Review on Biogeomorphology in Rivers: Processes and Scales

M.J. Baptist
Delft University of Technology, the Netherlands
WL | Delft Hydraulics, the Netherlands

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ABSTRACT: This literature review discusses the influence of biogeomorphological processes at different spatio-temporal scales for fluvial systems. It uses a hierarchical classification to describe these processes.

1. INTRODUCTION

The management of rivers in the Netherlands changes from fixing and stabilising the river system to letting go the natural processes. The aim is to restore the former dynamic conditions, in order to get a sustainable and more diverse river system. One of the challenges of river restoration is to redesign the floodplains in such a way that it will synergistically strengthen the functions of safety against flooding and natural diversity. The main problem here is that the hydraulic roughness of vegetation in combination with sedimentation in floodplains decreases the required discharge capacity. Therefore, a new management approach is proposed in which rejuvenation of landscape elements will clear the way for discharge of water and simultaneously will maintain the systems diversity.

This new approach requires understanding of the interaction between the biotic and abiotic components of river systems. This review therefore provides a literature review on the interaction between organisms and geomorphological factors, i.e. *biogeomorphology*. This review emphasises on processes and scales and describes biogeomorphological processes for different scales.

2. TEMPORAL AND SPATIAL SCALES FOR RIVER SYSTEMS

Geomorphological processes occur for time scales ranging from microseconds, which are relevant for turbulence velocities, up to hundreds millions of years for geological processes. The spatial scales are similarly wide, from millimetres for capillary flows in sediments up to the continental and global scales. Scale refers in this review to the spatial or temporal dimension of an object or process (Turner et al., 1989). Kirkby (1990) presents an example for the wide variety in scales for river systems, see Figure 1.

One way to deal with the spatial and temporal scales of patterns and processes of fluvial systems is to describe these in terms of a hierarchy of scales. Roughly speaking, spatial and temporal scale levels are coupled, in that small-scale phenomena are associated with small-scale processes, and large-scale phenomena with large-scale processes, or with small-scale processes that are coherent over a large scale (De Vriend, 2000).

A hierarchical classification for linked processes at multiple scales is a common method to cope with scale linkage problems of landscapes (Klijn, 1997). For river basins these hierarchical classifications have also been made. Naiman et al. (1992) and Townsend (1996) give an overview of various hierarchical approaches for stream and catchment classification. One of the most useful approaches is the classification of Frissell et al. (1986). They present a framework for hierarchical classification of streams and stream habitats. In this framework, streams and their watershed environments are classified within the context of geomorphic features and events, and spatio-temporal boundaries are identified. Frissell et al. distinguish between the *stream system*, *segment system*, *reach system*, *pool/riffle system* and the *microhabitat system*, see Figure 2.

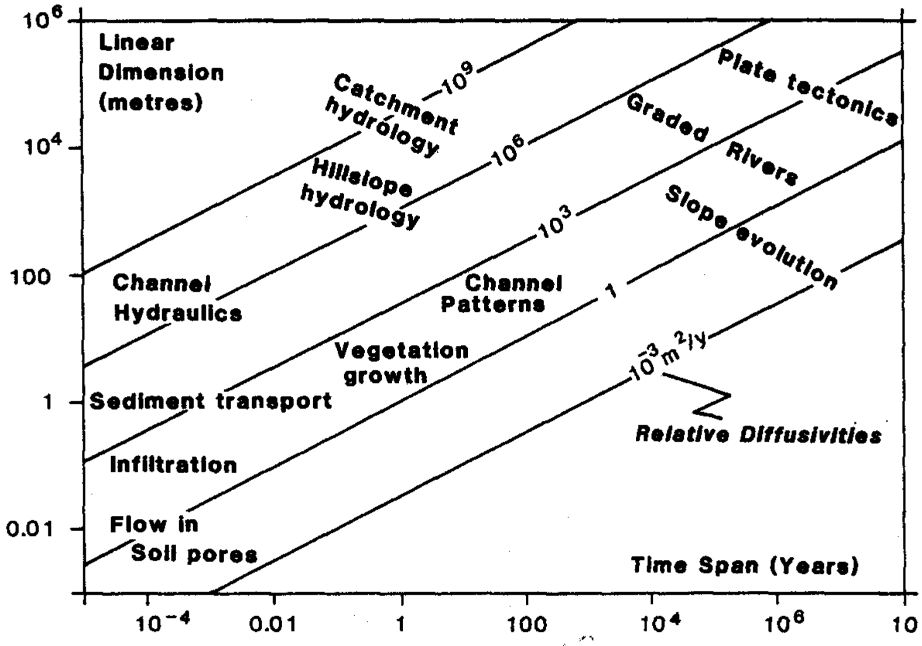

Figure 1. Temporal and spatial scales for river systems, from Kirkby (1990).

