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# Hydraulic geometry of cohesive lowland rivers

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Natural recovery may be extremely slow in cohesive, low-energy, lowland rivers. Therefore, a detailed understanding of the hydraulic properties of the channel is essential when designing restoration or environmental flood management measures. The aim of this study was to increase understanding on the channel size and geometry of cohesive rivers and channels. At-a-site hydraulic geometry of 34 cohesive river and channel reaches in Finland were determined from the field measurements and compared to those determined elsewhere. The computed values of the exponents of the hydraulic geometry were within the range of those presented in the literature and similar between natural and man-made channels. The results indicated that longitudinal channel variation had significant resistance effects during low water.

## Introduction

River restoration options can be divided into three basic approaches: (a) non-intervention, where the stream corridor is recovering rapidly and active restoration is unnecessary and even detrimental; (b) partial intervention, where a stream corridor is attempting to recover, but is doing it slowly or uncertainly; and (c) substantial intervention, where recovery of desired functions is beyond the repair capacity of the ecosystem and active restoration measures are needed (FISRWG 1998). Allowable stream power can be considered as a threshold for natural recovery. When the product of bankfull discharge velocity and shear stress, i.e. the stream power per unit bed area exceeds a certain limit, a straightened river tends to recover naturally. In Britain, a river is considered as a high-energy river when the stream power is over 35 W m$^{-2}$ (Brookes 1992). In Denmark, the boundary value of the allowable stream power for natural recovery is also considered to be 35 W m$^{-2}$ (Brookes and Shields 1996). The natural adjustment of the altered channel size and shape may be extremely slow, from tens to hundreds of years, in low-energy, lowland environment having cohesive soils (Brookes and Shields 1996).

River channel sizes are naturally adjusted on average to a flow, which just fills the available cross-section, i.e. the dominant or channel-forming discharge with an approximate recurrence interval of 1–2 years (Knighton 1984, Brookes and Shields 1996). Besides the cross-sectional size, in alluvial bed rivers, a channel-forming discharge may be largely responsible also for the channel geometry (Knighton 1984, Tilleard 2001). The river channel cross-sections are relatively small for flood with recurrence interval of 5, 10 or 20 years. Often the frequent occurrence of higher flows is forgotten or just neglected, and hence, infrastructure may be constructed in lowland areas that are actually floodplains during higher floods. Especially in cases of low stream power, under-sizing the channel may cause severe flood problems, especially in areas with existing high flood risk. Oversizing the channel may initiate degradation of biodiversity, because too large a channel may become separated from the surrounding flora and fauna. Therefore, a detailed understanding of the relationship between the channel geometry and flow is essential in both the river restoration and flood management works.

When investigating natural rivers at the catchment scale, the width and the depth increase downstream, and the width increases faster than the depth (Bathurst 1993, Western *et al.* 1997). Furthermore, longitudinal slope and bed material size decrease downstream. It is evident that in some cases this is not applicable (e.g. Pitlick and Cress 2002). Ridenour (1999) tried to link the hydraulic geometry to the drainage area above a given point on a stream, and the hydraulic geometry to proportional stream order, but found no connection between them. He also found no correlation of hydraulic geometry between a main channel and its tributaries. Instead, he concluded that more site-specific factors, including channel shape, bed composition, and bank stability, are probably controlling hydraulic geometry in stream networks. In restoration, it is essential to consider the changes of channel properties also in longitudinal direction. If a natural reference reach is found far upstream or downstream of the restored reach, the hydraulic geometry of the reach under restoration should be adjusted in a way that is characteristic to the stream under consideration.

