UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING, SCIENCE & MATHEMATICS

School of Geography

Determining Lateral River Channel Activity with Respect to Safety of Pipeline Crossings

by

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ABSTRACT

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When oil and gas pipelines cross rivers they are often buried in the ground beneath the floodplain and river bed. There is a risk that river will expose the pipe by lateral bank erosion, as well as bed erosion, and then there is a risk that the pipe will break. Pipe failure can cause loss of revenue, repair and reparation costs, political difficulties and adverse environmental impacts. Buried pipeline crossings correctly located and engineered do not affect the flow hydraulics and river regime. Therefore, pipeline crossing projects should be based on the study of natural processes including those which lead to lateral movement of the channel.

This study deals with the scientific knowledge of a variety of channel types and their evolution by lateral movements. The literature review and statistical analysis reveal that the rates of bank erosion depend on the type of river channel pattern. Data from different channel types are obtained from the literature with reference to a variety of parameters which are then grouped depending upon the scale of the problem under consideration (catchment, reach and local scales). These data for bank erosion rates are analyzed to develop general relationships with such factors as size of river system, shape of channel, bed type, gradient, riparian vegetation etc. Statistical examinations show that there is strong correlation between bank erosion rate and the catchment area and with channel geometry. Weak correlations with water discharge and with flow variability suggest that bank erosion rates will not be changed significantly in the near future if discharge and/or its variability alter under climate change. Results are used to provide science-based recommendations to estimate lateral activity applicable to many regions of the world.

CONTENTS PAGE

LIST OF FIGURES PAGE

LIST OF TABLES PAGE

LIST OF SYMBOLS

$a, b, c, d, a_*, a_{**}, k$	Empirical coefficients
A	Drainage area
Ap	Meander apex
API	Antecedent precipitation index
B	Channel depth on Parker's diagram
BI	Braiding index
C	Bank erosion rate
C_{ch}	Coefficient in the Chezy formula
C_i	Erosion rate in each river reach
$C_{\max}$	Maximum erosion rate
CON	Number of pairs that are concordant
$const$	Denotes constant value
Cv	Coefficient of variation
d	Channel depth
d_{avg}	Average depth of two riffles which limit a given meander bend
d_{bf}	Bankfull depth
$d_{\max i}$	Maximum depth in a given cross section
d_{pool}	Pool depth
D	Size of sediment material
D_{50}	Median size of sediment material
D_{bank}	Median bank grain size
D_{bed}	Median bed grain size
DIS	Number of pairs that are discordant
E	Specific kinetic energy
f	Darcy-Weisbach friction coefficient
F	Froude number
F_c	Resistant force due to cohesion
F_g	Resistant force due to gravity
g	Gravitational acceleration
h	Bank height
H_0	The null hypothesis
H_1	The alternate hypothesis
I_A	Distance between the midpoint of the spacing line and the meander apex
K_c	Specific coefficient of lateral migration rate
K_w	Specific coefficient of river width
l_b	Meander path length between the beginning and the end of cutoff
l_c	The length of the cutoff measured along a straight line
l_i	The length of island

l_m	Meander path length
L	Distance downstream
L_{bank}	Lateral shift of the bankline
L_m	Meander spacing
m	Mode – degree of braiding
M	Average annual runoff
MS_D	The mean square deviation
n	Number of observations
p	probability
P	sinuosity parameter
q	Unit discharge
q_s	Unit sediment transport
Q	water discharge
Q_{2f}	2-year flood discharge
Q_{av}	Average annual discharge
Q_{bf}	Bankfull discharge
Q_m	mean annual discharge
Q_{maf}	Median flood discharge
$Q_{\max}$	Maximum discharge
$Q_{\min}$	Minimum discharge
Q_{peak}	Peak discharge
Q_s	Sediment transport
r	Meander radius of curvature
R	Hydraulic radius
R^2	The coefficient of determination
S	Slope
So	Sorting index
S_a	The slope of potential avulsion course
S_c	Channel slope
SC	Silt-clay content
S_e	The slope of the existing channel
SS_X	The sum of squares
S_v	Valley slope
S_w	Water surface slope
t	*t*-test statistic
T	Time period
U	Vertically averaged flow velocity
U_*	Shear velocity
U_{*c}	Critical shear velocity
V	Average flow velocity
w	Channel width
w_{bf}	Bankfull width
w_i	The width of island

w_{rf}	Reference width
w_v	Valley width
X	Independent variable
$\overline{X}$	Mean of the sample
Y	Dependent variable
α	Angle of meander turn
α_1	Angle of meander incidence
α_2	Angle of meander departure
α_a	Constant equals 10^a
α_c	Coriolis coefficient
β	Angle of the mutual arrangement of two neighbouring meanders
ε	Index of meander skewness
ε^*	Parker's parameter
ϕ	Grain size at phi-scale
γ	The Goodman-Kruskal Gamma
γ_m	Angle formed by the meander height line and a line which is normal to the spacing line in its midpoint
κ_i	Coefficient of meander development rate
λ	Meander wavelength
μ	Hypothetical mean of total population
ν	Degree of freedom
π	Pi
θ	Schields parameter
θ_c	Critical Shields value
ρ	Water density
ρ_s	Sediment density
σ	Standard deviation of observations
σ_p	The pooled estimate of the standard deviation
τ	Shear stress
τ_0	Mean shear stress
τ_{avg}	Average value of mean shear stress
υ	Water velocity
ω	Specific stream power
ω_c	Critical unit stream power
Ω	Total stream power

DECLARATION OF AUTHORSHIP

I, Sergey Yurievich Krasnoshchekov,

declare that the thesis entitled

Determining Lateral River Channel Activity with Respect to Safety of Pipeline Crossings

and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
- where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- none of this work has been published before submission.

Signed: …………………………………………………………………………..

Date: ………………………………………………………………………….

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CHAPTER 1: INTRODUCTION

1.1. BACKGROUND

On 25 May 2005 the BBC announced that the BTC (Baku-Tbilisi-Ceyhan) 1600 km pipeline from Baku (Azerbaijan) through Tbilisi (Georgia) to Ceyhan (Turkey) had been opened. After a year, in July 2006, an official inauguration took place in Ceyhan. This project was carried out by many specialists and had taken more than ten years to finish. The pipeline crosses 1500 river reaches, climbs to a height of 2800 m, and has 220,000 welded pipe joints (Guliyeva, 2006).

Among many challenges for the pipeline project there were some for specialists of fluvial geomorphology. At river crossings problems had occurred with the Northern Route Pipeline in Georgia which had been commissioned in the 1990's. By 1999 some sections of the pipeline had been exposed by lateral channel migration at river crossings. Lateral shifting of a river could result in exposure of the pipeline and thus significantly reduce safety. In 1999 Prof. Paul Carling from Lancaster University (currently of the University of Southampton) and Dr. Roger Bettess from HR Wallingford were encouraged by BP to investigate this problem. By visiting all the pipeline crossings in Georgia it was seen that the problem may occur at aerial crossings (Fig. 1.1) and at buried crossings as well. The main reason for the problem was that in some instances the recommendations of consultant fluvial geomorphologists had not been sought or accepted, and instead the pipeline was installed by straight alignment, supposedly by the most economical route. However, as practice showed, a straight alignment is not necessarily the most economical, and also is not necessarily the safest route. The problem was managed retrospectively by the construction of riprap revetments at pipeline crossings. These works led to additional expenditures for the Northern Route Pipeline project. In some cases the expenditures were minor as shown in the first photograph of Fig. 1.2; in others cases the expenditures were significant (see the second photograph of Fig. 1.2). Subsequently BP commissioned this doctoral study.

Figure 1.1: Aerial pipeline exposure due to bank erosion, the Kvirila River near to Zestaphoni, Georgia. Photograph has been taken in 1999 by Prof. P.A. Carling.

Figure 1.2: Riprap revetment constructed to prevent bank erosion at buried pipeline crossings, Georgia. Photographs have been taken in 1999 by Prof. P.A. Carling.

Figure 1.3: Riprap revetment constructed to prevent bank erosion in a reach of the Middle Fork Koyukuk River, Trans Alaska Pipeline, Alaska. The dashed line locates a buried pipeline. Date of photograph is September 2001, from Veldman and Ferrell, 2002.

The situation with lateral movement of rivers at pipeline crossings in Georgia is not isolated and examples of the problem can be found elsewhere. An example is shown in Fig. 1.3. After several years of the Trans Alaska pipeline operation some rivers eroded their banks by such distance that it was necessary to construct riprap revetment to prevent bank erosion and to increase the safety of the pipeline. The site shown in Fig.1.3 is only one example described by Veldman and Ferrell (2002). Another example is reported by Lawler and Milner (2005), who reviewed reports for the Sakhalin Pipeline Project (Far East Russia) in regards to river crossings. They pointed out that at some crossing sites, lateral stability and bank protection were not considered at all or arguments for site selection were poor and not supported by evidence. Thus the problem of lateral stability is common and occurs in different parts of world. Also the problem of lateral stability is an important consideration in the planning stage of projects and as well as during the operational life-time of a pipeline.

1.2. RESEARCH AIMS AND SCOPE

In general terms, channels can be divided into bedrock, semi-alluvial and alluvial (Ashmore and Church, 2001). Bedrock channels are defined as reaches along which a substantial proportion (more than 50%) of the boundary is exposed bedrock, or is covered by an alluvial veneer which is largely mobilized during high flows such that underlying bedrock geometry strongly influences patterns of flow hydraulics and sediment movement (Tinkler and Wohl, 1998). Morphological changes, including bank erosion, in bedrock channels are generally extremely slow compared with those in alluvial channels because of the substrate resistance (Richardson and Carling, 2005). Therefore, in further consideration within this thesis, bedrock rivers will be eliminated since they are characterized as stable in respect to lateral movement. To the contrary, alluvial river channel form is determined predominantly by the action of water flow and alluvial channels are formed in the sediment that they have transported and deposited, i.e. such channels are self-formed (Church, 2006). Thus the objects of this study are alluvial rivers, their forms and processes. However, the study is limited to those rivers which do not have a tidal regime.

The crossing of alluvial rivers with buried or aerial pipelines is one of the more challenging and critical design issues in pipeline projects. When a pipeline crosses a river, several questions should be considered by a fluvial geomorphologist. These questions were outlined by Doeing and Williams (1996):

1) will the river bed scour during the design life of the pipeline and expose the pipe or reduce the cover enough to cause positive buoyancy of the pipeline?
2) will the channel banks erode, shift laterally, or migrate longitudinally and expose the pipeline in the overbank areas where depth of cover is less?
3) if the pipeline is carried by a bridge or other support structures over the river, is the structure safe from scour during construction, pier scour, abutment scour, or other hazards to structure in the river environment?
4) if water is being diverted during the construction phase, has the level of protection of the diversion structures been adequately determined?

In addition, in the list should be included the following questions (in the order of continuation):

5) will the channel pattern change its form during the design life of the pipeline?” Despite the fact that there are methods to predict river bank erosion, changes of environmental factors often are not taken into account during pipeline operation. Changes of environmental factors affect channel form (such that the channel type may be changed) and as a consequence the rates of erosion and accumulation may vary. An incorrect prediction of bank erosion or shortcomings in methods can lead to additional expenditure for rip-rap construction as shown by examples earlier or even to pipeline damage or rupture and the ensuing negative effects.
6) By trench laying of a pipeline a geomorphologist should eastimate bed sediment transport for filling rate of a trench by sediment which is delivered from upstream.
7) During construction by trench laying of a pipeline disturbance of pavement layer occurs and more fine underlying sediment could be transported downstream. What is impact of additional amount of fine sediment on geomorphology and fish fauna of downstream river reaches?
8) What is influence of bedrock outcrops in a channel on pipeline location? This question is related to previous two questions as there is change in hydraulics and as a consecuence in sediment transport at reaches with bedrock outcrops comparing with alluvial river reaches.
9) Will be the erosional processes more intensive on area of pipeline constraction with vegetation removal at river banks (lateral river erosion) and at catchment area (soil erosion)?
10) What is influence by other constructions which are located upstream and downstream from a pipeline crossing? For instance, there should be bridges of a road which is used for pipeline maintenance.
11) In permafrost area how pipeline constraction will impact on initialization and intensity of geomorphological processes under possible thawing of permafrost?

This list of questions does not claim to be exhaustive. The list could be broadened depending on local conditions of pipeline construction and assigned tasks for pipeline safety from impact of geomorphological processes.

The purpose of the current study is to find answers for the second and fifth questions in the list outlined above.Accroding these questions, the main goals of this study are formulated as following:

- Quantify rates of bank erosion for different channel types
- Predict change of channel type during the design life of the pipeline
- Produce engineering guidelines

In order to achieve these goals, comprehensive descriptions of channel types, factors and controls on channel types and bank erosion were completed reflecting the current knowledge of fluvial geomorphology.

Chapter 2 presents a review of existing alluvial channel classifications with some details for meandering, braiding and anabranching of channels. Afterward available methods for bank erosion estimation and prediction are considered in an overview. These methods are conventionally divided into (i) empirical methods, (ii) kinematic modelling and (iii) dynamic modelling. Due to the particularities of this study the last two methods are reviewed without details. In chapter 3 the methodology for the present study is detailed with a discussion of the use of regression analysis and methods for ordinal data analysis. Also in that chapter, variables are presented that may control bank erosion rate; methods to define these variables and some problems in measurement and collection of them are reviewed. Chapter 4 focuses on the results and statistical significance of the findings. In Chapter 4 comparisons of the resultant relationships with previous studies are also given. The remaining part of this thesis (Chapter 5) focuses on discussion of the results and presents the conclusions and derived recommendations for engineers regarding lateral stability at pipeline crossings.

CHAPTER 2: LITERATURE REVIEW

2.1. INTRODUCTION

Despite the vast number of publications concerning channel stability and bank erosion in general and for different regions around the world, there are only a few publications about channel stability at sites of pipeline crossings. Only one (Anonymous, 1985) specifically focuses on the problems of bank erosion at proposed pipeline crossings. However, this report is regarded as “grey literature” and is written in Russian and therefore is not available for wide international usage. Moreover, in that report the most detailed section considers only meandering rivers (where a kinematic model is suggested for bank erosion prediction) and for other channel types only general recommendations are given without details. In other publications concerned with pipeline construction and routing somewhat different problems are discussed. For examples, environmental issues, different engineering methods to effect crossings and some issues of legislation are the major focus in ASCE Manual (1998) and Anonymous (1996) with minor description of channel stability. The question of channel stability was elaborated more fully in the related engineering discipline of highway construction (e.g. Brice, 1982; Lagasse et al., 2004), where channel classifications based on channel stability and methods to estimate bank erosion rates at proposed river crossings by highways are the focus. Approaches from these studies are reviewed further in this chapter.

In according with the assigned main goals of this study, below a review of river channel classifications, controls on channel pattern, more detailed description of main channel types and methods, which are in exisance for prediction and estimation of bank erosion rate is given.

In a review of river channel classifications along with well-known classifications also classifications are marked out, which are based on lateral channel activity and stability, as such classifications are particularly relevant to this study.

Transition of one channel type to another is controlled by changes of channel-forming factors. These factors and methods are reviewed in section 2.3. A review is presented in chronological sequence to trace progress history of scientific and practical approaches.

Main channel types are reviewed in section 2.4. As there is a vast number of literature about channel types, a review is limited by considering (a) theories of channel form existance, from which initial conditions and sufficient conditions to maintain a channel form are revealed and (b) geometrical characteristics and schemes of channel evolutions, which could be used for estimation of lateral stability.

Finally, methods for bank erosion rate estimation are reviewed. Advantages and limitations of methods are given to select a method, which is used further in the current study.

2.2. CLASSIFICATIONS OF RIVER CHANNELS

There are many river channel classifications. In general, most are based on a consideration of the channel planform. Several river channel classifications have been reviewed by Mosley (1987) and Kondolf (1995). In some classifications, authors have attempted to allocate types according to metrics of the plan characteristics, notably the sinuosity and braiding index (e.g. Rust, 1978; Brice, 1975), while in others the schemes are based on the factors which control these types, for example material load, valley slope, water discharge (e.g. Mollard, 1973; Schumm, 2005; Church, 2006). Some authors distinguish several stages of channel development, i.e. they attempt to present the continuum of channel planform by distinguishing some intermediate forms (e.g. Hooke, 1995). In fact, as noted by Kondolf (1995), each of the channel classifications in common use has advantages and disadvantages in geological, engineering and ecological applications. No single classification can satisfy all possible purposes, nor is it likely to encompass all possible channel types (Montgomery and Buffington, 1998).

The earliest classification of river channel pattern (Leopold and Wolman, 1957) discerned three essential types: straight, meandering and braided. This classification is used still, mainly in diagrammatic form, where channels are distinguished by the main controlling factors: dominant discharge and valley slope. Subsequently scientists introduced additions and further specifications. In addition to the three types of channel planform noted above, in more recent research it has been suggested that anabranched channels should be recognized as distinct from braided channels (e.g. Knighton and Nanson, 1993; Nanson and Knighton, 1996). For multiple channels, Dury (1969) has used the terms reticulate and deltaic-distributary but these terms have not been used widely. Kondratiev (2001) pointed out that most existing classifications are incomplete because it is not always possible to take into account all factors and therefore in some case studies new names may appear for specific channel types. In the following text only the most well known and widely used classifications are considered; they are conventionally divided into three groups: 1) classifications based on planform alone; 2) classifications based on underlying processes and 3) classifications where lateral channel activity and stability are used to distinguish types. However, first of all, definitions are given of terms such as “meandering”, “braided”, “anabranched” and others frequently in use throughout the text.

2.2.1. Definitions of channel types

Straight channels are single-thread channels which follow a straight course for a significant distance (Thorne, 1997). Truly straight reaches with distances exciding ten times the channel width are rare in nature (Leopold and Wolman, 1957). Within a straight alignment of the banks it is usually found that the paths of maximum velocity and thalweg (line of deepest points) have a sinuous form because of an inherent property of channels to have pool-riffle sequences (Thorne, 1997). Pools are deep reaches and riffles are shallow reaches. Points of inflection on the thalweg path correspond to shallow reaches, i.e. to riffles. Usually straight channels are distinguished from meandering ones by a measure of the sinuosity. However, the value of sinuosity to distinguish straight from meandering is assigned arbitrary values in various studies. For example, Leopold and Wolman (1957) suggested using the value of sinuosity of 1.5, while van den Berg (1995) has used the value of 1.3.

Meandering channels are usually defined as single-thread channels that follow a winding, more or less sinuous course (Chebotarev, 1970; Thorne, 1997; Mayhew, 2004). The river Menderes (known to the Greeks as the Maiadros) in Anatolia, in what is now southwest Turkey, was well known for its sinuosity and has given its name to the meandering form (Twidale, 2004). As noted by Leopold and Wolman (1957) and Callander (1978) with reference to Russell (1954), this river has reaches where its windings are irregular, others where it is relatively straight and some places where it is braided; it exemplifies the continuum of river channels. Nevertheless, meandering is the most prevailing pattern for lowland rivers (Chebotarev, 1970). For instance, Kondrat’yev (1968) with reference to Pinkovskiy (1967) cited that 42% of the rivers of the former USSR are freely meandering. Also it is noted that meandering is the predominant channel pattern in North America (Leopold, 1994) and in the UK (Hooke, 1995). The process of meandering is studied by scientists of various disciplines and so there is a considerable literature describing the subject (see section 2.4.1).

For *braided* river channels, various authors have used definitions which have somewhat different meanings. In his comprehensive review, Bridge (1993) has cited papers with definitions of braided rivers, notably those of Leopold and Wolman (1957), Lane (1957), Brice (1964, 1984) and Schumm (1977). Following Schumm (1977), Ferguson (1984b), and Kamenskov (1987), among others, a braided river can be characterized as a wide single-channel with numerous shifting channel bars which are inundated at high flows and are not significantly vegetated. At low flow, the channel is therefore divided by these numerous channel bars. Braided rivers occur in a wide range of environments, from proglacial to semi-arid and at a large range of scales, from small streams on sandy beaches to the largest continental rivers, e.q. the Brahmaputra River (Knighton, 1998). Compared to meandering rivers, much less is known about the morphology and dynamics of braided rivers, because they are much more complicated (Thorne, 1997) and due to the difficulties involved in undertaking field measurements in the rapidly changeable braided river environment (Bristow and Best, 1993).

Anabranched rivers are defined as rivers consisting of multiple channels separated by vegetated semi-permanent alluvial islands excised from existing floodplain or formed by accretion within the channel or via deltaic accretion (Nanson and Knighton, 1996). Thus the distinct features of these rivers are vegetated islands which are not inundated at bankfull conditions. Following Nanson and Knighton (1996) within this group all multiple channel rivers with vegetated island are considered. Based on stream energy, sediment size and morphological characteristics, Nanson and Knighton (1996) recognized six subtypes of anabranched rivers. With respect to lateral stability two end members in this set of channels can be distinguished: anastomosing and wandering rivers.

The term '*anastomosing*' comes from medicine and is used to describe a distributary system of arteries in the body at locations such as the back of hand (Thorne, 1997). As noted by Leopold and Wolman (1957) and Smith and Putnam (1980) this term was initially applied to streams by Jackson (1834) and later by Peale (1879). The term came into wide usage following works by Miall (1977), Rust (1978) and Smith and Smith (1980). Recently, Knighton and Nanson (1993), Nadon (1994), and Makaske (2001) have reviewed the literature on anastomosed rivers. These authors proposed definitions for anastomosed rivers and outlined the differences between anastomosed rivers and other types. Knighton and Nanson (1993) formulated that "braided rivers consist of flow separated by bars within channel, whereas an anastomosing river consists of multiple channels separated by islands which are usually excised from the continuous floodplain and which are large relative to the size of the channels". Makaske (2001) proposed the following definition based on channel pattern and floodplain geomorphology: "an anastomosing river is composed of two or more interconnected channels that enclose floodplain". By these definitions there is no difference between the definitions given above for anabranch rivers and those for anastomosing rivers. Indeed, in some cases authors consider the anastomosed and the anabranched rivers as synonyms (e.g. Bridge, 1993, 2003). However, in widely cited studies, e.g. Smith and Putnam (1980), Smith and Smith (1980), Makaske (2001) among others, the term "anastomosing" is used for low-energy rivers with stable banks, which distinguishes them from other multi-channel rivers. Thus following Nanson and Knighton (1996) anastomosing rivers are considered as a subset of anabranching rivers characterized by low gradients, low stream power and stable banks composed of cohesive sediment.

The term "*wandering*" was used by Leopold and Wolman (1957) to describe the process of thalweg migration between channel banks. In contrast to anastomosing rivers, wandering rivers are laterally active, gravel-dominated rivers (Nanson and Knighton, 1996). According to the classification of Nanson and Knighton (1996), wandering rivers are largely discriminated from other anabranching types by greater specific stream power, larger sediment size and less cohesive banks. Such rivers commonly flow in irregularly sinuous, single-thread channels but are frequently split around large wooded islands, even at peak flows (Ham, 2005). Single-thread sections are characterized as narrower, stable 'transport zones', while anabranched sections accumulate coarse sediments and are characterized as unstable 'sedimentation zones' (Church, 1983).

From definitions of channel types it is clear that terms initially are based on channel form. Therefore, there is no wonder that early and relatively simple classifications are based on channel form or parameters of channel form (e.q. sinuosity and braiding index).

2.2.2. Classifications based on channel form

One of the simplest classifications has been proposed by Miall (1977) and Rust (1978) (Fig. 2.1.A). This classification is based on sinuosity and braiding parameters and initially was used for the purpose of interpreting ancient alluvial deposits. An advantage of the proposed classification is that it has the simple form of a two-by-two matrix. The classification defines four morphological channel types: the two most abundant are meandering (single-channel, high-sinuosity) and braided (multi-channel, low-sinuosity) and the others are straight (single-channel, low-sinuosity) and anastomosing (multi-channel, high-sinuosity) (Rust, 1978). However, Knighton and Nanson (1993) have argued that a consideration of sinuosity alone is probably not a sufficiently robust characteristic to discriminate anastomosing rivers. Moreover, more recent studies (e.g. Nanson and Knighton, 1996) have argued that anastomosing channels are a subset of anabranched channels which represent a broader class of channels.

Another classification based on planform characteristics is the one produced by Brice (1975) (Fig. 2.1.B). This scheme defines three basic types of channels characterized by degrees of sinuosity, braiding and anabranching. Sinuosity is defined as the ratio of channel length to valley length or valley slope to channel slope. The degree of braiding is expressed as the percent of reach length that is divided by one or more islands or bars. Thus if a reach is 5% braided, 95% of it is not divided. Finally, anabranching is defined as the division of a river by vegetated islands whose width is greater than three times the water width at average discharge (Brice et al., 1978). Thorne (1997) has recommended this classification for use in engineering geomorphological studies. Perhaps this recommendation is based on the fact that depicted classes were derived from analysis of air photographs and that the classification covers a wide variety of possible channel forms.

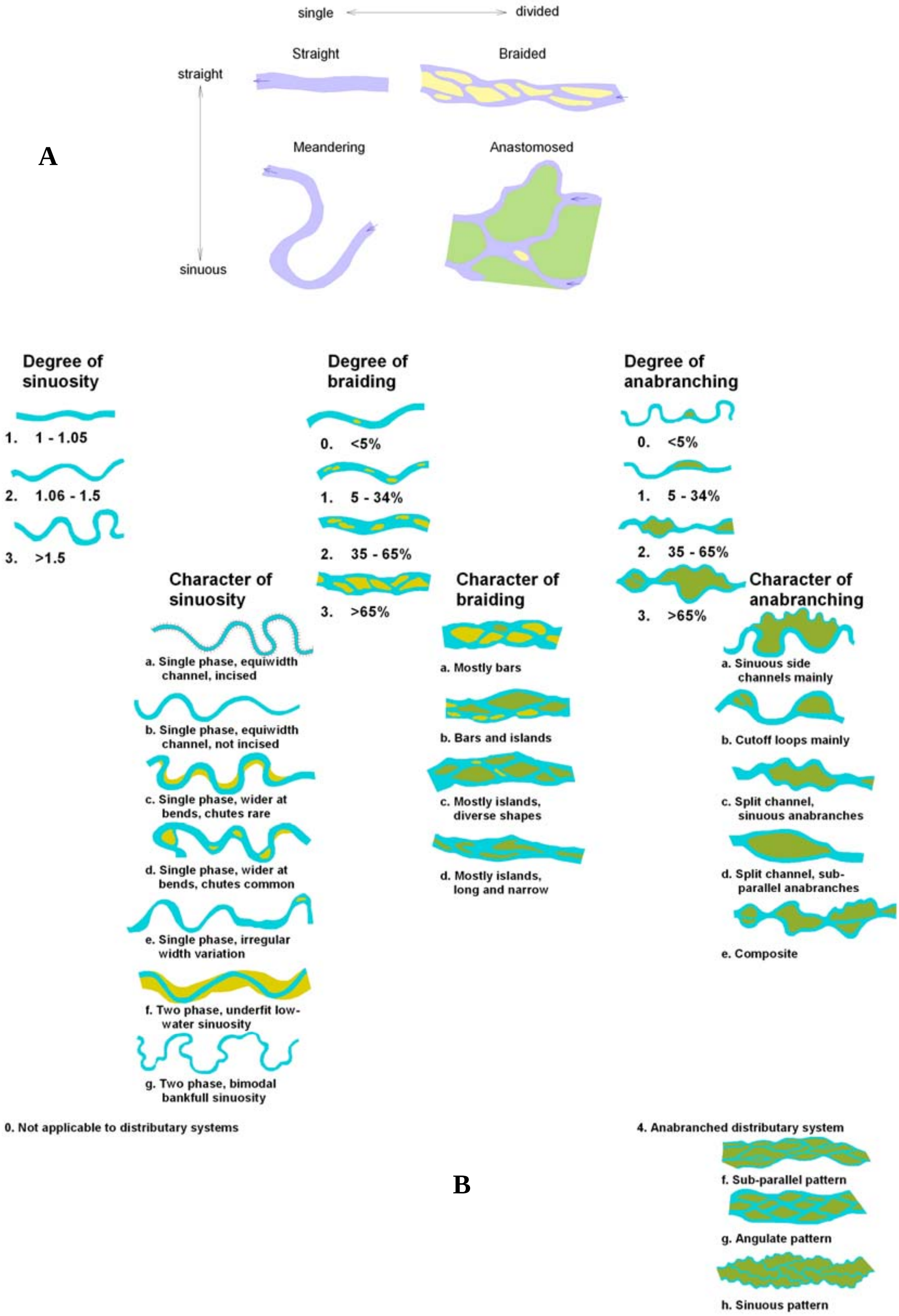


Figure 2.1: Classifications based on planform characteristics. (A) End members of the continuum of channel patterns after Miall (1977) and Rust (1978) (redrawn from Ferguson, 1987); (B) Types of channel patterns devised by Brice (1975) according to morphologic properties observable on air photographs.

A further classification based on channel form is used widely in the former USSR (Fig. 2.2). This classification has been elaborated in Moscow State University and presented most recently by Alabyan and Chalov (1998). They distinguish three structural levels: (i) low water channel, (ii) flood channel and (iii) valley bottom (in order of increasing structural level rank). Chalov et al. (1998) also define limiting conditions that distinguish (i) incised rivers from (ii) rivers with wide, essentially unconfined floodplains (wide-floodplain rivers) and (iii) transitional types of rivers with confined channels. Each of these classes could be subdivided to contain channels that are straight, meandering or branched. Thus, Alabyan and Chalov (1998) suggest that anabranched channels should be considered at a higher structural level than straight, meandering and braided channels. Although the classification presented in Fig. 2.2 provides enough flexibility to describe the planform of most rivers, it is not sufficient to characterize the behaviour of rivers (Jagers, 2003).

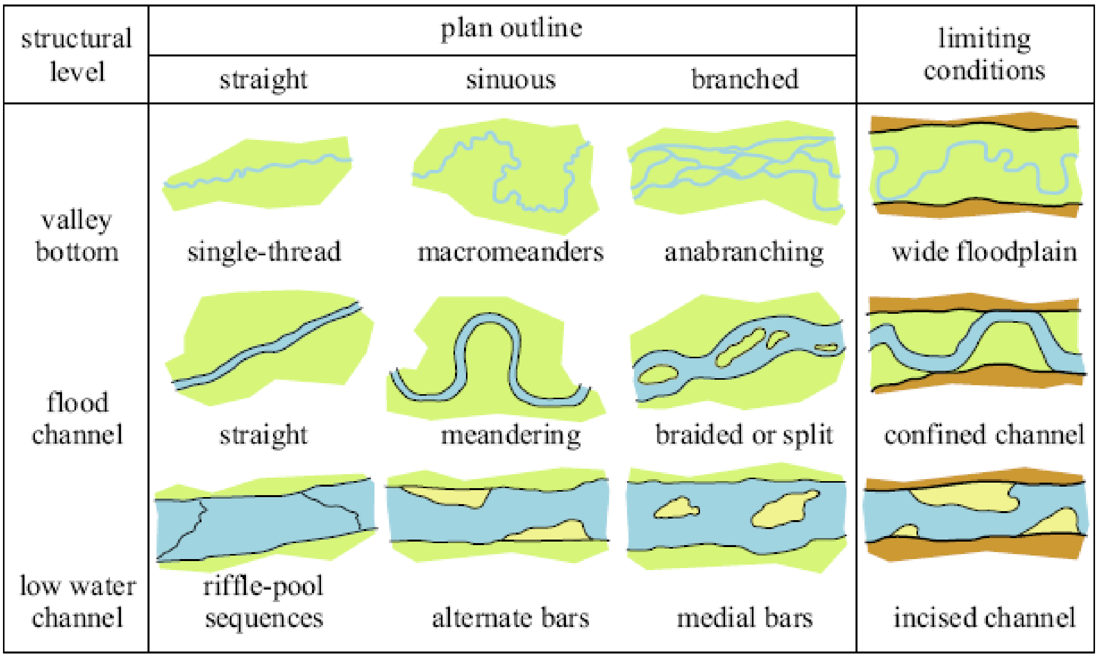


Figure 2.2: A classification of river channel patterns according to Alabyan and Chalov (1998) (redrawn from Jagers, 2003).

Thorne (1997) has noted that for completeness, cross-sectional and longitudinal dimensions should also be considered in classifications. Rosgen (1994) has used such parameters and developed probably the broadest classification of channels. He divided rivers into seven common types that are further divided into six subtypes each. Common types are dependent on entrenchment and width/depth ratio (cross-section characteristics), sinuosity (a planform characteristic) and channel slope (a longitudinal characteristic) (Fig. 2.3); subtypes are dependent on dominant bed material (Fig. 2.4). As pointed out by Thorne (1997) concerning Rosgen's classification "it is at present too early to judge the usefulness and reliability of Rosgen's method when applied by engineers and managers with only a limited background in fluvial geomorphology, although indications are that users can gain the knowledge required through intensive, short-course training". Some government agencies in the USA, particularly those funding restoration projects, have adopted this classification as a "standard" (e.g. see an evaluation of the classification by Simon et al., 2007). However, Montgomery and Buffington (1998) noted that the main shortcoming of Rosgen's classification is that it is not process-based. Recently, Simon et al. (2007) critically reviewed Rosgen's classification and by numerous examples showed inconsistencies in the classification. These inconsistencies mainly related to problems with bankfull level definition and classification of the dominant type of channel material. Moreover, as practice shows the classification is used for rivers from which information is used to develop this classification, i.e. Rosgen's classification has territorial limitation and is not verified for other areas in the world.

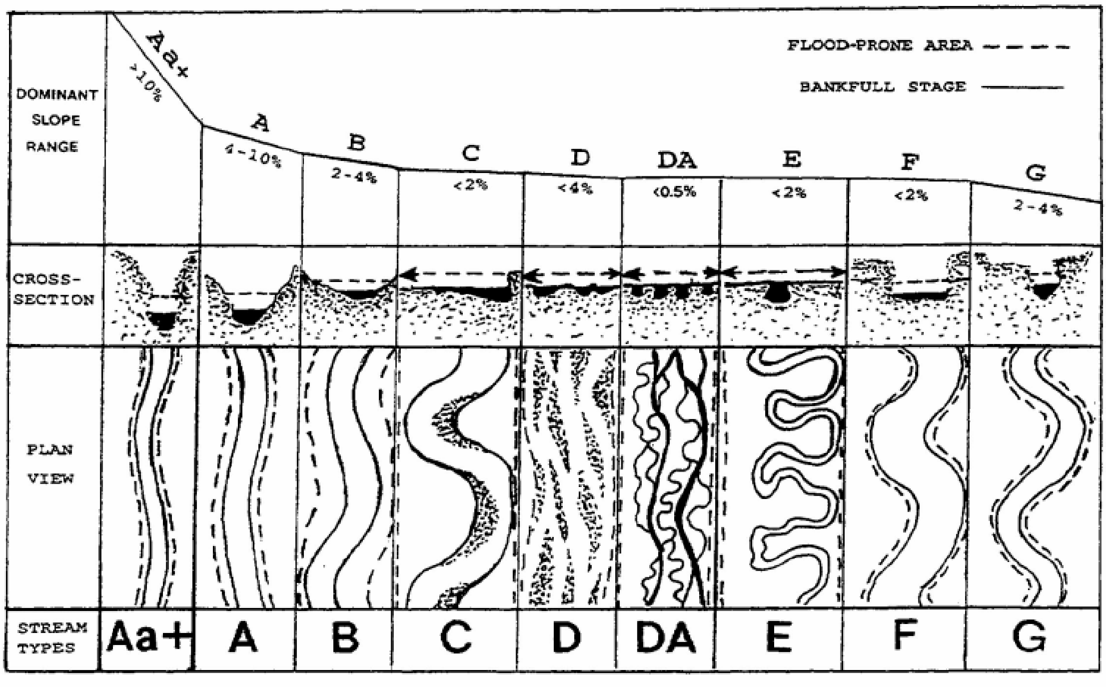


Figure 2.3: Longitudinal, cross-sectional and plan views of major stream types (from Rosgen, 1994).

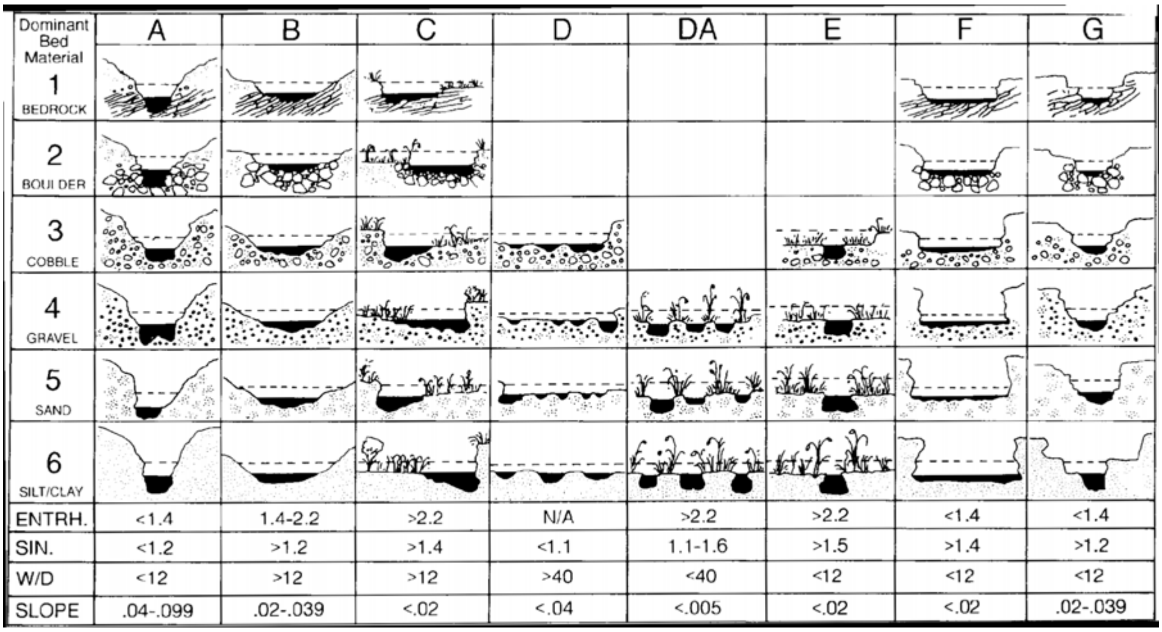


Figure 2.4: Cross-sectional configuration, composition and delineative criteria of major stream types (from Rosgen, 1994).

ENTRH. – entrenchment ratio is the ratio of the width of the flood-prone area to the bankfull surface width of the channel; SIN. – sinuosity; W/D – width to depth ratio.

Overall, classifications, which are based on channel form, are widely used because they allow scientists and engineers to communicate. It is specifically important to define common terms in research and projects which involve specialists with different background (Kondolf, 1995). However, channel form is only one aspect in channel classifications. The main disadvantage of classification based on channel form alone is that one may not relate a certain class to underlying processes. Therefore it is difficult to predict the behaviour of a channel when physical factors change. In addition, there is a considerable question – what is the length of river reach should be under consideration for classification? That question is faced with the necessity of developing classifications which take into account channel processes. In result it is recommended to take under consideration the length of river reach along which controlling factors remain constant or changes in controlling factors are gradual and insignificant. Therefore such river reaches are called “homogeneous” or “uniform” reaches. These reaches are objects of research to develop classifications, which are based on channel processes.

2.2.3. Classifications based on channel processes

Perhaps a classification developed by Schumm (1985) is the most cited classification in textbooks (Fig. 2.5). It was suggested that classification of alluvial channels should be based also on the variables that influence channel morphology. He argued that such classifications are more meaningful because they are based on cause-and-effect relations and illustrate the differences to be expected when factors differ among rivers. By this classification channels with material which move mostly as suspended load, are relatively stable with banks resistant to erosion. Schumm (1985) included in this 'Suspended Load' class, straight channels and meandering channels with an absence of point bars (types 1 and 3a in Fig. 2.5). These channels are also characterized by fine sediment, low velocities and low stream power. Schumm's 'Mixed Load' streams are characterized by more dynamic straight channels with alternate bars and meandering channels with point bars (types 2 and 3b in Fig. 2.5). These channels are characterized by more mobile bed sediments, greater sediment supply and somewhat more erodible banks. Finally, streams with a high proportion of material which moves as bed-load include meandering channels with point bars, meandering channels with mid-bars due to frequent chute cutoffs and detachment of point bars and braided channels (types 4 and 5 in Fig. 2.5). 'Bed Load' channels tend to have high width to depth ratios and steep slopes. Such rivers are characterized by high stream power, coarse bed material and relatively low lateral stability. As seen in Fig. 2.5 channel types are arranged along qualitative axes without abrupt breaks following the idea of Leopold and Wolman (1957) of a continuum of planform patterns.

However, in Schumm's (1985) classification there are some disadvantages. Only three 'classic' channel types are considered, which eliminates another main channel type – anabranched channels. Also a large braided river such as the Brahmaputra is characterized by a dominance of suspended load (Coleman, 1969) which does not coincides with Schumm's (1985) classification where braided rivers are associated with bed-load dominance.

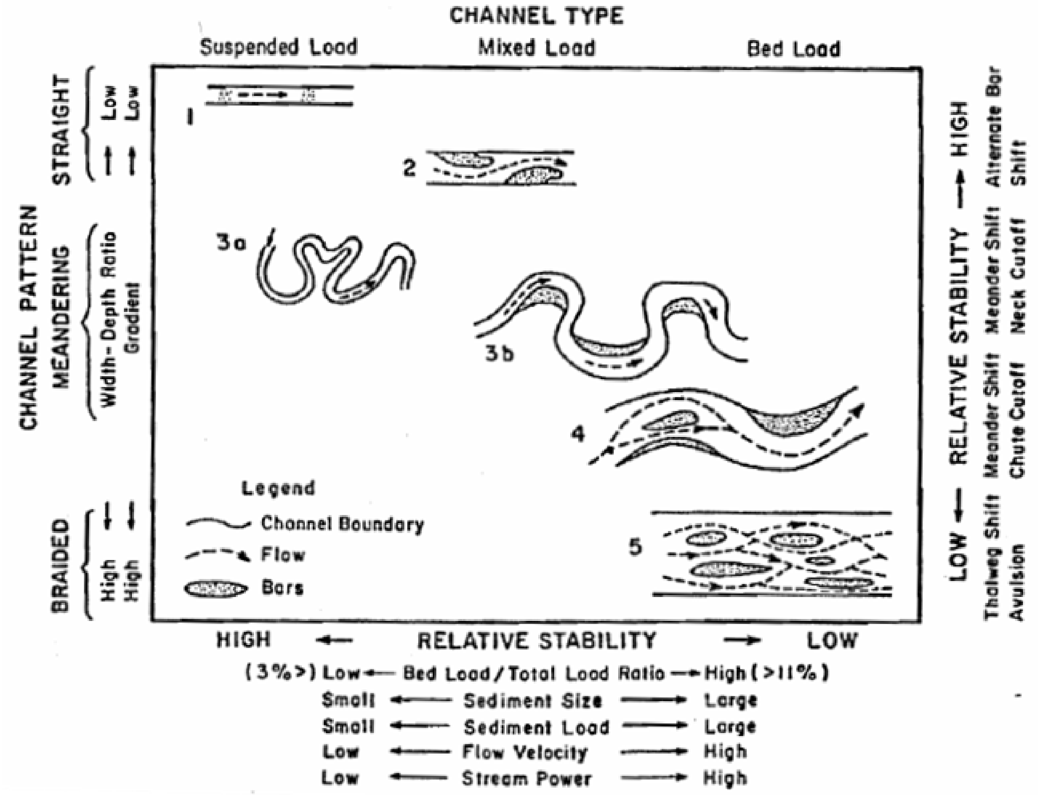


Figure 2.5: Channel classification based on pattern and sediment load, showing types of channels and some associated variables (from Schumm, 1985)

Another process-based classification was developed in the State Hydrological Institute (Russia) and presented in final form by Kondratiev et al. (1982). In the English language literature this classification was described by Popov (1964) and later by Raynov et al. (1986). Originally this classification was developed in the 1950s to predict lateral channel migrations but subsequently was elaborated further. This classification marks out seven types of channel process (Fig. 2.6):

1. Transverse bar process – downstream movement of transverse bars separated from each other by four to eight channel widths.
2. Alternate bar process – asymmetrical movement of alternate side bars.
3. Limited meandering – downstream shifting of undeveloped, loosely sinuous meanders along a narrow valley.
4. Free meandering – meanders increasing in curvature through all stages from a slightly curved channel to omega forms without any limit of horizontal migration.
5. Incomplete meandering – chute cut-off occurs before a meander reaches the maximum curvature.

1a. Channel multibranching – corresponds to ‘classic’ braiding.

5a. Floodplain multibranching – corresponds to anabranching.

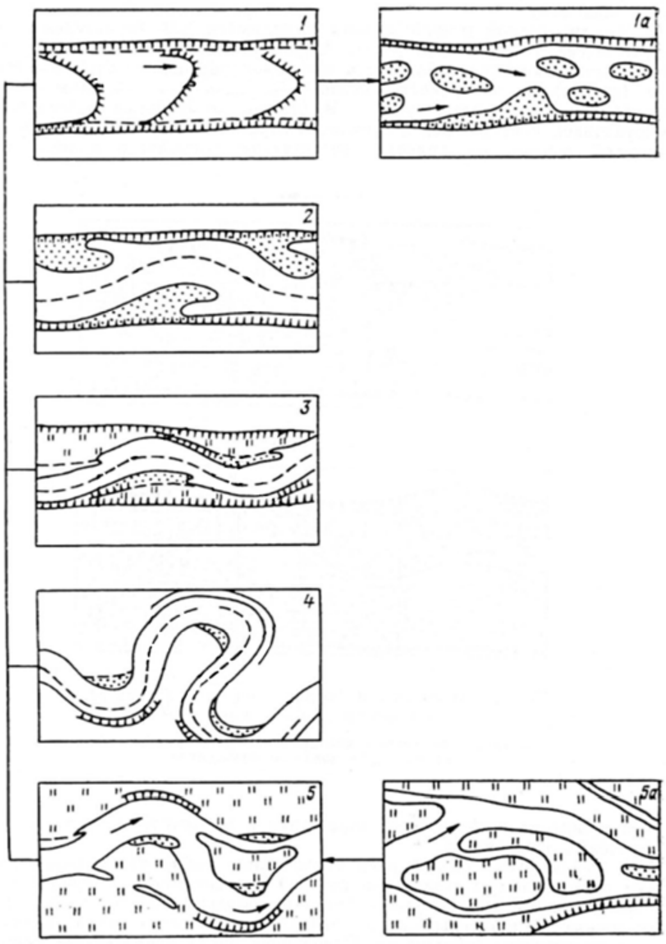


Figure 2.6: Classification of channel processes. The arrow indicates increasing in transport capacity (after Kondratiev et al., 1982)

These classes depend on the capacity of a stream to transport bedload. Thus anabranched channels in this classification have the lowest transport capacity, while braided channels have the highest transport capacity. Therefore, Fig. 2.6 can be used for a tentative prediction of channel change with changes in such variables as sediment calibre and supply, discharge and water speed through a reach as these variables define the transport capacity. This classification was criticized by Chalov (1983), who argued that it fails to distinguish the structural levels of fluvial relief: side bars and meanders, mid-channel bars and floodplain islands are all treated as comparable forms in terms of their role in the classification. The authors of this classification noted that the classification was developed for lowland rivers and it is not complete, especially for mountain rivers and for areas of permafrost.

Mollard (1973) proposed another classification, in which the relationship between channel patterns and various controlling factors is presented (Fig. 2.7). This classification was developed on the basis of interpretation of fluvial features from aerial photography and analysis of field data. Channel types were grouped into series. On one hand this integration helps to see distinct differences between the groups. On another hand, it may lead to difficulty in trying to neatly fit every reach of a river to the groups presented in the classification. The significance of various factors influencing channel type varies from stream to stream, and from one reach of a stream to an adjoining one. Therefore, channel types tend to intergrade from one “classical end member” to another under changes of the factors. The classification by Mollard (1973) is the most detailed process-based classification among others available in the literature. Moreover, Mollard (1973) summarized the main distinguishing features, derived from aerial photography, for each type (Table 2.1). Although, the summary was performed decades ago, the information presented in the table is still valuable nowadays. This information could help for prediction of channel changes and bank erosion rate estimation based on correct interpretation of features seen on aerial photographs. Only one note should be made about the terminology for “anastomosing” used in Fig. 2.7 and in Table 2.1. In recent studies the term “anastomosing” is mostly used to characterise multi-thread channels with vegetated islands, a low-energy pattern with insignificant rates of bank erosion, whereas in Fig. 2.7 “anastomosing” is located between “braided” and “wandering” as a laterally active type. By the description given by Mollard (1973) in Table 2.1 type “anastomosing” fits with type 5 of the anabranched channel classification by Nanson and Knighton (1996). Nanson and Knighton (1996) characterized anabranched channels as “gravel-dominated, laterally active anabranching channels”. Beechie et al. (2006) have used the term “island-braided” for such channels. Indeed, the “anastomosing” type in Fig. 2.7 is laterally active but has distinct differences from term “anastomosing” which is accepted for use in subsequent studies (e.g. Smith and Putnam, 1980; Makaske, 2001).

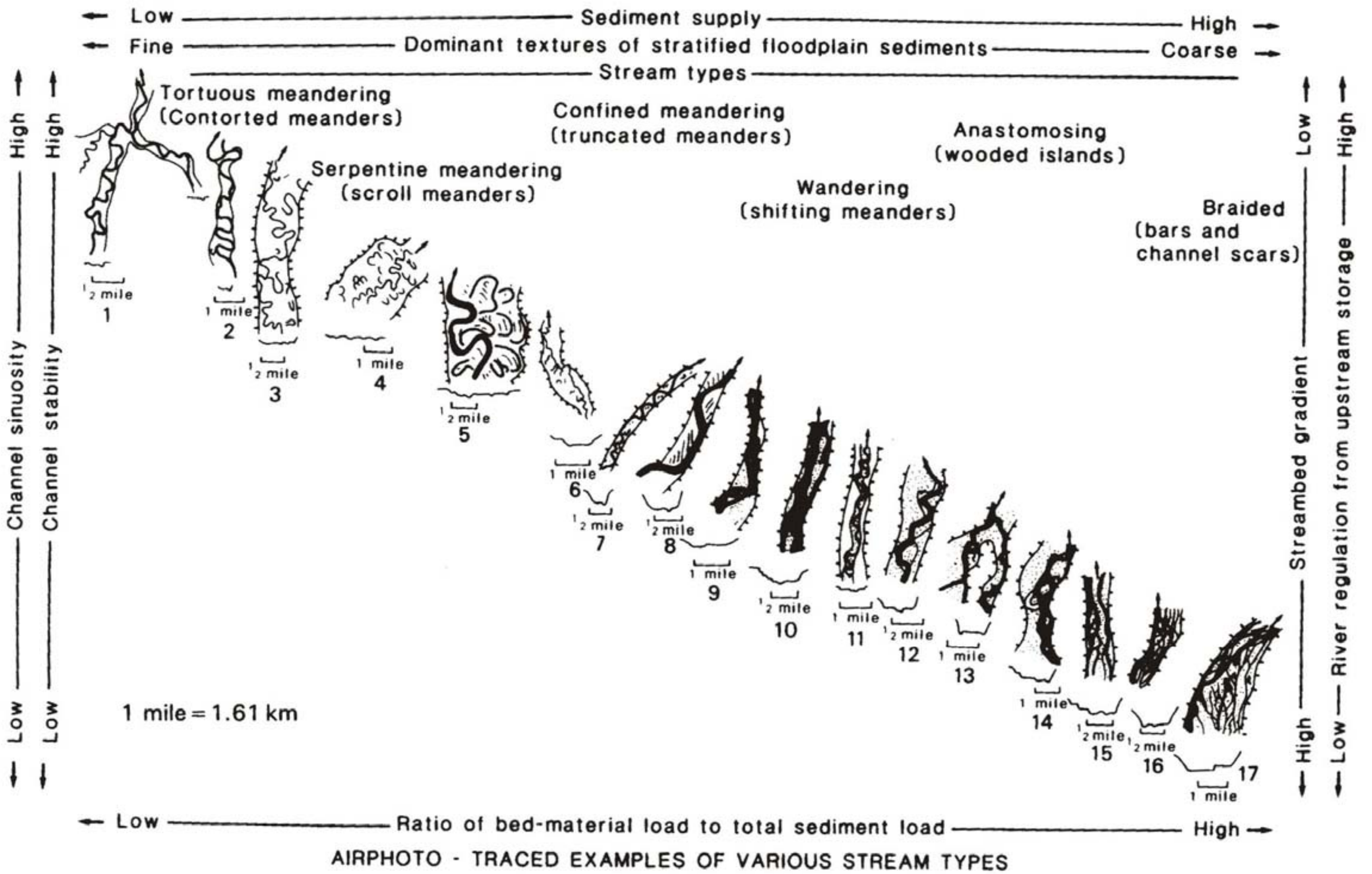


Figure 2.7: Classification by planform of river types, and their relationship to controlling variables (from Mollard, 1973)

Table 2.1: A summary of airphoto distinguishing features of various stream channel and floodplain types[1] (from Mollard, 1973)

Principal river types	Non-alluvial types (channels eroded in till, bedrock, or other non-alluvial materials)	Dominantly alluvial types[2]							
Classical channel patterns[3]	Straight v. entrenched (vertically incised) v. ingrown (asymmetrical slipoff and undercut valley-wall slopes)	Classically braided patterns	Integrading braided and meandering patterns		Classically meandering patterns				Straight patterns
Some stream channel and adjoining floodplain types	Straight v. crooked (e.g., inherited and superimposed meanders) reaches	Braided (gravelly and sandy types)	Anastomosing (wooded island type)	Wandering (shifting meandering)	Truncated meandering (confined meanders)	Scroll meandering (unconfined meanders)	Tortuous meandering (crooked meanders confined by fan and slopewash deposits)	Tortuous meandering (underfit streams in large glacial spillways and streams cut into level clay plains)	Straight reaches of stream channel
Dominant fluvial processes	Erosion, often with a coarse lag concentrate in the channel bed	Lateral (sideway) erosion and accretion with vertical bed-load accretions to the channel bottom		Slow vertical accretion of the floodplain with alternate lateral erosion of channel banks and lateral accretion of pointbars				Mainly vertical accretion of the floodplain, principally with suspended sediments	
Stream channel and floodplain stratigraphy	Shallow gravel, cobbles, boulders over till, bedrock, or other non-alluvial materials	Stream channel and floodplain substratum mainly clean gravel and/or sand, often gap-graded, and with coarser streambed armour. Bank materials composed mainly of cohesionless material, and representing a small part of the channel perimeter. Floodplain topstratum[4] mainly organic silt and fine sand. Wandering streams often have cobbly beds			Mainly fine to medium sand with minor silt, coarse sand, and fine gravel in the bed and floodplain substrarum. Stream banks and topstratum[4] consist mainly of cohesive organic silt and silty fine sand with minor clay sizes		Mainly stratified mixtures of clay, silt and fine sand. Coarsest in the bed and finer in banks. Flat featureless backswamps may be underlain by thick (15 to 30 m) highly plastic organic clays.[4] Coarser (silt, sand) substrata occur below abandoned meander scrolls and footslopes of alluvial fans		Mainly silt, clay and organic matter; minor fine sand
Common environments in sediment-source terrain	Stream downcutting commonly caused by lowered base level, locally or regionally	Proglacial, periglacial, semiarid, and arid environments. Generally little clay and sparse vegetation in sediment-source areas. Braided gravelly beds often associated with mountain, piedmont, and foothill regions; braided sandy beds associated with plains areas and lowlands			Mainly sandy outwash and sandy glaciolacustrine-deltaic plains and derived sand dunes. Locally, minor sandy alluvial fan and slopewash deposits on lower valley sides. Often formerly arid to semiarid landscapes that are now vegetated		Fine-textured marine and lake plains, and wide glacial-spillway valleys with small underfit streams. Vegetated environments. Often swampy or marshy unless drained.		Fine-textured paludal (swampy), lacustrine, and deltaic environments
Common distinguishing features in airphotos. Individual features, when isolated and considered by themselves, are seldom diagnostic. Includes fluvial features of stream channels, floodplains, and low alluvial terraces. Only a few or perhaps all of the features listed may occur at any given reach of river. The significance of individual distinguishing features varies from place to place, and from one environment to the next. Considerable experience may be necessary in order to give proper weight to the relative importance to these features when carrying out airphoto interpretation studies	Straight channel segments with occasional irregular bends. Entrenched meanders often appear inherited from stream originally eroding an alluvial veneer. Hard, non-mobile, difficult-to-erode materials in bank and bed. Low terraces, fans, landslides. Often absence of wide floodplain. May see rapids and waterfalls in bed at low-flow stages. Channels trends may be irregular sinuous (crooked), controlled by underlying bedrock structure (e.g., joints, faults, foliation) and thus show angular bends, often with near-orthogonal (rectangular) intersections of straight reaches. Also, deep, narrow valley cross-sections alternating with wider sections and possibly channel splitting	Gravelly variety: Interacting multiple channels (anabranches). Pools and riffles and diagonal flow over and around bars seen at low-flow stages. Unstable caving banks with scalloped outlines. Low steps and scarps. Longitudinal bars. Dull grey photo tones. Braided channel scars (braid scars) on floodplain. Usually distinct microrelief on relict bars and channels on floodplain. Sandy variety: Dunes on vegetated floodplain suggest sandy substratum and streambed. At low-water stages, braided channels in sands are often shallow, have wavy (i.e., scalloped) caving riverbank outlines, and show more numerous, smaller braid bars with less relief than channel bars on gravelly stream-beds. Darker streaks suggest wet (high water table) or finer (silty) channel-bottom materials. Dry sand bars generally photograph lighter (nearly white) than gravel bars. Sand bed forms can sometimes be seen on low-level airphotos	Vegetated elongate islands. Branching, interconnecting (reticulate) drainage pattern. Vestigial (relict) gently curving, braided channel markings on lower-lying floodplains. Narrow, broadly sweeping cutoff channels (commonly back channels shoreward of wooded islands). Infrequent, open, U-shaped abandoned meander segments. Common absence of classic meander scrolls and oxbows. Distinct bars on exposed channel bed at low-flow stages. Local converging of channels at nodes. Channel trends may alternate from relatively straight to wandering to irregularly meandering	Often appears as a two-phase system: meandering channel at high flows and a faintly braided, point-bar-forming channel at low-flow stages. Unstable-looking channel bed and banks. Irregular-shaped pointbars and channel-bank outlines. Variable channel width. Frequent chute cutoffs but infrequent neck cutoffs. Narrow wandering, semipermanent back-channels on wooded floodplain. Usually no dunes on floodplain. Large alluvial fans locally. Low-sinuosity meander scars suggest coarser substrata. May also appear braided with a dominant narrow meandering low-water channel	Low-sinuosity abandoned meander scrolls dominate the valley-bottom pattern. Truncated (flattened) ends of meander spurs. Trunceted upstream ends of old meander scrolls. Assymmetrical-shaped meander spurs with angular upstream and gently curvilinear downstream bends. Few oxbows. Floodplain occurs in straight or gently curving steep-walled glacial stream trenches having relatively uniform valley width. Scimitar-shaped pointbars seen at low-flow stages. Sloughs in bar-and-swale microrelief may be accentuated by ponded overbank floodwaters	Simmetrical sinuous pattern suggests uniform, easily eroded (sandy) beds. Light tones on thin organic silt and silty fine sand topstratum on abandoned pointbars. Darker tones on thicker organic silt in swales. Overlapping ("stacked") oxbows and abandoned concentric meander scrolls ("swirl" pattern). Water-filled swales (sloughs). Oxbows frequently both symmetrical and asymmetrical and are numerous. Whitish crescentic and sickle-shaped pointbars seen at low-flow stages. Frequent neck cutoffs and infrequent chute cutoffs. Mainly unconfined meanders	Meander belt often extends to base of fans and slopewash slopes. Locally stacked meanders; may be caused by some local anomaly or heterogeneity in bed or banks (fans, landslides, masses of roots, resistant clay plugs; also above tributary confluence, or above mouth of stream). Poorly developed pointbars. Meanders often appear contorted, kinky, buckled (double) meanders. Slender, elongate irregular lobate meander spurs having a low-water channel of varying width (lacine meanders). Few to usually numerous oxbows. Proportionately small area of flat valley floor (uniform tones) not covered by fans, colluvium, meander scrolls, and oxbows	Tiny underfit streams in large former glacial spillways. Stable banks usually composed of non-mobile cohesive materials. Poorly developed pointbars and weakly developed (faint) meander scrolls on narrow spurs. Extensive marshy or swampy floodplains ("backswamps", "backlands"), with or without stagnant ponded overbank floodwaters. Silty and fine sandy natural levees and crevasse splays usually only evident in photos taken during flood and flood recession. Usually few to many oxbows, often with organic clay plugs. Fewer oxbows and more symmetrical sinuous (serpentine or sine-generated) meanders occur where thick, uniform, cohesive deposits form the stream banks, including undercut valley walls and floodplain. Small meanders within large meanders, the latter swinging irregularly from one valley side to the other. Widespread uniform tones on clayey floodplains, especially where cultivated	Usually occur in locally very flat areas (reduced gradient) of valley bottoms and extensive lake basins, often where an increase in clay content is suspected in the bed and banks. Ponded floodwaters in backswamp and backland marshes often flank straighter reaches of channel, bordered by low natural levees. Straight channel reaches also often occur in valley bottoms opposite large low-gradient alluvial fans. Straight reaches are generally short and alternate with meandering ones. Relatively straight channels may also occur along steep, braided streams

1) The table prepared by Mollard (1973) based on Fig. 2.7 and from other references - mainly Mollard, 1972, and Lueder, 1959.

2) Streams in channels described as "alluvial" flow mainly in sediments deposited by the modern (postglacial) river. Locally, however, the river may erode into non-alluvial materials, which may form part or all of the channel bed and banks

3) Channel patterns are transitional and tend to intergrade. Only slight changes in one factor influencing stream behaviour may cause a stream channel to change from a braiding to a meandering habit, and vice versa; or a meandering channel to a straight one, and vice versa

4) Thickness of cohesive topstratum (mainly overbank suspended load) over coarse deposits in floodplains and low terraces is seldom over 6 m and is often thin (0.3 to 1 m) except for some tortuous and straight stream types, where fine-grained deposits may reach 30 m, in which case the topstratum may be partly alluvial and partly lacustrine in origin. Landscape expressions used to help predict dominant grain sizes in the substratum tend to fade and become progressively fainter with thicker overbank deposits. These features may not be discernible when the fine-grained topstratum becomes about 3 to 6 m thick. Vestigial braid scars, usually indicating gravelly alluvial substrata, and abandoned meander scrolls (subparallel bar-and-swale microrelief), usually indicating sandy alluvial substrata, tend to be easily identified when the cohesive (stratified clay, silt, fine sand, and organic matter of varying proportions) topstratum is less than about 1.5 m thick. Most older and higher-level floodplains and low alluvial terraces usually have a thicker silty topstratum and more uniform tones than do younger lower-lying floodplains

Recently, Church (2006) reviewed the association of bed material transport with morphology of alluvial channels. Combining the concepts used to classify rivers by Schumm (1985) and Mollard (1973), Church (2006) presented an evolved version of their classifications (Fig. 2.8). To illustrate the continuum of channel types, Church (2006) has used a qualitative model for graded rivers developed by Lane (1955). The model of Lane (1955) represents a relationship between water discharge, sediment supply, gradient and sediment calibre. The relation states that, for given flow power, a given quantity of sediment of some specified size can be transported. Water discharge chiefly determines the scale of the channel and gradient determines the rate of energy expenditure, whereas, for the given scale and gradient, the character of alluvial morphology is chiefly determined by the calibre and quantity of sediment delivered to the channel (Church, 2006). Thus to represent the classification, channel morphology was related to the conditions of sediment transport. From this classification, the braided channel type is unlikely to be observed in rivers with silt-clay channel composition. As with many channel classifications, the classification shown in Fig. 2.8 is a simplification of the variety of channels, which could be observed in nature. Also Church (2006) noted that the associations in the figure have not been placed on a physically firm foundation. Nevertheless, this diagram is the most powerful tool to study "cause-effect" relations available so far.

In addition, Church (2006) distinguished "threshold", "labile" and "transitional" channels. The "threshold" channels were defined as river channels in which the limit of competence for bed material transport is characteristically exceeded by only a modest amount, i.e. the transport of bed material occurs only at high flow. These channels are characterized by partial transport (only some of the grains on the bed are in motion at any time) and size-selective transport and typically are composed of coarse gravel or cobbles. Morphological changes for "threshold" channels are slow. The "labile" channels are defined as river channels in which the bed sediments are relatively easily and frequently entrained by the flow. Typically these channels are composed of sand and morphological changes may be relatively rapid. However, lateral instability is often strongly constrained by strong banks reinforced by vegetation. The "transitional" channels are river channels with characteristics intermediate between those of "threshold" channels and "labile" channels. Typically these channels are sandy channels with low energy or fine gravel-bed channels. Sediment transporting events that mobilize most of the bed material occur moderately frequently, along with associated morphological changes (Church, 2006). These three transport regimes are equivalent to Schumm's three categories (bed load, suspended load and mixed load).

