alternatives. In the present study, a further three definitions (Equations 11–13) were introduced, which resulted in significant differences in the computed shear velocities (Table 2). Measured and predicted velocities are compared in Figure 13 using the definitions of u_{*2} (left) and u_{*3} (right), which gave the best results.

Measured velocity profiles for the experiments carried out with wheat were described well by the approach developed by Stephan (2002) indicating that it could be applied beyond the original scope (highly flexible aquatic vegetation). The approach was a suitable method for determining velocity profile and flow resistance (by Equation 8) for a wide range of submerged vegetation from highly flexible aquatic plants to wheat. Introducing the simple definition of u_{*2} (Equation 12), which was determined using the flow layer above the mean deflected plant height, yielded good results for the comparison of measured and calculated velocity profiles. Similar results were obtained with the definition of u_{*3} (Equation 13), which included data from the turbulence measurements. However, u_{*2} was a convenient definition for the shear velocity as the mean deflected plant height $h_{p,m}$ can be easily measured. Consequently, for determining the friction factor, Equations 8 and 10 were modified to use the definition of u_{*2}, which did not require complicated turbulence measurements and was considered straightforward to apply within a numerical modelling framework (III).

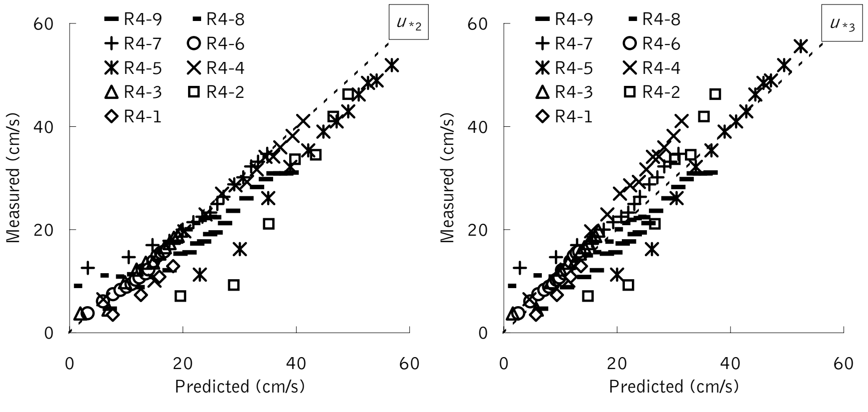

Figure 13. Velocity measured and predicted by Equation 10 with u_{*2} *(left) and* u_{*3} *(right). The dashed line denotes the perfect agreement.*

3.3 Determination of flow resistance caused by non-submerged, flexible and rigid woody vegetation (II, IV)

3.3.1 Characteristics of branched woody vegetation (II, IV)

In this section, the characteristics of leafless and leafy woody vegetation are reported and compared to simple cylinders, as it was expected that simple cylinder-based drag coefficient models offer limited applicability in treating branched vegetation, even without leaves. Before Equation 7 could be applied, a suitable approach for the estimation of an effective diameter (or A_p) and C_d was needed. For the studied leafless willows, the measured projected area increased approximately linearly with the willow height excluding the base and tip regions of the plants (II). Approximately 2/3 of the total projected area of the willows was contributed by the branches. Drag coefficients corresponding the measured projected area of the leafless willows were computed from 46 test runs. The average drag coefficients with standard deviations in parentheses for willow patterns Pa and Pf (Figure 2) were 1.55 (0.10) and 1.43 (0.12), respectively (II).

The experimental data were used to test the applicability of the computational methods developed by Lindner (1982) and Pasche (1984) in the case of leafless willows. Both approaches significantly underestimated the drag coefficient of the studied willow patterns (II, IV). With the same experimental data, additional calculations using the Lindner method were performed to compute C_d of an individual willow by replacing d and a_x with an average branch diameter and an average distance between the branches, respectively. These simple tests showed that the method again significantly underestimated the measured drag coefficient of a bush (IV). It was revealed that the complex three-dimensional plant structure with randomly orientated branches was not accounted for by the tested methods.