Leopold and Maddock (1953) developed a theory of the hydraulic geometry, where a river system develops in the way that an approximate equilibrium is developed between the channel cross-section and water flowing in the channel. This can be described as the following set of functions for the hydraulic geometry:

$$w = aQ^b, \qquad (1)$$
$$d = cQ^f, \qquad (2)$$
$$v = kQ^m, \qquad (3)$$

where $w$ = water surface width (m), $d$ = average depth (m), $v$ = average velocity (m s$^{-1}$), $Q$ = discharge (m s$^{-1}$), $a$ = numerical coefficient, multiplier for the width equation of hydraulic geometry, $b$ = numerical coefficient, exponent for the width equation of hydraulic geometry, $c$ = numerical coefficient, multiplier for the depth equation of hydraulic geometry, $f$ = numerical coefficient, exponent for the depth equation of hydraulic geometry, $k$ = numerical coefficient, multiplier for the velocity equation of hydraulic geometry, and $m$ = numerical coefficient, exponent for the velocity equation of hydraulic geometry. To maintain continuity ($Q = w \times d \times v$), the sum of the exponents ($b + f + m$) and the product of the constants ($a \times c \times k$) should equal 1.0, and thus the exponents and the constants are entirely inter-related.

According to Knighton (1984), channel geometry can be characterised either by the theory of hydraulic geometry with the help of channel width, depth slope and meander form, as done in this paper, or in terms of four parameters: (a) cross-sectional form, (b) bed configuration, (c) planimetric geometry (straight, meandering or braided), and (d) channel bed slope.

The values of the exponents for the equations of the hydraulic geometry have strong geomorphologic significance only in alluvial-bed rivers (Knighton 1984), but they can be used to describe the relationship between the channel geometry and flow in cohesive rivers, as well. Buhman *et al.* (2002) state that the discharge-based definition of hydraulic geometry presented in Eqs. 1–3 is useful to fluvial geomorphologists in studying the channel form. However, they also criticise that the numerical constants lack a physical intuitive meaning, and suggest that the hydraulic geometry should be linked to flow area, hydraulic radius and longitudinal bed slope, that appear in the governing equations for uniform flow. They suggest $A$ (cross-sectional area (m$^2$)) and $R$ (hydraulic radius, cross-sectional area divided by the wetter perimeter (m)) to be modelled as power functions of flow depth.

The exponent $m$ in Eq. 3 indicates the rate of change in velocity (and flow resistance) respect to discharge. Therefore, the ratio of exponent $f$ to exponent $m$ depends on the flow resistance characteristics (Bathurst 1993). The exponent $m$ could be relatively high in cases where there are high changes in flow resistance between high and low flows. The high variation of flow resistance between high and low flows can easily be related to larger relative roughness during low flows. Leopold and Maddock (1953), Knighton (1984) and Bathurst (1993) presented values of the exponents for several rivers in the U.S. Furthermore, Park (1977) enlisted and analysed values collected from literature, presenting rivers worldwide. The values of the exponents for Australian rivers have been presented by e.g. Lee and Ferguson (2002) and Huang and Nanson (1997), and for two rivers of New Zealand by Molnar and Ramirez (2002).

The aim of this paper was to increase understanding of the relationship between the channel geometry and flow in Finnish rivers, by quantifying the exponents for the equations of the hydraulic geometry (width, depth, velocity) in Finnish stream reaches. This is essential when designing of restoration or environmental flood management measures, allowing for complex channel geometry and several factors causing flow resistance. All design methods of restored channels listed by Brookes and Shields (1996) include the determination of hydraulic geometry as one of the main steps in the design process. At-a-site variation of the exponents for the equations of hydraulic geometry in different types of rivers and channels having cohesive bed materials, i.e. clay, silt and bedrock, were investigated. The aim was to investigate the applicability and consistency of the theory of hydraulic geometry in cohesive channels. Recently collected field data and extensive existing field data from the 1950s were utilized in the research.