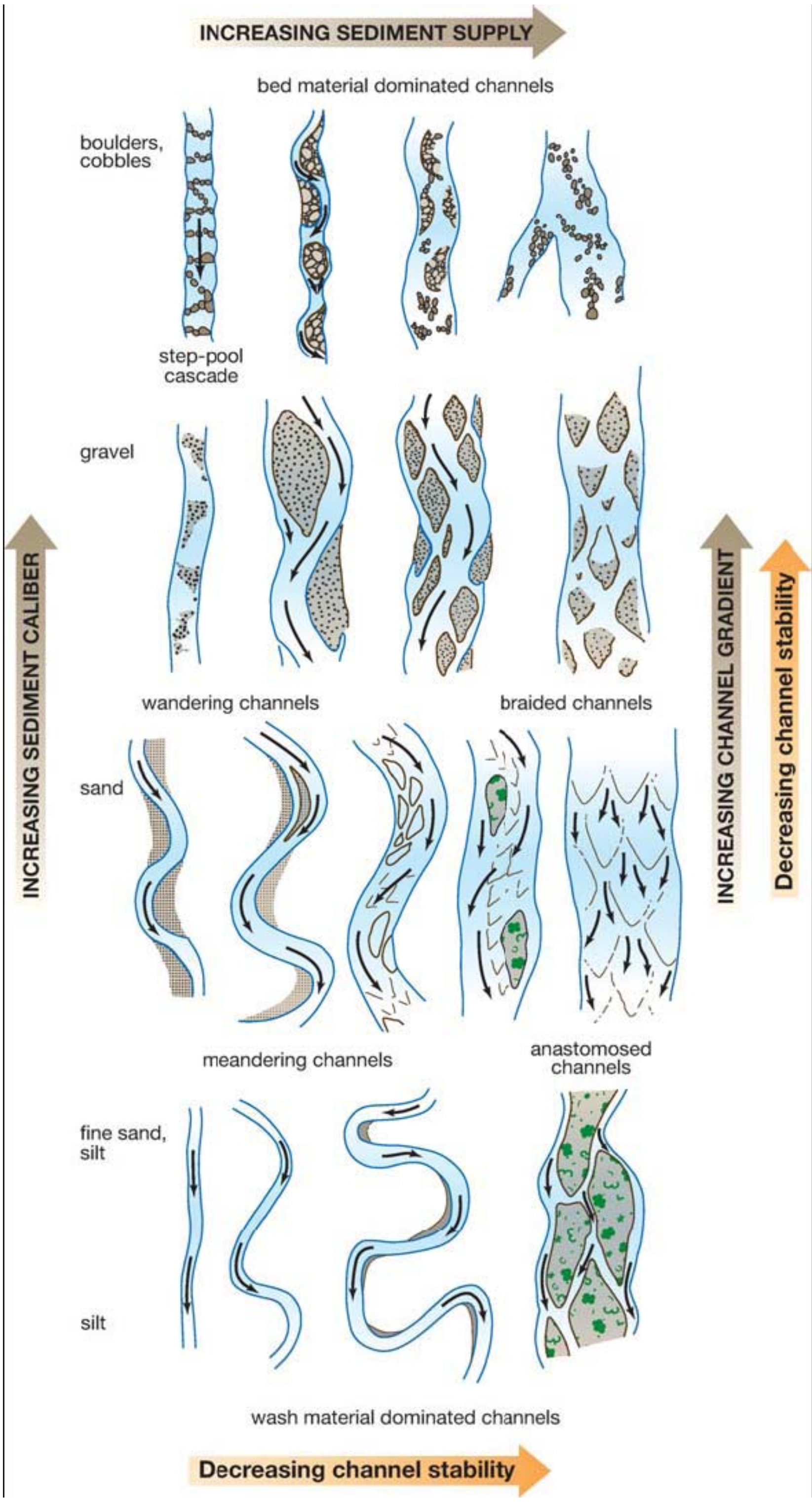


Figure 2.8: Diagram showing the association of alluvial river channel form and the principal governing factors (modified by Church (2006) after Church (1992), based on the concept of Mollard (1973) and Schumm (1985)). Classically named channel types are located at appropriate positions within the diagram. Shading is intended to reflect sediment character (from Church, 2006)

Above reviewed classifications are based on underlying processes and are the most scientifically grounded. Considering controlling factors by simplified examination turning into equation of equilibrium, presented by Lane (1955):

$$Q_s d \sim QS,$$

where

Q_s - is the quantity of sediment;

d – is the particle diameter or size of the sediment;

Q – is the water discharge;

S – is the slope of the stream.

The description of this equation is given in page 23.

The necessity and further development of such classifications are obvious as by study of channel processes it is possible to give qualitative prediction of channel type changes.

Although the process-based classifications are useful for qualitative predictions of channel evolution and changes in channel stability, there are more simple classifications for lateral activity and stability. In these classifications underlying processes are taken indirectly into account. In the same time, classifications for lateral activity and stability are simple in the sence of use as are based on channel form and are developed empirically.

2.2.4. Classifications by lateral channel activity and stability

Particularly relevant to this study is a classification based upon the lateral activity of river channels proposed by Kellerhals et al. (1976) (Fig. 2.9). Actually this is not a classification of river channels rather; it is classification of lateral processes which could be observed in rivers.

Description of these processes is given by Kellerhals et al. (1976) as follows:

1. Downstream progression – the whole meander pattern moves downstream without forming cutoffs; frequently associated with confined regular meanders but also possible in steep gravel-bed channels.
2. Progression and cutoffs – common on well-developed flood plains of meandering rivers.
3. Mainly cutoffs – typical for low-gradient streams with a flood plain consisting mainly of vertical accretion deposits.

4. Entrenched loop development – rivers working downwards and sideways into relatively easily erodible materials.
5. Irregular lateral activity – no clear pattern is detectable. Active gravel-bed channels frequently fall into this group. The occurrence of side channels, chutes, and sloughs, indicating shifts in the main channel position, is typical.
6. Avulsion – aggrading streams may break out of levées or former channel zones completely and adopt an entirely new course. In deltaic areas, breached levées and crevasse splays induce partial or total redirection of flow.

The first four processes are attributed to meandering rivers, whereas the last two could be observed in braided and anabranched rivers. To assign a river to types of lateral activity the presence or absence of the following features are used: meander scrolls (scroll bars, point bar deposits), meander scars, linear vegetation patterns, cutoffs and oxbows, and former channel or channel bar patterns on the present floodplain (Kellerhals et al., 1976). An additional type, which is not shown in Fig. 2.9, was distinguished by Kellerhals et al. (1976). This type does not have signs of lateral movement and as Kellerhals et al. (1976) noted such channels are generally deeply entrenched.

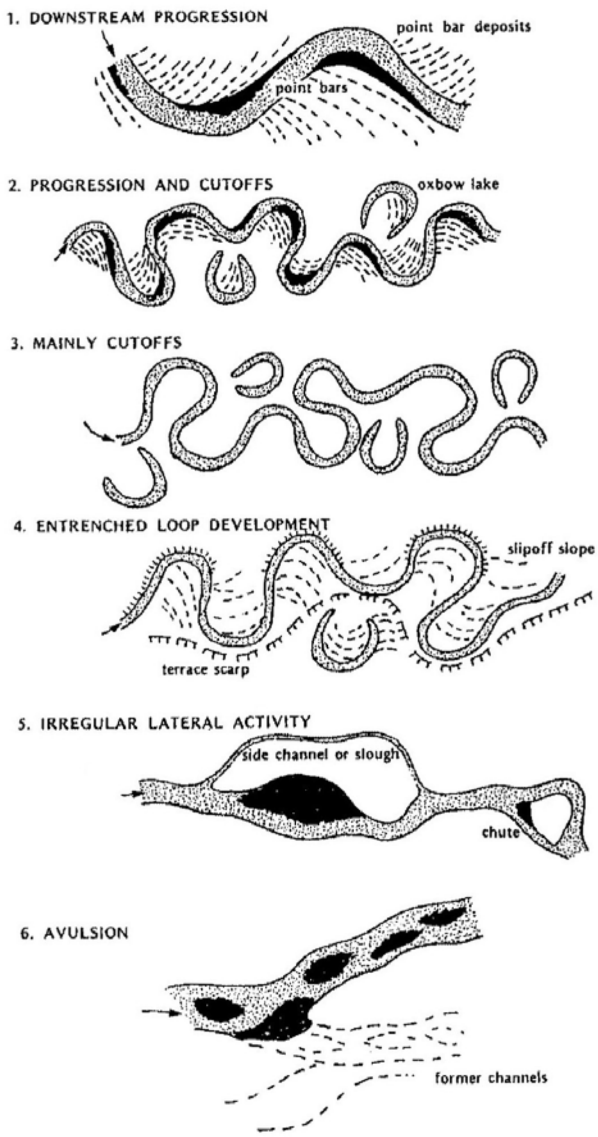


Figure 2.9: Lateral activity of river channels (from Kellerhals et al., 1976)

Another approach to classify channels by stability is based on some distinctive features of channels such as the presence of point-bars and/or mid-channel bars and width variability along a river reach. One early attempt at such an approach to classify channels by channel stability was performed by Neill (1973). The classification was used in a study of the hydraulic geometry of sand-bed rivers in Alberta, Canada. Neill (1973) assigned qualitative stability categories subjectively and used the following criteria: presence of mid-channel bars, regularity of channel width and bed-load contribution in the total load (Fig. 2.10). By using the last criterion the classification by Neill (1973) coincides with the classification presented by Schumm (1985), i.e. it predicts decreasing in-channel stability with increasing of bed-load portion in total sediment load. In the results of his analysis, Neill (1973) outlined the following in associating the characteristics of channel geometries and the stability categories: 1) there is no clear association between channel width and the stability categories, because suspended load may have a significant influence on the channel width; and 2) “low stability” channels tend to be shallow, and otherwise “high stability” channels tend to have greater channel depths. However, at the same time Neill (1973) warned that these findings were preliminary and should be clarified with more extensive data analysis.

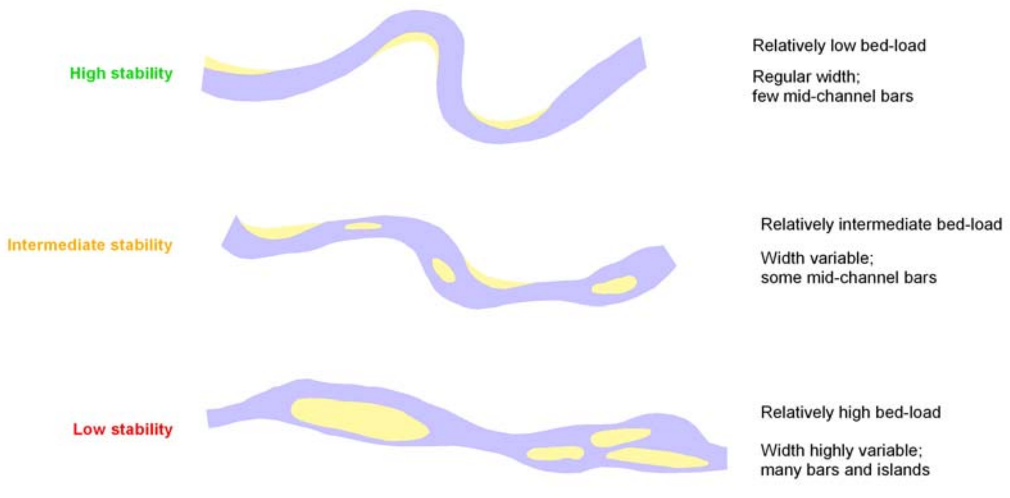


Figure 2.10: Channel stability categories assigned using subjective criteria by Neill (1973)

Brice (1981) assembled a more extensive database for rivers in the USA. The types are distinguished by various channel features. These features are uniformity of channel width and presence or absence of bars. The “equiwidth point-bar” channels are defined by Brice (1981) as channels with narrow point-bars and banks which tend to be well vegetated. Uniformity of width is designated to a channel if average width at the widest places is not greater than 1.5 times the average width at the narrowest places. Usually the widest places are observed at bends, whereas the narrowest places occur at straight reaches. Thus “wide-bend point-bar” channels have average width at the widest places greater than 1.5 times the average width at narrowest places. Also for this type, point-bars are more conspicuous at normal stage than for “equiwidth point-bar” channels. In “braided point-bar” channels point-bars tend to be irregular and marked with a braided pattern but a continuous thalweg tends to meander within a broad sinuous channel. Finally “braided, no point-bars” channels are defined by Brice (1981) as channels with many mid-channel bars and lateral bars and no continuous thalweg. These channels tend to be broad and shallow but the bars lie within well defined banklines of a single channel.

By plotting bank erosion rate for channel types with different features, Brice (1981) revealed that "braided point-bar" channels tend to have high bank erosion rates, whereas "equiwidth" channels are either stable or have low bank erosion rates. Between these counterparts, with low to moderate lateral stability, "wide-bend" channels were placed (Fig. 2.11). Other channels, which Brice (1981) classified as "braided, no point bars", show a wide range of lateral stability. In various geomorphological settings this type was found to be laterally stable with changes occurring mainly in the position of mid-channel bars, and with relatively stable banks. However, in some rivers of this type in Brice's (1981) study there were channel relocations owing to significant lateral instability. Some properties, as seen in Fig. 2.11, display gradients from one channel type to another. Almost all of them are presented as ratios, e.g. channel width related to discharge, ratio of bed load to suspended load.

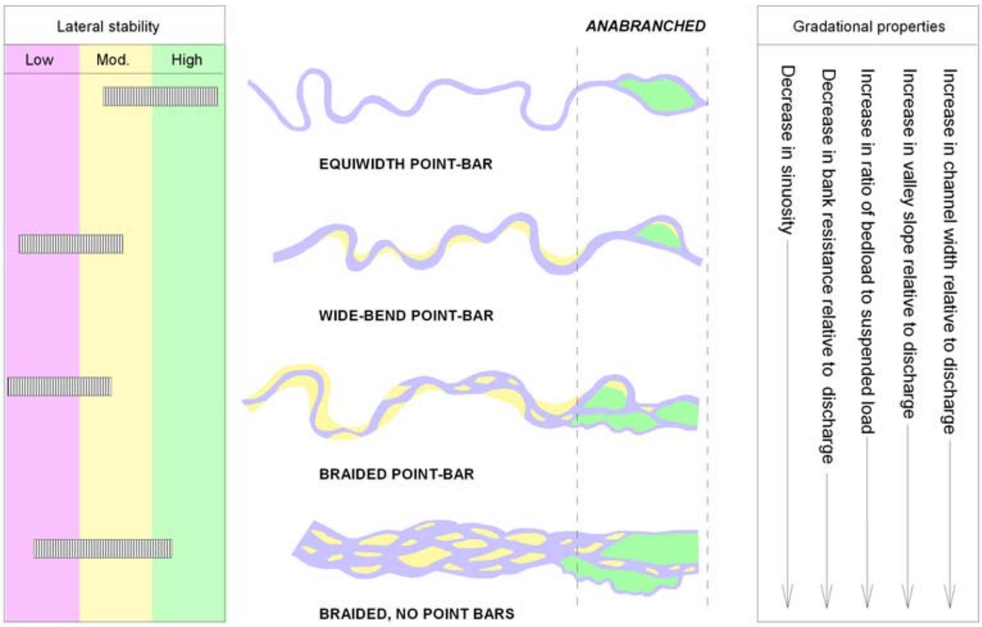


Figure 2.11: Alluvial stream types and associated lateral stability (from Brice, 1981)

The classification presented in Fig. 2.11 is similar to the Neill's (1973) classification but is broader with the addition of "anabranched" channels. The features of a channel are easy recognizable from maps and air photography and therefore this classification can be applied in the assignment of lateral stability to different channel types without observing the channel during a site visit.

Another one classification of such type is accepted as a basis in the current study. This classification is presented by Lagasse et al. (2004) and in more details is given in section 4.2.1, where a relationship between channel types and bank erosion rate is considered.

From a review of different kind of river channel classifications it is concluded that there is no universal classification which is suetable for all problems of fluvial geomorphology. Indeed, Montgomery and Buffington (1998) have concluded the same that any classification simply provides one of a variety of tools that can be applied to particular problems and it is not a panacea. In the scope of cuurent study the most suitable clasiifications those which are elaborated for estimation of lateral channel activity and stability.

In summary, the first step is performed concerning one of research goals – "to quatify rates of bank erosion for different channel types". Channel types are reviewed and a classification is selected for basis to create river bank erosion database and for further calculations. To achieve the second goal of study – "predict change of channel type during the design life of a pipeline" – in the next section a review of methods to analyse controls on channel form is presented.

2.3. CONTROLS ON CHANNELS PATTERN

Numerous methods are in existence to analyse the controls on channel pattern. Routine methods are empirical diagrams and theoretical equations, which consider equilibrium. Below, only methods which have been applied in a quantitative sense to distinguish different channel type by their main factors are considered.

The first empirical diagrams were defined by Leopold and Wolman (1957), and Lane (1957). They employed so-called *QS*-diagrams to discriminate channel types depending on slope and discharge (the discriminatory equations of various authors are listed in Table 2.2; *QS*-functions are combined in Fig. 2.12). In general form the equation can be written as:

$$S = aQ^{-b} , \qquad 2.1$$

where S = slope (m m^{-1}), Q = water discharge (m^3 s^{-1}), a = empirical coefficient and b = exponent.

Differences between the diagram of Leopold and Wolman (1957), and the diagram of Lane (1957) are that bankfull discharge is used by Leopold and Wolman (1957) whereas mean annual discharge is employed by Lane (1957). Furthermore, the data of Leopold and Wolman (1957), in general, concerns gravel-bed rivers, whereas Lane's (1957) data concerns sand-bed rivers. Hence different empirical coefficients and exponents of equation (2.1) were obtained in the two studies. On the diagram of Leopold and Wolman (1957), straight channels plot either side of a meandering–braided transition. Straight and meandering channels are distinguished by these authors by a sinuosity parameter (*P*=1.5). As pointed out by Leopold and Wolman (1957), this value of 1.5 is arbitrary but in their experience where the sinuosity is 1.5 or greater the stream is a true meander. In both studies it was shown that braided channels plot above meandering ones. Leopold and Wolman (1957) concluded: “For given discharge, meanders, as one would expect, will occur on the smaller slopes. At the same slope a braided channel will have a higher discharge than a meandering one”.

Table 2.2: Controls of channel patterns (from Bridge, 1993 with additions)

#	Author	Equation	Comments[a]
1	Lane (1957)	$S = 0.0007 Q_m^{-0.25}$ $S = 0.0041 Q_m^{-0.25}$	Meandering, sand-bed channels [***1***] Braided, sand-bed channels [***2***] Range 0.0028<*Q*<25535
2	Leopold and Wolman (1957)	$S = 0.0125 Q_{bf}^{-0.44}$	Meandering-braided [***3***]. Range 1.4<*Q*<85118
3	Henderson (1961)	$S = 0.000196 D^{1.14} Q_{bf}^{-0.44}$	Meandering-braided (see Fig. 2.14)
4[b]	Chien (1961)	$\left(\frac{\Delta Q}{0.5TQ_{bf}}\right)\left(\frac{d_{bf}S}{D_{35}}\right)^{0.6}\left(\frac{Q_{\max}-Q_{\min}}{Q_{\max}+Q_{\min}}\right)^{0.6}\left(\frac{w_{rf}}{w_{bf}}\right)^{0.45}\left(\frac{w_{bf}}{d_{bf}}\right)^{0.3} = 5$	Transitional-braided. First term is dimensional, units days^{-1}
5[b]	Chien and Zhou (1965)	$S = 100 Q_{bf}^{-0.44}$	Meandering-braided
6	Romashin (1968)	$S_v = 0.35 Q_{maf}^{-1}$ $S_v = 1.4 Q_{maf}^{-1}$	Free meandering-incomplete meandering [***4***] Incomplete meandering-braided [***5***] Range 28<*Q*<133000
7	Ackers and Charlton (1970)	$S_v = 0.001 Q^{-0.12}$ $S_v = 0.0014 Q^{-0.12}$	Straight-shoaled Shoaled-meandering [***6***] Range 0.006<*Q*<0.09
8	Antropovskiy (1972)	Various	See Table 2.3. Range 71.7<*Q*<34700
9[b]	Ikeda (1973, 1975)	$\frac{U_*}{U_{*c}} = 1.4\left(\frac{wS}{d}\right)^{1/3}$	Meandering-braided. Non-dimensional criterion
10	Parker (1976)	$S/F \approx d/w$	Meandering-braided (see Fig. 2.15)
11[b]	Muramoto and Fujita (1977)	$\frac{(w/D)^{2/3}}{(d/D)} = 6.7$ *for* $1 < \tau_0/\tau_c < 12$	Meandering-braided. Non-dimensional criterion
12	Fredsøe (1978)	$w/d \approx 50$	Meandering-braided. Weak dependence on θ and *f*
13	Osterkamp (1978)	$S = aQ_m^{-0.25}$	Meandering-braided [***7***] – for D_{50}<0.1 mm; [***8***] – for *So*>10, *SC*<50%; [***9***] – for D_{50}=0.1-2 mm, *So*≥3.0; [***10***] – for D_{50}=0.1 mm, *So*<3.0; Range 0.03<*Q*<200
14[b]	Snishchenko (1979)	Only graph $w; w_v; S; S_v$	See Table 2.4 and Fig. 2.16

Table 2.2 (Continued)

#	Author	Equation	Comments[a]
15	Hayashi and Ozaki (1980)	$2(wS/d)^{0.5} \approx F$	Meandering-braided
16	Begin (1981a)	$S = 0.0016{Q_m}^{-0.327}$	Meandering-braided for a standard channel with $\tau = \tau_{avg}$ [***11***] Range 0.672<*Q*<25200
17	Bray (1982)	$S = 0.07{Q_{2f}}^{-0.44}$	Meandering-braided for gravel-bed rivers [***12***] Range 5.52<*Q*<8920
18	Ackers (1982)	$S = 0.0008Q^{-0.21}$	Straight-meandering for sand-bed flumes and rivers [***13***] Range 10^{-4}<*Q*<10^{5}
19	Ferguson (1984b)	$S = 0.042Q^{-0.49}{D_{50}}^{0.09}$	Meandering-braided for gravel-bed rivers [***14***] – for D_{50}=2 mm [***15***] – for D_{50}=16 mm [***16***] – for D_{50}=64 mm [***17***] – for D_{50}=256 mm Range 3<*Q*<17000
20	Chang (1985)	$S \approx aQ^{-0.5}D^{0.5}$	Meandering-braided
21	Struiksma and Klaasen (1988)	$\frac{S}{F^2}\left(\frac{w}{d}\right)^2 f(\theta)$=*constant*	Meandering-braided
22	Fujita (1989)	$\frac{(w/D)^{2/3}}{(d/D)} = 3.5$ *to* 6.7 $2.2m^{2/3} < \frac{(w/D)^{2/3}}{(d/D)} < 6.7m^{2/3}$	Meandering-braided *m* is mode (degree of braiding)
23	Fukuoka (1989)	$S^{0.2}w/d \approx$ *10 to 20*	Meandering-braided. Weak dependence on θ/θ_c
24	Robertson-Rintoul and Richards (1993)	$\sum P = 1 + 5.52(QS_v)^{0.38}{D_{84}}^{-0.44}$ *and* $\sum P = 1 + 2.64(QS_v)^{0.4}{D_{84}}^{-0.14}$	Meandering-braided for gravel-bed rivers Meandering-braided for sand-bed rivers
25	van den Berg (1995)	$\omega = 900{D_{50}}^{0.42}$	Single-thread channels-braided channels(Fig. 2.17)
26	Xu (2004)	$S = 2.54w^{-1.44}$	Meandering-braided

[a] – numbers in square brackets correspond to numbers of lines on *QS*-diagrams (Fig. 2.12);

[b] – equations were taken from other sources: 4; 9 and 11 from Bridge (1993); 5 from Xiaoqing (2003); 14 from Popov (1982)

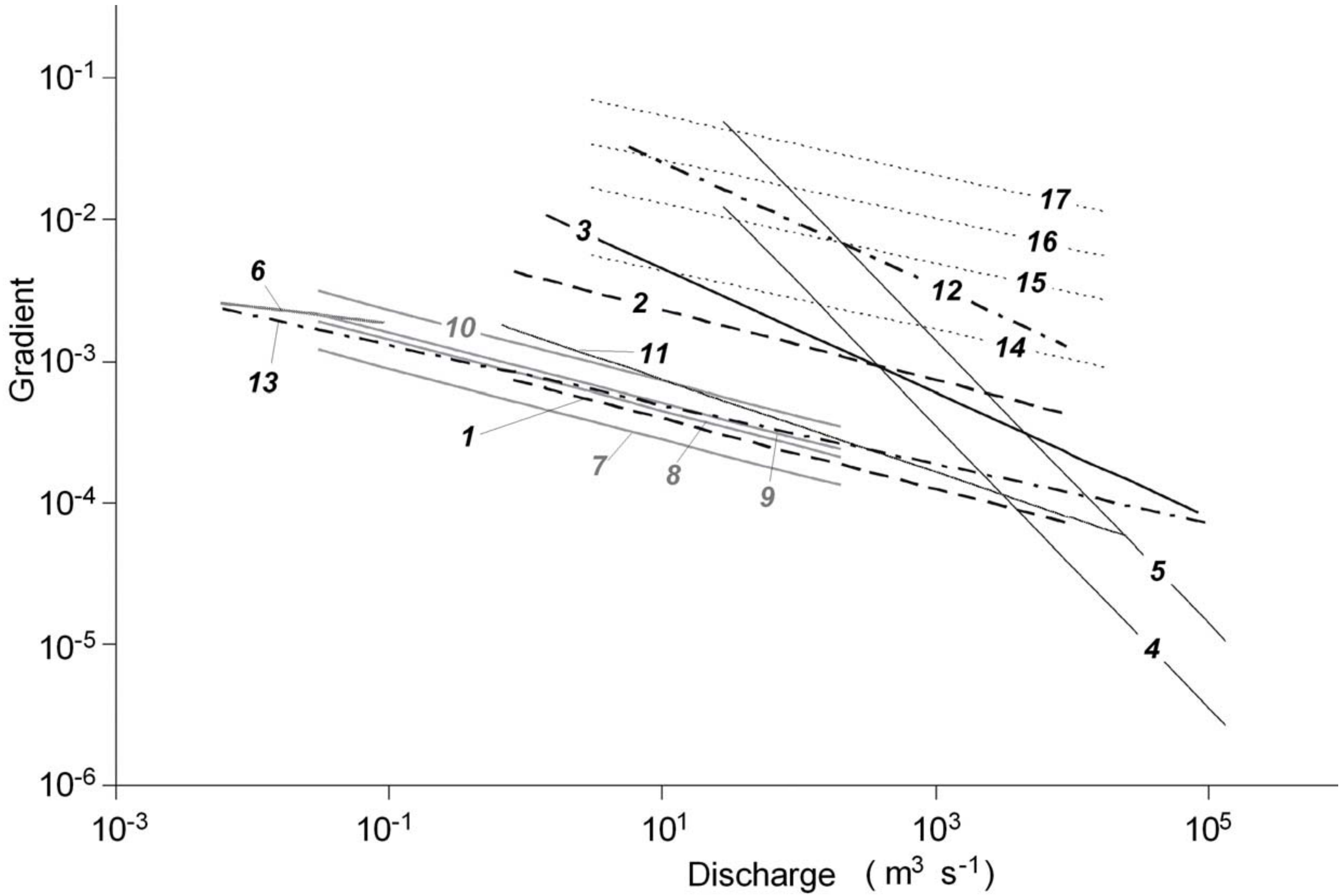


Figure 2.12: *QS*-diagrams by various authors. Numbers of lines in accordance with Table 2.2. (See column "Comments")

The physical meaning of *QS*-diagrams lies in the equation of stream power:

$$\Omega = \rho g Q S \approx 9810 QS\,, \qquad 2.2$$

where Ω = total stream power (W m^{-1}), ρ = water density (1000 kg m^{-3}), g = gravitational acceleration (9.81 m sec^{-2}). Therefore, on the diagrams of Leopold and Wolman (1957), and Lane (1957), braided channels correspond to higher stream power values than meandering ones. However, on both diagrams there is considerable scatter of data points for the channel types, which led Leopold and Wolman (1957) to conclude that a continuum of channel types in fact exist.

During the ensuing years other authors have attempted to modify and improve *QS*-diagrams and have given the physical interpretation of parameters in equation (2.1). One way to improve the method is to take into account the grain size of bed material. In general form, the equation can be written as:

$$S = a_* D^c Q^{-b}\,, \qquad 2.3$$

where D = size of bed material (mm), a_* = an empirical coefficient, c and b are exponents. The first work of this type was developed by Henderson (1961). Considering Type B channels as derived in threshold theory (the theory of stable channel profile developed at the United States Bureau of Reclamation Dept. of Interior along the lines laid down by Lane, 1955, see Fig. 2.13), Henderson (1961) obtained the parameters in equation 2.3 that give the value of slope at which the limiting channel shape (Type B) would be stable. Henderson obtained parameter values of b=0.46 and c=1.15. If the slope is greater than the limiting value, the wide Type A channel of less scouring capacity is required. If the slope is less than the limiting value then a Type C channel apparently is required (Fig. 2.13).

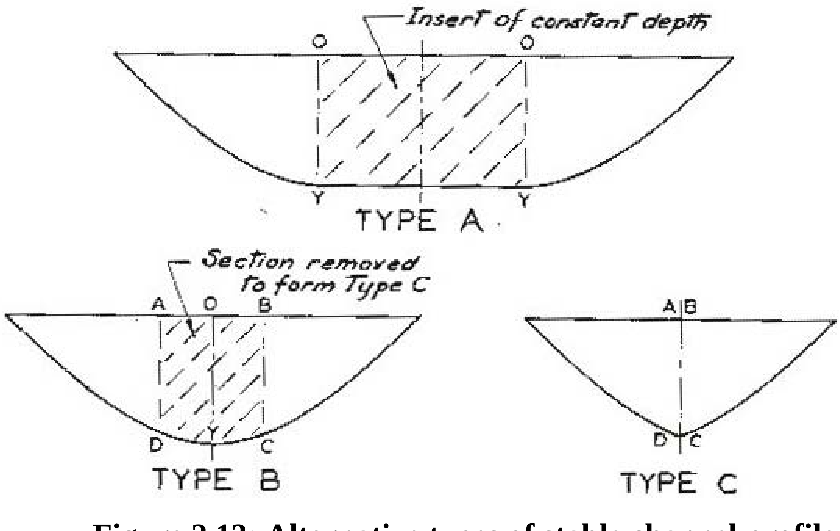


Figure 2.13: Alternative types of stable channel profile (from Henderson, 1961)

Henderson (1961) concluded that the resulting value of the exponent for discharge is very nearly equal to the exponent given by Leopold and Wolman (1957); and "if transporting power is to be the criterion that distinguishes braided from meandering channels then the size of the bed material, as well as the slope and discharge, ought to be taken into account". Using data for *S*, Q_{bf} and *D* given by Leopold and Wolman (1957), he attempted to refine their equation by empirical means. As a result Henderson (1961) derived an equation with parameters: a_*=0.000196, *b*=0.44 and *c*=1.14 (Fig. 2.14).

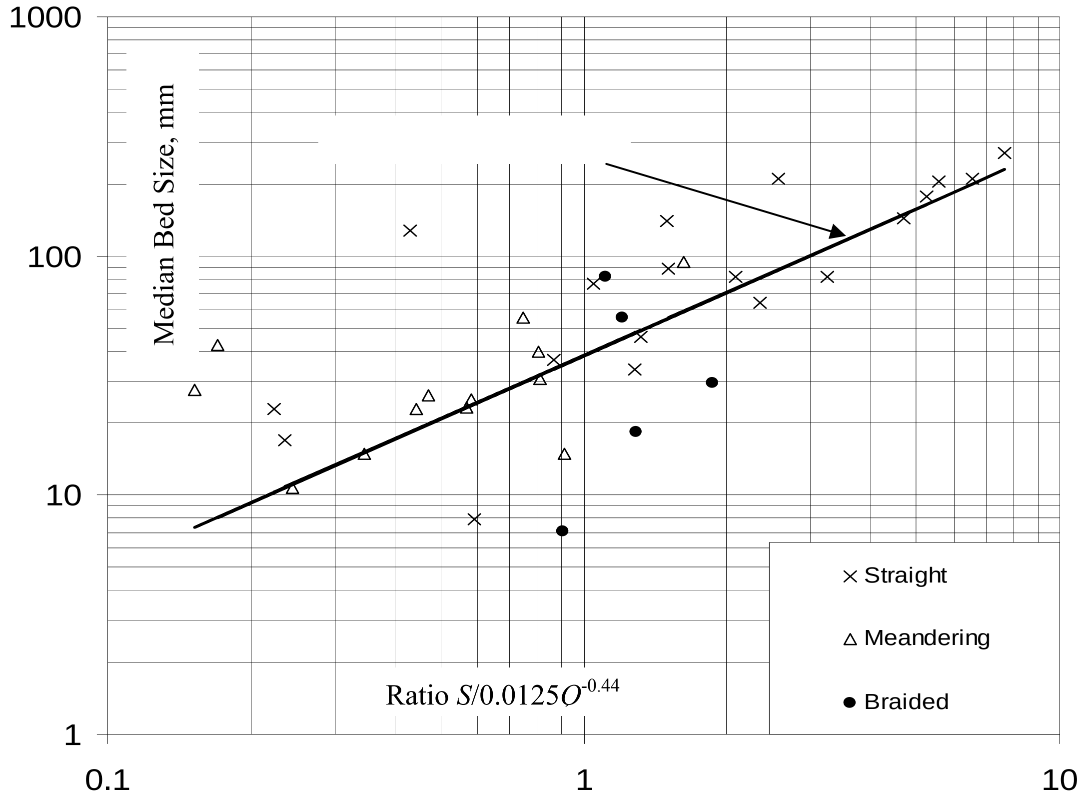


Figure 2.14: *S-D-Q* relationship modified from Henderson (1961)

However, the scatter of points was not significantly reduced. The number of points in Fig. 2.14 for braided rivers is only five, and two of them lie above and three lie below the line of discrimination. Bridge (1993) pointed out that "Henderson's approach is based on the stability of channels at the threshold of bedload motion and therefore cannot be correct in view of the requirement of sediment transport for channel bars to form." Moreover, application of Henderson's (1961) equation by Chitale (1973) did not give satisfactory results. Chitale (1973) used extensive data and he pointed out that "… values of slope estimated by Henderson's (1961) formula were found to be much flatter than the actual slope for both braided and non-braided rivers." Subsequently Henderson's method was not applied for a long time. Much later Carson (1984) gave an explanation of the inconsistency between Henderson's (1961) equation and Chitale's (1973) data: Chitale (1973) in general used data from rivers of India with sand-bed channels, whereas Henderson (1961) derived the equation based on data from rivers with gravel-bed channels.

Quite to the contrary to Henderson's (1961) approach, Romashin (1968) pointed out that taking into account the grain size of bed material is difficult, because data about grain size may be unrepresentative. Romashin (1968) constructed a *QS*-diagram using valley slope and median flood discharge for freely developing channels, i.e. unconfined by valley walls and rock outcrops. His results coincide with the conclusions of Leopold and Wolman (1957) and Lane (1957) in general but the slope of the discriminant line between meandering and braided rivers is more than twice as steep on his chart (see Fig. 2.12). Perhaps this difference is caused by using different data definitions in the work of Romashin (1968) compared with Leopold and Wolman (1957) (i.e. valley slope instead of channel slope and median flood discharge instead of bankfull discharge).

Romashin (1968) examined more than 250 river reaches. The following preconditions were obeyed: 1) proximity to a gauging station with enough data for discharge calculation; 2) absence of limiting conditions for channel changes; 3) only relatively large rivers were examined. There is a clear differentiation of points from different channel types on his diagram. Romashin (1968) derived equations in the form of (2.1) which distinguish free meandering, incomplete meandering and multibranching (in terms of the classification by Kondratiev et al. (1982)). Antropovskiy (1972) adduced values of stream power from Romashin's discriminant function (assuming that the slope of the water surface is equal to the slope of the valley floor): the transition from free to incomplete meandering occurs when the stream power equals ≈ 3.4 kW m^{-1} and incomplete meandering to floodplain multibranching occurs when the stream power equals ≈ 14 kW m^{-1}. As Chalov et al. (1998) have noted, Romashin's (1968) analysis is the most reasonable, because he used valley slope (independent of channel form) rather than channel slope (dependent upon channel form).

Ackers and Charlton (1970) performed laboratory studies with the purpose of analyzing meandering processes. They described stages of channel evolution from initially straight to meandering and braided channels. From the results of their studies conclusions were made that an initially straight channel becomes meandering only if there is a certain sediment supply (greater than critical). When the slope is too low to transport the supplied sediment, accumulations of alluvium arise in the channel. On the basis of these studies they derived equations in the form of (2.1), which distinguish straight, shoaled (straight channels with prominent shoals) and meandering channels. On their diagram straight channels plot below meandering ones. For straight channels water surface slopes were used and for meandering channels – valley slopes were used. For comparison, meandering points with values of channel slope also were shown. In the latter case all points plotted below points obtained using the valley slope and it is impossible to derive a line that distinguishes straight and meandering channels clearly. The conclusion was that there is a limiting gradient below which channels in alluvium may remain straight, but above which meandering will occur. The same conclusion was made by Schumm and Khan (1972). In laboratory studies they showed that the transition from one channel type to another depends on valley slope, discharge and sediment supply. It should be noted that channels may be relatively straight at the transition to meandering and again relatively straight at the transition from meandering to braided. Further, braided streams are sometimes reported as being straight as their major planform is less sinuous than meandering rivers. Thus great care is required in the definition, selection and treatment of ‘straight’ channel data (see Section 4.2.1).

Later Ackers (1982), using further data from field and laboratory sources, refined the equation. For this analysis a steeper line was obtained (exponent b=0.21). He also concluded that “meandering is associated with steeper slopes and higher sediment transport rates than can remain stable in a straight channel with erodible banks, and that this limiting slope is dependent on the water discharge”. Edgar (1973) had earlier obtained a similar exponent to that obtained by Ackers (1982) for a lower range of experimental discharges.

These flume studies are useful to understand the process of channel transition from one type to another. Besides, in the laboratory it is possible to study and control changeable parameters (slope, discharge, bedload). However, in laboratory studies data are limited in terms of the range of values of discharge, and grain size often is imposed as a constant. For these reasons, the results of such studies often can be used only in a qualitative manner.

Antropovskiy (1972) suggested considering shear stress (τ), and the resistance of the channel to this force. He pointed out that grain size should not be used as a measure of resistance, because it is possible to represent grain size by other parameters. He suggests that such parameters could be the coefficient C_{ch} in the Chezy formula and the width to depth ratio. His results showed that the highest values of C_{ch} and width-to-depth ratio for the same τ value relate to braided channels and channels with incomplete meandering; the lowest values are associated with free meandering channels. Moreover, Antropovskiy (1972) also derived equations with other parameters (Table 2.3) which can be used to distinguish different channel types. He pointed out that “different types of channel processes can be easily separated if the slope, or an expression containing it, is plotted along one of the axes of the graph”. Also, Antropovskiy (1972) carried out an analysis of the following nondimensional parameters:

$$\frac{C_{ch}}{\sqrt{g}} = f(S), \ \frac{w}{d} = f(S) \text{ and } \frac{C_{ch}}{\sqrt{g}} = f(F), \ \frac{w}{d} = f(F).$$

However, in this case the results showed more scatter of points which belong to reaches with different types of channel processes.

In his analysis Antropovskiy (1972) used data from 70 gauging stations which were located in greatly differing regions of the former Soviet Union, except the Caucasus. For rivers in Central Asia with intense channel changes a poor relationship between water surface slope and discharge was obtained and sometimes a total lack of such a relationship occurred. On a diagram, using data with the slope of the valley floor from 150 gauging stations, Antropovskiy plotted the following expression: $\frac{E}{\alpha_c} = \frac{V^2}{2g}$, where *E* is specific kinetic energy, α_c is the Coriolis coefficient, and concluded that for the same water discharge, braided and anabranching channels have the highest kinetic energy, streams with incomplete meandering have a lower energy, and streams with free meandering have the lowest kinetic energy”.

On one hand the study by Antropovskiy (1972) are interest as there is a try to analyse all possible parameters. However, on another hand, there is no any physical explonations for obtained relationships. Moreover, unreasonably the Coriolis coefficient (α_c) was used without interpretation. A relationship or any influence of the Coriolis coefficient up to now does not find any convincing evidences in nature.

Table 2.3: Criterial relations describing the transition of the channel process from one type to another (from Antropovskiy, 1972)

Form of criterial relation	Coefficient ***a*** and exponents ***b***, ***c***, ***d*** in criterial relations								Percentage of points falling into zone of		
	for transition from free to incomplete meandering				for transition from incomplete meandering to channel braiding				free meandering	incomplete meandering	channel braiding
	a	***b***	***c***	***d***	***a***	***B***	***c***	***d***			
$C_{ch} = a\tau^b = ad^b S^b$	1,87	-0,44			2,85	-0,44			85	85	83
$w = a\tau^b = ad^b S^b$	0,013	-1,4			0,041	-1,4			90	75	90
$d = aS^b$	0,046	-0,51			0,084	-0,51			70	75	80
$Q = a\tau^b = ad^b S^b$	0,095	-1,3			0,93	-1,3			85	80	83
$w = aV^b C_{ch}{}^c$	0,013	-2,8	2,8		0,041	-2,8	2,8		85	80	86
$w = aV^b n^b d^c$	0,013	-2,8	0,46		0,041	-2,8	0,46		85	80	86
$w = aV^b n^b S^c$	0,013	-2,1	-0,35		0,041	-2,1	-0,35		90	80	90
$Q = aw^b S^c$	0,0695	0,24	-1		0,255	0,24	-1		85	80	80
$Q = aC_{ch} S^b$	0,01	-0,96			0,032	-0,96			90	80	93
$V = a\tau^b = ad^b S^b$	1,87	0,06			2,85	0,06			90	85	86
$V = aS^b$	2,72	0,08			3,57	0,08			100	85	86
$\lambda = a\tau^b = ad^b S^b$	5,6	0,88			2,4	0,88			80	85	92
$Q = aS^b$	0,13	-1,1			0,4	-1,1			90	80	90
$Q = aC_{ch} d^b S^c$	0,013	0,1	-0,9		0,041	0,1	-0,9		90	80	83
$Q = aC_{ch} w^b d$	0,21	0,64			0,32	0,64			95	80	90
$Q = an^b d^c S^d$	0,013	-1	0,27	-0,9	0,041	-1	0,27	-0,9	90	80	83
$Q = an^b w^c d^d$	0,21	-1	0,64	1,17	0,7	-1	0,64	1,17	95	80	90
$d = a\left(\frac{V^2}{2g}\right)^b$	0,025	-2,2			0,14	-2,2			98	85	80

Somewhat different approach is used by Parker (1976). He described a stability analysis of meandering and braiding and derived an analytical description to obtain a parameter $\varepsilon^* = \frac{1}{\pi}\frac{S}{F}\frac{B}{d_0}$. According to the theory, meandering occurs for $S/F << d_0/B$, braiding occurs for $S/F >> d_0/B$ and a transition between the two occurs for $S/F \sim d_0/B$. This theory does not indicate any conditions for a straight channel, so on the basis of previous studies (Chang et al., 1971 and Vincent, 1967) Parker (1976) suggested the following condition for the maintenance of a straight channel: $d_0/B > 10^{-1}$. He plotted in a diagram (Fig. 2.15) data from 75 laboratory flume experiments, 22 irrigation canals and reaches of 53 natural rivers. In addition, on the basis of stability theory Fredsøe (1978) indicated that the major control on braiding is the width to depth ratio.

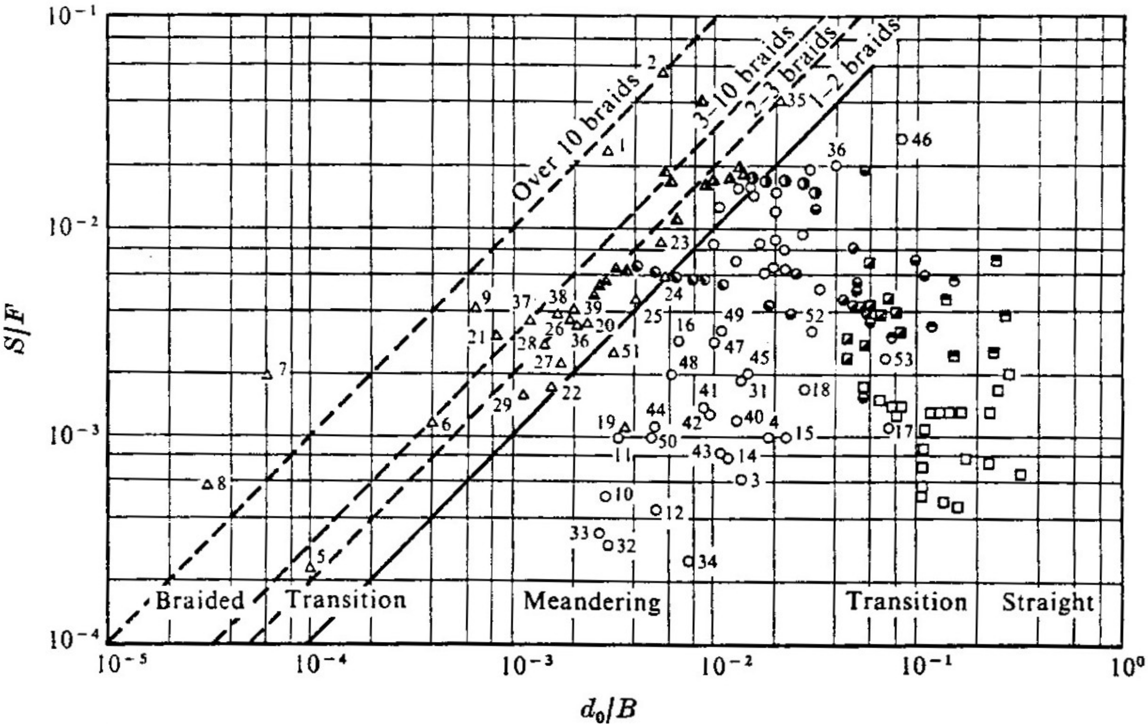


Figure 2.15: Meandering/braided/straight regime diagram (from Parker, 1976)

However, theoretical methods such as Parker's (1976) and Fredsøe's (1978) have some disadvantages. As reported by Bridge (1993) their criteria do not agree very well with field data. Furthermore, parameters in these criteria are require more field data, such as flow velocity to define, e.g. the Froude number: $U/\sqrt{gd}$.

Going back to the classical *QS*-approach Osterkamp (1978) carried out an analysis of river reaches in Kansas and suggests an equation of the form of (2.1) with an imposed exponent. This exponent equals b=0.25. The coefficient a is suggested to be dependent on median grain size and a sorting index. During the process of analysis, data sets were subdivided by sinuosity, grain size and sorting index. Then regression analysis of these samples was performed. The results of the regression analysis provided values of exponents, which are nearly equal to the exponent given by Lane (1957). Therefore Osterkamp (1978) imposed an exponent value as a constant in all equations. Perhaps nearly equal exponents were obtained because the same parameters were used, i.e. channel slope and mean annual discharge. It was noted by Osterkamp (1978) that because the equation of Leopold and Wolman (1957) is based on discharges at bankfull stage, it is not directly comparable to the equations presented in his paper. Moreover, he argued out that bankfull discharge is an inappropriate parameter for regression analysis. He added the following comment about bankfull discharge: "Bankfull discharge at a site is dependent on channel conveyance at the bankfull stage for the time of measurement, which in turn can be a function of recent erosive flow events. The result is a wide range of possible cross-sectional areas at bankfull discharges for streams of similar mean discharges. The problem is acute when the data represent a diverse range of climatic and geologic conditions, as do the data of Leopold and Wolman (1957)."

For samples grouped by sinuosity, Osterkamp (1978) obtained unsatisfactory results. Satisfactory results were obtained for samples grouped by median-grain size and sorting index. Perhaps such satisfactory results are determined by the regional character of study, admitting little variation in parameter values.

Snishchenko (1979) suggested using relative rather than absolute values of slope, discharge and width, because he argued that the use of absolute values induce statistical inhomogeneity within samples. He used a relationship between valley slope and channel slope S_v/S, valley width and channel width w_v/w and their product. (Table 2.4 and Fig. 2.16). Snishchenko (1979) made the conclusion: "according as width of valley decrease, channel types vary from free meandering to incomplete meandering, to floodplain multibranching, to limited meandering, to channel multibranching" (channel types terminology in accordance with the classification by Kondratiev et al. (1982)).

Chalov et al. (1998) criticized this method. They noted that the relation of valley slope and channel slope is sinuosity, so diagrams show the well-known fact that meandering channels have higher sinuosity than braided ones. Also they suggested that is better to use absolute values of variables but did not provide any explanation for that statement.

Table 2.4: Relative values of valley slopes and widths under various types of channel processes according to Snishchenko (1979) (from Popov, 1982)

Type of channel process	Average/standard σ			
	S_v/S	w_v/w	Multiplication of S_v/S and w_v/w	Relationship of channel slope (S) to valley slope (S_v)
Free meandering	2.0/0.22	18.3/4.6	36.6/11.5	S=0.50S_v
Incomplete meandering	1.4/0.02	10.39/5.7	14.6/4.05	S=0.71S_v
Floodplain multibranching	1.2/0.09	6.5/1.8	7.9/2.4	S=0.82S_v
Limited meandering	1.2/0.06	5.1/1.1	5.9/1.3	S=0.86S_v
Alternate bar process	1.07/0.04	2.4/0.5	2.6/0.6	S=0.93S_v
Channel multibranching	1.03/0.03	1.9/0.6	1.97/0.6	S=0.97S_v

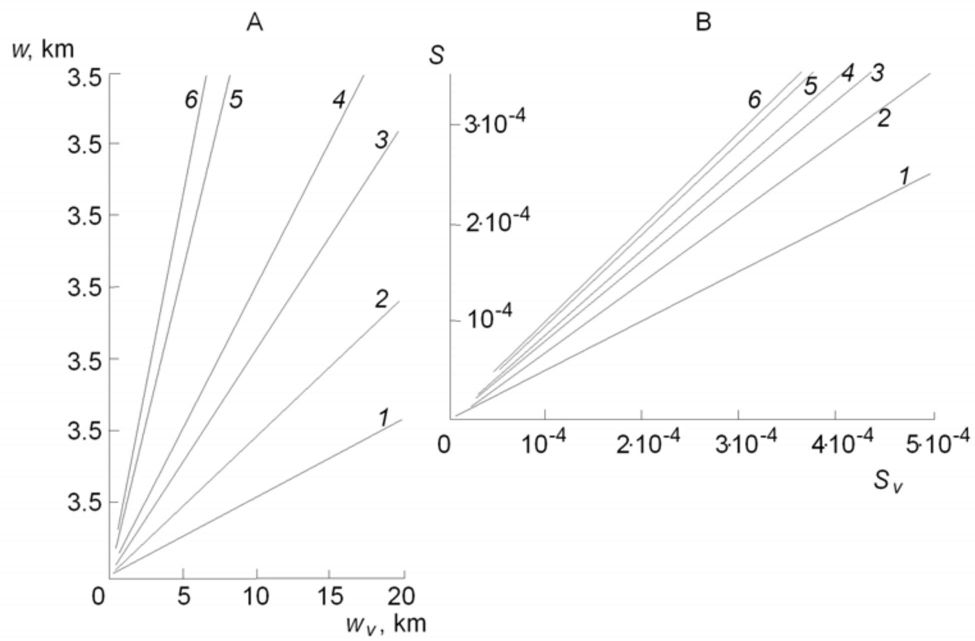


Figure 2.16: Channel pattern types according to relationship between valley width and channel width w_v/w (A) and relationship between valley slope and water surface slope S_v/S (B) as proposed by Snishchenko (1979).

1 – free meandering; 2 - incomplete meandering; 3 - floodplain multibranching; 4 - limited meandering; 5 - alternate bar process; 6 - channel multibranching. (Terminology according to the classification by Kondratiev et al. (1982))

Begin (1981a) produced a physical interpretation of the coefficient a in equation (2.1) by combination of the equation for mean shear stress $\tau_0 = \rho g D S$ and the relationship of depth and annual discharge $d = a_{**}Q^b$ suggested by Leopold and Maddock (1953). In general, the coefficient a in (2.1) is not a constant value and depends on mean shear stress and the coefficient a_{**}. On the basis of extensive data Begin (1981a) derived an average value of the mean shear stress τ_{avg}, which may be used as standard. Next he determined values of the relative shear stress τ_0/τ_{avg} thus eliminating the unknown value of a_{**}. The resulting diagram was plotted with a family of lines, which relate to different values of τ_0/τ_{avg}. The conclusion is made that, in general, braided streams have higher values of τ_0/τ_{avg} than meandering streams. However, this diagram shows that there is no clear-cut division between braided and meandering channels. From this Begin (1981a) concluded that "…the passage from one pattern to another is gradual, and the geomorphic thresholds, defined by relative shear stress, are fuzzy ones".

Bray (1982) for gravel-bed rivers in Alberta, Canada developed regime equations using the 2-year flood flow (Q_{2f}). He plotted channel slope against Q_{2f} and derived an equation in the form of (2.1), which distinguishes channels with sinuosity greater and less than 1.25. Channels with sinuosity greater than 1.25 lie below this line. Selection of the 2-year discharge was based on the following criteria. Firstly, for the Alberta gravel-bed river data the adopted discharge resulted in the highest coefficient of determination and the lowest standard error, when computing the simple hydraulic geometry relationship of Leopold and Maddock (1953). Secondly, the adopted discharge was of sufficient magnitude that it was near or somewhat above the flow at which the bed material commenced to move in the channel.

Ferguson (1984b) by empirical analysis revealed that the threshold slope for braided depends on bed material size, with gravelly braided rivers having steeper slopes than do sandy ones at the same discharge. Ferguson constructed a graph of gravel braided and sand braided channels differentiated on a slope-discharge plot with median grain size (D_{50}).

van den Berg (1995) differentiated between braided channels and single-thread sinuous channels (P>1.3) in a plot of specific stream power against median grain size (Fig. 2.17). This diagram show that as boundary resistance increases through either more cohesive banks or coarser bed material, a greater stream power is required for the onset of braiding. van den Berg (1995) defined specific stream power as:

$$\omega = 2.1 S_v Q_{bf}^{0.5} \text{ for sand-bed rivers} \qquad 2.4$$

$$\omega = 3.3 S_v Q_{bf}^{0.5} \text{ for gravel-bed rivers} \qquad 2.5$$

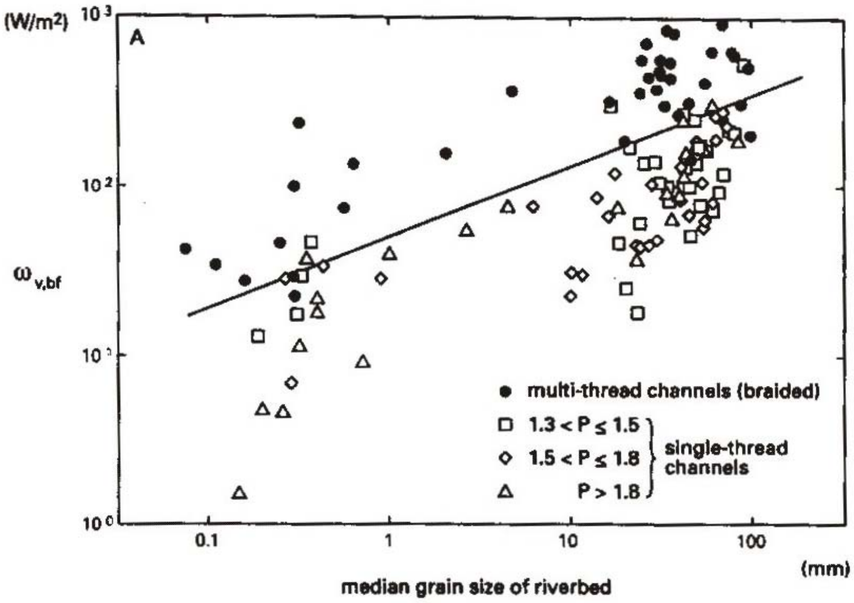


Figure 2.17: Channel pattern in relation to grain size and unit stream power (from van den Berg, 1995)

These two different equations (2.4 and 2.5) for specific stream power reflect the different cross-sectional geometry for the same discharge in sand-bed and gravel-bed rivers (Thorne, 1997). Although Thorne (1997) has concluded that for the van den Berg approach “a discriminant function of this type may well represent the logical endpoint of the line of investigation into the meandering/braiding threshold begun by Lane and by Leopold and Wolman nearly 40 years ago”, Lewin and Brewer (2001) argued by the same data that the analysis of van den Berg (1995) is invalid, because he applied the two regime-based width estimates on meandering and braided rivers, rather than actual width. Bledsoe and Watson (2001) have used $S_vQ^{0.5}$ instead of specific stream power and a logistic regression approach, which provide a probabilistic version of van den Berg’s (1995) threshold. In these papers (van den Berg, 1995; Lewin and Brewer, 2001; Bledsoe and Watson, 2001) and following discussions (van den Berg and Bledsoe, 2003 and Lewin and Brewer, 2003) has risen the question of whether sand-bed rivers and gravel-bed rivers should be analysed separately or not. Xu (2004) has concluded that there is significant difference in the hydraulic geometry among sand-bed and gravel-bed rivers with different channel patterns. This conclusion was derived from a comparison between hydraulic geometry of sand-bed and gravel-bed rivers, based on data from alluvial rivers around the world.

From the methods cited above, in most cases braided river reaches correspond to higher stream power, which is defined by the product of slope and discharge raised to some power. Various authors used different indices of the flow discharge: e.g. mean annual, median flood, or dominant discharge. Also different slopes have been used, e.g. valley, channel and water surface slope. Usually channel and water surface slopes are accepted as the same. Also generally accepted, is that appropriate parameters are the valley slope and the dominant (channel-forming) discharge. Valley slope should be used instead of channel slope to avoid biasing the plotting position of sinuous rivers that have a lower channel slope than valley slope. A channel-forming discharge should be used because it does not depend on a reference to channel geometry (Bridge, 2003) (see a definition of the channel-forming discharge in section 3.3.1.). However, there is a contradiction between field and laboratory data: in most cases from natural rivers braided river reaches correspond to higher power. But within laboratory studies as slope is decreased with constant discharge and bedload (i.e. under decrease of power), the channel can be transformed from meandering to braided because bed material overloading is occuring.

2.4. MAIN RIVER TYPES

2.4.1. Meandering rivers

2.4.1.1. Why do rivers meander?

This question is still not resolved. There are numerous theories and hypotheses explaining causes of meandering more or less for some initial (sometimes idealized) conditions but no single one has been developed that can be applied for all varieties of settings wherein meandering rivers are known to exist. The majority of the theories and hypotheses are reviewed by Yang (1971), Sakalowsky (1974), Callander (1978), Shen (1979), Chang (1988), and more recently by Knighton (1998), Chalov et al. (1998) and Da Silva (2006).

An early hypothesis stated that the Earth's rotation is responsible for flow deviation and initiation of meandering form. However, as reported by Shen (1979), there is no convincing evidence that streams in the northern hemisphere have more pronounced erosion on their right banks than on their left banks. That hypothesis nowadays has only historical interest in the science of fluvial geomorphology. Subsequently other hypothesis and theories which have a more reasonable basis and convincing evidence were put forward. The main theories and hypothesis may be grouped as: (i) theory of most probable path, (ii) bank erosion due to local disturbance, (iii) unstable response initially of the bed and afterward of the banks to a small-amplitude perturbation (stability theory), (iv) theories of energy dissipation, (v) initiation due to large-scale horizontal turbulence, alternate bars, etc. Sometimes disputes about causes of meandering are similar to the dispute concerning whether an egg or a hen came first. Obviously, for meandering initiation there must be certain initial conditions and later conditions, which support meander development. Considering an idealized straight channel (with parallel stream flow lines to the banks) to initiate a sinuous form a perturbation should occur to deviate the flow from the straight alignment and the banks should be erodible to change the channel form. The occurrence of a perturbation is germaine to the hypothesis relating bank erosion to local disturbance (e.g. Friedkin, 1945) and latteral stability theory (e.g. Engelund and Skovgaard, 1973; Parker, 1976; Callander, 1978) with a difference of the scale of perturbation. Following stability theory, and assuming that low-amplitude perturbation on a bank instead of the bed could lead to the same results, it could be concluded that an erodible bed is not a necessary initial condition for meander formation. Evidence of channels with sinuous flow and alternate bars within a straight channel (probably because the banks are not erodible for certain conditions) suggest that erodible banks are a necessary initial condition for meander formation, though the bank erodibility as a property is not a cause of meandering. After initiation due to perturbation, conditions for further development and supporting meander formation should occur. These conditions lead to formations of secondary currents or large-scale horizontal turbulence (e.g. Da Silva, 2006) and alternate bars (e.g. Nagata et al., 2000). As seen from this discussion many hypothesis and theories interlace one with another or follow on. This situation led Shen (1979) to conclude that the basic causes and explanations of meandering are possibly numerous.

2.4.1.2. Geometrical characteristics of meandering channels

Any attempt to predict and explain meander development is dependent on an adequate definition of the plan geometry of river meanders (Hey, 1984). Various characteristics have been used to define the plan geometry of meandering channels. Some of these characteristics were assembled by Leopold et al. (1964), Popov (1965, 1982), Kondrat'yev (1968), Hey (1984) and Allen (1984) and include the following (see definition sketches in Fig. 2.18):

- Wavelength (λ) – the repeating length of the meander pattern measured along the centreline of the meander belt between one inflection point and the next but one downstream. Variants include the measurement of the straight line distance through the axis of the meander pattern.
- Radius of curvature (r) - the radius of the circle defining the curvature of an individual bend and measured at the channel centreline.
- Sinuosity (P) - the ratio of channel length to meander belt axis length. Sinuosity is usually measured over a reach including several bends.
- Meander path length (l_m) – the distance along the axial line of the channel between neighbouring inflection points.
- Meander spacing (L_m) – the straight line distance connecting neighbouring inflection points.

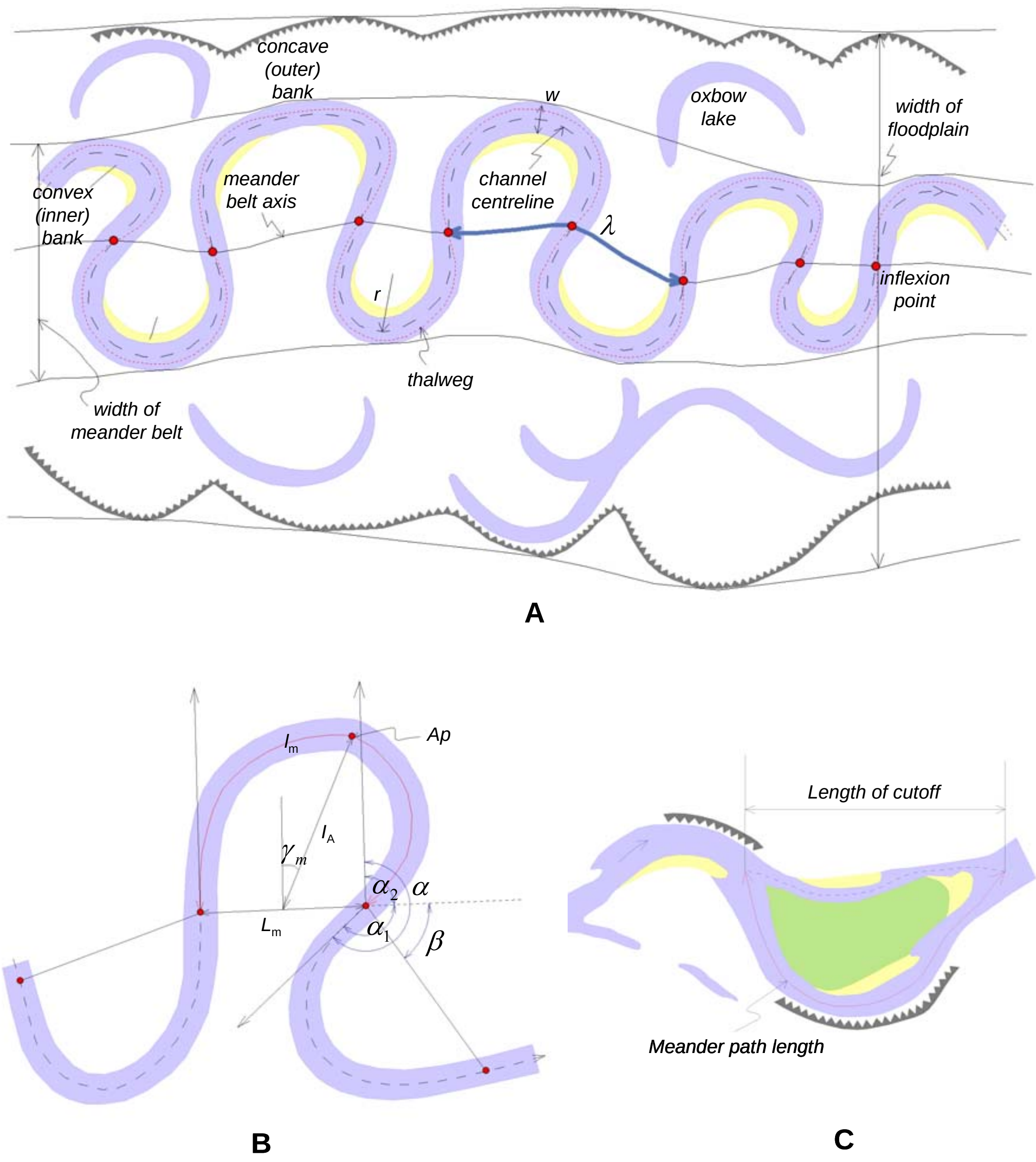


Figure 2.18: Definition sketches for geometrical characteristics of meandering rivers. Explanations in text.

