Helsinki University of Technology Water Resources Publications

Teknillisen korkeakoulun vesitalouden ja vesirakennuksen julkaisuja

Espoo 2004 TKK-VTR-11

EFFECTS OF CROSS-SECTIONAL GEOMETRY, VEGETATION AND ICE ON FLOW RESISTANCE AND CONVEYANCE OF NATURAL RIVERS

Terhi Helmiö

Dissertation for the degree of Doctor of Science in Technology to be presented with due permission of the Department of Civil and Environmental Engineering for public examination and debate in Auditorium R1 at Helsinki University of Technology (Espoo, Finland) on the 18th of June, 2004, at 12 o'clock noon.

Helsinki University of Technology

Department of Civil and Environmental Engineering

Laboratory of Water Resources

Teknillinen korkeakoulu

Rakennus- ja ympäristötekniikan osasto

Vesitalouden ja vesirakennuksen laboratorio

Helmiö, T., Effects of cross-sectional geometry, vegetation and ice on flow resistance and conveyance of natural rivers, Helsinki University of Technology, Water Resources Publications, TKK-VTR-11, Espoo, 2004, 56 pp.

Distribution:
Helsinki University of Technology
Laboratory of Water Resources
P.O.Box 5300
FIN-02015 HUT
Tel. +358-9-451 3821
Fax. +358-9-451 3856
E-mail: contact@water.hut.fi

ISBN 951-22-7072-2
ISSN 1456-2596

Espoo 2004

HELSINKI UNIVERSITY OF TECHNOLOGY P.O. Box 1000, FIN-02015 HUT, http://www.hut.fi/	**ABSTRACT OF DOCTORAL DISSERTATION**

Author Terhi Helmiö

Effects of cross-sectional geometry, vegetation and ice on flow resistance and conveyance of natural rivers

Date of the manuscript 2 April, 2004	Date of the dissertation 18 June, 2004

[ ] Monograph [X] Article dissertation (summary + articles)

Department	Civil and Environmental Engineering
Laboratory	Water Resources
Field of research	Hydraulics
Opponent	Professor Erik Pasche (Technische Universität Hamburg-Harburg, Germany)
Supervisor	Professor Tuomo Karvonen (Helsinki University of Technology)
Pre-examiners	Professor János Józsa (Budapest University of Technology & Economics, Hungary)
	Docent Timo Huttula (University of Helsinki, Finland)

The accurate estimation of local hydraulics, i.e. local flow velocities and water depths, is necessary for the restoration and protection of biodiversity. The aim of the thesis was to develop methods and models for designing and evaluating the hydraulic aspects of restoration, rehabilitation and environmental flood management in running waters.

Methods for the estimation of flow resistance in natural complex rivers and channels that have composite flow resistance and/or a compound channel shape were tested, and an unsteady 1D flow model for partially vegetated channels with complex geometry was developed. These methods were used to quantify different factors causing flow resistance, e.g. cross-sectional geometry, vegetation, ice cover and momentum transfer, in lowland rivers of different shapes and sizes. The relationship between the flow resistance and the cross-sectional geometry was analysed.

Traditional methods used to estimate composite friction factors were found to be accurate in simple concave channels with simple hydraulic properties, but an adjustment of the methods would be necessary for reaches with significant head losses due to lateral momentum transfer. It was seen that the effect of the momentum exchange process between the main channel and the floodplain or streambank vegetation was significant. A procedure for applying the success criteria in a post-project evaluation of local hydraulics was developed, based on the hypothesis of flow resistance and cross-sectional geometry determining local hydraulic conditions in boreal streams.

Based on the results from the proposed flow model, the restoration of flood retention areas and local hydraulics is a vital component of the restoration of catchment-scale hydrology, but not sufficient by itself to restore flood peaks to their earlier state, because the changes in land use have often been drastic.

Keywords hydraulics, river, flow resistance, vegetation, geometry, ice

UDC	556.5:532.5:556.18	Number of pages 56	
ISBN (printed)	951-22-7071-4	ISBN (pdf)	951-22-7072-2
ISBN (others)		ISSN	1456-2596

Publisher	HUT, Laboratory of Water Resources
Print distribution	Fax +358 9 451 3856, E-mail contact@water.hut.fi

[X] The dissertation can be read at http:// lib.hut.fi/Diss/2004/isbn9512270722

TEKNILLINEN KORKEAKOULU
PL 1000, 02015 TKK, http://www.hut.fi/

VÄITÖSKIRJAN TIIVISTELMÄ

Tekijä Terhi Helmiö

Poikkileikkausgeometrian, kasvillisuuden ja jääpeitteen vaikutus virtausvastukseen ja vedenjohtokykyyn luonnonuomissa

Käsikirjoituksen jättämispäivämäärä 2.4.2004	Väitöstilaisuuden ajankohta 18.6.2004
[ ] Monografia	[X] Yhdistelmäväitöskirja (yhteenveto + erillisartikkelit)
Osasto	Rakennus- ja ympäristötekniikka
Laboratorio	Vesitalous ja vesirakennus
Tutkimusala	Hydraulikka
Vastaväittäjä	Professori Erik Pasche (Hampurin-Harburgin teknillinen korkeakoulu, Saksa)
Työn valvoja	Professori Tuomo Karvonen (Teknillinen korkeakoulu)
Esitarkastajat	Professori János Józsa (Budapestin teknillinen ja kaupallinen korkeakoulu, Unkari) Dosentti Timo Huttula (Helsingin yliopisto)

Luonnon monimuotoisuuden parantaminen edellyttää yksityiskohtaista paikallisen hydrauliikan tuntemusta ja kehittyneitä mitoitusmenetelmiä. Väitöskirjan tavoitteena oli arvioida ja kehittää menetelmiä luonnonmukaisen uomahydrauliikan ennallistamiseen ja kunnostukseen virtavesissä.

Työssä testattiin yksinkertaisia komposiittivastuskertoimien arviointimenetelmiä ja kehitettiin muuttuvan virtauksen yksiulotteinen malli tulvatasanteisille ja/tai osittain kasvillisuuden peittämille uomille, joilla on monimutkainen poikkileikkausgeometria. Näiden avulla määritettiin eri osavastustekijöiden, mm. poikkileikkausgeometrian, kasvillisuuden, jääpeitteen sekä poikittaisen liikemäärän siirtymisen vaikutuksia komposiittivastuskertoimiin. Lisäksi tutkittiin virtausvastuksen ja poikkileikkausgeometrian välistä riippuvuutta.

Testatut perinteiset komposiittivastuskertoimien arviointimenetelmät olivat suhteellisen tarkkoja hydraulisesti yksinkertaisille uomajaksoille. Menetelmät olivat kuitenkin puutteellisia uomajaksoilla, joissa oli merkittäviä virtaushäviöitä poikittaisen liikemäärän siirtymisen takia joko penkkakasvillisuuden tai tulvatasannegeometrian takia. Paikallisen hydrauliikan määräsi suhteellisen hyvin virtausvastus ja poikkileikkausgeometria. Tämän perusteella kehitettiin menetelmä, jolla voidaan arvioida paikallisen hydrauliikan kunnostamisen onnistumista.

Virtausmallinnuksesta saatujen tulosten perusteella tulva-alueiden palauttaminen ja ennallistaminen ovat olennaisia tekijöitä laajemmassa valuma-aluehydrologian palauttamisessa, mutteivät yksinään riittäviä, koska maankäytön muutokset valuma-alueella ovat usein muuttaneet alueen hydrologiaa merkittävästi.

Avainsanat	hydrauliikka, joki, virtausvastus, kasvillisuus, geometria, jääpeite		
UDK	556.5:532.5:556.18	Sivumäärä	56
ISBN (painettu)	951-22-7071-4	ISBN (pdf)	951-22-7072-2
ISBN (muut)		ISSN	1456-2596
Julkaisija	TKK, Vesitalouden ja vesirakennuksen laboratorio		
Painetun väitöskirjan jakelu	Telefaksi 09 451 3856, sähköposti contact@water.hut.fi		
[X] Luettavissa verkossa osoitteessa http://lib.hut.fi/Diss/2004/isbn9512270722			

LIST OF APPENDED PAPERS

This thesis is based on the following seven Papers, which are referred to in the text in Roman numerals.

I Helmiö, T. 2001. Friction measurements of ice cover: theory and practise in River Päntäneenjoki. 2nd IAHR Symposium on River, Coastal and Estuarine Morphodynamics, 10-14 September 2001, Obihiro, Japan. pp. 179-187.

II Helmiö, T. & Järvelä, J. 2004. Hydraulic aspects of environmental flood management in boreal conditions. Boreal Environment Research, 9(3/4) (in press).

III Järvelä, J. & Helmiö, T. 2004. Hydraulic Considerations in Restoring Boreal Streams. Nordic Hydrology, Vol. 35(3) (in press).

IV Helmiö, T. 2004. Hydraulic geometry of cohesive lowland rivers. Boreal Environment Research, Vol. 9 (in press).

V Helmiö, T. 2002. Unsteady 1D flow model of compound channel with vegetated floodplains. Journal of Hydrology, 269(1-2): 89-99.

VI Helmiö, T. 2004. Unsteady 1D flow model of a river with partly vegetated floodplains – application to the Rhine River. Environmental Modelling & Software. (in press).

VII Helmiö, T. 2004. Flow resistance due to lateral momentum transfer in partially vegetated channels. Water Resources Research, Vol. 40 (in press).

The contribution of the author to Papers from *I* to *VII* is as follows:

I The author of this thesis and Juha Järvelä were equally responsible for the design of the study. The West Finland Regional Environment Centre carried out the field studies. The author was responsible for the rest.

II The author and Juha Järvelä were equally responsible for the design of the study, data analysis and writing the manuscript. Uusimaa Regional Environment Centre carried out the field studies in the River Tuusulanjoki. The West Finland Regional Environment Centre carried out the field studies in the River Päntäneenjoki.

III The author and Juha Järvelä were equally responsible for the design of the study, data analysis and writing the manuscript. Uusimaa Regional Environment Centre carried out the field studies in the Myllypuro Brook.

IV The author was responsible for all other phases of the study except the data collection. The field data from Saari (1955) was measured by the Finnish National Board of Agriculture in 1954. The West Finland Regional Environment Centre carried out the field studies in the River Päntäneenjoki. Uusimaa Regional Environment Centre carried out the field studies in the River Tuusulanjoki and in the Myllypuro Brook.

V The author was responsible for all phases of the study.

VI The author was responsible for all other phases of the study except the data collection. The field data from the River Rhine came from the University of Karlsruhe with the permission of Gewässerdirektion Südlicher Oberrhein/ Hochrhein, Projektegruppe Breisach.

VII The author was responsible for all other phases of the study except the data collection. The field data from the River Rhine came from the University of Karlsruhe. The West Finland Regional Environment Centre carried out the field studies in the River Päntäneenjoki.

ACKNOWLEDGEMENTS – KIITOKSET

I wish to thank Professor Tuomo Karvonen and my colleague and co-author Juha Järvelä, who have been my Environmental River Engineering 'research group' at the HUT Laboratory of Water Resources. Our collaboration has been extremely valuable and I have benefited greatly from their scientific and intellectual support. I would also like to thank Professors Pertti Vakkilainen and Ari Jolma (HUT) who have also supported my work extensively. Special thanks go to my pre-examiners Professor Józsa (BUTE) and Dr Huttula (HY). Finally I would like to extend my thanks to all my former and present colleagues at the laboratory, especially Harri Koivusalo, Teemu Kokkonen and Olli Varis.

The research was financed by several organizations. The first half of the work was part of the 'Hydraulics of natural open channels' project of the Academy of Finland (Grant no. 44395), and the second half was supported by the Land and Water Technology Foundation and the Alfred Kordelin Foundation. Additional funding came from the Finnish Cultural Foundation, the Foundation of Technology, the Oskar Öflund Foundation, the Sven Hallin Foundation and Helsinki City.

Of my foreign associates I wish to express my gratitude to Professor Pasche (Hamburg-Harburg Technical University) for his enthusiasm for the research topic and for his valuable support and advice on my work. I also wish to thank Professor Dittrich and Dr. Specht (Technical University of Brunswick), for valuable comments on the research and for the field data from the River Rhine, which came from Gewässerdirektion Südlicher Oberrhein/ Hochrhein. I would also like to acknowledge Professor Salonen (HUT) for his patience with my studies in fluid mechanics. In particular, I learnt a lot from him as a teacher. Furthermore, I wish to thank Professor Salonen and Professor Józsa (BUTE) for the encouragement they gave me in my studies of hydraulics. Finally, I wish to thank my friend David Freeman and Professor Franti (Univ. of Nebraska) for checking the English language content of some of my journal papers.

Kiitokset Väinö Haapamäelle, Ulf Höglundille ja Heikki Kalliokoskelle (Länsi-Suomen ympäristökeskus); Jori Hellgrenille, Tanja Dubrovinille ja Katri Saukkoselle (Uudenmaan ympäristökeskus); ja Matti Kedolle (TKK) maastomittauksista 1997-2001 suomalaisilla joilla, sekä Antti Louhiolle ja Jyrki Kotolalle (TKK) kuusimittauksista kourussa. Kiitos Jukka Jormolalle (SYKE) yhteistyöstä luonnonmukaisen vesirakennuksen parissa.

Lopuksi kiitokset perheelleni ja ystävilleni kannustuksesta jatko-opiskelussa ja muilla elämän osa-alueilla. Kiitokset myös judoseura FinnDain väelle, joka on jaksanut piristää päiviäni ja riepotella minua pitkin tatamia silloin kun olen sitä eniten tarvinnut.

“Once there lived a village of creatures
along the bottom of a great crystal river.
The current of the river swept silently over them all -
young and old, rich and poor, good and evil,
the current going its own way, knowing only its own crystal self.
Each creature in its own manner clung tightly
to the twigs and rocks of the river bottom,
for clinging was their way of life,
and resisting the current what each had learned from birth.
But one creature said at last, 'I am tired of clinging.
Though I cannot see it with my eyes,
I trust that the current knows where it is going.
I shall let go, and let it take me where it will.
Clinging, I shall die of boredom.'
The other creatures laughed and said,
'Fool! Let go, and that current you worship will throw you
tumbled and smashed by the current across the rocks,
and you will die quicker than boredom!'
But the one heeded them not, and taking a breath did let go,
and at once was tumbled and smashed by the current across the rocks
Yet in time, as the creature refused to cling again,
the current lifted him free from the bottom,
and he was bruised and hurt no more.
And the creatures downstream, to whom he was a stranger, cried,
'See a miracle! A creature like ourselves, yet he flies!
See the Messiah, come to save us all!'
And the one carried in the current said, 'I am no more Messiah than you.
The river delights to lift us free, if only we dare let go.
Our true work is this voyage, this adventure.'
But they cried the more, 'Saviour!' all the while clinging
to the rocks, and when they looked again he was gone,
and they were left alone making legends of a Saviour.”

– Richard Bach from "Illusions" –

TABLE OF CONTENTS

1 INTRODUCTION

1.1 Background

Rivers have been used by man more than any other type of ecosystem (Boon 1992). Over the past 6,000 years, river channels have been altered by over-engineering and ineffective management. In Europe, areas near rivers have been utilized for the past 500 years, and this was never more so than during the 20th century. Flood retention areas were drained and separated from river channels step by step so as to allow for the different functions of agriculture, housing and infrastructure, and rivers were also utilised for hydropower. Land use of the catchments was changed, altering the natural hydrological processes. River channels were dredged and straightened, and the natural vegetation was removed. Thus, rivers were altered into hydraulically optimal but ecologically catastrophic stereotyped canal systems (Mellequist 1992). The floodwater was conveyed downstream all the way to the sea as quickly as possible. The natural retention capacity of rivers was reduced, raising flood peaks and reducing the duration of floods. In all, the impact of humans on floodplains and river channels has been extensive throughout history (Brookes & Shields 1997).