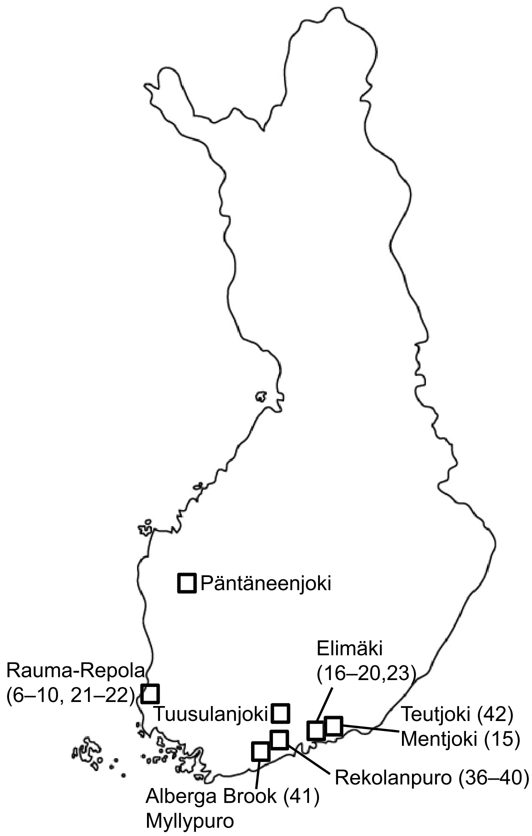


**Fig. 1**. The map of the locations of investigated rivers and channels in Finland.

## Field studies

### Conversion of the field data to the hydraulic geometry

For the determination of the exponents and constants for the hydraulic geometry, the cross-sectional topography, or at least the cross sectional area $A$ and the water surface width $w$, and the velocity distribution were measured. The discharge $Q$ and the average velocity $v$ were determined from the velocity distribution, as usual, and the average water depth $d$ was computed as $A/w$. To determine at-a-site hydraulic geometry of the river, measurements over the range of discharge are needed. Widths, depths and velocities corresponding to each measured discharge were determined separately and plotted against discharges on logarithmic scales. This way, constants $b$, $m$ and $f$ represented the slopes of the three lines fitted to data (*see* e.g. Leopold and Maddock 1953).

### Field studies in 1954

The data of 20 Finnish river and channel reaches collected by Saari (1955) were re-analysed. In 1954, the Finnish National Board of Agriculture carried out hydraulic field measurements in 60 different reaches of 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.

**Table 1**. At-a-site average values of longitudinal bottom slope, surface width, average depth, velocity, and the exponents for the equations of hydraulic geometry for the rivers and channels investigated in 1954 (based on Saari 1955). *S* = longitudinal bottom slope.