3.3.2 Development of a new procedure (IV)

This section presents the development of a procedure, which is capable of determining flow resistance caused by non-submerged woody vegetation. Separate formulations were developed for leafless and leafy cases, which are presented below. To support this work, data published by the writer (I, II) and others were used and reanalysed.

Flow resistance caused by leafless woody vegetation: Based on Equation 7, a new computational procedure for determining f was developed. The approach used measurable parameters of vegetation while taking into account the branched structure of woody plants. Leafless vegetation was characterized by a bulk drag coefficient and a characteristic plant diameter computed from the projected area.

The projected area was derived utilising theory on mechanical design of trees. The fundamental idea in this theory developed by McMahon (1975) and McMahon and Kronauer (1976) is to apply the Strahler (1952) stream ordering scheme to trees (Figure 14). McMahon and Kronauer (1976) showed that the branching pattern within any tree species is approximately stationary, which means that the structure is self-similar, and any patch of the structure is a model of the entire tree. Furthermore, they conclude that the principle of mechanical design is the maintenance of elastic similarity, and for elastically similar beams, the diameters are proportional to the 3/2 power of their length. They presented three equations of branching, diameter, and length ratio that are based on the geomorphic laws of drainage network composition by Horton (1945) and Schumm (1956). In the present study, a new application for this knowledge was proposed, namely the determination of the projected area of a branched plant.

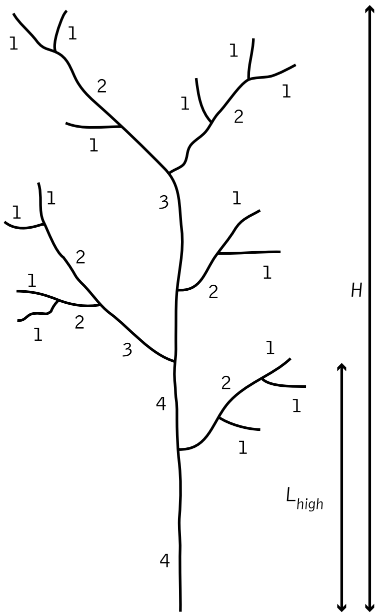

Figure 14. The principle of the Strahler ordering scheme applied to a woody plant.

The branching, diameter, and length ratios as well as the average diameter of the smallest branches were defined as the plant structure parameters and could be estimated from literature or field measurements. A further three parameters were needed to describe a particular plant individual: the average diameter of the highest order (trunk), the plant height, and the length of the highest order (L_{high} in Figure 14). These three parameters could be easily determined in the field. Accordingly, the total projected area was derived. To determine the projected area as a function of the plant height $A_p(h)$ it was approximated that the total projected area was linearly distributed over the height (II). However, if a particular height-area function is known, it could easily be incorporated in the computation. The computational steps are described in detail elsewhere (IV).

Finally, the friction factor could be computed by modifying the diameter definition in Equation 7 as

$$f = \frac{4d_r h}{a_x a_y} C_d \tag{15}$$

where $d_r = A_p(h)/h$, and a_x and a_y = the mean longitudinal and lateral distances, respectively, between the plants. Based on the research reported in section 1.2.5, it was assumed that $C_d = 1.5$ can be used as a base value in Equation 15, which is analogous to the typically made assumption of $C_d = 1.0$ for cylinders. The advantage of Equation 15 was that it was based on the physical laws (conservation of momentum) and characteristics of vegetation. The approach could be easily used to compute also the volume (or biomass) of vegetation (IV).

Flow resistance caused by leafy woody vegetation: It was concluded that the fundamental properties to be considered in establishing a resistance equation were density of vegetation and deformation of plants in a flow. Leaf area index (LAI, definition in section 2.1.2) was shown to be a useful measure to take into consideration the effects of the density of vegetation (IV). Subsequently, leafy vegetation was characterized by a vegetation parameter χ, leaf area index (LAI), and a new species-specific drag coefficient $C_{d\chi}$. The vegetation parameter χ accounted for the effects of plant deformation (flexibility and shape) in a flow, and was unique for a particular species.