According to Naiman et al. (1992) advantages of the classification by Frissell et al. are that it is useful at several scales, it is highly adaptable and it can describe both temporally stable (e.g. valley segment) and temporally unstable units (e.g. dynamic stream types). However, it must be noted that the scale hierarchy concept may hold for a single river basin, but probably not between basins. In other words: one cannot transfer a hierarchy from one basin to another without adjusting the overall scale (De Vriend, pers. comm.).

System analysis may provide valuable insight in the functioning of scaled systems. O'Neill et al., 1989 present a framework for the analysis of scale in landscapes based on what they think are three basic properties of scaled systems, i.e. *hierarchical structuring*, *disequilibrium* and *metastability*. Firstly, hierarchical structuring implies that a biological system has an upper constraint defined by environmental limits and a lower constraint defined by biotic potential. The consequence is that it is easier to state that a certain system falls within the envelope of constraints, than to state the exact location of any system within the envelope. O'Neill et al. secondly propose that some constraints can form attractors toward which the ecological system will move through time. They try to find evidence from thermodynamic principles applied on microbial cultures, but this is still far away from landscapes. Thirdly, they state that ecosystems are metastable. A stability analysis of dynamical systems points out that systems may drastically change from one stable state to another. This metastability is found in several ecosystems and may well apply to landscapes.

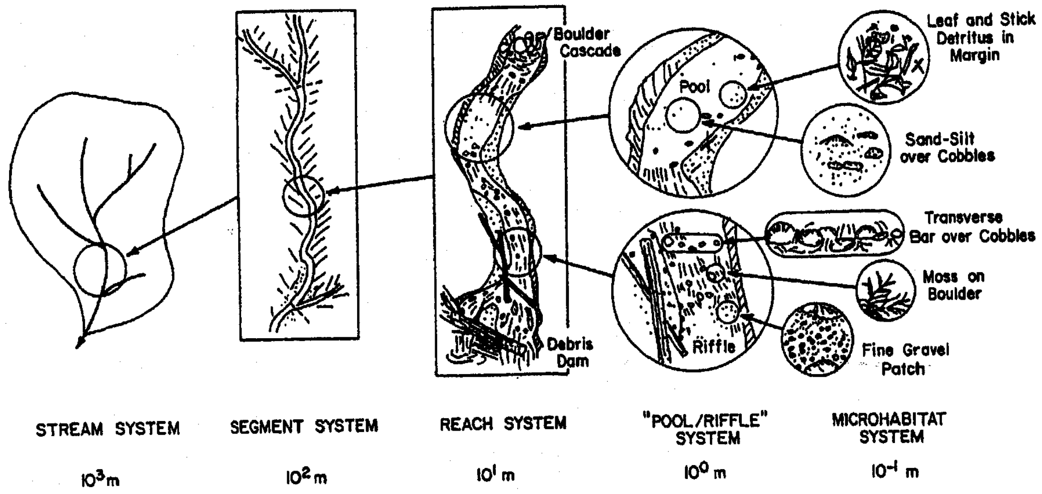

Figure 2. Hierarchical organisation of a stream system, from Frissell et al. (1986)

Phillips (1995) applies four quantitative approaches for scale interactions in biogeomorphology. The first one is the *'transient form ratio'*, the ratio between mean relaxation time and mean recurrence time. For floodplain vegetation, the relaxation time may stand for the time it takes for succession to restore the pre-disturbance vegetation community and the recurrence time may stand for the interval of recurrent geomorphic disturbances. When the ratio is larger than one, frequent rejuvenation occurs before a climax stage is reached. A second approach is the *'information criterion'*. This is actually the Courant-Friedrichs-Lewy criterion that is used in numerical modelling. The basis of this theory is that information is not transferred through space faster than through time. The application in biogeomorphology gives an indication when geomorphic and ecological responses should be examined together or when one can be treated as boundary condition for the other. A third approach is the *'abstracted earth surface system'*. This approach is based on the description of the dynamical earth surface system into a description of known processes, the abstracted system and unknown processes, the omitted system, both in the form of matrices. It can be shown that when the elements of both systems differ an order of magnitude, both systems can be treated independently. Applying this approach in biogeomorphology suggests that where geomorphic and vegetation responses occur at rates that differ by an order of magnitude or more, they may be treated independently. The fourth approach is based on *changes, perturbations and stability*. It deals with a comparison of the duration of a perturbation in boundary conditions in relation to the duration of change of the system for both short and long-term perturbations.