| No. | Channel classification | *Q* | *S* 1/1000 | Surface width (m) | Avg. depth (m) | Avg. velocity (m s$^{-1}$) | *b* (width) | *f* (depth) | *m* (velocity) |
|---|---|---|---|---|---|---|---|---|---|
| 6 | Rauma-Repola man-made channel; 4-yr-old; riprap | MQ | 0.062 | 3.11 | 0.69 | 0.41 | 0.29 | 0.27 | 0.44 |
| 7 | Rauma-Repola man-made channel; 4-yr-old; gravel-bed | MQ | 0.023 | 4.27 | 0.66 | 0.19 | 0.46 | 0.48 | 0.06 |
| 9 | Rauma-Repola man-made channel; 4-yr-old; rock, cracked zones fixed with stone walls | MQ | 0.345 | 2.26 | 0.61 | 0.59 | 0.07 | 0.57 | 0.36 |
| 10 | Rauma-Repola man-made channel; 4-yr-old; rock | MQ | 0.053 | 2.27 | 1.28 | 0.26 | 0.07 | 0.54 | 0.39 |
| 15 | Mentjoki; dredged channel, densely cracked rock | NQ-MQ | 0.461 | 5.57 | 0.22 | 0.30 | 0.005 | 0.46 | 0.53 |
| 16 | Channel from Lake Elimäki; man-made, 2-yr-old; peat and muddy clay | NQ-HQ | 0.004 | 9.00 | 0.60 | 0.14 | 0.14 | 0.13 | 0.73 |
| 17 | Channel from Lake Elimäki; man-made, 2-yr-old; bed material peat, mud above NW | NQ-HQ | 0.004 | 13.0 | 0.58 | 0.11 | 0.18 | 0.17 | 0.65 |
| 18 | Channel from Lake Elimäki; man-made, 3-yr-old; bed material clay and peat | NQ-HQ | 0.002 | 7.16 | 0.80 | 0.09 | 0.14 | 0.14 | 0.72 |
| 19 | Channel from Lake Elimäki; man-made, 3-yr-old; bed material fat clay | NQ-HQ | 0.021 | 4.66 | 0.52 | 0.17 | 0.27 | 0.27 | 0.46 |
| 20 | Channel from Lake Elimäki; man-made, 3-yr-old; bed material fat clay | NQ-HQ | 0.016 | 6.43 | 0.52 | 0.13 | 0.16 | 0.18 | 0.66 |
| 21 | Rauma-Repola man-made channel; 4-yr-old; bed material peat; sparse grass on the banks | MQ | 0.006 | 6.25 | 0.79 | 0.16 | 0.41 | 0.08 | 0.51 |
| 22 | Rauma-Repola man-made channel; 4-yr-old; bed material peat; sparse grass on the banks | MQ | 0.010 | 8.31 | 0.69 | 0.14 | 0.34 | 0.34 | 0.32 |
| 23 | Porrassuonoja channel (Elimäki); newly dredged, sandy clay | NQ | 0.031 | 8.16 | 0.48 | 0.26 | 0.05 | 0.26 | 0.69 |
| 36 | Rekolanpuro Brook; natural; gravel, pebbles and boulders (0.2–0.8 m); some grass and trees on the banks | NQ-HQ | 0.883 | 2.17 | 0.15 | 0.25 | 0.34 | 0.33 | 0.33 |
| 37 | Rekolanpuro Brook; natural; mud and clay; bank slopes densely grassed | NQ-HQ | 0.157 | 2.24 | 0.30 | 0.18 | 0.24 | 0.24 | 0.52 |
| 38 | Rekolanpuro; natural; mud and clay; bank slopes densely grassed | NQ-HQ | 0.220 | 3.14 | 0.35 | 0.19 | 0.19 | 0.20 | 0.61 |
| 39 | Rekolanpuro; natural; mud and clay; bank slopes densely grassed | NQ-HQ | 0.094 | 3.30 | 0.15 | 0.09 | 0.28 | 0.28 | 0.44 |
| 40 | Rekolanpuro; natural; mud and clay; bank slopes and the MW level densely grassed | NQ-HQ | 0.122 | 2.75 | 0.24 | 0.12 | 0.26 | 0.27 | 0.47 |
| 41 | Alberga Brook; dredged; clay; grass on the banks | NQ-HQ | 0.152 | 2.39 | 0.53 | 0.35 | 0.12 | 0.12 | 0.76 |
| 42 | Teutjoki; dredged; mud and clayey till; grass on the banks | MQ-HQ | 0.022 | 12.2 | 1.63 | 0.28 | 0.08 | 0.08 | 0.84 |

The characteristics of the channel and river reaches are briefly described in Table 1 and the locations are presented in Fig. 1. Average values of surface widths, average depths and flow velocities over the range of discharges are presented to give an idea of the size and shape of the rivers and channels. Average depths and surface widths were computed from cross-sectional areas and the descriptions of the shapes of cross sections documented by Saari (1955), to graphically determine the parameters of the hydraulic geometry. The reference numbers of the reaches are the same as in Saari (1955). The studied reaches were relatively short and they had approximately constant frequency of discharge along the reach, as required by Leopold and Maddock (1953). They determine the constant frequency of discharge as the whole reach having the same flow regime (NQ/MQ/HQ; where NQ = low discharge ($m^3$ $s^{-1}$), MQ = mean discharge ($m^3$ $s^{-1}$), HQ = high discharge ($m^3$ $s^{-1}$)) at the same time.