(A – modified partly from Allen, 1984, partly from Kamenskov, 1987; B – from Popov, 1982; C – from Luchsheva, 1976)

- Angle of incidence (α_1) – the angle, formed by the spacing line and the ray tangent to the axial line at the upper inflection point of a meander and directed downstream.
- Angle of departure (α_2) – the angle, formed by the continuation of the spacing line and a similar ray at the lower inflection point of the meander.
- The sum of these angles is an angle of turn of the meander ($\alpha = \alpha_1 + \alpha_2$). The angle α, as well as the ratio of meander path length to meander spacing, can be regarded as indices of the degree of development of a meander.
- The mutual arrangement of two neighbouring meanders can be defined by the angle β, formed by the continuation of the spacing line of the neighbouring upper meander and the spacing line of the lower meander. The absolute magnitude of this angle is equal to the difference between the angle of incidence of the lower meander and the angle of departure of the upper meander.
- Apex of the meander (*Ap*) – a point on the axial line which is most remote from the midpoint of the spacing line.
- Meander height (I_A) – distance between the midpoint of the spacing line and the apex of the meander.
- Index of meander skewness $\varepsilon = \text{tg } \gamma_m$, where γ_m - the angle, formed by the meander height line and a line which is normal to the spacing line in its midpoint. Thus ε is the tangent of the angle γ_m.

In addition, as a characteristic of incomplete meandering, the ratio of meander path length between the beginning and the end of a cutoff (l_b) to the length of the cutoff measured along a straight line (l_c) is used (Fig. 2.18 C). The value of this ratio indicates that the cutoff formed at an early stage of meander development when it is roughly equal to unity, and that the cutoff formed at a later stage of meander development when it is about equal to zero.

The above listed characteristics define the form and size of meanders in plan view. In addition, such characteristics as channel width, width of the meander belt and floodplain width, depths in pools and riffles and the height of the floodplain are used. As reported by Hey (1984) for mathematical models of directional change characteristics such as azimuth, amplitude meander spectra and others are used. These characteristics are applied for various modelling techniques which are reviewed by Ferguson (1973). However, there are some practical and interpretative problems in the application of these techniques to river meanders (Hooke, 1984). Moreover, they do not relate in a predictive way to the processes responsible for meander development and are essentially descriptive techniques applied to suites of meanders rather than individual examples. The simpler geometric characteristics offer a more practical solution to the problem of defining the plan shape of river meanders (Hey, 1984), especially if few meanders are considered in a group.

The geometric characteristics of meanders are probably the simplest and most widely used but their exact definition and details of methods employed often vary between users and these details are also often not given in papers (Hooke, 1984). This applies particularly to wavelength, radius of curvature, sinuosity, meander belt width and meander amplitude. Therefore it can be difficult to compare the results of analyses presented by different authors.

2.4.1.3. Schemes of meander evolutions

According to Hooke (1977, 1984) meandering rivers change their position by primary elements of movement (extension, translation and rotation) and double or triple combination of these elements (Fig. 2.19). Each type of adjustment is uniquely defined by the vector of movement of points of inflexion and the apex and by the change in orientation of the apical line (Hooke, 1977). Statistical treatment of data from streams in East Devon, UK by Hooke (1977) resulted in the observation that 55% of studied bends involved some combination of extension and translation. Rotation is relatively infrequent but development of a secondary lobe is quite common. Also Hooke (1977) has concluded, that for the streams considered, in general, change around bends tends to be gradual and consistent in time, taking place by progressive erosion and deposition rather than by catastrophic change causing cut-offs or complete alteration of the direction of movement. These results were obtained via analysis of cartographic evidence of movement of channels. The classification of possible change of meander form on the one hand is detailed and shows wide variety of possible meander change but, on another hand, it does not give any conditions under which specific types of change will occur. In other words, it is not clear how to use the classification to predict meander change, rather it is useful to describe changes of meander form in the near past time.

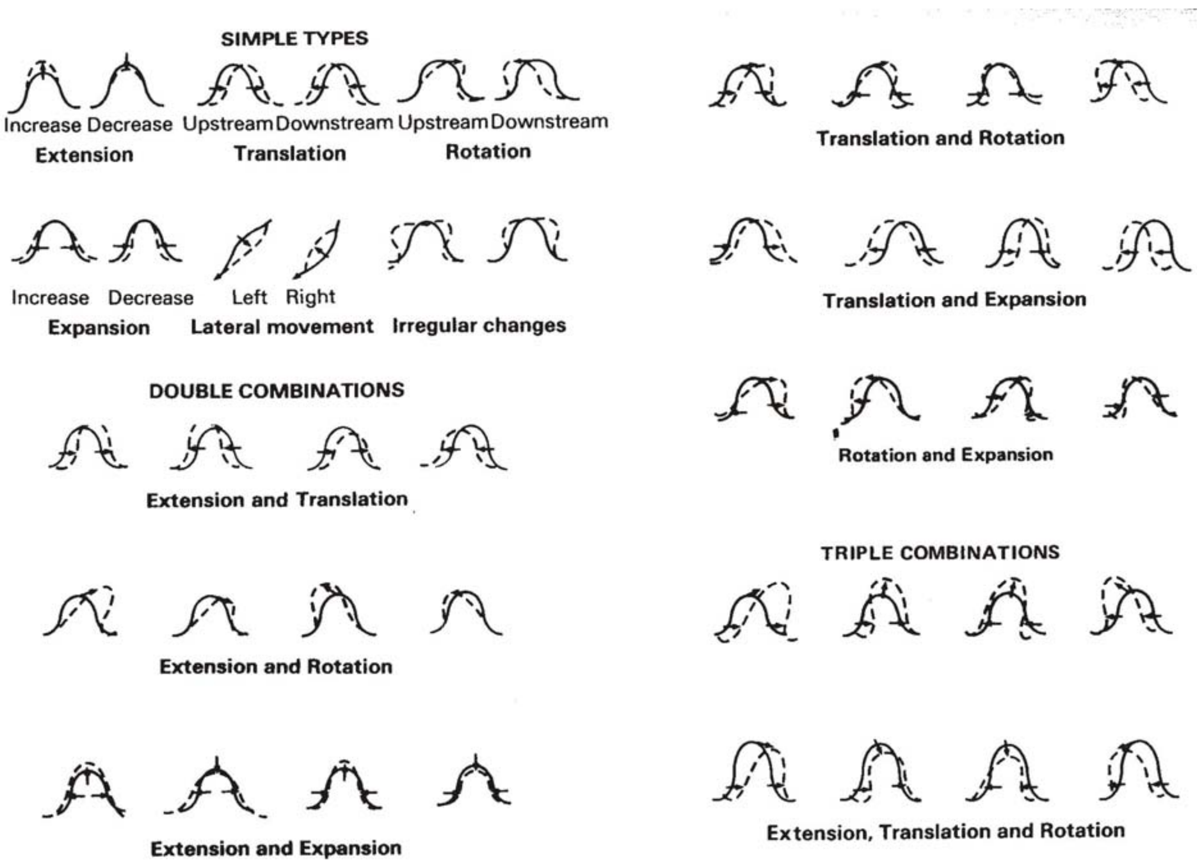


Figure 2.19: Models of meander planform change (from Hooke, 1984)

Another descriptive scheme is proposed by Brice (1974) for the evolution and classification of meander loops (Fig. 2.20). This scheme is defined by circle combinations and analysis of sequences of change. The common sequence is an increase in height of a simple symmetrical loop, then the development of asymmetry via growth of a second arc, prior to evolution into a compound loop. From the description of Brice (1974) it could be emphasized that incision and vegetation are factors of influencing cutoff and elongation. Both incision and vegetation inhibit cutoffs and thus permit the elongation of meander loops. Elongated simple loops correspond to E and F within the Brice (1974) scheme.

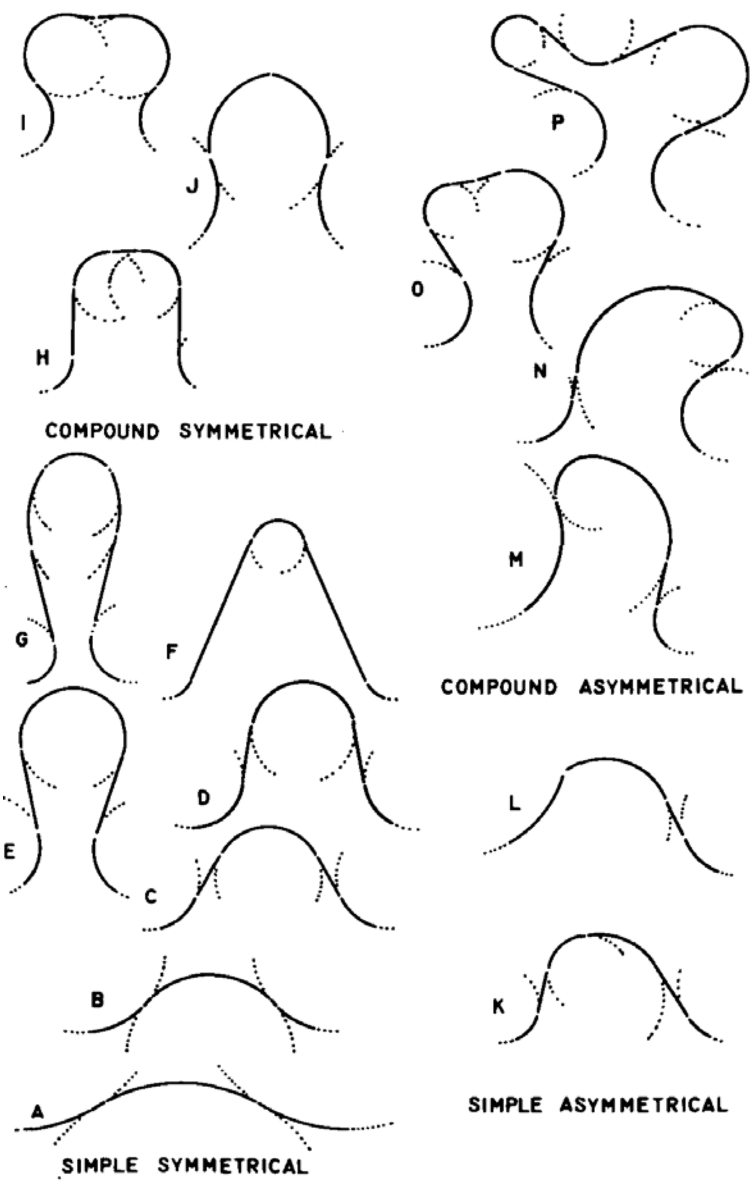


Figure 2.20: Meander loop evolution and classification scheme proposed by Brice (1974). Flow direction from left to right.

More practical is Hickin's (1974) investigation of meander scrolls on the Beatton River. By studying the surface configuration of floodplains, notably meander scrolls and the inferred erosion pathlines obtained from them, he considered the development of typical meander patterns (Fig. 2.21). Erosion pathlines provide information about the direction in the development of a meander, while the distance between ridges and dendrochronological methods can provide important information about the absolute ages of the ridges and previous hydrological conditions. In Fig. 2.21 channel types D, E, and F are the upstream-oriented counterparts of types A, B, and C.

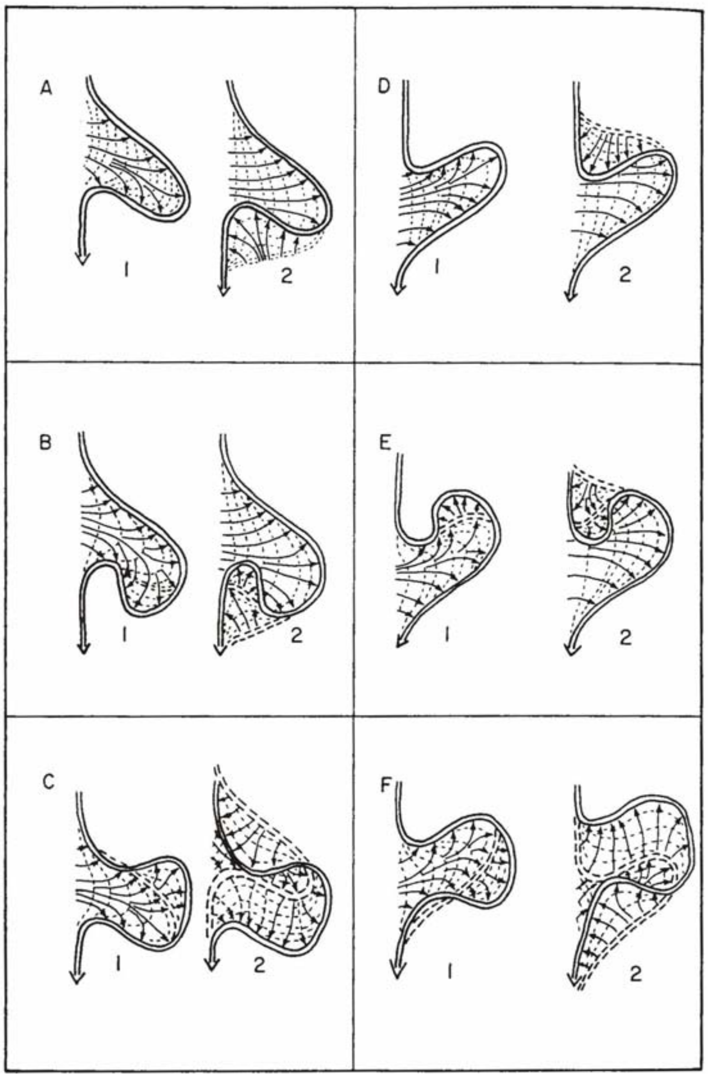


Figure 2.21: The development of typical meander patterns
(from Hickin, 1974)

Hickin (1974) proposed four general principles of meander development. However, he noticed that the principles were developed for the Beatton River and might therefore not be generic. One general principle of meander development is based on the relationship between the ratio *r*/*w* and the rate of lateral migration. Three other general principles given by Hickin (1974) are as follows:

1. During the early stages of meander development, the points of channel inflection are essentially fixed, and lateral migration of the channel bend invariably results in a reduction of the radius of channel curvature along the principal erosion-axis.
2. The radii of curvature of adjacent meander loops tend to be inversely related; that is, an increase in the radius of curvature of a given bend often results in a decrease in the radius of the adjacent meander bend.

Consequently the rate and direction of lateral erosion on a given channel bend are not independent of the erosional activity in adjacent bends.

3. Although it is generally accepted that a maximum rate of concave bank erosion occurs just downstream of the axis of symmetry of a point bar, it should nevertheless be recognized that, in many cases, a channel will respond to a critical curvature condition by eroding the concave banks on the upstream limb of a channel bend.

Kondrat'yev (1968) provided explanations of meander development on the basis of changes in the angle of turn and the symmetry of meander (Fig. 2.22). In the early stages of development the angle of turn is close to 90^o. In this case the pool hollow is shifted somewhat downstream. The symmetry is disturbed with a further increase in the angle α. The further development of a meander, and an increase in the angle of turn, are accompanied by the splitting of the pool, as shown at position 3 in Fig. 2.22. At positions 4, 5, and 6 two neighbouring meanders, located above and below, draw together and the end result is a breach of the neck connecting them.

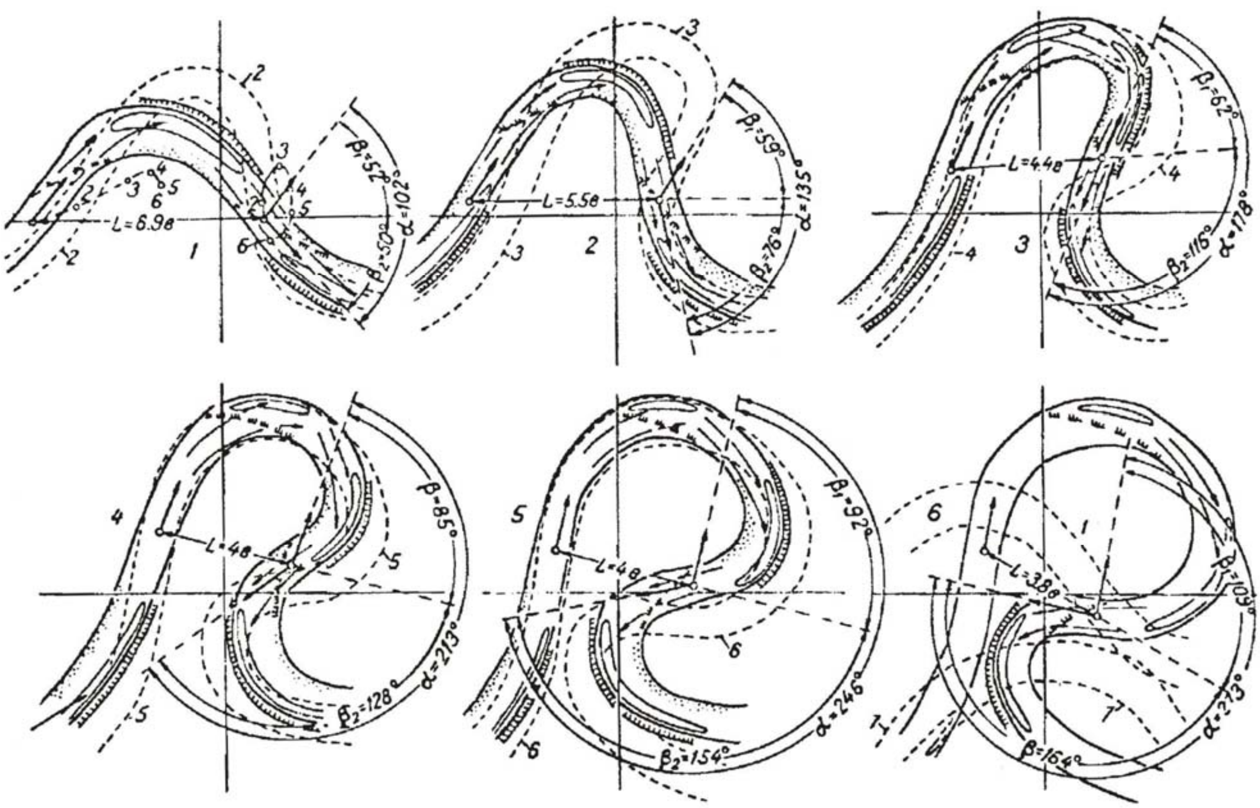


Figure 2.22: Development of a meander in free meandering (from Kondrat'yev, 1968)

On the basis of long term investigations of meandering rivers in Britain, Hooke (1995) has proposed a scheme describing the sequence of change in meander form (Fig. 2.23), which is similar to the scheme of Kondrat'yev (1968).

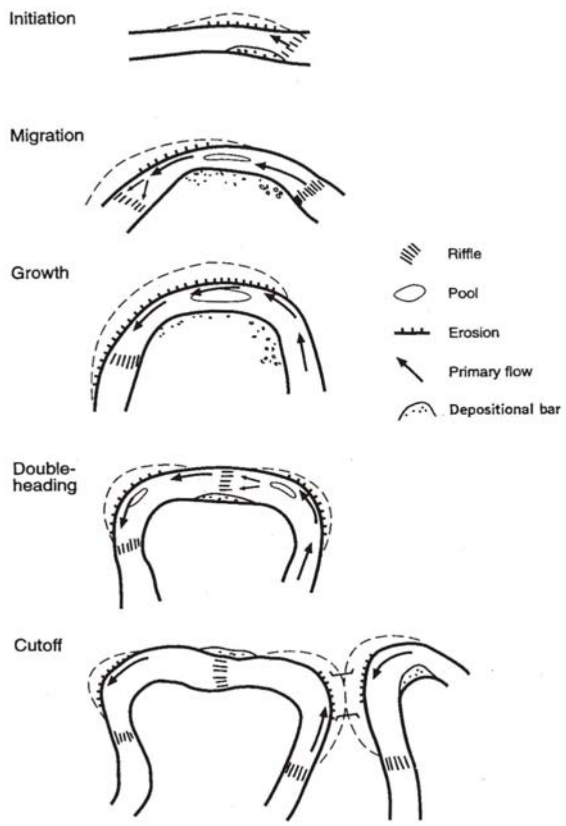


Figure 2.23: Qualitative model of sequence of change in meander form (from Hooke, 1995)

Hooke (1995) proposed the following description of meander stages:

1. New bends – these develop from straight reaches; the current becomes directed against the bank and the bend develops rapidly.
2. Migrating bend – after a certain stage, a moderately curved bend is formed. It usually has a riffle symmetrically across the channel at the entrance to the bend and flow is direct against the bank just downstream of the apex.
3. Growth bends – many exhibit a later stage of growth. These bends are often smoothly curved and the main current hugs the outer bank for much of its length.
4. Double-headed bends – the flow becomes deflected against the bank upstream of the original apex and erosion is initiated there, leading to

development of a lobe. The bends become too long for sediment to be carried right through the pool and a second riffle is deposited in the central zone.

5. Cutoff – this occurs by continuation of erosion in the lobes such that neighbouring lobes intersect.

Chalov et al. (1998) have given the following description of the stages of meander evolution, based on using the criterion l_m/L_m, which was proposed by Makkaveev (1955). If l_m/L_m>1.6 then the hydraulic prerequisites occur for either cutoff or transformation to another meander form. Free meanders in their evolution pass several stages, which are characterized by specific features of lateral migration (Fig. 2.24).

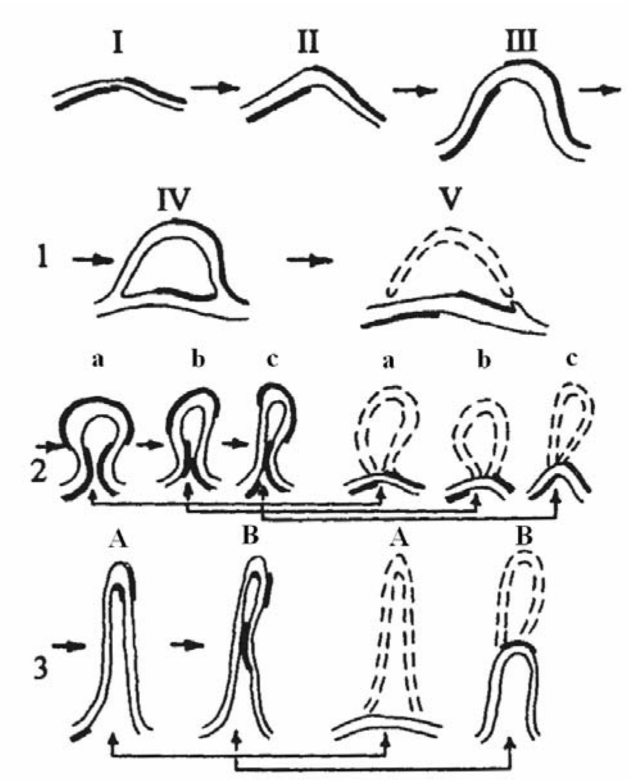


Figure 2.24: Scheme of evolution for free meandering channel (from Chalov et al., 1998)

I-V – stage of meander evolution; 1, 2, 3 – schemes of evolution when l_m/L_m >1.6; a, b, c – variants of evolution of folded meanders; A, B – variants of evolution of elongated meanders. Thick lines refer to zones of bank erosion.

At stage I a meander is weakly curved, the degree of development is 1.15<l_m/L_m<1.30; and in general a meander migrates due to downstream progression. Because the curvature of the channel and the transverse slope are small, secondary flow is poorly developed and so lateral erosion is slow. The second stage of the meander

($1.30<l_m/L_m<1.50$) is noted by activation of both sideways and lengthwise migration. At the third stage the degree of development is about l_m/L_m~1.6. The rates of migration then attain their maximum values. When the degree of development is greater than 1.6, the fourth stage is obtained. Evolution of meanders at this stage may vary. The first variant is cutting off. Cutoffs form along the lowest part of floodplains, where the maximum slope is located. This maximum value sometimes exceeds the slope in the meandering channel by two to three times. In this case the last and fifth stage is either when the old channel becomes abandoned or the old channel becomes a branch, thereby forming floodplain multibranching. The latter planform is characteristic for rivers in which the dominant discharge occurs when the floodplain is submerged (Chalov, 1979). When $l_m/L_m>1.6$, vegetation, incision into the floodplain and clay soils can inhibit cutoff. Further meander evolution occurs according to second or third schemes (Fig. 2.24). A second scheme of evolution is the transformation of meanders into meanders with a folded form in the fourth stage. In this case development is the same as the 4, 5 and 6 positions in Fig. 2.22 of Kondrat'yev (1968). When banks consist of clay, due to their high resistance to erosion, meanders can acquire an elongated form (Fig. 2.24 3). Channel reaches between two adjacent apices have straight, relatively stable banks. In the apex of the meander, the zone of erosion is localized along a short section. After this stage three variants are possible. First stabilization of the channel and banks may occur, the second possibility is chute cutoff, and the third is neck cutoff. The type of cutoff is determined by the conditions of dominant (channel forming) discharge flow and also by the height, relief, vegetation and structure of the floodplain (Chalov, 1979). In all cases when $l_m/L_m>1.6$, rates of migration gradually decrease. Therefore, the first period of evolution is two to three times less than the second period – until either cutoffs occur or the stabilization of elongated meanders is obtained. (Chalov, 2000)

2.4.2. Braided rivers

2.4.2.1. Why do rivers become braided?

Lane (1957) reported that there are two main causes of river braiding. The first is overloading, that is when the river is supplied with more sediment than it can carry, such that sediment is deposited from the flow. The second cause is due to a steep slope. With steep slope bars and islands readily form in a wide and shallow channel. Indeed, studies of natural rivers, flume and theoretical studies (e.g. Leopold and Wolman, 1957; Schumm and Khan, 1972; Parker, 1976) confirm that braiding develops when the slope is above a threshold value (see section 2.3.). Also theoretical studies (e.g. Parker, 1976; Chang, 1979) suggest that with increasing slope the degree of braiding increases. However, braiding may occur with low slopes (e.g. the Brahmaputra River (Coleman, 1969)). Possibly the critical factor is a high stream power or high specific stream power rather than simply a steep slope (Knighton, 1998). In addition, highly erodible banks and a highly variable discharge have been suggested as key factors. Shen and Vedula (1969) suggested that the basic cause of braiding is the following principle: in a narrow stream, the entire bed can act as a unit to aggrade or degrade according to the difference between the sediment supply and capacity of the flow for transport. When a stream cross section becomes too wide (due to excess bank erosion during a high flow, or weak bank resistance, or both), the entire channel cross section cannot act as a single unit, and thus part of the wide channel may be covered by numerous small channels and a braided stream occurs. Indeed, theoretical analyses (Engelund and Skovgaard, 1973; Karasev, 1975; Fredsøe, 1978; Fukuoka, 1989) indicate that braiding occurs when the width to depth ratio > 50.

As noted by Knighton (1998), none of these conditions appears by itself to be sufficient to produce braiding, although overloading, erodible banks and a relatively high stream power are probably necessary. Where these factors occur in conjunction, as in proglacial areas, braiding tends to be most prevalent.

2.4.2.2. Geometrical characteristics of braided channels

Bridge (1993) summarized some of the most widely used measures of the degree of braiding (braiding index) (Table 2.5). He divided them into two general categories. The first category considers the mean number of active channels or braid bars per transect across the channel belt. The second category considers the ratio of the sum of channel lengths in a reach to a measure of reach length. Bridge (1993) noted that classifications of the first type are more desirable, because firstly, they are related to the 'mode' of alternate bars and secondly, measurements of the second type are a combined measure of channel-segment sinuosity and degree of braiding. Consequently, it is preferable to determine separately the braiding index and average sinuosity.

In comparison with meanders, the geometrical properties of braided channels have received little attention from geomorphologists. In fact, the braiding index is not necessarily constant in the short term and tends to decrease at high stages (Thorne, 1997). Thorne (1997) has reviewed two types of braiding indices and concluded that ideally, both a measure of flow division and a measure of total sinuosity should be used to define the planform morphology of a braided reach.

Table 2.5: Braiding indices (from Bridge, 1993)

Author	Braiding index
Brice (1960, 1964)	$\frac{\text{2 (sum of lengths of bars or islands in a reach)}}{\text{centreline reach length}}$
Howard et al. (1970)	Average number of anabranches bisected by several transects perpendicular to flow direction
Engelund and Skovgaard (1973), Parker (1976), Fujita (1989)	Mode = number of rows of alternate bars (and sinuous flow paths) = 2 times the number of braid bars and number of side (point) bars per transect
Rust (1978)	Number of braids per mean curved channel wavelength = mode – 1 (see above)
Hong and Davies (1979)	Total sinuosity = $\frac{\text{Length of channel segments}}{\text{channel belt length}}$
Mosley (1981)	$\frac{\text{total length of bankfull channels}}{\text{distance along main channel}}$
Richards (1982), Robertson-Rintoul and Richards (1993)	Total sinuosity = $\frac{\text{total active channel length}}{\text{valley length}}$
Ashmore (1991)	Mean number of active channels per transect. Mean number of active channel links in braided network.
Friend and Sinha (1993)	Braid channel ratio = $\frac{\text{sum of mid-channel lengths of all channels in reach}}{\text{length of mid-line of widest channel}}$

Another way to characterize the geometry of braided rivers is ordering of channels and bars. There are various schemes to assign such orders which are summarized by Bridge (1993) (Fig. 2.25). As Bridge (1993) noted the existing channel and bar ordering schemes are difficult to apply and are not defined consistently. Williams and Rust (1969) proposed a system of braided channel classification with three levels of channels and bars (Fig. 2.25 A). First order channels formed the main anabranches of a braided system that flow around first order islands or bars. Second and third order channels in the approach by Williams and Rust (1969) dissect these first order bars to form second and third order segments of bars. The distinction between the second and third order channels is unclear (Bridge, 1993). The second and third order bars that they form are actually only dissected segments of first order bars, and these second and third order channels may well contain mid-channel bars of their own.

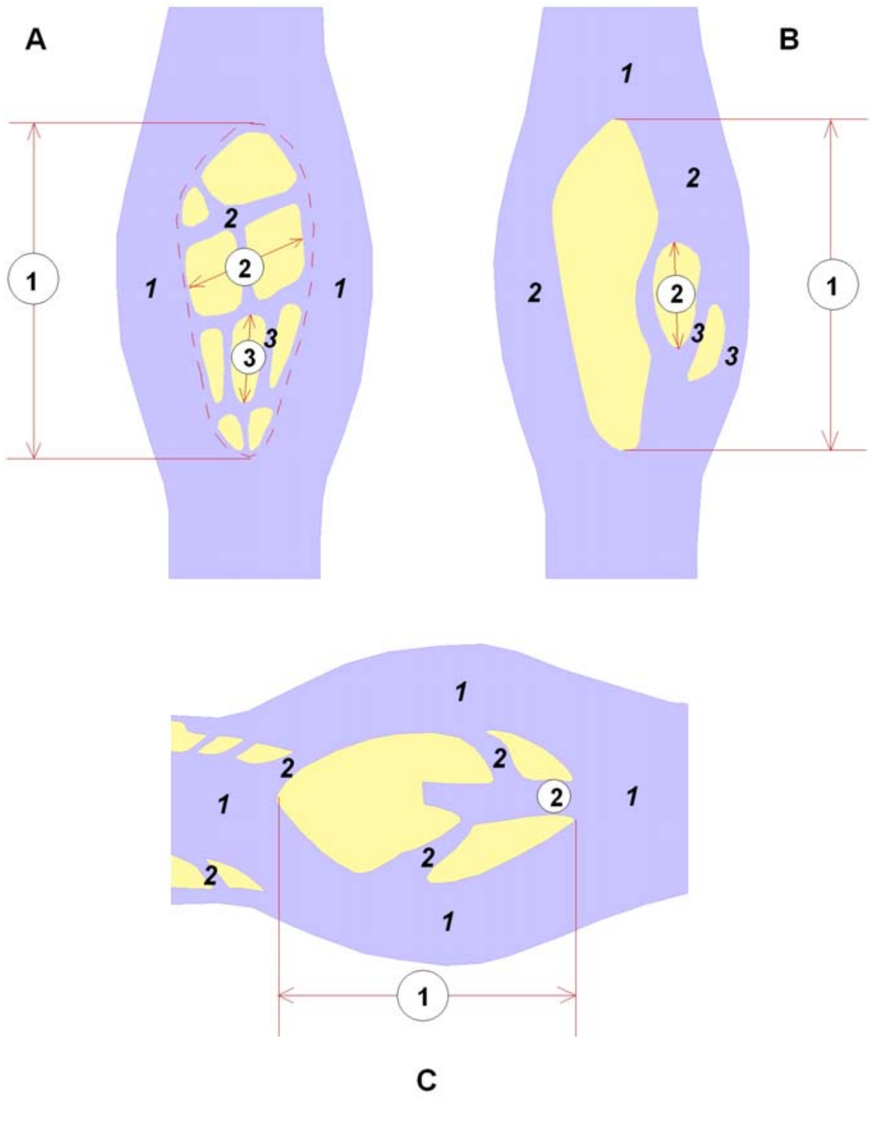


Figure 2.25: Channel and bar ordering schemes of (A) Williams and Rust (1969), (B) Bristow (1987), (C) Bridge (1993). (Redrawn from Bridge, 1993)

Bridge (1993) put forward a two level channel and bar hierarchy system, in which the largest scale of bars or islands in a system and their adjacent channels are first order, but unlike Williams and Rust's (1969) scheme, all of the channels cutting across first order bars are second order. However, the dissected segments that the second order channels form are not themselves second order bars. Second order bars are defined as those which form in and at the termination of second order channels (Fig. 2.25 C).

In a study of channel migration and deposition on the Brahmaputra River, Bangladesh, Bristow (1987) defined a three level channel hierarchy system (Fig. 2.25 B). The entire river system makes up the first order channel, with the channel margin being defined by the outermost river banks. First order channels may be comprised of several second order channels that form the main anabranches of the system, and were observed on the Brahmaputra River to display a variety of channel patterns. These second order channels may themselves contain third order channels such as cross-bar channels. Bristow (1987) found that the bars around which the channels divide and rejoin, scale with the bankfull depth and width of each channel. Further work on the Brahmaputra River by Thorne et al. (1993) confirmed the existence of Bristow's (1987) channel hierarchy system. Thorne et al. (1993) went on to describe in more detail the nature of the hierarchy system and the way in which islands, bars and various bed features were scaled by the various channel orders.

2.4.2.3. Bar types and their evolution

Various types of bars and islands have been identified in the literature with an accompanying proliferation and confusion of terminology (Hooke, 1997). Reviews are provided by Miall (1977), Church and Jones (1982) and Bridge (2003). One early and simple scheme was proposed by Popov (1965) where three types of bars are presented. Popov (1965) distinguish A) detached alternate bars; B) mid-channel bars and C) detached point bars (Fig. 2.26). Detached alternate bars have forms that are triangular in plan (Fig. 2.26 A). Their surface is weakly fixed and is composed of fine alluvium. In some cases it is possible that bars remain in the same position for a long time, allowing the formation of floodplain alluvium on their surfaces. The elevation of bars increases downstream and from the bank to the axis of flow. The height of the bars is lower than the height of the banks. Mid-channel bars (Fig. 2.26 B) frequently have a tear-shaped planform. Shifting of these bars may occur either downstream or upstream and also sideways. The flat part of the bar is depositional and steep parts are eroded. For an estimation of bar shifting overlay maps could be used. Detached point bars and islands occur under conditions of incomplete meandering and sometimes under free meandering. These bars and islands have crescent-shaped planforms (Fig. 2.26 C).

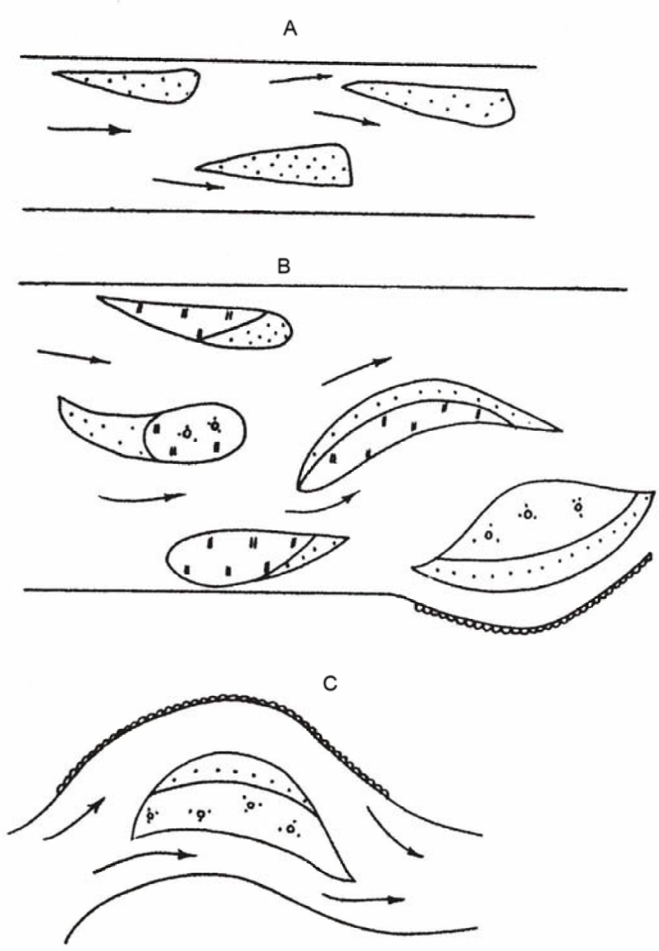


Figure 2.26: Types of bars, proposed by Popov (1965): (A) detached alternate bars; (B) mid-channel bars; (C) detached point bars. Adapted from Kamenskov (1987)

For gravel-bed rivers, Church and Jones (1982) distinguished three main bar types: 'hydraulic element' bars, 'storage element' bars and bars produced by non-fluvial effects. The first type is produced by river bed deformation and that type constitutes important flow resistance elements but may store relatively little sediment. In contrary, the second type of bars comprises the main volume of stored sediment. Although the third type is produced by non-fluvial effects, it may be incorporated into the channel pattern. In nature, combinations of these main types may occur with compound form (Church and Jones, 1982). Church and Jones (1982) further distinguished the following bar types by such basic criteria as location within a channel, degree of elongation, symmetry and presence or absence of distal avalanche faces: longitudinal and crescentic, transverse, medial, point and diagonal bars. The main evolutionary transformation from one type to another was presented as a scheme (Fig. 2.27) with a direction of stability change. As noted by Church and Jones (1982), the most common transformation is towards the diagonal form, although transformation from the diagonal form to the longitudinal form may also occur. Regarding stability, the attached diagonal bar is apt to be stable and therefore it is an important, stabilizing feature of the channel (Church and Jones, 1982)

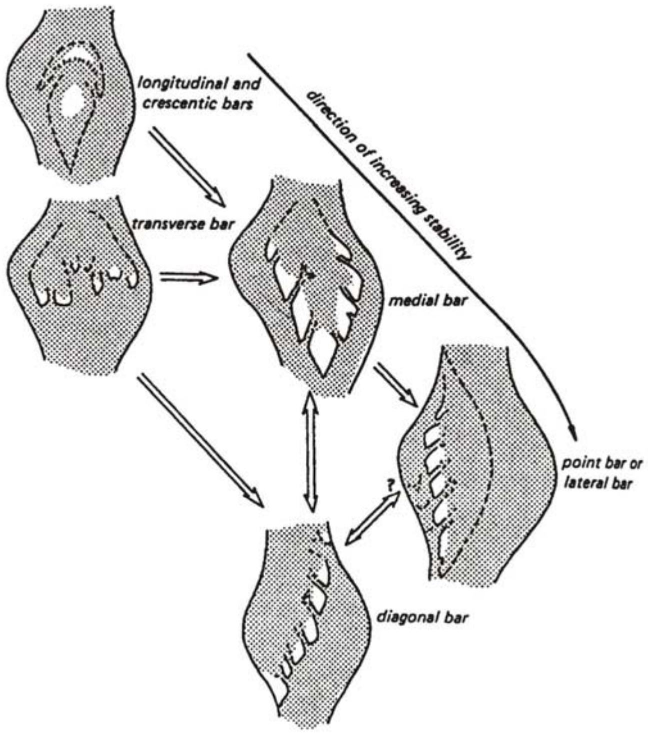


Figure 2.27: The main evolutionary transformations of gravel bars (from Church and Jones, 1982)

2.4.3. Anabranched rivers

2.4.3.1. Why do rivers anabranch?

Huang and Nanson (2007) noted that until recently a convincing theoretical explanation of anabranched rivers has remained elusive. They explained the formation of anabranches on the basis of the principle of the maximum flow efficiency of alluvial channels. The maximum flow efficiency is defined as the maximum amount of sediment that can be transported per unit stream power. In self-adjusting systems, when a river must transport supplied sediment load with available energy, the slope could be adjusted to maintain equilibrium, but in the case when the slope can not be increased because the valley slope is particularly low, a river should increase its efficiency in order to transport supplied sediment load. This increasing of flow efficiency could be achieved by developing in-channel islands and ridges to reduce channel width/depth ratios in accordance with the quantitative theory proposed by Huang and Nanson (2007). However, in that theory the relationship between the width/depth ratio and the transport capacity is complex because, beyond a certain point, an increase in the number of anabranches can cause a decrease in the transport capacity. Therefore anabranching is usually dominated by one or two major anabranches that achieve most of the transport efficiency (Huang and Nanson, 2007). Such interpretation could be applied also for braided river formation when braiding occurs at low slopes. Therefore, in regard to anabranching, Huang and Nanson (2007) have noted that the adjustment can lead to anabranching only with the aid of suitable riparian vegetation, and with associated deposition of relatively cohesive sediments on the channel banks and islands.

There are such processes as accretion and avulsion which are essential for forming and maintaining multiple anabranch channels (Nanson and Knighton, 1996; North et al., 2007). Avulsion, as defined by Allen (1965), is the relatively rapid abandonment of a part or the whole of the river channel for some new course at a lower part on the floodplain. Causes of avulsion were reviewed by Jones and Schumm (1999), Makaske (2001), Bridge (2003), Slingerland and Smith (2004), and Stouthamer and Berendsen (2007). Jones and Schumm (1999) organized the causes of avulsion into four groups (Table 2.6). Also they introduced the concept of the avulsion threshold, i.e., a state of extreme channel instability resulting in avulsion. The closer a channel is to the avulsion threshold, the smaller the event needed to trigger the avulsion. Triggers may determine the time, as well as the location of avulsion (Makaske, 2001). From their overview of the causes of avulsion Jones and Schumm (1999) concluded that the processes which lead to the attainment of the avulsion threshold (sinuosity increase, delta growth, natural levee growth, alluvial fan growth and increase in delta convexity) are integral (intrinsic) to the river and appear to be related to sedimentation. If the rate at which those processes proceed is a predictable function of sedimentation rate, then a relationship between avulsion frequency and sedimentation rate may exist in some settings. Other processes (tectonism, sea- or lake-level change, mass failure, aeolian dune migration, log jams, vegetative blocking and presence of animal trails) are the result of external (extrinsic), non-fluvial influences. In settings where these types of processes occur, avulsion frequency may be less predictable and may be unrelated to sedimentation rate (Jones and Schumm, 1999).

Table 2.6: Causes of avulsion. (from Jones and Schumm, 1999).

Processes and events that create instability and lead toward an avulsion threshold, and/or act as avulsion triggers		**Can act as trigger?**	**Ability of channel to carry sediment and discharge**
Group 1. Avulsion from increase in ratio, S_a/S_e*, owing to decrease in S_e	a. Sinuosity increase (meandering)	No	Decrease
	b. Delta growth (lengthening of channel)	No	Decrease
	c. Base-level fall (decreased slope†)	No	Decrease
	d. Tectonic uplift (resulting in decreased slope)	Yes	Decrease
Group 2. Avulsion from increase in ratio, S_a/S_e, owing to increase in S_a	a. Natural levee/alluvial ridge growth	No	No change
	b. Alluvial fan and delta growth (convexity)	No	No change
	c. Tectonism	Yes	No change
Group 3. Avulsion with no change ratio, S_a/S_e	a. Hydrological change in flood peak discharge	Yes	Decrease
	b. Sediment influx from tributaries, increased sediment load, mass failure, aeolian processes	Yes	Decrease
	c. Vegetative blockage	No	Decrease
	d. Log jams	Yes	Decrease
	e. Ice jams	Yes	Decrease
Group. 4. Other avulsions	a. Animal trails	No	No change
	b. Capture (diversion into adjacent drainage)	-	No change

* S_a is the slope of the potential avulsion course, S_e is the slope of the existing channel.
† In settings where the up-river gradient is greater than the gradient of the lake floor or shelf slope, base-level fall may result in river flow across an area of lower gradient.

The somewhat different process of channel relocation is described by North et al. (2007) which they refer as channel obtrusion. The difference between obtrusion and avulsion is that obtrusion is a gradual formation of an alternative channel. By examples from dryland anabranching rivers, North et al. (2007) showed that in some rivers there is no evidence of abrupt avulsions. Anabranches instead seem to occur incrementally over a great number of flood events by the slow expansion of selected floodplain-surface channels until they become large enough to capture bankfull flows (North et al., 2007).

2.4.3.2. Geometry and evolution of anabranched channels

To describe the geometry of an anabranched system one could use braiding indices similar to those for braided rivers (see Table 2.5 for various ways to define braiding indices). For example, Burge and Lapointe (2005) have used a braiding index for the wandering section of the Renous River (Canada) and Nanson and Knighton (1996) have used the ratio of island length to channel width for types and subtypes of anabranching rivers. Tooth and Nanson (2004) as a measure of the degree of anabranching used the number of channels across a section. However, they noted that defining the number of channels involves a degree of subjectivity.

Chalov (2000) has proposed a scheme of erosion and accumulation locations in anabranched rivers on the basis of geometrical characteristics. If the form of islands satisfies the condition l_i=3-4w_i (l_i – length of island, w_i – width of island), then the locations of erosion correspond to those as in a slightly widening meander (Fig. 2.28 A). Usually erosion occurs in the upstream parts of islands and opposite downstream banks. However, in gravel-bed rivers and in rivers with large bedload, island shoals form in the upstream part. In this case the island has a spindle-shaped form (Fig. 2.28 B). Locations of erosion occur only on the banks. When islands are elongated (l_i>3-4w_i), smaller islands may occur in each branch, thereby forming secondary branching (Fig. 2.28 C). When l_i>3-4w_i the sideway development of islands dominates (Fig. 2.28 D). If the length of the branch l/L=1.4-1.6, where L = the length of straight branch, then discharges are redistributed and the greater part of the flow goes into the straight branch, the winding branch become shallow, and the processes recur. As a result, fan branching may occur. Each branch is in a different degree of development and differs from others by its intensity and length of erosion.

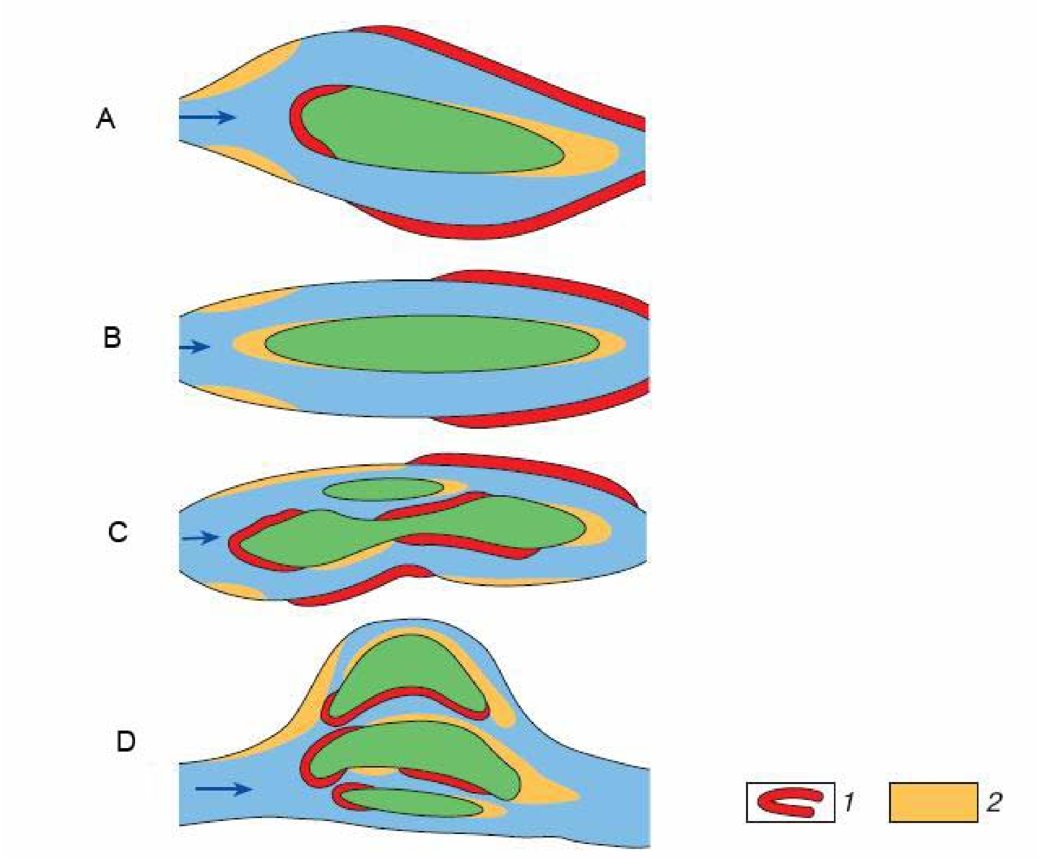


Figure 2.28: Locations of erosion and accumulation: A and B – simple branching; C – with secondary branching; D – fan-like branching. 1 – erosion; 2 – accumulation. From Chalov (2000).

2.5. BANK EROSION ESTIMATION AND PREDICTION METHODS

The literature reveals that a wide variety of methods for bank erosion estimation and prediction have been formulated. Each of these methods has their own particular advantages and limitations. All methods could be divided into empirical methods and models. In turn, the models could be divided as kinematic and dynamic (Ferguson, 1984a, Mosselman, 1995, Piégay et al., 2005).

2.5.1. Empirical methods

Studies using geometrical and flow characteristics of channels have yielded a number of empirical relationships with bank erosion rate. These studies reviewed by Kondratiev et al. (1982), Knighton (1998) and recently reviewed by Richard et al. (2005). A summary of empirical relationships for bank erosion rate is presented in Table 2.7. From this table it can be seen that the majority of empirical relationships are for geometrical characteristics. Relationships between erosion rate and the curvature radius to channel width ratio have been widely used since studies by Hickin and Nanson (1975, 1984). They demonstrated that the erosion rate (C) normalized by width (w) increased with decreasing r/w to a maximum when $2<r/w<3$ (Fig. 2.29). Hooke (1997) compiled data from various sources to represent the relationship between erosion rate and curvature, which confirms the finding by Hickin and Nanson (1975). Hickin and Nanson (1975) and Nanson and Hickin (1983) obtained channel migration rates C for the Beatton River by applying the methods of dendrochronology to trees growing on the scrolls. They found the following equations:

$$C=2.0\ w/r\ (w/r \leq 0.32) \qquad 2.6$$

$$C=0.2\ r/w\ (w/r>0.32) \qquad 2.7$$

Hickin and Nanson (1984) further suggested that the coefficients in these equations are closely related to the texture of the bank materials. An amount of point scatter occurs in these relationships and partly is explained by variations in factors such as stream power and outer-bank sediment size, and may in part be related to other aspects of bend geometry (Knighton, 1998).

Table 2.7: A summary of empirical relationships between bank erosion rate and other parameters (after Richard et al. (2005) with additions)

Source	Significant relationship	Notes
Hickin and Nanson (1975), Nanson and Hickin (1983)	$C \sim r/w$	Also identified bank texture, planform, and sediment supply rate as important
Hooke (1979)	$C \sim Q_{peak}$, API	API = Antecedent precipitation index
Hooke (1980)	$C \sim A$ (drainage area) $C \sim$ % silt-clay in bank	
Begin (1981b)	$C \sim r/w$	
Kondratiev et al. (1982)	$C \sim w$	
Popov (1982), Krutovskiy (2002)	$C \sim l_m/L_m$	
Berkovich and Vlasov (1982)	$C \sim Q$, S, h and D_{50}	
Nanson and Hickin (1983)	$C \sim Q$ and S $C \sim w$ and S $C \sim Q$, S and D_{50} $C \sim w$, S and D_{50}	
Hickin and Nanson (1984)	$C \sim r/w$	Also identified bank resistance as important
Nanson and Hickin (1986)	$C \sim Q$, S, D_{50}, w, h, ω and Ω	
Biedenharn et al. (1989)	$C \sim r/w$	
Thorne (1991)	$C \sim r/w$	Also identified bank material and geologic controls as important
Antropovskii (1991)	$C \sim w$	
Klaassen and Masselink (1992)	$C \sim w$, r/w	Assuming that bank resistance and sediment concentration do not vary. Bank vegetation was not important
MacDonald (1991)	$C \sim h$	
Xu (1997)	$C \sim BI$	BI – braiding index
Lawler et al. (1999)	$C \sim L$	L = distance downstream. Also found stream power and bank material to be important
Walker and Rutherfurd (1999)	$C \sim A$, Q, S, d, w and Ω	Also identified bank resistance as important
Rutherfurd (2000)	$C \sim Q$	
Shields Jr. et al. (2000)	$C \sim w$, r/w	Comparing pre- and post-dam rates
Van De Wiel (2003)	$C \sim A$	
Richard et al. (2005)	$C \sim Q$, S, D_{50}, w and Ω	Comparing pre- and post-dam rates

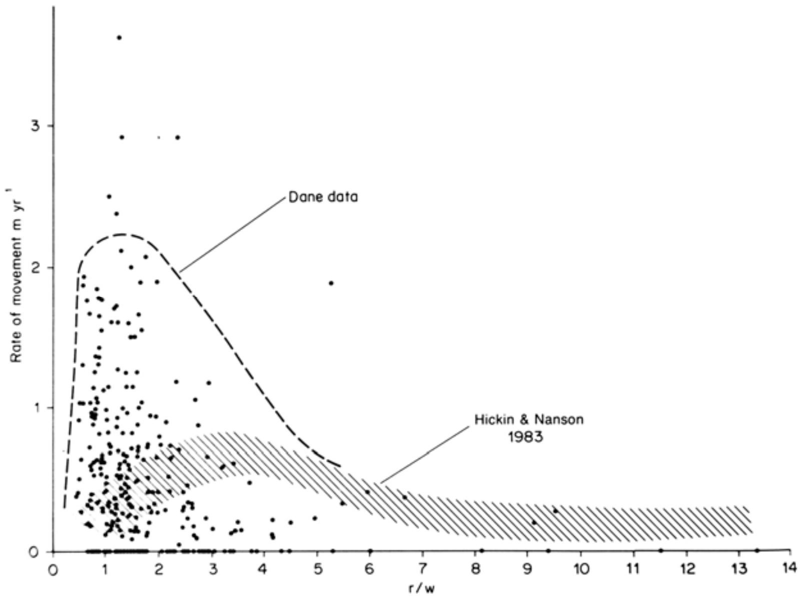


Figure 2.29: A relationship between average migration rate and the ratio of radius of curvature to channel width.

It is nevertheless difficult to consider the radius of curvature of the channel as the sole factor governing bank erosion. This difficulty is encapsulated in Fig. 2.29 wherein it is evident that two distinct data sets plot with dissimilar r/w peaks. Indeed, Furbish (1988, 1991) showed that the migration rate varies with bend length as well as curvature. In his studies the average migration rate increases monotonically with average curvature if differences in bend length are taken into account. Popov (1982), on the basis of extensive experimental studies, noticed that in the course of the development of free meanders, erosion rates increase until a value of l_m/L_m=1.6 (l_m=meander or bend length) is reached, and then decrease. For example, Krutovskiy (2002) using data from a number of bends in the Chulym River (Western Siberia, Russia), has plotted a curve which shows a relationship between maximum erosion rate and l_m/L_m (Fig. 2.30). Popov (1982) also found that rates of meander migration are directly proportional to channel depth and that with an increase in the frequency of floodplain submerge, cutoffs occur in earlier stages of meander development (for incomplete meandering).

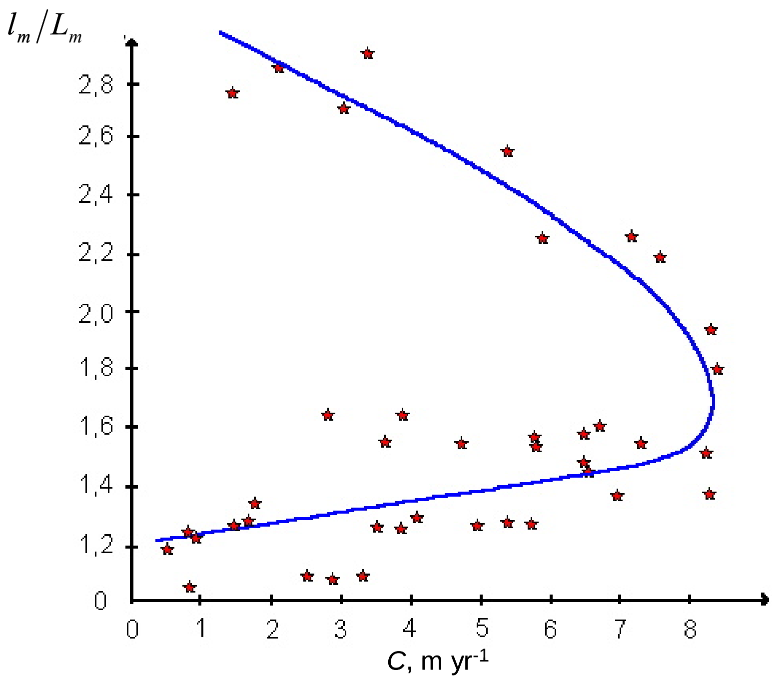


Figure 2.30: A relationship between maximum bank erosion rate (*C*) and l_m/L_m for the Chulym River (from Krutovskiy, 2002)

The scatter in Fig. 2.30 could be due to the variation in resistance of bank material to erosion. For example, from observations by Kamenskov (1987) on the Ob and Chulym rivers (Western Siberia), erosion of terraces occurs five to ten times more slowly than erosion of floodplain banks, which are lower in height than terraces, under the same degree of meander development. Thus, the relation between bank erosion rate and degree of meander development shown in Fig. 2.30 may be without scatter only in the case of uniform bank structures and with constant discharge and sediment load in all meander bends. Therefore, rates of bank erosion should depend on the degree of meander development, bank material resistance to erosion, bank height, water discharge and sediment load.

Findings by Hickin and Nanson (1975) and by Popov (1982) show that bank erosion rates have nonlinear relations with the degree of meander development (r/w and l_m/L_m). Kamenskov (1987) provided the following explanation of that phenomenon. As the degree of meander development is increased, the slope of the water surface is decreased which in turn leads to a reduction of water velocity. But, in the early stages of meander development the asymmetry of the flow pattern is increased such that maximum flow velocities occur near to the outer bank. The action of this factor ceases to be effective as meander bends become more developed and the slope continues to decrease. Consequently, rates of bank erosion decrease.

Makkaveev (1955) determined that the hydraulic utility of the meandering form is lost when the local increase in the kinetic energy of flow becomes equal to the energy loss of the flow. Makkaveev (1955) defined this condition as l_m/L_m=1.6. Bagnold (1960) on the basis of experimental results found that total resistance of the boundary reaches a minimum when *r*/*w* is approximately 2. At values of *r*/*w* below 2, Bagnold (1960) suggested that the flow along the inner boundary becomes unstable and breaks away from the boundary. Energy dissipation occurs and the flow loses energy. At values above 2, there is higher resistance of the boundary. More recently Markham and Thorne (1992) have studied flow patterns in different zones of a bend and the development of flow separation. They have concluded that separation at the inner and outer bank is an important bend flow process for channels with small width to depth ratios. Outer bank separation occurs at a lower *r*/*w* value than that for inner bank separation. When flow at the inner bank separates, meander evolution switches from lateral growth to downstream migration. If outer bank separation occurs, the bend may divide in two (double heading) or cut off (Lagasse et al., 2004).

Using a somewhat different empirical method, Hooke (1980) related bank erosion rates from several streams in Southeast Devon to catchment area (as a surrogate of discharge and width). The analysis reveals an approximate square-root relationship between bank erosion rate and catchment area. The equation obtained is:

$$C=2.45A^{0.45} \qquad 2.8$$

where C = bank erosion rate (m yr^{-1}); A = catchment area (km^2).

However, this relation is broad, since the many factors other than catchment area that might influence migration rates are not accounted for (Hasegawa, 1989a). Indeed, after investigating the relation between *C*/*w* and various parameters expected to influence bank erosion rate, Hooke (1980) found that bank erosion may be influenced by a complex combination of other factors (e.g. silt-clay content of bank material, presence of a gravel layer, width-depth ratio, radius of curvature, slope, bank height). Lewin (1987) reported that maximum bank erosion rates occur in ‘middle reaches’ of a catchment. In middle reaches stream power is quite high, indeed may be at its maximum, but material is alluvial and usually highly erodible because of maximum sand content in these reaches, whereas further downstream gradient declines and clay content tends to increase (Hooke, 1995). However, for Welsh rivers a high correlation between meander mobility and stream power was not found by Lewin (1987). Atkinson et al. (2003) have used a geographically weighted logistic regression model to study the relations between riverbank erosion and geomorphological variables, finding that the relation between stream power and bank erosion is inverse and direct for different positions along a river.

Berkovich and Vlasov (1982) developed an equation to calculate bank erosion rate where several parameters are related with bank erosion rate. In this equation the relationship between bank erosion rate (*C*) and mean annual discharge (*Q*), slope (*S*), grain size (*D*) and bank height (*h*) is given by:

$$C = k\frac{Q^2 S}{Dh} \quad 2.9$$

Using bank erosion rate data, Berkovich and Vlasov (1982) were able to define the values of the empirical coefficient (*k*), showing that it depends on discharge and channel width (Table 2.8).

Table 2.8: Values of the empirical coefficient *k* in the equation of Berkovich and Vlasov (1982) (from Makkaveev and Chalov, 1986)

***Q*, m sec^{-1}**	***w*, m**	***k*, (sec m^{-3})**
>5000	>15000	$0.8*10^{-5}$-$1.1*10^{-5}$
5000-1000	1200-600	$8.5*10^{-5}$-$9.2*10^{-5}$
1000-500	350-200	$3.0*10^{-4}$-$3.4*10^{-4}$
500-300	150-100	$5.1*10^{-4}$-$5.8*10^{-4}$
<300	<50	$5.0*10^{-3}$-$6.0*10^{-3}$

Chalov (2000) pointed out that this method considers also the relation between bank erosion rate and bank height. From equation 2.9, the higher the bank, the lower the rate of bank erosion. Antropovskii (1991) has used the method of Berkovich and Vlasov (1982) and other two methods to estimate the rate of lateral migration in the Amur River and for several rivers in Western and Middle Siberia. One method is based on constructing regional relations of the equiprobable values of the specific coefficients of the lateral migration rate (K_c) and river width (K_w). He found that for morphologically uniform stretches of the Amur River $K_c=K_w^{1.70}$, whereas for morphologically uniform stretches of rivers in the southern part of Western and Middle Siberia $K_c=1.50K_w-0.50$. However, it is not clear how these coefficients are defined and Antropovskii (1991) did not provide a description. Another method is based on the assumption that the ratio of the lateral migration rate to the river width at the edges of the low-water banks, characteristic for a morphologically uniform stretch, remains the same during the design time, i.e. C/w*100%=*const*. Also Antropovskii (1991) used the probability curve C/w*100%=$f(p)$, which was plotted from the data on the investigated river reaches under natural conditions (Fig. 2.31). Then in the calculations the probability p=50% is used to determine the average long-term rates (“normals”) of lateral migration.