Fathi-Moghadam and Kouwen (1997) propose a linear relationship between LAI and the friction factor, and the present study confirmed this relationship for the used willows. Thus, substituting the reference area A_p with the leaf area A_l in Equation 5 and introducing a dimensionless vegetation parameter α gave

$$f = 4C_{d\chi} \frac{A_l}{A_b} \alpha \tag{16}$$

where $C_{d\chi}$ is a species-specific drag coefficient and α accounts for the deformation effects of plants in a flow. Based on experimental data (Fathi-Moghadam 1996 and I), α could be expressed as a function of velocity $\alpha = (U/U_\chi)^\chi$. U_χ was used to normalize the relationship and was equal to the lowest velocity used in determining χ, i.e. typically $\alpha \approx 1$, when flow velocity is only a few cm/s. Inserting the definition of α and LAI into Equation 16 and assuming that canopies have a uniform distribution of LAI over the height of vegetation (Kouwen and Fathi-Moghadam 2000) yielded

$$f = 4C_{d\chi} \mathrm{LAI} \left(\frac{U}{U_\chi} \right)^\chi \frac{h}{H} \tag{17}$$

Equation 17 could be used to estimate the friction factor for flow inside leafy woody vegetation on floodplains and wetlands, where $h/H \leq 1$ and $U \geq U_\chi$. Previously published data were reanalysed to obtain values for the parameters $C_{d\chi}$, χ and U_χ, and were presented for different plant species in IV. Equation 17 was necessary to solve iteratively; the computational steps are described in detail elsewhere (IV).

Application, capability and limitations of the procedure: The proposed procedure could be applied to estimate the flow resistance for any canopy height, density, and any relative submergence ($h/H \leq 1$) where total resistance was dominated by vegetation rather than channel boundary roughness. Further research on minimum acceptable vegetation density was found necessary before exact limits of application can be established. The application of the procedure was limited to non-submerged flow, i.e. flow-through vegetation. The procedure was capable of predicting flow resistance caused by woody vegetation of different flexibility. The study was limited to the condition of relatively low velocity ($U <$ ~1 m/s, transitional to turbulent flow), which is often the case in low-gradient stream valleys and wetlands. The range of conditions for which the empirically calibrated vegetation parameters employed in the analysis of leafy vegetation are valid was presented in IV.

3.4 Effect of characteristics of environmental channels on flow resistance and local hydraulics (V, VI)

This section presents three topics. First, field measurements and an overall analysis of flow resistance in three rivers or streams featuring environmental flood management and stream restoration functions are reported. Second, an analysis of the relationship between flow resistance and cross-sectional geometry, and further, their role in assessing local hydraulic conditions is presented for the Myllypuro Brook. Third, success criteria for the restoration of local hydraulic conditions are presented, and a simple procedure for applying the success criteria in post-project evaluation is proposed.

Field data on flow resistance were gathered in degraded, restored, and natural channel reaches. In the Myllypuro Brook, 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 (V). Excluding the low flows, the friction factors for all the studied channels were mostly in line with the values presented by Cowan (1956) and Chow (1959) (V, VI). However, the results differed significantly from these values in reaches with considerable bank vegetation (VI), which was understandable considering the diversified hydraulic effects of vegetation observed in the laboratory experiments (I, II). The total friction factors were divided into sub-factors, which represented 1) surface roughness and vegetal drag, 2) sinuosity, and 3) all other resistance factors including local losses, woody debris and momentum transfer. In two out of the six studied reaches, the third group contributed more than 50% to the total friction factor (VI). In the River Tuusulanjoki, significant changes in the friction factors caused by vegetation growth were not detected during the growing season, whereas some yearly differences were found. In the River Päntäneenjoki, seasonal or yearly variation in Q–f relationships could not be detected.