The exponents were calculated by the least squares fit through the measurement points of $w$, $d$ and $v$ as a function of $Q$. In this research, 20 river and channel reaches had measurements from so many different flow regimes, i.e. 4–12 different discharges, that it was possible to determine the exponents for the hydraulic geometry. Satisfaction of the continuity conditions of Eqs. 1–3, i.e. if the sum of the exponents and the product of the constants equalled 1.0, were the criteria by which the quantity of data was judged. There were not enough measurements to compute separately the exponents for low and mean-to-high discharges.

## Field studies in 1997–2001

In 1997–2001, hydraulic field measurements were carried out in the Päntäneenjoki, a river in western Finland, in the Tuusulanjoki, a river in southern Finland, and in the Myllypuro, a brook in southern Finland, to determine the parameters of hydraulic geometry for the rivers, and to investigate the longitudinal variation of hydraulic geometry. Some numerical parameters to describe the rivers are presented in Table 2. To give an idea of the size and shape of the 14 reaches of the Päntäneenjoki, Tuusulanjoki and Myllypuro, average values of surface widths, average depths and flow velocities over the range of discharges are presented in Table 3. The surface widths were measured and the average depths were computed as $d = A/w$.

Reaches were selected for measurements of cross-sectional topography and stage-discharge-relationships. The hydraulic properties along the selected field measurement reaches were rather uniform and the reaches were relatively short with approximately constant frequency of discharge along the reach. The measurement reaches of the Päntäneenjoki and Tuusulanjoki are described in detail in Helmiö and Järvelä (2004), and of the Myllypuro in Järvelä and Helmiö (2004). The measurement device and methods, and the sensitivity analysis of the measurements are presented in detail in Helmiö (1997).

The exponents for the equations of hydraulic geometry for the Päntäneenjoki, Tuusulanjoki and Myllypuro were also computed separately for the different flow regimes, i.e. for low discharge (NQ) and mean-to-high discharge (MQ-HQ), to investigate the relationship between exponent $m$ and the high changes in friction factors. Notation NQ-HQ means the whole discharge scale from low to high discharge.

The Päntäneenjoki is located in a rural area (Fig. 1). It is a small boreal lowland river with high friction factors, dense bank vegetation, complex cross-sections and an undulating longitudinal profile. One-third of the catchment area is under cultivation, and the rest is mainly forest and undeveloped fields and meadows. The bed material of the Päntäneenjoki is mainly clay and clayey silt and the river is strongly meander-

**Table 2**. Some properties of the Päntäneenjoki (P), Tuusulanjoki (T) and Myllypuro (M).

| | P | T | M |
|---|---|---|---|
| MQ ($m^3$ $s^{-1}$) | 1.4–1.8 | 1.2 | 0.24 |
| MHQ ($m^3$ $s^{-1}$) | 19–22 | | 1.6 |
| $HQ_{1/20}$ ($m^3$ $s^{-1}$) | 30–40 | 14–16 | 2.6 |
| Length (km) | 22.6 | 15 | 8.8 |
| Catchment area ($km^2$) | 210 | 125 | 24.5 |
| Lake area (%) | 0 | 6 | 7 |
| Avg. longit. slope | 0.00091 | 0.00090 | 0.00016 |
| Avg. sinuosity | 1.6 | 1.3 | 1.1 |

ing. Three reaches of the river were selected for investigation:

— reach P3 (10290–11300 m upstream from the confluence of the Kainastonjoki) has very dense stiff vegetation on the banks above mean water level, and the bed material is clayey silt;
— reach P2 (6485–7706 m) was constructed to a compound channel by broadening the channel above mean water level, the bed material is silt; and
— lowest reach P1 (2483–3450 m) has some sparse grassy vegetation in the channel and sparse willows on the banks, and the bed material is clayey silt.

Variable discharges are presented in Table 2 for the Päntäneenjoki, because the reaches are a few kilometres apart and there are several larger tributaries along the river.