The background of this research lies in the concept of environmental river engineering initiated in Central Europe a few decades ago. Besides restoration and rehabilitation, a fundamental idea of environmental river engineering is that all new construction measures aim at sustaining the natural hydraulic and geomorphic state and ecological status of waterways. The restoration of riverine landscapes has become a vital topic in river engineering, and the hydraulics of flow with vegetation and fluvial hydraulics must support such restoration (Tsujimoto 1999). Recent developments in river management have given further emphasis to ecological issues. The EU Water Framework Directive (2000) states: “Member States shall protect, enhance and restore all bodies of surface water… with the aim of achieving good surface water status” and “Member States shall protect and enhance all artificial and heavily modified bodies of water, with the aim of achieving good ecological potential and good surface water chemical status”. At the moment, the exact meaning of the term “good ecological potential” is not yet established in Finnish legislation, but improvements can be expected in at least some running waters in Finland.

At present, for the first time in 1,000 years of fighting against floods, decision makers in the EU are now convinced that rivers should be allowed to take over more natural space, with all the subsequent consequences: severe economic restrictions, abandoning arable land in favour of the re-development of ‘natural’ rivers, and changing peoples' attitude towards flood hazards (Nienhuis & Leuwen 2001). The aim is to rehabilitate and restore dredged and otherwise engineered channels, floodplains and other flood retention areas. The decision-making and design of restoration measures should be carried out on a catchment or river basin scale. River problems will not be solved in the rivers alone, because these problems for the most part originate in the rivers' catchment areas (Mellequist 1992).

Environmental river engineering has created the challenge of designing "natural" rivers that have an increased hydraulic and geomorphic complexity compared to dredged and straightened channels. The accurate estimation of local hydraulics, i.e. the local flow velocities and water depths, is necessary for the restoration and protection of biodiversity. This is especially important in cohesive lowland rivers with low stream power, where the natural adjustment to the channel is extremely slow and under- or over-sizing of the channel may either cause severe flooding or ecological degradation, respectively. In restoration, consideration of the longitudinal changes of channel properties is also essential. If a natural reference reach is found far upstream or downstream of the restored reach, the hydraulics of the reach under restoration should be adjusted in a way that is characteristic of the stream under consideration.

Environmentally acceptable methods are also essential in flood management. The restoration of retention areas to reduce flood peaks, channel enlargement above the mean water level to increase conveyance, and variable bioengineering methods to prevent erosion provide effective flood management. In the design of hydraulically complex rivers with floodplains and vegetation, it is essential to accurately estimate the conveyance of unsteady flows, i.e. the propagation of a flood wave, and the retention capacity of the channel. However, this should be interconnected with the estimation of local velocities and water depths, to provide a suitable habitat for flora and fauna.

The foundation for this research was the need to develop methods and models for designing and evaluating the hydraulic aspects of restoration, rehabilitation and environmental flood management in running waters.

1.2 Objectives of the present study

In natural channels, the traditional assumptions of uniform flow and uniform boundary roughness are rarely valid. Even approximations of one-dimensional flows with logarithmic velocity profiles are highly erroneous from the theoretical point of view in most natural conditions. Recently, several unsteady multi-dimensional turbulence models, have been developed to satisfactorily simulate the local flow conditions for habitat and overall flood wave propagation in natural complex channels (e.g. Murota *et al.* 1984, Shimizu & Tsujimoto 1993, Fischer-Antze *et al.* 2001).

The aim of the thesis was to test and develop simple practical methods for the estimation of flow resistance in natural complex rivers and channels with either a) composite flow resistance in simple concave cross sections, or b) composite flow resistance in compound cross sections, and then to develop an unsteady 1D flow model for partially vegetated channels that have complex geometry. Thus, the aim was to characterise and to quantify the effects of channel topography and different flow resistance parameters (ice, vegetation etc.) on the conveyance of a river channel and furthermore, on the retention capacity.

Knight (2001) and Evans *et al.* (2001) have listed topics requiring special consideration when overbank flow occurs. These include the interaction between the main channel and the floodplain flows, the proportion of flow in the main channel and the floodplains, the roughness differences between the main channel and the floodplains, stiff and flexible vegetation, significant variation in resistance parameters in a depth and flow regime and their effect on flow levels and the extent of flooding, the distribution of boundary shear stresses, the use of the hydraulic radius in calculations, sediment transport, and overbank flow in meandering channels. In this thesis, information on several of these topics has been extended and refined.

The topics in this thesis can be listed as follows:

1. Differences in the flow resistance and conveyance properties in lowland rivers of different sizes, varying from the Myllypuro Brook (MQ = 0.24 m^3/s) to the River Rhine (MQ = 2300 m^3/s)
2. Effects of different channel construction measures on the flow resistance, including a) comparison of the flow resistance in dredged, restored and natural reaches, and b) comparison of the flow resistance in a reach before and after applied flood management and bioengineering measures
3. Subdivision of the composite flow resistance in simple concave channel cross sections with and without ice cover
4. Validity of simple methods used to estimate the composite flow resistance
5. Interconnection of flow resistance and channel geometry in defining the local hydraulic conditions of a channel reach
6. Development of a simple unsteady one-dimensional flow model for partly vegetated channels which have significant head losses due to lateral momentum transfer, to simultaneously estimate both the flood retention and the components of discharges and velocities in the main channel and the vegetation zone
7. Flow resistance due to the lateral momentum transfer in lowland rivers with vegetated floodplains or vegetated stream banks

In practise, the objectives can be divided into two sub-groups: a) Field studies and data analysis of flow resistance and conveyance in Finnish rivers, and b) computation of flow and flow resistance in partly vegetated channels. To clarify their interconnections, the Papers are classified by topic, channel types, field studies and the used methods in Table 1.

In the first part, factors causing flow resistance in Finnish lowland rivers were characterised and the components of friction factors for different features causing flow resistance, e.g. channel geometry, vegetation, sinuosity and ice cover, and their influence on the composite flow resistance and total conveyance were quantified. The overall composite flow resistances were estimated for the rivers from the measurements of channel topography and discharge-water level relationships, and subdivided into parts by different methods. Furthermore, the variation of flow resistance with the variation of flow regimes, and the hydraulic geometry of Finnish rivers were investigated. The parameters of channel geometry and flow resistance were used to develop success criteria and thus, a procedure for post-project evaluation of restoration of local hydraulic conditions. The data collection and detailed hydraulic analysis of the Finnish rivers is provided in Papers *I*, *II*, *III* and *IV*.

Table 1. The Papers appended in the thesis classified with topics, investigated channel types, field studies and used computational methods

<table>
<tr><th>Paper</th><th>Topics</th><th>Channels</th><th>Field studies</th><th>Methods</th></tr>
<tr><td>I</td><td>Flow resistance of ice cover</td><td rowspan="4">Simple, concave</td><td rowspan="4">Finnish lowland rivers</td><td>Composite roughness equations</td></tr>
<tr><td>II</td><td>Composite flow resistance, environmental flood management</td><td rowspan="2">Composite flow resistance methods</td></tr>
<tr><td>III</td><td>Composite flow resistance, restoration of local hydraulics</td></tr>
<tr><td>IV</td><td>Hydraulic geometry</td><td>Regime theory</td></tr>
<tr><td>V</td><td rowspan="2">Flood wave propagation, composite flow resistance</td><td rowspan="2">Compound</td><td>—</td><td rowspan="3">Unsteady 1D flow model for partially vegetated channels</td></tr>
<tr><td>VI</td><td>River Rhine</td></tr>
<tr><td>VII</td><td>Lateral momentum transfer</td><td>Compound / simple, concave</td><td>River Rhine, River Päntäneenjoki</td></tr>
</table>

In the second part, the flow in natural complex channels with composite flow resistance and compound cross sections were investigated. The additional flow resistance caused by the lateral momentum exchange process between zones of different velocities, i.e. the main channel and floodplain, or the vegetated and the non-vegetated channel part, was quantified from the field data. A simple unsteady 1D flow model was formulated for such natural channels, where the lateral momentum transfer has a significant role in causing flow resistance, to investigate composite flow resistance and conveyance in simple concave channels and compound channels. The aim of the model was to serve as a tool for channel design from both the flood management and habitat restoration viewpoint. A conceptual model of the compound channel geometry and flow resistance was derived to assist in the development of an unsteady 1D flow model for a partially vegetated natural channel with irregular floodplains. The theory of the model and its application to two rivers are provided in Papers *V*, *VI* and *VII*. The additional flow resistance caused by the interaction process due to lateral momentum transfer is considered in detail in Paper *VII*.

1.3 Limitations of the present study

Research into erosion and sediment transport processes and supercritical flow were excluded from the thesis. Typically Finnish rivers have cohesive soils, mild longitudinal slopes and low stream power, which limit the sediment transport to suspended sediments and the flows to sub-critical. The lack of the field data from mid-sized rivers limits the generalization of the results into rivers of different scale.

Also excluded from the research are meandering channels with overbank flows, because meandering two-stage channels where the overbank flow direction differs significantly from the inbank flow direction rarely exist in Finland. In this thesis, evaluation of the methods for computing the flow resistance of vegetation zones has been limited to the estimation of the friction factor of the interface.

2 FLOW AND FLOW RESISTANCE IN NATURAL RIVERS

2.1 Open-channel flow resistance

Until the late 18th century, not much was known about fluid resistance. In the late 1700's, Chezy developed a simple resistance relationship for streams. In the mid-1800's, Weisbach proposed the head loss equation for pipe flow, and Darcy published his work on the relationship between pipe diameter and friction. Their efforts resulted in the widely used Darcy-Weisbach equation, which is based on a logarithmic velocity profile. This was later applied to open channel flow as well. The Manning-Strickler formula developed in the late 1800's for uniform open channel flow is still the most widely used formula in practical river hydraulics. (Rouse & Ince 1963)

In this thesis, flow resistance is described with the help of several parameters: the Darcy-Weisbach friction factor f, the Manning resistance coefficient n, and the roughness height k. Darcy–Weisbach f is preferred to Manning's n in this thesis due to its dimensional homogeneity, its linear relationship to the head loss H_f, and the recommendation of the use of f proposed by the ASCE Task Force on Friction Factors (1963) and Hydraulics Research Wallingford (1988). The relationships between the parameters can be found in any basic literature on open-channel hydraulics and also in Paper *II*.

Local hydraulic conditions are determined by flow resistance and the geometry of a channel (Broadhurst *et al.* 1997). The properties of channel geometry and flow can be related to each other by the concept of hydraulic geometry forming a part of the regime theory (Leopold & Maddock 1953). Aspects of local hydraulics are presented in Paper *III* and the theory of hydraulic geometry in Paper *IV*.

Nowadays, the resistance to flow in a river channel is often subdivided into the following components that are partially interconnected:

– bed grain roughness,
– form resistance associated with acceleration or deceleration and flow separation over small-scale structures such as pebble clusters,
– form resistance associated with large-scale bed undulations,
– flow resistance associated with irregular and asymmetric cross-sectional shape,
– roughness height of flexible vegetation,
– flow resistance of stiff vegetation,
– flow resistance caused by the momentum exchange between the main channel and the floodplain,
– flow resistance caused by the momentum exchange between vegetated and non-vegetated section,
– sinuosity,
– large obstructions, e.g. rocks and woody debris, and
– ice cover.

The estimation of flow resistance due to bed roughness is represented by the size and shape of the grains of the material forming the wetted perimeter (Chow 1959). The friction factor of the bed can be related to the boundary shear stress and the velocity distribution, which is generally assumed to be logarithmic (Graf 1998). The bed form resistance can be divided into small-scale and large-scale bed undulations. The former is mainly a consequence of forms shaped by existing bed material (e.g. ripples and dunes in alluvial river beds, frequent rocks along the river bed). The latter is caused by the longitudinal profile undulation, e.g. pool-riffle variation or step-pool variation, where the flow regime may vary from sub-critical near-zero velocity to supercritical flow and even free-fall occurrence (Lawless & Robert 2001, Lee & Ferguson 2002).

Another longitudinal large-scale resistance factor is the sinuosity, which is closely interrelated to the effects of cross-sectional asymmetry and secondary currents (Leopold *et al.* 1960). Meandering can be regarded as a method for adjusting the channel slope when the valley slope is treated as constant in the short and medium time scales (Knighton 1984), because it increases flow resistance and reduces the channel gradient relative to the straight reach between the same fixed points.

The effect of wooden debris on flow resistance can be large-scale or small-scale, depending on the size of the woody debris relative to the size of the channel cross section (Shields & Gippel 1993, Manga & Kirchner 2000).

The flow resistance of vegetation can be roughly divided into two components: a) resistance of flexible vegetation that can be viewed as boundary roughness (Kouwen 1988, Lopez & Garcia 1997), and b) resistance of stiff vegetation that is dominated by the flow-through processes (Petryk & Bosmajian 1975). The resistance effects are even more complex when both vegetation types are present in the same reach. This has recently been studied by Järvelä (2004).

In compound channels, the origin of the increased flow resistance is a strong vortex structure in the region of contact between the flood plain flow and that in the main channel (Sellin 1964, Posey 1967). The momentum transfer is able to significantly reduce the conveyance capacity of the main channel, especially in cases of low water depths on the floodplains. A similar interaction process can develop at the boundary between a vegetated and non-vegetated channel section (Mertens 1989, Naot *et al.* 1996a, 1996b), or between any other two zones having a large velocity difference between them.

In some areas, a significant factor causing flow resistance is river ice cover. In general it is estimated that ice cover almost doubles the wetted perimeter causing boundary friction (Ashton 1986).

Turbulence and secondary currents were not listed above as separate factors causing flow resistance, although they have a significant retarding effect on flow. The list was assembled from the properties of the channel shape and the resistance that affects flow.

The effects of the single components on the overall flow resistance have been investigated in different papers appended in this thesis.

2.2 Composite flow resistance

2.2.1 Composite flow resistance in concave open channels

Natural channels often have a complex topography. Asymmetric cross sections with variable roughness along the wetted perimeter, and undulation of the longitudinal profile and planform complicate the estimation of the total flow resistance and conveyance of flow. In this thesis, conveyance is determined as the volume of water that can flow through a certain area of cross section in a certain time. The methods used to compute the total conveyance in a channel with simple concave cross sections can be placed into two groups (Fig. 1):

1. Separate resistance coefficients f_j are assigned to different factors contributing to flow resistance, and then combined to deliver a composite resistance coefficient for the channel. In the computation, the channel has only the total wetted perimeter p and hydraulic radius $R = A/p$.

2. The cross section is subdivided into elements, for each of which a single resistance coefficient f_i that includes all the resistance factors is determined. The partial discharge conveyed by each element is computed separately and summed up to obtain a composite resistance coefficient. A wetted perimeter p_i and/or hydraulic radius R_i is associated with different resistance factors.

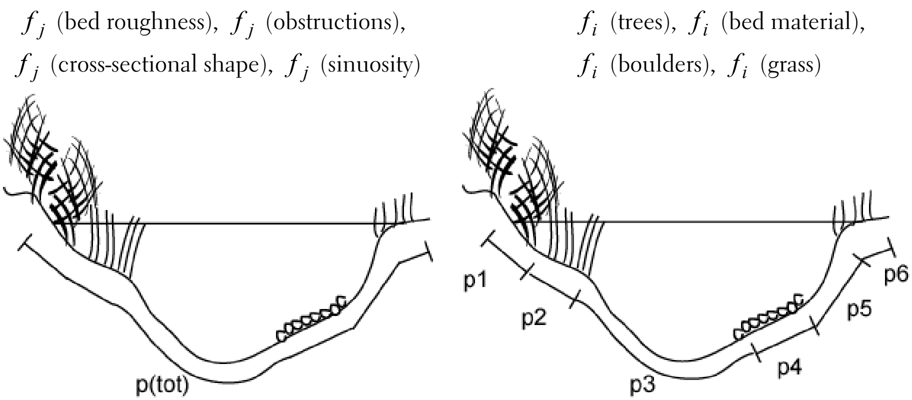

Figure 1. The methods for computing composite flow resistance: Group-1-type (left) and Group-2-type (right).

In this thesis, composite flow resistance is determined as the total flow resistance that is computed by combining separate partial resistance coefficients by either of the two methods presented above, resulting in the flow resistance corresponding to the total head loss between two consecutive cross sections.