Furthermore, the tested bioengineering methods had no significant effect on the flow resistance, and therefore in this case their application did not reduce the conveyance of the channel (VI).

In the Myllypuro Brook, the parameters describing the cross-sectional geometry (width-depth ratio and hydraulic radius) correlated weakly with the observed flow resistance (V). The sinuosity or longitudinal bottom 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 was evident that in small channels site-specific factors such as individual logs could significantly contribute to flow resistance (V). However, the results suggested that the hypothesis of flow resistance and cross-sectional geometry determining local hydraulic conditions was relevant. The differences in meeting the design objectives between the restored reaches showed 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 needed to be considered (V).

Design and success of a restoration project should be based on several variables that can easily be measured in the field (V). These variables could 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 suitability for certain flora and fauna) (V). In the restored reaches of the Myllypuro Brook, the parameters for the cross-sectional geometry and flow resistance were used as simple success criteria for the restoration of local hydraulic conditions. Fulfilling only one of these criteria could result in failure of the design to meet the desired hydraulic conditions (V). Furthermore, these criteria were be used to propose an assessment tool for post-project evaluation (V). The structure and application of this procedure is presented in Figure 15. In brief, for both a reference reach and a restored reach, 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 16 (V). In addition to fulfilling both criteria at reach-averaged scale, it was necessary to consider natural variability of local hydraulics (V).

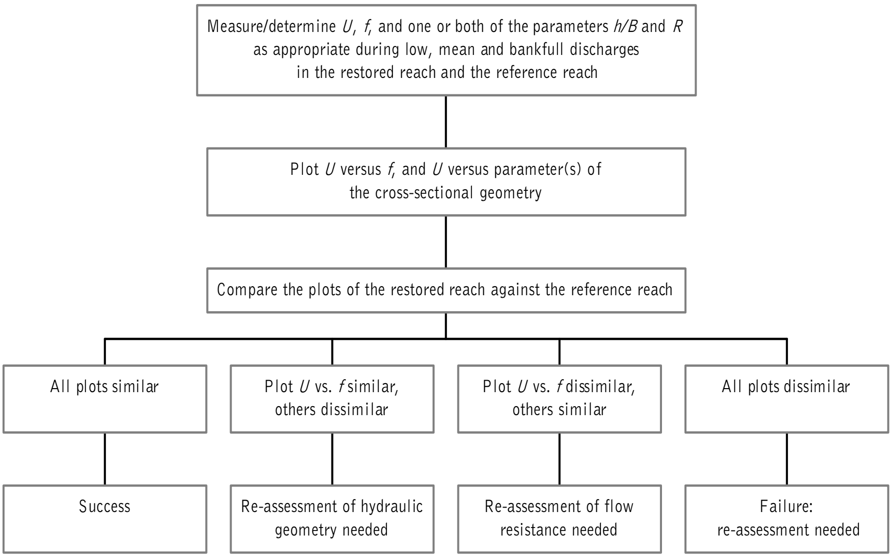

Figure 15. Procedure for applying the success criteria in post-project evaluation of local hydraulics (V).