The Tuusulanjoki is located in an urban area and is moderately sinuous (Fig. 1). The land use of the catchment area is divided into lakes (6%), forest (55%), fields (28%) and infrastructure (11%) (Lempinen *et al*. 1999). Four reaches of the river were selected for investigation:

— reach T4 (13610–14000 m upstream from the confluence of the Vantaa River) has moderately vegetated banks, the bed material is clay, silt and gravel;
— reach T3 (8527–9085 m) is a moderately vegetated channel with mild bank slopes, and the bed material is clay with some gravel locally;
— reach T2 (5165–5411 m) has variable bed material of clay, gravel, bedrock, and pebbles, and it is moderately vegetated;
— lowest reach T1 (1507–2185 m) has steep slopes and dense bank vegetation, and it is sinuous, with the bed material of clay, silt and sand, and very local areas of gravel.

The Myllypuro is located in Nuuksio National Park outside the capital area of Helsinki (Fig. 1). It is a partly natural, partly dredged and partly restored stream. The bed material of the study reaches is mainly clay or clayey silt. Seven channel reaches were investigated, listed here from upstream to downstream:

— reach M1 (6000–6303 m upstream from Pitkäjärvi) is moderately sinuous, has vegetation and some woody debris in the channel, and the bed material is muddy clay;
— reach M2 (4651–4849 m) is dredged to narrow and deep, is only moderately vegetated, and the bed material is silt and clay;
— reach M6 (3655–4130 m) is sinuous, moderately vegetated reach that is in close to natural condition, the bed material is clay;

**Table 3**. At-a-site values of the exponents for the equations of hydraulic geometry for the reaches of the Päntäneenjoki (P), Tuusulanjoki (T) and Myllypuro (M).

| | *Q* | Surface width (m) | Average depth (m) | Average velocity (m s$^{-1}$) | *b* (width) | *f* (depth) | *m* (velocity) |
|---|---|---|---|---|---|---|---|
| P3 | NQ-HQ | 10.05 | 1.35 | 0.32 | 0.29 | 0.40 | 0.31 |
| P2 | NQ-HQ | 8.52 | 1.20 | 0.32 | 0.28 | 0.39 | 0.33 |
| P1 | NQ-HQ | 11.17 | 1.30 | 0.35 | 0.19 | 0.31 | 0.50 |
| T4 | NQ-MQ | 7.35 | 0.64 | 0.17 | 0.26 | 0.18 | 0.56 |
| T3 | NQ-HQ | 8.57 | 0.90 | 0.24 | 0.25 | 0.20 | 0.55 |
| T2 | NQ-MQ | 8.27 | 0.99 | 0.13 | 0.11 | 0.17 | 0.72 |
| T1 | NQ-HQ | 6.93 | 0.90 | 0.33 | 0.24 | 0.43 | 0.33 |
| M1 | NQ | 3.79 | 0.24 | 0.06 | 0.54 | 0.07 | 0.39 |
| M2 | NQ | 2.03 | 0.35 | 0.08 | 0.09 | 0.25 | 0.66 |
| M6 | NQ-HQ | 2.71 | 0.26 | 0.39 | 0.34 | 0.26 | 0.40 |
| M3 | NQ-HQ | 3.18 | 0.36 | 0.24 | 0.18 | 0.45 | 0.37 |
| M7 | NQ-HQ | 3.29 | 0.46 | 0.22 | 0.28 | 0.19 | 0.53 |
| M5 | NQ-HQ | 2.92 | 0.33 | 0.10 | 0.09 | 0.34 | 0.57 |
| M8 | NQ-HQ | 3.75 | 0.48 | 0.17 | 0.24 | 0.19 | 0.57 |

— reach M3 (2713–2894 m) was dredged earlier, being now wider and shallower than natural reaches, and the bed material is clay;
— reach M7 (53–232 m) along the new channel, numbering started from cross section 1443 m) was restored in 1997 by conducting it to its original sinuous channel, the bed material is clay and silt;
— reach M5 (885–1098 m) was dredged and straightened in the 1950s, and it has some woody debris and shrubs on the banks, the bed material is clay and silt; and
— lowest reach M8 (625–760 m) was restored in 2000 by construction of a new channel with meanders and woody debris, and the bed material is mainly clay.