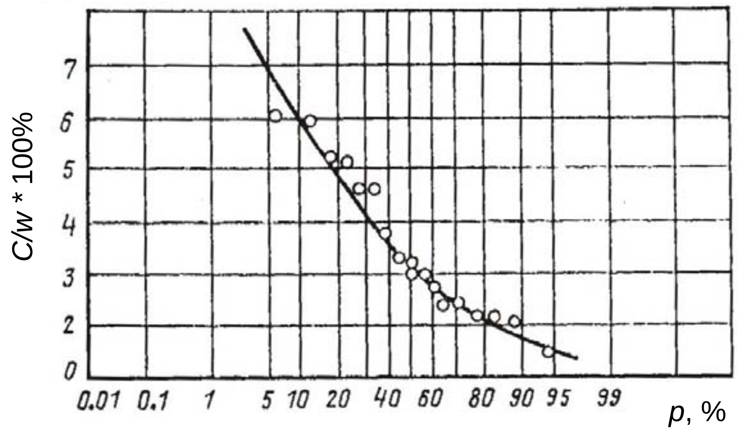


Figure 2.31: Probability curve of the maximum lateral migration rates of the main channel of the Lower Katun River (in % of the river width *w*) during the period from 1970 to 1987. (from Antropovskii, 1991)

For the last two methods, channel width was determined from empirical hydraulic geometry relations, notably the relations which were suggested by Altunin (1958) and Kroshkin (1984). Antropovskii (1991) has used these methods to predict rates of bank erosion under conditions which will occur after the construction of a dam. By comparison with measured bank erosion rates, all methods give lower values of bank erosion rate with a difference of c.20-25% from the measured rates.

In comparison with meandering rivers, for braided rivers it is more difficult to construct a relationship of plan-view characteristics (braiding indices) and rates of bank erosion, because these parameters are more changeable in time and space than for meandering rivers. Therefore, methods to predict lateral bank erosion for braided rivers are still very poorly elaborated. However, in the literature there is at least one example with somewhat high correlation between braiding index and bank erosion rate which was presented by Xu (1997) for the middle Hanjiang River (Fig. 2.32). From this relationship bank erosion rate is likely to be higher in river reaches with higher values of braiding index, i.e. with greater number of mid-channel bars.

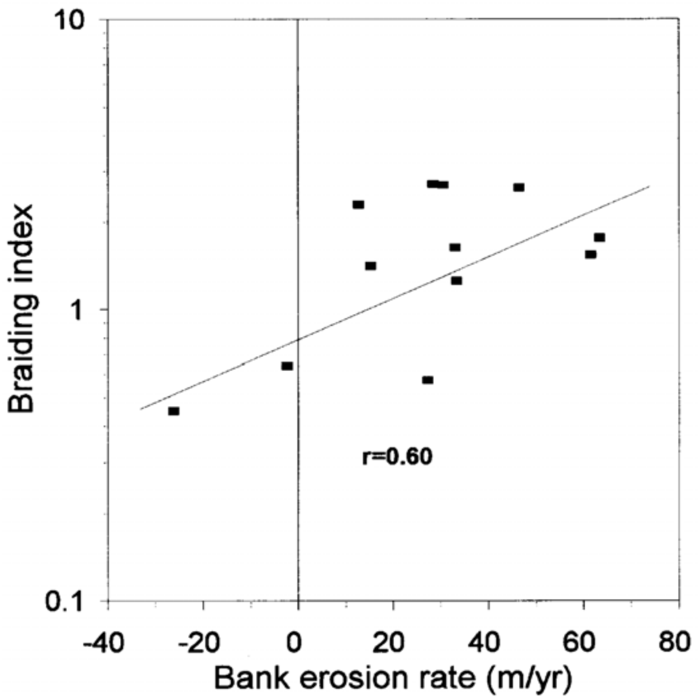


Figure 2.32: A relationship between braiding index and bank erosion rate. Negative values indicate bank deposition. (from Xu, 1997)

2.5.2. Kinematic models

Ferguson (1984a) defined kinematic models as those which involve geometry and time. From this definition, approaches based on historical analysis also are kinematic models, although in the literature authors refer to kinematic models as only those studies which are based on relations between bank erosion rates and curvature.

Prediction of meander migration may be made using two or more previous maps or aerial photographs by comparison of graphical materials of different dates and then extrapolation of lateral erosion rates into the future. Ideally the maps should be modern as historic maps are often inaccurate or only indicative of the position of banklines. In recommendations given in Anonymous (1985) it is suggested that graphical materials should have dates with intervals of not more than five to seven years and one map should be recent. Brice (1971) stated that erosion rates defined from analysis of graphical materials can be used for prediction if the period between different dates include a representative number of high flows, during which most lateral erosion occurs. The basis of this method is an assumption that rates of parameter change, which are determined from map overlays, will remain constant during the period of prediction. Comprehensive development of this method was performed recently by Lagasse et al. (2004). Authors have used such parameters as outer bank radius of curvature, and the amount and direction of migration of the bend centroid. An example of using this method is illustrated in Fig. 2.33. The advantage of the method by Lagasse et al. (2004) is that the method can be easily used with GIS. In this case the subjectivity of measurements and calculations is reduced. However, it does not take into account that the relation between bank erosion rates and degree of development is nonlinear.

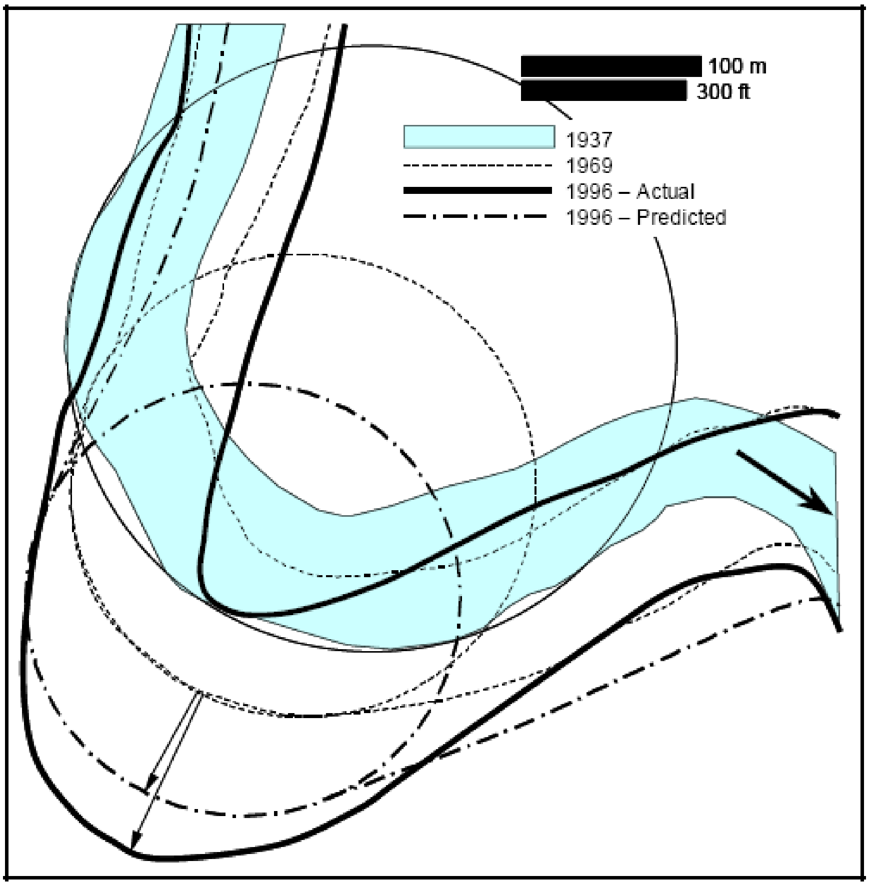


Figure 2.33: Channel migration comparison for the Tombibee River near Amory (from Lagasse et al., 2004)

The most widely used kinematic models are models that use the relation proposed by Hickin and Nanson (1975). As noted by Hooke (2003) tests in applying kinematic models produced realistic-looking meanders, with lobing and double-heading (Fig. 2.34). From applying this model to actual rivers (e.g. Gilvear et al., 2000) it has been concluded that the model replicates the major features of the meandering course.

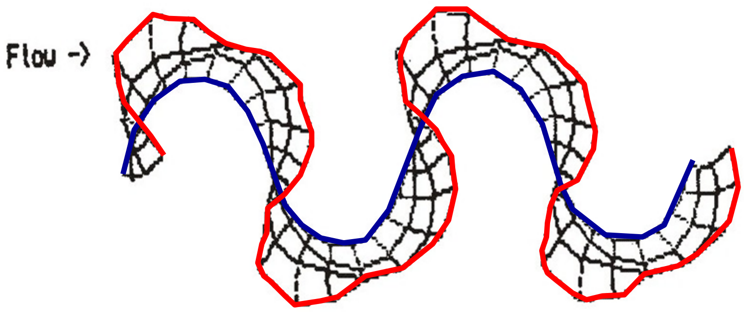


Figure 2.34: Simulation of changes of a simple sine wave using Ferguson's (1984a) model, producing asymmetry (from Hooke, 2003)

blue curve – initial position of a channel; red curve – in the end of simulation.

If maps and aerial photographs of previous dates are not available for a meander bend, and there are data available for adjacent bends which have similar conditions of meander development, then prediction may be realized using the following method [Anonymous, 1985]. The first step is to estimate the maximum erosion rate on the basis of available data. Using data from adjacent meander bends C_{max} is calculated using:

$$C_{\max} = \frac{\sum_{i=1}^{n} (C_i / \kappa_i)}{n}, \qquad 2.10$$

where C_i = maximum erosion rate in each meander, for which data is available; κ_i = coefficient of rate of meander development, which depends on the angle of turn α (Table 2.9); n = number of meander bends.

Table 2.9: The coefficient κ_i in the equation 2.10 for different α (from Anonymous, 1985)

α	10	20	30	40	55	70	85	100	125	170	215	240	260
κ_i	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	0.9	0.8	0.7

The lateral shift of the bankline L_{bank} in a given cross section can be calculated by the equation of Kondrat'yev (1968):

$$L_{bank} = \kappa_i C_{\max} T \left(d_{\max i} - d_{avg}\right)\left(d_{pool} - d_{avg}\right), \qquad 2.11$$

where $d_{\max i}$ = the maximum depth in a given cross section; d_{pool} = the maximum depth in the whole meander bend; d_{avg} = the average depth of the two riffles which limit the given meander bend; T = the time period of the prediction. For this method a longitudinal profile along the thalweg is required.

This equation can be also used if initial cartographic materials are available for a given meander bend. In this case C_{max} is determined directly for a given meander bend by overlay of maps or aerial photographs. Also for this method a longitudinal profile along the thalweg is required.

Kinematic models also are used for braided rivers. A review of kinematic models for braided rivers is given by Jagers (2003). As an example from studies in the braided Brahmaputra-Jamuna River, Mosselman et al. (1995) concluded that the correlation between annual erosion and magnitude and duration of the annual flood was weak, and that channel abandonment was clearly correlated with upstream bifurcation geometry. Therefore they simulated bank migration of individual channels in a braided river using a kinematic model. However, employing a kinematic model for braided rivers is more complicated than for meandering rivers because the model should be applied for each branch of a braided system.

2.5.3. Dynamic models

Dynamic models, in comparison to kinematic models, are based on descriptions of physical processes which influence bank erosion. Reviews of dynamic models were provided by Mosselman (1995) and more recently by Piégay et al. (2005) and Duan (2005). Klaassen et al. (1993) roughly divided dynamic models into categories in the order of increasing complexity:

1) Meander models based on the equations for water flow and bank migration in curved equiwidth channels (e.g. Ikeda et al., 1981);
2) Meander models based on the equations for water flow, sediment transport and bank migration in curved equiwidth channels (e.g. Johannesson and Parker, 1989; Crosato, 1990);
3) Meander models based on the equations for water flow and bank migration in channels with arbitrary geometries (e.g. Mosselman, 1992).

In the last decade also many papers which describe and develop dynamic models were published (e.g. Darby and Thorne, 1996; Sun et al., 1996; Meakin et al., 1996; ASCE Task Committee, 1998; Mosselman, 1998; Nagata et al., 2000; Seminara et al., 2001; Darby et al., 2002; Lancaster and Bras, 2002; Olsen, 2003; Duan and Julien, 2005; Duan, 2005; Jang and Shimizu, 2005). Advantages and disadvantages of these models were reviewed by Piégay et al. (2005). Mosselman (1995) discussed the utility of several 2-dimensional, depth averaged models. He concluded that while mathematical models of river planform changes were able to help in understanding how river planform evolve, none of them had reached the level of being a generally valid and easy to apply software package suitable for routine application. The diversity of processes and forms present in natural, meandering rivers means that, even assuming that the governing equations are fully understood and are correctly formulated mathematically, a single computational model is unlikely to have universal validity. Computational models are developed to simulate specific, idealized representations of natural fluvial systems (Darby, 1998). Moreover, meander migration is usually simulated using a functional relationship between bank erosion rate and near-bank flow velocity, using a proportionality coefficient determined by calibration (Bridge, 2003). Another disadvantage is that dynamic models require a very large amount of high-quality input data to produce reliable results. Darby (2005) has reported a database for 62 British gravel-bed rivers. This database can be used to calibrate and verify morphological models. However, this is a tool only for these UK rivers. Piégay et al. (2005) have concluded that numerical modelling approaches have the potential of attaining reliable quantitative predictions but their use is not common in practical applications, and the costs involved in collecting the necessary data can be much higher than the stakes concerned.

CHAPTER 3: APPLIED METHODS AND USED VARIABLES

3.1. INTRODUCTION AND DATABASE DESCRIPTION

As it is reviewed in the previous chapter, there are three main approaches to estimate bank erosion rate – empirical approach, kinematic and dynamic modelling. In order to achieve a goal of this study – general recommendation for river crossing site selection, the first approach is the most appropriate, because it allows derivation of general relationships from the available data, and allows a certain level of confidence in conclusions about relationships between bank erosion rate and other parameters of a system where a river operates. However, in terms of system consideration, a statistical treatment of such data often result in so-called black box models. In black box models the internal components of the system are ignored or excluded from direct treatment and only the relationship between inputs to the system and outputs from the system are considered (Thomas and Goudie, 2000). Therefore from such results dependence or independence of bank erosion rate upon the considered parameters cannot be determined and only statistical correlation (or association) could be revealed. This is the main disadvantage of all "black box" models; a researcher will never be sure about causal mechanisms. At the same time "black box" models are widely used by engineers due to their simplicity in application without deep knowledge of bank erosion processes.

In the subsequent sections descriptions of applied statistical methods are given. To realize these methods in this study Microsoft ® Office Excel 2003 and SPSS14.0 for Windows are used. Also variables, which are involved in the statistical analyses, are discussed below. All these variables are combined from as many publications as it is possible to collect at this stage. Data and a list of literature references are presented as a database in an appendix, and an interested reader could verify the obtained results.

Bank erosion rate depends from different parameters and the problem of lateral river activity is multivariate. There are some efforts to describe the problem in physical processes framework. The most detailed empirical analyses of the relationships between bank erosion rate and underlying channel processes are provided by researches of Hickin and Nanson (1984) and Nanson and Hickin (1986). They proposed that bank erosion rate can be expressed by the following function:

$$C = f\left(\omega, w, D_{50}, h, r\right),$$

where ω = stream power; w = channel width; D_{50} = mean sediment size; h = bank height and r = radius of meander curvature.

They eliminated sediment transport as a significant variable because of lack of data and because for meandering rivers suspended load is from bank erosion, rather than vice versa. It was assumed that bank strength is determined primarily by the sediment size of the outer bank. Bank strength declines as grain size declines from cobbles to fine sand, with fine sand representing the minimum bank strength. Bank strength increases again with cohesion.

Thus, by study of Nanson and Hickin (1986) it was assumed to use geometrical characteristics of a channel, stream power as a characteristic of driving force and sediment size as a characteristic of resistant force.

To follow above described framework data are assembled in a database of bank erosion rate. The database at initial stage was based on data from Van De Wiel's (2003) study, where information about bank erosion rates and drainage area is collected. Consequently the database was extended by new datasets and by adding extra parameters which a priori have influence to bank erosion rate. The entire list of parameters of the database with descriptions is given in Table 3.1. A part of parameters is essential for the database, other parameters were tabulated as available in the literature. Some of parameters characterize the same, for example for water discharge different values are in use (e.q. mean annual, bankfull). Such of dilemma, which parameters should be involved in analysis, is described with details in section 3.3.

There are more than 900 observations in the database. However, it should be noted that the database is disparate itself as datasets are collected from different studies of bank erosion rate. Mostly datasets are for areas where bank erosion studies are performed either for scientific reason or for practical problems. Therefore, it is no wonder that majority of datasets from Northern American and Europian rivers. Also a huge portion of datasets added to the database for rivers of the former USSR.

Table 3.1: Description of information in the bank erosion database

Name of column in the database	Description	Notes
Source	reference to literature source	
River	name of river	
Location	description of reach location (e.g. 5 km from the river mouth, near Southampton)	
Country	e.g. UK, USA, Laos.	
Part of World	descriptive location, e.g. Asia or North America	
Channel type	e.g. braided, meandering, straight.	
Classification	sometimes authors have used name of channel types according to special classifications (e.g. equiwidth meandering according to Brice's classification)	
Type	channel type used in Krasnoshchekov's analysis	
Bank being eroded	right or left	
Maximum bank erosion rate, m/year		
Average from maximum bank erosion rates on the reach, m/year		
Average bank erosion rate on the reach, m/year		
Rate	values of bank erosion rate which are used in Krasnoshchekov's analysis	
Rate_type	the type of bank erosion (e.g. average or maximum or average from maximum, see above)	
A, km2	drainage area	
Maximum observed discharge, m^3/s		
Average annual discharge, m^3/s		
Cv for Qav	coefficient of variation for average annual discharge	
Qbf (m3/s)	bankfull discharge	**Parameters for bankfull condition**
Bankfull width (m)		
Bankfull depth (m)		
Qbf Area (m2)	cross-section area at bankfull condition	
Average Velocity at Qbf (m/s)		
Qbf Wetted Perimeter (m)		
Qbf Hydraulic Radius (m)		
Qbf Recurrence Interval (years)		
Qmaf (m3/s)	mean annual flood discharge	**various characteristics of water discharge**
Q 2-Year Peak (m3/s)	two-year flood	
Q5.0, m3/s	five-year flood	
Q95 (m3/s)	ninety-fifth percentile flood	

Table 3.1 (cont.)

Effective Discharge Qe (m3/s)	(see individual references for definition)	**Parameters for effective discharge condition**
Qe Width (m)	''	
Qe Depth (m)	''	
Qe Area (m2)	''	
Average Velocity at Qe (m/s)	''	
Qe Wetted Perimeter (m)	''	
Q	discharge value which are used in Krasnoshchekov's analysis (note that average discharges were adjasted to bankfull)	
Water surface slope		**dimensionless parameters**
Channel slope, Sc		
Valley slope, Sv		
Avg. Floodplain or Valley Width (m)		
radius of curvature, m	only for meandering rivers	
Width, m	channel width if there is no indication of either bankfull width or effective width	
Depth, m	channel depth if there is no indication either bankfull depth or effective depth	
width	width values which are used in Krasnoshchekov's analysis	
depth	depth values which are used in Krasnoshchekov's analysis	
width/depth	width/depth ratio	
Bank height, m	as given in individual sources	
Half wavelength, m	only for meandering rivers	
meander length, m	only for meandering rivers	
Bed D16 (mm)		**Parameters for bed**
bed D50, mm		
Bed D84 (mm)		
Avg Bed Material Sorting (non dimension)		
Avg Bed Material %Si/Cl (%)	% content of silt and clay in bed material	
Avg Bed Material %Sand (%)	% content of sand in bed material	
Avg Bed Material % Gravel (%)	% content of gravel in bed material	
Bed material	e.g. gravel, sand, silt (descriptive)	
bedload transport, kg s-1		
Bank D16 (mm)		**Parameters for bank**
bank D50, mm		
Bank D84 (mm)		
Avg Bank Material Sorting (non dimension)		
bank silt-clay content, %	% content of silt and clay in bank material	
Avg Bank Material %Sand (%)	% content of sand in bank material	
Avg Bank Material % Gravel (%)	% content of gravel in bank material	
bank material	e.g. gravel, sand, silt (descriptive)	
bank vegetation	e.g. grass, trees, shrubs (descriptive)	

Table 3.1 (cont.)

riparian_vegetation	categories of riparian vegetation which are used in Krasnoshchekov's analysis	
Channel Manning's n		
Floodplain Manning's n		
P	channel sinuosity	
Gravel layer	absence of gravel layer in bank (0-absent, 1-present)	
Period of measurement	date from the begining to the end of measurements (e.g. 1972-1999)	
Timespan of measurement, yr	how many years (e.g. 27 years)	
Used technique(s)	which technique(s) was used for bank erosion measurement (e.g. historical sourses(from maps), erosion pins)	
Techniques	categories of techniques which are used in Krasnoshchekov's analysis	
Notes	additional important information, which is not included in above-listed cells	
Taken from	if data were taken from not original source (see the first cell), than reference is given from which it was taken	

in bold red – information which is essential and is collected for each river site.

in bold blue – characteristics of bank erosion rate. So at least one from the list of characteristics is essensial for the database.

in black – other characteristics of river sites which were tabulated as available in the literature.

in red – information which is generated from the existing data to ease further analysis

3.2. APPLIED METHODS

3.2.1. The *t*-test

The *t*-test description and particularities of use are given, consistent with Sumner (1978) and Davis (1973). Usually the *t*-test is used to test the hypothesis that a sample of mean $\overline{X}$ could have been drawn from a total population whose means is μ. It is thus a development of the standard error of the mean, and is given by:

$$t = \frac{\text{difference between sample and population means}}{\text{standard error of the mean}}$$

$$= \frac{\mu - \overline{X}}{\sigma/\sqrt{n}}, \qquad 3.1$$

where $\overline{X}$ = mean of the sample; μ = hypothetical mean of total population; n = number of observations and σ = standard deviation of observations. The value of *t* obtained by this formula must then be compared with tabulated values of *t* for different probabilities. These are given in most statistical texts; herein statistical tables by Lindley and Scott (1984) have been used. The significance of any one result is increased if a larger sample size is used. In general, for constant *n*, a higher *t*-value indicates that there is a smaller probability that the sample was drawn from the total population.

Also the *t*-test is used for a somewhat different problem. The *t*-test is appropriate to answer the question: "Are the means of the two sample collections the same?" In this case the mean values of two samples are compared against one another, rather than against a hypothetical mean of population. The null hypothesis is

$$H_0 : \mu_1 = \mu_2 \qquad 3.2$$

which states that the mean of the population from which the first sample was drawn is the same as the mean of the parent population of the second sample. This hypothesis is posed against the alternative

$$H_1 : \mu_1 \neq \mu_2 \qquad 3.3$$

that the two population means are not equal. The test statistic in this case has the form

$$t = \frac{\overline{X}_1 - \overline{X}_2}{\sigma_p \sqrt{(1/n_1) + (1/n_2)}} \qquad 3.4$$

where the quantity σ_p is the pooled estimate of the population standard deviation, based on both samples. The estimate is found from the pooled estimated variance, given by

$$\sigma_p^2 = \frac{(n_1 - 1)\sigma_1^2 + (n_2 - 1)\sigma_2^2}{n_1 + n_2 - 2} \qquad 3.5$$

where the subscripts refer, respectively, to the first sample and second sample. The degree of freedom in this case is $\nu = n_1 + n_2 - 2$. Then the value of *t* obtained by formula (3.4) must be compared with tabulated values of *t* with ν degrees of freedom and a certain level of significance. If the *t*-statistic defined by (3.4) exceeds the tabulated value of *t*, then the hypothesis (3.2) is rejected and the alternative hypothesis (3.3) is accepted.

3.2.2. Simple linear regression

A simple linear regression models the relationship between two variables by fitting a linear equation to observed data. One variable is considered to be a dependent variable (also known as an outcome, or response variable), and the other is considered to be an independent variable (also known as a predictor or explanatory variable). This does not necessarily imply that one variable causes the other, for instance, wider channel widths do not cause higher bank erosion rates, but that there is some significant correlation between the two variables.

Before attempting to fit a linear model to observed data, it should be first determined whether or not there is a relationship between the variables of interest. A scatterplot can be a helpful tool in determining the strength of the relationship between two variables. If there appears to be no correlation between the proposed independent and dependent variables (i.e., the scatterplot does not indicate any increasing or decreasing trends), then fitting a linear regression model to the data probably will not provide a useful model. In old publications linear equations are derived by the best “eye” fit from a scatterplot, i.e. the equations included some part of subjectivism. With progress of computer sciences in state-of-the-art publications statistical program packages of analysis are used. The most common method for fitting a regression line is the method of least-squares. This method calculates the best-fitting line for the observed data by minimizing the sum of the squares of the vertical deviations from each data point to the line (if a point lies on the fitted line exactly, then its vertical deviation is 0). Because the deviations are first squared, then summed, there are no cancellations between positive and negative values.

Simple linear regression analysis produces estimates of the model parameters. The simple linear regression model is a mathematical equation for a line. It has the following form:

$$Y = a + bX, \qquad 3.6$$

where Y is the dependent variable and X is the independent variable. The slope of the line is b, and a is the intercept with y-axis when $x = 0$. The parameters a and b of the equation are estimated using mathematical formulae, which are applied to data. The regression analysis procedure tests the null hypothesis that the slope parameter of the independent variable is 0 versus the alternative hypothesis that the slope parameter is different than 0. If the value of the t test statistic lies within the critical region (e.g. at a significance level of 5%), the null hypothesis is rejected and it is concluded that there is a statistically significant correlation between the dependent variable and the independent variable. The significance is checked by outputs of the t-test statistic in SPSS14 or alternatively from the table of percentage points, which can be found, for instance, in Lindley and Scott (1984). This issue is most crucial for the cases of small samples. It should be noted that a relationship can be strong and yet not significant and conversely, a relationship can be weak but significant. The test of the null hypothesis that the slope parameter equals 0 actually is a special case of test of the slope of a linear regression. In general the t-test can be used to test the hypothesis that the regression slope is equal to some value β, which may be not equal 0 (Davis, 1973):

$$t = \frac{b - \beta}{\sqrt{MS_D / SS_X}}, \qquad 3.7$$

where b = the regression slope, MS_D = the mean square deviation and SS_X = the sums of squares of X. The mean square deviation is defined as:

$$MS_D = \frac{\sum_{i=1}^{N} \left(\hat{Y}_i - Y_i \right)^2}{n - 2}, \qquad 3.8$$

where $\hat{Y}_i$ = estimated value, Y_i = original value, n = number of observations. The sums of squares of X as:

$$SS_X = \sum_{i=1}^{N} X_i^2 - \frac{\left(\sum_{i=1}^{N} X_i \right)^2}{n}. \qquad 3.9$$

This test is used when two regression lines with different slopes are compared. Using this test analysis one can conclude that the regression slope from one dataset is significantly different from the other regression slope or not from a statistical point of view.

The slope parameter can be interpreted also as the amount of change in the average of the dependent variable for a one-unit increase in the independent variable.

However, in this study the log-transformed values are used. It means that the equation (3.6) with transformed variables takes the form:

$$\log Y = a + b \log X. \qquad 3.10$$

Hence, the resulting regression equation takes the form of a power function, which can be expressed as:

$$Y = \alpha\ X^{b}, \qquad 3.11$$

where Y is the dependent variable, α is a constant, which equals 10^{a}, and X is the independent variable with b as the exponent. The use of log-transformed values is common within physical geography (Sumner, 1978), and particularly within studies of bank erosion rates (e.g. Richard et al, 2005).

A valuable numerical measure of association between two variables is the Pearson correlation coefficient. For given set of observations (X_1, Y_1), (X_2, Y_2), ... , (X_N, Y_N), the formula for computing the correlation coefficient is given by

$$r = \frac{N\sum X_i Y_i - \sum X_i \sum Y_i}{\sqrt{N\sum X_i^2 - \left(\sum X_i\right)^2}\sqrt{N\sum Y_i^2 - \left(\sum Y_i\right)^2}}. \qquad 3.12$$

The Pearson correlation coefficient measures how closely the variable X and Y are correlated. The correlation coefficient is a number between -1 and +1. A positive correlation indicates a positive association between the variables (increasing values in one variable correspond to increasing values in the other variable), while a negative correlation indicates a negative association between the variables (increasing values is one variable correspond to decreasing values in the other variable). A correlation value close to 0 indicates no association between the variables. A correlation greater than 0.7 is generally described as strong, whereas a correlation less than 0.5 is generally described as weak. These values can vary based upon the "type" of data being examined (Field, 2005). Because the formula for calculating the correlation coefficient standardizes the variables, changes in scale or units of measurement will not affect its value. For this reason, the correlation coefficient is often more useful than a graphical depiction in determining the strength of the association between two variables.

Another valuable numerical measure of association between two variables is the coefficient of determination, more widely known as R^2. It is useful because it gives the proportion of the variance of one variable that is predictable from the other variable. The coefficient of determination is a number between 0 and +1 and denotes the strength of the linear association between X and Y. For example, if the correlation coefficient between log-transformed bank erosion rate and log-transformed bankfull water discharge equals $r = 0.47$ and then $R^2 = 0.22$, which means that 22% of the total variance in log-transformed bank erosion rate can be explained by the linear relationship between log-transformed bankfull water discharge and bank erosion rate as described by the regression equation. The other 78% of the total variance remains unexplained. If the regression line passes exactly through every point on the scatter plot, it would be able to explain all of the variance. The further the line is away from the points, the less it is able to explain.

3.2.3. Multiple regression

Multiple regression allows researchers to examine the effect of many different factors on some dependent variable at the same time. The general purpose of multiple regression is to learn more about the relationship between several independent variables and a dependent variable. In the sciences and particularly in studies of bank erosion, multiple regression procedures are widely used (e.g. Hooke, 1979; Nanson and Hickin, 1986; Alvarez, 2005; Richard et al., 2005). However, all these studies were regional in nature and collected comprehensive data sets that quantified all the variables to be included in multiple regression. Thus, regionally significant relationships can be derived with small data sets, whereas in the present study an attempt is made to draw together a larger but disparate dataset. Walker and Rutherfurd (1999) applied multiple regression for meandering channels for a dataset from different regions around world with four independent variables and with only a sample size of 33. Even though Walker and Rutherfurd (1999) obtained statistically significant correlations, there is a large effect of sample size and according to Fig. 3.1 the sample size is even not enough for a condition of required sample size for four independent variables.

Applying multiple regression analysis in this study failed. Using a model, where Nanson and Hickin (1986) proposed to use stream power, sediment size, channel width, bank height and radius of curvature, the resulting statistic (adjusted R^2) obtained to be low (<0.2). It is assumed that there are two main reasons. The first reason is the necessary amount of data for regression and the second is the effect of multicollinearity. Regarding the amount of data, some authors recommend that one should have at least 10 to 20 times as many observations as one has variables, otherwise the estimates of the regression line are probably unstable. Field (2005) has given more concrete guidelines and summarized them as a graph (Fig. 3.1). Fig. 3.1 shows the sample size required to achieve a high level of power depending on the number of independent variables and the size of the expected effect (Field, 2005). In all attempts to make multiple regression with three or more independent variables the sufficient amount of data does not meet the requirement from guidelines in Fig. 3.1. For two independent variables instead of multiple regression the simple linear regression is used where as the independent variable ratios and products of two variables are involved.

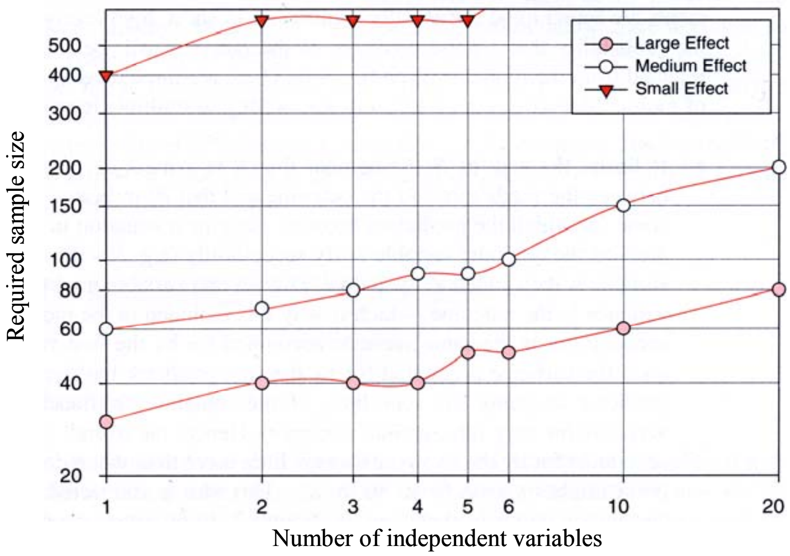


Figure 3.1: Graph to show the sample size required in regression depending on the number of independent variables and the size of expected effect (Redrawn from Field, 2005)

Another reason why multiple regression has not been used in this study is multicollinearity. Multicollinearity is a common problem in many correlation analyses. Multicollinearity refers to linear inter-correlation among variables. A strong correlation is obtained between such independent variables as water discharge and geometrical characteristics of a channel (depth, width and bank height). The main danger of high levels of collinearity is that the probability of rejecting of a good independent variable increases as it will be found to be non-significant (Field, 2005). Using other independent parameters which are not strongly correlated to each other, it is found that there is insufficient number of data to make a robust regression equation. Consequently, taking into account these two reasons and obtained "negative" results for multiple regression with parameters, which are somewhat physically-based, in further analysis the multiple regression has not been used by "playing" with other combinations of parameters. Perhaps, with more data it will be possible to apply multiple regression.

3.2.4. Association for ordinal data

In this study there is a need to define an association between two ordered cross-classifications. Usually methods to calculate such kind of association are used in the social and medical sciences (Field, 2005), and so far are not used widely in geomorphology. The problem is how to define an association between bank erosion rate expressed in qualitative terms (e.g. "low", "medium", "severe") and such classifications as channel type, vegetation, bed and bank types, which are described by qualitative terms as well.

The outcome variable may include a continuous scale (e.g. rates of bank erosion), binary measures (e.g. stable and unstable), or an ordered category (e.g. severe, medium, low). Bank erosion rate is inherently a continuous variable. Therefore, for a continuous dependent variable there are two ways of analysis. If the independent variable is expressed as a continuous one, then linear regression analysis is applicable to the dependent variable (see previous section). If the independent variable is expressed as a categorical one, then an analysis might be used to show the distribution of bank erosion with categories such as channel, vegetation, bed and bank types. As an example in Fig. 3.2 a distribution of bank erosion rates with main channel types is shown. This way is useful and informative, because one can compare mean values and ranges between categories (in the example between different channel types). However, in this case it is impossible to conclude how close two categories are associated to each other by quantitative means.

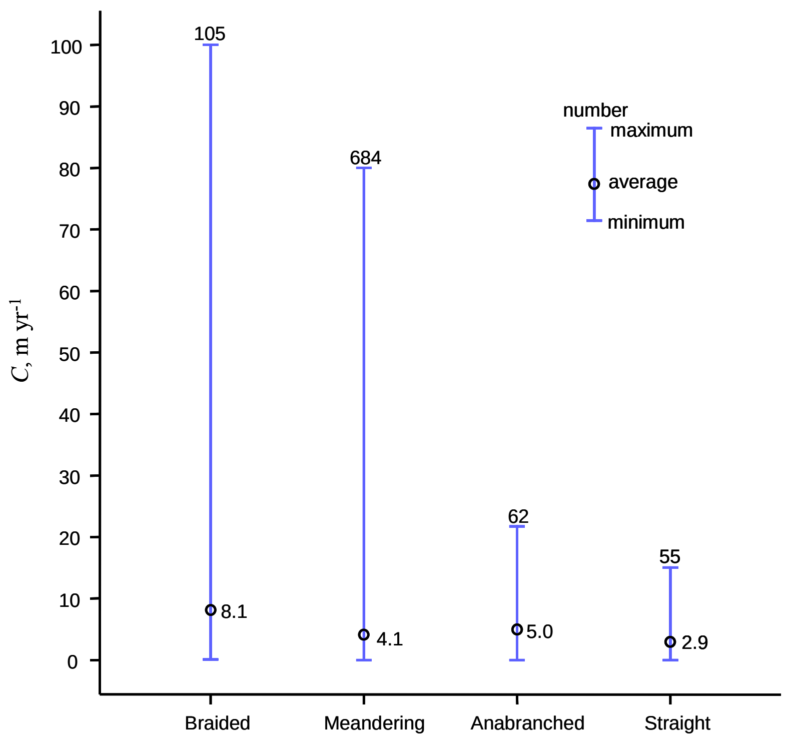


Figure 3.2: An example of distribution for bank erosion rate by channel types.

Logistic regression analysis works well only for the binary or dichotomous outcome. For example, Atkinson et al. (2003) have performed a logistic regression to study absence or presence of bank erosion phenomena along the Afon Dyfi river in North Wales, UK. In the current study it is actually not appropriate to analyse conditions for presence or absence of bank erosion because collected data indicate information only for river reaches where bank erosion is ongoing. For the binary outcome as “stable” and “unstable” it is impossible to perform the logistic regression in this study too. The main reason is that it is difficult to distinguish between “stable” reach and “unstable” reach with the same bank erosion rate. As example, for a river 10 m wide with bank erosion rate 1 m yr^{-1} in an urbanized area a reach may be classified as “unstable”, and for a river 100 m wide in rural area a reach with the same bank erosion rate may be classified as “stable”. So there is no generally accepted threshold between “stable” and “unstable” even along the same river and any classification arbitrarily depends on relative river size and the value of eroded riparian land.

Consequently, estimation of association for ordinal data followed by frequency analysis seems to be the most suitable in this study. The distribution of bank erosion rates reveals the order of categories for channel, bank, bed and vegetation types. Consequent estimation of association for two ordered cross-classifications reveals the strength and the significance of this association.

A continuous variable of bank erosion rate can be converted into an ordinal variable by categorizing the range of values. There are some arbitrary classifications in the literature, where bank erosion rates are presented as an ordinal variable. As an example (from Chalov, 2000), in Table 3.2 ranges of bank erosion rates for different bank compositions are shown. Using this table one can define how severe bank erosion rate is for a given bank composition. However, as it has been noticed, these classifications are arbitrary and are not generally accepted, because in different geomorphological conditions the same bank erosion rate can be either severe or mild. Even though this classification is based on Chalov’s experience and generalization of many observations, it is useful to the present study as it can indicate how to categorize a continuous variable such as bank erosion rate. It is obvious that the actual values of ranges may vary depending on the whole range of available data and amount of data inside ranges.

Table 3.2: Bank erosion rate (m yr^{-1}) with different bank types (from Chalov, 2000)

Level of erosion	Sand and loamy sand	Loam	Clay	Peat; Semi-bedrock
Very severe	>10	>5	>2	>1
Severe	5-10	2-5	1-2	0.5-1
Medium	2-5	1-2	0.5-1	0.2-0.5
Low	<2	<1	<0.5	<0.2

A mathematical explanation of a measure of association and its significance for ordered data is presented herein after Goodman and Kruskal (1954, 1959, 1963, 1972), Berry et al. (1976), Brown and Benedetti (1977), Liebetrau (1983) and Field (2005). Suppose that two ordinal variables X and Y are sampled jointly, and that resulting sample (X_1, Y_1),…, (X_n, Y_n) is classified into an $I \times J$ contingency table. Then n_{ij} is the number of observations that fall into cell (i, j) of the table; that is n_{ij} is the number of observations that X_k falls into (raw) category i and Y_k falls into (column) category j. In this case as a measure of association may be used the following widely used measures: Spearman's correlation (Rho); Kendall's Tau and Goodman-Kruskal Gamma. In this study the Goodman-Kruskal Gamma is used for several reasons. Firstly, Spearman's correlation has been avoided in calculations because data for bank erosion rate were transformed into percentages inside each category. This transformation was performed due to the big difference in the amount of data between categories, for instance, for the meandering channel type there are more than 600 datapoints, while for the straight channel type, a few tens of datapoints. The Spearman's correlation can not take into account this transformation of data as it applies to the ranks of the data rather than to the actual data values themselves. Secondly, the Kendall's Tau is not used in this study because it is most appropriate for square tables. In general this condition not always is satisfied. The Goodman-Kruskal Gamma is more appropriate; it can take into account data transformation and can be used for any dimensions of tables. The Goodman-Kruskal γ is defined by

$$\gamma = \frac{CON - DIS}{CON + DIS}, \qquad 3.13$$

where CON = number of pairs that are concordant, DIS = number of pairs that are not concordant (discordant pairs). CON is calculated as

$$CON = \sum_{i=1}^{I} \sum_{j=1}^{J} n_{ij} CON_{ij}^{*}, \qquad 3.14$$

where

$$CON_{ij}^{*} = \sum_{i^{'} > i} \sum_{j^{'} > j} n_{i^{'} j^{'}} \qquad 3.15$$

is the total number of observations "southeast" of cell (i, j).

Number of pairs that are discordant D is calculated as

$$DIS = \sum_{i=1}^{I} \sum_{j=1}^{J} n_{ij} DIS_{ij}^{*} , \qquad 3.16$$

where

$$DIS_{ij}^{*} = \sum_{i^{'} < i} \sum_{j^{'} > j} n_{i^{'} j^{'}} \qquad 3.17$$

is the total number of observations "southwest" of cell (i, j).

If there is independence, one expects that the order of the X has no connection with the order of the Y. If there is high association one expects that the order of the X would generally be the same as that of the Y. If there is high counter association one expects that the orders would generally be different. As given by Goodman and Kruskal (1954) some important properties of γ follow:

- γ is indeterminate if the population is concentrated in a single row or column of the cross-classification table.

- γ is 1 if the population is concentrated in an upper-left to lower-right diagonal of the cross-classification table. γ is -1 if the population is concentrated in lower-left to upper-right diagonal of the table.

- γ is 0 in the case of independence, but the converse need not hold except in the 2 by 2 case.

In terms of its interpretation, the Goodman and Kruskal γ is more similar to Kendall's Tau than Spearman's Rho. Spearman's Rho is considered as the regular Pearson's correlation coefficient in terms of the proportion of variability accounted for, whereas Kendall's Tau and Goodman and Kruskal γ represent a probability, i.e., the difference between the probability that the observed data are in the same order versus the probability that the observed data are not in the same order.

To test the significance of the Goodman and Kruskal γ the chi-square statistic has concomitantly come to be used. However, the clarification of using the chi-square statistics revealed the fact that there exists no functional relation between the sampling distributions of chi-square and the Goodman and Kruskal γ (Berry et al., 1976). Because the chi-square statistic is the most widely used statistic, Berry et al. (1976) warn that it is imperative to use the chi-square statistic appropriately. In this study the hypothesis of independence is checked to conclude that γ is significantly not equal to zero. Under the hypothesis of independence, γ equals zero. For this case, Brown and Benedetti (1977) give the formula for variance of γ

$$\sigma^2(\gamma) = \left[\sum_{i=1}^{I} \sum_{j=1}^{J} n_{ij} \left(CON_{ij} - DIS_{ij} \right)^2 - \frac{4}{n} \left(CON - DIS \right)^2 \right] / \left(CON + DIS \right)^2 , \tag{3.18}$$

where *CON* and *DIS* are defined by equations (3.14) and (3.16) respectively; *n* – the total number of observation; CON_{ij} and DIS_{ij} are defined as

$$CON_{ij} = \sum_{i^{'} < i} \sum_{j^{'} < j} n_{i^{'} j^{'}} + \sum_{i^{'} > i} \sum_{j^{'} > j} n_{i^{'} j^{'}} \tag{3.19}$$

and

$$DIS_{ij} = \sum_{i^{'} < i} \sum_{j^{'} > j} n_{i^{'} j^{'}} + \sum_{i^{'} > i} \sum_{j^{'} < j} n_{i^{'} j^{'}} . \tag{3.20}$$

CON_{ij} is the number of observation concordant with one in cell (*i*,*j*). DIS_{ij} is the number of observation discordant with one in cell (*i*,*j*).

The formula (3.18) should be used for testing the hypothesis that γ=0 (Liebetrau, 1983). One can suppose if $|\gamma| \geq 2\sigma$, it is certainly safe to conclude that $\gamma \neq 0$. Otherwise, γ is not accepted due to its large variance.

3.3. USED VARIABLES

The major conceptual limitation of all regression techniques is that one can only ascertain relationships, but never be sure about the underlying causal mechanisms. Therefore all possible physically reasonable variables have been identified to study relationships with bank erosion rates.

The variables identified as potentially controlling bank erosion rates are conventionally divided into three groups. This division is based on the scale effect when the bank erosion problem is considered. As stated by Schumm (1991) '…, the components of the fluvial system can be investigated at many scales, but no component can be totally isolated because there is an interaction of hydrology, hydraulics, geology and geomorphology at all scales,…'. Therefore, the bank erosion phenomenon is considered at all available scales. Fig. 3.3 shows the three groups based on scale. In Table 3.3 all variables are listed, which are related to bank erosion. The number of variables also was dictated by availability and amount of data.

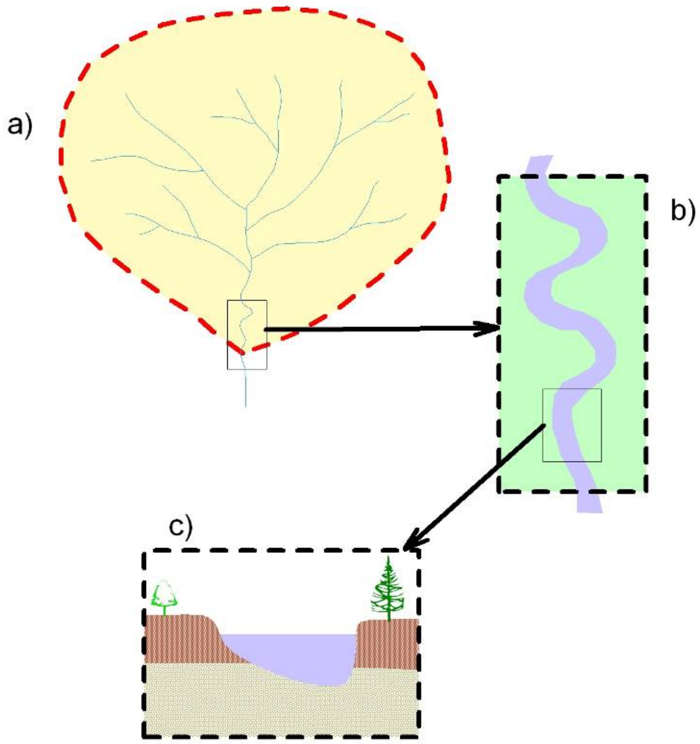


Figure 3.3: Scales at which the bank erosion rate is considered: a) catchment scale; b) reach scale and c) cross-section scale. Modified after Schumm (1991).

Table 3.3: Variables to relate with bank erosion

#	Variable	Units	Scale*	Used scale*	Data type
1	2	3	4	5	6
1	Drainage area (*A*)	km^2	a	a	interval
2	Water discharge (*Q*)	$m^3\ sec^{-1}$	a; b; c	a	interval
3	Average annual runoff (*M*)	mm $year^{-1}$	a	a	interval
4	Sediment transport (Q_s)	kg sec^{-1}	a; b; c	a	interval
5	Channel depth (*d*)	m	b; c	b	interval
6	Channel width (*w*)	m	b; c	b	interval
7	Bank height (*h*)	m	b; c	b	interval
8	Floodplain/valley width (w_v)	km	b	b	interval
9	Water surface slope (S_w)	-	b; c	b	interval
10	Channel slope (S_c)	-	b; c	b	interval
11	Valley slope (S_v)	-	b	b	interval
12	Depth to width ratio (*d*/*w*)	-	b; c	b	interval
13	Bank height to width ratio (*h*/*w*)	-	b; c	b	interval
14	Unit discharge (*q*)	$m^2\ sec^{-1}$	b; c	b	interval
15	Gross stream power (Ω)	W m^{-1}	b; c	b	interval
16	Unit stream power (ω)	W m^{-2}	b; c	b	interval
17	Shear stress (τ)	N m^{-2}	b; c	b	interval
18	Coefficient of variation (*Cv*)	-	b	b	interval
19	Channel type	descriptive	b	b	categorical
20	Water velocity (υ)	m sec^{-1}	b; c	c	interval
21	Median bed grain size (D_{bed})	mm and ϕ	c	c	interval
22	Median bank grain size (D_{bank})	mm and ϕ	c	c	interval
23	Bank silt-clay content	%	c	c	interval
24	Bed material type	descriptive	b; c	c	categorical
25	Bank material type	descriptive	b; c	c	categorical
26	Riparian vegetation type	descriptive	b; c	c	categorical

* Scales are presented accordingly to Fig. 3.3.

In statistical analysis, units for variables are used as shown in column 3 of Table 3.3. It was essential to convert data to the same units as in some sources the English system has been used. The scales, at which variables are considered, are shown in the fourth column. Because there is an interaction at all scales (Schumm, 1991), there are overlaps of scales for some variables. Overlap of scales in Table 3.3 can be explained also by consideration of application. For example, water discharge can be used as a characteristic of the catchment scale as this amount of water drained from the whole drainage area to the river station where it is measured. Similarly as a characteristic of a river reach, the same water discharge could be used because it is one of the key factors of channel form. There is a velocity-cross section area approach to define water discharge, so water discharge can be also used to characterize conditions at the scale of the cross-section. However, in this study each variable is assigned into a single scale (column 5, Table 3.3) for simplification and logical construction for further consideration. Finally, in column 6, types of data for variables are shown, as selection of a proper statistical method depends upon the data type (Liebetrau, 1983). There are two types: 1) interval and 2) categorical. Different statistical methods are used for these types of data and description and particularities of the methods are given in a chapter of applied methods description.

3.3.1. The catchment scale

Catchment scale considerations frame the boundary conditions within which rivers operate, constraining the range of river behaviour and associated morphological attributes (Brierley and Fryirs, 2005). The variables, which fall into the catchment scale, are drainage area, water discharge, average annual runoff and sediment transport (Table 3.3). While drainage area characterizes the size of a catchment, discharge and sediment transport reflect not only catchment size but also climate and geology of the drainage basin.

Drainage area is delimited by a topographic divide or watershed as the land area which collects all the surface runoff flowing in a network of channels to exit at a particular point on a river (Downs and Gregory, 2004). Although there is no problem with defining this variable, three uncertainties exist (Fig. 3.4). In the first case drainage area is given up to the mouth of a river when particular sites of bank erosion observations are located upstream from the mouth (Fig. 3.4 A). In the second case drainage area is given for the nearest hydrological station where data about discharge are available (Fig. 3.4 B). In the third case only one value of drainage area is given when several observation sites on adjacent meander loops are considered (Fig. 3.4 C). In the last two cases the difference between given value and actual value is not marked, but in the first case may differ from the actual value significantly. Therefore when drainage area is given up to the river mouth, the location of observation is checked and as far as possible is corrected based on cartographic materials. If it was not possible to make a correction due to lack of cartographic materials then the value of drainage area was rejected.

(**A**) (**B**) (**C**)

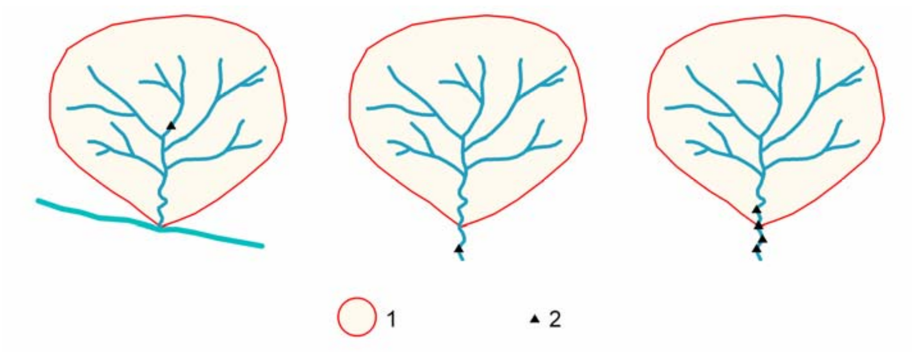


Figure 3.4: Cases of uncertainties for drainage area. 1 – given drainage area; 2 – actual sites of bank erosion observations. See text for explanation of each case.

Water discharge. There is a conceptual discharge which is related to channel formation and consequently to channel adjustment and bank erosion. This is the concept of dominant or channel-forming discharge. The concept is a simplification of the true complexity of the natural processes which lead to channel formation (Carling, 1988). This simplification assumes that a single value discharge is responsible for the channel morphology in alluvium (Charlton et al., 1978). The concept provides a relationship between the hydrologic characteristics of the channel, the hydraulic characteristics of the channel and the geomorphic characteristics of the channel (Tilleard, 1999). It is used in studies of channel pattern (e.g. Alabyan and Chalov, 1998), processes of bedload transport (e.g. Emmett and Wolman, 2001), river restoration (e.g. Tilleard, 1999) and channel stability (e.g. Carling, 1988; Olsen et al., 1997).

The dominant discharge is a single discharge measure that determines the geometry of an alluvial channel at a particular location (Bridge, 2003). This discharge depends on the character and quantity of sediment transported and on the composition of the bed and bank materials (Thomas and Goudie, 2000). Wolman and Miller (1960) suggested that the dominant discharge is defined by the magnitude of event and its occurrence frequency. As a channel conveys a certain amount of water and sediment, channel form and erosion/deposition processes depend on the relative magnitude of flows and the thresholds of material motion. The low flows have not enough energy to erode channel bed and banks but they occur often. The largest flows have the highest energy and consequently can erode channel bed and banks at the greatest rate but they occur seldom. More moderate flows have less energy then the high flows and erode channel bed and banks with lower rate. However, these moderate flows can actually do more work as they influence the channel boundaries for longer time. Therefore there is likely to be a discharge, at neither the high nor the low extreme, that is both sufficiently frequent and sufficiently effective to be most important in forming and maintaining the channel (Leopold, 1994).

Three measures for dominant discharge are commonly applied: effective discharge, bankfull discharge and a discharge of a certain occurrence interval (Pickup and Warner, 1976; Doyle et al., 2007). The effective discharge is that discharge which transports the most bed load in a stream that is close to steady-state conditions (Pickup and Warner, 1976; Carling, 1988). The bankfull discharge is the flow which just fills the channel to the tops of the banks (Williams, 1978). The discharge of a certain occurrence interval is used as a statistical definition of dominant discharge and flows with return intervals ranging from 1 to 2 years are typically used (Doyle et al., 2007).

There is no common agreement concerning which of these three measures should be used in studies of channel stability. Although Doyle et al. (2007) have recommended the effective discharge as it provides process-based insight of drivers of current and future trajectories of channel stability, the bankfull and the discharge of a certain occurrence interval are widely applied as to estimate them information about sediment load is not necessary. By a quantitative analysis Andrews (1980) found that, at least for the Yampa River basin in Colorado and Wyoming, the effective discharge is near equal to the bankfull discharge. Moreover, Gomez et al. (2007) have concluded that the effective discharge probably is more relevant to the overall picture of sediment movement, while the overall channel geometry is determined by discharges at or near bankfull. As stated by Leopold (1994), actual field observations confirm that the erosion rate, the sediment transport rate, and the bar building by deposition are most active when the discharge is near bankfull. By these reasons, in this study the bankfull discharge is used as the main characteristic of water discharge to relate with bank erosion. However, it should be borne in mind that for the bankfull discharge there are uncertainties in methods to determine this discharge (e.g. Williams, 1978 or more recent examination by Navratil et al., 2006 and a review by Lenzi et al., 2006).

During collection of bankfull discharge data a problem of necessary and sufficient number of datapoints for statistically meaningful analysis has arisen. The determination of bankfull discharge requires special fieldwork or special calculations. In contrast, average annual discharge is published for every gauging station and is ready available (Leopold, 1994). It seems to be a reason why in many papers, in considerations of study reaches, the average annual discharge is used more frequently than the bankfull discharge. To define the bankfull discharge for reaches where only data about average annual discharge are available a relationship between average annual discharge and bankfull discharge is used (Fig. 3.5). From the relationship it is evident that such an adjustment is necessary as the bankfull discharge is considerably greater that the average annual discharge.

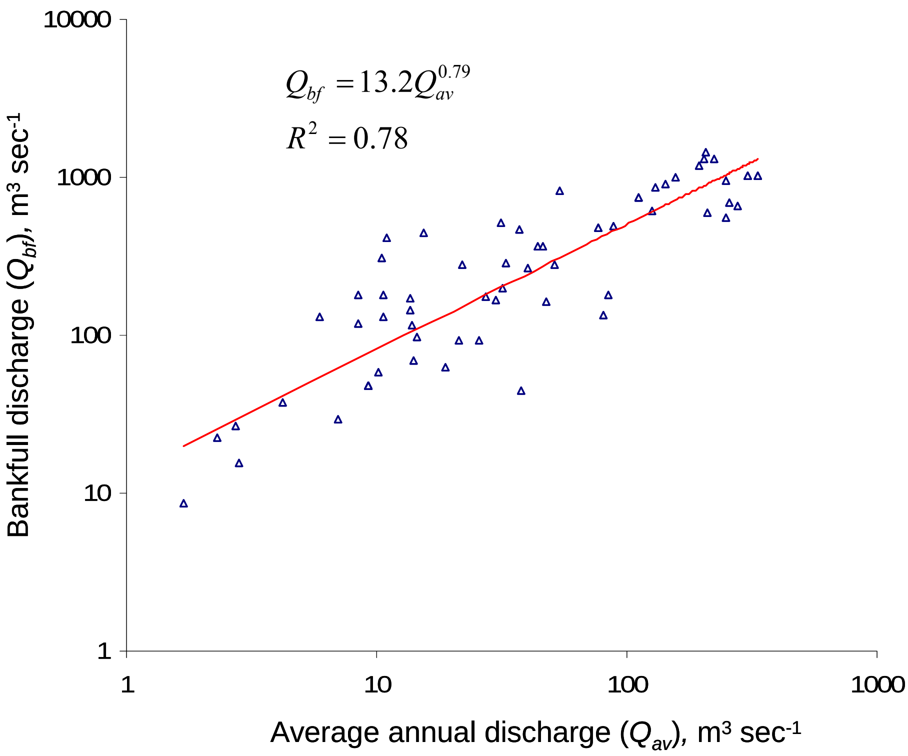


Figure 3.5: A relationship between bankfull discharge and average annual discharge. Number of observations is 69.

Herein the relationship is constructed in general sense for all available data from different geomorphological setting, though Leopold (1994) found that such relationships depend upon drainage area. From his example, for the Seneca Creek at Dawsonville, Maryland with drainage area 262 km^2 the ratio of bankfull discharge to average "long-term" discharge is 20:1, while for the Watts Branch near Rockville in the same country with drainage area 9.6 km^2 the ratio is about 60:1. Consequently, the ratio may increase as the basin size decreases. Also the ratio varies for different regions. For instance, in Coast Range area of California the ratio is about 30:1, and in Front Range of Colorado the ratio is about 7:1 (Leopold, 1994). Despite these facts, and taking into account that the obtained relationship is statistically strong (R^2=0.78) and significant (at a significance level of 5%, the critical value of t is 1.66, and the test statistic is 15.3, i.e. lies within the critical region, so the hypothesis that the slope is zero must be rejected), as presented in Fig. 3.5 the relationship between average annual discharge and bankfull discharge has been used in further analysis for bank erosion.

Average annual runoff is used here because maps of average annual runoff are ready available from government or environment agencies. Usually maps of average annual runoff are produced as isolines maps. However, in the last decades with development of GIS technology choropleth (gridded) maps are used as well (e.g. Arnell, 1995; Sauquet, 2006). Another reason to use the average annual runoff, is because values of discharge depend on the drainage area and rivers of different sizes are not comparable using water discharge values. Comparison is facilitated by expressing water discharge as average annual runoff because it is expressed as runoff per unit catchment area (Leopold, 1994). In hydrology, maps of average annual runoff are used for water resources and water budget studies and also to estimate water discharge for ungauged sites. The value of this characteristic shows how much water drains from a catchment per year, expressed as a water layer which is equally distributed over drainage area. The average annual runoff is defined as:

$$M = \frac{31536 \times Q}{A}, \qquad 3.21$$

where M = average annual runoff (mm year^{-1}); Q = average annual discharge (m^3 sec^{-1}); A = drainage area (km^2); 31536 = a coefficient to convert units. Note that in this case in order to calculate the runoff the average annual discharge is used, not the bankfull discharge.

Sediment transport. There are numerous sediment transport equations in the literature. Recently the applicability and accuracy of many popular sediment transport equations have been evaluated and re-examined (e.g. Gomez and Church, 1989; Reid et al., 1996; Martin and Church, 2000; Yang and Huang, 2001; Almedeij and Diplas, 2003; Bravo-Espinosa et al., 2003; Martin, 2003; Barry et al., 2004; Martin and Ham, 2005; Wong and Parker, 2006). Results and conclusions from these studies are summarised in

Table 3.4. From these studies there is no unambiguous answer as to which equation is better to use. However, following Gomez and Church (1989) the Bagnold (1980) equation is adopted herein to calculate sediment transport as there is limited hydraulic information in the assembled database.

The final form of the Bagnold (1980) equation with substitution of all reference values has the following form:

$$q_s = 0.1\frac{\rho_s}{\rho_s - \rho}\left(\frac{\omega - \omega_c}{0.5}\right)^{3/2}\left(\frac{d}{0.1}\right)^{-2/3}\left(\frac{D}{0.0011}\right)^{-1/2}, \qquad 3.22$$

where q_s = the sediment transport rate per unit width (kg m^{-1} sec^{-1}); ρ_s = the sediment density (taken equals 2650 kg m^{-3}); ρ = the water density (taken equals 1000 kg m^{-3}); ω = stream power exerted by the water flow (W m^2); ω_c = the critical value of stream power required to initiate sediment transport (W m^2); d = flow depth at bankfull conditions (m); D = bed material particle size (m) (median grain size is used). The stream power exerted by the water flow at unit channel width is given as:

$$\omega = \frac{\rho g Q S}{w}, \qquad 3.23$$

where ρ = the density of water (1000 kg m^{-3}); g = the acceleration due to gravity (9.81 m sec^{-2}); Q = the bankfull discharge (m^3 sec^{-1}); S = channel slope; w = the bankfull width (m). The critical value of stream power required to initiate sediment transport is given by Bagnold (1980) as:

$$\omega_c = 290 D^{3/2} \lg\left(\frac{12d}{D}\right). \qquad 3.24$$

Consequently, to calculate sediment transport by the Bagnold (1980) equation the following data are necessary: bankfull discharge, channel slope, width, depth and median grain size of bed material. In order to calculate the total sediment transport rate through the cross-section in kg per sec, the sediment transport rate per unit width defined by equation (3.22) is multiplied by the channel width.

Table 3.4: A summary of evaluations and re-examinations for bed-load equations.

Study by	General description of study	Main results and conclusions
Gomez and Church, 1989	Evaluation of the performance 12 bed-load equations	None of the tested equations performed consistently. Under limited hydraulic information, best is the equation of Bagnold (1980), whereas the Einstein (1950) and Parker et al. (1982) equations should be used when local hydraulic information is available.
Reid et al., 1996	Evaluation of the performance 6 bed-load equations	Meyer-Peter and Müller (1948) equation performed best for conditions of unarmoured beds in desert and semidesert environments. The Bagnold (1980) and Parker (1990) equations underpredict considerably, but perform better than others tested equations.
Martin and Church, 2000	Re-examination of Bagnold (1980) equation	A rational version of the Bagnold (1980) equation has been derived on the basis of dimensional analysis. Using a large dataset the most consistent empirical coefficients have been obtained.
Yang and Huang, 2001	Evaluation of the performance 13 bed-load equations	Bed-load equations based on energy dissipation rates or stream power concepts more accurately described the observed transport data and the degree of equation complexity did not necessarily translate into increased model accuracy.
Almedeij and Diplas, 2003	Evaluation of the performance 5 bed-load equations	The Almedeij and Diplas (2003) equation performed best, but performance varied between sites. Other tested equations overpredict or underpredict observed bed-load rates by several orders of magnitude.
Bravo-Espinosa et al., 2003	Evaluation of the performance 7 bed-load equations	Equations by Parker et al. (1982), Schoklitsch (1962), and Meyer-Peter and Müller (1948) adequately predicted sediment transport in channels with transport-limited condition, whereas the equations by Bagnold (1980) and Schoklitsch (1962) performed well for partially transport-limited and supply-limited conditions. Overall, the equation of Schoklitsch (1962) predicted well the measured bedload data for eight of 22 streams, and the Bagnold (1980) equation predicted the measured data in seven streams.
Martin, 2003	Evaluation of the performance 5 bed-load equations	Results do not suggest that one particular equation is preferred. Bed-load equations appear to consistently underpredict transport rates for the Vedder River, British Columbia.
Barry et al., 2004	Evaluation of the performance 9 bed-load equations	Results show substantial differences in performance but no consistent relationship between equation performance and degree of calibration or complexity. Equations which contain a transport threshold (Meyer-Peter and Müller, 1948; Bagnold, 1980; Ackers and White, 1973) typically exhibit worse performance than nonthreshold equations (Parker et al., 1982). The transport data are best described by a simple power function of discharge.
Martin and Ham, 2005	Evaluation of the performance 4 bed-load equations	Bagnold (1980) equation provides the most consistently reasonable results. However, the range of error may typically be up to an order of magnitude.
Wong and Parker, 2006	Re-examination of Meyer-Peter and Müller (1948) equation	By the database of Meyer-Peter and Müller (1948) it was shown that the form drag correction is unnecessary for plane-bed conditions and should be dropped. Simplified versions of Meyer-Peter and Müller (1948) equation have been presented.