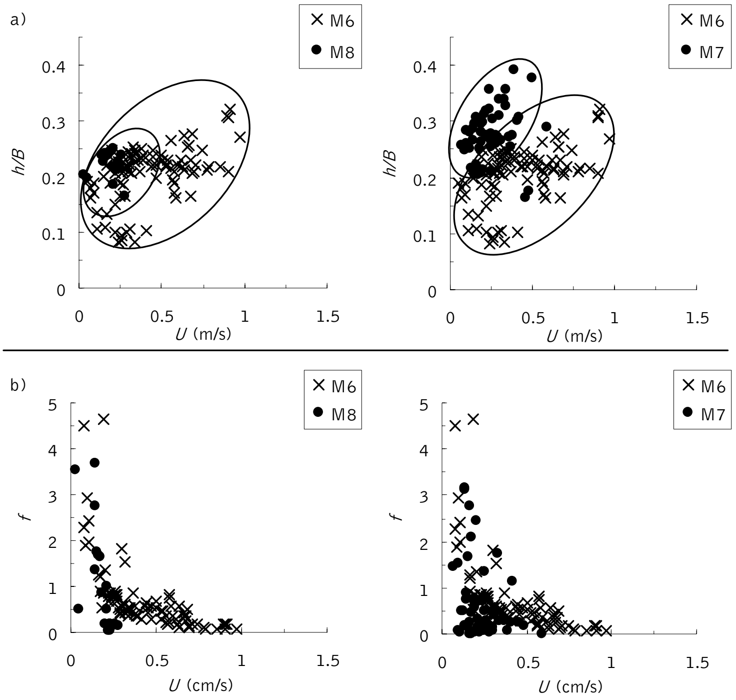

Figure 16. Application of the procedure for two restored reaches M7 and M8: a) Depth-width ratio vs. flow velocity differed in reach M7 from reference reach M6. b) Friction factors vs. flow velocities matched relatively well. (V)

4 DISCUSSION

The following discussion draws together the findings from both the field and laboratory studies.

In general, the experimental results on friction factors from the field studies were in agreement with the values presented in the literature. Excluding the low flows, the experimental values lie mostly within the range presented in Chow (1959). Cowan's and Chow's methods predicted well resistance coefficients for mean flow, but not for low flows, which were regarded as being important in terms of stream ecology. The investigations by Saari (1955) are limited to low and mean flows, and in most cases, only one or two measurements are available from each location in contrast to the present study which represents 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 study reaches in the Myllypuro Brook (V). A sensitivity analysis was carried out for the field measurements, which showed that a maximum error of 10–30% in the roughness coefficient was realistic for most cases (V, VI). The field studies in the Myllypuro Brook indicated that in the case of small channels cross-sectional geometry and flow resistance were weakly interconnected, and were influenced by factors such as local roughness elements. The analysis of the relationship between cross-sectional geometry and flow resistance was supported by a statistical analysis, in which 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 were small and confirmed that no clear dependency between the parameters existed.

In many restoration projects, the design objectives and success criteria are not clearly stated (e.g. Brookes and Sear 1996). Ideally, the design and success of a restoration project should be based on several variables that can easily be measured in the field (V). For hydraulic conditions, the criteria could relate, for example, to depth, velocity or flow resistance. Based on the field studies, the parameters for the cross-sectional geometry and flow resistance were used to formulate simple but nonetheless valuable success criteria for the restoration of local hydraulic conditions. Fulfilling only one of these criteria could result in the failure of the design to meet the desired hydraulic conditions (V). Furthermore, these criteria were used for developing an assessment tool for post-project evaluation (Figure 15) (V). The hydraulic effect of vegetation was studied in more detail by conducting laboratory experiments with living plants, which is discussed in the following.

Most earlier laboratory studies were limited to investigating vegetative roughness types separately, one roughness type at a time, under given specific flow conditions. Studies that include several types of natural vegetation in different flow conditions were very rare in the literature. Based on the present experimental work, a better understanding of flow resistance due to different combinations of natural rigid and flexible vegetation under non-submerged and submerged conditions was gained. The experiments revealed that the contribution of different vegetative roughness types to the total flow resistance depended strongly on the type and combination of the vegetation and exhibited considerable variability (I). The most notable finding was that, when compared to leafless conditions, the presence of leaves increased the friction factor up to seven-fold. The streamlining of leaves and smaller branches caused a strong dependency on flow velocity. Thus, it was crucial to take the velocity effects (deformation of vegetation) into consideration in determining the friction factor.