3. BIOGEOMORPHOLOGICAL INTERACTIONS

Hierarchical classification

Biogeomorphological processes can be found at several scale levels, some more and others less dominant. This review discusses the influence of biogeomorphological processes at different spatio-temporal scales for fluvial systems. It uses a hierarchical classification to describe these processes in fluvial systems. The hierarchical classification scheme of Frissell et al. (1986) is used as a basis for this review. This classification is slightly revised, because their classification is oriented toward small mountain streams in forested environments, whereas this review focuses on river systems such as the Rhine and the Meuse. The revised classification is based on Klijn (1997) and Rademakers & Wolfert (1994). The classes of Frissell et al. are changed into a more generic framework of hierarchical ecosystem classification. The hierarchical scales used here are the *river basin scale*, *segment scale*, *reach scale*, *ecotope scale* and *eco-element scale*.

River basin scale

On the scale of the entire river basin, for an idealised river, Schumm (1977) distinguishes three zones in terms of the overall water and sediment balance. These zones are the *production zone*, the *transfer zone* and the *deposition zone*. The production zone is the uppermost zone from which water and sediment are derived. This zone is primarily eroding. Downstream from the drainage basin lies the transfer zone in which the sediment input equals the sediment output. Eventually the sediment is deposited in the deposition zone (Schumm, 1977), Figure 3.

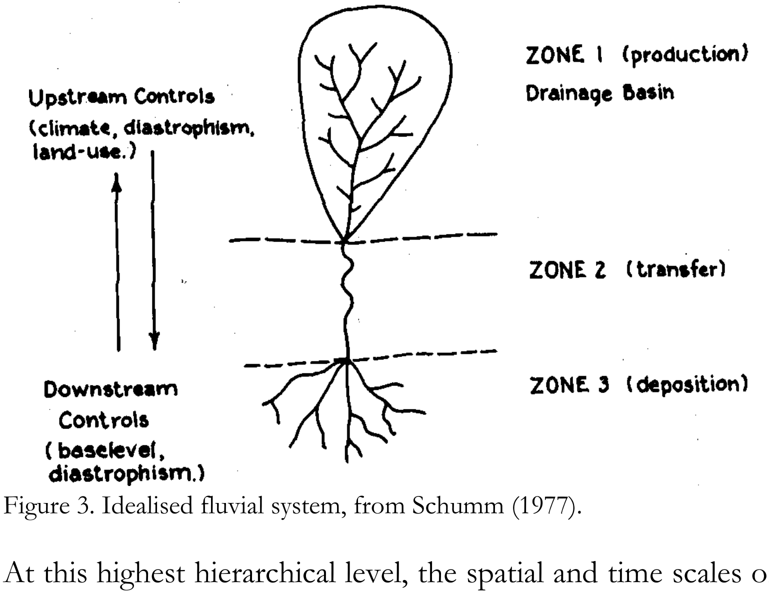

Figure 3. Idealised fluvial system, from Schumm (1977).

At this highest hierarchical level, the spatial and time scales of the developmental processes and patterns are very large, ranging from hundreds to ten thousands of kilometres and thousands to hundreds of thousands of years. The initial conditions for present-day river processes are provided by the environmental changes in the Late

Quaternary, i.e., the last 125,000 years of Earth history (Thorne et al., 1997). Dominant processes for the development and physical characteristics are tectonic movements, climatic change and sea level changes. Typical indicators for classification are the biogeoclimatic region, the slope and shape of the longitudinal profile and the drainage network structure (Frissell et al., 1986).

However the processes on the time and spatial scales of the river basin are associated with the geologic history, biogeomorphological processes are relevant. During the Pleistocene glacial periods, for instance, reduced vegetation cover increased runoff and sediment supply to rivers, consequently leading to widespread valley floor aggradation (Thorne et al., 1997). Another example is that of deforestation in the last 5,000 years of human land use, which has had a considerable influence on river channel evolution at the basin scale. It has been accepted that changes in vegetation cover have a significant influence upon hydrology of the geologic past (Gregory & Gurnell, 1988).

Segment scale

A river segment is a portion of the river basin delineated by major topographic discontinuities in the structure of the bed, slope, river discharge and sediment quantities. At this hierarchical level, the spatial and temporal scales of the evolutionary processes and patterns are large. Characteristic dimensions for river segments are lengths of hundreds to one thousand kilometres. Within segments, channel planforms can be defined. These planforms remain in a dynamic equilibrium for hundreds to thousands of years (Frissell et al., 1986; Rademakers & Wolfert, 1994; Gregory et al., 1991).

The development of a specific type of river planform is dependent on abiotic parameters, such as discharge, slope, median grain size, stream power, and width/depth ratio, but also on the biotic factor of vegetation cover. The channel planform of alluvial river segments can be classified into four main types, viz. those with straight, meandering, braided or anabranching planforms, but within each type there is a range of morphologic characteristics. Thorne et al. (1997) provide many classification schemes and figures from literature.