3.3.2. Reach scale

The river reach is defined as a homogeneous section of a river channel within which hydrological, geological, and adjacent watershed surface conditions do not change significantly, i.e. there is no change in the imposed controlling factors, such that the river maintains a near consistent structure (Kellerhals et al., 1976; Downs and Gregory, 2004; Brierley and Fryirs, 2005). At this scale the following parameters are considered: channel depth, channel width, bank height, floodplain/valley width, channel slope, valley slope, some ratios and products of them and others (see Table 3.3). Some of the geometrical variables are defined by Fig. 3.6. Below concerns about defining of the parameters are given because there are uncertainties for some of them. Also equations to define some of parameters are presented.

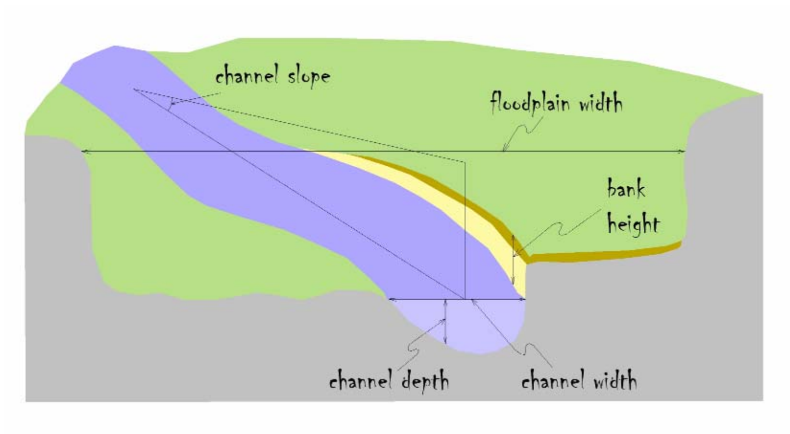


Figure 3.6: Definition sketch for some geometrical parameters at the reach scale.

Channel depth and width. It should be noticed that depth and width for a channel are defined for bankfull conditions where it was possible. The channel depth is more sensitive to a chosen bankfull level than channel width. Consequently, the channel depth is more variable even for adjacent river reaches. Also there is dependence on where measurements were taken, e.g. whether they were taken at a pool or riffle. For the channel width in some cases difficulties arise in its estimation as well. In the case of a single-thread river it is not a problem. For braided rivers channel width can be estimated at bankfull conditions when in-channels bars are submerged and the river represents itself as a single-thread channel. But for anabranched rivers, even at bankfull conditions, channel width is determined for each separated channel, because the width, when all channels of anabranched system are submerged, represents the width of the floodplain rather than the width of the channel.

Bank height. By the definition of bankfull discharge, which is has been given above, the bank height is equal to the bankfull channel depth. This is the case when banks have nearly the same height. However, usually on meandering rivers the eroded (concave) bank is higher than the opposite (convex) bank, consequently bank height is not always equal to the depth in bankfull conditions. It seems that this was the reason to give the following additional definition for the bankfull discharge: discharge at a stage when there is incipient overflow to the adjacent floodplain (Wolman and Leopold, 1957). In this case only one bank can be inundated. It is not obvious how bank height is measured in different studies. In some studies the bank height is the distance from the top edge of the bank to the thalweg, in others to the water level in low water, in others to the "normal" level, and in some studies at the date of observation, which can be done at different seasons. It was important to know about how the bank height was measured while compiling data, but unfortunately in many studies bank height is given without mention of how it was measured. In the used database all available data about bank height are used in further analysis, despite the above noted uncertainties in the bank height definition.

Floodplain/valley width. Both the floodplain width and valley width were used, because in cases when the floodplain is confined by valley walls than it occupies the whole width of the valley.

Slope. Three characteristics of slope are used, notably water surface slope, channel slope and valley slope. In relatively straight channels channel and valley slopes are nearly equal. In meandering rivers channel slope and valley slope are related through sinuosity as follows:

$$P = \frac{S_v}{S_c}, \qquad 3.25$$

where P = sinuosity; S_v = valley slope; S_c = channel slope. Using this relation for slope either channel or valley slope has been calculated if data about sinuosity have been given in original sources.

Regarding water slope it should be noted that during a year this characteristic is subject to change. The only one value of water slope for a river reach is used as is given in original sources, although water slope at high water and at low water, or at rising limb and at dropping limb during flood time can differ from each other markedly.

Gross stream power is given as:

$$\Omega = \rho g Q S , \qquad 3.26$$

where Ω = the gross stream power (W m^{-1}); ρ = water density (1000 kg m^{-3}); g = gravitational acceleration (9.81 m sec^{-2}); Q = water discharge (m sec^{-3}); S = channel slope. Unit stream power is defined by equation (3.23).

Shear stress. An estimate of the shear stress exerted by water flow can be obtained from:

$$\tau = \rho g R S , \qquad 3.27$$

where τ = shear stress (N m^{-2}); ρ = water density (1000 kg m^{-3}); g = gravitational acceleration (9.81 m sec^{-2}); R = hydraulic radius (m); S = slope. In the assumption for wide channels the channel depth is used instead of hydraulic radius.

Coefficient of variation of water discharge is defined as:

$$Cv = \frac{\sigma}{\overline{Q}} , \qquad 3.28$$

where Cv = coefficient of variation; σ = standard deviation which is a measure of how widely values are dispersed from the average value of water discharge $\overline{Q}$. In order to calculate the coefficient of variation, initial data for discharge values were downloaded from the USGS website (http://waterdata.usgs.gov/nwis/sw). Therefore, it was possible to make a relationship only for rivers where USGS operates.

Channel type is defined qualitatively from planview of the river channel from the air and it is considered over the length of a river channel reach (Downs and Gregory, 2004). For channel types a special consideration has been given. In this study the relationship between bank erosion and channel types has been considered in a separate section.

3.3.3. Cross-section scale

Definition of the cross-section is not easy because channels can be compound in cross-section, they may not be clearly differentiated from the floodplain and they may alter because of short-term storm events. Definition can be given based either on morphology, sedimentological evidence, ecological/biotic evidence or evidence from recent flood events (Downs and Gregory, 2004). However, herein the concern is which parameters to use in the scale of cross-section. As the shape of the cross-section is a function of the flow, the quantity and character of the sediment, the character or composition of the boundaries, including the vegetation (Leopold, 1994), then in this scale the following parameters are of concern: water velocity, median grain size, bank silt-clay content, sediment types and vegetation types.

Water velocity is used as a characteristic which reflect the ability of water flow to erode river banks. The values of water velocity are taken as given in original sources or have been calculated as water discharge divided by cross-section area. Consequently, the values represent the average water velocity for the cross-section.

Erosion rate depends not only on the power of water flow to erode but also on properties of the sediment which is under the action of flowing water. The erodibility of sediment depends upon its properties such as grain size distribution (Allen et al., 1999), grain shape (Oakey et al., 2005), bulk density (Wynn and Mostaghimi, 2006), cohesiveness (Osman and Thorne, 1988) and others. These properties determine the resistance of sediment to erosive action of water flow. Also some properties for cohesive sediment change due to the type and intensity of subaerial processes (also known as "preparatory" or "weakening the bank" processes) (Couper, 2003).

Median grain size. To characterize size of bed and bank sediments the median grain size is used. The values of median grain size are available only from sources where the grain size analysis was undertaken. Consequently, data about median grain size is limited. To create a relationship with bank erosion rate the median grain size values were converted into the phi-scale (Krumbein, 1936; Sumner, 1978) as:

$$\phi = -\log_2 D = -3.32 \times \log_{10} D \qquad 3.29$$

where D = median grain size in mm. The boundaries between successive size classes in phi-scale and in mm are shown in Table 3.5.

Bank silt-clay content data also are available only from grain size analysis. However, some sources provide qualitative data by describing fractions as "silt", "sand" and so on.

Sediment type. While the median grain size and the bank silt-clay content give quantitative description of sediment, sediment types as qualitative description are used widely as well. Herein sediment types are given in two senses. Firstly, by grain size, and secondly by cohesiveness as defined below.

For grain size, the Udden (1914) and Wentworth (1922) grain scale is widely used as the practical standard (Blair and McPherson, 1999). A summary of used grain scales is given by Blott and Pye (2001) and presented in Table 3.5. Herein a broad scale is adopted, which includes the following gradations: "boulders", "gravel", "sand" and "silt and clay". Table 3.5 is used to define sediment type by grain size where data about median grain size are available. Use of descriptive terms for sediment is also dictated by the fact that often there are no quantitative information about median grain size in some publications, and only descriptive information such as "sand-bed" or "gravel-bed" is available.

Table 3.5: Grain size scales (from Blott and Pye, 2001)

Grain size ϕ	mm	Udden (1914) and Wentworth (1922)	Friedman and Sanders (1978)	Blott and Pye (2001)	
			Very large boulders		
-11	2048				
			Large boulders	Very large	
-10	1024				
			Medium boulders	Large	
-9	512	Cobbles			
			Small boulders	Medium	Boulders
-8	256				
			Large cobbles	Small	
-7	128				
			Small cobbles	Very small	
-6	64				
			Very coarse pebbles	Very coarse	
-5	32				
			Coarse pebbles	Coarse	
-4	16	Pebbles			
			Medium pebbles	Medium	Gravel
-3	8				
			Fine pebbles	Fine	
-2	4				
		Granules	Very fine pebbles	Very fine	
-1	2				
		Very coarse sand	Very coarse sand	Very coarse	
0	1				
		Coarse sand	Coarse sand	Coarse	
1	0.5				
		Medium sand	Medium sand	Medium	Sand
2	0.25				
		Fine sand	Fine sand	Fine	
3	0.125				
		Very fine sand	Very fine sand	Very fine	
4	0.063				
			Very coarse silt	Very coarse	
5	0.031				
			Coarse silt	Coarse	
6	0.016	Silt			
			Medium silt	Medium	Silt
7	0.008				
			Fine silt	Fine	
8	0.004				
			Very fine silt	Very fine	
9	0.002	Clay			
			Clay	Clay	

With respect to cohesiveness there is no clear distinction as to which sediment is cohesive and which is not cohesive as cohesion depends upon many physical and chemical properties of sediment. In the context of this study two simple approaches are considered to categorize sediment by cohesiveness. The first one is based on grain size, and the second one on the silt-clay content.

In the first approach a basic conceptual model (according to Makkaveev and Chalov, 1986) is used. By this concept there are two main forces resisting erosion: the resistant force due to gravity and the resistant force due to cohesiveness. Both depend on the grain size of sediment, and a graphical representation is shown in Fig. 3.7. The effect of the resistant force due to gravity increases as grain size increases. In contrast, the resistant force due to cohesiveness has an inverse relationship with grain size. The intersection of the curves corresponds to grain size around 0.05 mm. The minimum point for the total curve (sum of both forces, presented as a dashed curve in Fig. 3.7) also corresponds to this grain size. At this point total resistance reaches its minimum. Based on this analysis Makkaveev and Chalov (1986) suggested to divide sediments as follows: if grain size is coarser than 0.05 mm then noncohesive; if less than 0.05 mm then cohesive. However, there is a range of grain sizes (approximately 0.002-0.1 mm from Fig. 3.7) for which both resistance forces are of significance. This range is considered as intermediate. A slightly different (shifted toward coarser grain size) range for intermediate sediments has been given by Sundborg (1956), notably 0.006-0.6 mm. These ranges are broad. Indeed, comparing with grain size scale (Table 3.5) the lower limit 0.002 mm include all categories of silt and equals to the upper limit for clay; the upper limit 0.6 mm for intermediate sediments by cohesiveness include gradations of sand up to the "coarse sand". According to the sediment classification of van Rijn (2007), sediments with grain sizes smaller than 0.008 mm are classified as "very cohesive", and larger than 0.062 mm as "noncohesive". Thus by various authors different and wide ranges for the intermediate sediments by cohesiveness are suggested. To be consistent with the widely used grain size scale (Table 3.5) the following arbitrary range is adopted for intermediate sediments by cohesiveness: from 0.008 mm up to 0.125 mm including "medium silt", "coarse silt", "very coarse silt" and "very fine sand" gradations. Assumptions are made that the gradation "fine silt" is fine enough to possess cohesion, and the gradation "fine sand" is coarse enough to not possess cohesiveness.

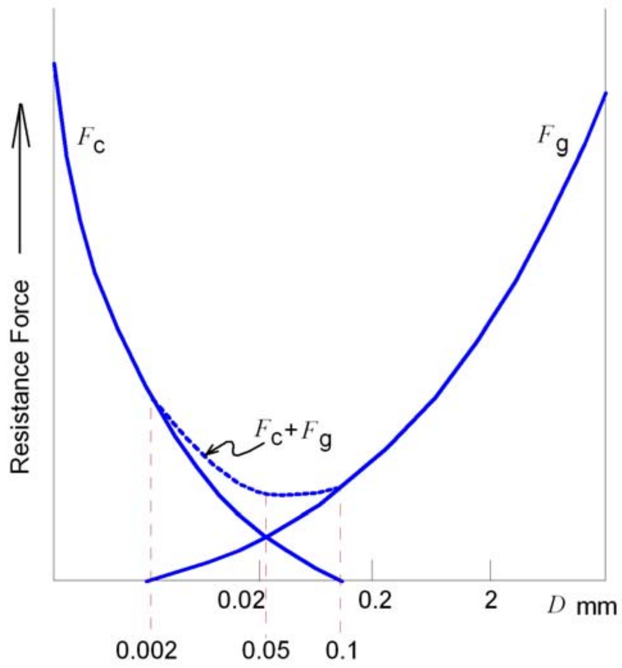


Figure 3.7: Relative effect of resistant forces due to gravity (F_g) and due to cohesion (F_c). Redrawn from Makkaveev and Chalov (1986), after Mohr (1944).

In the second approach the distinction between noncohesive and cohesive sediments is related to silt-clay and sand content. Wynn and Mostaghimi (2006) have noted that cohesion decreases with increased sand content. van Rijn (2007) has presented a table (his Table 1, p. 650) where types of sediments are related to percentage of organic material, clay, silt and sand content. Herein a simplified and modified version of van Rijn's table is adopted (Table 3.6). Three categories by cohesiveness have been related only to silt and clay percentage and sand percentage, ignoring the organic material percentage.

Table 3.6: Types of sediment by cohesiveness (simplified and modified after van Rijn, 2007)

Type of sediment	Percetage of silt and clay, %	Percentage of sand, %
Noncohesive	<10	>90
Intermediate	<40 and >10	>60 and <90
Cohesive	>40	<60

Riparian vegetation type. The effect of riparian vegetation type on the hydraulic geometry of gravel rivers has been shown by Hey and Thorne (1986). They have used the following four categories of bank vegetation types: (I) – grassy banks with no trees or bushes; (II) – 1-5% tree/shrub cover; (III) – 5-50% tree/shrub cover; (IV) – more than 50% tree/shrub cover or incised into floodplain. However, the studied rivers are laterally stable and there are no observations about significant lateral erosion on these rivers. Subsequently a number of studies about the effect of vegetation to bank erosion have been done. Recent reviews can be found in e.g. Wynn and Mostaghimi (2006) and Pollen (2007). In short, lateral erosion is particularly dependent on riparian vegetation type and its density, but the complexity of natural, vegetated streams often makes it difficult to establish a direct causal relation between riparian vegetation and channel characteristics (Gran and Paola, 2001). In further analysis a simple arbitrary classification of vegetation is used. The categories as “no vegetation”, “grass”, “shrubs”, “trees” are adopted to describe riparian vegetation type and to construct a relationship with bank erosion rate.

CHAPTER 4: RESULTS AND DISCUSSION OF STATISTICAL EXAMINATIONS

4.1. INTRODUCTION

In this chapter different parameters are considered which may be related to lateral stability. Usually the bank erosion, or recession, rate expressed as a unit loss per time period (e.g. m per year) is used to describe lateral stability, but other characteristics such as the volume of eroded material (e.g. m^3 per year), the plan area (e.g. hectares per year) or relative bank erosion rates (e.g. % of channel width per year) can also be used. However, the latter are still calculated based on data describing bank erosion rates. Furthermore, there are more data about bank erosion rates in the literature than other indices of lateral stability. For these reasons data about bank erosion rates as the main characteristic of lateral stability are used in this study. Another characteristic, which is used in this study, is a relative bank erosion rate which shows a proportion of the channel width being eroded every year. This characteristic is useful to compare activity of channels in a “dimensionless” sense where data about channel width are available.

The aim of this chapter is to develop general relationships between bank erosion rate and such characteristics as channel types, water discharge, slope, bank and bed material grain size, riparian vegetation types and others using statistical analyses.

There is an extensive literature concerning bank erosion rates. The data extracted were obtained from different parts of world, in different parts of river systems (upper, middle and lower reaches), from different channel types (straight, meandering and others) and from various hydrological and geomorphological conditions. Thus there is a wide range of bank erosion rate values reported, from a few mm per hundred years (in bedrock rivers) up to several hundreds metres per year in alluvial rivers (for instance, braided sections of the Brahmaputra River). Moreover, scientists use different techniques of measurement and calculation for bank erosion rates (Fig. 4.1). A comprehensive review of techniques, which are used for measurement and calculation of bank erosion rates, can be found in an article by Lawler (1993). As noted by Lawler (1993) the use of specific techniques depends upon various reasons, notably, the multiplicity of possible approaches to the study of bank erosion (e.g. emphasis on process rates, mechanics, or geotechnics); the differing disciplinary backgrounds of researchers; the appropriate time scale of interest for a particular study; the variety of riverine environments (e.g. in terms of channel size, boundary materials and climate/hydrological regime); the varying constraints of time, finance and logistics between projects; and changing measurement technology over time (Lawler, 1993). Since the review of Lawler (1993), research has been done with modern equipment, as a result with very high spatial resolution. For example, Barker et al. (1997) have used terrestrial photogrammetry and Thoma et al. (2005) have used airborne laser scanning. In the papers these techniques were examined for use in studies of bank erosion rates, but these techniques are not widely used in practice yet.

In this study the majority of collected data (74%) represents the technique of utilizing historical sources (maps and air photographs) (Fig. 4.1). For 12% of the data, information about the techniques used is not available. In recent decades scientists have used the erosion pin technique with increasing frequency. The peculiarities of this technique result in a large number of data from small rivers, where, in general, low bank erosion rates are observed. This bias towards studies of low bank erosion rates affects the global distribution of bank erosion rate values recorded in the literature and may explain the skewness of this distribution (Fig. 4.2 A). Rarely, scientists have used other techniques (5%). Following Lawler (1993) a list of other techniques is given in the notation for Fig 4.1.

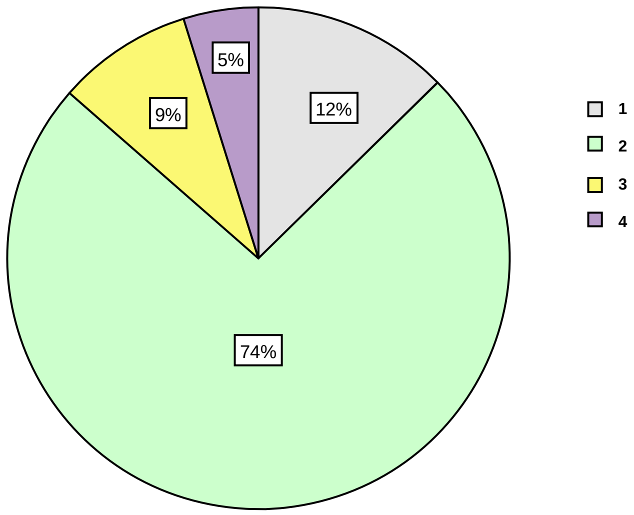
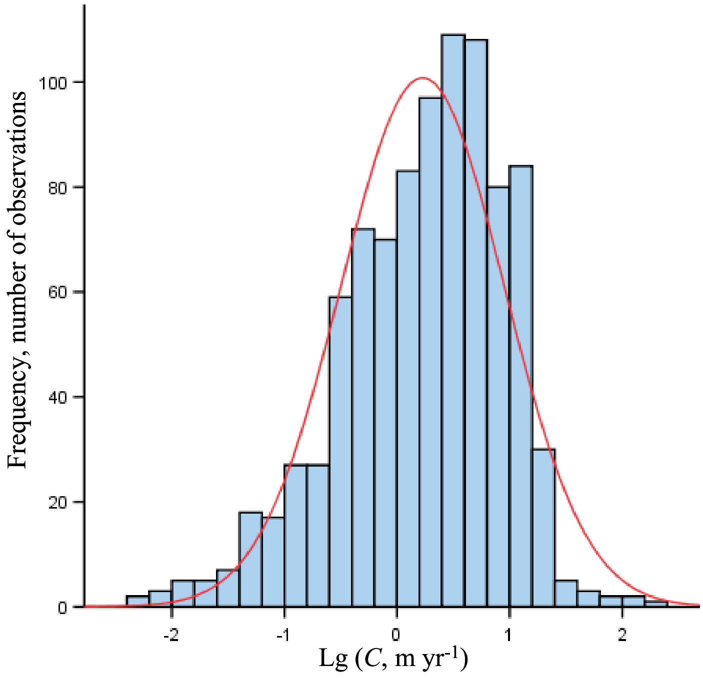
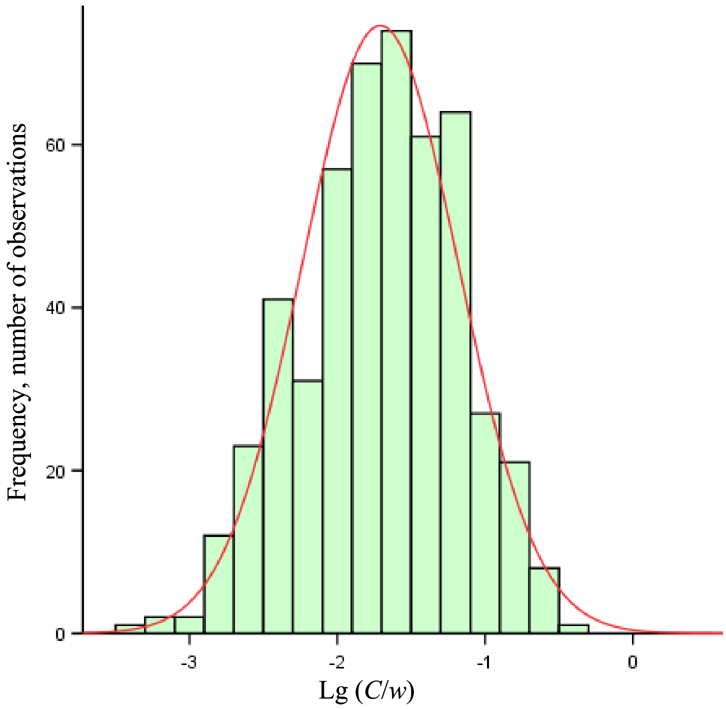


Figure 4.1: Techniques of bank erosion measurement and calculation for data used in this study. Number of observations is 906.

1. No information about used techniques; 2. Historical sources or combinations of historical sources; 3. Erosion pins (including PEEP – Photo-Electronic Erosion Pin) or combinations with erosion pins; 4. Other methods: botanical evidence; planimetric resurveys; repeated cross-profiling; sedimentological evidence; interview with local inhabitants; terrestrial photogrammetry; airborne laser scanning; morphological criteria; sediment traps/catchment trays; erosion box; thermal disturbance; painted pebbles/sections; contemporary repeated photography.



(**A**)



(**B**)

Figure 4.2: Bank erosion rate log-normal distributions. (A) Bank erosion rate values. Number of observations is 906. (B) Relative bank erosion rate values. Number of observations is 487. Red curves represent Normal distribution.

In bedrock rivers bank erosion rates are not significant for engineering purposes, therefore only data for alluvial rivers are used in this study. Alluvial rivers also may have low bank erosion rates ranging upwards from several mm per year. Taking into consideration the range of bank erosion rate and relative bank erosion rate values (Fig. 4.2), in statistical analysis Log_{10} transformed values are used. The transformed distribution for bank erosion rate (Fig. 4.2 A) shows that most values are found within the interval 1-10 m per year (Log-transformed values from 0 to 1). High bank erosion rates with values of more than 100 metres per year (higher than Log-transformed value 2) are observed more rarely providing isolated, if not exceptional examples. The majority of observation for relative bank erosion rate (Fig. 4.2 B) is found within the interval 1-10% (or 0.01-0.1 in proportions of unity) of channel width per year (Log-transformed values from -2 to -1). As for absolute values of bank erosion there is a bias to low values, though it is not as obvious as in Fig. 4.2 A. Nearly log-normal distributions of bank erosion rates and relative bank erosion rate show a similar frequency distribution as many natural phenomena, such as floods, earthquakes, storms (Wolman and Miller, 1960; Sumner, 1978). In general, large events of the same process occur seldom and small events occur often.

Some statistical relationships for bank erosion rates have been proposed prior to this study (e.g. Hooke, 1980; Nanson and Hickin, 1986; Richard et al., 2005), but all of them have been made for specific regions of the world. Consequently, the relationships derived in these earlier works can be applied within regions with similar physiographic settings. In this study an attempt is made to derive general relationships with data from different regions representing a wide range of conditions. In this case some limitations occur, primarily a greater scatter in the defined relationships. In this study, although parameters are adduced for regression equations, and from the statistical standpoint they are well-founded, derived statistical relationships are recommended to be regarded as approximations for bank erosion rate estimation. As was noted above, the main aim is to derive general relationships for bank erosion rate, and not to describe and discuss specific site situations, which in some cases may be contrary to the results obtained in this study. It is significant to notice that there are a few studies where general relationships for bank erosion are considered in the literature. Among them a relationship with drainage area derived by Hooke (1980), a study by Walker and Rutherfurd (1999), where relationships with many variables were derived, but only for the meandering channel type, and a relationship of bank erosion rate with water discharge by Rutherfurd (2000), also only for meandering rivers. These studies are valuable for comparison with results obtained in this study and are considered further where corresponding relationships are presented.

All the following sections are divided into two parts. In the first, results for bank erosion rate are given, while in the second, results for relative bank erosion rate are described.

4.2. ASSOCIATION WITH CHANNEL TYPES

4.2.1. Bank erosion rate and channel types

As a first stage of analysis, channel types were tentatively divided into four main types: straight, anabranched, meandering and braided (following Nanson and Knighton, 1996). Straight channels were defined as those that were reported in the literature as 'straight' but which lacked prominent reported shoals in accord with the definition of Acker and Charlton (1970). Fig. 4.3 shows how many data for each channel type were involved in the analysis. Almost 76% of overall data are for meandering channels. Much less data are available for braided channels and about equal proportions are available for anabranched and straight channels.

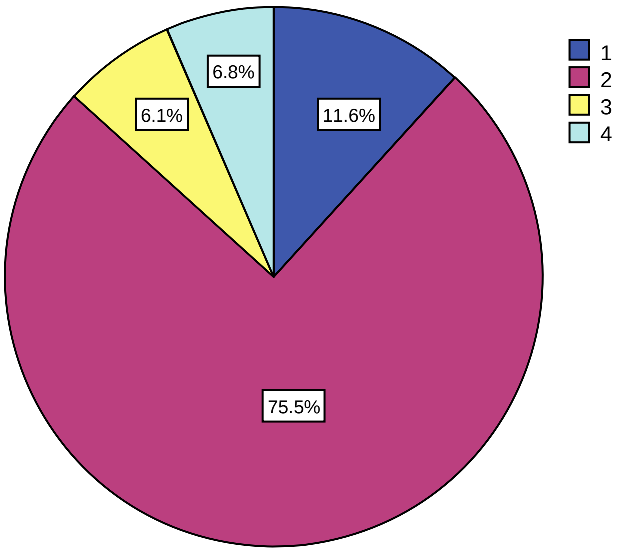


Figure 4.3: Distribution of data for different channel types. Channel types: 1. Braided; 2. Meandering; 3. Anabranched; 4. Straight. Number of observations is 906.

In Fig. 4.4 a distribution of bank erosion rate values by main channel types is shown. From Fig. 4.4 it is evident that the ranges of values and maximum valves decrease from braided to meandering to anabranched, and are minimum for straight channels. The minimum of the mean values also is for straight channels. Consequently, straight river reaches are the most stable in relation to bank erosion rate for given natural conditions. In this study data are used for natural channels alone, and so data for modified rivers with artificially straightened channels are not taken into account. As is known (e.g. Lewin, 1976) modified channels can be laterally unstable. With respect to their degree of bank stability, anabranched channels follow after straight channels by range, having a greater range of values. However, the mean value is slightly higher than for meandering channels.

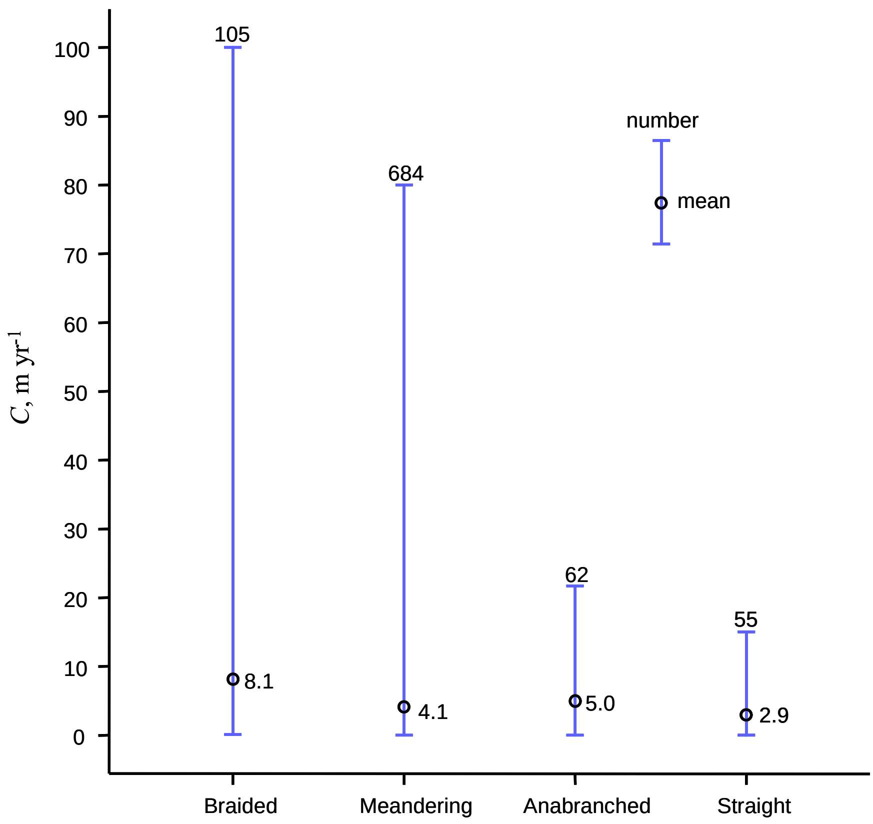


Figure 4.4: Ranges and mean values of bank erosion rate by channel types.

The mean value of bank erosion rates for meandering channels is 4.1 m per year, but the range is much bigger than for anabranched channels. This result for the range is explained because meandering channels are the predominant type (Leopold, 1994) with the greatest number of data about bank erosion rates (Fig. 4.3). Moreover, as will be shown below in an analysis for meandering subtypes, for different subtypes of meandering channels bank erosion rates vary. The mean value for meandering channels obtained by Walker and Rutherfurd (1999) is slightly less than that found in this study and equals 3.44 m per year. This difference is not significant taking into account the comment of Walker and Rutherfurd (1999) that the mean value is heavily biased by a few large values of bank erosion rate.

Among all channel types, braided channels are characterized by the largest range and the largest mean value of bank erosion rate. Consequently from Fig. 4.4, braided channels are the most active in terms of bank erosion rate.

To estimate the association between main channel types and bank erosion further, the Goodman and Kruskal γ is used as defined in the methodology for ordinal data association. The initial data of bank erosion rate were transformed into categories and the percentage of the number of observations that fall into each category was counted (Table 4.1). The ordering and directions of categories are shown in Fig. 4.5. A graphical representation of data in Table 4.1 is shown in Fig. 4.6. In Fig. 4.7 cumulative bank erosion rate graphs for the main channel types are presented. With these graphical representations it is easier to interpret the tabulated data.

Table 4.1: Initial data to define the Goodman and Kruskal γ. Number of observations is 906.

Channel type	**Categories of bank erosion rate, m yr^{-1}**				
	<0.1	**0.1-2**	**2-5**	**5-10**	**>10**
Braided	1 %	27 %	17 %	25 %	30 %
Meandering	6 %	43 %	25 %	15 %	11 %
Anabranched	9 %	33 %	29 %	15 %	14 %
Straight	30 %	57 %	8 %	0 %	5 %

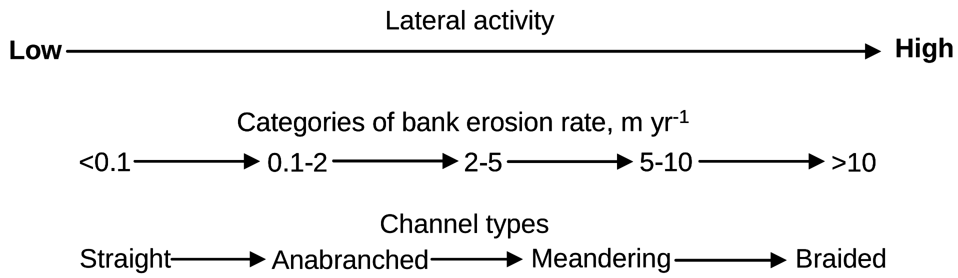


Figure 4.5: Ordering of categories for bank erosion rate and channel types by lateral activity.

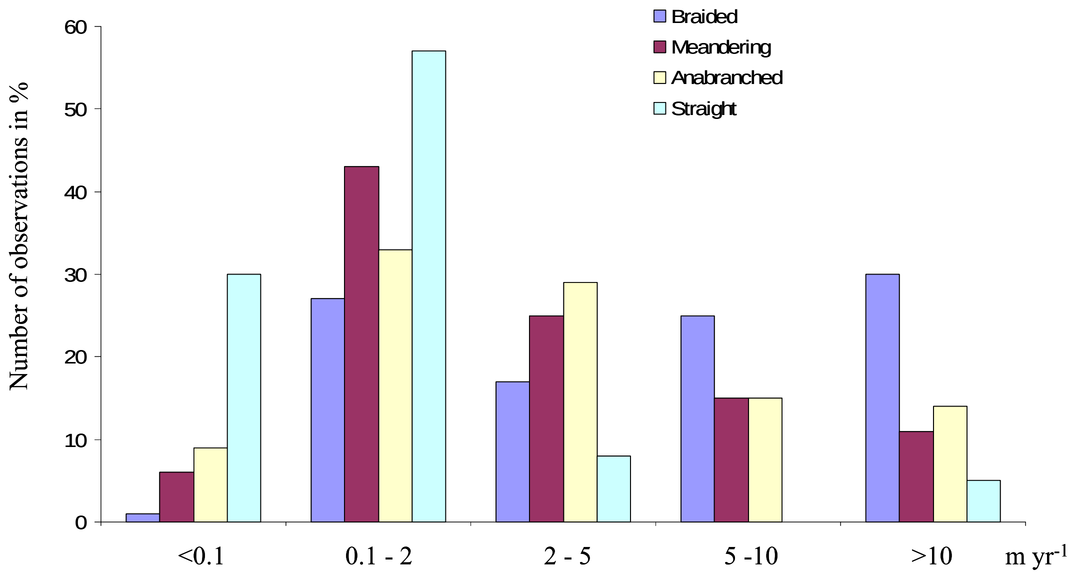


Figure 4.6: Distribution of observation number by bank erosion rate categories. Colour bars indicate channel types.

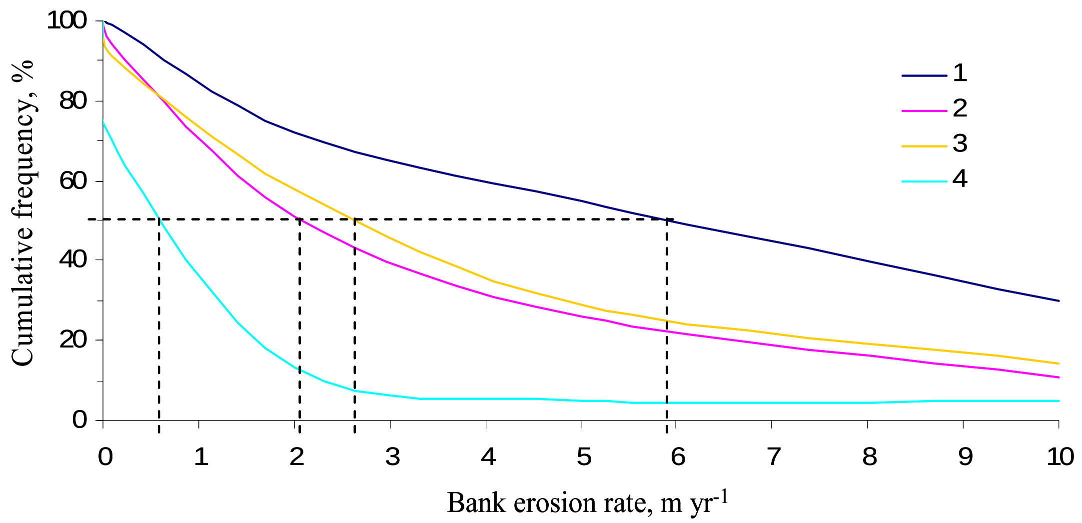


Figure 4.7: Cumulative bank erosion rate curves for the main channel types (based on data from Table 4.1). 1 – braided channels; 2 – meandering channels; 3 – anabranched channels and 4 – straight channels.

The value of the Goodman and Kruskal γ is -0.49. It means that the observed data are in the inverse order (Fig. 4.5) with the probability 0.49. The variance of γ, $\sigma^2(\gamma)$=0.00236. The condition that $\gamma \geq 2\sigma$ is satisfied and therefore, one can safely conclude that $\gamma \neq 0$ (Liebetrau, 1983). Although the Goodman and Kruskal γ is far from 1 (when there is a perfect association), the value of 0.49 indicates that there is an association between bank erosion rate and the order of channel types.

The graphical representation (Fig. 4.6) of data in Table 4.1 shows that the majority of data are in the category of bank erosion rate between 0.1 and 2 m yr^{-1}. For straight, meandering and anabranched channel types the distributions indicate that from 0 to 2 m yr^{-1} the percentage of observation number increase and for bank erosion rates more than 2 m yr^{-1} consistently decrease. Meanwhile, for the braided channel type the distribution shows different behaviour. For bank erosion higher than 2 m yr^{-1} the percentage of observation number is consistently increased with the maximum in the bank erosion rate category of more than 10 m yr^{-1}. The distributions for meandering and anabranched types are similar and the cumulative graphs (Fig. 4.7) for these types are also similar. Using the cumulative graphs it is possible to define the median bank erosion rate for each channel type. The median bank erosion rate is read at the intersection of the 50% line and the cumulative curves (Fig. 4.7). From the intersections: median bank erosion rate for straight channel type is 0.6 m yr^{-1}; for meandering – 2.1 m yr^{-1}; for anabranched – 2.6 m yr^{-1}; for braided – 5.9 m yr^{-1}. From this analysis one can conclude that, for instance, for braided rivers the bank erosion rate is higher than 5.9 m yr^{-1} in 50% of cases. For other percentages of bank erosion frequency values have been read from Fig. 4.6 and combined in Table 4.2. However, this analysis is a generalization and must be viewed as a tentative first step. A comparison of mean values is possible to make only for meandering channels because previously Walker and Rutherfurd (1999) have analysed statistical characteristics of meander migration rate for 91 river reaches in eight different countries. In the results they obtained the median bank erosion was 0.86 m per year, which is considerably less than that obtained in this study (2.1 m per year).

Another application of cumulative graphs is that one can choose an order of categories for channel types. As was shown by the distribution analysis (Fig. 4.4) the following order based on ranges has been used (from the most active to the least active): braided, meandering, anabranched and straight. However, Fig. 4.7 shows the following order: braided, anabranched, meandering and straight. Indeed, the Goodman and Kruskal γ is a bit higher for the latter order based on median values (-0.51 with $2\sigma = \pm 0.096$) which confirms that the order (braided, anabranched, meandering and straight) is more reliable for association of channel types and bank erosion rate. Though the difference in the two γ values is not large, a graphical representation of initial data as cumulative graphs is a useful tool to choose proper ordering for categories.

Table 4.2: Bank erosion rates in m per year for different frequencies and channel types

Frequency, %	Channel type			
	Braided	Anabranched	Meandering	Straight
10	>10	>10	10	2.2
20	>10	7.8	6.6	1.6
30	10	4.9	4.2	1.2
40	8.0	3.6	2.9	0.8
50	5.9	2.6	2.1	0.6
60	4.0	1.8	1.4	0.3
70	2.2	1.2	1.0	0.1
80	1.2	0.6	0.6	<0.1
90	0.7	0.1	0.2	<0.1

In the case when only the classical channel types classification, notably braided, meandering and straight (after Leopold and Wolman, 1957), are taken into the analysis, then the association becomes more robust with the Goodman and Kruskal γ equal to -0.65 with $2\sigma = \pm 0.12$.

Below an attempt is made to compare bank erosion rates for subtypes of the main channel types. It is possible to perform this analysis only for meandering channels, because for them subtype classifications were elaborated prior and enough data are available. There are classifications of subtypes for straight, anabranched and braided as well (e.g. a classification of Nanson and Knighton, 1996 for anabranched rivers; a schematization of Chalov, 2001 for braided and anabranched rivers), but at present there are not enough data within each subtype for meaningful statistical analysis. For meandering rivers such a comparison is possible to make as in Lagasse et al. (2004) initial data for meandering rivers of different subtypes in the United States were collated. Lagasse et al. (2004) modified a classification of Brice (1975). This classification is useful also for this study, because it is based on the plan-view features of channels, and the subtypes are thus easily recognized on maps and air photographs. A distribution of mean values and the ranges in relation to each of the subtypes of meandering channels is shown in Fig. 4.8.

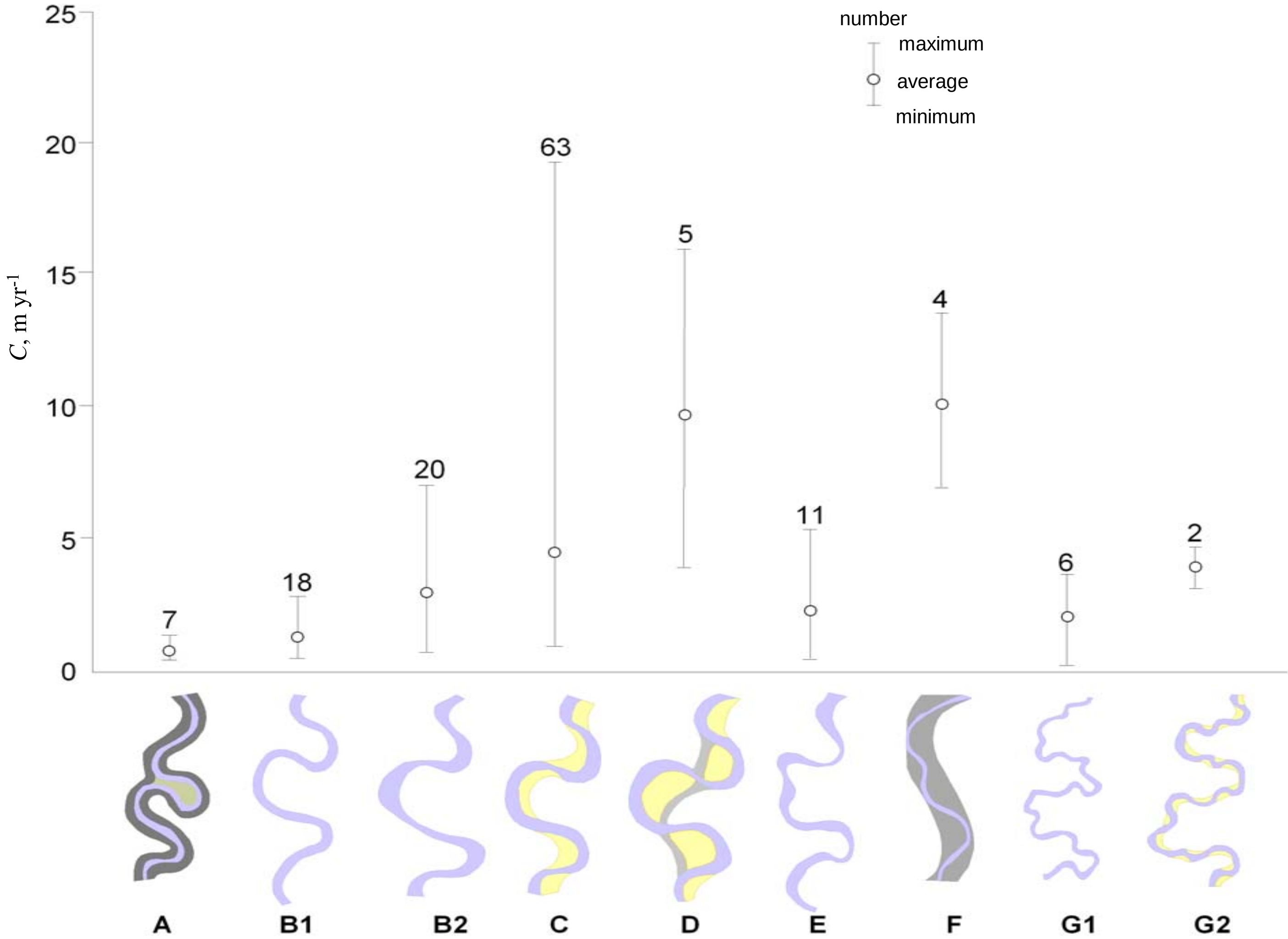
The least laterally active channels are channels of type A. Bank erosion rate values are found within a narrow interval and do not exceed 1.5 m per year. Types B1 and G1 are relatively laterally inactive too. All these types are characterized as equal width channels. Brice (1982) also discovered that rivers with equiwidth channels are either static or relatively stable. Although for types B1 and G1 mean values are slightly higher than for type A, they do not exceed 2.5 m per year.

Channels with irregular width are more laterally active than equiwidth channels (Fig. 4.8). This was also found by (Brice, 1982). The other types (B2, C, D, E, F, and G2) are types with irregular width, though between them there are essential distinctions. It is significant that rivers with bars have higher bank erosion rates than rivers without bars. Based on this characteristic, a group of subtypes (B2 and E) may be distinguished. Although these types differ from each other by form, the mean values and ranges do not differ markedly and are less than the values for channel types with bars. An exception is type G2. The mean value of bank erosion rate for type G2 is higher, but the range is narrow. It is explained by limited amount of data for type G2 (only 2 observations). Possibly the range for type G2 will be bigger if more data for this type were available. Nevertheless, with data for other types the conclusion is that one sign of lateral activity is a presence of bars in a channel.

The most predominant type of meandering is type C, so it sets the conditions for observing the maximum range of bank erosion rates. The mean value does not exceed 5 m per year, but in some cases bank erosion rates reach tens of metres per year.

Types D and F are most active. However, this statement is based on data from a few rivers. Perhaps the true ranges are bigger than shown in Fig. 4.8.

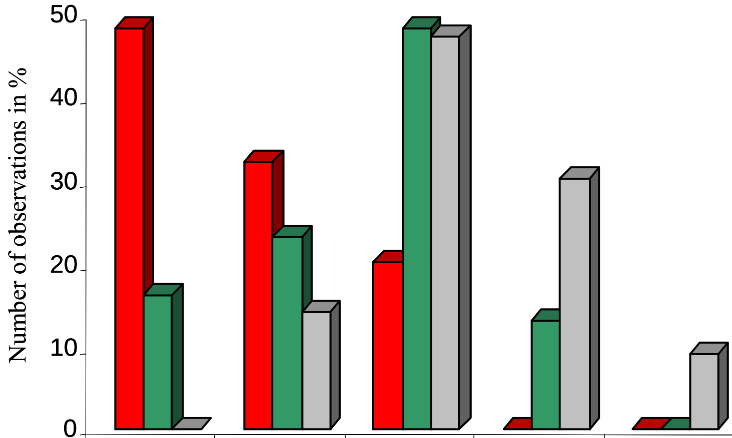
Based on the above described analysis three groups of meandering channels are distinguished. In the first group types A, B1 and G1 are considered and have the following common features: equiwidth and absence of bars. In the second group, which are characterised with irregular width and absence of bars, types B2 and E are in consideration. Finally, types C, D and G2 fall in the third group. The last group is characterized by irregular width and presence of bars. Type F is ignored as no common features with the three groups and mainly because of limited data (only 4 observations) for this type are available.



Type	Description
A	single phase, equiwidth channel incised or deep
B1	single phase, equiwidth channel
B2	single phase, wider at bends, no bars
C	single phase, wider at bends with point bars
D	single phase, wider at bends with point bars, chutes common
E	single phase, irregular width variation
F	two phase underfit, low-water sinuosity (wandering)
G1	two phase, bimodal bankfull sinuosity, equiwidth
G2	two phase, bimodal bankfull sinuosity, wider at bends with point bars

Figure 4.8: A distribution of bank erosion rates with respect to subtypes of meandering (based on initial data from Lagasse et al., 2004)

These three groups have been analysed for ordinal data association with bank erosion categories. Initial data and their graphical representation are shown in Fig. 4.9. From this figure the largest number of observations for “equiwidth channels without bars” are in the bank erosion category less than 1 m per year and the number of observations consistently declines with increasing bank erosion rate. Meanwhile, for the “irregular width channel without bars” and “with bars” channel subtypes the distribution shows different behaviour. For both these groups, up to the category 2 – 5 m per year the number of observations increases and for bank erosion rates higher than 5 m per year decreases consistently. The difference between “irregular width without bars” and “with bars” is the skewness of distributions. For “without bars” there is skewness to smaller values of bank erosion rate, while for “with bars” there is skewness to higher rates of bank erosion.



	<1	1 - 2	2 - 5	5 - 10	>10	m yr^{-1}
Equiwidth no bars	48%	32%	20%	0%	0%	
Irregular width no bars	16%	23%	48%	13%	0%	
Irregular width with bars	0%	14%	47%	30%	9%	

Figure 4.9: Distribution of observation number by bank erosion rate categories. Colour bars indicate meandering subtypes.

For the association between the three groups of subtypes of meandering channels and bank erosion rate categories the value of the Goodman and Kruskal γ is 0.74. The $2\sigma = \pm 0.10$, i.e. a conclusion is that $\gamma \neq 0$. Consequently, the observed data for meandering subtypes are in direct order with bank erosion rate with the probability 0.74, which is closer than in the case of general channel types. Although the variance is twice as high as in the general case, the value of variance is still acceptable statistically. The difference in the variance is partly explained by number of observations: for meandering subtypes the number of observations is 132 and is much less than for general channel types with 906 observations.

The cumulative curves of bank erosion rate for the groups of different meandering subtypes (Fig. 4.10) have been used to define bank erosion rates at different cumulative frequencies (Table 4.3) and to compare these curves with the cumulative curve in general case (4 in Fig. 4.10). For "equiwidth channels without bars" across the whole range of frequencies bank erosion rates are less than in the general case. To the contrary, for "irregular width channels with bars" bank erosion rates are higher than in the general case for the whole range of frequencies. Due to different steepness of the curves, "irregular width channels without bars" are characterized by higher bank erosion rates in the frequency range from c. 40 to 100% than meandering channels in "general". Otherwise, in the range 0 – c. 40%, "irregular width channels without bars" are characterized by lower bank erosion rates than in the general case. The median bank erosion rate (50%) in the general case is 2.1 m per year. This value is likely to be exceeded for "equiwidth channels without bars" in 20% of cases, for "irregular width channels without bars" in 60% of cases and for "irregular width channels with bars" in 85% of cases.

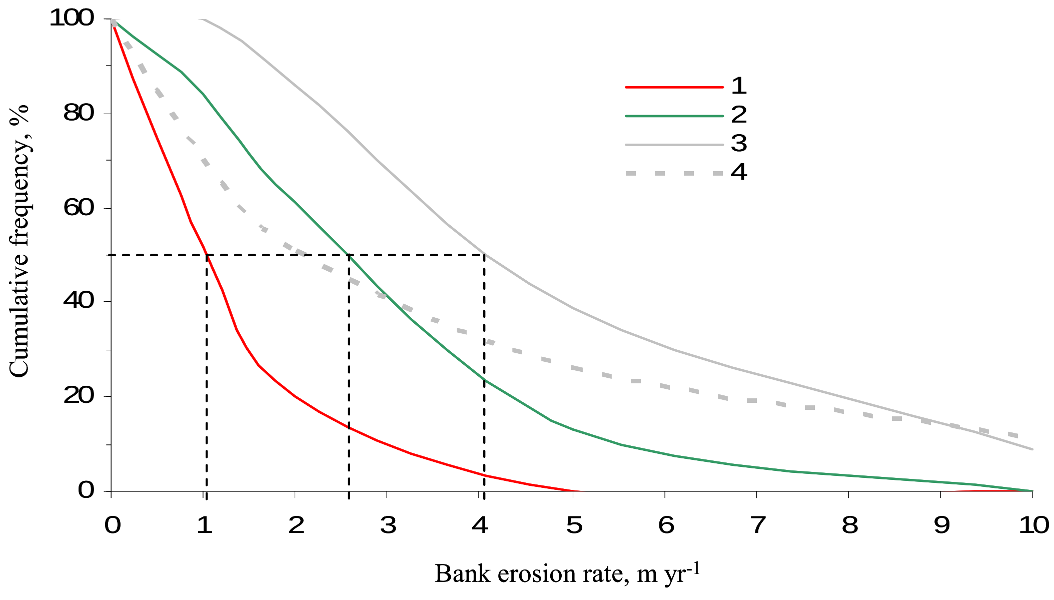


Figure 4.10: Cumulative bank erosion rate curves for meandering subtypes (based on data from Fig. 4.9). 1 – "equiwidth channels without bars"; 2 – "irregular width channels without bars"; 3 – "irregular width channels with bars" and 4 – meandering channels in general case from Fig. 4.7 is shown for comparison purpose.

Table 4.3: Bank erosion rates in m per year for different frequencies and meandering subtypes.

Frequency, %	Meandering subtype		
	equiwidth channels without bars	irregular width channels without bars	irregular width channels with bars
10	3.0	5.5	9.9
20	2.0	4.3	7.9
30	1.4	3.7	6.2
40	1.2	3.1	4.8
50	1.0	2.6	4.1
60	0.8	2.1	3.4
70	0.6	1.6	2.9
80	0.4	1.2	2.3
90	0.2	0.7	1.8

4.2.2. Relative bank erosion rate and channel types

The same analyses as for absolute values of bank erosion rates for relative bank erosion rate (*C*/*w*: ratio of bank erosion rate to channel width) have been performed and results are presented below.

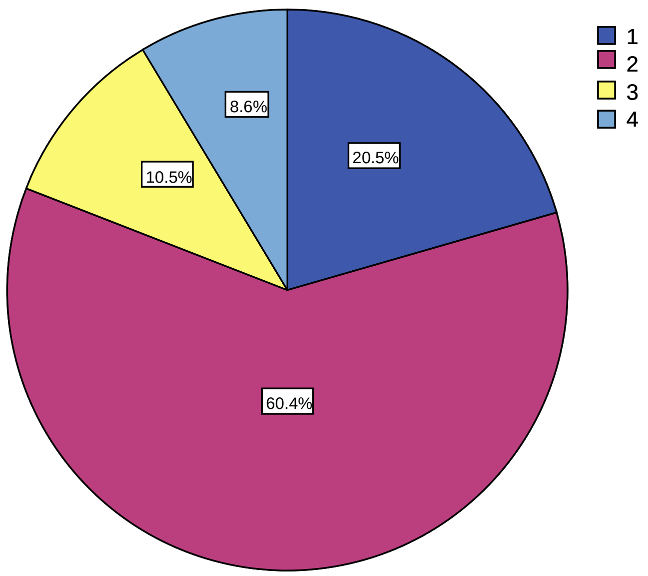


Figure 4.11: A distribution of relative bank erosion data for different channel types. Channel types: 1. Braided; 2. Meandering; 3. Anabranched; 4. Straight. Number of observations is 487.

The distribution by main channel types of how many data were involved in the analysis is shown in Fig. 4.11. The portion of data for meandering channels is less than in the analysis of absolute values of bank erosion rate, though it is still the majority of available data (60%). 20% is for braided channels; 10% of data are available for anabranched channels and the minor part (8.6%) is for straight channels.

The ranges and mean values of the relative bank erosion rate distributed by channel types are shown in Fig. 4.12. In this case, comparing with Fig. 4.3, one can conclude that the most active channels are meandering channels instead of braided channels. The maximum relative bank erosion rate is 0.36, i.e. 36% of channel width could be eroded in a meandering channel per year. To compare, an analysis performed by Kondratiev et al. (1982) for 800 meandering reaches in rivers of the former USSR revealed that the maximum of the relative bank erosion rate is 0.20, i.e. 20% of channel width per year, which is less than obtained herein. Perhaps this is because the current study data were obtained from different countries with wider variation in environmental conditions than for the data used by Kondratiev et al. (1982). Indeed, Walker and Rutherfurd (1999) obtained a higher maximum value (C/w*100% = 25%) using data mainly for rivers in the USA but also for Canada, Australia, the UK and other countries. However, the maximum value of relative bank erosion revealed herein shows that the bank in a meandering river can be eroded as much as a third part of the channel width, while in the study of Walker and Rutherfurd (1999) – as much as a quarter. The maximum for braided channels is 0.15; for anabranched = 0.14 and for straight = 0.11. The mean values are in the same order (Fig. 4.12). Consequently, the following order of channel types in regards to the relative bank erosion rate is revealed: meandering $\rightarrow$ braided $\rightarrow$ anabranched $\rightarrow$ straight from the most active to the least active. Again the straight channels are the least active as well as from the analysis of absolute values of bank erosion rates. There are no big differences in ranges and mean values between braided and anabranched channels. The values are only slightly higher for braided channels and probably are more robust as the number of observations is more than twice that for anabranched channels.

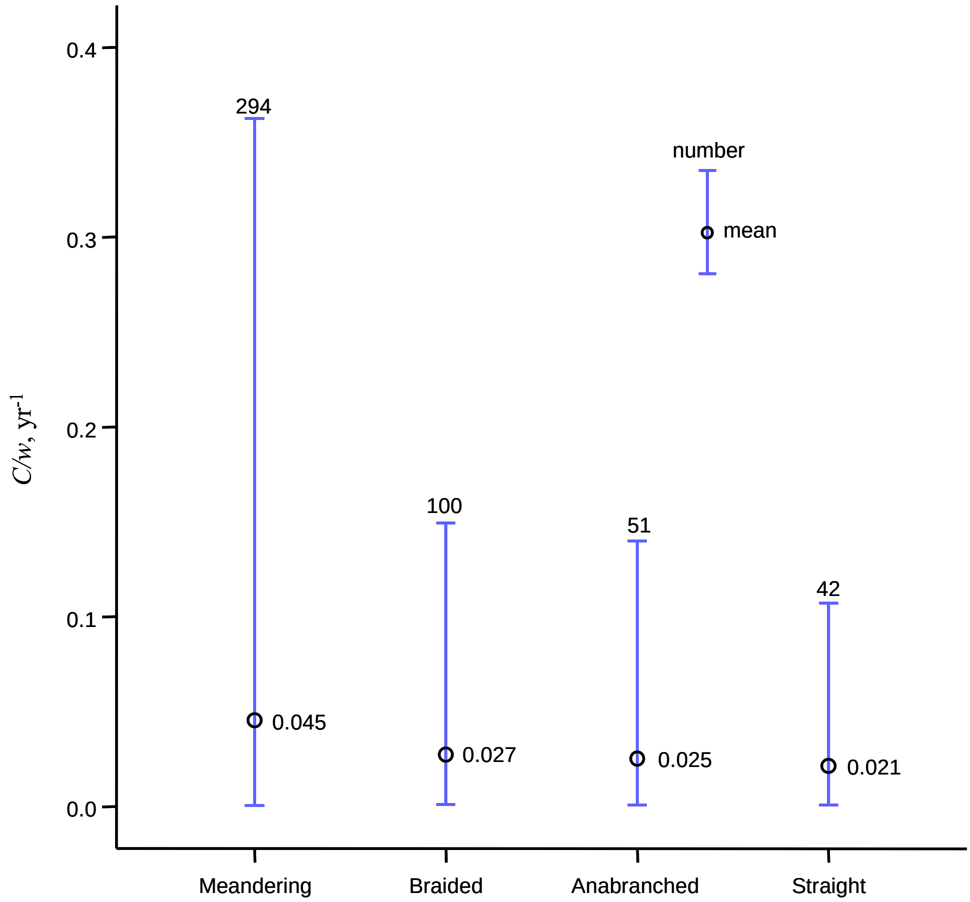
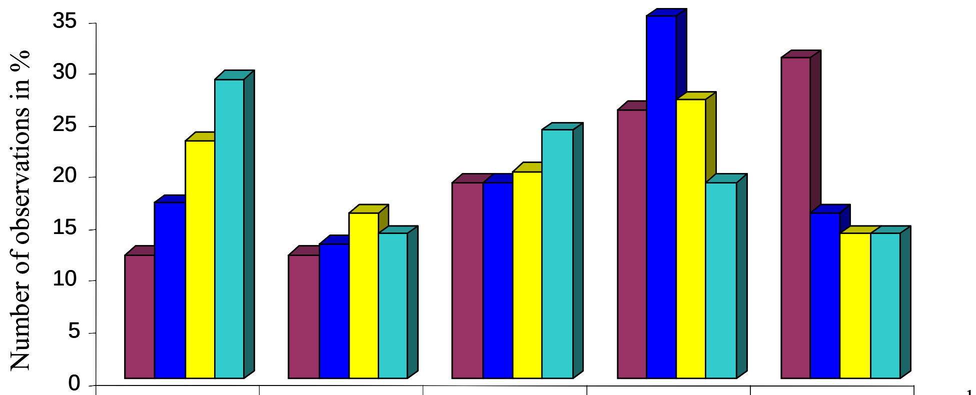


Figure 4.12: Ranges and mean values for relative bank erosion rate (*C/w*) by channel types.

For the revealed order of channel types the association with categories of relative bank erosion rate, i.e. the Goodman and Kruskal γ is -0.22. The initial data to calculate the coefficient of association and the data distribution by categories are shown in Fig. 4.13. The distribution for meandering channels shows the consistent increase in the number of observations with increasing of relative bank erosion categories. The maximum observation number (31%) is for relative bank erosion more than 5% of the channel width per year. The distributions for braided and anabranched channels are similar to each other. From the category “less than 0.5% of channel width per year” to the category “0.5% - 1% of channel width per year” the number of observation declines, then increases and reaches a maximum in the category “2% - 5% of channel width per year”: 35% of data are for braided and 27% are for anabranched channels. For these channel types the minimum number of observation lies in the category “more than 5% of channel width per year”. For straight channels the minimum number of observations also is within that category and the distribution is similar to that for braided and anabranched channels. However, the maximum number of observations (29%) is in the category “less than 0.5% of channel width per year". Due to the similarity of distributions for braided, anabranched and straight channels the value of the Goodman and Kruskal γ is low and shows that statistically there is no association between the order of channel types and the order of relative bank erosion categories. Despite the low value of the Goodman and Kruskal γ, the sign (minus) shows the correct direction of the prior chosen order for channel types (meandering $\rightarrow$ braided $\rightarrow$ anabranched $\rightarrow$ straight) from the most active to the least active.



	<0.005	0.005 - 0.01	0.01 - 0.02	0.02 -0.05	>0.05
Meandering	12	12	19	26	31
Braided	17	13	19	35	16
Anabranched	23	16	20	27	14
Straight	29	14	24	19	14

Figure 4.13: Distribution of observation number by relative bank erosion rate categories. Colour bars indicate main channel types.