The friction factor f was dependent mostly on 1) the relative roughness of the submerged grasses and wheat; 2) the flow velocity and leaf area (LAI) of the non-submerged leafy willows; and 3) the flow depth of the non-submerged leafless willows. These dependencies have also been reported earlier by others. Several cylinder-based studies show that the element pattern significantly affects wakes and flow rates (e.g. Li and Shen 1973, Rouvé 1987). In this study, different spacing for the same number of leafless willows with grasses did not have a significant effect on the friction factor. Doubling the number of leafless willows also approximately doubled the f values for the same flow conditions. Fathi-Moghadam and Kouwen (1997) have reported similar observations for both vegetation distribution and vegetation density. The drag of a rigid element is expected to increase in proportion to the square of the velocity. Fathi-Moghadam (1996), Werth (1997), Oplatka (1998) and Freeman et al. (2000) showed that this relationship does not hold for flexible trees and bushes. The present study confirmed this for the studied leafy willows.

A considerable number of flow resistance formulas or models have been developed which treat vegetation simply as static rigid cylinders and/or bottom roughness. The present study showed that for the studied leafless willows approximately only 1/3 of the total projected area of a willow consisted of the main stem; the projected area was determined by means of digital imaging with an expected accuracy of ~5% (II). However, it is often assumed in modelling approaches that a drag coefficient $C_d \approx 1.0$ determined for cylinders can be used for vegetation; recently, for example, in Fischer-Antze et al. (2001), though they recognize that for practical applications the drag coefficient for complex shaped vegetation with leaves will probably have to be determined for each type of vegetation. Crucial process descriptions are lacking from most current methods or models, since the domination of laboratory studies that use simple artificial roughness has not allowed for the identification and assessment of all the important processes and mechanisms that control vegetation-induced flow resistance. For example, it was revealed that complex three-dimensional plant structures with randomly orientated branches were not accounted for in the methods developed by Lindner (1982) and Pasche (1984) in determining C_d (II, IV). For the studied leafless willows, the simpler Lindner approach provided similar predictions for C_d than the more sophisticated method of Pasche (1984). Of particular concern is the fact that the use of some of the methods that were originally derived based on theory and experiments on rigid cylinders, have been extrapolated beyond the limits of their applicability.

The problems discussed above were addressed by developing a new procedure, one which was intended to allow the determination of friction factor f or Manning's n using the measurable characteristics of the vegetation and flow. The new procedure used sound hydraulic principles and methods that are already available but also incorporated some adjustments based on knowledge of the mechanical design of trees and the deformation of foliage in a flow. The procedure was found to be capable of predicting flow resistance caused by non-submerged: 1) leafless bushes or trees (Equation 15) and 2) leafy bushes or trees (Equation 17). The procedure was evaluated by comparing predicted and measured friction factors for leafless and leafy willows. The data selected for the comparison were not used in determining the parameters in the procedure; i.e. they could be used for independent evaluation. The largest individual discrepancies were 13% and 61% for the leafless and leafy cases, respectively, while the mean errors ranged between 2% and 9% (IV). It was found that the presented methodology could be used for estimating the relationship between plant characteristics and flow resistance for flows over floodplains and wetlands with woody vegetation.

Several studies report that maximum turbulence intensity is found at the top level of vegetation (e.g. Tsujimoto et al. 1992, Ikeda and Kanazawa 1996). In the present study, the maximum values for u_{rms} and $-\overline{u'w'}$ were recorded at approximately $h_{p,up}$, i.e. slightly above the mean deflected plant height. To determine the velocity profile and flow resistance caused by submerged flexible vegetation, the approach developed by Stephan (2002) was found to be a suitable method for a wide range of submerged vegetation from highly flexible aquatic plants to wheat. However, a new modification was proposed, namely the definition of the shear velocity u_{*2} (Equation 12) based on the mean deflected plant height $h_{p,m}$, which could be easily measured under both laboratory and field conditions. Alternatively, $h_{p,m}$ can be related to plant length (Temple 1987, Kouwen 1988, Temple 1991). With this modification, the approach offered better practical applicability than the original formulation, which requires complicated turbulence measurements. A further benefit was that this approach would be straightforward to apply within a numerical modelling framework. To evaluate the proposed modification, the mean error and the efficiency (Nash and Sutcliffe 1970) between the measured and predicted velocity profiles were computed. The efficiency ($\mathrm{R}_{\mathrm{eff}}$) is a dimensionless transformation of the sum of squared errors and is defined for a parameter x as $\mathrm{R}_{\mathrm{eff}} = 1 - \sum(x_{\mathrm{mes},i}-x_{\mathrm{pred},i})^2 / \sum(x_{\mathrm{mes},i}-x_{\mathrm{mes,mean}})^2$ where the subscripts mes,*i*; pred,*i* and mes,mean refer to the *i*th measurement, the *i*th prediction and the mean of the measurements, respectively. Here, $\mathrm{R}_{\mathrm{eff}}$ covered a wide range of flow conditions (velocity and relative submergence) well representing the overall reliability of the approach. Results from the statistical analysis showed that the mean error was 15% when using the new definition of shear velocity u_{*2}, which was regarded as a very satisfactory result. However, using a turbulence-based definition of the shear velocity u_{*3} a smaller mean error of only –2% was obtained, but laborious measurements were required. The efficiency was 0.84 and 0.88 when using the definitions of u_{*2} and u_{*3}, respectively. Thus, the simpler definition of u_{*2} was preferred.