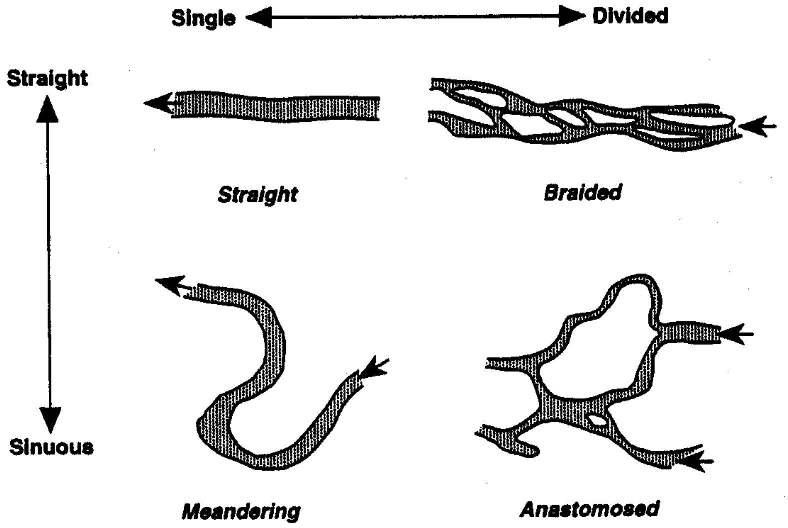

Figure 4. Classification of channel pattern, from Thorne et al. (1997).

For floodplain classification of alluvial channels, the genetic classification of floodplains by Nanson & Croke (1992) is a basic piece of literature. They recognise three main classes of floodplains: high-energy non-cohesive, medium-energy non-cohesive and low-energy cohesive. These three classes are further subdivided into thirteen suborders based on nine factors. These nine factors are all geomorphic or fluvial factors, so any influence of organisms on floodplain forms is not taken into account.

Other authors state that indeed vegetation affects channel patterns and characteristics on the segment scale (>15.000 years). Developments in vegetation cover, for example due to climate change, can alter river runoff and the relation between resisting power and stream power and therefore change the channel pattern (Starkel, 1990), see Figure 5.

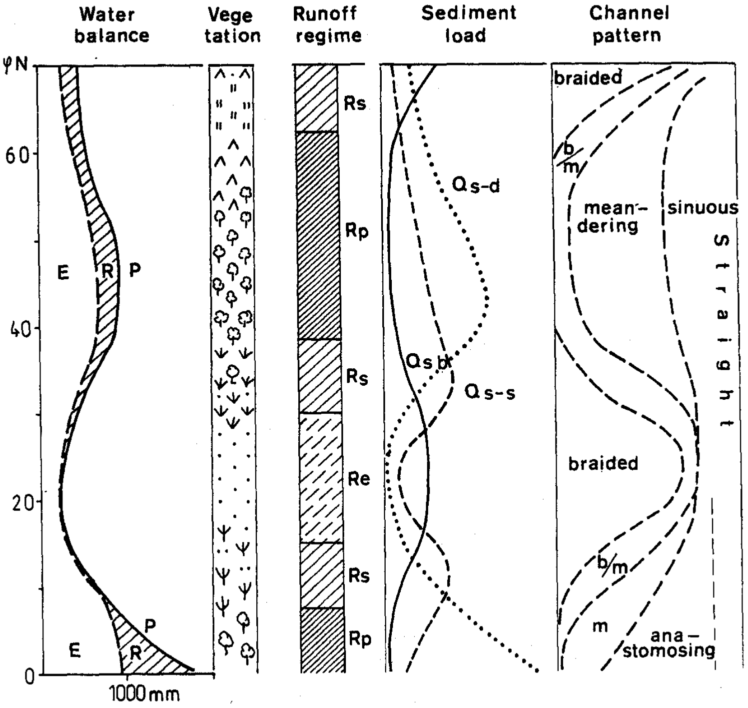

Figure 5. Changes of elements of fluvial systems in N-S transect Europe-Africa, from Starkel (1990).

An interesting biogeomorphologic feature in the history of channel classification is the presence of vegetated islands in anabranching rivers. Leopold and Wolman (1957) originally described three classes of river channels, i.e. straight, meandering and braided. In early definitions, braided channels were single-channel, bed-load rivers that, at low water, have relatively mobile emerged shoals, or more resistant *vegetated* islands exposed in the channels. The development of vegetated or otherwise stable alluvial islands was seen as a particularly intense form of braiding. More recent research led to the idea that anabranching channels are a specific feature of low-energy fluvial systems and therefore anabranching rivers are now generally accepted as a fourth distinct channel planform type (Nanson & Knighton, 1996). Tooth & Nanson (1999) provide a comprehensive description of the characteristics of anabranching rivers and state that vegetation plays a key role in the initiation, survival and growth of depositional forms through its influence on flow and sediment transport.