Group-1-type methods are useful when the effect of a single resistance factor in the overall flow resistance can easily be quantified, whereas the location of the resistance along the wetted perimeter is not easily determined. Cowan's (1956) method is one of the most widely known methods using this approach, and is based on the assumption that realistic estimates of Manning *n* in a channel of small to moderate size are made through the recognition of six primary factors as

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)m_5 \tag{1}$$

where n_0 accounts for the bed roughness, n_1 for the irregularity of the channel bed, n_2 for the irregularity of cross sections, n_3 for the obstructions, n_4 for the vegetation, and m_5 for the channel sinuosity. Chow (1959) presented several tables and figures for estimating Manning *n* for rivers with different types of resistance parameters.

Einstein & Banks (1950) developed a linear superposition approach for combining the shear stresses of bed roughness and bed forms to produce the total shear stress. This was later expanded to combine shear stresses associated with other factors. The friction factors may be summed up in the same way due to the linear dependence of the friction factor *f* and the shear stress τ in a uniform flow as

$$\tau = \rho g R S = \frac{\rho f v^2}{8} \tag{2}$$

where *R* is the hydraulic radius, *S* is the longitudinal slope, ρ is the fluid density and *v* is the average flow velocity. Thus, in concave simple channels, the composite friction factors can be estimated by the linear superposition

$$f_{TOT} = \sum f_j \tag{3}$$

where f_j is the friction factor evaluated for a single factor causing flow resistance, e.g. bed roughness, sinuosity and vegetation (Fig. 1).

Group-2-type methods are applicable when zones of cross sections, which have different roughness, can be clearly defined. Indlekofer (1981) evaluated 13 methods used for superimposing roughness coefficients that utilised the group 2 approach, concluding that only the five methods based on the shear stress approach of Einstein delivered correct results. Rouvé (1987) suggested that the composite friction factor of a channel with variable roughness along the boundary is iterated from equations

$$\frac{1}{\sqrt{f_i}} = 2.03 \cdot \lg\left(\frac{4 \cdot 3.71 \cdot R_i}{k_i}\right) \tag{4}$$

$$R_i = \frac{f_i \cdot A}{\sum(f_i \cdot p_i)} \tag{5}$$

where f_i is the friction factor, k_i is the roughness height, p_i is the wetted perimeter, and R_i is the hydraulic radius of element *i*, and A is the total area of cross section. The friction factor f_i for each element *i* is computed from Eq. 4, using the first estimate of R_i as the hydraulic radius for the whole channel. The friction factor is then used as input into Eq. 5 to obtain a new estimate of R_i. The iteration is carried out until the hydraulic radii and friction factors for each element *i* remain constant. The total Darcy-Weisbach friction factor of the channel is then computed from equation

$$\frac{1}{\sqrt{f_{TOT}}} = \sqrt{\frac{\sum p_i}{\sum(f_i \cdot p_i)}} \tag{6}$$

where Σp_i is the wetted perimeter of the whole channel.

The methods of Cowan (1956) and Einstein & Banks (1950) were tested and used in Papers *II* and *III* to subdivide the composite friction factors estimated from the field studies carried out in Finnish rivers. Rouvé's method (1987) was implemented in the method proposed by Nuding (1991) used in the unsteady flow model presented in Papers *V*, *VI* and *VII*.

2.2.2 Composite flow resistance in ice-covered simple channels

Composite flow resistance also exists in ice-covered channels, where the ice cover forms a part of the wetted perimeter. Some empirical suggestions of doubling the wetter perimeter etc. can be found in literature for hydraulic engineers, and the presence of ice cover is generally expected to increase the flow resistance. However, the situation is often not that simple. Pressure is an additional variable in determining the flow conditions under ice cover.

The flow resistance of ice cover has not been widely researched. A few field measurements of ice roughness were carried out in natural rivers in the 1970's and 1980's (Ashton 1986, Yamashita *et al.* 1992). Several detailed studies have been carried out on the velocity distribution, discharges, and approximation and modelling of velocity profiles under ice cover (Tatinclaux & Gögüs 1983, Teal *et al.* 1994, Walker 1994, Walker & Wang 1997, Wang 2000, Wang *et al.* 2000, Hirai *et al.* 2000). In Finland, e.g. Kuuskoski (1968) has suggested methods to estimate head loss due to ice cover.

The presence of the ice cover alters the velocity profile from the one that exists in an ice-free open channel, and makes the discharge measurements more laborious. Therefore, the aim of these studies has generally been to simplify discharge measurements under an ice cover. Some laboratory flume studies on ice cover roughness and velocity profiles have been carried out with artificial ice cover (e.g. Muste *et al.*

2000). The process of ice cover formation and growth has been researched, especially with regard to seas. The methods used to estimate the composite flow resistance and the flow resistance of the ice cover are discussed and tested in more detail in Paper *I*.

2.3 Lateral momentum transfer

2.3.1 Lateral momentum transfer in compound channels

A compound channel is generally understood to be a two-stage channel consisting of a low flow channel and a wider overbank flow channel, i.e. floodplains that are inundated during high flows. The estimation of discharge conveyance in compound channels is very complex, firstly because of the composite flow resistance and secondly because of the lateral momentum transfer between the main channel and the floodplain, which decreases the discharge in the main channel and increases the discharge on the floodplain (Fig. 2). Cross-sectional irregularities and multi-stage channel shapes further complicate the conveyance estimation.

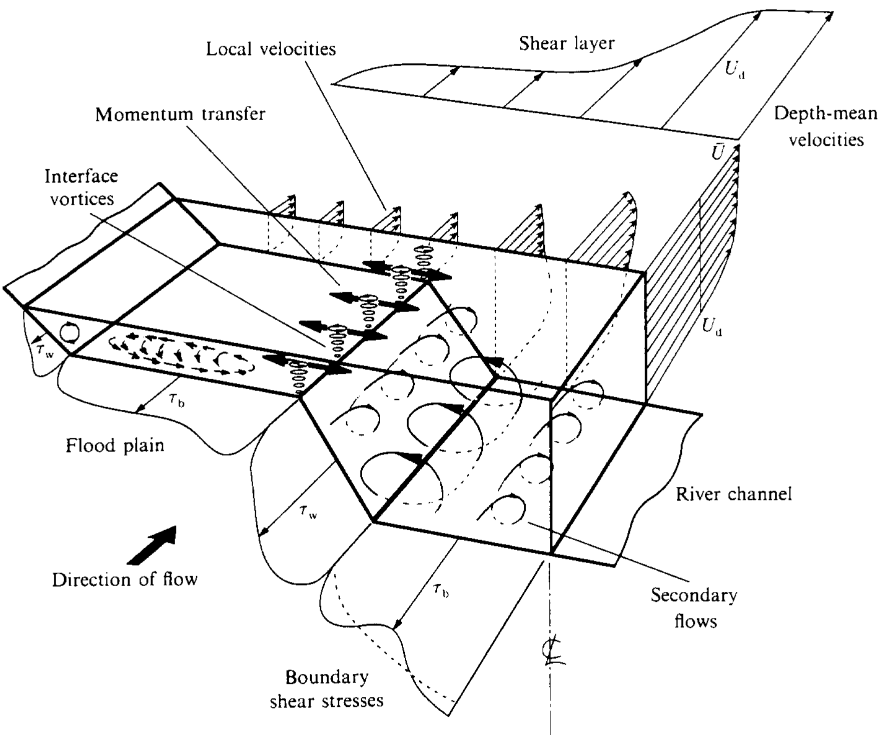

Figure 2. Hydraulic parameters associated with overbank flow in a two-stage channel (Shiono & Knight 1991; © Cambridge University Press)

Sellin (1964) was among the first to discover that when a river rose above bank-full discharge the overbank flow reduced the velocities of the flow contained within the normal river channel, because of an intensive vortex shedding at the boundary of the main channel and the floodplain. He also found that maximum average velocities were present in near bank-full stage. Wright & Carstens (1970) further investigated flow in wide and narrow symmetric compound channels.

Myers & Elsawy (1975) expanded studies on asymmetric compound cross sections to exclude possible compensating effects, finding that because of lateral momentum transfer, the division and values of the shear stresses are significantly altered when moving from a simple channel to a compound channel shape under the same hydraulic conditions. Wormleaton *et al.* (1982), Knight & Demetriou (1983), Stephenson & Kovlopoulos (1990), Myers & Brennan (1990) and Shiono & Knight (1991) further contributed to the research into flow and the boundary shear stresses in compound channels of different shapes and roughness, by describing the complex flow pattern, distribution of the boundary shear stresses and the causes and consequences of the momentum transfer between the main channel and the floodplain. Shiono & Knight (1991) divided the lateral momentum shear in compound channels into two components, one caused by turbulence and one caused by secondary flows. A summary of the main hydraulic parameters recognized so far in the compound channel flow are presented in Fig. 2. Lai *et al.* (2000) confirmed the earlier results of Sellin, which stated that when the water level rises over the level of the floodplain or decreases below the floodplain level, peak velocities occur. Prinos *et al.* (1985), Shiono & Knight (1991), Shimizu & Tsujimoto (1993) and Lambert & Sellin (1996) have contributed to the study of the structure of turbulence in compound channels.

The flow pattern in compound channels is further altered by floodplain vegetation. Pasche (1984) and Pasche & Rouvé (1985) observed that when there is no floodplain vegetation, the slope of the bank between the main channel and the floodplain and furthermore, the width of the floodplain has a significant effect on the shear stress at the interface; but when the floodplain is vegetated, the slope has no significant influence on the shear stress, although the width of the floodplain has, especially when the vegetation is very dense. Naot *et al.* (1996a) and Thornton *et al.* (2000) discovered that apparent shear stress at the interface of the main channel and the floodplain can be quantified as a function of the local turbulence at the interface, and that it is influenced by the main channel and floodplain velocities, flow depth and vegetation density. Rowinski *et al.* (1998) carried out laboratory experiments in compound channels with smooth, rough and vegetated floodplains, finding that with smooth and rough floodplains the logarithmic velocity law applies in the main channel, but not on the floodplains. Further, it does not apply in the main channel even when high vegetation is present on the floodplains.

2.3.2 Lateral momentum transfer in partially vegetated channels

A vortex structure similar to that existing in compound channels is also present in partially vegetated channels. An oscillatory pattern of longitudinal vortices can develop at the boundary of the penetrable domain, i.e. the vegetation zone (Mertens 1989, Naot *et al.* 1996b, Tsujimoto 1999). For example, Pasche (1984), Mertens (1989) and Nuding (1991) carried out flume studies to characterise the flow parameters in partly vegetated channels with different shapes of cross sections. The streambank vegetation has a significant effect on channel conveyance if the channel width-depth ratio is low (Masterman & Thorne 1992). Coon (1998) assessed several equations for their ability to estimate the resistance coefficients for several field study sites, including channels with streambank vegetation, and did not find a single equation that could estimate the resistance coefficients accurately in densely vegetated narrow channels.

Nezu & Onitsuka (2001) suggested further investigations into a mutual interaction between the coherent horizontal vortices and the secondary currents in partially vegetated open-channel flows, e.g. in the same way as such an interaction in a shallow/deep compound channel.

2.3.3 Conveyance estimation methods

Several conveyance estimation methods have been developed for channels that have two zones with high velocity difference and thus, a strong velocity gradient between them, i.e. compound channels and partially vegetated channels. The principles of the basic 1D and 2D methods are introduced here.

In the single channel method (SCM), a single hydraulics radius is computed for a compound channel using the total area of the cross section and the total wetted perimeter. According to Posey (1967), it gives erroneous values when the floodplain water depth is low. He tested different computational methods for a symmetric compound channel and suggested the use of the divided channel method (DCM), in which the components of the hydraulic radius and thus, discharge, are computed for the main channel and the floodplains separately, and the interfaces between the main channel and the floodplains are included in the wetted perimeter of the main channel and given the same roughness as the main channel.

Wormleaton *et al.* (1982), Knight & Demetriou (1983), Knight & Hamed (1984) and Myers (1987) studied the flow pattern and the distribution of the boundary shear stresses in a double-rectangular channel, quantifying the momentum transfer mechanism in terms of apparent shear forces and stresses. In the apparent shear stress (ASS) method, the boundaries between the main channel and the floodplains are treated as interfaces which have a separate roughness parameter. This approach was based on the idea that the components of discharge must be estimated correctly, and not just the total discharge. According to Myers (1987), DCM overestimates the discharge in compound channels, but the ASS method was closer to reality than the earlier methods, because it assumed that the shear stress at the interface of the main channel and the floodplain is significantly higher than the boundary shear stress of the main channel or the floodplain. Pasche (1984) carried out extensive laboratory research on a double-trapezoidal channel with stiff floodplain vegetation, developing another ASS method, in which the Darcy-Weisbach friction factor of the interface depends mainly on the relationships between plant diameter and plant distances, and the contributing width of the floodplain that has influence in the interaction process.

The coherence (COH) method developed by Ackers (1993) provides estimates of discharge within a few percent of measurements for most flow cases in compound channels. According to Samuels *et al.* (2002), it is well established for compound channels with deviations of up to 10 degrees between main channel and floodplain alignments. Haidera & Valentine (2002) further developed the coherence method of Ackers (1993) to get better estimates for discharge. The COH method has limitations for natural rivers, because it requires simplification of the cross-sectional geometry to a double trapezoidal shape, and it does not predict the individual components of discharge or velocities in the main channel and the floodplains.

Darby & Thorne (1996) developed a method for predicting stage-discharge curves for straight gravel-bed channels with flexible vegetation on the floodplains and steady, uniform flow, using an eddy viscosity model and Kouwen's (1988) roughness estimation methods of flexible vegetation. Darby (1999) included the computation of sand bed and rigid floodplain vegetation in the model. However, it does not predict the individual components of discharge or velocities in the main channel and the floodplains.

The Shiono & Knight method (SKM) and the lateral division method (LDM) were developed to improve the coherence method (Knight 2001). They are 2D methods, in which calibration coefficients are estimated for bed friction, lateral shear and secondary flow (the last of these is neglected in LDM). However, these methods are relatively complex in many practical applications.

Mertens (1989) carried out laboratory research in a trapezoidal channel with bank vegetation, and Nuding (1991) did laboratory research in a partly vegetated rectangular channel, both developing an ASS method to account for the momentum transfer between vegetated and non-vegetated channel parts. Nuding (1998) later expanded the use of his method for compound channels as well. Compared to Pasche's method (1984), it is relatively simple to apply in practise.

All 1D methods with the exception of the single-channel method are similar to the group-2-type equations for simple concave channels presented in Chapter 2.2.1. Each of the ASS and COH methods presented above has at least one of the following limitations when applied to compound river channels: a) they require simplification of the cross-sectional geometry to a double trapezoidal shape, b) they do not predict the individual components of discharge or velocities in the main channel and the floodplains, and/or c) they have been developed originally for steady flow and thus need some modification to be used in estimation of the retention of unsteady flood flows. The methods and their application to compound channels with vegetated and non-vegetated floodplains are discussed in Papers *V*, *VI* and *VII*. The model proposed in this thesis is an attempt to simultaneously combine unsteady flow, complex cross-sectional geometry and the prediction of parameters to estimate local hydraulics.

2.4 Modelling of unsteady river flow

2.4.1 Unsteady flow modelling of open channels

It can be said that the mathematical formulation of open-channel hydraulics began in the mid-1600's, when Newton first used the principle of momentum correctly and von Leibniz simultaneously formulated the principle of energy correctly. Navier attempted the extension of the Euler equations of acceleration first, to include the flow of a viscous fluid in the early 19th century, and although he did not understand the essential mechanism of viscous action, his results were mathematically correct. In the late 19th century, Reynolds experimented with flow through tubes, introducing the viscosity to form a parameter marking the borderline between laminar and turbulent flow, known as the Reynolds number. Stokes eventually applied the viscous fluid equations to the resistance of small spheres. In the meantime, a more general form of hyperbolic one-dimensional equations was developed by de Saint-Venant and later found to be applicable both in laminar and turbulent flow. (Rouse & Ince 1963).