Finally, it was emphasized that flow resistance needs to be assessed by taking into consideration the aggregate or assembly that the individual species or types create (IV). The implications of this can be illustrated by the following two examples that examine a floodplain with dense willows and grasses. Firstly, in the midst of a growing season, the leaves on the willows are likely to dominate the total drag, and bottom grasses may only be a minor source of flow resistance. Secondly, in winter, when the willows are leafless, the bottom grasses may contribute more than the willow stems to the total flow resistance. The ability to predict the flow resistance for such conditions was seen as being highly relevant, for example, in evaluating the effects of winter and summer floods.

5 CONCLUSIONS

The main findings of the study can be summarised in the following points:

1. The literature review revealed that the effects of the natural characteristics of vegetation on flow resistance have not been adequately addressed in hydraulic design and modelling. The present experiments confirmed this observation for the tests carried out with natural woody vegetation in a non-submerged flow. In the experiments, most notably, the effect of leaves on the contribution to flow resistance was of great importance. Here, the presence of leaves increased the friction factor by a ratio of up to seven when compared to the leafless case and was strongly dependent on the flow velocity (I, II). Furthermore, it was revealed that in the case of natural (branched) vegetation the pattern of vegetation was only of minor importance in determining the flow resistance (I). These points have been raised in some earlier studies, but generally, very little attention has been paid to them.
2. As most current models or methods are based on theory and experiments on rigid cylinders, crucial process descriptions, such as the streamlining or deformation of vegetation in a flow, are lacking from these approaches. Based on the present experimental work, a better understanding of flow resistance caused by natural rigid and flexible vegetation under non-submerged and submerged conditions was gained, which was utilised to improve earlier computational approaches (III, IV).
3. To determine friction factor f or Manning's n for non-submerged woody vegetation, a new procedure based on the measurable characteristics of vegetation and flow was developed. A major advantage of this procedure over the old methods was its ability to estimate the flow resistance of woody vegetation both in leafless (Equation 15) and leafy (Equation 17) conditions. The procedure was novel in that it used sound hydraulic principles and methods that are currently available but incorporated some adjustments based on knowledge of the mechanical design of trees and the deformation of foliage in a flow. The procedure presented was found to be a practical tool in estimating the relationship between plant characteristics and flow resistance for flows over floodplains and wetlands with woody vegetation. (IV)