From the cumulative curves (Fig. 4.14) the median relative bank erosion values have been determined. For meandering channels the median relative bank erosion is 2.7% of channel width per year; for braided – 2.1%; for anabranched – 1.4% and finally for straight channels – 1.2%. For other frequencies of exceedance the values of the relative bank erosion rate are combined in Table 4.4. A comparison with the results of Kondratiev et al. (1982) for meandering channels shows that values obtained herein are considerably less. The median relative bank erosion rate obtained by Kondratiev et al. (1982) is 5%, almost twice the value found here. According to Kondratiev et al. (1982) for 75% of observations the relative bank erosion rate exceeds 3.5% of channel width per year and for 25% of observations – exceeds 9%. The values from Fig. 4.14 are 1.1% and "more than 5%" for 75% and 25% of observation respectively. Consequently, Kondratiev et al. (1982) have dealt in general with data which came from more active meandering channels with respect to the relative bank erosion rate. To the contrary, Walker and Rutherfurd (1999) have obtained the median relative bank erosion rate as 1.6% of channel width per year, which is considerably less than that obtained from Fig. 4.14. To compare these results with a so-called "rule-of-thumb" for river managers in Fig. 4.14 red dashed lines are shown for 1% of channel width per year. The rule of thumb states that a meandering channel migrates at about 1% of channel width per year (Walker and Rutherfurd, 1999). The values of exceedance are the following: for meandering channels in 76% of cases; for braided – 70%; for anabranched – 61% and for straight channels in 58% of cases the relative bank erosion rate 1% of channel width per year is likely to be exceeded.

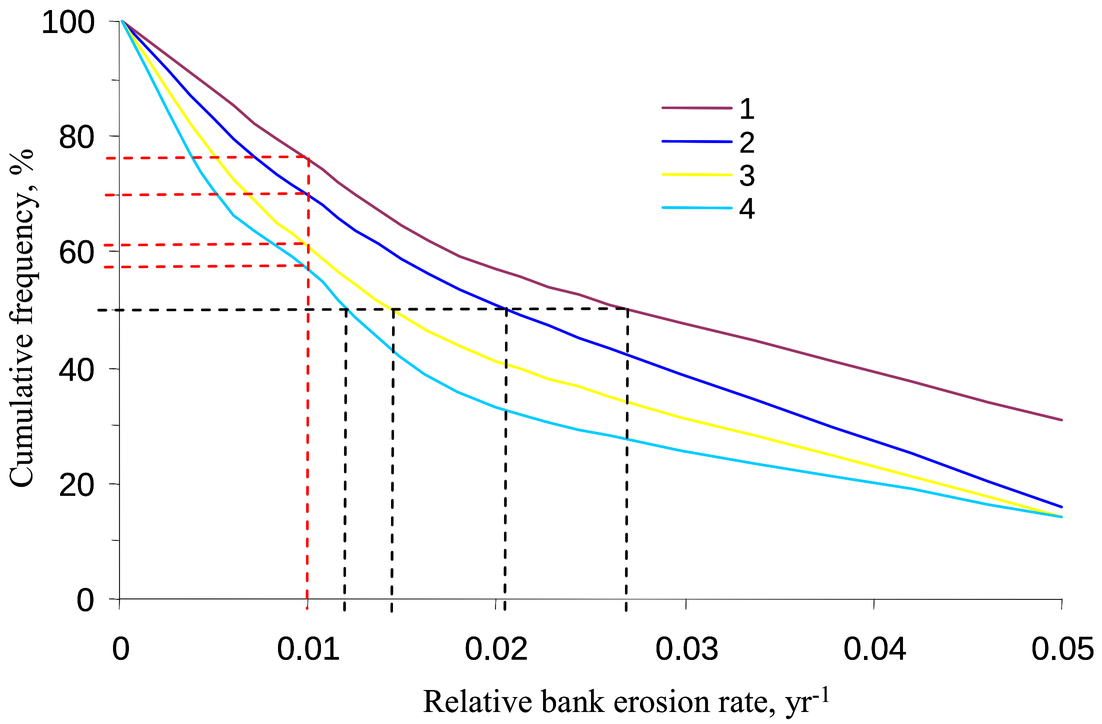


Figure 4.14: Cumulative relative bank erosion rate curves for the main channel types (based on data from Fig. 4.13). 1 – meandering channels; 2 – braided channels; 3 – anabranched channels and 4 – straight channels. Black dashed lines – determination of median values; red dashed lines – determination of the exceedance probability of the 0.01 relative bank erosion value (1% of channel width per year). See text for explanations.

Table 4.4: Bank erosion rates in proportion of channel width per year (yr^{-1}) for different frequencies (%) and channel types.

Frequency, %	Channel type			
	Meandering	**Braided**	**Anabranched**	**Straight**
10	>0.05	>0.05	>0.05	>0.05
20	>0.05	0.046	0.043	0.039
30	>0.05	0.037	0.031	0.023
40	0.039	0.028	0.022	0.015
50	0.027	0.021	0.014	0.012
60	0.017	0.014	0.010	0.008
70	0.012	0.010	0.007	0.005
80	0.008	0.006	0.004	0.003
90	0.004	0.003	0.002	0.0015

An analysis for meandering subtypes has been performed as well as for absolute values of bank erosion rates. However, due to data limitation not all subtypes were involved. For type G2 there are no observations at all; for types D and G1 only single observation and for type F only two points. Consequently, these types are not presented in Fig. 4.15 where distributions of the mean values and the ranges of relative bank erosion rates by meandering subtypes are shown. In contrast with Fig. 4.8, the type A by the mean value and range is not the least active subtype for relative values of bank erosion rate. Nevertheless, for all subtypes the maximum relative bank erosion rate does not exceed 10% of channel width per year, except for subtype C. Taking into consideration that the means and ranges for A, B1, B2 and E do not differ markedly, two categories of channels are distinguished. The above listed subtypes fall into the first category. In the second category the subtype C is considered. The distinct characteristic is the absence or presence of point bars. The subtype C is characterized as channels with point bars, while the other subtypes are characterized as channels without bars.

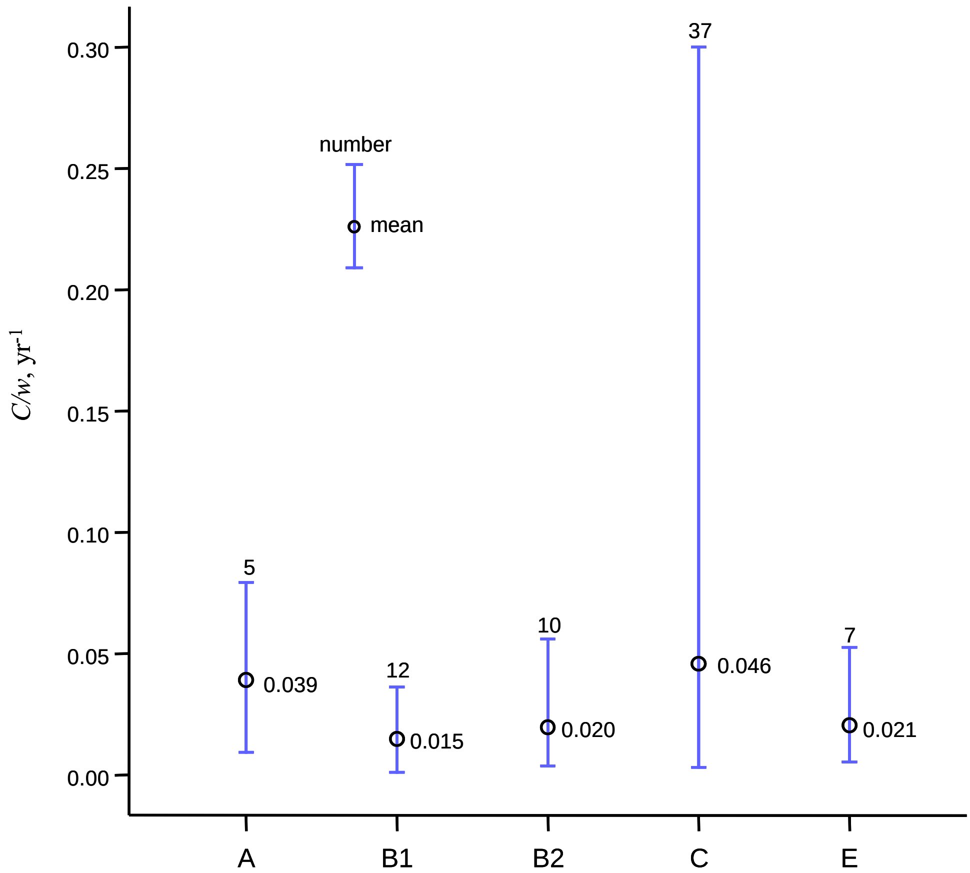
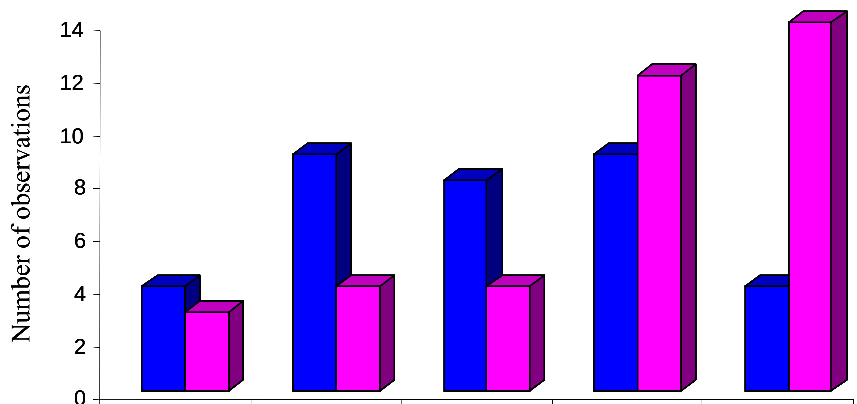


Figure 4.15: Ranges and mean values of relative bank erosion rates by meandering subtypes (based on initial data from Lagasse et al., 2004). For descriptions of meandering subtypes see Fig. 4.8.



	<0.005	0.005 - 0.01	0.01 - 0.02	0.02 -0.05	>0.05
Meandering without bars	4	9	8	9	4
Meandering with bars	3	4	4	12	14

Figure 4.16: Distribution of observation number for meandering subtypes by relative bank erosion rate categories.

Two types of meandering, notably meandering channels "without bars" and "with bars" have been analysed for association with relative bank erosion rate categories. Because the number of observations for the two categories of meandering is approximately equal (34 observations for "meandering without bars" and 37 for "meandering with bars"), in calculation of the Goodman and Kruskal γ the number of observations by categories are used without conversion to percentage. A distribution of observation numbers by relative bank erosion categories is shown in Fig. 4.16. For "meandering channels without bars" the minima of number of observations are in extreme categories. For other categories the numbers of observations are approximately the same. Meanwhile, for "meandering channels with bars" the number of observations consistently increases with the maximum in the category "more than 5% of channel width per year". Due to the regular distribution for "meandering channels without bars" with absence of a tendency to increase or decrease along the categories, the Goodman and Kruskal γ is low and equals 0.46.

Although the Goodman and Kruskal γ is low, the cumulative curves for meandering subtypes (Fig. 4.17) are considerably different. From Fig. 4.17 the median value of the relative bank erosion rate for "meandering channels with bars" is higher by as much as 2.5 times than that for "meandering channels without bars". The median relative bank erosion values are 1.5% and 3.8% for "without bars" and "with bars" respectively. For other probabilities of exceedance values are combined in Table 4.5.

A comparison of cumulative curves for meandering subtypes and meandering channels in general revealed that relative bank erosion is higher than in general for "meandering channels with bars" and otherwise is lower than in general for "meandering channel without bars" in the whole range of probabilities of exceedance (see Fig. 4.17).

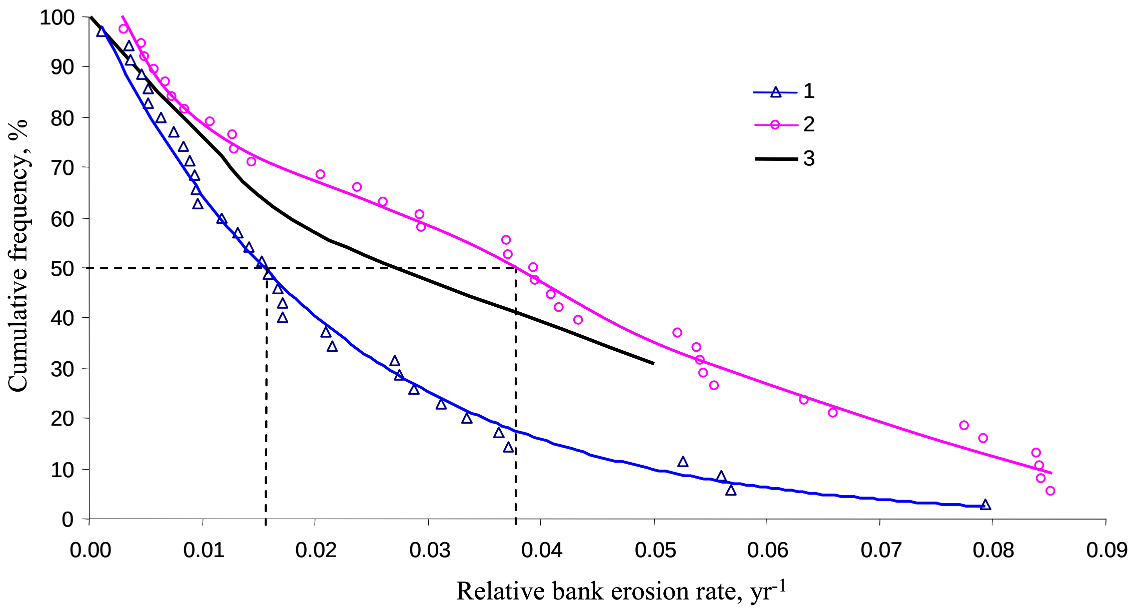


Figure 4.17: Cumulative relative bank erosion rate curves for the meandering subtypes. 1 – meandering channels without bars; 2 – meandering channels with bars; 3 – meandering channels in general case from Fig. 4.14 is shown for comparison purpose.

Table 4.5: Relative bank erosion rates (yr^{-1}) for different frequencies and meandering subtypes

Frequency, %	Meandering subtype	
	meandering channels without bars	meandering channels with bars
10	0.050	0.083
20	0.034	0.069
30	0.027	0.056
40	0.020	0.045
50	0.016	0.038
60	0.012	0.029
70	0.008	0.017
80	0.005	0.010
90	0.003	0.005

4.3. RELATIONSHIPS AT THE CATCHMENT SCALE

4.3.1. Bank erosion rate at the catchment scale

Drainage area. Since the publication of Hooke (1980), where a relationship between bank erosion rate and drainage area was produced, scientists have considered the relationship either with criticism (e.g. Hasegawa, 1989a) or with improvement on the basis of adding new data (e.g. Van De Wiel, 2003). The idea of developing such relationships is to estimate bank erosion rates with data which are easy to obtain from maps. Statistically, such relationships may be well founded. In this study a relationship between bank erosion rate and drainage area was constructed as well using all available data, i.e. for all river types (Fig. 4.18). By the relationship higher bank erosion rates are more likely on rivers with bigger drainage area.

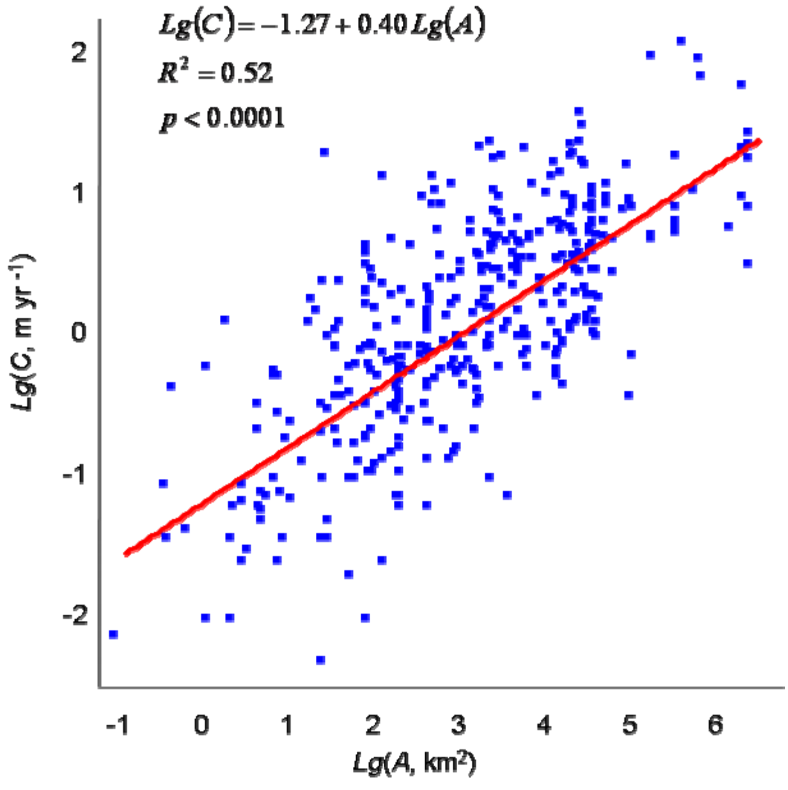


Figure 4.18: Relationship between bank erosion rate and drainage area. Number of observations is 397.

Statistically the relationship presented in Fig. 4.18 is less well defined than in the study of Van De Wiel (2003) where R^2 = 0.67 but is better than in the earlier study of Hooke (1980) where R^2 = 0.39. Walker and Rutherfurd (1999) obtained an even weaker relationship between drainage area and bank erosion rate with R^2 = 0.35. Rewriting the equation from Fig. 4.18 in the power form (see Table 4.6) shows that the power exponent is 0.4. In other studies the power law has been obtained with slightly different values of the exponent. For instance, Walker and Rutherfurd (1999) derived the exponent as 0.38 which is close to obtained herein. Hooke (1980) and Van De Wiel (2003) obtained slightly higher values than in Fig. 4.18 and almost the same values – 0.45 and 0.44, respectively. From the analysis of the resultant equation Hooke (1980) concluded that there is the square-root relationship between bank erosion rate and drainage area. However, in all consequent studies it has been shown that the power is slightly less than square-root, i.e. always less than 0.5. But note that for the relationship Hooke (1980) has used the maximum bank erosion rates while in other studies the mean erosion rates have been used (see Table 4.6). Despite varying values of the parameters, the relationships show the same direct relationship between bank erosion rate and drainage area.

Table 4.6: A comparison of equations for relationship between bank erosion rate and drainage area.

From	Derived equation	N	R^2	Notes
Hooke (1980)	$C = 2.45A^{0.45}$	55	0.39	A relationship between maximum bank erosion rate and drainage area
Walker and Rutherfurd (1999)	$C = 0.052A^{0.38}$	46	0.35	A relationship between mean bank erosion rate and drainage area
Van De Wiel (2003)	$C = 0.053A^{0.44}$	162	0.67	A relationship between mean bank erosion rate and drainage area
This study	$C = 0.053A^{0.40}$	397	0.52	A relationship between mean bank erosion rate and drainage area

A comparison of the coefficients in the equations revealed that for the mean bank erosion rate the coefficients are nearly equal. By the coefficients, one can conclude that in a river with drainage area 1 km^2 bank erosion rate is likely to be 0.05 m per year in average and up to 2.5 m per year as maximum.

Water discharge. As a parameter considered in catchment scale water discharge is used too. The initial premise is that the larger the water discharge the higher the bank erosion rates. In general, the premise is justified (Fig. 4.19). In Fig. 4.19 points are shown in different colour by channel types. Note that almost all points for straight channels are located below the regression line and consequently are associated with lower bank erosion rates than other channel types. Meandering and braided channels occupy the whole range of values for both water discharges and bank erosion rates. Anabranched channels are located in a narrow range of medium and high values of bankfull discharge and with broad range in bank erosion rates values.

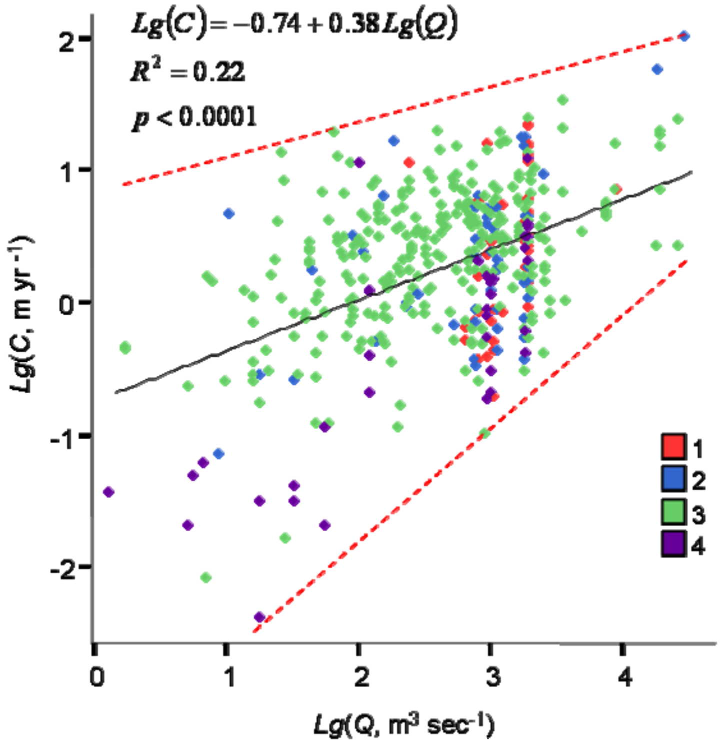


Figure 4.19: Relationship between bank erosion rates and bankfull discharge. Number of observations is 427. Channel types: 1. Anabranched; 2. Braided; 3. Meandering; 4. Straight. Red dashed lines represent envelope lines.

From a statistical point of view there is a slight heteroscedasticity in Fig. 4.19 (see dashed red lines). The condition of heteroscedasticity indicates that the error variance is not constant, and rather depends from the independent variable values (Lewis-Beck, 1990). As bankfull discharge increases, the variation of residuals for bank erosion rate decreases. Possibly this situation can be improved by additional datapoints in the region of large values of the discharge and bank erosion rate. However, in this case the scatter of points will be bigger and R^2 smaller. Berry and Feldman (1985) noted that a slight heteroscedasticity has little effect on the significance test. Therefore, despite the slight heteroscedasticity, at current stage of study the relationship between bankfull discharge and bank erosion rate presented in the Fig. 4.19 can be statistically accepted.

The relationship between bank erosion rates and water discharge is positive, but not as well defined as that for drainage area due to bigger point scatter. For comparative reasons the results from previous studies and from this study are combined in Table 4.7.

Walker and Rutherfurd (1999) obtained a close relationship using 68 datapoints. Afterwards Rutherfurd (2000) added several points with data for mean annual discharge and obtained slightly different results (with higher power and less close), but this difference is not significant. From Fig. 4.19 using much more datapoints, the relationship differs from the previous studies significantly. The power is considerably less than that in studies by Walker and Rutherfurd (1999) and Rutherfurd (2000). R^2 is about half that obtained in previous studies. Consequently, in this case adding more datapoints lead to bigger scatter point. Also using a larger number of datapoints, the power value in the equations is changed significantly. In contrast, for the drainage area relationship the power in all studies lies in narrow range.

Table 4.7: A comparison of equations for relationship between bank erosion rate and water discharge.

From	Derived equation	R^2	Notes about used discharges for relationship
Walker and Rutherfurd (1999)	$C = 0.042Q^{0.59}$	0.44	Bankfull discharge
Rutherfurd (2000)	$C = 0.044Q^{0.60}$	0.43	Either bankfull or mean annual flood discharge
This study	$C = 0.182Q^{0.38}$	0.22	Bankfull discharge – either given in original sources or calculated by the equation of the relationship between bankfull and average annual discharge

Considering the derived equations in Table 4.7, one can conclude that for bankfull water discharge 1 m^3 sec^{-1} bank erosion rate is expected to be 0.04 m per year from studies of Walker and Rutherfurd (1999) and Rutherfurd (2000) and 0.18 m per year from this study. This significant difference (almost five times) in the coefficients can not be explained by using different characteristics of water discharge, though in this study adjusted bankfull discharges have been also used. Perhaps in other similar studies different values of the coefficient can be obtained depending on the available dataset. Also note that the range of bank erosion rates in the area of small discharge is the widest (see Fig. 4.19). From obtained results it is important to underline that the relationship with discharge is more sensitive to additional datapoints than the relationship with drainage area.

Average annual runoff. As a ratio of water discharge and drainage area the average annual runoff is used. From consideration of the water balance this parameter reflects the climate conditions of an area. It is supposed that in deserts with dry climate the amount of average annual runoff is small and in tropics it is large due to the amount of rainfall. A relationship between bank erosion rate and average annual runoff is shown in Fig. 4.20. There is no statistically strong relationship (R^2=0.12) although it is significant (p<0.0001) due to large amount of datapoints. Consequently, due to the extreme scatter the parameter is not useful for predictive purposes. Also one can conclude that a tropical river is as likely to be laterally active as a river in dry or temperate environment. Indeed, from a bank erosion study of the Rio Grande de Añasco in humid tropical environment Alvarez (2005) has concluded that both the mean bank erosion rate and the ratio of meander curvature to channel width for maximum migration in a humid tropical river are similar to those in humid temperate rivers.

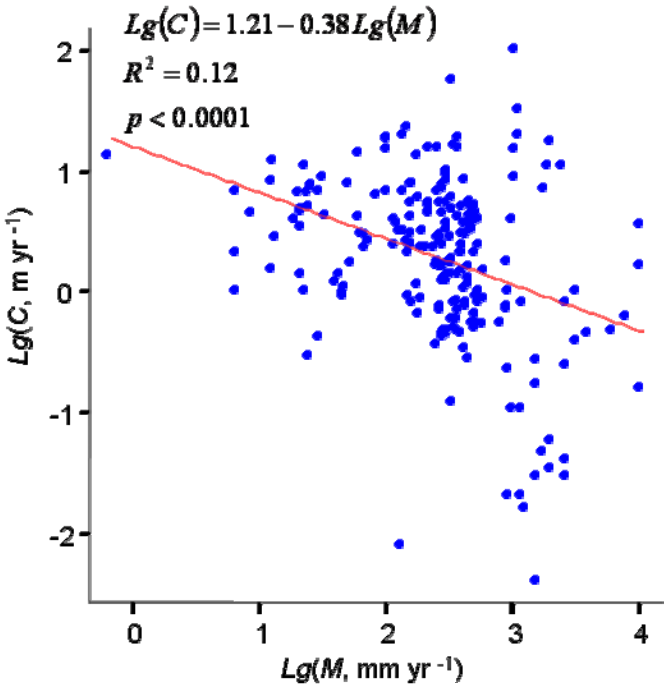
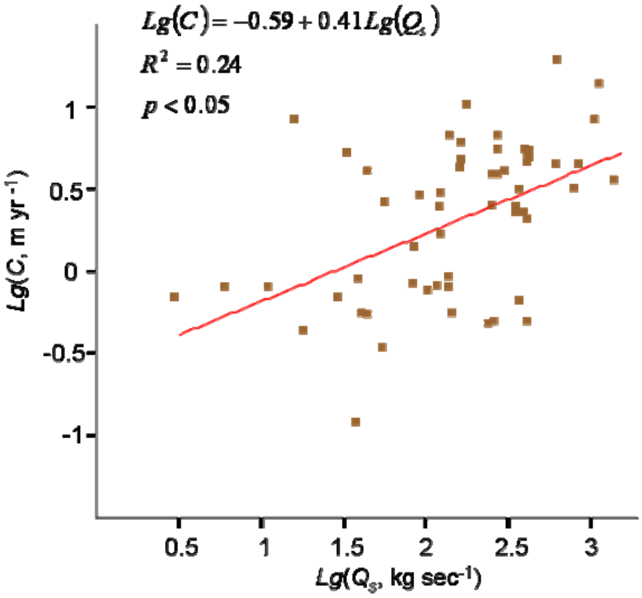
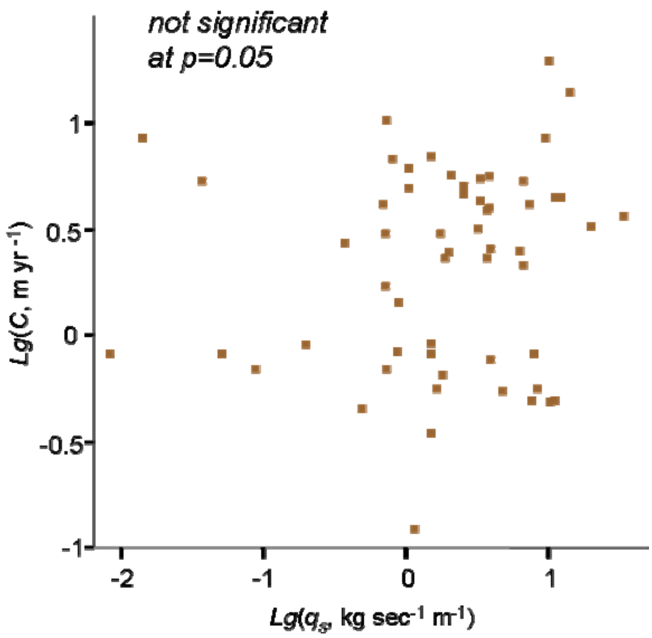


Figure 4.20: A relationship between bank erosion rates and average annual runoff. Number of observations is 226.

Sediment transport rate. The last parameter considered in the catchment scale is sediment transport rate. In some models (e.g. Popov, 1965; Neill, 1984; Richardson, 2002) for meandering rivers it is supposed that the amount of transported sediment is directly related to the meander migration rate. Only in general does the constructed relationship between bank erosion rate and total sediment transport rate (Fig. 4.21 A) support this idea. Although the regression line shows a positive relation, there is a big point scatter. From a statistical point of view this relationship is weak but it is significant. If sediment transport is expressed in terms of unit sediment transport rate (Fig. 4.21 B) then the relationship becomes not significant at p=0.05. Despite the logical consideration that bank erosion rate should be related to the amount of sediment transported by water, by statistical results obtained herein (Fig. 4.21), and considering the data scatter, one could conclude that a river with high bedload is as laterally active as a river with a low transported sediment amount. However, the relationships shown in Fig. 4.21 are for catchment scale reports of sediment transport (yield), whereas sediment transport acts at the reach and cross-section scale.



(A)



(B)

Figure 4.21: Relationship between bank erosion rate and (A) gross sediment transport rate (number of observations is 57); (B) unit sediment transport rate (number of observations is 57).

4.3.2. Relative bank erosion rate at the catchment scale

An analysis of relationships between relative bank erosion rate and variables considered at the catchment scale revealed that there are no statistically meaningful correlations (Fig. 4.22). Even by the directions of the regression lines any conclusion about behaviour of relative bank erosion rate with parameters of the catchment scale can not be derived because R^2 values are nearly equal to zero. When points are labelled by channel types (Fig. 4.22 A and C), then there is also no tendency in relative bank erosion rate values with parameters of the catchment scale. Points for different channel types are scattered widely as well. Consequently, relative bank erosion rate does not depend upon parameters used to characterize a catchment and one could expect the same relative bank erosion rate in either a small river or a large river. Also from the relationships with water discharge and with average annual runoff the relative bank erosion rate is expected to be similar for rivers conveying different amount of water. These results confirm a conclusion of Hooke (1980) from an analysis of a relationship between bank erosion rate and drainage area that erosion rates are similar for all sizes of catchment if scaled as channel width per year.

A relationship between relative bank erosion rate and sediment transport rate is not presented in Fig. 4.22 because there are only 7 points. It is not a large enough number of datapoint to construct a statistically meaningful relationship. Therefore at this stage of study it is impossible to make any rational conclusion about this relation.

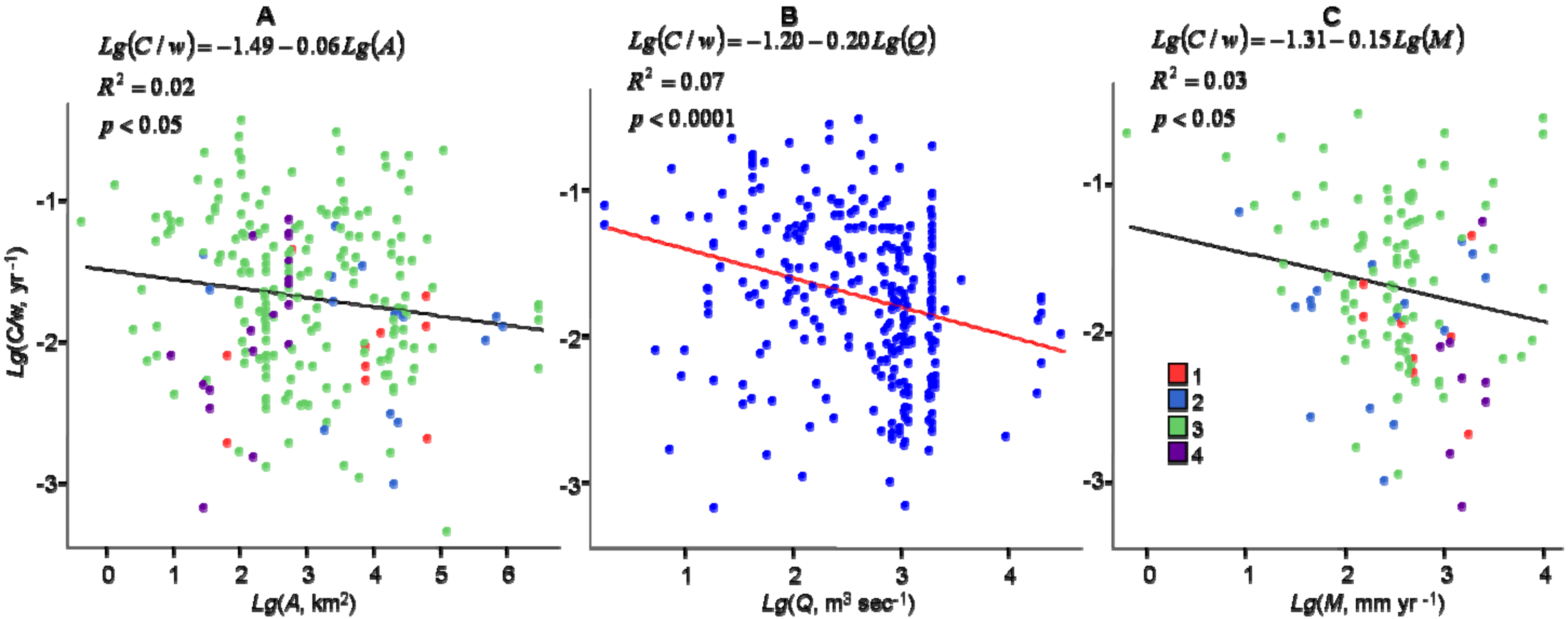


Figure 4.22: Relationship between relative bank erosion rate and (A) drainage area (number of observations is 229); (B) bankfull discharge (number of observations is 292); (C) average annual runoff (number of observations is 129). For (A) and (C) channel types are: 1. Anabranched; 2. Braided; 3. Meandering; 4. Straight.

4.4. RELATIONSHIPS AT THE REACH SCALE

4.4.1. Bank erosion rate at the reach scale

In this section relationships between bank erosion rate and various parameters of a channel at the scale of the river reach are considered. Channel size can be geometrically defined by channel depth and width. Other geometrical parameters such as height of eroded bank, floodplain/valley width, channel and valley slopes, depth to width and bank height to width ratios are used as well. Also water surface slope, gross stream power, unit discharge, unit stream power, shear stress and coefficient of variation are considered at this scale. Because erosion occurs locally along banks, it is supposed that relationships of bank erosion rates with parameters of the river reach scale would be closer than with parameters of the catchment scale. However, it is should be borne in mind that channel size characteristics are functions of water discharge (Leopold and Maddock, 1953):

A function for channel depth:

$$d = cQ^f \; ; \; d = 0.51Q^{0.34}, R^2 = 0.66, \mathrm{N} = 63, p<0.01. \qquad 4.1$$

A function for channel width:

$$w = aQ^b \; ; \; w = 1.91Q^{0.63}, R^2 = 0.72, \mathrm{N} = 292, p<0.0001 \qquad 4.2$$

where w = width, m; d = depth, m; Q = bankfull water discharge, m^3s^{-1}; a,b,c, and f are numerical constants. Results using data from the current study are shown in equations 4.1 and 4.2. These results are produced only to show that geometrical parameters of the channel closely correlate with water discharge, rather than to examine hydraulic geometry at-a-station and downstream as was performed by Leopold and Maddock (1953).

Channel depth. Constructing a relationship between bank erosion rate and channel depth, it is found that this relationship is better defined than for water discharge (Fig. 4.23). However, there is still quite a big scatter of points, especially in the region of large values of channel depth. The scatter of points partly can be explained by variability of channel depth during a year, which can reach more than 10 metres in large rivers. Even though an attempt was made to reduce data to the same conditions (bankfull), channel depth is sensitive to chosen bankfull level. In general, the relationship between bank erosion rates and channel depth is positive. Deep channels characterize big rivers with large water discharges, i.e. the dependence on water discharge is imposed on the relationship.

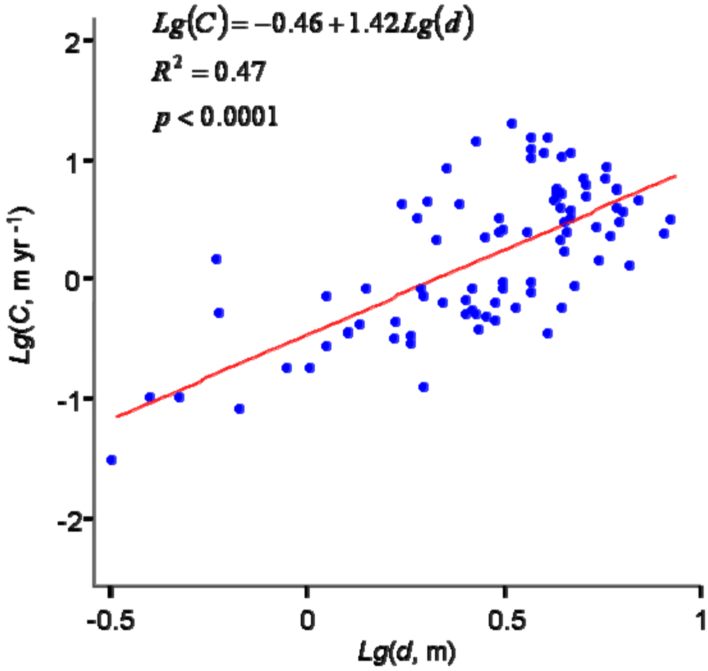


Figure 4.23: Relationship between bank erosion rate and bankfull depth. Number of observations is 91.

Rewriting the equation from Fig. 4.23 in the power form is $C = 0.35d^{1.42}$. The obtained coefficient shows that bank erosion rate is likely to be 0.35 m per year when bankfull depth is 1 m.

Channel width. An alternative parameter, which is not as sensitive as bankfull depth to chosen bankfull level (see section 3.3.2), is channel width. Nanson and Hickin (1986) found that width was better than other parameters as a single predictor for bank erosion rate. A relationship of bank erosion rate with channel width is shown in Fig. 4.24, where points are divided by channel types. From a statistical point of view this relationship is as good as that for channel depth (R^2 equals 0.47), but more robust as the number of datapoints is almost five times bigger than for the relationship with channel depth. Moreover, for Fig. 4.24 all available data about channel width were used whether this was width at bankfull, at low water, as given on maps and at date of observations, although data for bankfull condition were prefered. Perhaps, the fact that all available data about channel width are used partly explains the scatter of points in Fig. 4.24. As noted already it is supposed that channel width is not as sensitive to level change as channel depth.

Points for straight channels are mainly located below the regression line, especially for channels narrower than 20 metres. In other words, for given width, one would expect lower bank erosion rates will occur in straight channels than in other channel types, especially in small rivers.

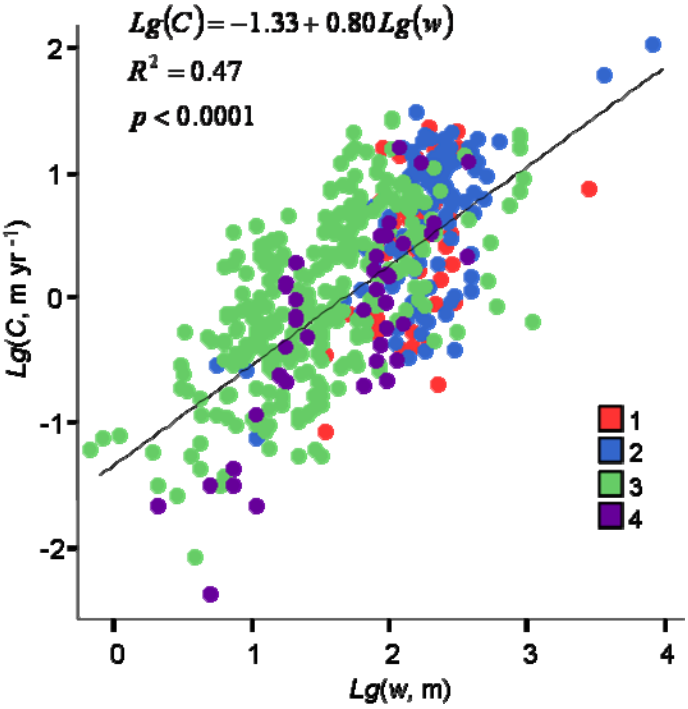


Figure 4.24: A relationship between bank erosion rate and channel width. Channel types: 1. Anabranched; 2. Braided; 3. Meandering; 4. Straight. Number of observations is 487.

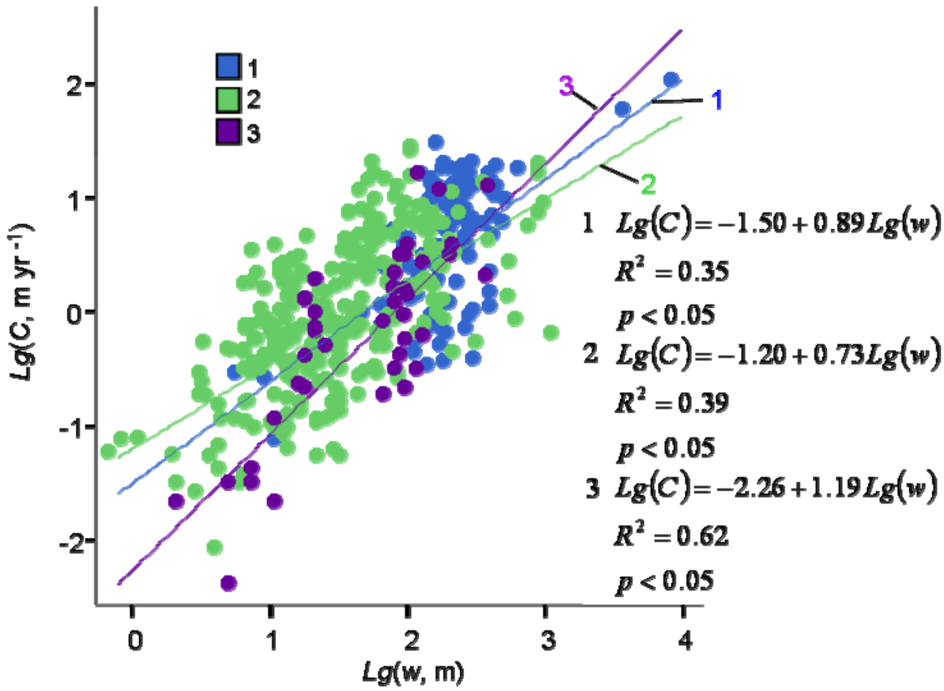


Figure 4.25: Relationship between bank erosion rate and width for 1 – braided channels (number of observations is 100), 2 – meandering channels (number of observations is 294) and 3 – straight channels (number of observations is 42).

With available data it is possible to construct relationships for braided, meandering and straight channels separately (Fig. 4.25). For anabranched channels a statistically meaningful regression line is not possible to obtain at this stage of analysis. Comparing with Fig. 4.24 for braided and meandering channels the relationship is less well defined than in the general case, while for straight channels the relationship is better defined than that in general (see R^2 values).

Table 4.8: Test results for the null hypothesis that the slopes (1 and 2) are equal.

slope 1	**slope 2**	ν	t	$t_{5\%}$
braided vs meandering				
0.89	0.73	98	1.316	1.661
braided vs straight				
0.89	1.19	98	2.467	1.661
meandering vs braided				
0.73	0.89	292	2.987	1.650
meandering vs straight				
0.73	1.19	292	8.587	1.650
straight vs braided				
1.19	0.89	40	2.028	1.684
straight vs meandering				
1.19	0.73	40	3.110	1.684

The regression lines have different values of slope (coefficient b). The less steep line is for meandering channels, steeper is for braided channels and the steepest is for straight channels. That slopes for these channel types in Fig. 4.25 significantly differ was tested and results are shown in Table 4.8. In this table ν = degree of freedom; t = the computed value of t-statistic; $t_{5\%}$ = the table value of t at the significance level 5% from Lindley and Scott (1984). For large values of the degree of freedom the harmonic interpolation is used as suggested by Lindley and Scott (1984). From the results it can be concluded that the slopes significantly differ, because the t-statistic in all tests lies in the critical region. The only exception is when the slope for braided channels statistically is compared with the meandering one. In this case the computed value of the t-statistic is less than the tabulated value, which means that the slope for braided channels does not differ statistically from the slope for meandering channels. On the other hand, the slope for meandering channels is statistically different from the slope for braided channels (see “meandering vs braided”). Therefore, after this analysis it is concluded that the slopes for channel types statistically differ from each other. It means that, in a statistical sense, the rate of bank erosion for straight channels increases more rapidly as a function of channel width than for braided and meandering channels.

Regression equations from Figs. 4.24 and 4.25, which are rewritten in the power form, are combined in Table 4.9. Considering the coefficient in the equations of Table 4.9, one can derive that for a channel 1 m wide it would be expected that bank erosion rate is likely to be 0.05 m per year in total case, 0.03 m per year for braided channels, 0.06 m per year for meandering channels and 0.005 m per year for straight channels. Because 1 m width is so narrow for natural channels using the obtained equations values of bank erosion rate are calculated for round values (10; 50; 100; 500) of channel width and presented in Table 4.9.

Table 4.9: Regression equations for relationship between bank erosion rate (C, m yr^{-1}) and channel width (w, m).

Type	Equations	w=10	w=50	w=100	w=500	N	R^2
Total	$C = 0.047w^{0.8}$	0.30	1.07	1.87	6.78	487	0.47
For braided channels	$C = 0.032w^{0.89}$	0.25	1.04	1.93	8.08	100	0.35
For meandering channels	$C = 0.063w^{0.73}$	0.34	1.10	1.82	5.88	294	0.39
For straight channels	$C = 0.005w^{1.19}$	0.077	0.53	1.20	8.14	42	0.62

There is a dependance from water discharge imposed on the relationship between bank erosion rate and channel width (Fig. 4.26). It is again evident that channel size depends upon the amount of water which the channel must convey. In general the relationship between bank erosion rates and channel width is positive and is better defined than with water discharge, as it was supposed at the beginning of the analysis. In addition, the closer relation with width than with water discharge can be explained as follow. At-a-station channel width is not as changeable as water discharge, particularly in channels with steep banks. In the extreme case of a rectangular channel, the width is a constant with all possible water discharge values below bankfull. Finally, discharge is more difficult to measure accurately than is channel width and, as noted above, different values of discharge were reported in the raw data sets from which standardized bankful values were caculated.

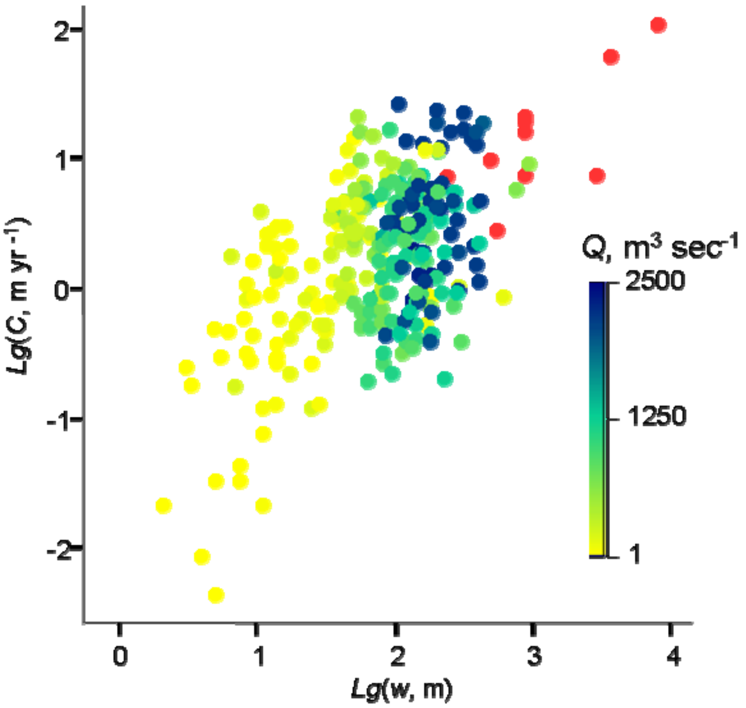


Figure 4.26: A relationship between bank erosion rate and width showing the dependence of width on discharge. Change of colour shows increasing in water discharge; red points with water discharge more than 2500 up to 33 250 m^3 sec^{-1}. Number of observations is 292.

Bank height. If, for the sake of argument, it is acceptable to negate the correlation of bank height with discharge, there are two contrary explanations for the relationship between bank erosion rate and bank height in the literature. On the one hand, bank erosion rates increase with increasing bank height, due to the increasing instability with respect to mass failure (Osman and Thorne, 1988); i.e. a positive relationship. On the other hand, the higher the bank then the greater the volume of sediment delivered into the channel. The flow's ability to erode the bank will therefore decrease because the flow has to carry more sediment away from the bank toe (Hasegawa, 1989b; Chalov, 2000); a negative relationship. On account of these contrary explanations, it is uncertain how bank erosion rate and bank height may be related in the general case.

Results of the linear model are shown in Fig. 4.27 A. In general, the relationship is positive and shows that with increasing of bank height the bank erosion rates are likely to increase; i.e the positive trend is the same as for bank erosion and discharge. Despite a big point scatter, the relationship is closer than that for discharge, depth and width (R^2 = 0.53). As for relationships with water depth and with channel width, in the relationship between bank height and bank erosion rate the co-linearity of water discharge cannot be negated and has an effect (Fig. 4.27 B). Thus, high banks are characteristic features of large rivers with rapid rates of bank erosion. An existence of river reaches with high, steep banks consequently is a reliable sign of lateral movement of channel in these reaches. From the equation which is rewritten in the power form $C = 0.2h^{1.23}$, one can conclude that with a bank 1 m high there is likely to observe a bank erosion rate of 0.2 m per year.

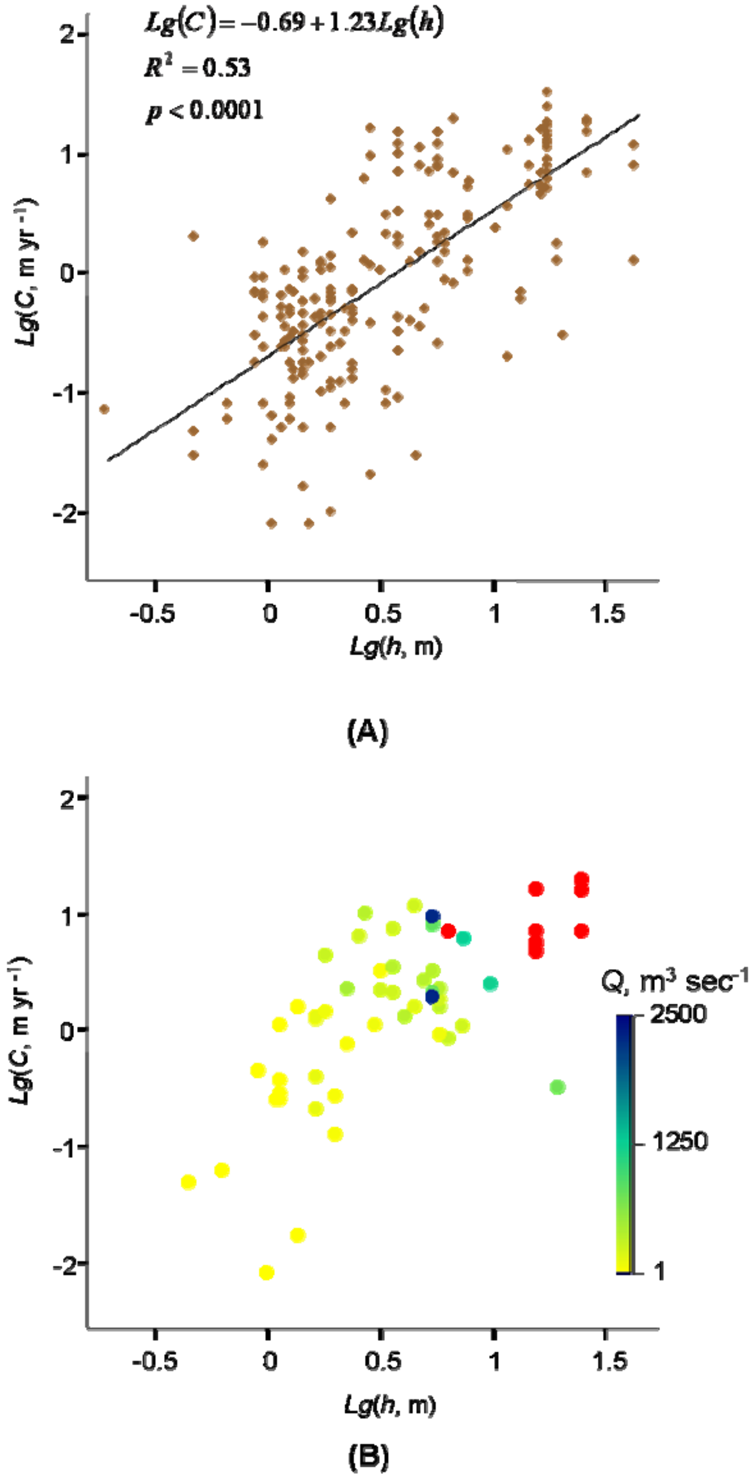


Figure 4.27: Relationship between bank erosion rate and bank height. Change of colour in (B) shows increasing in water discharge; red points with water discharge more than 2500 up to 33 250 m^3 sec^{-1}. Number of observations for (A) is 235 and for (B) is 61.

Floodplain and/or valley width. To check how bank erosion rate is associated with average width of either the floodplain or valley (as appropriate) on a reach a relationship is constructed (Fig. 4.28). It might be surmised that broad plains indicate extensive lateral channel migration activity and so should be associated with relatively high rates of bank erosion. It is obvious from the diagram that there is a big scatter of points. Nevertheless, wide floodplain or valley of rivers is an indicator of high bank erosion rates as there is positive correlation between bank erosion rate and floodplain/valley width. At the same time it should be borne in mind that there is an effect of river size, because steep mountain rivers with small drainage area are characterised by narrow floodplains sometimes confined by rock, and lowland rivers with bigger drainage area are characterized by wide unconfined floodplains. The power form of the regression line from Fig. 4.28 is rewritten as $C = 1.07 w_v^{0.97}$. Therefore, by the coefficient it is derived that bank erosion rate is likely to be c.1 m per year in rivers with floodplain/valley 1 km wide, and otherwise is directly proportional to floodplain width.

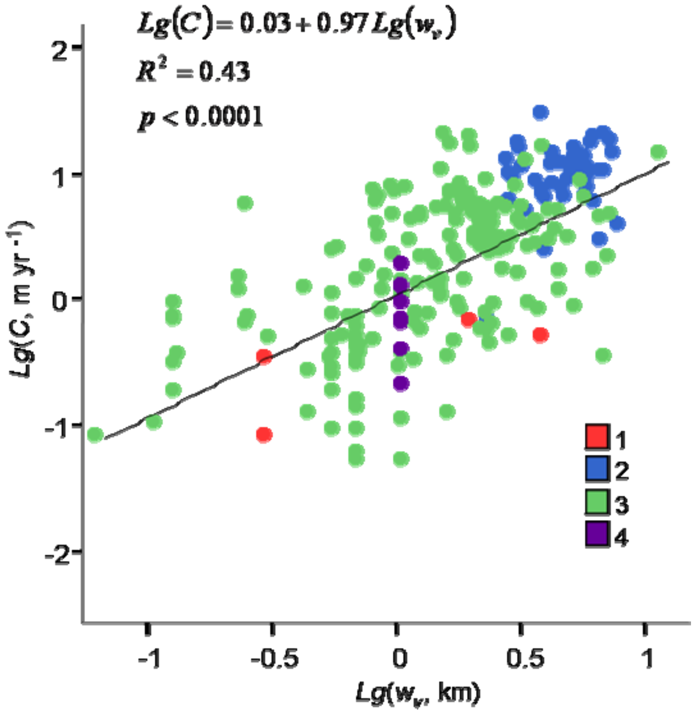


Figure 4.28: Relationship between bank erosion rate and average width of floodplain or valley. Number of observations is 237. Channel types: 1. Anabranched; 2. Braided; 3. Meandering; 4. Straight.

Slope. Considering channel slope, one might expect that the steeper the channel the higher the stream power and shear stress, and as consequence the capability of stream is greater to erode banks. However, results show an inverse relationship of bank erosion rate and channel slope (Fig. 4.29 B). Regarding water slope and valley slope there are relationships which are not significant (Fig. 4.29 A and C).

Although the correlation between bank erosion rate and channel slope is not strong (R^2 equals 0.23) with big point scatter, in general with a steep channel slope, low bank erosion rates are more likely to occur. However, this can be explained by the following. River reaches with steep channel slopes are usually located in upper parts of river system where small amounts of water are observed. As was shown above, bank erosion rate is associated with characteristics of river size, notably drainage area and water discharge. Therefore, in headstreams though steep slopes of the channels occur, there is not enough discharge to create high stream power for bank erosion. Moreover, it is assumed that in headstreams bed and banks are composed by coarser sediments, which may be more resistant to erosion.

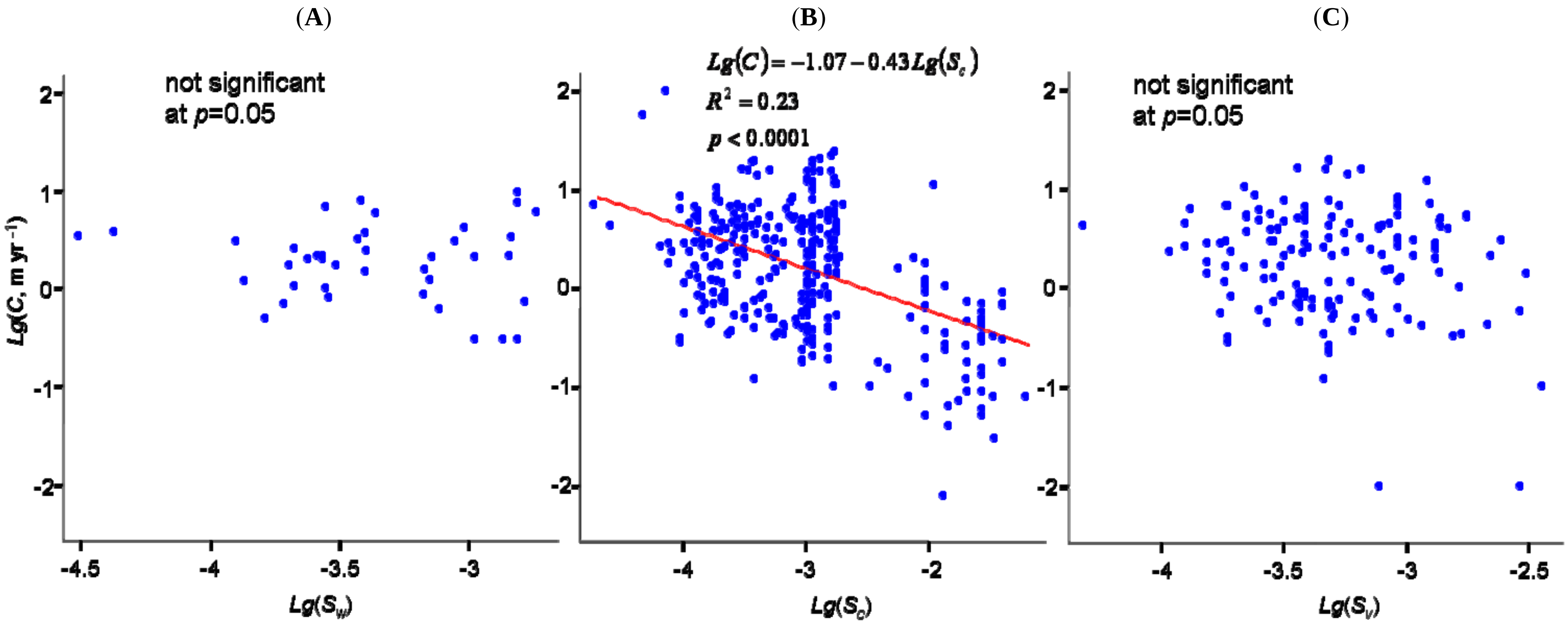
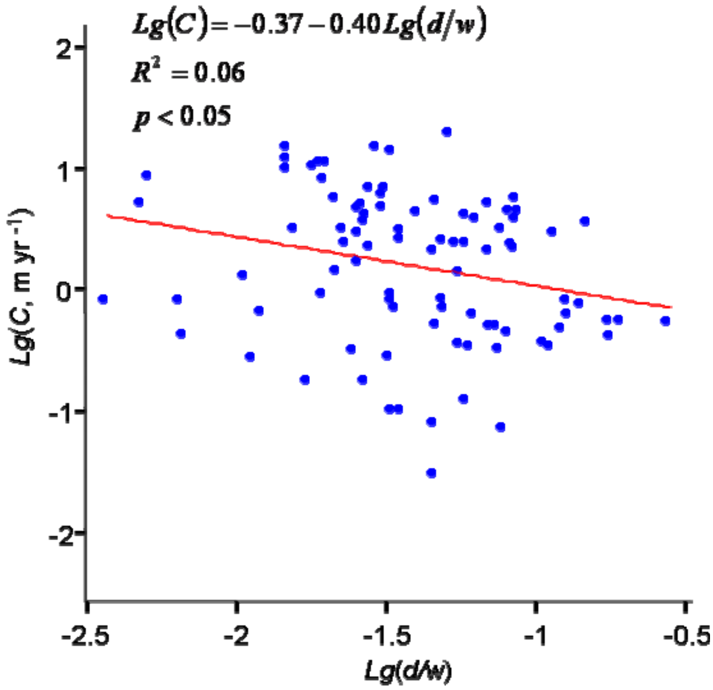


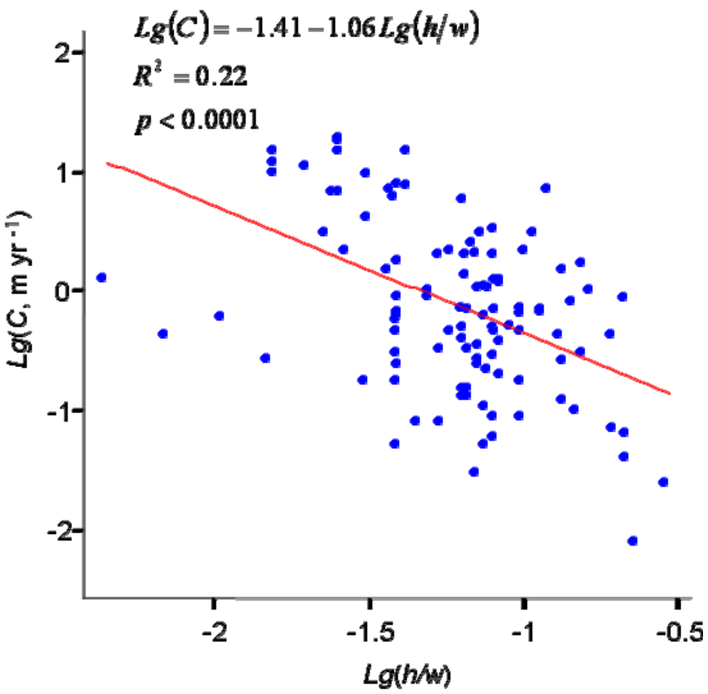
Figure 4.29: Relationship of bank erosion rate with (A) water surface slope (number of observations is 41); (B) channel slope (number of observations is 339); and (C) valley slope (number of observations is 156).

Ratios. Relationships with the ratios of bankfull depth and bank height to channel width are weak from statistical point of view (see R^2 values in Fig. 4.30). Therefore, there are no correlations between bank erosion rate and the ratios of bankfull depth and bank height to width. However, considering the direction of regression lines it can be concluded that the width has a bigger effect on erosion rates than bankfull depth and bank height because the direction is negative in both relationships and the channel width is a denominator. Taking into account the relationships for the ratios, one can conclude that the relationship for channel width is more robust than that for bankfull depth and bank height, despite that the above derived relationships for bankfull depth, channel width and bank height (Figs. 4.23, 4.24 and 4.27 A) show the R^2 values are the same for both bankfull depth and channel width and even the R^2 for bank height is higher than that for channel width. This result support the finding of Nanson and Hickin (1986) that channel width is a better predictor of erosion rates than other parameters.