Computational hydraulics has developed as a consequence of the development of computers that are able to provide a numerical solution for St Venant equations. Computation has mainly been based on numerical solution methods, which are in turn based on different types of discretisation: methods of characteristics, finite difference methods, finite volume methods and finite element methods. Finite difference methods have been used widely due to their simplicity, the first ones being the explicit scheme that Lax developed in the 1950's, the Lax-Wendroff two-step scheme developed in the 1960's, the leap-frog method and the McCormack two-step scheme developed in the early 1970's (Cunge *et al.* 1980). The biggest step in improving implicit methods was probably made when the four-point Preissmann (1961) scheme was developed.

Numerical solutions for a one-dimensional unsteady open-channel flow were widely investigated and developed in the 1970's and 1980's. These methods are not discussed here in detail, but comprehensive overviews and documentation of developed schemes are found in the literature (e.g. Mahmood & Yevjevich 1975, Cunge *et al.* 1980, Abbott & Minns 1998). MIKE11, the most widely used commercial computational river flow model in the world, developed by the Danish Hydraulic Institute, is based on the Abbott-Ionescu 6-point implicit scheme presented in, for example, Cunge *et al.* 1980. Another widely researched topic has been the computation of dam-break flood wave propagation in open channels, for example by Fread (1988), who developed one of the most famous commercial computer programs, DAMBRK, to model dam-break floods.

In Finland, unsteady open channel flows have been modelled by, for example, Forsius & Huttula (1982), Forsius (1984) and Karvonen (1984). An example of river ice cover modelling is Huokuna (1991).

2.4.2 Challenges in flow modelling of natural compound channels

When a flood propagates downstream a compound channel, flood hydrograph is deformed and the peak discharge is attenuated. The average velocity at the rising stage of the flood is higher and at the falling stage is lower with the same water level (Stephenson & Kovlopoulos 1990, Watanabe *et al.* 2002).

The estimation of the flood wave propagation and the flood retention capacity in natural rivers is essential in areas where effective flood management is needed. However, the modelling of unsteady flows in natural rivers that have composite flow resistance with a complex compound cross-sectional shape is often considered challenging.

Complex multi-dimensional flow models and turbulence models have been developed to simulate the flow conditions in natural complex channels (see e.g. Rodi 1993), but their application is very difficult and time-consuming. Furthermore, they require a significant amount of very accurate topographic and calibration data. In simpler models, the difficulty is often to convert the 3D topographic field data obtained from, for example, digital terrain models into a simple format to be input into the flow model. Many of the existing steady state methods require a simplification of the cross-sectional geometry into a two-stage shape.

The methods used in modelling flows in regular open-channels are often unstable in regions that have steep gradients of flow and geometrical properties. In general, the methods available for shock capturing have been especially developed for the computation of dam-break flood wave propagation in open channels. Among the traditional schemes developed, a more advanced method is the McCormack predictor-corrector scheme, which is a second order accurate explicit finite difference scheme capable of handling supercritical and subcritical flow with steep gradients of flow and geometrical properties (Anderson *et al.* 1984, Tseng 1999).

2.5 Environmental flood management

In some areas, the recurrence interval of high flows, e.g. $HQ_{1/20}$ or $HQ_{1/50}$, has been neglected, and infrastructure may have been constructed on lowland areas that are actually floodplains during high floods. The natural retention capacity of rivers has been decreased by measures that reduce flood retention areas, causing a rise in flood peaks and a reduction in the duration of these floods. Often it is assumed that the reduction in the flood retention capacity of rivers is the main cause of the changes in flood water levels and recurrence intervals. However, the changes in runoff due to altered land use and other man-made measures have an enormous impact, too.

The cross-sectional size of the river channel is naturally adjusted on average to a flow, which just fills the available cross section, i.e. the dominant discharge with an approximate recurrence interval of 1-2 years (Knighton 1984, Brookes & Shields 1996). Recently, policies have been applied by the United Nations Economic and Social Council (ECE 2000) to prevent construction on floodplains with a flow recurrence interval of 100 years. However, in many locations with limited space for flooding, a compromise between technical and environmental aspects is necessary in flood management (Fisher 1996).

The conveyance capacity of channels can be improved by adopting several measures including the removal of large woody debris and vegetation, the enlargement of the channel, straightening, the construction of bypass channels and diversions, the construction of levees or the construction of a compound channel. However, a detailed understanding of the relationship between the channel geometry and flow is essential in both river restoration and flood management works to avoid design failures. Some of the complex interactions between different measures are discussed below.

A channel that is too small will be inadequate and will not prevent flood damage, especially in areas with an existing high flood risk. However, oversizing a river channel may initiate degradation of the biodiversity, because a channel that is too large may become separated from the surrounding flora and fauna, and it may cause channel instabilities, erosion and sedimentation problems (Darby & Thorne 1994). Dredging and straightening may cause a reduction in the bottom roughness and the channel length, and increase the longitudinal bed slope and thus, flow may be accelerated and retention time reduced. This can solve flooding problems locally, but the problems may move downstream. Construction of levees may increase peak discharges because of the decrease in overbank storage and in flow resistance due to the elimination of rough floodplains, increase erosion, and increase meander length and amplitude if the stream banks are not stabilized (Brookes & Shields 1996). Construction of a two-stage channel may be an effective solution that is achievable at a relatively low cost. It can provide effective flood management, but simultaneously allows for more natural morphological and hydraulic characteristics of the river during low flows (Darby & Thorne 1996).

Aspects of environmental flood management are discussed to some extent in Papers *III*, *IV* and *V*.

3 SITES AND METHODS

3.1 River Päntäneenjoki

The River Päntäneenjoki (MQ 1.8 m^3/s, MHQ 22 m^3/s, $HQ_{1/20}$ 40 m^3/s) is located in the agricultural lowland area of Western Finland (Fig. 3). The land of the 210-km^2 catchment area is one-third under cultivation, and the rest is mainly forest and uncultivated fields and meadows. The river is meandering and erosion-prone. Floods are a result of the low conveyance capacity and obstructions caused by collapsed riverbanks.

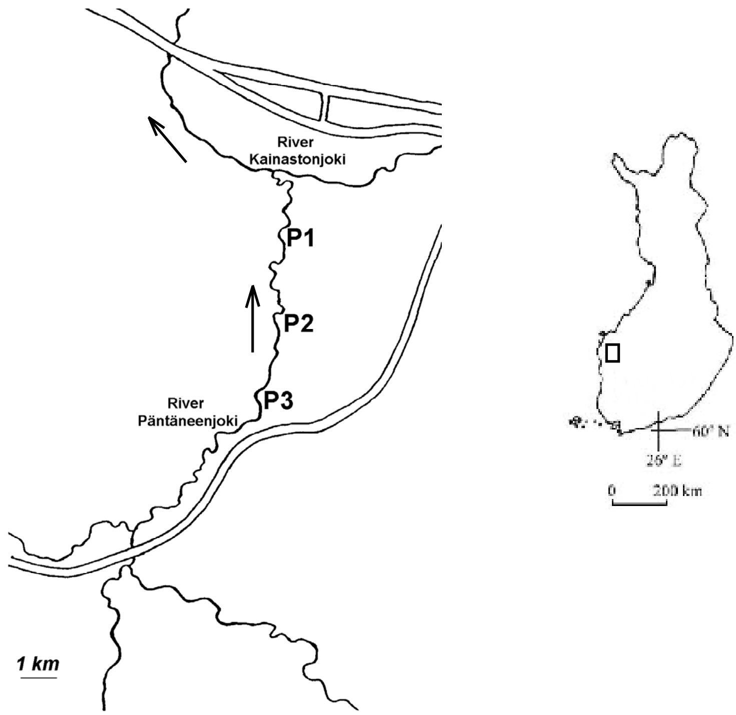

Figure 3. The field measurement reaches of the River Päntäneenjoki

Field measurements were carried out in the River Päntäneenjoki in 1997-2001 during the open water season by the West Finland Regional Environment Centre. Between 1997-2000, measurements were also carried out in wintertime during periods of ice cover. The measured discharges varied from 0.3 m^3/s (NQ) to 20.6 m^3/s (MHQ) during open water, and in winter from only 0.3 m^3/s to 0.85 m^3/s. Therefore, the results of the winter measurements were compared only to the summer measurements of the low flow regime. The surface width varied from 3 m to about 25 m across the whole discharge scale and the thickness of the ice cover varied from 0.18 m up to 1.60 m.

Cross-sectional geometries and stage-discharge relationships were measured on three river reaches. The procedure and equipment for the measurements, and the sensitivity analysis of the measurements is presented in Papers *I* and *II* for wintertime and summertime measurements, respectively.

Reach P3 (10290 - 11300 m upstream from the confluence of the River Kainastonjoki) was a strongly meandering reach with a channel bed with clayey silt and moderate grassy vegetation. Dense shrubs grew on the stream banks below the mean water level, and dense willows and trees on the stream banks. There was woody debris and collapsed bank material in the channel. Reach P2 (6485 - 7706 m) was a meandering reach with a channel bed of silt, clayey silt, sparse grassy in-stream vegetation and locally collapsed banks on the mid-reach. Sparse willows grew on the stream banks. Passive and active flood management works were carried out on the reach in 1998. Field measurements were done before and after the construction, to improve conveyance during high flows by increasing the cross-sectional area above the mean water level. Meandering and variation in the cross-sectional profiles was enhanced. In addition, various bioengineering methods were tested along the reach to stabilize the stream banks and reduce erosion. Woody debris dams existed before and after the construction works. Reach P1 (2483 - 3450 m) was a sinuous reach with a channel bed of clayey silt and sparse grassy in-stream vegetation. Sparse willows and dense grassy vegetation grew on the stream banks.

The field data from the River Päntäneenjoki have been used in Papers *I*, *II* and *IV* to evaluate the hydraulic geometry, the composite friction factors and their components using group-1-type methods to compute composite flow resistance. Furthermore, the data have been used in Paper *VII*, where steady flow simulations have been made to estimate the friction factor of the interface between vegetated and non-vegetated channel parts, using a group-2-type method to compute composite or compound flow resistance. More detailed site information can be found in Papers *I* and *II*.

3.2 River Tuusulanjoki

The River Tuusulanjoki (MQ 1.2 m^3/s, MHQ 7.0 m^3/s, $HQ_{1/20}$ 14-16 m^3/s, MNQ 0.07 m^3/s) is located in Southern Finland (Fig. 4). Over half of the 125-km^2 catchment area is covered with forests, 28% with fields and 11% with infrastructure. The lake area percentage is 6%.

Field measurements were carried out in the River Tuusulanjoki in 1997-2001 during the open water season by the Uusimaa Regional Environment Centre. The measured discharges varied from 0.27 to 7.43 m^3/s, i.e. from a very low discharge to about a mean high discharge (MHQ). The water surface width varied from 3 m to 18 m.

The cross-sectional geometries and stage-discharge relationships were measured on four river reaches, of which two reaches were omitted from the research after the first few years. The procedure and equipment used for the measurements and the sensitivity analysis of the measurements is presented in Paper *II*.

Reach T3 (8527 - 9085 m upstream from the confluence of the River Vantaanjoki) was a straight, moderately vegetated reach with mild bank slopes and bed material of clay with some local gravel. Sparse to moderately dense willows grew on the stream banks. Reach T1 (1500 - 1978 m) was a meandering, narrow channel with steep bank slopes. Its bed material was clay, silt and sand. There was no in-stream vegetation, but very dense willows on the stream banks. Some banks had collapsed locally on the mid-reach.

The field data for the River Tuusulanjoki have been used in Papers *II* and *IV* to evaluate the hydraulic geometry, the composite friction factors and their components using group-1-type methods to compute composite flow resistance. More detailed site information can be found in Paper *II*.

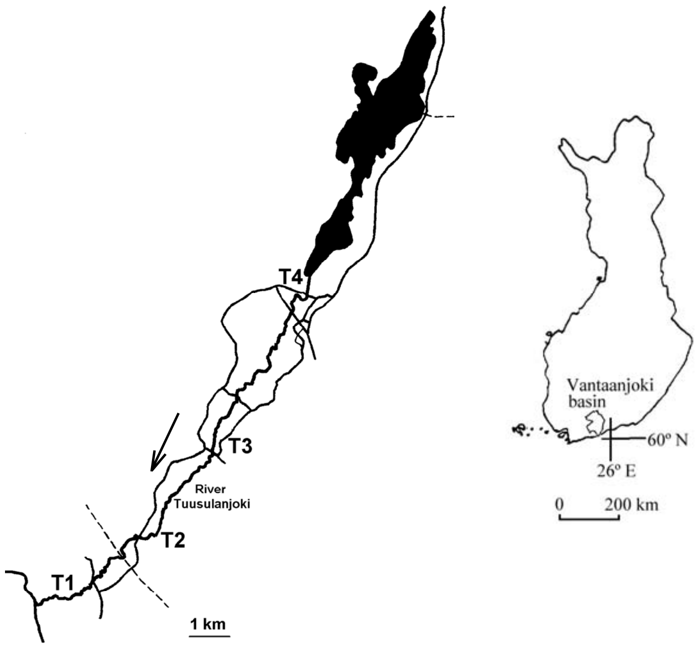

Figure 4. The field measurement reaches of the River Tuusulanjoki

3.3 Myllypuro Brook

The Myllypuro Brook (MQ 0.24 m^3/s, MHQ 1.6 m^3/s, $HQ_{1/20}$ 2.6 m^3/s, MHQ 0.03 m^3/s) is located in the Nuuksio National Park in Southern Finland (Fig. 5). Only 0.5% of the forested 24.5-km^2 catchment area is under cultivation.

Field measurements were carried out in the Myllypuro Brook in 1997-2001 during the open water season by the Uusimaa Regional Environment Centre. The cross-sectional geometries and stage-discharge relationships were measured on nine reaches. The procedure and equipment for the measurements and the sensitivity analysis of the measurements is presented in Paper *III*.

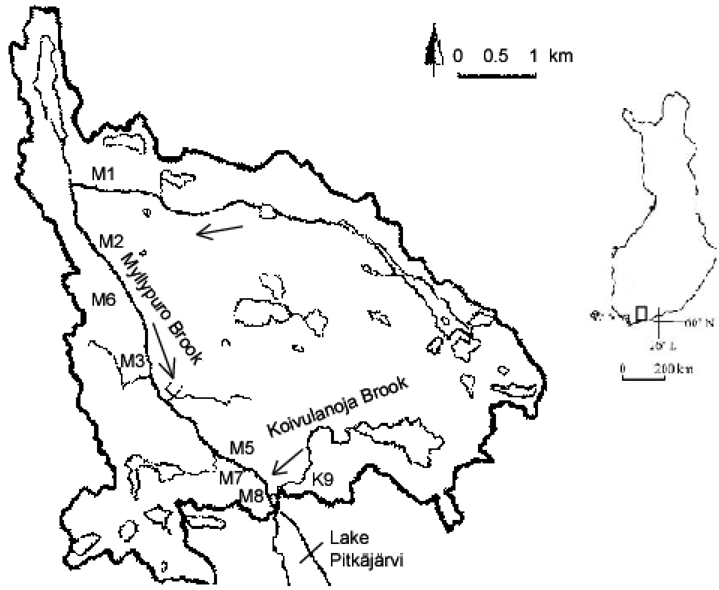

Figure 5. The field measurement reaches of the Myllypuro Brook and its tributary Koivulanoja Brook

Reach M1 (6000 - 6303 m upstream from the Lake Pitkäjärvi) was in a natural condition, having a channel bed of peat, mud and aquatic plants. The stream banks were dominated by grassy vegetation. Reach M2 (4651 - 4849 m) was a straightened channel with a clay and silt bottom and sparse aquatic vegetation. The stream banks provided a moderate cover of vegetation. Reach M6 (3655 - 4130 m) was pristine and strongly meandering. It had narrow cross sections with steep side slopes with moderate streambank vegetation. In-stream woody debris caused damming. Reach M3 (2713 - 2894 m), which had been dredged in the 1960's, was straight and had uniform, wide cross sections. Vegetation cover at the bottom was almost non-existent, but moderate on the stream banks. Reach M7 (53 - 232 m along the new channel, numbering started from cross section 1443 m) had been restored by excavating its historical meandering alignment in 1997. The restored channel was strongly meandering with only sparse streambank vegetation. Reach M4 was excluded from the measurements in the early phase of the study, because very high relative roughness due to large stones in the bottom made the discharge measurements during the low water level inaccurate. Reach M5 (885 - 1098 m) had quite a similar history and properties to reach M3; after the second restoration phase the reach was partially filled and partially left as a backwater. Reach M8 (625 - 760 m) was excavated to replace the earlier straightened channel in December 1999. There was no in-stream vegetation, and sparse to moderate cover of grassy vegetation on the stream banks. In July 2000 woody debris was installed into the reach to enhance diversity and flooding. Reach K9 was located in the Koivulanoja Brook, a small tributary of the Myllypuro Brook (102 - 137 m from the confluence with the Myllypuro Brook). The soil of this recently restored stream was mostly clay, but sands and gravels were found and in-stream woody debris was present. Grassy vegetation and small trees were present on the stream banks.