Reach scale

The river reach is defined as a length of a river segment lying between breaks in channel slope, local side slopes, valley floor width, vegetation and / or bank material (Frissell et al., 1986). The river reach is primarily defined on the basis of *longitudinal* characteristics or gradients. At the hierarchical level of river reaches, spatial and time scales of the developmental processes and patterns are smaller than for river segments. Channel characteristics for river reaches range from one to hundreds of kilometres and typical time scales of development range from tens to hundreds of years. This means that the developmental processes in rivers get close to the specific time scales for ecological developments such as tree growth.

An important ecological concept on the functioning of streams that can be applied to the reach scale is the River Continuum Concept of Vannote et al. (1980), see Figure 6. Vannote et al. couple the macrofauna communities found in different reach sections to the dynamic physical conditions in the channel.

Biogeomorphologic interaction becomes stronger on this hierarchical level. Effects on river channel process by influencing the channel roughness can be due either to over-channel vegetation, viz. the vegetation that occurs alongside the channel including riparian growth, and the within-channel vegetation (Gregory & Gurnell, 1988). The riparian zone is defined as that part of the biosphere supported by and including recent fluvial landforms and is inundated or saturated by the bankfull discharge (Hupp & Osterkamp, 1996). Together with the within-channel vegetation they have considerable impact on the hydraulic roughness and the transport of sediment.

A biogeomorphological process on the scale of river reaches is an increased bank resistance to erosion due to vegetation cover, which frustrates meandering. Tree-lined channels are deeper and narrower and therefore have a lower width-depth ratio than channels with grassland on their banks (Gregory & Gurnell, 1988). The ratio of the rooting depth of vegetation versus channel depth also plays a role. It is argued that in small channels rooting depths of grass sods are a significant proportion of the channel depth so that grass-lined channels may be narrow. In larger channels grass rooting depths are very small in relation to the channel depth and hence grassed channels have a high width-depth ratio (Gregory & Gurnell, 1988). Prosser et al. (1995) executed experiments on overland flow in flumes placed on natural grasslands. They concluded that most of the shear stress is exerted on the stems of the plants and that the bottom shear stress is below the critical shear stress for erosion. Rates of erosion were very low for vegetated parts. Even after full clipping of the plant stems, Prosser et al. found that the cohesive root mat prevented further erosion. In general, differences in channel form under different types of vegetation are caused mainly by relative disturbance of the vegetation above the ground, rather than by differences in shear strength resulting from different root systems (Gregory & Gurnell, 1988). Thornes (1990) describes a basic model for the competition between erosion and vegetation growth using simple differential equations.

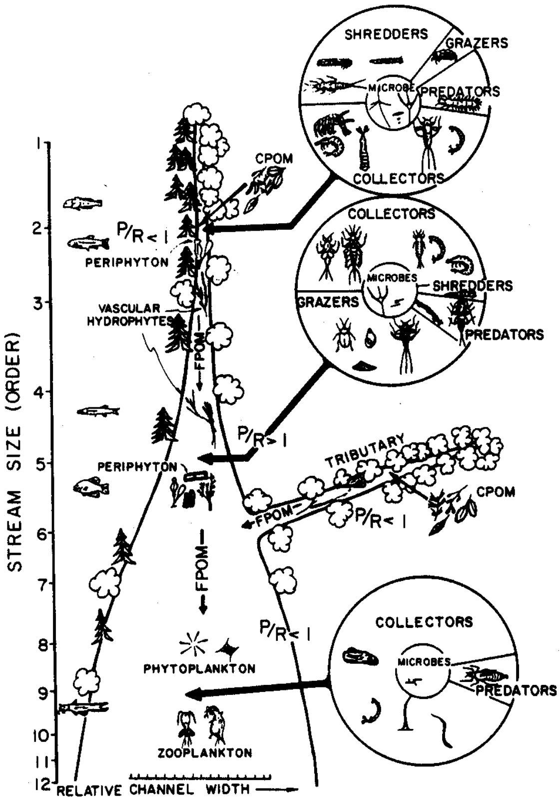

Figure 6. River Continuum Concept, from Vannote et al, 1980.

Vegetation affects erosion and bank retreat in three ways (Abernethy & Rutherford, 1998): *subaerial preparation*, *fluvial entrainment* and *mass failure*. The dominance of each of these processes varies with channel-scale changes going downstream. Subaerial preparation is the transport of bank sediment to the flow via windthrown trees that divert the flow direction. This effect is mostly present in the upper parts of (wooded) streams. Erosion as a result of fluvial entrainment is reduced by vegetation because of the increased hydraulic resistance. The reduction of flow erosivity by vegetation is largest in mid-basin reaches where mean streampower peaks. Mass failure is hindered by increased bank-substrate strength due to the presence of roots. This mainly is present in floodplain reaches of downstream parts.