Reach M4 was excluded from the measurements in early phase of the study, because very high relative roughness ($k/h$) due to large stones in the bottom made the discharge measurements during the low water level very inaccurate.

## Results and analysis

In the investigated 34 Finnish river and channel reaches, the average at-a-site values of the exponents for the equations of hydraulic geometry were $b = 0.22$, $f = 0.27$, $m = 0.51$, varying in ranges of $b = 0.005$–$0.54$, $f = 0.07$–$0.57$ and $m = 0.06$–$0.84$. In the 23 natural river reaches the exponents were $b = 0.23$, $f = 0.26$, $m = 0.51$, varying in ranges of $b = 0.08$–$0.54$, $f = 0.08$–$0.45$ and $m = 0.31$–$0.84$ (Tables 1 and 3). Although the average values between all channel reaches and the natural rivers were about the same, the variation was higher in man-made channels.

Leopold and Maddock (1953) presented average values of the exponents for the equations of hydraulic geometry of 20 river cross-sections, biased towards the semi-arid conditions of the midwestern U.S. Exponent values of 139 streams around the world were collected by Park (1977). Bathurst (1993) collected exponent values of 57 streams in temperate climatic zones. Average values and the range of the exponents for the hydraulic geometry listed by these authors are presented in Table 4 along with the results of this study. The values of the exponents in the Finnish rivers are well within the range of the values presented in literature.

In general, the at-a-site values of the exponent $f$ are high and values of $b$ low in cohesive-bed rivers, and just the opposite in loose sand and gravel-bed rivers. When comparing with the values presented by Bathurst (1993), the values of the exponent $b$ were to some extent higher in Finnish rivers but corresponded to the values of the exponent $b$ in some sand, gravel and cobble-bed rivers (Table 4). In the data of Leopold and Maddock (1953), the depth increased with discharge somewhat faster than did the width ($f > b$). In the Finnish rivers under research, the depth and width increased with discharge as fast ($f \approx b$). Mild longitudinal slopes (Tables 1 and 2) in Finnish rivers may be a reason for low width-depth ratios.

According to Bathurst (1993), the values of the exponent $m$ (velocity) are approximately the following: for sand-bed channels $m < 0.40$, for gravel-bed rivers $0.35 < m < 0.45$, for boulder-bed rivers $0.45 < m < 0.55$, and for pool-riffle sequences $m > 0.55$. In Finnish cohesive soil reaches of the natural rivers studied, the values of exponent $m$ were expected lower, as they were low in fine sediment alluvial rivers, too. In some rivers the reason may be that only a limited number of different discharges biased toward low and mean flows were measured. However,

**Table 4**. Summary of at-a-site values of the exponents for the hydraulic geometry presented in literature.

| Source | No. of reaches/ rivers | *b* | | *f* | | *m* | |
|---|---|---|---|---|---|---|---|
| | | Average | Range | Average | Range | Average | Range |
| Leopold & Maddock 1953 | 20 | 0.26 | 0.03–0.59 | 0.40 | 0.06–0.63 | 0.34 | 0.07–0.55 |
| Park 1977 | 139 | – | 0.00–0.59 | – | 0.06–0.73 | – | 0.07–0.71 |
| Bathurst 1993 | 57 | – | 0.08–0.29 | – | 0.19–0.55 | – | 0.34–0.70 |
| Helmiö (present study) | 23 | 0.23 | 0.08–0.54 | 0.26 | 0.08–0.45 | 0.51 | 0.31–0.84 |