The field data from the Myllypuro Brook have been used in Papers *III* and *IV* to evaluate the hydraulic geometry, the composite friction factors and their components using group-1-type methods to compute composite flow resistance. More detailed site information can be found in Paper *III*.

3.4 Field studies in Finland in 1954

In 1954, the Finnish National Board of Agriculture carried out hydraulic field measurements in 60 reaches of Finnish natural rivers and man-made channels. The data was first analysed by Saari (1955) to estimate Manning resistance coefficients and later again by Hosia (1983) to estimate Darcy-Weisbach friction factors for different channel types. The data from 20 of these river and channel reaches located in Southern Finland were re-analysed in this study to investigate their hydraulic geometry. The data have been used in Paper *IV*, where more detailed site information and a map of the locations of the reaches can also be found.

3.5 The Upper Rhine

The River Rhine (MQ 2300 m^3/s) has a total length of 1,320 km and a catchment area of 185,000 km^2, flowing from Switzerland through Germany, France and Netherlands to the Atlantic Ocean. More than 50% of the River Rhine basin is used for agriculture, a third for forestry and natural lands, and the rest for urban and suburban areas (Wessel 1995).

A 28-km-long reach (186.156 km…214.244 km downstream from Lake Constance) in the Upper Rhine area, between Rheinweiler (upper end of the reach) and Hartheim (lower end) was under research (Fig. 6). The topographic data and the hydrographs were received from Gewässerdirektion Südlicher Oberrhein/ Hochrhein, Projektegruppe Breisach. Hartmann *et al.* (1998) determined the roughness and vegetation parameters. The studied reach has 140 cross sections, 100…320 m apart from each other. Along the reach there is mostly a vegetated streambank on the left (French) side and a mostly vegetated floodplain on the right (German) side of the main channel.

The field data from the Upper Rhine have been used in Papers *VI* and *VII*, to model the propagation of the flood wave and to evaluate the friction factors of the interfaces between the main channel and floodplains, using the apparent shear stress methods to estimate compound flow resistance. More detailed site information can be found in the papers.

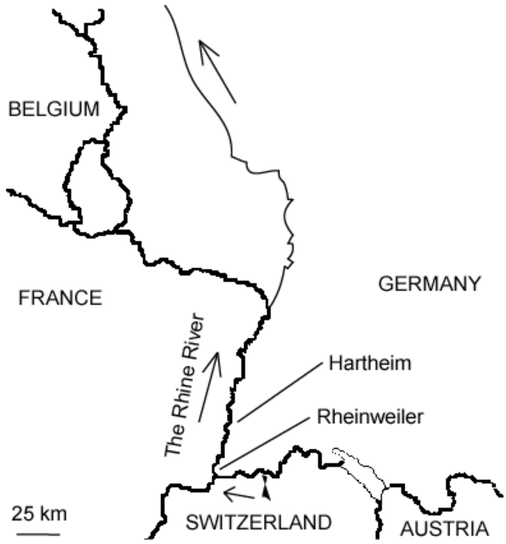

Figure 6. The location of the modelling reach between Rheinweiler and Hartheim in the Upper Rhine

3.6 Flume study on spruces

Laboratory flume measurements were carried out at HUT Laboratory of Water Resources, to investigate the influence of the longitudinal plant distance a_x on the friction factors of the interface, floodplains and vegetation zones. The friction factors for tree rows with variable longitudinal distances apart from each other were studied. The flume data of the friction factors for different longitudinal distances of plants have been used in Paper *VII*, where more detailed information on the laboratory set-up can also be found.

3.7 Unsteady 1D flow models

Traditionally, unsteady 1D flow in compound channels has been modelled using a single channel method (SCM), in which the floodplains are considered only as storage areas with zero longitudinal velocity, i.e. the cross-sectional area and the width of the floodplains are included in the continuity equation but not in the momentum equation (see e.g. Cunge *et al.* 1980). In this way, only the roughness of the main channel is needed. The model does not predict the individual components of discharge or velocities in the main channel and the floodplains.

A traditional model was used as a comparison to a new proposed model. The basic form of the hyperbolic, non-linear St Venant equations was used in the traditional model with a McCormack two-step explicit finite difference scheme, being accurate to the second order in space and time and thus having the capability for shock-capturing (Tseng 1999). The principle of the model, the used form of St Venant equations and the discretisation, are shown in detail in Paper V.

A simple unsteady 1D flow model was developed for a river channel with vegetated floodplains or vegetation zones. To the best of the author's knowledge, the proposed model is the first attempt to simultaneously a) solve 1D unsteady flow to estimate the retention of flood waves, b) predict average velocities, friction factors and the components of discharge in the main channel and the floodplains or vegetated zones separately using an apparent shear stress (ASS) method to estimate local hydraulic conditions, and c) allow for the detailed description of complex cross sections of irregular and natural rivers.

In the proposed model, the unsteady solution of St Venant equations was combined with Nuding ASS method (1991) which estimates separately a) the friction factors of the vegetation zones/ floodplains, and b) the friction factors due to the lateral momentum transfer through the interface between the main channel and the floodplain or vegetated zone, or between any two zones having a high velocity gradient between them.

The same form of St Venant equations and the same McCormack two-step explicit finite differentiation scheme was used as is the case of the traditional model, but the flow resistance was estimated by using the Nuding method (1991, 1998). The used equations are presented in detail in Paper *V*.

The applicability of the models was limited to rivers with mild slopes, i.e. those having sub-critical flows. In paper *V*, the proposed model was applied to a hypothetical case of a flood event in a symmetric double-trapezoidal channel with floodplain vegetation. The results and performance of the proposed model were compared to the traditional model. Furthermore, the sensitivity of the changes in vegetation densities and floodplain widths in the computation of the water levels were investigated.

In Paper *VI*, a conceptual model and a pre-processing program for a compound channel with complex geometry and composite flow resistance was developed to aid the application of the proposed model to natural rivers that have a large topographic longitudinal and cross-wise deviations. The pre-processing program combines the multipart topographic field data obtained from, for example, a digital terrain model with the roughness and vegetation data. It then converts them into a form of hydraulic parameters as functions of water depth suitable for input into the flow model. Thus, the model is applicable to complex and highly irregular channel shapes. The conceptual model and the pre-processing program are presented by Helmiö & Jolma (2003) and in Paper *VI*. The proposed unsteady 1D flow model for partially vegetated rivers and its pre-processing program were applied to a river reach on the Upper Rhine, to simulate the propagation of flood waves. The results and performance of the model were again compared to those in the traditional model.

In Paper *VII*, the proposed unsteady 1D flow model was further applied to the River Päntäneenjoki. The friction factors for the interfaces between vegetated and non-vegetated zones were quantified by calculating them backwards from the model for the River Rhine, a river that has wide floodplains and the River Päntäneenjoki that has vegetated stream banks.

4 RESULTS AND DISCUSSION

4.1 Flow resistance and local hydraulics

4.1.1 Composite friction factors

Spatial and temporal variation in the flow resistance of different river reaches were investigated in the River Tuusulanjoki, the River Päntäneenjoki, the Myllypuro Brook and its tributary the Koivulanoja Brook based on hydraulic field measurements carried out in 1997-2001. The variation in the friction factor as a function of the Reynolds number is presented in Figs. 7 and 8 for these rivers.

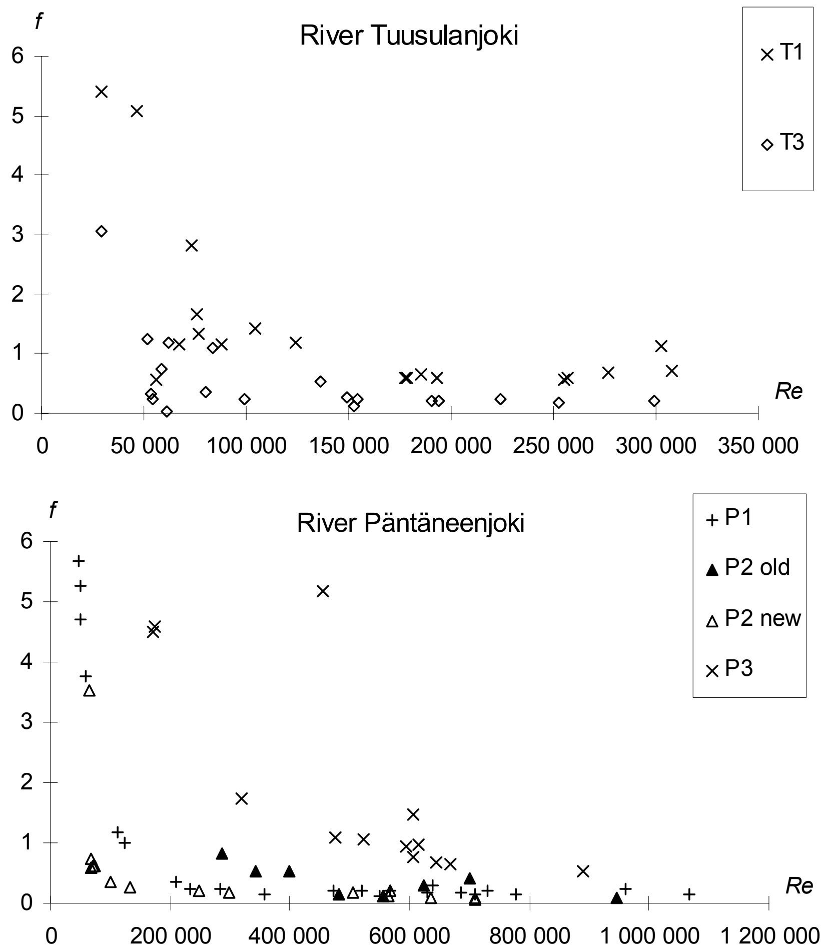

Figure 7. Variation of friction factor *f* as a function of Reynolds number *Re* in reaches T1 and T3 of the River Tuusulanjoki and reaches P1, P2 and P3 of the River Päntäneenjoki (without ice cover) (*Paper II*)

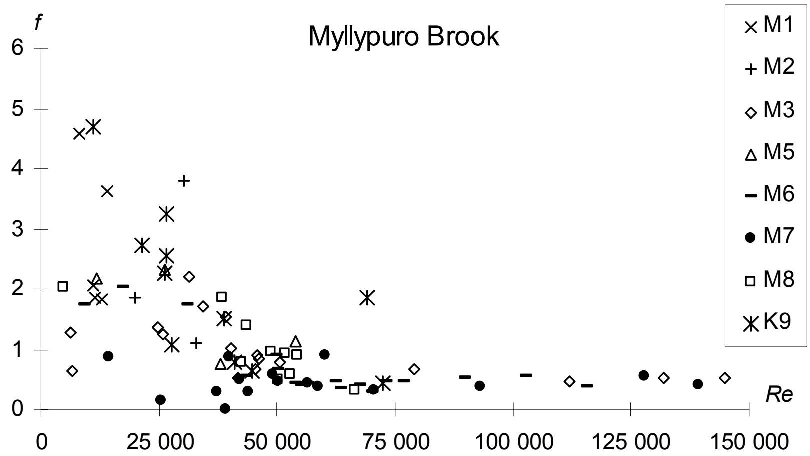

Figure 8. Variation of friction factors *f* as a function of Reynolds number *Re* in the Myllypuro Brook (M1 - M8) and the Koivulanoja Brook (K9).

In general, the friction factors were relatively high compared to values presented in literature (Chow 1959, Coon 1998). This was mainly because the lower end of the discharge scale was emphasised in the measurements. In Fig. 9, the resistance coefficients determined from the field measurements in the River Tuusulanjoki and the River Päntäneenjoki are compared to the values presented by Cowan (1956) and Chow (1959) as Manning coefficients. The values were of about the same magnitude near mean flows. However, the results differed significantly from these values in reaches T1 and P3 that have considerable streambank vegetation. In the River Päntäneenjoki, the friction factors were significantly smaller in wintertime than in summertime during the same discharges (Paper *I*).

In the Myllypuro Brook, the measured resistance coefficients were higher than the values presented by Cowan (1956) and Chow (1959) in reaches M1, M2, M5 and M6 which have in-channel vegetation (Fig. 10). It would appear that the methods of Cowan and Chow predict the resistance coefficients well for simple concave channels in mean flow situations, but they are not able to give proper resistance coefficient values for either low flow situations or for flow in channels with floodplains or densely vegetated stream banks (Paper *II*).

The hydraulic properties of natural, dredged and restored reaches of the Myllypuro Brook were compared. The differences in *f* were surprisingly small between the pristine reach M6, the restored reach M7 and the degraded reach M3 despite significant geomorphic and vegetative differences (Fig. 8) (Paper *III*).

The construction of reach P2 of the River Päntäneenjoki into a mild two-stage shape did not significantly change the composite friction factors. The tested bioengineering methods had no significant effect on the flow resistance, and therefore their use did not reduce the conveyance capacity of the channel. The application of bioengineering methods in the River Päntäneenjoki proved to be relatively successful in general.

However, many live stakes and fascines died during the first winter because of extreme winter conditions with a thick ice cover of up to 1.6 metres (Papers *I* and *II*).

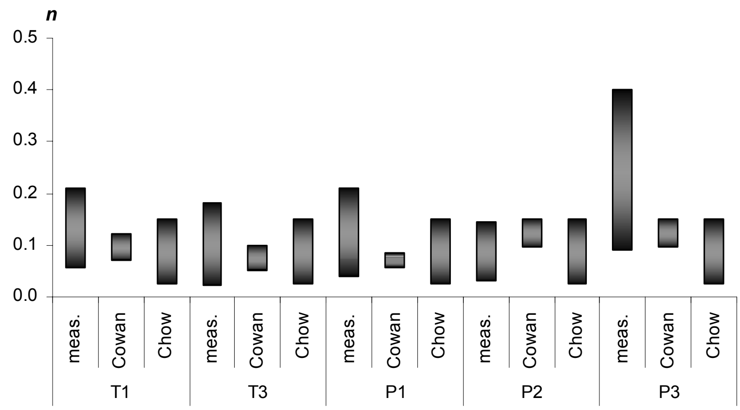

Figure 9. Comparison between Manning coefficients that were measured and determined using the methods employed by Cowan (1956) and Chow (1959) in reaches T1 and T3 of the River Tuusulanjoki and reaches P1, P2 and P3 of the River Päntäneenjoki.

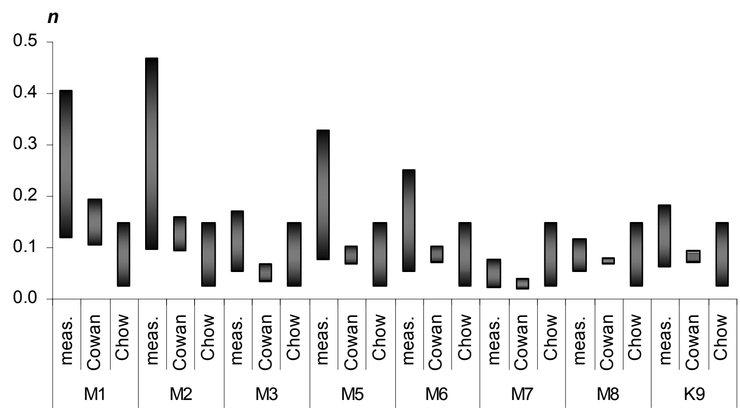

Figure 10. Comparison between Manning coefficients that were measured and determined by the methods of Cowan (1956) and Chow (1959) in the Myllypuro Brook (M1…M8) and the Koivulanoja Brook (K9).