In their review of articles that deal with the geomorphic effects of cattle grazing, Trimble & Mendel (1995) explore the field of *zoogeomorphology* of riparian zones. Cow grazing reduces vegetation cover and density and thus decreases erosional resistance and exposes more vulnerable substrate. The tramping of their hoofs breaks riverbanks and thus increases hydraulic roughness, which accelerates bank erosion. Together, these impacts lead to a direct and indirect modification of stream channels, see Figure 7.

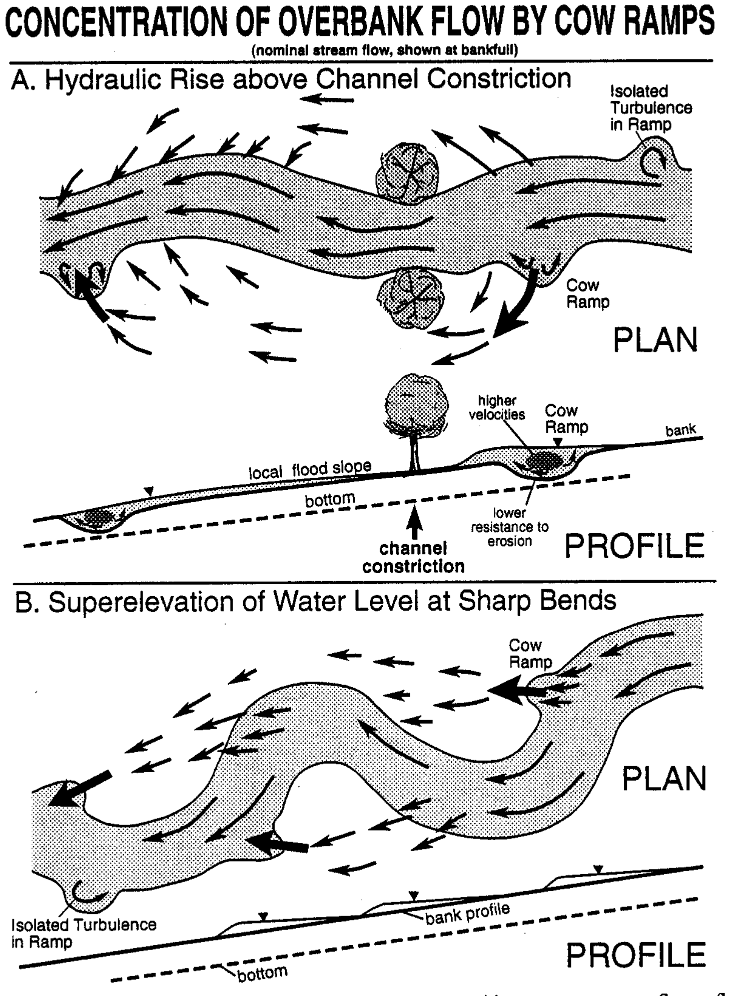

Figure 7. Concentration of overbank flow by cow ramps, from Trimble & Mendel (1995)

Ecotope scale

A river ecotope is a subsystem of a reach determined by bed topography, water depth and velocity and position relative to the main channel (Frissell et al., 1986). The definition of a river ecotope is mainly based on *lateral* gradients within a river reach. At the hierarchical level of river ecotopes, spatial and temporal scales of processes and pattern development are small. Characteristic ecotopes range from tens of metres to one kilometre and typical time scales of development range from one to tens of years. Biogeomorphologic influence on the ecotope scale is therefore high.

Log and debris dams

Perhaps the most significant way in which morphology is influenced by vegetation is through the development of log and debris dams. This will mainly occur in small streams of woody areas (Gregory & Gurnell, 1988; Gregory 1992). Coarse woody debris affects the morphology of streams and creates dams, pools, rapids and embayments and therefore a more diverse environment with an uneven topography that favours a high floral and faunal diversity (Brown, 1997). The transport and storage of sediments and organic material is affected by woody debris and together with the creation of a range of habitats this will positively affect the biodiversity of streams (Gurnell & Gregory, 1995). Windthrow is a process that is also common in floodplains due to the limited rooting depth and structural soil weakness, caused by the layered character of the soil (Brown, 1997).