Also the unit discharge is used as a ratio, because it represents the ratio of water discharge to channel width. Relationships between unit discharge and bank erosion rate are shown in Fig. 4.31. There two relationships shown – for all channels and for straight channels only. The relationship for straight channels is shown as for this channel type a high correlation is obtained (R^2 is 0.53), but for other types there are no correlations between unit discharge and bank erosion rate. R^2 values for other types are approximately equal to the R^2 value for all channels. However, if the straight channels ($P<1.3$) are seen as representing low sinuosity meandering channels and thus represent the lower portion of the meandering channel data cloud, then there is no justification to fit a regression equation to this data sub-set. The issue of defining straight channels as separate from meandering channels is considered in the 'Discussion'.



(A)



(B)

Figure 4.30: Relationship between bank erosion rate and (A) the depth to width ratio (number of observations is 92); and (B) the bank height to width ratio (number of observations is 112).

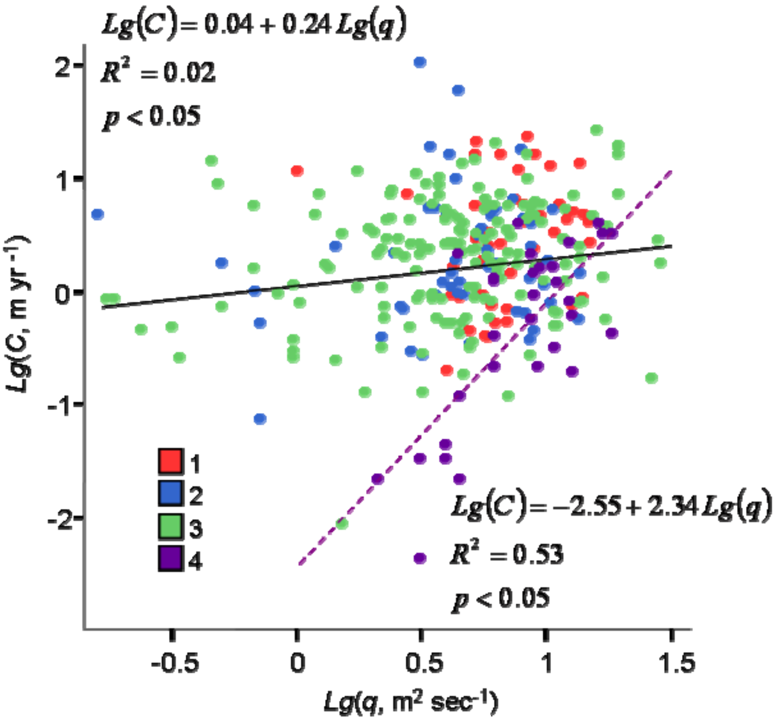
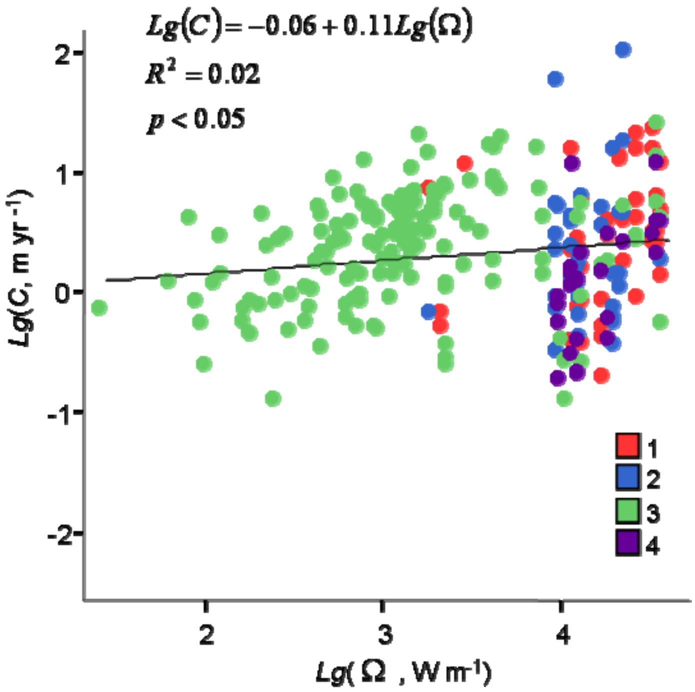


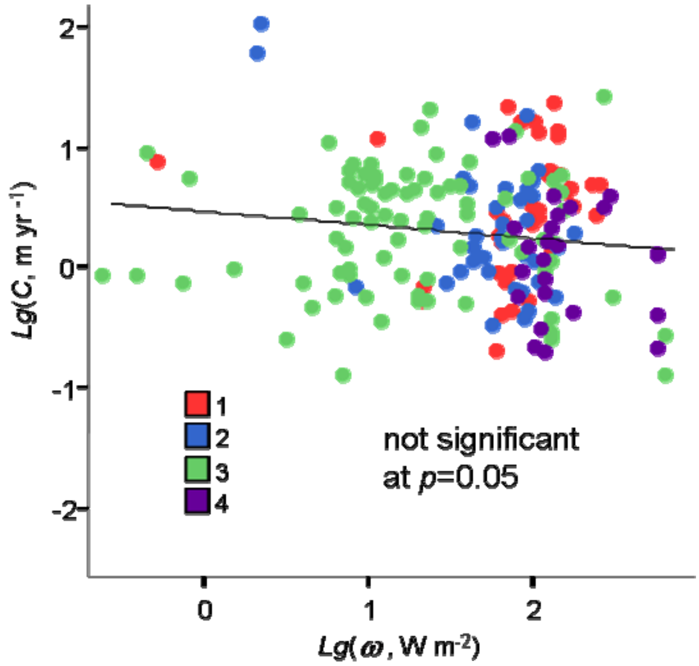
Figure 4.31: Relationship between bank erosion rate and unit discharge.

Total regression line is shown as a solid line; total equation is shown in the top left corner; total number of observations is 290. Regression line for straight channels is shown as a dashed line; equation for straight channels is shown in the bottom right corner; number of observations for straight channels is 30. Channel types: 1. Anabranched; 2. Braided; 3. Meandering; 4. Straight.

Stream power. Plotted sets of data for analysis of the relationship between bank erosion rate and gross and unit stream power (Fig. 4.32), show that there are no correlations and for unit stream power; the relationship is even not significant. R^2 values are very low. Even a division by channel types does not reveal any tendencies. Moreover, points for straight and anabranched channels are grouped in an area of high stream power. The fact that points for braided channels are located also in the area of high stream power supports the earlier empirical finding by *QS*-diagrams that braided channels possess higher stream power than meandering ones. But straight and anabranched channels are distributed on *QS*-diagrams with wide ranges of stream power (e.g. straight channels on *QS*-diagram by Leopold and Wolman (1957); anabranched channels by Nanson and Knighton (1996)). In addition, based on the representation by Bridge (2003) of the continuum of equilibrium channel patterns, straight channels should possess lower stream power than meandering channels. Also, anastomosing channels as a subtype of anabranched channels (Nanson and Knighton, 1996) are characterized by low stream power (e.g. Nanson and Croke, 1992; Knighton and Nanson, 1993; Makaske, 2001). Therefore, the dataset collated herein for bank erosion study does not completely coincide with previous studies of channel types, where different datasets have been used.



(A)



(B)

Figure 4.32: Relationship between bank erosion rate and (A) gross stream power (number of observations is 261); and (B) unit stream power (number of observations is 188). Channel types: 1. Anabranched; 2. Braided; 3. Meandering; 4. Straight.

Table 4.10: A comparison of equations for relationship between bank erosion rate and gross stream power.

From	Derived equation	N	R^2	Notes
Walker and Rutherfurd (1999)	$C = 0.025\Omega^{0.53}$	63	0.35	Only for meandering channels
This study	$C = 0.871\Omega^{0.11}$	261	0.02	For different channel types

A comparison with an earlier study of relationship between bank erosion rate and gross stream power is combined in Table 4.10. While herein the obtained relationship is not significant, Walker and Rutherfurd (1999) have derived a positive relationship between bank erosion rate and gross stream power. But the relationship by Walker and Rutherfurd (1999) is not strong and is constructed only for meandering channels with 63 datapoints. In the current study many more datapoints have been used and for different channel types. Therefore, with adding more data for the relationship of bank erosion rate with gross stream power the association becomes weaker. Perhaps, such statistically meaningful positive relationships would be possible to obtain only for regional studies. But from this analysis, in the general case, one can conclude that bank erosion rate is not correlated with stream power.

Shear stress. Regarding the shear stress, a scatter plot is possible to create only for meandering channels (Fig. 4.33) as data about shear stress are available only for this channel type. There is no significant correlation between bank erosion rate and shear stress. However, an envelope curve for the upper limit of values (a dashed curve in Fig. 4.33) shows the following behaviour. By the envelope curve, the maximum value of bank erosion rate is observed in the area of moderate values of shear stress. This result suggests that high magnitude of shear stress does not always lead to severe bank erosion. The behaviour of the envelope curve is contrary to some fluvial bank erosion models, where a simple exceedance of the shear stress is used. In these models bank erosion rate is not linear, but positively depends upon the magnitude of shear stress. The behaviour of the envelope curve rather supports the theory of magnitude-frequency of Wolman and Miller (1960) that moderate values that are more frequent are responsible for bigger changes of channels. Indeed, incorporating duration of shear stress impact in a fluvial bank erosion model and in a conceptual model of bank erosion of cohesive banks, Julian and Torres (2006) have concluded that, for cohesive banks, bank erosion rates depend more on the impact duration, while for noncohesive banks the magnitude is important.

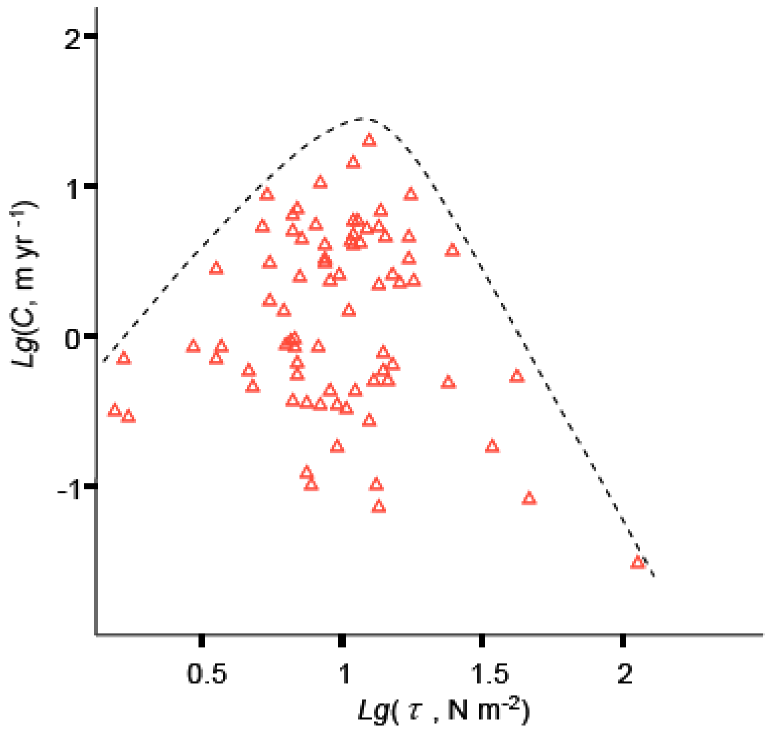


Figure 4.33: Relationship between bank erosion rate and shear stress. Number of observations is 79.

Coefficient of variation. With variation of annual average water discharge in "long term" bank erosion rate does not correlate from statistical standpoint (Fig. 4.34). Note that the coefficient of variation is presented without Log10 transformation. From the relationship between bank erosion rate and coefficient of variation, one can conclude that the same bank erosion rate is likely in a river with very variable average annual discharge from year to year and in a river which is characterized by more stable values of average annual discharge in the long term period.

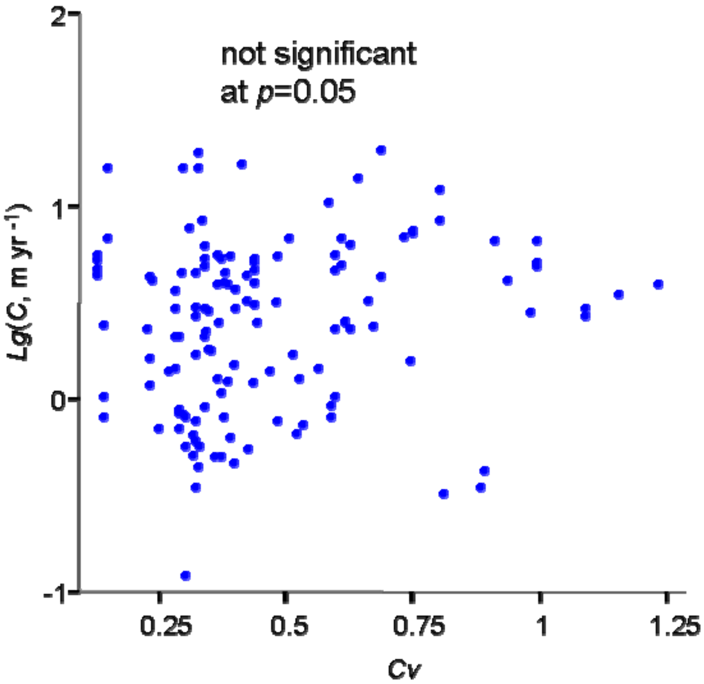


Figure 4.34: Relationship between bank erosion rate and coefficient of variation. Number of observations is 135.

4.4.2. Relative bank erosion rate at the reach scale

In general, relationships for relative bank erosion are weak compared with absolute values of bank erosion. The scatter plots for bankfull depth, bank height, floodplain/valley width and different characteristics of slope are combined in Fig. 4.35. In Fig. 4.36 other remaining relationships are presented. From all of them there are no strong correlations and between relative bank erosion rate and variables which are considered in the reach scale and most of them are not significant. Even division of points by channel types does not reveal any tendencies in the scatter plots as shown by examples in Fig. 4.35 B and Fig. 4.36 B for bank height and for ratio of bank height to channel width, respectively.

Slope. Comparing relationships for characteristics of slope in Fig. 4.29 and Fig. 4.35 D, E, F, the following differences could be noticed. For water surface relationship (Fig. 4.35 D) there is no significant correlation as well as in the case of absolute bank erosion rate values (Fig. 4.29 A). However, the heteroscedasticity is more obvious for relative bank erosion rate (see red dashed lines in Fig. 4.35 D), which indicate bigger variations of residuals in the area of high water surface slope values than in Fig. 4.29 A. For the channel slope relationship there is no significant correlation (Fig. 4.35 E), while for a relationship between actual values of bank erosion rate and channel slope an inverse slight correlation has been obtained (Fig. 4.29 B). Such a slight, but positive, correlation is revealed for a relationship between relative bank erosion rate and valley slope (Fig. 4.35 F), whereas there is no correlation in the case of actual bank erosion rate values (Fig. 29 C). The direction of a relationship in Fig. 4.35 F shows that the steeper the valley the higher relative bank erosion rate is likely to be observed.

Stream power. In relationships for stream power characteristics (gross stream power and unit stream power, Figs 4.36 C and D, respectively) points are distinguished by channel types. As in the case of actual bank erosion rate values (Fig. 4.32), there are no significant correlations, and grouping of points for straight, braided and anabranched channels in the area of high stream power than for meandering ones. Another result which is similar to that for actual bank erosion rate has been obtained for a relationship with shear stress (Fig. 4.36 E). By the envelope curve, relative bank erosion rate reaches its maximum at moderate shear stress. It should be noticed that in Fig. 4.36 E data are available only for meandering channels.

Relationships of relative bank erosion rate with channel width (Figs 4.37 and 4.38) and with unit discharge (Fig. 4.39) are presented separately from other parameters.

Channel width. As with many parameters there is no correlation between relative bank erosion rate and channel width (Fig. 4.37), where a big point scatter is obtained even with point division by channel types. However, if a relationship of actual bank erosion rate with channel width like that in Fig. 4.24 is represented with adding of relative bank erosion rate bounds (Fig. 4.38), then some important information is revealed. The bounds show the following ranges of the relative bank erosion rate. The blue bound represents the interval of bank erosion rate to width ratio in percent from 0.01 to 0.1. The yellow bound – from 0.1 to 1% of width. The green bound – from 1 to 10% of width. The red bound – from 10 to 100% of width. This analysis reveals that in about 90% of cases relative bank erosion rates are not greater than 10% of channel width. Thus, one could say with confidence that relative bank erosion rate greater than 10% of channel width can be observed rarely and in exceptional cases and most likely to be observed in the range of 1 to 10% of channel width.

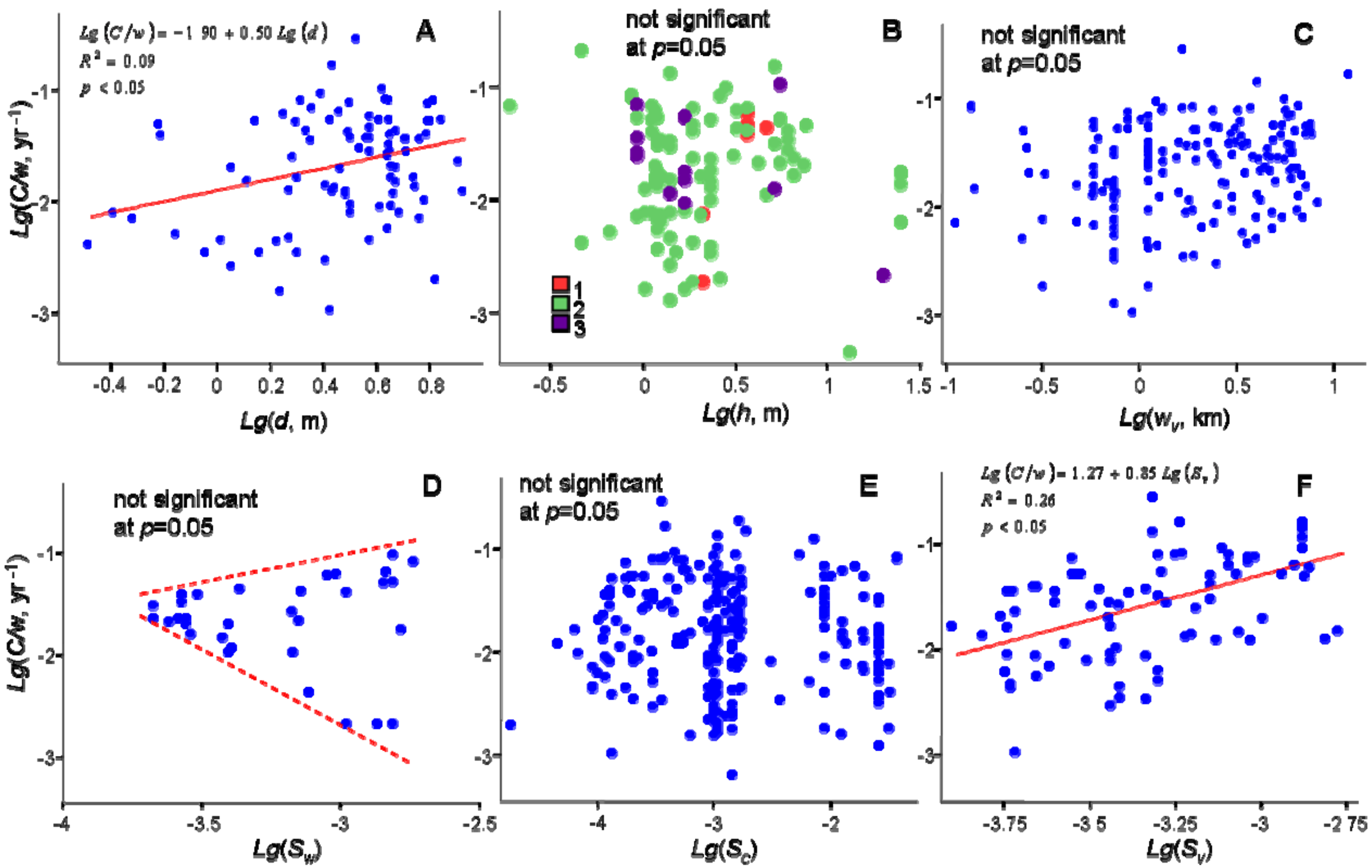


Figure 4.35: Relationship of relative bank erosion rate with (A) bankfull depth (number of observations is 91); (B) bank height (number of observations is 112); (C) floodplain/valley width (number of observations is 168); (D) water surface slope (number of observations is 32); (E) channel slope (number of observations is 253); and (F) valley slope (number of observations is 83). Channel types: 1. Anabranched; 2. Meandering; 3. Straight.

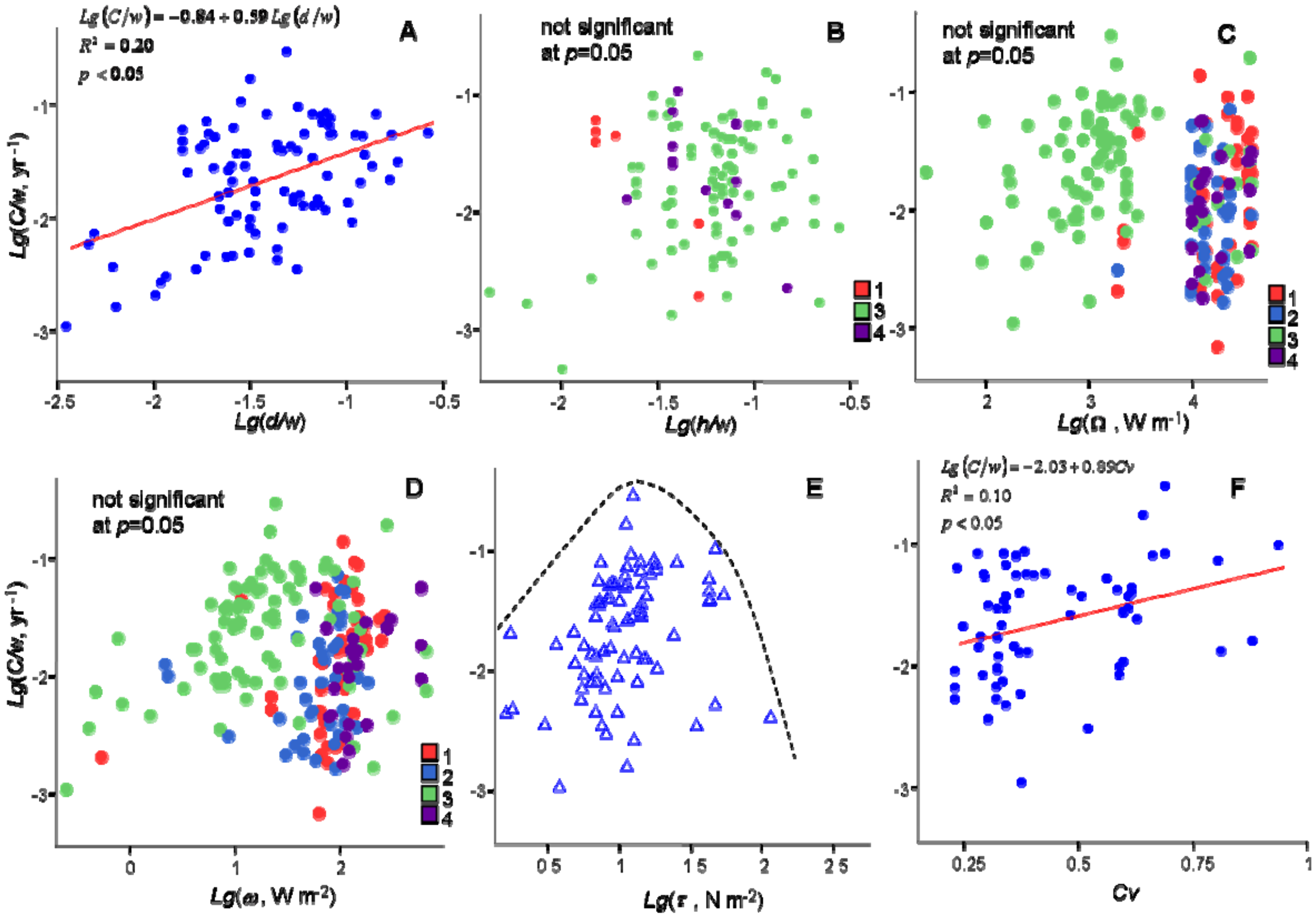


Figure 4.36: Relationship of relative bank erosion rate with (A) channel depth to width ratio (number of observations is 92); (B) bank height to channel width ratio (number of observations is 112); (C) gross stream power (number of observations is 188); (D) unit stream power (number of observations is 188); (E) shear stress (number of observations is 85); and (F) coefficient of variation (number of observations is 67). Channel types: 1. Anabranched; 2. Braided; 3. Meandering; 4. Straight.

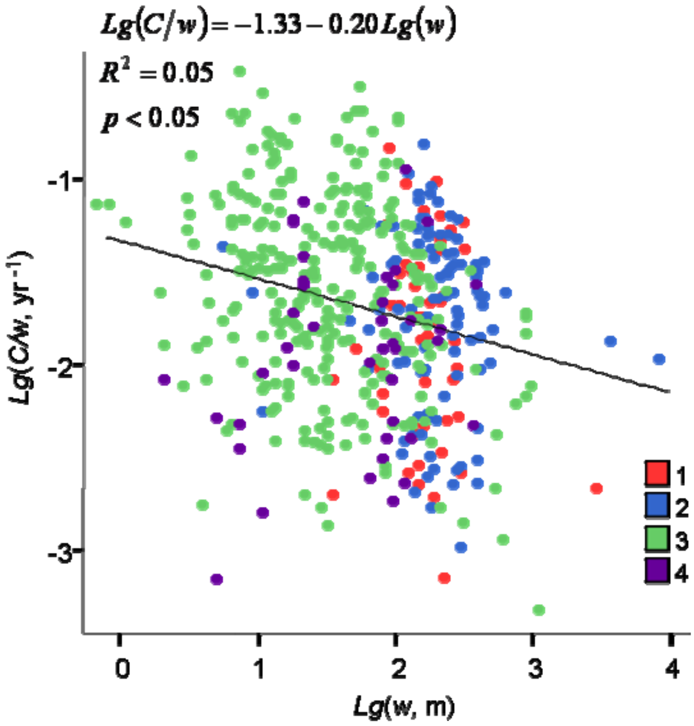


Figure 4.37: Relationship between relative bank erosion rate and channel width. Number of observations is 487. Channel types: 1. Anabranched; 2. Braided; 3. Meandering; 4. Straight.

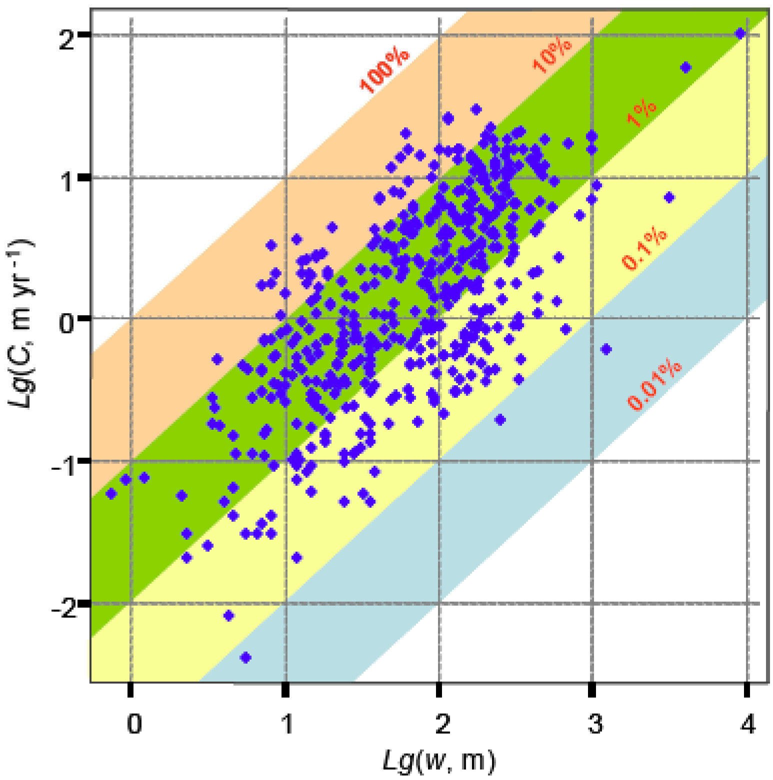


Figure 4.38: Relationship between bank erosion rate and width with different relative bank erosion rate bounds. Explanation in the text.

Unit discharge. Considering a relationship between relative bank erosion rate and unit discharge for all channel types, there is no significant correlation. However, the regression line, which is constructed only for anabranched channels, shows a positive and significant (R^2 = 0.32) relationship (Fig. 4.39). Although for anabranched channels the relationship is closer than in total, the value of the coefficient of determination shows that only a third of variance could be explained by the regression and is consequently not considered of predictive capacity.

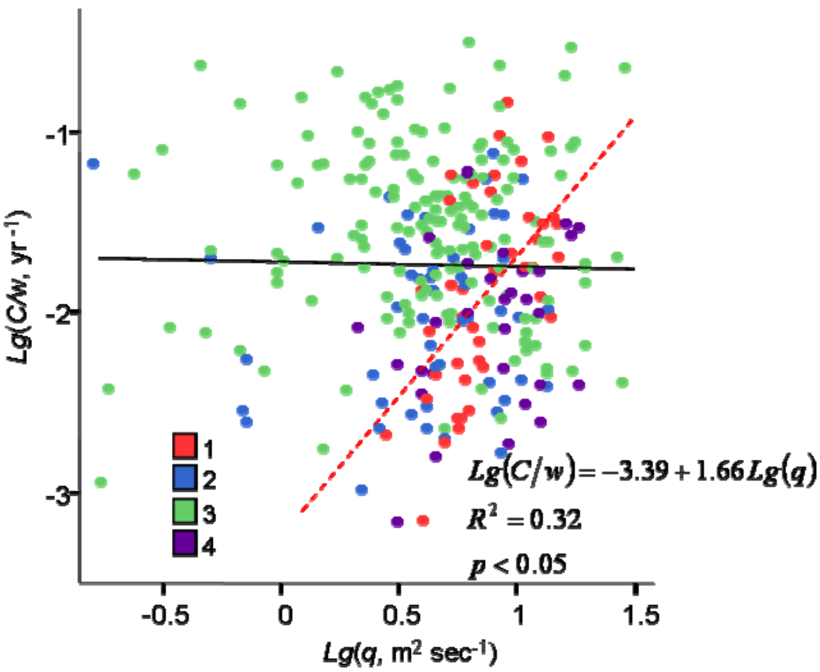


Figure 4.39: Relationship between relative bank erosion rate and unit discharge.

Total regression line is shown as a solid line; total number of observations is 290. Regression line for anabranched channels is shown as a dashed line; equation for anabranched channels is shown in the bottom right corner; number of observations for anabranched channels is 45. Channel types: 1. Anabranched; 2. Braided; 3. Meandering; 4. Straight.

4.5. RELATIONSHIPS AT THE CROSS-SECTION SCALE

4.5.1. Bank erosion rate at the cross-section scale

In this section relationships between bank erosion rate and variables at the scale of cross-section are considered. These variables are water velocity, bed and bank median grain size and types, bank silt-clay content and riparian vegetation types.

Average water velocity. The coefficient of determination and a scatter plot in Fig. 4.40 show that there is a weak correlation between bank erosion rate and average water velocity at bankfull condition. The R^2 value is low and points are widely scattered.

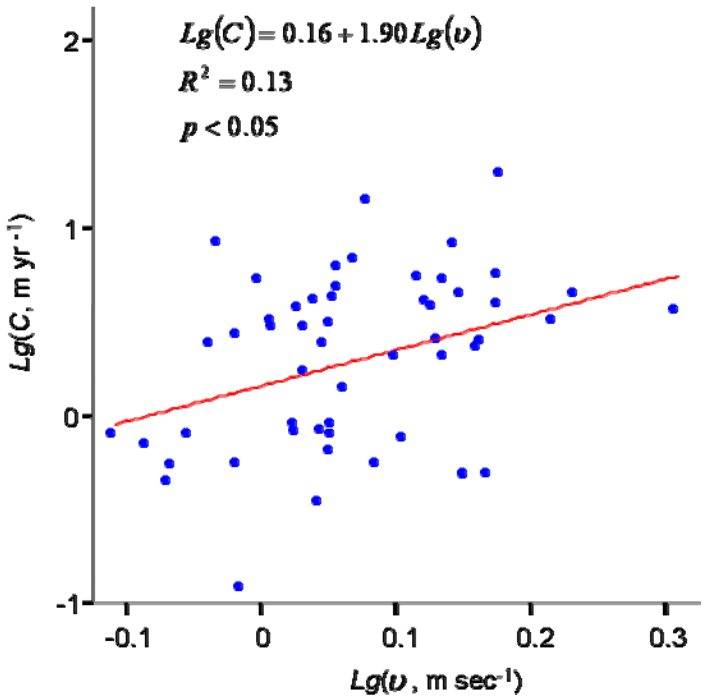


Figure 4.40: Relationship between bank erosion rate and water velocity at bankfull conditions. Number of observations is 54.

Grain size. Regarding the grain size of bank and bed material, by relationships presented in Fig. 4.41, one could conclude that there is no correlation between bank erosion rate and either median bank grain size or median bed grain size. The dashed vertical lines in Fig. 4.41 bound the categories of bank and bed material by grain size. The majority of points are located in the "sand" category for bank and for bed as well. Consequently, the majority of analysed data represent sand-bed rivers or rivers with sandy banks. Because of wide ranges and scatter distribution of points inside each category it is likely to observe the same magnitude of bank erosion rate in rivers with banks composed by sand or by gravel, and in sand-bed or gravel-bed rivers. Taking into account this wide point scatter and absence of correlation, data is not proceeded further for ordinal association analysis. It is clear that the ordinal association analysis will show absence of any association between categories of bank erosion rate and either bank or bed material categories. These results for grain size coincide with a previous regional study by Nanson and Hickin (1986). They have found for rivers in western Canada that the coefficient of correlation between bank median grain size and bank erosion rate equals 0.27, which means that R^2 is 0.073. Because Nanson and Hickin (1986) performed their analysis only for 18 rivers, the coefficient of correlation was found statistically insignificant at the level of significance of 1%.

Silt-clay content. In Fig. 4.42 a relationship of bank erosion rate with silt-clay content of bank in percent is presented. According to this figure there is no correlation between these two variables. Points are widely scattered even for different channel types. The majority of presented points are for meandering channels, much less for straight channels. For braided and anabranched channels it is impossible to derive any meaningful conclusion for this kind of relation due to limited number of points in Fig. 4.42.

Cohesiveness. As it is pointed out in the previous chapter, the cohesiveness is an important factor for bank resistance, but it is difficult quantitatively to distinguish which material is either cohesive or noncohesive. Indeed, using an approach to distinguish bank material by cohesiveness based purely on median grain size failed in this study. It happened because in the category "cohesive" there is only one data point and thus it is impossible to compare this category with others. Despite the simplicity of this approach supported by logical explanation in earlier studies (Sundborg, 1956; Makkaveev and Chalov, 1986), using alone the median grain size is not sufficiently robust to distinguish cohesive and noncohesive sediments. Another approach based on silt-clay and sand content allowed the comparison different categories. A distribution of ranges and mean values of bank erosion rate by cohesiveness categories is presented in Fig. 4.43. The ranges are almost equal. Only the "intermediate" range is slightly less than for others categories. At the same time the category "intermediate" is characterized by the minimum number of observations and perhaps with additional data the range would be wider. The mean values in Fig. 4.43 increase from "cohesive" to "noncohesive". The mean value for the category "noncohesive" is nearly twice as large as for "cohesive" category.

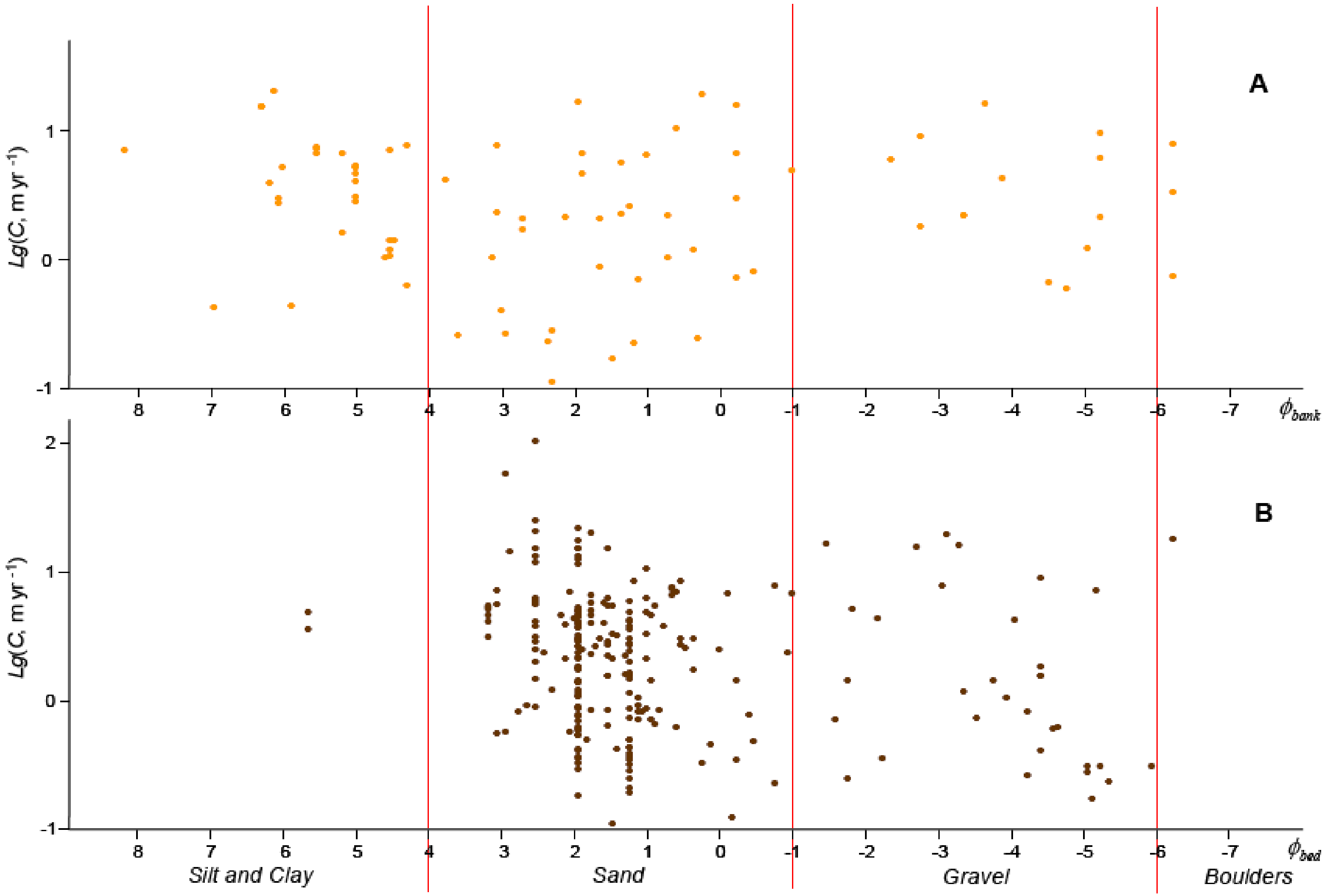


Figure 4.41: Relationship between bank erosion rate and median grain size of (A) bank (number of observations is 91) and (B) bed (number of observations is 248).

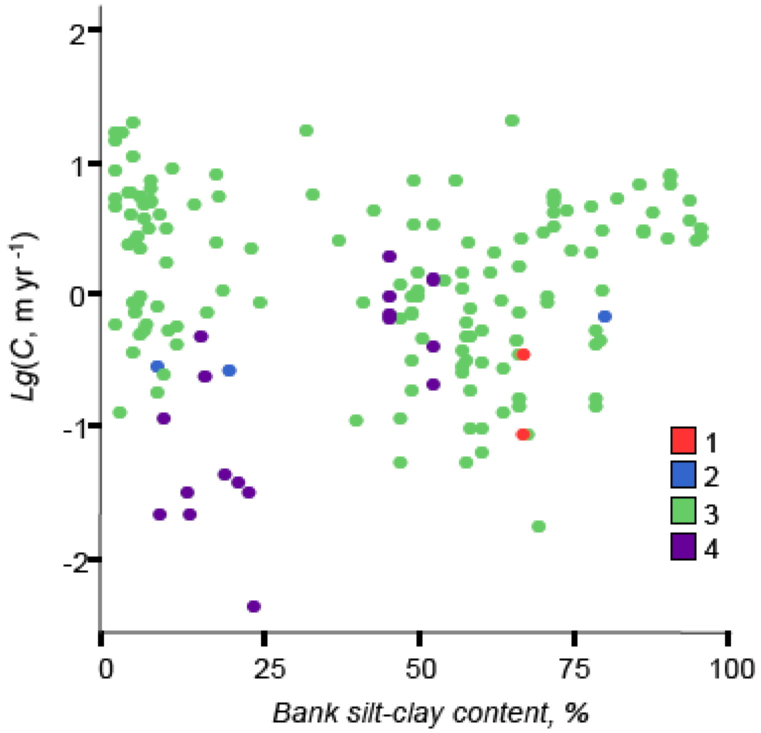


Figure 4.42: Relationship between bank erosion rate and bank silt-clay content. Number of observations is 165.

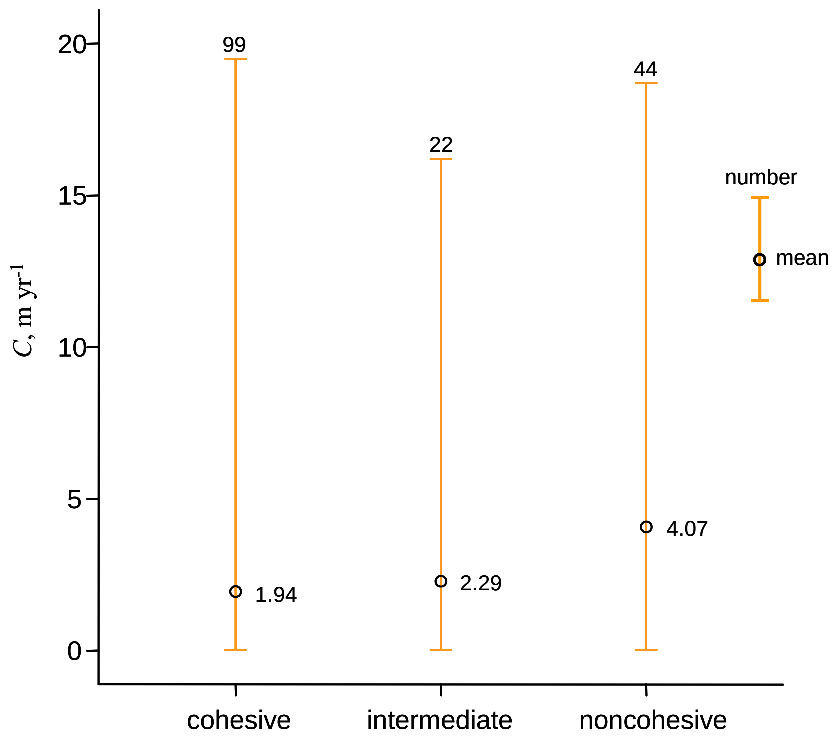
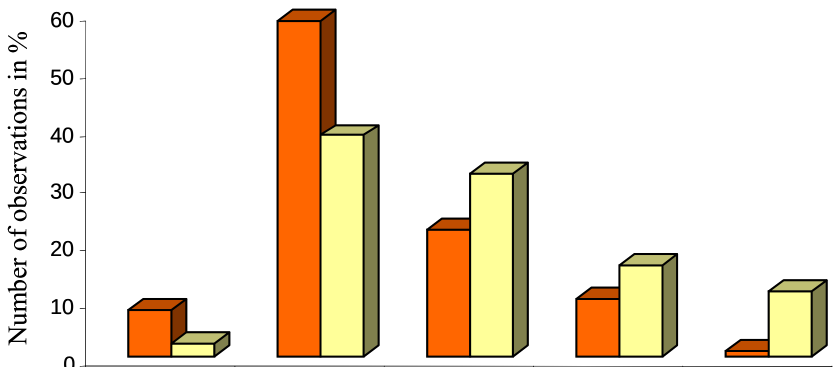


Figure 4.43: Ranges and mean values for bank erosion rate by categories of bank cohesiveness.

Due to difficulties to distinguish sediments by cohesiveness and taking into account the number of observations for different categories (the number of observations for the "intermediate" category is considerably less than for others categories), in further analysis of ordinal association categories "cohesive" and "noncohesive" are involved whilst ignoring the category "intermediate". It becomes clear from the distribution in Fig. 4.44 why the mean value of erosion for "noncohesive" material is higher than that of "cohesive". The distribution shows that numbers of observations of "noncohesive" material with bank erosion rate higher than 2 m per year are greater than those of "cohesive" material. Thus the bias to higher values of erosion rate for "noncohesive" category cannot be related to just a few data of extreme bank erosion rate. In the same time, the distributions for "noncohesive" and "cohesive" categories show the same behaviour with maximum numbers of observations in the category "0.1 – 2 m per year". The difference in the distributions is that data for "noncohesive" material is distributed more evenly amongst bank erosion rate categories than for "cohesive" material.



	<0.1	0.1-2	2-5	5-10	>10	m yr^{-1}
cohesive	8	59	22	10	1	
noncohesive	2	39	32	16	11	

Figure 4.44: Distribution of observation number by bank erosion rate categories. Colour bars indicate bank material types by cohesiveness.

Data presented in Fig. 4.44 have been used for computing the Goodman and Kruskal γ. In result the γ equals 0.45. Therefore two cross tables associated to each other with probability 0.45 and that this association is positive. However, the value is low due to almost the same distributions in Fig. 4.44. The $2\sigma = \pm 0.12$, i.e. a conclusion is that $\gamma \neq 0$. Thus, on average, it is likely to observe higher bank erosion rate in rivers with noncohesive bank than in rivers with cohesive banks.

Vegetation type. The same analysis of bank erosion rate distribution (Fig. 4.45) and ordinal association is performed for riparian vegetation type. Due to limited data for the categories “no vegetation” (10 observations) and “shrubs” (only 4 observations), these categories are omitted from the further analysis. For the categories “grass” and “trees” the mean values differ from each other only slightly, while the range for “trees” is narrower than that for “grass”. The order “trees”→”grass” has been analysed with the order of bank erosion rate categories for association. The initial data to calculate the Goodman and Kruskal γ and the distribution by categories are presented in Fig. 4.46.

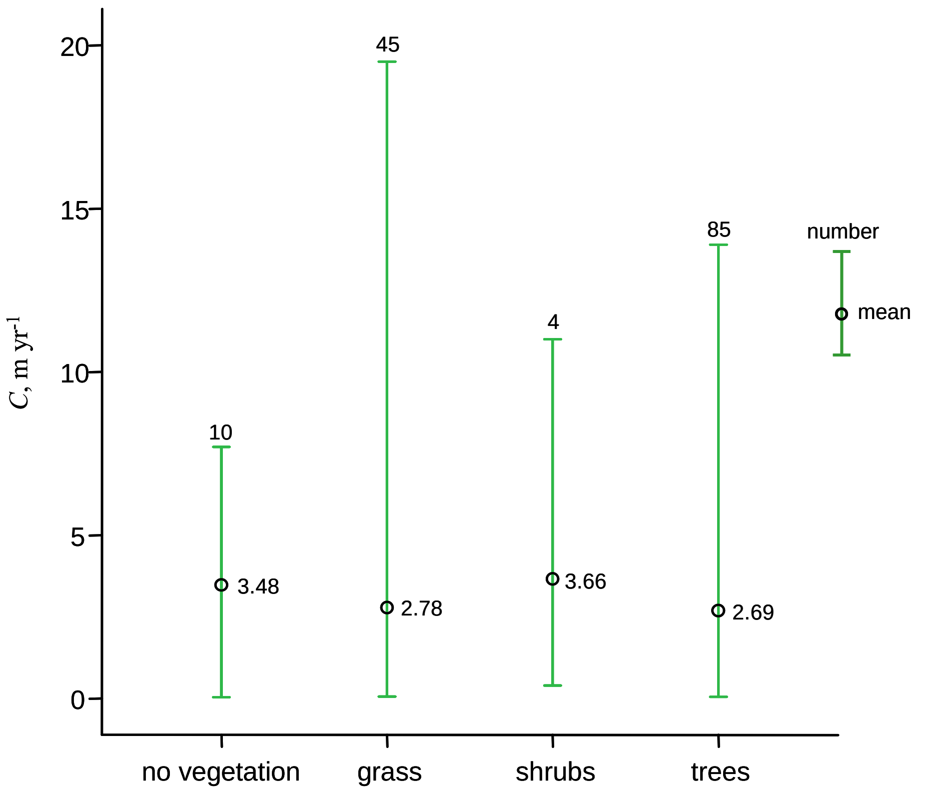
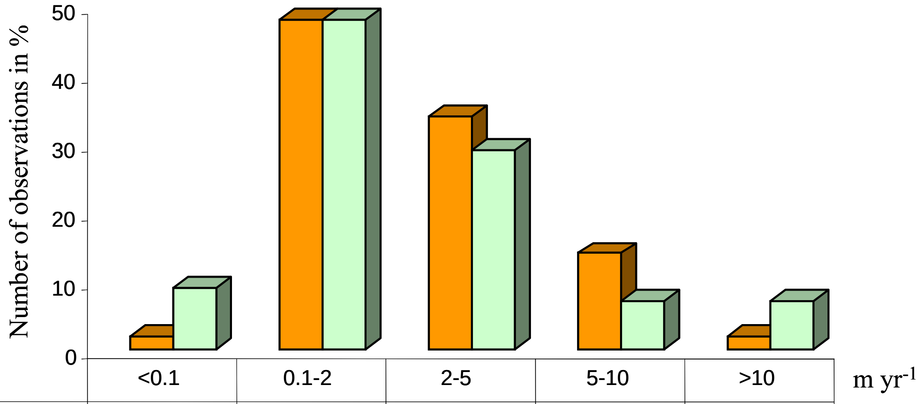


Figure 4.45: Ranges and mean values of bank erosion rates for riparian vegetation categories.



	<0.1	0.1-2	2-5	5-10	>10
trees	2	48	34	14	2
grass	9	48	29	7	7

Figure 4.46: Distribution of observation number by bank erosion rate categories. Colour bars indicate riparian vegetation categories.

A distribution in Fig. 4.46 shows that for the riparian categories the bank erosion categories are distributed in a similar way with the maximum number of observation in the category 0.1 – 2 m per year. Also from this distribution it is revealed that the wider range and slightly higher mean value for the "grass" category is dictated by few extreme data for bank erosion rate. Indeed, the calculated Goodman and Kruskal γ equals -0.14 and the negative sign shows that the categories should be inversely related. The γ value is low due to similar distribution and suggests that there is no association between the orders for bank erosion rate and riparian vegetation type. The $2\sigma = \pm 0.14$, i.e. a conclusion is that the association is not significant. Therefore, from this analysis it should be concluded that it is likely to observe the same bank erosion rate in river with banks covered either by grass or trees.

4.5.2. Relative bank erosion rate at the cross-section scale

Average velocity. For the relative bank erosion rate at the cross-section scale results are slightly different from relationships for absolute values of bank erosion rate. For instance, results for a relationship between relative bank erosion rate and average velocity at bankfull conditions (Fig. 4.47) show that correlation is greater than in case of absolute bank erosion rate (see R^2 values). However, the R^2 is still too low to conclude that there is a close correlation. Consequently, the average velocity should not be used alone to estimate bank erosion rates, though the relationships show a positive direction.

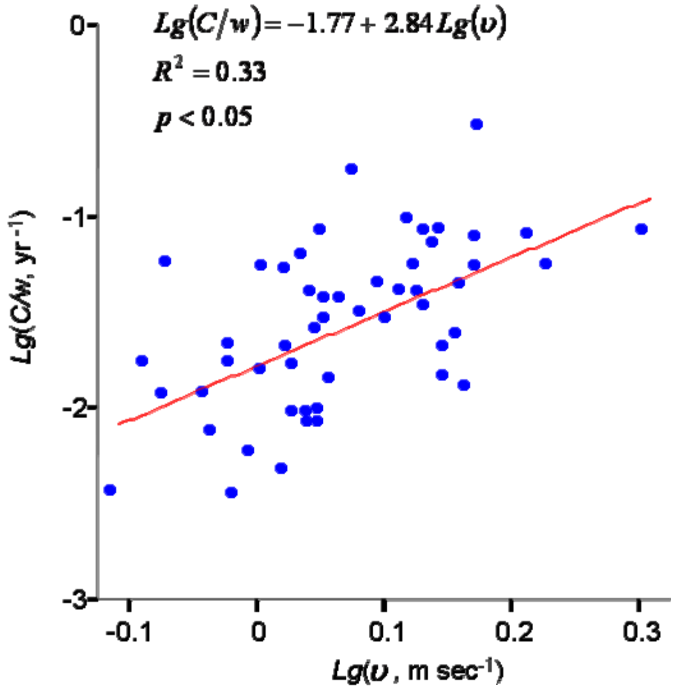


Figure 4.47: Relationship between relative bank erosion rate and water velocity at bankfull conditions. Number of observations is 52.

Grain size. Similar results have been obtained for median grain size of bank and bed as for absolute values of bank erosion rate (Fig. 4.48), i.e. there are no correlations. The majority of points are located in the grain size range for sand class. Taking into account a big scatter on both diagrams for all classes of grain size, an ordinal analysis has not been performed to associate categories of materials by grain size and relative bank erosion rate. From the diagrams presented in Fig. 4.48 one could conclude that the same magnitude of relative bank erosion is likely to be observed in rivers with banks composed by sand or gravel, and in sand-bed or gravel-bed rivers.

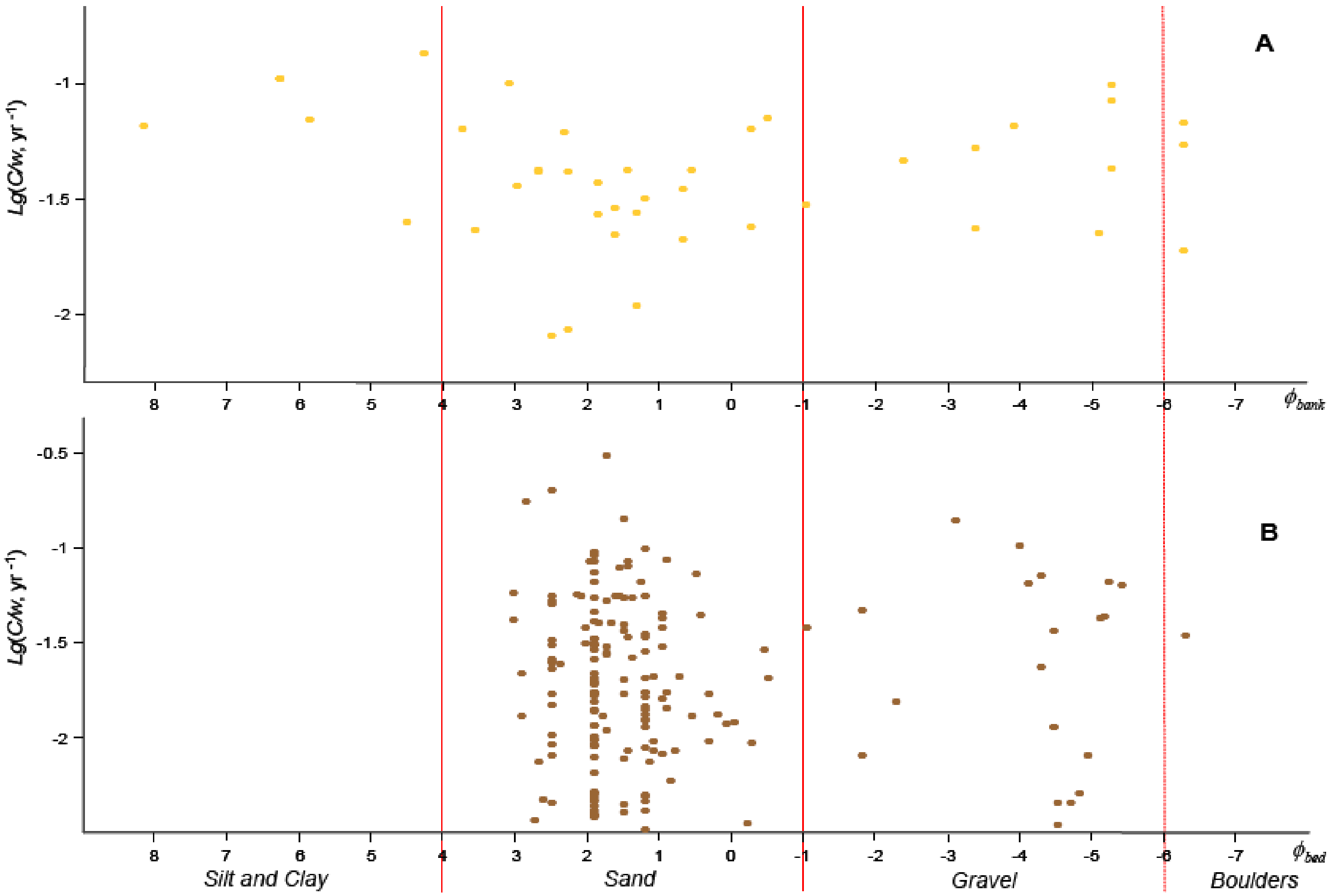


Figure 4.48: Relationship between relative bank erosion rate and median grain sizes of (A) bank (number of observations is 48) and (B) bed (number of observations is 207).

Silt-clay content. A scatter-plot presented in Fig. 4.49 shows no correlation between relative bank erosion rate and silt-clay content in river banks. The same results are obtained when points are distinguished by channels types. But in another hand, points mainly represent meandering and straight channels and only a few points available for braided and anabranched channels. From this analysis it could be concluded that bank silt-clay content cannot be used to estimate relative bank erosion rate even tentatively.

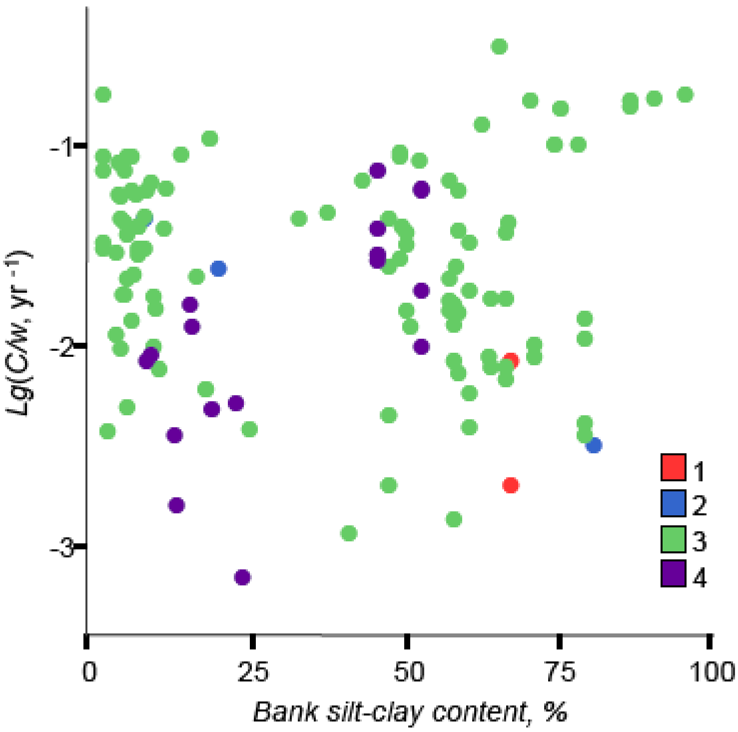


Figure 4.49: Relationship between relative bank erosion rate and bank silt-clay content. Number of observations is 125.

Cohesiveness. An approach to distinguish bank material types by cohesiveness using median grain size alone failed as well as in the case of absolute values of bank erosion rate. Therefore, an approach using silt-clay and sand content has been applied to categorize bank material. Fig. 4.50 shows distributions of ranges and mean values for these categories. For the "intermediate" category the narrowest range and minimum mean are resulted. At the same time the minimum number of observations occurs for this category and perhaps with more available data the range would be wider and the mean higher. Due to considerably low amount of data comparing with others categories, the "intermediate" category has been not used in further analysis for ordinal association. Regarding the remaining categories, the mean values only slightly differ from each other, but the range for "cohesive" category is wider than for "noncohesive" one. Consequently, an order based on ranges from the least active to the most active by lateral movement of a channel, i.e. "noncohesive"→"cohesive" has been analysed for ordinal association.

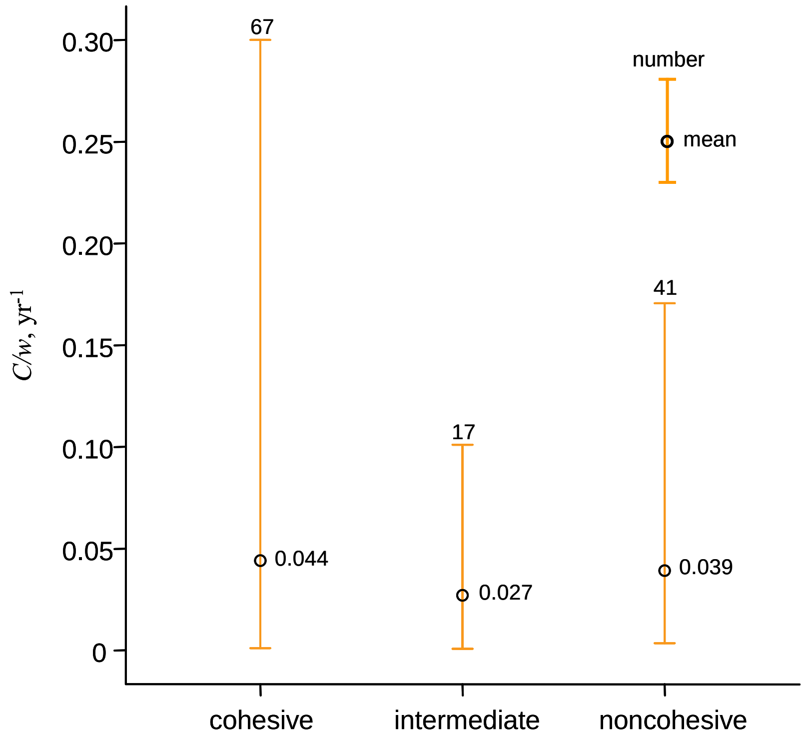
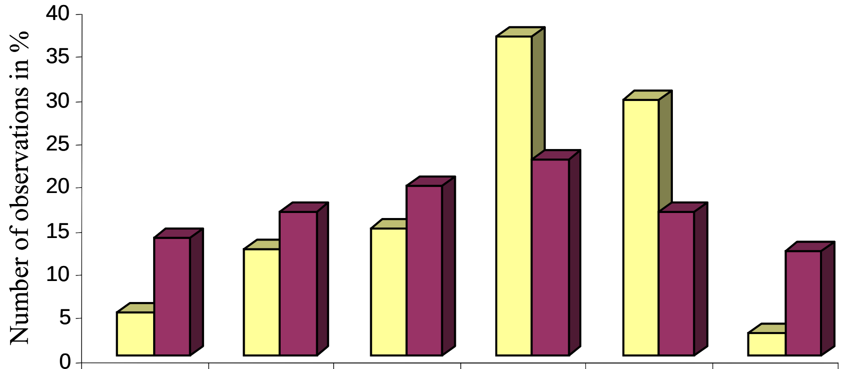


Figure 4.50: Ranges and mean values for relative bank erosion rates by categories of bank cohesiveness.

Initial data and distribution by categories are combined in Fig. 4.51. Numbers of observations for two categories are distributed in a similar way with maximum in the category "more than 0.02 and less than 0.05" of relative bank erosion rate. The only difference between distributions is that for the "cohesive" category the numbers of observations are distributed more evenly along relative bank erosion rate categories than for "noncohesive". The resulted Goodman and Kruskal γ is low and equals -0.16, and the association is not significant. The sign minus indicates that the prior chosen order for bank material is incorrect and should be inverse and the low value of association is dictated by similarity of distributions in Fig. 4.51. Therefore, there is no association between categories of bank material by cohesiveness and relative bank erosion rate. From this analysis it could be concluded that it is likely to observe the same relative bank erosion rate in river with either cohesive or noncohesive banks.



	<0.005	0.005-0.01	0.01-0.02	0.02-0.05	0.05-0.1	>0.1
noncohesive	5	12	15	37	29	2
cohesive	13	16	19	22	16	12

yr^{-1}

Figure 4.51: Distribution of observation number by relative bank erosion rate categories. Colour bars indicate bank material types by cohesiveness.