4. For determining the velocity profile and flow resistance caused by submerged flexible vegetation, the approach developed by Stephan (2002) was found to be suitable but a new formulation was proposed for the shear velocity. The definition of the shear velocity u_{*2} (Equation 12) based on the mean deflected plant height $h_{p,m}$ was found to be useful as it could be easily measured under both laboratory and field conditions. With this modification, the approach offered better practical applicability than the original formulation, which requires complicated turbulence measurements. (III)
5. In the field studies, the experimental results on friction factors for mean flows were in agreement with the values presented in the literature. However, in the case of low flows, which were seen as being important in terms of stream ecology, friction factors were typically underestimated by the used methods and literature (V, VI). This was especially so for small streams, where it was observed that vegetation and local roughness elements such as large woody debris could significantly contribute to the total flow resistance (V). Overall, the gathered field data from the degraded, restored, and natural channel reaches formed a reference data set, which could be useful in other similar restoration or engineering projects. Comparable data sets were not previously available for Finnish conditions.
6. The Myllypuro Brook study showed that both the flow resistance and cross-sectional geometry were vital factors in determining local hydraulic conditions (V). Ideally, the design and success of a restoration project should be based on several variables that can easily be measured in the field. In this study, the parameters for the cross-sectional geometry and flow resistance were found to be simple but nonetheless valuable in evaluating the success of a project which aims to restore local hydraulics (V). Restoration design based on the consideration of only one of these two factors was found to be inadequate and could result in a failure to replicate natural hydraulic conditions. In addition to fulfilling both criteria at the reach-averaged scale, it was necessary to consider natural variability (V). A new procedure (Figure 15) for applying the success criteria in post-project evaluation of local hydraulics was developed (V).

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APPENDIX A: LIST OF SYMBOLS

A	[m^2]	cross-sectional area
A_b	[m^2]	bottom area
A_l	[m^2]	leaf area
A_p	[m^2]	projected area
a_x, a_y	[m]	longitudinal and lateral distance between the plants
B	[m]	surface width
C	[–]	integration constant
C_d	[–]	drag coefficient
C'_d	[m^{-1}]	vegetal drag coefficient
C_{dw}	[–]	drag coefficient of a cylinder in 2-D laterally limited flow
ΔC_{dw}	[–]	drag coefficient due to the free surface effects
$C_{d\chi}$	[–]	drag coefficient of a leafy bush or tree
d	[m]	diameter of an element
d_r	[m]	characteristic diameter
E	[N m^{-2}]	modulus of elasticity
f	[–]	Darcy–Weisbach friction factor
F_d	[N]	drag
F_g	[N]	gravitational force
Fr	[–]	Froude number
g	[m s^{-2}]	gravitational acceleration
H	[m]	plant height
H_f	[m]	energy loss
h	[m]	flow depth (bottom to free surface)
h_0	[m]	flow depth at the beginning of the test area
h_p	[m]	deflected plant height (subscript additions *m*, *low*, and *high* specify mean, minimum, and maximum deflected plant heights, respectively)
h^*	[m]	flow depth corresponding to the maximum measured Reynolds stress
I	[m^4]	moment of inertia
k_s	[m]	equivalent sand roughness
L	[m]	length of the channel reach
L_{high}	[m]	length of the highest Strahler order
LAI	[–]	leaf area index
MEI	[N m^{-2}]	flexural rigidity per unit area
n	[s m$^{-1/3}$]	Manning's resistance coefficient
Q	[m^3 s^{-1}]	discharge
R	[m]	hydraulic radius
Re	[–]	Reynolds number
S	[–]	bottom or energy slope for uniform and non-uniform flows, respectively
U	[m s^{-1}]	mean cross-sectional velocity
U_χ	[m s^{-1}]	lowest velocity used in determining χ

u, v, w	[m s^{-1}]	mean velocity component (longitudinal, lateral, vertical direction)
u_*	[m s^{-1}]	shear velocity
u_i	[m s^{-1}]	mean approach velocity at the *i*th plant
u_{rms}	[m s^{-1}]	RMS turbulence intensity
$-\overline{u'w'}$	[m^2 s^{-2}]	Reynolds stress
x, y, z	[m]	longitudinal, lateral, vertical coordinate
α	[–]	vegetation parameter
β	[–]	velocity distribution coefficient
χ	[–]	vegetation parameter
κ	[–]	von Karman constant
ν	[m^2 s^{-1}]	kinematic viscosity
ρ	[kg m^{-3}]	fluid density
ξE	[N m^{-2}]	vegetation index