Vegetation

The distribution of plant species and communities on the ecotope scale is a reflection of the characteristics of the physical environment and the biological relationships. Gurnell (1997) sums up the physical factors that are relevant to the distribution of vegetation: the degree and frequency of waterlogging, the energy and frequency of flooding, substrate composition, soil and river quality, the character and organic content of sediments and the rate of sedimentation or erosion. In addition to these physical factors, biological factors play a role, such as the ability to compete with other species, and stages of vegetation colonisation and succession. In assessing the effects of hydro- and geomorphology on vegetation it is important to realise that the hydrological regime may affect vegetation germination of (floating) seeds and that flood discharges can scour away seedlings (Gregory & Gurnell, 1988). The timing of these events is therefore very important for the start and further succession of vegetative growth, as Johnson (1998) found in the Platte River. Gurnell (1997) concludes that the above mentioned interactions can lead to patterns in the vegetation that can reveal the nature and relative importance of hydrogeomorphological processes.

The riparian interaction between land and water is large. Gregory et al. (1991) provide an overview of riparian interactions from an ecosystem perspective. They mention the influence of shading by overhanging leaves, the inputs of dissolved nutrients and terrestrial particulates, retention of organic and inorganic material, processing of organic matter and the abundance of primary producers and aquatic invertebrates and vertebrates. They conclude that within river valleys water, nutrients, sediment, particulate organic matter are transferred not only downstream, but also laterally. Furthermore, organisms can be transported, or transport themselves downstream and even upstream. By these processes, riparian zones are very important for river ecosystems.

In the review paper of Goodwin et al. (1997) the importance of hydro- and geomorphic processes on riparian vegetation is stressed.

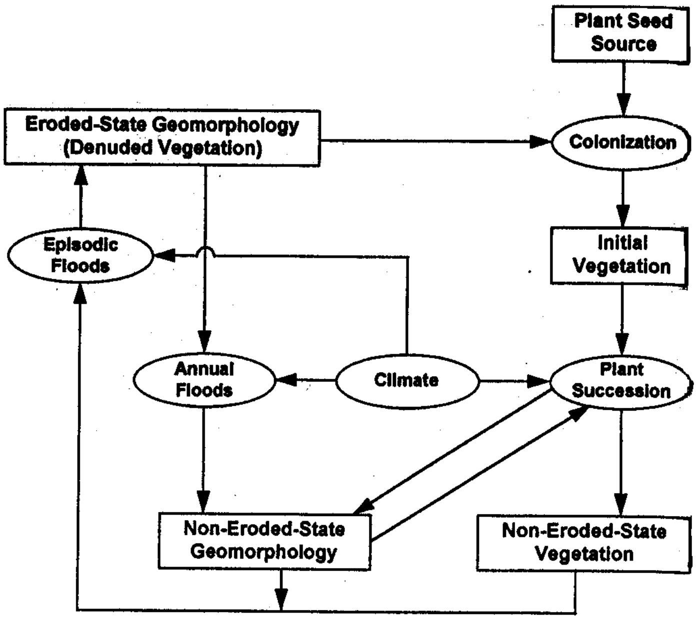

Figure 8. Interaction of fluvial and ecological processes, from Goodwin et al. (1997).

Floodplain forests

Piégay (1997) studied the interaction between floodplain forests and overbank flow in French rivers. Floodplain forests are able to laterally reduce the water level due to the hydraulic resistance of the biological structures, whether they are dead (coarse woody debris) or alive. Piegay even found an extreme slope in water level of 2.2% perpendicular to the flow direction. Within the floodplain forest, variations in energy and direction of flow induces a patchwork of morphosedimentary and vegetation units. He concluded that biogeomorphology is influenced by overbank flows, which in turn are affected by topography, hydraulic roughness and the supply and orientation of coarse woody debris.

Sediment transport

There is less research on the effects of vegetation on sediment transport than on the effects of vegetation on flow, although the processes behind sediment transport rely heavily on flow. Recent experimental work is carried out by Abt et al. (1994). They tested sediment entrapment and retention potential in an experimental, meandering stream system as a function of discharge and vegetative blade length, using submerged plants (primarily Kentucky bluegrass). Abt et al. distinguish between deposition enhancement and sediment retention. They observed that the sediment deposition was inversely related to blade length. This effect was attributed to the characteristics of the blades; the shorter blades were stiff, the medium-sized blades were oscillating in the flow and the longest blades flattened to the bed and thus preventing sediment to deposit. The retention of sediment was largest for the longer blades, due to the same phenomenon that these armour the deposited sediments. Finally, the sediment gradation was measured and it was found that the fines were transported through the system and that the larger grain sizes were transported as a bed-load and entrapped inside the vegetation, resulting in a doubling of medium grain size.

A mathematical analysis of the turbulent flow around cylinders was carried out by Li & Shen (1973). They specifically analysed the mean drag coefficient for multiple cylinders distributed in a given pattern. In addition Li & Shen used the Shield's sediment transport equation to calculate the sediment transport rate for parallel and staggered patterns. They concluded that staggered patterns are more effective in reducing flow rate and sediment transport than parallel patterns. Staggered patterns have a mean drag coefficient that is close to 1.3 for a low density of cylinders and 1.2 for a high density. Parallel patterns show a much broader range of close to 0.65 for a low density to 1.2 for a high density.