The composite friction factors from the River Rhine are presented in Table 2. They were computed with the proposed unsteady 1D flow model for partially vegetated channels using the method of Nuding. It can be seen that in the River Rhine the friction factors are significantly lower than in the small Finnish rivers (Papers *II* and *III*).

4.1.2 Division of composite friction factors into components

For the data from the River Tuusulanjoki and the River Päntäneenjoki, a detailed analysis of the total composite friction factors was carried out to determine which parameters most affect the friction factors. The composite friction factors f_{TOT} for each reach were subdivided into parts of bottom roughness, sinuosity and other resistance factors using Einstein's superposition approach. This was done in order to quantify the significance of different resistance parameters on the composite friction factor.

Table 2. The composite friction factors f_{TOT} of the River Rhine at different discharges.

Q (m^3/s)	680	1430	3040
average	0.052	0.043	0.034
stdev	0.009	0.008	0.007
min	0.018	0.011	0.008
max	0.068	0.057	0.048

Friction factors f_{TOT} were well explained by the superposition approach in simple concave channel reaches of the River Tuusulanjoki and the River Päntäneenjoki. About 70-90% of the total flow resistance was assumed to be due to bed roughness and small-scale bed undulations. The rest of the flow resistance was associated with sinuosity and large-scale undulations.

Relatively high friction factors were found, especially for reaches with streambank vegetation, in which more than 50% of the total flow resistance was associated with additional flow resistance other than bed roughness, small- and large-scale undulations and sinuosity, i.e. the resistance effects of woody debris, local bank collapses, and momentum exchange (Paper *II*). This is also consistent with the results in Paper *VII* where extremely high values for the friction factors for the interfaces f_j are given for reach P3, which has dense streambank vegetation.

In wintertime, the values of the friction factors for the River Päntäneenjoki were found to be lower than in the summertime during the same discharges. Based on the vertically symmetric velocity distributions measured, the ice-cover roughness was of the same magnitude as the bottom roughness. However, not enough data was available to accurately subdivide the resistance into its components (Paper *I*). Small values during the ice cover are probably due to the lack of very sparse vegetation existing in summertime in the channel.

In the Myllypuro Brook, no subdivision of friction factors was carried out. The effects of individual roughness elements, e.g. logs and boulders, overlaid the effects of the cross-sectional geometry. In a small stream with high flow resistance, the delimitation of the study reach can strongly affect the magnitude of the flow resistance coefficient (Paper *III*).

The components of the friction factors for the River Rhine are presented in Paper *VI*. They were computed with the proposed unsteady 1D flow model for partially vegetated channels using the Nuding method, having steady discharge as input. The main channel friction factors varied from 0.04 to 0.08 when the friction factors of the interfaces were limited to the maximum value f_{Jmax} = 0.40. The friction factors of the floodplains varied from 0.10 to 20, being locally relatively high compared to the composite friction factors presented in Table 2.

4.1.3 Effects of the momentum transfer

The effects of streambank vegetation on the reduction of channel capacity are significant when the channel is narrow. The Finnish river reaches studied were relatively narrow: the *B/h* ratio varied in the River Tuusulanjoki from 3.2 to 10.5, in the River Päntäneenjoki from 3.3 to 17.4, and in the Myllypuro Brook from about 2.5 to 20 (Papers *II* and *III*). In the River Rhine, however, the bank-full *B/h* ratio varied from about 12 to 80. From the results it was also seen that in those reaches of the River Päntäneenjoki and the River Tuusulanjoki that had dense streambank vegetation the composite friction factors were higher than in the other reaches. Significant changes in friction factors caused by vegetation growth were not detected during the growing season in any river, whereas some yearly differences were found. No general dependence was found between the width-depth ratio and the friction factor *f* in the rivers.

The friction factors for the interfaces have been investigated in several laboratory flume studies. Becker (1999) presented friction values of f_J = 0.2 for the main channel side and f_J = 0.2-0.3 for the floodplain side of the interface. The highest measured values in the laboratory studies by Nuding (1991) were about f_J = 0.23. The values presented by Becker (1999) and Nuding (1991) are well in line with the flume measurement results of Pasche (1984), where the average values for f_J are about 0.20 - 0.24 and the maximum are about 0.34.

In this thesis, the friction factors for the interfaces were determined for the River Rhine and the River Päntäneenjoki by computing backwards from available field data. In the River Päntäneenjoki, the mean value of the friction factor of the interface, f_J, was about 0.39 at a discharge rate of 3 m^3/s, at 7 m^3/s up to 2.35 and at 12 m^3/s about 0.63. In the River Rhine, the maximum value of the friction factors for the interfaces were limited to f_{Jmax} = 0.40. A limitation of the friction factor was necessary in situations with very dense vegetation, low water depths and a wide channel, in which f_J became significantly overestimated. This may be because in a wide compound channel (a wide main channel and wide floodplains), the momentum transfer does not have an effect on the longitudinal flow velocities over the whole main channel width or over the whole floodplain width, i.e. the estimation of the contributing width of the floodplain is not accurate. In the River Rhine, the friction factors were highest at the lowest discharge 680 m^3/s and decreased along the increase of discharge and water level.

In the River Päntäneenjoki, the friction factors for the interfaces were significantly higher than the values presented in literature. It may be that other factors causing flow resistance are implicitly included in the friction factor of the interface because of the longitudinal variation of the cross sections and the profile. In the River Päntäneenjoki, significant local losses are present due to channel contractions and expansions, in contrast to the River Rhine that is relatively regular in its longitudinal direction, as are the channels studied in the flume experiments. However, inclusion of the local losses in the model would further complicate the collection of the field data.

Pasche (1984) assumed that when the vegetation density at the interface of the main channel and the floodplain increases, the friction factor of the interface increases as well, until it reaches a certain density after which the vegetation begins to dampen the momentum exchange. The effect of the longitudinal spacing of plants on the flow resistance was verified in a laboratory flume study with spruce saplings. The detailed results are presented in Paper *VII*.

4.1.4 Local hydraulic conditions and hydraulic geometry

Broadhurst *et al.* (1997) stated that the local hydraulic conditions are determined by flow resistance and the geometry of the channel. The study showed that both the flow resistance and the cross-sectional geometry are vital factors in determining local hydraulics. In stream restoration, design based on the consideration of only one of these two factors is inadequate and may result in a failure to replicate the local hydraulic conditions of the reference reach. Criteria for evaluating the success of the restoration of local hydraulics were developed. The application of the procedure for using the success criteria in post-project evaluation is presented in detail in Paper *III* for a case of the Myllypuro Brook.

In the success evaluation of the restoration of local hydraulics, the channel cross-sectional geometry was described with the help of depth-width ratio h/B and/or hydraulic radius R. The research into channel cross-sectional geometry was further expanded to include research into the hydraulic geometry that relates the local channel geometry to the flow parameters and furthermore, the local hydraulics into the channel properties in the longitudinal direction. For this, the exponents for the equations of hydraulic geometry were determined for several river and channel reaches. The values of the exponents in the Finnish rivers were well within the range of the values presented in literature. In the 23 Finnish river and channel reaches under research, the average at-a-site values of the exponents for the equations of hydraulic geometry were $b_{hg} = 0.23$, $f_{hg} = 0.26$, $m_{hg} = 0.51$.

In the data from Leopold & Maddock (1953), channel depth increased with discharge somewhat faster than it did for channel width ($f_{hg} > b_{hg}$). The ratio was higher than in the Finnish rivers under research, where depth and width increased with discharge at the same speed ($f_{hg} \approx b_{hg}$). Mild longitudinal slopes in Finnish rivers may be the main reason for low width-depth ratios.

In the Finnish cohesive soil reaches of the natural rivers of this study, the values of exponent m_{hg} were at the higher end of the range presented in the literature. In some rivers the reason may be that only a limited number of different discharges biased toward low and mean flows were measured. According to Bathurst (1993), high m_{hg} values could indicate high changes in flow resistance between high and low flows. The results are presented in detail in Paper *IV*.

4.1.5 How to improve the field studies in the future

In general, the results of this study derived from the field measurements were as expected. However, some aspects of the measurements need special consideration in order to improve the possibilities for data analysis.

Emphasis is needed in delimitation of field study reaches. The selection of the reach length and location must be considered carefully, especially in small channels, where site-specific factors such as individual logs may significantly contribute to flow resistance locally.

More detailed and systematic vegetation mapping should be carried out along the hydraulic field measurements for two reasons. Firstly, detailed data is needed to determine the flow resistance due to vegetation and the additional flow resistance due to the momentum transfer. Secondly, the vegetation data allows for the evaluation of seasonal changes in hydraulics due to vegetation growth.

Several methods for estimating the roughness of ice cover exist, but the results produced by these methods are variable. More physical research should be carried out to verify the methods developed for estimating the friction of ice cover e.g., in a flume with a real ice cover.

4.2 Flow modelling

4.2.1 Comparison of unsteady flow models

Both the traditional unsteady model for compound channels and the proposed unsteady 1D flow model for partially vegetated channels using the Nuding method (1991) were used for the flow computation for the River Rhine and the River Päntäneenjoki. The results were very similar with both models in both the River Rhine and the River Päntäneenjoki. Unlike the traditional model, the proposed model predicts the components of discharge, average velocities and the friction factors separately for the floodplains and the main channel.

The proposed model was more accurate for the River Rhine, a channel with wide partially vegetated floodplains, after the maximum values of the friction factors for the interfaces were limited. This limitation was made based on the investigation into the effect of the longitudinal plant distance on the friction factor of the interface in a laboratory flume made by Pasche (1984). The flume studies carried out at HUT verified that the point of maximum flow resistance is reached at a certain plant distance, after which any increase in the distance decreases the flow resistance. In the River Päntäneenjoki, a simple concave channel with bank vegetation, the model was not as accurate, especially with regard to the reach with no streambank vegetation but a slightly widened channel shape due to high longitudinal variation.

In the traditional model, the floodplains are used as storage and thus, the effects of the flow resistance due to vegetation and changes in flow resistance due to vegetation density are totally neglected. In the proposed model, the changes in vegetation density and floodplain width had a significant effect on the transport capacities of the main channel and the floodplains. The biggest difference between the models is that the proposed model estimates the flow velocities and components of discharge in the main channel and the floodplains or vegetation zones, unlike the traditional model. Therefore, the proposed unsteady model combined with Nuding method, is better applicable to compound channels with vegetated floodplains than the traditional model. The results are presented in further detail in Papers *V*, *VI*, *VII*.

4.2.2 How does restoration of floodplains influence floods

In general, three main factors have been presented, that may have had effect on changes of floods: a) the changes in land use and thus runoff in the whole river basin, b) dredging of river channels and reduction of natural flood retention areas, and c) possible climate change. The proposed unsteady 1D flow model for partially vegetated channels can serve as a tool for estimating the effects of floodplains on flood retention. As an example of the investigation of the impact of floodplains on the retention capacity of the channel, flood propagation was modelled on the 28-km-long reach of the River Rhine studied in Paper *VI*. The flow simulation for flood event case 1 presented in Paper *VI* was carried out in the following situations (Fig. 11):

a) The river reach as it is at present.
b) The same reach. The wide floodplains that exist in 91 cross sections (out of 140) are dredged 2 meters lower, maintaining the initial vegetation roughness. The estimated increase in the floodplain volume is 15 million m^3 at the reach.
c) The same reach with 5 m high levees constructed to prevent flow on the outer floodplains, reducing the floodplain volume to about 5 million m^3 at the reach.

The discharges and water levels for the simulated flood event case 1 (Paper *VI*; 20-24 Feb 1999; $Q = 292\text{-}2319\ m^3/s$) were computed on different cross-sectional alterations a), b) and c). Situations b) and c) were compared to situation a). The relative changes for discharges (RE) and the relative changes for peak discharges (RE-p) are presented in Table 3, and the relative changes for water depths (REw) and the relative changes for peak water depths (REw-p) are presented in Table 4.

From the results it can be seen that a reduction or increase in the channel retention volume may have a very small effect on the change in the attenuation of the flood peak. The effect would be more significant on a longer reach. The overall elevation of the floodplain obviously has a great influence on its capacity to retain the flood. This is because of the recurrence interval of floods of different magnitudes, and thus, the effect of the enlargement or dredging of the floodplains on the increased flood retention is highly dependent on the elevation of the floodplain. When the floodplain is lowered, the recurrence interval of inundation of the floodplain is shortened. Furthermore, when the elevation of the floodplain is dredged to too low a level, this may actually increase the flow depth, flow velocities and thus cause erosion. The erosion may be of such a magnitude that it significantly increases the channel conveyance and reduces the retention capacity.

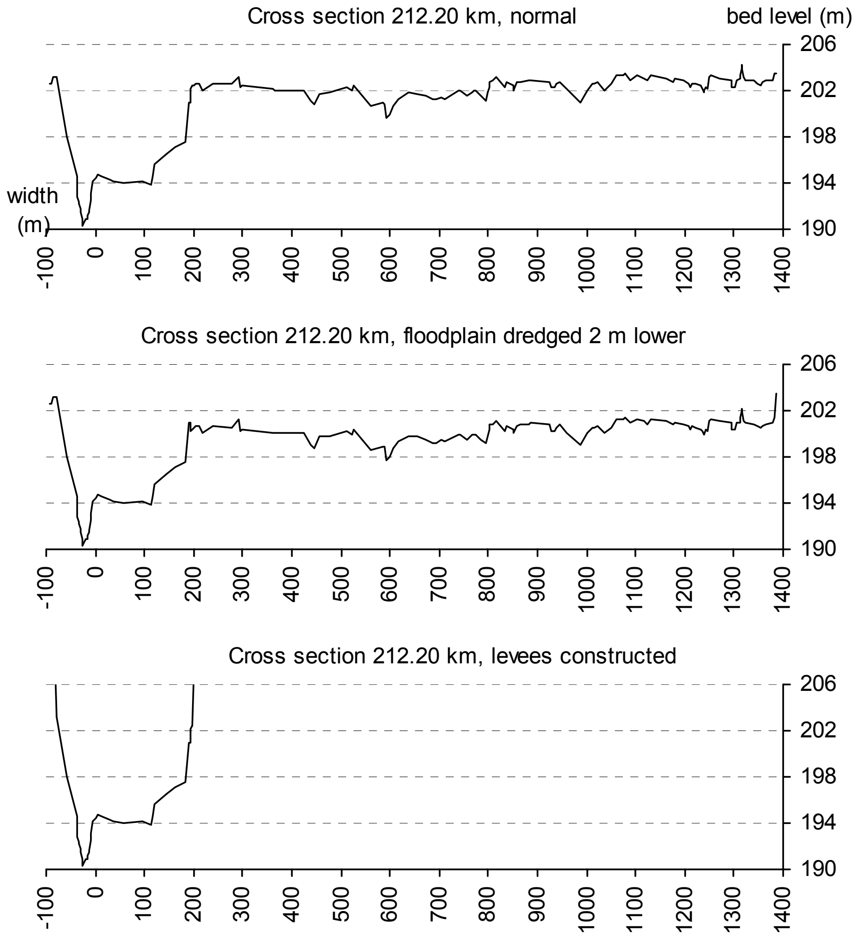

Figure 11. An example of an altered cross section for the estimation of changes in retention: normal (top), wide floodplains dredged 2 m lower (middle), and levees constructed to prevent floodplain flow (lowest).

Based on these results, it is insufficient to consider the rehabilitation of the channel retention capacity as being the only necessary measure needed to restore the flows in the river basin scale. As Mellequist (1992) stated: "River problems will not be solved in the rivers alone, because these problems for the most part originate in the rivers' catchment areas". Restoration should be considered in a broader catchment-scale sense, including restoration of the hydrological and hydraulic conditions, in which the restoration or rehabilitation of flood retention areas and local hydraulics is only one part of the solution, albeit, a significant one. Enlargement of the floodplains and other flood retention areas along the catchment area can help in compensating for the effects of the changes in runoff on the flood peaks. However, a detailed analysis of the effects of the planned changes on floodplains is needed to avoid any reverse effects on retention.