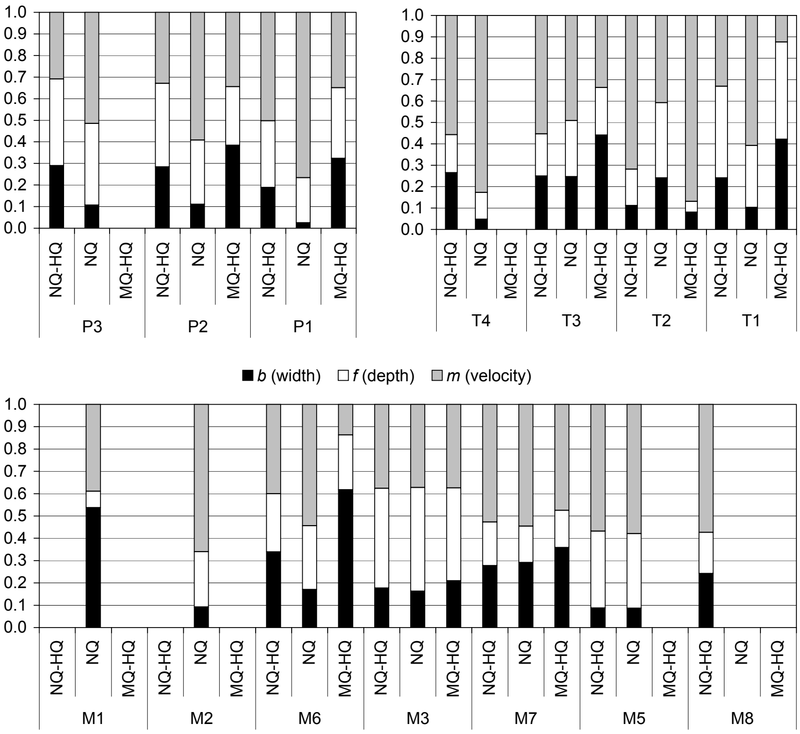


**Fig. 2**. Variation of the values of the exponents for the equations of hydraulic geometry by the discharge in Päntäneenjoki (P), Tuusulanjoki (T) and Myllypuro (M).

at least Knighton (1984) has listed values of the exponents for different discharge regimes. High *m* values also indicate that the longitudinal variation of the channel causes an increase in flow resistance during low flows, because according to Bathurst (1993), high *m* values could indicate high changes in flow resistance between high and low flows. Man-made channels and rivers having clay, silt and peat as bed material were compared to each other. In these man-made channels the exponent *m* was 0.59, when in natural rivers it was only 0.52. Significant cross-sectional variation existing in the Päntäneenjoki was expected to increase the *m* value, but it was found to be lower than in the Tuusulanjoki and Myllypuro. This may be because the Päntäneenjoki is larger than the others. The downstream hydraulic geometry was not investigated because the study reaches were relatively close to each other and no channel networks were under research. In nine reaches of fourteen, the exponent *m* was higher during low discharges than during high discharges (Fig. 2). Only on reach T2 the results were the opposite.

The values of the exponents for the equations of the hydraulic geometry for the man-made channels are relatively close to ones of the natural rivers (Table 1). However, it is not assumed that the man-made channels would have reshaped themselves like natural rivers, as they are relatively new and have mild longitudinal slope and low stream power.

## Conclusions

In alluvial rivers, the channel geometry depends on the dominant or channel-forming discharge. These parameters can be linked together with the theory of hydraulic geometry. In this paper, the theory of hydraulic geometry was used to describe cohesive lowland rivers and channels. In river restoration works, it is essential to have adequate knowledge on the channel hydraulics, because a low-energy cohesive lowland river adjusts itself naturally extremely slowly, and therefore severe flooding or degradation may be caused with poor design.

The values of hydraulic geometry determined for Finnish rivers and channels were in the range of the values presented in literature. The values of exponent *m* (velocity) were expected lower in cohesive soil reaches, as they were low in fine sediment alluvial rivers, too. However, they were at the higher end of the range presented in the literature. High values of exponent *m* in natural rivers indicated that longitudinal channel variation had significant resistance effects during low water.

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