Vegetation type. For a relationship between relative bank erosion rate and riparian vegetation types the same methodology as for types of bank material by cohesiveness has been applied and results are presented below. In Fig. 4.52 distributions of ranges and mean values are shown, Due to limited data for the categories "no vegetation" (8 observations) and "shrubs" (2 observations), these categories are omitted from the analysis of ordinal association. For the categories "grass" and "trees" the mean values and ranges differ from each considerably. For "grass" category the range is wider and the mean value is higher than those for "trees" category. Consequently, the order "trees"$\rightarrow$"grass" has been analysed with the order of relative bank erosion rate categories for association. The initial data to calculate the Goodman and Kruskal γ and the distribution by categories are presented in Fig. 4.53. From the distributions in Fig. 4.53 it is evident that the majority of data for "trees" and "grass" represent relative bank erosion rate higher than 0.02 (i.e. 2% of channel width per year). It is also evident that for "grass" the relative bank erosion rate as high as more than 10% of width per year has been observed in 30% of cases.

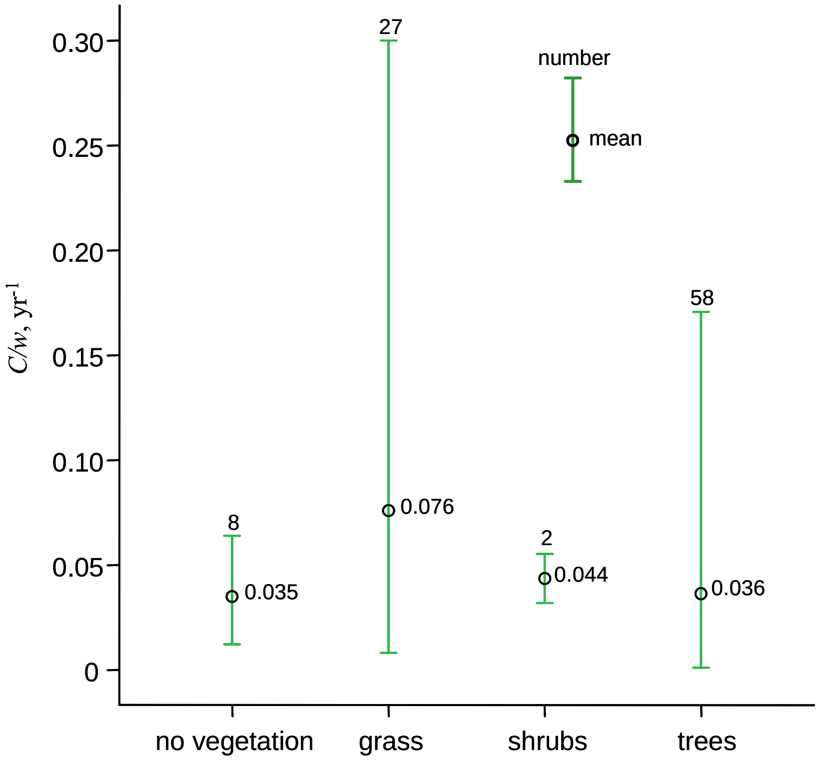
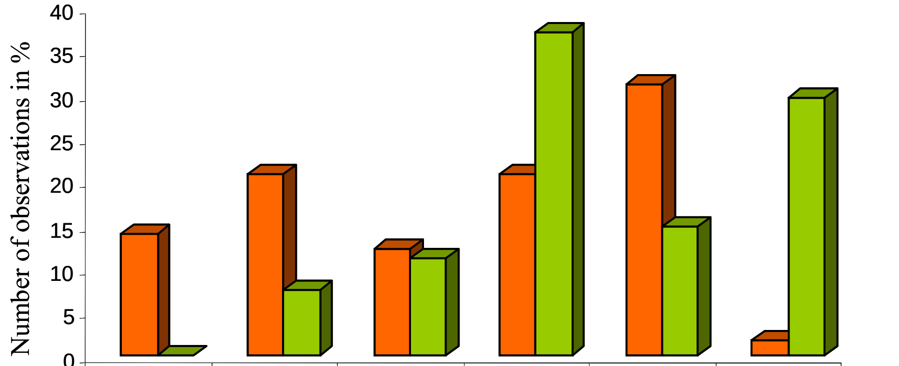


Figure 4.52: Ranges and mean values for relative bank erosion rates by riparian vegetation categories.



	<0.005	0.005-0.01	0.01-0.02	0.02-0.05	0.05-0.1	>0.1	yr-1
trees	14	21	12	21	31	2	
grass	0	7	11	37	15	30	

Figure 4.53: Distribution of observation number by relative bank erosion rate categories. Colour bars indicate riparian vegetation categories.

Using data given in Fig. 4.53, the Goodman and Kruskal γ has been computed and equals 0.45. This value is considerably higher than in the case of absolute values of bank erosion rate (where it equals -0.14), and suggests that the two cross tables are associated with each other with probability only 0.45 (note that value 1 shows perfect association). The positive sign shows that the prior chosen order of riparian vegetation types is positively related to relative bank erosion rate categories from the least active to the most active channels. The $2\sigma = \pm 0.12$, i.e. a conclusion is that the association is significant. Therefore, it is likely to observe higher relative bank erosion rate in rivers with banks covered by grass than in rivers with banks covered by trees.

CHAPTER 5: CONCLUDING DISCUSSION

5.1. CONTROLS ON CHANNEL PATTERN

From the review of the different approaches that have been adopted to quantify the conditions for transition in channel types – it is difficult, if not impossible, to solve this problem in a generic sense with the available methods and information because even using the same approach different results often are achieved using different data sets (see the range of separating lines in *QS*-diagrams, Fig. 2.12). Ferguson (1984b) suggested using such *QS*-diagrams taking into account the location of a particular point on the diagram with respect to distance to the discriminatory line. If a point is located close to the discriminatory line, then a river corresponding to this point is more prone to change its form. However, a wide range of discriminatory lines appears and the log-scale of the variables shows that often the main controls (discharge, slope) would have to change by a large amount if a given river was to change its form. On this basis, it seems unrealistic that a river would change its form within a short period of time due to natural forcing. Therefore in natural conditions it would not be expected to witness changes of channel types in the period of engineering time (typically 20-50 years). Only extreme events (such as earthquake, volcanic eruption, dam collapse, forest fire) which could lead to a significant increase or decrease in the supplied amount of water and sediment to a river reach could result to rapid change of channel type of a river. River channels have changed more slowly due to land-management, for example, the South Platte River is a famous example. However despite numerous studies of the Platte River, exemplified most recently by Joekel and Henbry (2008), planform changes have been gradual over decades and it has proven difficult to predict the changes on the Platte. Further, it is usually impossible to predict the timing of the extreme events noted above for a 20-50 years perspective. That being said, there is a requirement in river engineering management to recognise distinct channel patterns, to identify rivers which might be sensitive to disturbance and to develop procedures that are more sustainable – the latter requiring the adoption of a longer-term perspective than was the purview of river engineers in the past.

Despite the fact that the utility of *QS*-diagrams becomes weak in practice when data are combined on one plot from different studies and different regions, that combination does reveal some patterns in the relationships between controlling factors. The first pattern is that points on the diagram are distributed depending upon the bed median grain size; an issue remarked upon previously by many workers. The second is related to a dependence of channel form transition upon the size of the river system, which implies a system-scale dependence; an issue that has not received comment previously.

Grain-size control. The control exercised by grain-size has been addresses using trend-surface analysis (Davis, 1973) implemented using interpolation within Surfer™ 8 (Golden Software, Golden, CO, USA). Trend surfaces change gradually and capture general coarse-scale patterns in data but are susceptible to outliers. The latter issue was explored by completing surfaces with and without outliers to check for surface stability and those surfaces reported below do reproduce the general tendencies of the sampled data. Considering the first point, Fig. 5.1 shows a trend-surface of median bed grain size (phi) within the coordinates of a *QS*-diagram. The partial correlation coefficient of phi with slope is $|r|$=0.78, while with discharge it is only 0.38. Therefore, grain size increases as slope increases, and has only a weak negative dependency upon changes of water discharge (Fig. 5.1). Indeed, Ferguson (1984b) stated that the coefficient *a* in equation (2.1) is not constant and depends on bed grain size. Consequently, when a larger amount of empirical data is used to define a *QS*-diagram, as herein, it is evident that a single discriminatory *Q*-*S* straight-line cannot be defined and it has some dependency on grain size. This supposition is supported by the suggestion of considering the hydraulic geometry for sand-bed and gravel-bed rivers separately (Xu, 2004). Xu (2004) suggested to apply approaches pertaining to hydraulic geometry for sand-bed and gravel-bed rivers separately to reduce the point scatter in resultant relationships. From Fig. 5.2 it is clear that gravel-bed points plot above sand-bed points and consequently gravel-bed rivers are characterized by higher stream power, as indexed by the *QS* product.

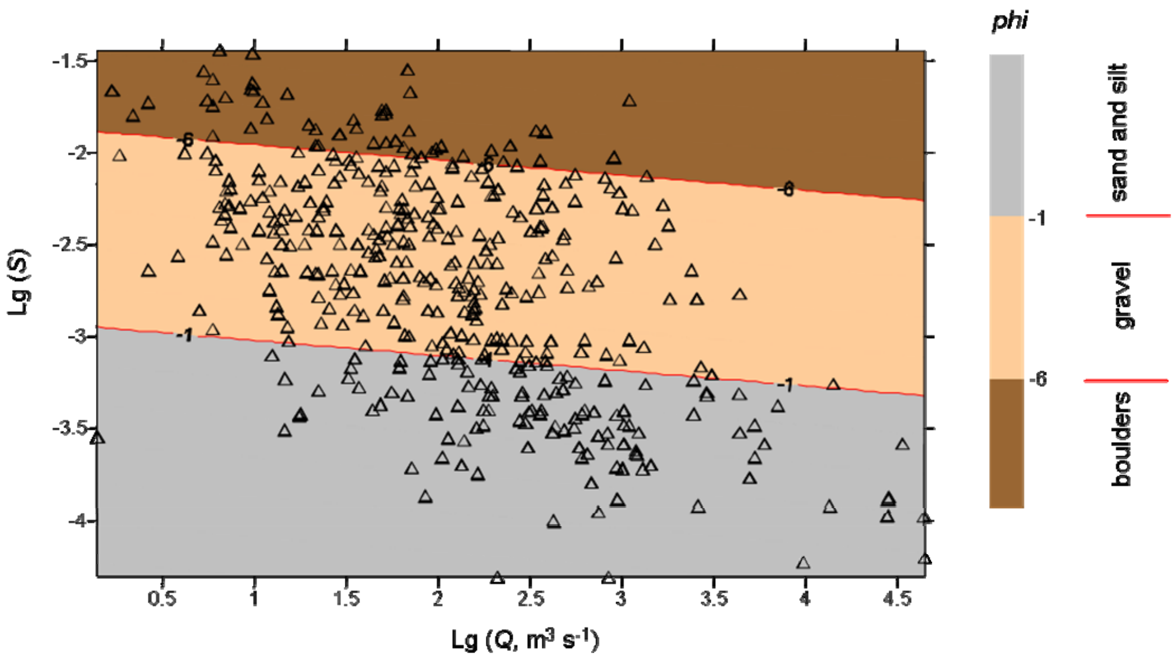


Figure 5.1: Linear trend-surface of bed median grain size (phi) on *QS*-diagram and locations of points.

While a separate consideration by bed type in studies of hydraulic geometry could improve obtained relationships by reducing point scatter, it does not illuminate more clearly any discriminatory lines between meandering and braided channel types. The approach only shows a tendency for braided channels to plot above meandering channels, especially for gravel-bed rivers, but there are a lot of interpenetrating points (see Fig. 5.2). The best separation could be observed if only data samples for gravel-bed braided and sand-bed meandering channels are considered. However, on another hand, if one would consider data samples for gravel-bed meandering and sand-bed braided channels alone, then a contrary conclusion can be derived, that braided sand-bed channels are characterized by lower stream power than meandering gravel-bed ones. These results imply that two mechanisms of braiding occur: (i) due to a steep slope and (ii) due to sediment overloading, which idea accords with Lane (1957). The first mechanism is more prone to apply to gravel-bed rivers (Fig. 5.2), while the second one applies appositely to sand-bed rivers. Because of these two different mechanisms of braiding occurrence, Simpson and Smith (2001) argued that the Leopold and Wolman (1957) *QS* relationship is unable to predict channel pattern in the case of the sand-bed Milk River. From the present analysis it becomes evident why Simpson and Smith (2001) reach such a conclusion, because much of the Leopold and Wolman (1957) data came from gravel-bed rivers and mostly represent the first mechanism of braiding occurrence, while in the study by Simpson and Smith (2001) the behaviour of the sand-bed Milk River is dominated by the second mechanism, i.e. sediment overloading.

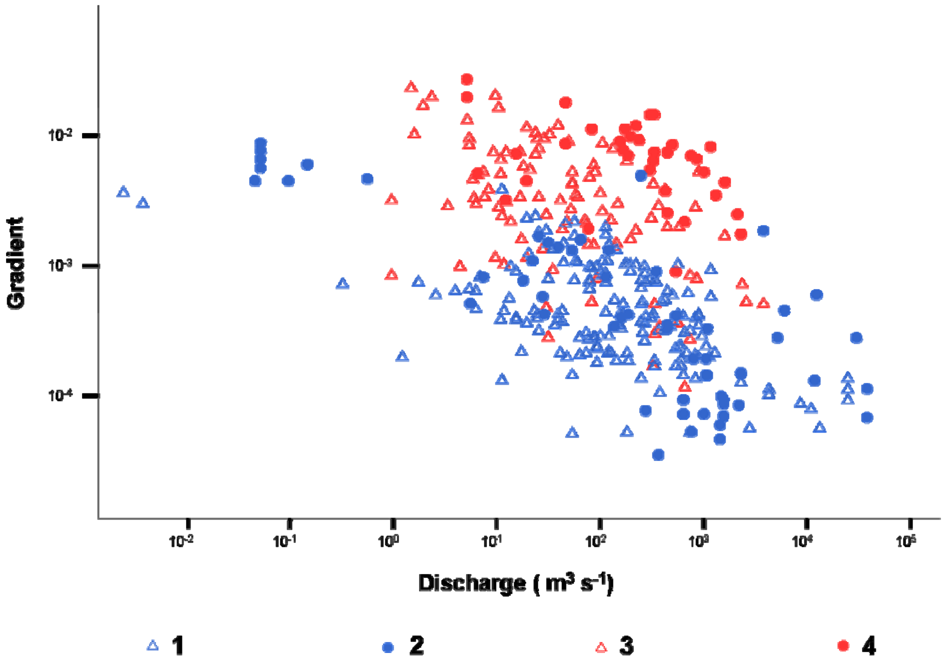


Figure 5.2: *QS*-diagram with points divided into groups with different bed types.

1 – meandering sand-bed; 2 – braided sand-bed; 3 – meandering gravel-bed; 4 – braided gravel-bed.

System scale dependence. Another implication that arises from consideration of all available data combined is that it reveals a dependence of the exponent in the equation (2.1) upon the discharge magnitude and therefore scales with the size of a river system. Data obtained from a variety of small-scale laboratory studies often have been used to populate *QS*-diagrams and these plots reveal important results. The main finding is that at this small-scale, channel slope is the prevalent control discriminating between meandering and braiding (Schumm et al, 1987). The channel type present does not depend to any significant degree upon the discharge magnitude or upon discharge fluctuations. In fact, from the laboratory studies the value of the exponent b is known to be small (0.1-0.25) (e.g. Ackers and Charlton, 1970; Edgar, 1973; Ackers, 1982) and this reflects the small influence of discharge on channel types. However, when data are added to *QS*-diagrams from natural rivers the exponent increases as the scale of the system increases. This behaviour of the exponent is shown in Fig. 5.3. The discriminator for larger rivers systems is characterized by a larger exponent, significantly equal to -1 for the largest rivers. Therefore, when large rivers are under consideration, water discharge becomes as important a factor as slope.

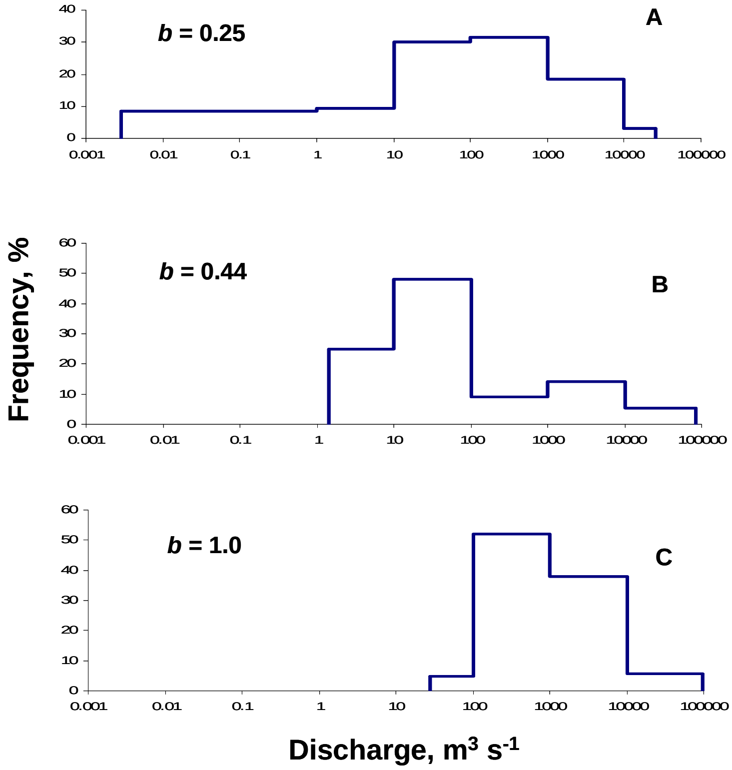


Figure 5.3: Frequency distribution of discharge datasets used in various approaches.

(A) based on data from Lane (1957); (B) based on data from Leopold and Wolman (1957); (C) based on data from Romashin (1968).

As the physical meaning of *QS*-diagrams lies in the equation of stream power, due consideration should be given to the stream power distribution throughout the longitudinal profile of a river. In the distribution of total stream power on a *QS*-diagram (Fig. 5.4) isolines of total stream power have an exponent of -1 and reflect the 'equal' influence of slope and discharge. The arrow 1 in Fig. 5.4 is not a discriminatory curve but rather has a trajectory with an exponent (*b*) less than 1 and reflects increasing power with increasing of discharge. Arrow 1 is generalised but, for *b*-values in the range -0.1 to -0.25 and for suitable *a*-values in Equation 2.1, would project back to values of slope between 0.1 and 0.01 which is the range of slopes reported for small discharges systems (10^{-6} m^3 s^{-1} to10^{-2} m^3 s^{-1}) from flume studies at which the meandering-braided transition occurs (Tiffany, 1935; Hooke, 1967; Zimpfer, 1975; Hong and Davies, 1979; Zarn and Davies, 1994; Zhang et al., 2001; Ashmore, 1982). Arrow 2 again is generalised and is not a descriminator; it has an exponent equal to -1 and shows that with increasing discharge the stream power remains constant. Arrow 3 has an exponent greater than 1 and shows decreasing power with an increase of discharge. This latter curve is hypothetical and is included for completeness but has no support from large river data. Lawler (1992) proposed a distribution of stream power for an hypothetical river system

(Fig. 5.5). In this hypothetical drainage system, stream power reaches its maximum in the middle part of the system and decreases as the system increases in absolute size. The reason for this is that the increase in discharge with catchment size is more than off-set by a reduction in channel slope; thus to maintain power on low slopes a considerable increase in discharge is required. It is recognised however that a direct analogy cannot be draw between the multiple catchment data and the proposal of Lawler (1992) which applies to increments in catchment area within a single representative catchment. However, the principle remains applicable, that as system scale increases and slope declines, the stream power can only be sustained by high discharges. Such an adjustment however cannot explain the changes in the exponent of the discriminatory equation (2.1) from small to medium sized systems. It is notable that when considering data from large river systems, Romashin (1968) obtained an exponent of $b = 1.0$. Note that in the present study, despite obtaining *Q*-*S* data for some of the largest river systems in the world, streampower values do not exceed 100,000 W m^{-1} and although discharges for the largest rivers span the range 10^3 to 10^5, slope declines in this range from c. 10^{-2} to 10^{-4}. Note also that for high slopes in the streampower range: 10,000 to 100,000 W m^{-1}, channels are almost universally coarse-grained and braided, whereas for the same power range but for lower slopes channels are predominately finer-grained and anastomosed. Finally it is evident that a *QS* discriminator with slope $b = 1.0$ drawn along the 10,000 W m^{-1} curve neatly distinguishes multi-channel systems from single channel meandering systems for systems > $Q = 10^2$ m^3 s^{-1}. Thus a suitable discriminator is:

$$S = Q^{-1}, \quad \text{where } 100 < Q < 100{,}000 \text{ m}^3 \text{ s}^{-1} \qquad 5.1$$

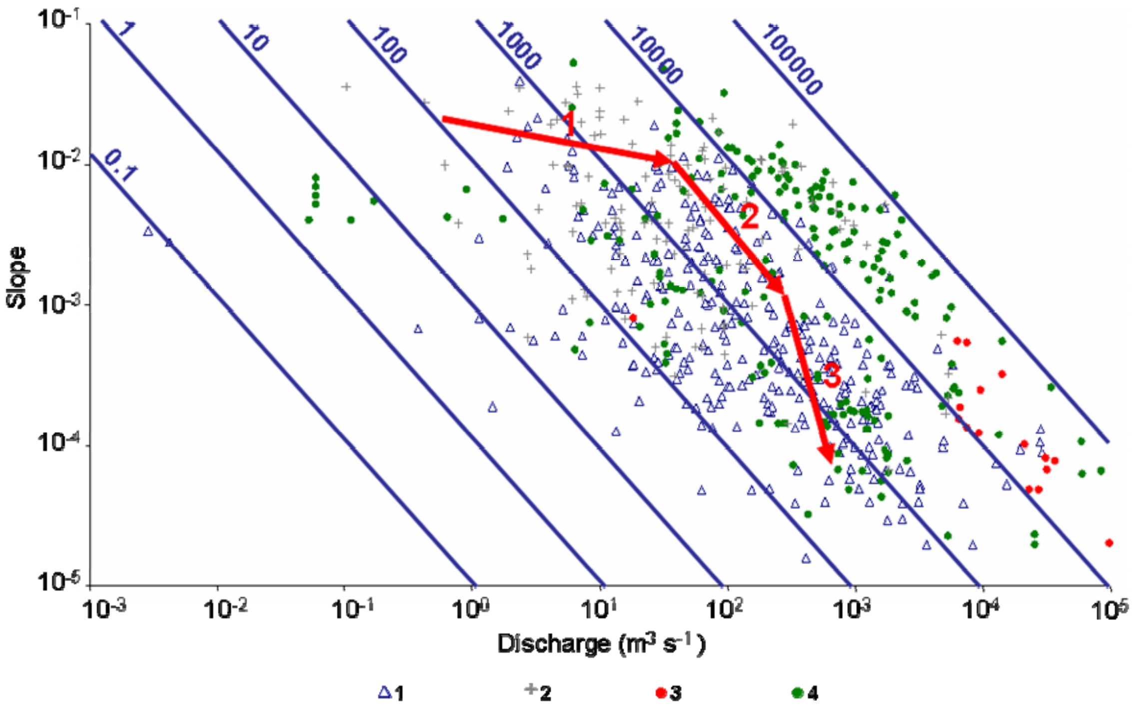


Figure 5.4: Isolines of gross stream power (W m^{-1}) on *QS*-diagram. Explanation in text.

1 – meandering; 2 – straight; 3 – anabranched; 4 – braided.

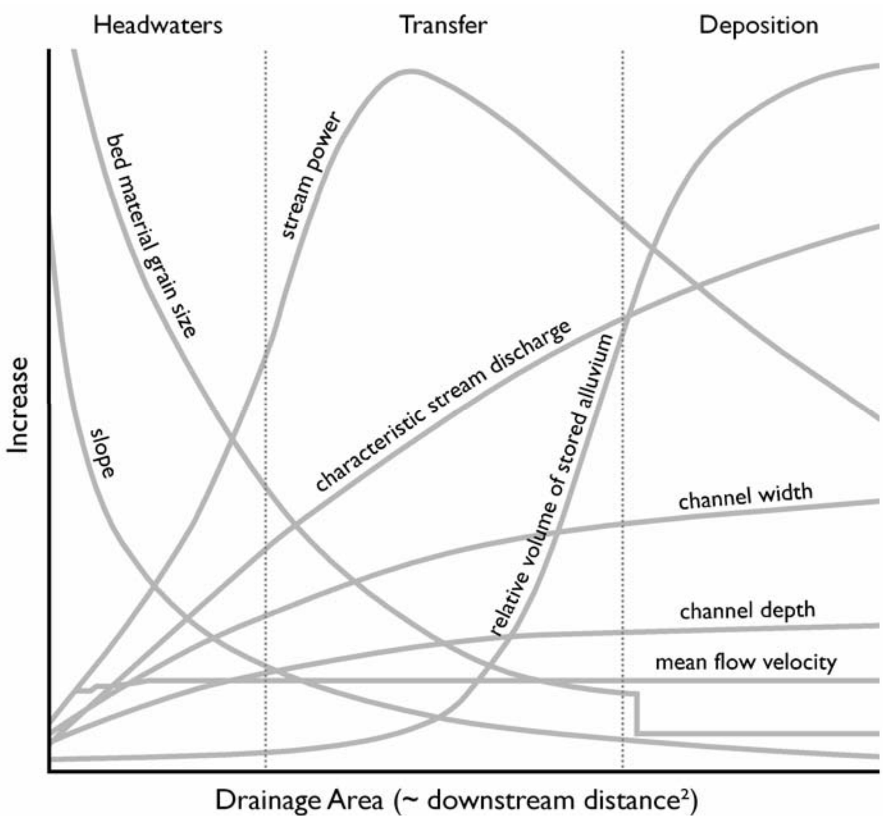


Figure 5.5: Hypothetical stream power (according to Lawler, 1992), flow, channel size, and sediment characteristics change throughout the longitudinal profile.

Note that Equation 5.1, although robust, cannot be extrapolated to provide a discriminator for smaller systems and this is a significant observation which will be refered to below. Note also that for streampower values greater than 10,000 W m^{-1} there are practically no meandering rivers evident in Fig. 5.4. However, there are scattered examples of braided streams to the left of the discriminator. The overlap of meandering and braided stream channel types in this study is less evident than in most prior representations of the *QS*-diagram and yet the presence of braided rivers to the left of the discriminator requires comment. There are three main reasons why this may occur. Firstly, and generally, the definition of channel type is always imprecise and some channels may have been mis-classified within this study as in other studies but yet rigorous checking within this study reduced this possibility significantly. More importantly, other controlling variables, such as grain size (noted above) or vegetation (considered below), may be locally important and will influence the threshold value of streampower for transition. Notable are a group of braided channels plotted just below $S \sim 10^{-2}$ within the low value discharge decades of 10^{-1} to 10^{1} m^3 s^{-1}. A careful check of the source literature shows that these are indeed braided systems, characterised by loose sediment and little vegetation, and that they plot more in accord with the *QS* transition criteria suggested by the laboratory experiments in similar-scale, small systems noted above. The position of these data, although few, add to the suspicion that the exponent of the discriminator might be low for small natural systems. Unfortunately it has not been possible to obtain reliable data for additional small systems during this investigation to test or strengthen the argument for a scale-dependent exponent (b) further. This dearth of small-scale field examples has also been noted by Paola et al. (2009).

As a key characteristic of channel form, the sinuosity (P) can also be distributed on a *QS*-diagram (Fig. 5.6). By the application of the trend-surface analysis (as reported for grain-size control) it was anticipated from theory and simulation (Schumm, 1979; Stølum, 1996) that P would be low in the bottom-left of the diagram, increase to a maximum in mid-plot and then decrease again towards the top-right (Fig. 5.7). The values of P decrease as expected in the top-right but a high sinuosity area is located towards the bottom-left of Fig. 5.6 with low slope and low discharge. Four rivers are numbered 1 through 4 to exemplify the high sinuosity low-power systems. However, it is traditional to assume that in the area of low discharge and low slope (lower-left white region in Fig. 5.6) channels have low sinuosity, as flume studies have shown that straight channels are characterized by low stream power (e.g. Ackers and Charlton, 1970; Edgar, 1973; Zimpfer, 1975; Schumm and Khan, 1972 a&b). The Ackers and White discriminator for straight to meandering channels is shown in Fig. 5.6 and lies well above many data points for natural meandering channels. Neglecting consideration of the bottom-left of the figure (which is considered subsequently), the trend-surface of *P* reveal important results. The red band in Fig. 5.6 represents sinuosity between 1.3 and 1.5. These values are used here because by various authors different values of sinuosity are used to define straight:meandering transition, for example, van den Berg (1995) has used 1.3 while Leopold and Wolman (1957) have used 1.5. As it seen in the figure the red band does not follow a power function trend (i.e straight line plot on log-log coordinates) but rather is curved throughout. Although the portion between 1 and 3.5 log *Q* might be approximated by a power law function, the extremities of the red band clearly deviate from the general trend. Within low magnitude of water discharge the sinuosity depends upon slope alone, but sinuosity becomes increasingly dependent on the increase in discharge. In a general sense, the trend of the red band mimicks the trend of the red streampower curves, 1, 2 and 3 in Fig. 5.4.

A conceptual distribution of sinuosity change with slope is shown in Fig. 5.7 A and according to Schumm (1979) there are two threshold slopes (1 and 2 in Fig. 5.7 A). The first threshold slope corresponds to the change from straight to meandering; the second threshold slope – from meandering to braided/anabranching. On another hand, for a given low slope, the sinuosity depends upon discharge alone and the sinuosity change shows the same behaviour with discharge as with slope. Consequently, there are two threshold discharges. The first for transition from straight to meandering and second threshold discharge represents critical discharge when river can not maintain a single-thread channel. The first transition cannot be isolated either by using a single threshold value of streampower (Fig. 5.4) or a single threshold value of sinuosity (Fig. 5.6) and many notionally straight channels are found in the same *Q*-*S* space as meandering channels. However, in Fig. 5.6 the second transition most commonly reported in the literature (i.e P = 1.3 to 1.5) has a distinct, near-linear (using log-log coordinates) trend equivalent approximately to the 10,000 W m^{-1} critical streampower threshold (Fig.5.4) across a range of discharge values between about 100m^3 s^{-1} and 3,000m^3 s^{-1}. To the left and right of these latter discharge values the critical sinuosity is achieved for lower stream power values. There are however no data for multi-channels for high slopes and moderate discharges and insufficient data for large rivers with high discharge and low slopes to ascertain is this second threshold is indeed variable and consequently scale dependent. This issue is considered further below.

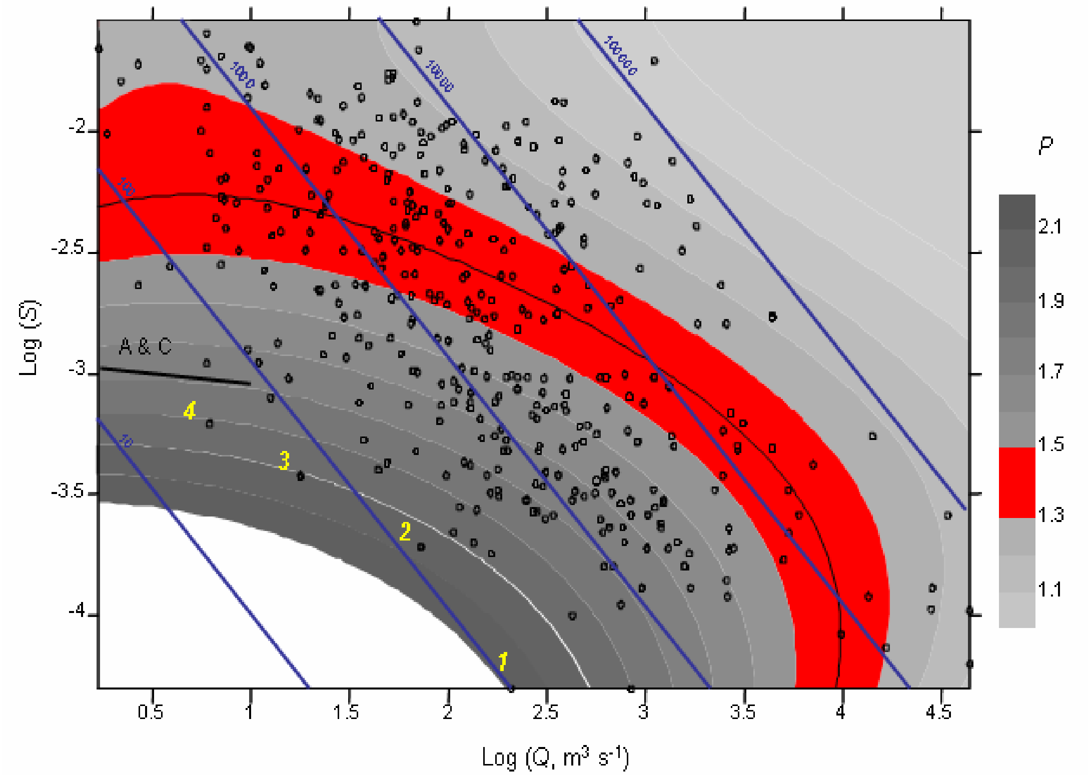


Figure 5.6: Cubic trend-surface of sinuosity (*P*) on *QS*-diagram and locations of points. The points 1 through 4 represent the River Barwon, Mississippi, Fawn River and Yellow Creek respectively. The curve for the Ackers and Charlton (1970) straight:meandering discriminator is shown. Further explanations in the text.

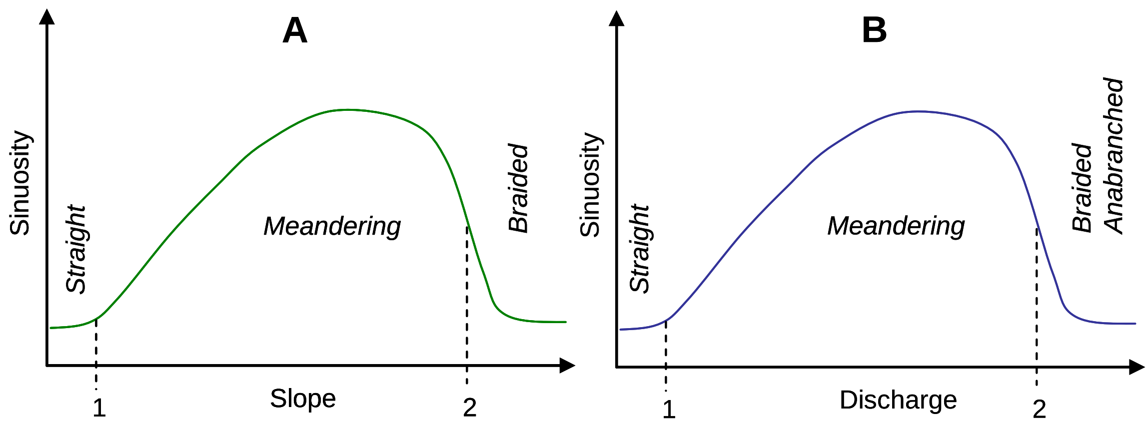


Figure 5.7: Conceptual relations between sinuosity and (A) slope and (B) water discharge. Explanations in the text.

The preceding analysis reveals two important points:

Firstly, the fact that data for both meandering and notionally straight channels overlap and span the P = 1.3 to 1.5 'threshold' begs the question as to whether it is reasonable to consider any natural channel reach to be 'straight'. It is evident from reviewing the literature (e.g. Leopold and Wolman, 1957; van den Berg, 1995), that these two threshold values high-lighted by Schumm (1979) have not been associated with a mechanistic process interpretation; rather they seem to have been selected as convenient conceptual transitions, indeed Leopold and Wolman (1957, p.53) state "truly straight channels are so rare among natural rivers as to be almost nonexistent". Given that natural 'straight' channels often exhibit alternate bars and have meandering talwegs that periodically impinge on the banklines it is unlikely that truly straight channels (i.e. P = 1.0) have been recorded from natural systems. Indeed, all the P data in Fig. 5.6 have values of 1.1 or greater. Thus the concept of a straight natural channel has little utility and no support from field data. Rather, the only theoretical condition proposed for the maintenance of a straight channel appears to be $D_{bed}/W > 10^{-1}$ (Parker, 1976); this condition has not been tested thoroughly and although large values of D_{bed}/W can be attained in the laboratory and in canals they are but rarely attained in natural rivers.

Secondly, the scale-dependence of the streampower threshold for meandering to multi-channelled is an important and novel observation. It is evident from Fig. 5.4 (and Fig. 5.6) that some low slope, high discharge channels could exhibit low sinuosity and, with an increase in discharge, there would a shift to multi-channeled form i.e. anastomosed without a strongly meandering transitional phase. This adjustment in planform for large rivers requires further attention and only recently has this issue received some attention by additional empirical data from large alluvial rivers (Latrubesse, 2008). Latrubesse (2008) found a mean discharge threshold of 17 000 m^3s^{-1} for low gradient rivers above which "only anabranching systems can achieve efficient ways to move water and sediment over exceptionally low gradients".

Given the comments made above with respect to straight channels the issue warrents additional attention. In the traditional QS-diagram only meandering and braided channels are considered, and attention is not paid to straight channels. However, 'straight' and anabranched channels are distributed on QS-diagrams with a wide range of stream power. The range for anabranch channels plotted herein (Fig. 5.4) ranges through one order of magnitude of power whilst straight channels plotted herein (Fig 5.6) range through several orders. These results are contrary to the representation by Bridge (2003) of the continuum of equilibrium channel patterns; small-discharge, straight channels should possess lower stream power than meandering channels. However, some large-discharge, low-power channels can exhibit low-sinuosity and these large rivers are often mud-rich and usually exhibit anastomosed tendencies (Galloway and Hobday, 1983, p.57). Further, in contrast to Bridge's supposition, many studies (e.g. Schumm, 1963; 1969; Ebisemiju, 1994; Swamee et al., 2003; Hinds et al., 2004) have noted that streams of gentle bed gradient and high proportion of suspended fine sediment load (Allen, 1965) tend to have high sinuosities. Often these systems are small, poorly drained, aggrading systems, such as mountain meadow streams incised into peat (e.g. Watters and Stanley, 2007; Aswathy et al., 2008) but can include large systems such as deltaic and coastal plain rivers (e.g. Mississippi – Leeder, 1982; Rhine-Meuse – Gouw and Berendsen, 2008). Ironically although the traditional *Q-S* diagram was developed to apply to natural channels much of the publications on the existence criteria for 'straight' channels are from small flume studies wherein the 'straight' channels were artificially cut trapezoidal sections at the being of flume runs (e.g. Leopold and Wolman, 1957; Ackers and Charlton, 1970; Shumm and Khan, 1972) and so the idea that low power is associated with straight channels persists, largely because the context of the temporal development of sinuosity was not considered in any detail in the early flume experiments used to define the straight:meandering transition (Leopold and Wolman, 1957; Ackers and Charlton, 1970; Edgar, 1973; Shumm and Khan, 1972). Rather, simulations and field data have shown that high sinuosity values (e.g. > 3.0) and low sinuosity values (e.g. → 1.0) alternate in time and space as river meanders cut-off (Martinsen, 1983; Stølum, 1996) which process largely explains the co-existence fields of 'straight' and meandering channels in Fig. 5.6.

Herein it has been found that points for 'straight' channels scatter on the *QS*-diagram without any regularity. However, using another approach, notably the diagram of Parker (1976), points for 'straight' channels (i.e. $P < 1.3$) show quantitative properties which discriminate them from other channel types (Fig. 5.8). In principle, the Parker (1976) diagram should not be useful as it is based on theory developed to discriminate meandering and braided channels and does not include theoretically supported conditions to discriminate straight channels. Indeed, points plotted in Fig. 5.8 represent natural rivers and all fall to the left of the Parker discriminator between meandering and braided. As noted by Bridge (1993) the criteria of Parker (1976) often do not agree well with field data and this is the case herein. Perhaps this failing is because the majority of data used by Parker (1976) to check the criteria came from laboratory experiments and do not reflect conditions in natural rivers. Nevertheless, despite Bridge's ascertion, the points for low sinuosity (straight) channels in Fig. 5.8 are distinct from meandering and braided channels and are grouped to the right of more sinuous channels ($P > 1.3$) within the area with high values of *S*/*F* and *d*/*w*. Therefore, very low-sinuosity (straight) channels are characterized by higher channel slope or lower Froude number or more equant aspect ratio than meandering and braided channels which have broader shallower channels. Thus the diagram of Parker (1976) shows qualitative properties of low sinuosity channels by which they can be distinguished from other channel types. Similarly, braided channels fall to the left of meandering channels. Finally it should be noted that Parker's analysis cannot be extended to small systems characterised by small discharge and steep slopes as the discriminator would extend to slopes greater than the angle of repose. At this point it is worth noting that the majority of discriminators proposed in the literature apply only for a limited range of discharge values which suggest that other discriminators must apply for other ranges of discharge, a point not made explicity in the prior literature.

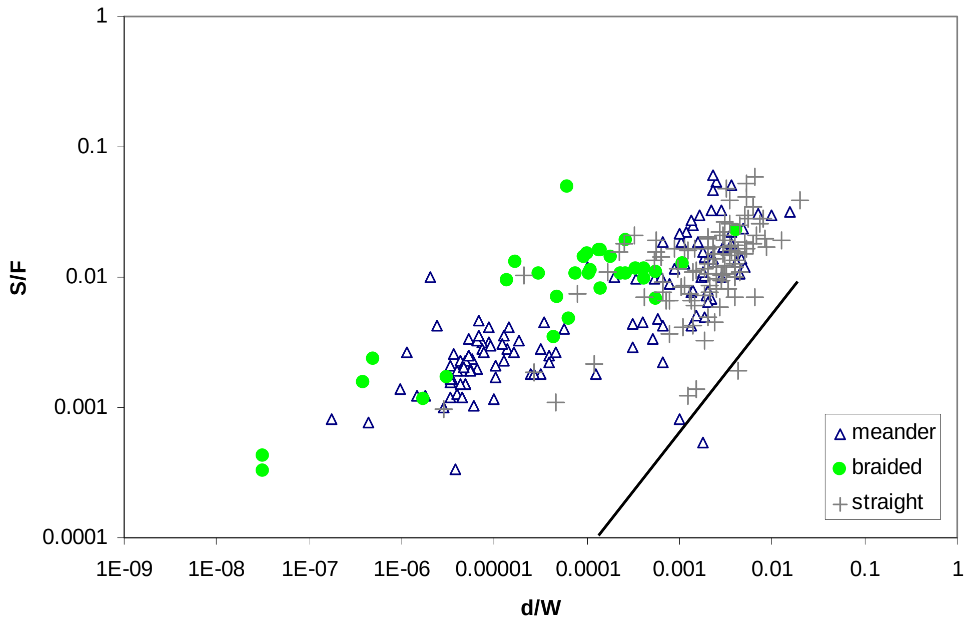


Figure 5.8: Diagram of Parker (1976).

Similarly, a suggestion by Parker (2008, pers com.) to affect separation of channel types, is to plot the dimensionless particle number:

$D^* = \dfrac{g^{1/3} D_{50}}{\nu^{2/3}}$ as a function of the dimensionless streampower:

$$P^* = \frac{g^{1/3} Q S_v}{\nu^{5/3}}$$

This latter approach achieved only separation by grainsize and not by channel type (results not shown). Finally in this section, some comment has to be made with respect to another popular approach introduced by van den Berg (1995) using unit power and grain size. From Fig. 5.1 there is a strong linear trend in grainsize within the *Q*-*S* framework which, in principle, supports an analysis based on streampower (*QS*) and grainsize. However, the actual analysis of van den Berg (1995) is flawed. Points used by van den Berg (1995) were artificially adjusted by using empirical hydraulic geometry equations to calculate channel width. Lewin and Brewer (2001) argued that such adjustment does not have any considered theoretical support and they showed using actual channel width that the approach of van den Berg (1995) does not work and is invalid. Consequently, the van den Berg model is not considered herein.

In summary, referring to Table 2.2, despite numerous attempts to produce combinations of controlling parameters as non-dimensional ratios, it is evident that most reasonably-successful approaches are based on the balance between the potential energy represented by valley slope and the kinetic energy as represented by a representative discharge, usually the bankfull value. Indeed, this balance underpins the popular analysis of Parker (1973) – Parkers's ratios *S/F* and *d/W* readily can be re-arranged to show the simple dependency of *S* on *Q*, i.e. Parker's analysis is a *QS* approach.

From the above discussion of extensive data sets, an approach using a *QS*-diagram with a traditional 'straight-line' discriminator alone would be meaningful in a quantitative sense only with respect to regional studies considering a small range of discharge values when the braiding occurrence is driven by one of two mechanisms: steep slope or sediment overloading, and the effects of the river size are not strong. So far *QS*-diagrams work satisfactorily for gravel-bed rivers where rivers are more prone to braid due to steep slopes (e.g. Bray, 1982) and less attention have been paid to braiding occurrence due to overloading, except for studies of particular river reaches (e.g. Coleman, 1969; Simpson and Smith, 2001). Although the control of sediment overloading might influence the position of any discriminator it is difficult to see that this would be system-scale dependent. Rather the importance of scale-dependent variation in the streampower threshold values for transition between meandering and multi-channel needs additional consideration especially in respect of small headwater streams and large, low-gradient rivers (see also Baker, 1978). Such an analysis goes beyond the perview of this thesis but a possible system-scale control on the discriminator is proposed below.

A key control on bank stability refered to throughout this thesis is vegetation cover. A clue to its importance is found in the trend of the aspect ratio (width/depth) on the *QS* diagram. Width scales with bankfull discharge whilst depth tends to scale with valley slope such that the trend surface has equivalue lines angled at 55° across the diagram (Fig. 5.9) with low values of *W/d* to the left of the diagram and vice versa. Numerous studies (Schumm, 2005) have demonstrated the effect of vegetation in constraining the value of *W/d* to smaller values compared to unvegetated systems. The influence of vegetation within this present study however are ambiguous indicating, for example, more rapid bank recession for grassed banks than for tree-covered banks in accord with studies such as Hey and Thorne (1986) but with low bank recession rates for unvegetated banks (Figs. 4.52 and 4.53). The complexity of the effect of vegetation on riverbank stability is a common throughout the literature (Schumm, 2005) and the variance reflects the strong influence of local factors, such as vegetation type. However, some commonalities emerge when individual river behaviour is considered. The majority of studies have shown that on individual rivers without vegetative bankcover, riverbank recession is more rapid than within those reaches where there is good cover (e.g. Beeson and Doyle, 1995). The study of Hey and Thorne (1986) demonstrates that for a given valley slope, channel widening occurs for a lower discharge where vegetation cover is less dense. Thus channel widening occurs at a lower value of streampower when vegetation is absent or less effective.

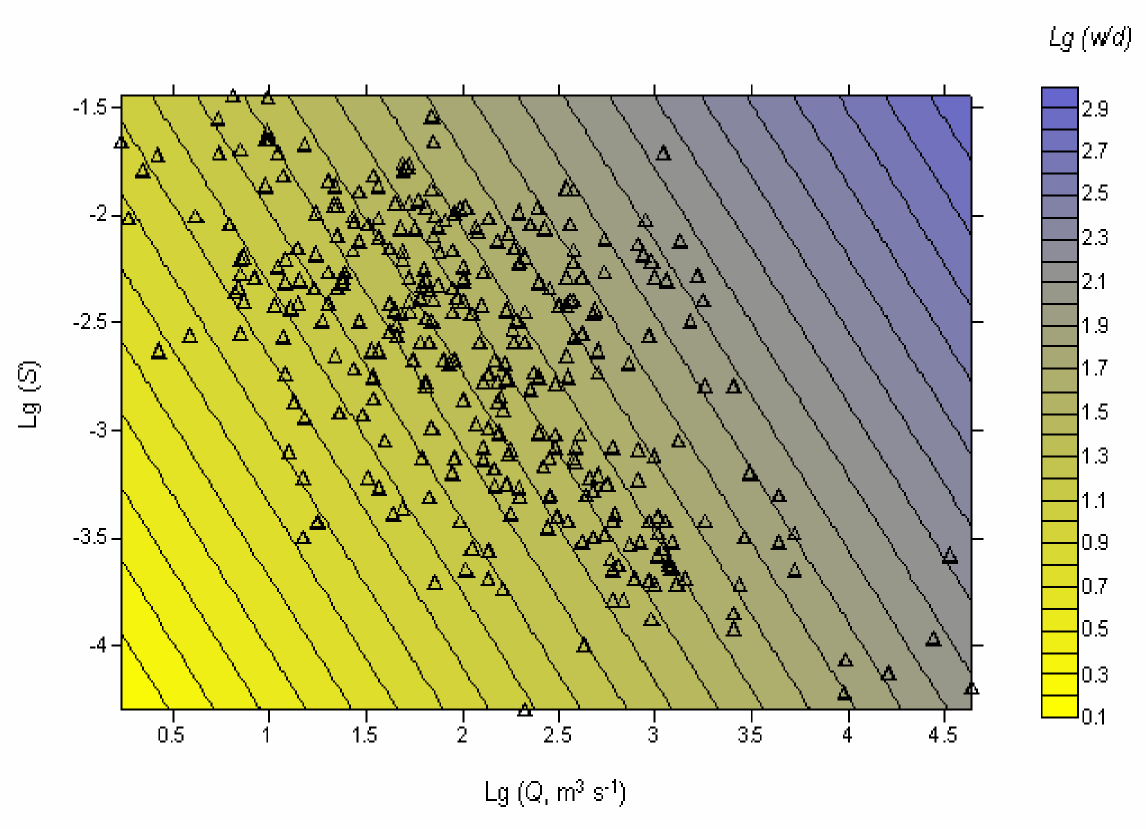


Figure 5.9: Trend surface of Lg (*W/d*) on *QS*-diagram.

Several small-scale flume studies were cited above as examples of experiments in which the transition from straight to meandering or meandering to braided could occur for smaller values of critical streampower than have been recorded for moderate sized rivers. Although there are scaling issues to be considered (e.g. Davies et al., 2003), numerous studies reviewed for example by Parker (1999) have shown qualitative dynamic similitude between experimental studies and natural conditions (see also Paola et al., 2009). Rather flume experiments usually have loose bank materials and transition from meandering to braided occurs at lower threshold power values than vegetated systems. Gran and Paola (2001) and Tal and Paola (2007) demonstrated this effectively; when vegetatation was added to a braidplain in a small flume the channel changed to a meandering habit and higher values of streampower were required to change from meandering to braided once the vegetation was present. Millar (2000) observed similar effects; when forest cover was removed from banks of a natural river, the river changed from meandering to a braided habit. Thus the absence of, or ineffectual presence of, vegetation in small systems might explain the low values of streampower required for transition and the low values of the exponent b in the regression equations relating Q and S for small systems in flume studies. The importance of vegetation in stabilizing riverbanks and stabilizing the threshold value for transition appears from the present study to possible become important when $Q > 10^2\ m^3\ s^{-1}$, above which value constant streampower induced by higher critical discharges is required to induce transition. To support this ascertion, in the case of a single catchment study, Abernethy and Rutherfurd (1998) noted that sub-aerial processes where important for erosion of exposed river banks in headwater catchments but that vegetation cover became increasingly important farther down the system to stabilize the banks as streampower increased (Lawler, 1992) and bank sediments became finer. In distal portions of the river system, river banks were of a height that much of the bank profile was below rooting depth. Root complexes on the bank top enhance soil strength, but rooting depth is rarely greater than 1.0m (Jackson et al., 1996; Sun et al., 1997; Tufekcioglu et al., 1999) and the exposed bank profile below this soil thickness is often unvegetated with no protection from erosion (Simon and Collison, 2002). Under these conditions the bare banks in downstream locations failed more so than any vegetated banks further up the system (Abernethy and Rutherfurd, 1998). This latter study demonstrates the system-scale complexity of the effect of vegetation on bank stability compounded by the system-scale trends in streampower (Lawler, 1992). The largest rivers of the world, often have high river banks (e.g 8 m to 20 m) but there are insufficient studies of the effects of vegetation on bank stability for these large systems to deduce if the threshold for channel change occurs at a lower value of streampower. There is insufficient high discharge:low valley-slope data within Fig. 5.4 to suggest such an effect, although there is some suggestion that sinuosity might decrease for these large rivers at lower threshold streampower for systems with $Q > 10^3$ m^3 s^{-1} (Fig. 5.6).

5.2. BANK EROSION RATE AND CHANNEL TYPES

From the results of the ordinal data analysis there is a close association between bank erosion rate and the main channel types. The association is not strong when the anabranched type is included in the analysis but when considering the classical channel types alone (after Leopold and Wolman, 1957), i.e. by omitting the anabranched type, the association becomes more robust with an association coefficient of 0.65 (see section 4.2.1). Perhaps this result is explained by the fact that anabranching systems may include braided, meandering and straight types of channels for particular branches and consequently may display the different character of lateral activity associated with the classic types. From the association values the following order by lateral activity is revealed: braided, meandering, anabranched and straight, i.e. from the most active to the least active. Such an order is obtained on the basis of the cumulative curves distribution for different channel types (see Fig. 4.7).

Another important result is that there are features of meandering channel form such as the presence of bars and width uniformity, which indicate channel lateral activity. This result is derived from an analysis for subtypes of meandering rivers. The presence of bars and width uniformity were pointed out to be qualitatively important in channel activity estimation by Brice (1982) and herein this idea has received support by quantitative statistical analysis (see Goodman and Kruskal γ values in Fig. 5.10 and in the ‘Results’ section, Fig. 4.10). By assuming that these channel features might very-well indicate lateral activity in ‘straight’ and braided channels as well, a classification is proposed and presented in Fig. 5.10. The assumption is made, as at this stage, that there are not enough data for subtypes of straight and braided rivers to make a meaningful statistical analysis but with adequate data the Brice classification could be further tested by robust statistical methods as used herein.

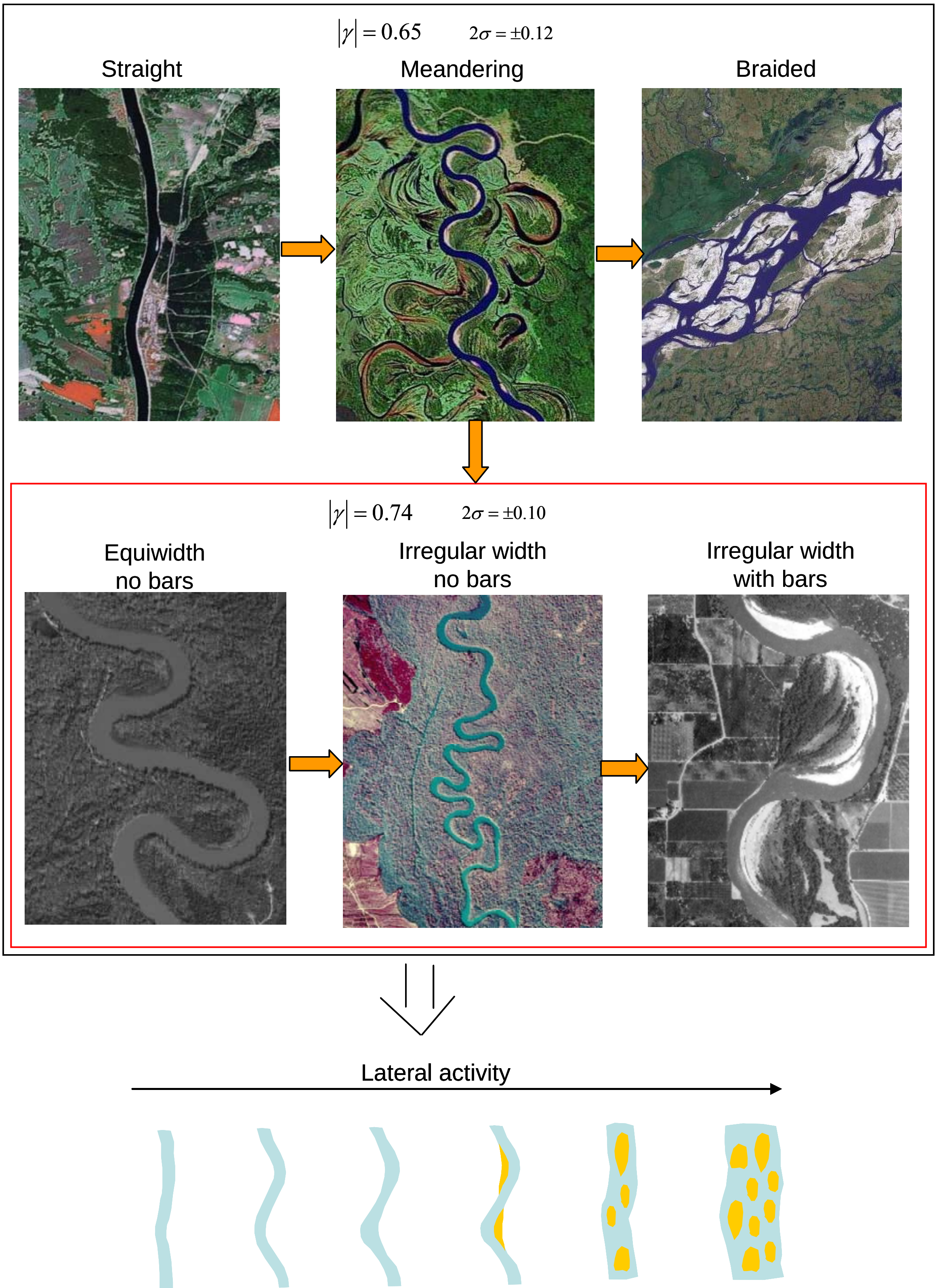


Figure 5.10: A proposed classification of channel types by lateral activity.

Goodman and Kruskal γ values noted above are statistically significant

(see section 4.2.1)

Pictures from Google Earth and Lagasse et al. (2004)

The proposed classification (Fig. 5.10) is based on an analysis of absolute bank erosion rates and the most laterally active channels from this analysis are braided channels. However, when relative bank erosion rates are under consideration, the most laterally active channels are meandering channels (see Fig. 4.12). Overall, channel type and features of channel form may be used to estimate lateral activity. Therefore, maps and air photographs of river reaches with information about (i) channel types and (ii) channel features are valuable when choosing a location of a pipeline crossing.

Another implication of the analysis is that a widely accepted "rule-of-thumb" for river managers does not work. The axiom states that a meandering channel migrates at about 1% of channel width per year. This axiom is common, especially in the USA (Walker and Rutherfurd, 1999). However, results for 1% of channel width per year values of exceedance are more than 50% for all channel types with maximum for meandering channels (76% of cases) (see Fig. 4.14). Consequently, a river manager should be cautious of simply applying the "rule-of-thumb", as in most cases a river is more active than is supposed by the rule.

5.3. BANK EROSION RATE RELATIONSHIPS

There is a strong correlation between bank erosion and the size of rivers (catchment area) and with the geometry of channels, but no strong correlation with the driving characteristics (discharge, sediment transport, shear stress, velocity). Taking into account that there is a weak correlation with water discharge and no correlation with flow variability (C_v), one could conclude that with changes of these variables due to climate change it is unlikely that bank erosion rates will be changed significantly in the near future.

At the scale of the catchment, the closest correlation is obtained between bank erosion rate and drainage area. Although the relationship between bank erosion rate and water discharge is positive, there is a bigger point scatter than in the relationship with drainage area. Perhaps this result is dictated by the fact that drainage area can be measured fairly precisely using planimetry, while for water discharge, even for the same measure of discharge, such as bankfull discharge, measurements and calculations can be made by different methods (e.g. Williams, 1978) which introduce uncertainty when data are combined from various studies. Taking into account the obtained weak relationship between bank erosion rate and water discharge, an engineer should be cautious of applying statistical generic relationships for any particular site. For example, Evans et al. (2003) have used the fixed power 0.6 in an empirically derived relationship by Rutherfurd (2000) between bank erosion rate and water discharge. Evans et al. (2003) studied sediment loads generated by streambank erosion for twenty-eight watersheds in Pennsylvania. They concluded that the applied statistical model performed very well. However, this conclusion is dictated by the model having an statistically adjusted coefficient. For watersheds in Pennsylvania the range of the coefficient is across orders of magnitude from 0.00001 to 0.00068. These values are significantly lower than that derived for data from around the world reflecting only the chosen value of the fixed power. One can wrongly conclude from the derived coefficients that apply to the Pennsylvanian examples that bank erosion rates are lower than elsewhere. Therefore, investigators and river managers should be cautious of applying statistical relationships with fixed power value in the equations as this procedure can lead to misinterpretation of other resulting parameters. It should be always be kept in mind that statistical treatment is a generalization of available data. This caution should be applied not only for the relationship with water discharge but for all relationships obtained in this study. Another important result at the catchment scale reveals that there is no correlation between bank erosion rate and bed-load sediment transport (see Fig. 4.21). Therefore, such classification of channel types as that of Schumm (1985) where types associated with sediment transport and channel stability, should be considered on a basis probably of the vertical stability rather than lateral stability. Another implication of that result (i.e. Fig.4.21) is that perhaps suspended load might better represents lateral channel activity than bed load transport in an assumption that eroded fine material from banks are transported preferentially in suspension rather than as bed load. However, this speculation was not possible to check in this study due to data absence for suspended load transport.

At the scale of the river reach, overall the best predictor is the channel width, as was noted by Nanson and Hickin (1986). This characteristic is an indicator of the channel geometry and is less affected by water level changes as is the channel depth. Moreover, the channel width can be derived directly from maps and air photographs and therefore it is the most useful characteristic in lateral activity estimation. In the scatterplot of bank erosion rate and channel width (Fig. 4.25), points for 'straight' channels with widths narrower than c. 20 metres are located below the regression line. This result means that narrow, 'straight' channels have lower bank erosion rate than others channel types. In addition the erosion rates for 'straight' channels less than 10m wide are very low ($<0.1 m\ s^{-1}$) but the data points are few. This indicates clearly that erosion rates for 'straight' channels of low width are small but, as a rider, it should be noted that investigators rarely select straight channels for investigation of erosion rates and so the data sets are biased against small straight channels. These result for 'straight' channels are more general than a regional study by Beechie et al. (2006) for forested mountain rivers. They found that there is a threshold channel width (15-20 m) below which rivers show non-migrating behaviour (laterally stable), whereas channels wider than 20 m are migrating. Beechie et al. (2006) explained this threshold on the basis of interrelationship of channel size and riparian vegetation: when a river is narrow and shallow, it does not have enough erosive force to erode banks as the channel depth is less than the rooting depth; when a river becomes deep enough (channel depth exceeds the rooting depth) it would erode banks beneath the roots. Beechie et al. (2006) concluded that when a river becomes deep enough to erode its banks, it has a threshold width of 15-20 m. This explanation can be applied for small rivers with forested floodplains. For other small rivers, larger grain size, confinement by valley walls in upper parts of river systems and a small amount of supplied water all favour a high resistance force and insufficient erosive force as to result in low rates of migration.

5.4. CONCLUSIONS AND RECOMMENDATIONS

From the review and discussion section a novel issue is recognised that in equation 2.1 the exponent may depend upon the river scale. It is found that an explanation for this behaviour is possibly related to the balance between potential and kinetic energy distribution of stream power along a conceptual river mediated by grainsize and vegetation trends down system. Also it is concluded that in the near future (engineering time) it is unlikely that a river will change its channel type and it not expected that bank erosion rates will be accelerated noticeably due to climate change. The results of statistical examinations for bank erosion rate can be used as approximations to estimate lateral activity at a proposed site of a pipeline crossing.

The following list of recommendations from the results is derived which could be used by engineers:

1. select relatively straight river reaches. In results of ordinal regression the straight sections are the most laterally inactive (see section 4.2.1 and Fig. 5.10);
2. in meandering rivers select sites at the bend inflection, not nearby to a possible cutoff. This recommendation is based on review of schemes of meander evolutions (see section 2.4.1.3);

3. consider meandering subtypes as meandering channels with bars are characterized more active than channels without bars. The recommendation is derived from ordinal regression analysis for meandering subtypes (see section 4.2.1 and Fig. 5.10)
4. in braided rivers select sites with fewer bars and uniform channel width. As the previous recommendation is based on ordinal regression and supposition of analogy with meandering rivers (see section 5.2);
5. use the cumulative curves (Figures 4.7; 4.10; 4.14 and 4.17; Tables 4.2; 4.3; 4.4; 4.5) to estimate bank erosion rates for different channel types, but be aware that it is a rough estimation;
6. select sites where valley form is relatively straight. This recommendation is based on review of anabranched rivers and Table 2.6 (see section 2.4.3.1);
7. select sites with low, flat banks as high, steep banks are a reliable sign of lateral movement of channel in these reaches (see Fig. 4.57)
8. select sites with narrower floodplains (see Fig. 4.28);
9. use the relationships with channel width (Figs 4.24; 4.25; Table 4.9) for rough estimation of bank erosion rate;

In conclusion it should be noted that at this stage of study it is difficult to analyse and derive scientific-based recommendation for multiple channels and large rivers and the main reason for that situation is limited available data for processing. Therefore, one of the way is to concentrate efforts for more thorough research for multiple channels and large rivers.

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APPENDIX

Database for bank erosion rate

References for database of bank erosion rate

See accompanying CD