Table 3. The relative changes of discharges RE and relative changes of peak discharges RE-p for studied flood events on different cross-sectional alterations (Fig. 11)

Change of discharges *Q*	RE (%)	RE-p (%)
b) Wide floodplains dredged 2 m lower	0.37	-0.04
c) Levees constructed to prevent floodplain flow	0.53	0.16

Table 4. The relative changes of water depths REw and relative changes of peak water depths REw-p for studied flood events on different cross-sectional alterations (Fig. 11)

Change of water depths *h*	REw (%)	REw-p (%)
b) Wide floodplains dredged 2 m lower	0.73	-0.16
c) Levees constructed to prevent floodplain flow	1.05	0.29

4.2.3 How to further develop the modelling of compound channels

When comparing the proposed unsteady 1D flow model for partially vegetated channels to earlier developed models, there are several advantages:

- It is applicable to channels with complex and irregular cross-sectional geometries, and to floodplains that are partly, totally or not vegetated.
- Variable roughness parameters can be input into different parts of the channel to account for the composite flow resistance.

The model was tested on a small river and on a larger river with different types of cross-sections and vegetation zones, with relatively good results. Thus, although the model is quite simple, it is also relatively flexible.

However, a limit on the number of maximum values for the friction factors for the interfaces f_J was necessary in the model for situations where there was a very wide main channel and floodplains. This was necessary so as not to overestimate the composite flow resistance. The Nuding method (1991, 1998) should be further developed to manage cases with wide channels more accurately. The Pasche method might produce more accurate results for compound channels with floodplain vegetation, but the Nuding method is simpler to apply in practice, so its use can be recommended in cases when approximate results are needed for practical cases.

Some numerical errors remained in the model in cases where there was a very steep gradient of wetted perimeter near the bank-full level. This was especially noticeable in the computation of flow in a regular double-trapezoidal channel with wide level floodplains. A local numerical disturbance was found at water levels near the floodplain level. When the water level in some cross sections rose just above the floodplain level, it caused a rapid increase in the wetter perimeter and thus, an increase in the composite friction factor in the Nuding method. This was returned to St Venant equations, causing an increase in water levels, and at the next time step it again caused a decrease in the composite friction factor. This could be neglected by solving the Nuding method and the St Venant equations simultaneously with a complex iteration process. However, the disturbance was lower in natural irregular channels, and even in regular channels it stabilised after the water level had passed the floodplain level.

Difficulties with the model occur in relation to the objective quantification of the different vegetation parameters, and the objective division of the channel into the floodplain and main channel parts and thus, the decision relating to the location of the interfaces. According to Shiono & Knight (1991), the apparent shear stress method that sees the increased boundary shear stress as a single vertical is not physically correct, because of the wider distribution of the shear stresses along the zone between the main channel and the floodplain. However, according to Pasche (1984) it can be estimated as a single vertical with increased shear stress relatively reliably.

To further verify and ensure the use of the proposed unsteady 1D flow model, an objective method for dividing the channels into the main channel and the floodplain components is needed. To ensure the correctness of the components of discharge in the floodplains and the main channel, the comparison of the results to a detailed field data of the local velocities or partial discharges is necessary in the development of the division method.

A more complex but accurate way of modelling floods in a complex compound channel might be to divide the channel into parts that have different average velocities, "tubes", for which the St Venant equations would be solved separately but simultaneously.

4.2.4 How do the hydraulics of small and large rivers differ

In this research, brooks and rivers of very different sizes were investigated. Although the physical basis of flow and flow resistance remained the same, some differences were found in the conveyance estimation between small and large rivers. The lack of the field data from mid-sized rivers restricts the generalization of the results into rivers of all sizes.

Generally it can be seen from the results, that the smaller the river discharge (and *Re* number), the higher the friction factors (Fig. 12). In rivers with a high water depth, the resistance can more often be treated as boundary friction, and the approximation of the logarithmic velocity profile is more accurate. However, in the case of high relative roughness k/R, which is more common in small rivers, the approximation of the logarithmic velocity profile is always highly inaccurate.

High relative roughness and high local losses can be caused in small channels by a) the effects of the form resistance associated with acceleration or deceleration and flow separation over small-scale structures such as pebble clusters; b) the form resistance associated with large-scale bed undulations; c) the flow resistance associated with irregular, asymmetric cross-sectional shape, and d) large obstructions.

It was seen in the research into the Myllypuro Brook, that the effects of spatial variations (e.g. positioning of vegetation and woody debris) were far more important than temporal variations in the friction factors. In small channels, site-specific factors such as individual logs may significantly contribute to flow resistance. Thus, particular emphasis is needed in the delimitation of field study reaches, i.e. detailed consideration of the reach length and the reach location. This also indicates that in small channels the temporal variation may easily be covered by the errors made in topographic measurements, and thus unsteady flow modelling may not be worthwhile, but emphasis should be given to the accurate determination of the topographic and resistance parameters. Furthermore, floods rarely rise and fall so rapidly that the flood wave propagation can be detected and measured in small rivers, but generally the rise/ fall of a flood is seen as an overall rise/ fall in the water level along the whole length of the river simultaneously.

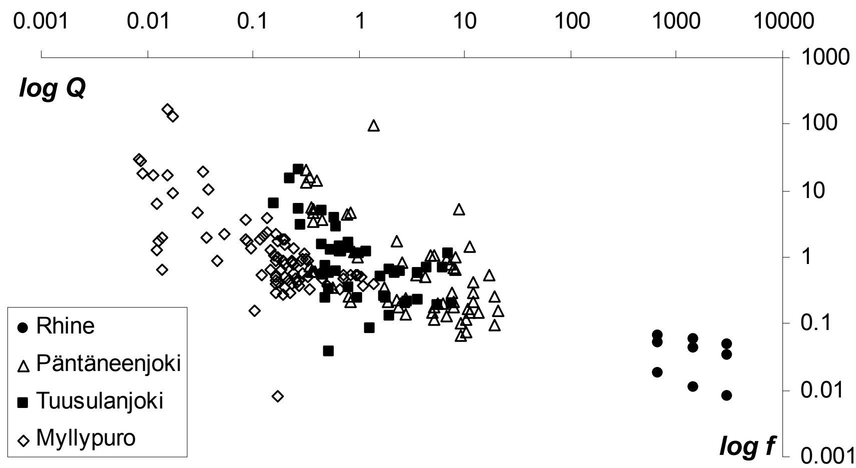

Figure 12. Friction factors as functions of discharges for the River Rhine, the River Päntäneenjoki, the River Tuusulanjoki and the Brook Myllypuro. The values are presented on a logarithmic scale.

In very small channels a single log or stone may cause a step-pool-type longitudinal structure with significant local losses and totally different flow structure (see e.g. Lee & Ferguson 2002, MacFarlane & Wohl 2003).

5 CONCLUSIONS

In river restoration and environmental flood management, several factors must be combined; these include engineering, ecological, geomorphic and hydrological aspects. In river restoration work, it is essential to have adequate knowledge of the many complex hydraulic problems, such as the effects of irregular profiles and vegetation, because especially low-energy cohesive lowland rivers naturally adjust themselves extremely slowly, and therefore severe flooding or degradation may be caused by poor channel design. Therefore, complex river channels were investigated in this thesis to increase the understanding of their hydraulic properties.

The main conclusions relating to the hydraulic properties based on field studies on the target rivers can be summarized in the following points:

1. The differences in the friction factors were small between the pristine, restored and degraded stream reaches of the Myllypuro Brook, despite the fact that the geomorphic and vegetative characteristics of the reaches were markedly different.

2. The environmental flood management and bioengineering measures applied in reach P2 in the River Päntäneenjoki did not significantly alter the friction factors. The application of the bioengineering methods was found to be relatively successful in the river, although it seems that the success of the bioengineering methods is highly dependent on weather conditions during the first couple of years, and re-installation and re-planting may be needed during the first few years after the construction works.

3. In the Finnish lowland rivers studied, the Darcy-Weisbach friction factors determined from the field measurements were well in line with the values presented in literature for mean and high flows. In simple concave channel reaches, about 70-90% of the total flow resistance was explained by the bed roughness and small-scale bed undulations, and the rest by the sinuosity and large-scale undulations. The friction factors were significantly higher in reaches with considerable streambank vegetation due to the flow resistance caused by the vegetation and by the lateral momentum transfer.

4. In the River Päntäneenjoki, the friction factors during ice cover were smaller than those during open water with the same discharges. The result differed from the values presented in literature. However, small values during the ice cover are probably due to the lack of very sparse vegetation existing in summertime in the channel.

5. The theory of hydraulic geometry, linking the channel geometry to the flow parameters, was applied to 34 boreal cohesive river and channel reaches in Finland

to give further information on the cross-sectional geometry for channel restoration. The values of exponent m_{hg} (velocity) were at the higher end of the range presented in the literature, indicating that the longitudinal channel variation had significant resistance effects during low water.

Several different methods used to determine composite friction factors were tested, and an unsteady 1D flow model for partially vegetated natural channels was proposed in the thesis. Success criteria for evaluating the restoration of local hydraulics and a methodology for applying them were developed. The main conclusions concerning the models and methods that were used and developed were:

6. The superposition approach of Einstein (1950) and the method used by Cowan (1956) proved to be applicable in partitioning the friction factor into components in small, simple concave channels near mean flows. Both methods were accurate in the channel reaches with simple hydraulic properties, but an adjustment in the methods would be necessary in complex channel reaches, e.g. reaches with significant head losses due to lateral momentum transfer.

7. Success criteria for the restoration of local hydraulic conditions were developed based on results that suggested that the hypothesis of flow resistance and cross-sectional geometry determining local hydraulic conditions were relevant in boreal streams. A procedure for applying the success criteria in a post-project evaluation of local hydraulics was developed.

8. In order to achieve a sound restoration design that provides similar hydraulic conditions to those found at a natural site, both success criteria for cross-sectional geometry and flow resistance need to be fulfilled at the reach-averaged scale. In addition, the natural variability of local hydraulics must be taken into account, and furthermore, the downstream hydraulic geometry of the river should be taken into account as an advisory parameter for the design of the cross-sectional geometry. This is especially important in situations where the reference reach is located far upstream or downstream from the restored reach.

9. An unsteady 1D flow model was formulated for partially vegetated natural channels, in which the additional flow resistance due to lateral momentum transfer has a significant role in investigating flow resistance and conveyance in compound/composite channels. The proposed model computes the components of discharge, average velocities and friction factors for the main channel and the floodplains in each cross section, and is therefore a valuable tool for assessing local hydraulic conditions in compound channels, ensuring suitable conditions for habitat diversity in environmental flood management projects. The model takes into account a) the resistance of floodplain vegetation, and b) the additional resistance caused by lateral

momentum transfer, by combining the Nuding method (1991) with St Venant equations. To assist with the application of the proposed model into complex natural channels, a pre-processing program was developed to convert the topographic field data and the vegetation data into a form suitable for input into the unsteady flow model.

10. The proposed model was applied to the Upper Rhine and to the River Päntäneenjoki to test its applicability to different channel types and sizes. It was found to be relatively accurate in simulating the measured discharges and composite friction factors in the River Rhine which has wide floodplains, despite the intentionally and inexactly assumed simplification of a one-dimensional flow in a wide compound channel. However, the determination of a maximum value for the friction factor of the interface was necessary in cases with wide floodplains so as not to overestimate the effect of the interaction process. In the River Päntäneenjoki that has dense streambank vegetation, the model was not as accurate as it was with regard to the River Rhine.

11. The additional flow resistance caused by the lateral momentum transfer process was quantified from the field data from the River Rhine and the River Päntäneenjoki. The values were higher than the values presented in the literature, mainly because the literature values were determined in longitudinally uniform flumes and were therefore lower than the values determined for rivers with a strong longitudinal variation. Other factors that cause flow resistance may be implicitly included in the friction factor of the interface because of a) the longitudinal variation of cross sections and profiles, and b) the model neglecting local losses. The effects of the streambank vegetation and the momentum transfer were significant on the composite friction factors in the River Päntäneenjoki.

12. The study clearly showed that the restoration of flood retention areas and local hydraulics is vital, but in small volumes, not sufficient in itself to restore the flood peaks to their earlier state. Based on the computed example for the River Rhine, the changes in land use have had more significant effects on flood peak attenuation.

REFERENCES

Abbott, M.B. & Minns, A.W. 1998. *Computational hydraulics*. 2nd edition. Ashgate Publishing Ltd. 557 p.

Ackers, P. 1993. Flow Formulae For Straight Two-Stage Channels. *Journal of Hydraulic Research*, 31 (4): 509-531.

Anderson D., Tannehill J., & Pletcher R. 1984. *Computational Fluid Mechanics and Heat Transfer*. Hemisphere Co. New York. 792 p.

ASCE Task Force on Friction Factors. 1963. Friction factors in open channels. *Journal of the Hydraulics Division*, 89: 97-143.

Ashton, G.D. (ed.). 1986. *River and lake ice engineering*. Michigan, USA. 485 p.

Bathurst J. C. 1993. Flow resistance through the channel network. In: Beven, K. & Kirkby, M.J. (eds.) *Channel Network Hydrology*. John Wiley & Sons, Chichester. pp. 69-98.

Becker, K. 1999. Der Einflub von kurzen Gehölzstreifen auf den Hochwasserabflub in Flüssen mit gegliedertem Querschnitt. *Heft 202*, Institut für Wasserwirtschaft und Kulturtechnik, Universität Karlsruhe. 195 p.

Boon, P.J. 1992. Essential Elements in the Case for River Conservation. In: Boon, P.J., Calow, P. & Petts, G.E. (eds.). *River Conservation and management*. John Wiley & Sons, Chichester. pp. 11-34.

Broadhurst, L.J., Heritage, G.L., van Niekerk, A.W., James, C.S. & Rogers, K.H. 1997. Translating discharge into local hydraulic conditions on the Sabie River: an assessment of channel flow resistance. *Water Research Commission Report* 474/2/97. 232 p.

Brookes A. & Shields F.D. (eds.) 1996. *River channel restoration: guiding principles for sustainable projects*. John Wiley, Chichester. 440 p.

Chow, V.T. 1959. *Open-channel hydraulics*. McGraw-Hill, New York. 440 p.

Coon, W.F. 1998. Estimation of Roughness Coefficients for Natural Stream Channels with Vegetated Banks. *USGS Water Supply Paper 2441*. 133 p.

Cowan, W. L. 1956. Estimating hydraulic roughness coefficients. *Agricultural Engineering*, 37(7): 473-475.

Cunge, J.A., Holly, F.M.Jr. & Verwey, A. 1980. *Practical Aspects of Computational River Hydraulics*. Pitman Publishing Ltd, London. 405 p.

Darby, S.E. 1999. Effect of Riparian Vegetation on Flow Resistance and Flood Potential. *Journal of Hydraulic Engineering*, 125(5): 443-454.

Darby, S. & Thorne, C. 1996. Predicting Stage-Discharge Curves in Channels with Bank Vegetation. *Journal of Hydraulic Engineering*, 122(10): 583-586.

ECE 2000. *Guidelines on Sustainable Flood Prevention*. United Nations, Economic Commission for Europe. MP.WAT/2000/7.

Einstein, H.A. & Banks, R.B. 1950. Fluid resistance of composite roughness. *Transactions, AGU*, 31: 603–610.

EU 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. *Official Journal L* 327, 22/12/2000.

Evans, E.P., Pender, G., Samuels, P.G. & Escarameia, M. 2001. Scoping Study for Reducing Uncertainty in River Flood Conveyance. *Environment Agency R&D Technical Report for DEFRA*, U.K. 119 p.

Fisher K.R. 1996. Handbook for assessment of hydraulic performance of environmental channels. *Report SR 490* (draft). HR Wallingford, U.K. 346 p.

Fischer-Antze, T., Stoesser, T., Bates, P. & Olsen, N.R.B. 2001. 3D numerical modelling of open-channel flow with submerged vegetation. *Journal of Hydrology*, 39(3): 303-310.

Forsius, J. 1984. Computing unsteady flow and tracer in a river. *Vesientutkimuslaitoksen julkaisuja*, Helsinki. 46 p.

Forsius, J., & Huttula, T. 1982. Application of a mathematical model to a branched watercourse. *Geophysica* 19(1):55-64, Helsinki.

Fread, D. L. 1988. The NWS DAMBRK Model: Theoretical background/User documentation. *Rep. No. HRL-256*, Hydrologic Research Laboratory, National Weather Service, Silverspring, MD. 315 p.

Graf, W.H. 1998. *Fluvial Hydraulics. Flow and transport processes in channels of simple geometry*. John Wiley & Sons, Chichester. 681 p.

Haidera, M.A. & Valentine, E.M. 2002. A practical method for predicting the total discharge in mobile and rigid boundary compound channels. In: Bousmar, D. & Zech, Y. (Eds.): *River Flow 2002*, Belgium. pp. 153-160.

Hartmann, G., Dittrich, A. & Träbing, K. 1998. *Untersuchungen zum Vorlandabtrag zwischen Märkt und Karpfenhod*. Schlußbericht; Auftrag AZ 40.80/2. 78 p.

Helmiö, T. & Jolma, A. 2003. Conceptual Model of a Compound Channel Geometry and Resistance. *Proceedings of the XXXth IAHR Congress*, Theme CI, 1: 1-8. Thessaloniki.

Hirai, Y., Yamazaki, M., Hirayama, K. & Shen, H.T. 2000. The March 1995 ice jamming in the Shokotsu River and Ashibetsu River. *Proceedings of the 15th International Symposium on Ice*, pp. 331-338. Gdansk.

Hosia, L. 1983. *Pienten uomien virtausvastuskerroin*, Ph.D. Thesis, Helsinki University of Technology, Finland. 119 p.

Huokuna, M. 1991. The observations of the Finnish river ice research project. *Vesi- ja ympäristöhallituksen monistesarja*, 52 p.

Hydraulics Research 1988. Assessing the hydraulic performance of environmentally acceptable channels. *Report EX 1799*. Wallingford, U.K. 132 p.

Indlekofer, H. 1981. Überlagerung von Rauhigkeitseinflüssen beim Abfluß in offenen Gerinnen. *Mitteilungen* 37, Institut für Wasserbau und Wasserwirtschaft, Rheinisch-Westfälische Technische Hochschule Aachen. pp. 105-145.

Järvelä, J. 2004. Determination of flow resistance caused by non-submerged woody vegetation. *Journal of River Basin Management*, 2(1): 1-10.

Karvonen, T. 1984. *Real-time flood forecasting using extended Kalman filter*. L.Sc.(tech.) Thesis, Helsinki University of Technology. 118 p.

Knight, D. W. 2001. *Scoping study on reducing uncertainty in river flood conveyance – conveyance in 1-D river models*, School of Civil Engineering, The University of Birmingham. 31 p.

Knight, D.W. & Demetriou, J.D. 1983. Flood Plain and Main Channel Flow Interaction. *Journal of Hydraulic Engineering*, 109(8): 1073-1092.

Knight, D. W. & Hamed, M. E. 1984. Boundary shear in symmetrical compound channels. *Journal of Hydraulic Engineering* 110(10): 1412-1429.

Knighton, D. 1984. *Fluvial forms and processes*. John Wiley, London. 218 p.

Kouwen, N. 1988. Field estimation of the biomechanical properties of grass. *Journal of Hydraulic Research*, 26(5): 559-568.

Kuuskoski, M. 1968. Hydrauliikka. In: Mustonen, S. (ed.). Maa- ja vesirakennus. *Suomen Rakennusinsinööriliiton julkaisusarja*, 67. Vammalan kirjapaino. pp. 49-68.

Lai, C. J., Lui, C.-L. & Lin, Y.-Z. 2000. Experiments on flood-wave propagation in compound channel. *Journal of Hydraulic Engineering*, 126(7): 492-501.

Lawless, M. & Robert, A. 2001. Scales of boundary resistance in coarse-grained channels: turbulent velocity profiles and implications. *Geomorphology*, 39: 221-238.

Lee, A. J. & Ferguson, R. I. 2002. Velocity and flow resistance in step-pool streams. *Geomorphology*, 46: 59-71.

Leopold, L.B., Bagnold, R., Wolman, M.G. & Brush, M.L. 1960. Flow resistance in sinuous or irregular channels. *United States Geologic Survey Professional Paper*, 282-D: 111–134.

Leopold L.B. & Maddock T.Jr. 1953. The Hydraulic Geometry of Stream Channels and Some Physiographic Implications, *Geological Survey Professional Paper*, 252. U.S. 57 p.

Lopez, F. & Garcia, M. 1997. Open-Channel Flow through Simulated Vegetation: Turbulence Modeling and Sediment Transport. *USGS Wetlands Research Program Technical Report* WRP-CP-10. 123 p.

MacFarlane, W. A. & Wohl, E. 2003. Influence of step composition on step geometry and flow resistance in step-pool streams of the Washington Cascades. *Water Resources Research* 39(2): 1-13.

Mahmood, K. & Yevjevich, V. (eds.) 1975. *Unsteady flow in open channels*. Vols. I & II. Water Resources Publications, Fort Collins, CO. 921 p.

Masterman, R. & Thorne, C.R. 1992. Predicting influence of bank vegetation on channel capacity. *Journal of Hydraulic Engineering*, 118: 1052-1058.

Manga, M. & Kirchner, J.W. 2000. Stress partitioning in streams by large woody debris. *Water Resources Research*, 36(8): 2373–2379.

Mellequist, P. 1992. River Management – Objectives and Applications. In: Boon, P.J., Calow, P. & Petts, G.E. (eds.). *River Conservation and management*. John Wiley & Sons, Chichester. pp. 1-10.

Mertens, W. 1989. Zur Frage hydraulischer Berechnungen naturnaher Fließgewässer. *Wasserwirtschaft*, 79(4): 170-179.

Murota, A., Fukuhara, T. & Sato, M. 1984. Turbulence Structure in Vegetated Open Channel Flows. *Journal of Hydroscience and Hydraulic Engineering*, 2(1):47-61.

Muste, M., Braileanu, F. & Ettema, R. 2000. Flow and sediment transport measurements in a simulated ice-covered channel. *Water Resources Research*, 36(9): 2711-2720.

Myers, W. R. C. 1987. Velocity and discharge in compound channels. *Journal of Hydraulic Engineering*, 113(6): 753-765.

Myers, W. R. C. & Brennan, E. K. 1990. Flow resistance in compound channels. *Journal of Hydraulic Research*, 28(2): 141-155.

Myers W.R.C. & Elsawy, E.M. 1975. Boundary shear in channel with flood plain. *Journal of Hydraulics Division*, 101(7): 933-947.

Naot, D., Nezu, I. & Nakagawa, H. 1996a. Hydrodynamic Behaviour of Partly Vegetated Open Channels. *Journal of Hydraulic Engineering*, 122(11): 625-633.

Naot, D., Nezu, I. & Nakagawa, H. 1996b. Unstable Patterns in Partly Vegetated Channels. *Journal of Hydraulic Engineering*, 122(11): 671-673.

Nezu, I. & Onitsuka, K. 2001. Turbulent structures in partly vegetated open-channel flows with LDA and PIV measurements, *Journal of Hydraulic Research*, 39(6): 629-642.

Nienhuis, P. H. & Leuwen, R. S. E. W. 2001. River restoration and flood protection: controversy or synergism? *Hydrobiologia*, 444: 85-99.

Nuding, A. 1991. Fließwiederstandsverhalten in Gerinnen mit Ufergebüsch. Entwicklung eines Fließgewässer mit und ohne Gehölzufer, unter besonderer Berücksichtigung von Ufergebüsch. *Wasserbau-Mitteilungen* 35, Technische Hochschule Darmstadt. 116 p.

Nuding, A. 1998. Zur Durchflußermittlung bei gegliederten Gerinnen. *Wasserwirtschaft*, 88(3): 130-132.

Pasche, E. 1984. *Turbulenzmechanismen in naturnahen Fliebgewässern und die Möglichkeiten ihrer mathematischen Erfassung*. Rheinisch-Westfälische Technische Hochschule Aachen. 244 p.

Pasche, E. & Rouvé, G. 1985. Overbank Flow with Vegetatively Roughened Flood Plains. *Journal of Hydraulic Engineering*, 111(9): 1262-1278.

Petryk, S. & Bosmaijan, G. 1975. Analysis of Flow Through Vegetation. *Journal of Hydraulics Division, ASCE*, 111(7): 871-884.

Posey, C. J. 1967. Computation of discharge including overbank flow. *Civil Engineering*, 37(4): 62-63.

Preissmann, A. 1961. *Propagation des intumescences dans les canaux et rivieres*. First Congress of the French Association for Computation, Grenoble, France. pp. 433-442.

Prinos, P., Townsend, R. & Tavoularis, S. 1985. Structure of Turbulence in Compound Channel Flows. *Journal of Hydraulic Engineering*, 111(9): 1246-1261.

Rodi, W. 1993. *Turbulence Models and Their Application in Hydraulics*. A *state-of-the-art review*. IAHR Monograph. A. A. Balkema, Rotterdam. 104 p.

Rouse, H. & Ince, S. 1963. *History of Hydraulics*. Dover Publications Inc. 269 p.

Rouvé, G. (ed.) 1987. *Hydraulische Probleme beim naturnahen Gewässerausbau*. Deutsche Forschungsgemeinschaft (DFG), Weinheim. 267 p.

Rowinski, P. M., Czernuszenko, W., Koziol, A., Kusmierczuk, K. & Kubrak, J. 1998. Longitudinal turbulence characteristics in a compound channel under various roughness conditions. *3rd International Conference on Hydroscience and Engineering*, Cottbus, Germany. Paper 91, 9 p.

Saari, S. 1955. *Hankauskertoimen arvosta pienissä vesiväylissä*. M.Sc. Thesis, Helsinki University of Technology, Finland. 105 p.

Samuels, P.G., Bramley, M.E. & Evans, E.P. 2002. Reducing uncertainty in conveyance estimation. In: Bousmar, D. & Zech, Y. (eds.): *River Flow 2002*. pp. 293-302.

Sellin, B. 1964. A laboratory investigation into the interaction between the flow in the channel of a river and that over its flood plain. *La Houille Blanche*, 7: 793-802.

Shields, F.D. & Gippel, C.J. 1995. Prediction of effects of woody debris removal on flow resistance. *Journal of Hydraulic Engineering*, 121(4): 341–354.

Shimizu, Y. & Tsujimoto, T. 1993. Comparison of flood-flow structure between compound channel and channel with vegetated zone. In: *IAHR Congress 1993*, Tokyo, 1(A-3-4): 97-104.

Shiono, K. & Knight, D.W. 1991. Turbulent open-channel flows with variable depth across the channel. *Journal of Fluid Mechanics*, 222: 617-646.

Stephenson, D. & Kolovopoulos, P. 1990. Effects of Momentum Transfer in Compound Channels. *Journal of Hydraulic Engineering*, 116(12): 1512-1522.

Tatinclaux, J.C. & Gögüs, M. 1983. Asymmetric Plane Flow with Application to Ice Jams. *Journal of Hydraulic Engineering*, 109(11): 1540-1554.

Teal, M.J., Ettema, R. & Walker, J.F. 1994. Estimation of flow velocity in ice-covered channels. *Journal of Hydraulic Engineering*, 120(12): 1337-1400.

Thornton, C.I., Abt, S.R., Morris, C.E. & Fischenich, J.C. 2000. Calculating Shear Stress at Channel-Overbank Interfaces in Straight Channels with Vegetated Floodplains. *Journal of Hydraulic Engineering*, 126(12): 929-936.

Tseng, M-H. 1999. Verification of 1-D Transcritical Flow Model in Channels. *Proceedings of the National Science Council, ROC(A)*, 23(5): 654-664.

Tsujimoto, T. 1999. Fluvial processes in streams with vegetation. *Journal of Hydraulic Research*, 37(6): 789-803.

Walker, J.F. 1994. Methods for measuring discharge under ice cover. *Journal of Hydraulic Engineering*, 120(11): 1327-1336.

Walker, J.F. & Wang, D. 1997. Measurement of flow under ice covers in North America. *Journal of Hydraulic Engineering*, 123(11): 1037-1040.

Wang, D. 2000. Discharge Calculation of Natural Channel Flows with AFM Data. *CD Proceedings of the ASCE Joint Conference on Water Resources Engineering and Water Resources Planning and Management*, Minneapolis, U.S.

Wang, D., McCurry, P. & Bourdages, R. 2000. Application of Flow Velocity Distribution Models to Channel Discharge Measurements. *CD Proceedings of the ASCE Joint Conference on Water Resources Engineering and Water Resources Planning and Management*, Minneapolis, U.S.

Watanabe, A., Fukuoka, S. & Mutasingwa, A.G. 2002. Analysis on the flood flow storage in compound meandering channels by using unsteady two-dimensional numerical model. In: Bousmar, D., Zech, Y. (eds.) *River Flow 2002*, pp. 213-221.

Wessel, J. 1995. Flood management of the transnational River Rhine. *U.S.-Italy Research Workshop on the Hydrometeorology, Impacts and Management of Extreme Floods*, Perugia, Italy.

Wormleaton, P.R., Allen, J. & Hadjipanos, P. 1982. Discharge Assessment in Compound Channel Flow. *Journal of the Hydraulics Division*, 108(9): 975-994.

Wright, R.R. & Carstens, M.R. 1970. Linear-momentum flux to overbank sections. *Journal of Hydraulics Division*, 96(9): 1781-1793.

Yamashita, S., Shimizu, Y. & Hohjo, K. 1992. Characteristics of shear stress in the ice-covered river. *Proceedings of the 11th International Symposium on Ice*, Vol. 1: 355-360. Banff, Canada.

ATTACHMENT 1. NOMENCLATURE

A	[m^2]	cross-sectional area
a_x	[m]	longitudinal plant distance
B	[m]	water surface width
b_{hg}	[-]	exponent for the width equation of hydraulic geometry
f_{hg}	[-]	exponent for the depth equation of hydraulic geometry
f	[-]	Darcy-Weisbach friction factor
f_i	[-]	D-W friction factor of a cross-sectional element *i*
f_j	[-]	D-W friction factor of a resistance factor *j*
f_J	[-]	D-W friction factor of the interface
f_{Jmax}	[-]	maximum D-W friction factor of the interface
f_{TOT}	[-]	composite D-W friction factor
H_f	[m]	head loss
HQ	[m^3/s]	high discharge
h	[m]	water depth
k	[m]	roughness height
k_i	[m]	roughness height for a cross-sectional element *i*
MHQ	[m^3/s]	mean high discharge
MNQ	[m^3/s]	mean low discharge
MQ	[m^3/s]	mean discharge
m_{hg}	[-]	exponent for the velocity equation of hydraulic geometry
m_5	[-]	coefficient for meandering in Cowan's method
NQ	[m^3/s]	low discharge
n	[s/m$^{1/3}$]	Manning resistance coefficient
n_0	[s/m$^{1/3}$]	Manning *n* for bed roughness in Cowan's method
n_1	[s/m$^{1/3}$]	Manning *n* for channel bed irregularity in Cowan's method
n_2	[s/m$^{1/3}$]	Manning *n* for cross-sectional irregularity in Cowan's method
n_3	[s/m$^{1/3}$]	Manning *n* for obstructions in Cowan's method
n_4	[s/m$^{1/3}$]	Manning *n* for vegetation in Cowan's method
p	[m]	wetted perimeter
p_i	[m]	wetted perimeter for a cross-sectional element *i*
R	[m]	hydraulic radius A/p
R_i	[m]	hydraulic radius for a cross-sectional element *i*
S	[-]	longitudinal bottom slope
v	[m/s]	average flow velocity
ρ	[kg/m^3]	fluid density
τ	[N/m^2]	shear stress