Combined mathematical and experimental Japanese research includes Nakagawa et al. (1992) and Tsujimoto (1999). In Nakagawa et al., a numerical 1D k-ε turbulence model was applied with additional formulations for the drag force in the field of vegetation. The modelled results for velocity, Reynolds-stress and turbulence intensity were compared to measurements in a flume. Using the predictions for the turbulent structure of flow in the vegetation bed they derived equations for the vertical suspended sediment concentration distribution resulting from resuspension. Their computations show that when the vegetation density is high enough, there will be no suspended sediment in the layer above the vegetation.

Tsujimoto (1999) presents a 2D depth-averaged model that solves the horizontal distributions of shear velocity, depth-averaged velocity and kinematic eddy viscosity and applies this to analyse sediment transport. Tsujimoto divides sediment transport into suspended load and bed-load and uses equations for graded sediment. He shows that with an increase of vegetation density, the total shear stress of the water column increases, but the bottom shear stress decreases. In other words, the vegetation layer increases flow resistance, but it decreases erosion. Applying the 2D model, Tsujimoto computes the horizontal velocity distribution and the bed form changes. Increased sedimentation is predicted in front of a vegetated area and a scour hole behind the vegetation area. Finally, the model is used to predict the erosion of a stream with vegetated banks that invade the channel and to predict the development of a sand island that has vegetation on it. Flume experiments for these phenomena were also carried out.

Eco-element scale

River eco-elements are defined as patches within an ecotope that have a homogeneous substrate type, water depth and velocity (Frissell et al., 1986). Indicators for eco-elements are sediment type, moisture, nutrients and land use (Rademakers & Wolfert, 1994). Tickner et al. (2000) use mesohabitats in their study. They define mesohabitats as medium-scale habitats which arise through the interactions of hydrological and geomorphological forces. In small rivers and streams, instream mesohabitats are discrete areas of habitats as viewed from the river bank, such as macrophyte stands and patches of gravel or silt.

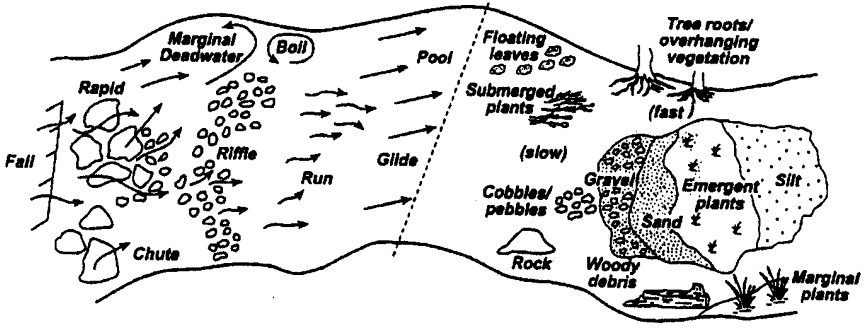

Figure 9. Physical biotopes and functional (meso-) habitats, from Newson & Newson, 2000.

At the lowest hierarchical level of river eco-elements, spatial and time scales of the developmental processes and patterns are correspondingly small. Characteristic eco-elements range from one to tens of meters and typical time scales of development are seasonal or yearly, from one month to a year. There are strong links on this level between the physical factors that denote habitat conditions for macrophytes and macrofauna.

4. SUMMARY AND DISCUSSION

This review provides an overview of biogeomorphological interactions in river systems for different scales. Although the discipline of 'biogeomorphology' is only recently invented (mid-eighties), a lot of literature that deals with geomorphology and ecology can be found. A characteristic of the literature, however, is the qualitative nature of most papers. Process-interactions are often defined, but seldom quantified. This lack of quantification is typical for the field of biogeomorphology. We understand that there is a complex interaction between geomorphology and organisms, but are hardly able to put these into parameters and values.

Table 1 summarises the main processes, scales and references used in this review. This literature review provides evidence that biogeomorphological interactions can be found on various temporal and spatial scales. The processes found were categorised according to a hierarchical classification. Considering the lack of better, more quantitative methods, this is probably the best method available, but it proofs difficult to put one scale-label to a process. Since biogeomorphological interactions can have effects on different scale levels, the scale cascade of De Vriend (figure) is applicable in biogeomorphology.

Table 1. Overview of processes, scales and references used in this review.

Process	**Scale**	**Reference**
Reduced vegetation cover leading to valley floor aggradation.	Basin.	Thorne et al., 1977.
Human deforestation affected river channel evolution.	Basin.	Gregory & Gurnell, 1988.
Climatic effects on vegetation cover changes channel pattern.	Segment.	Starkel, 1990.
Vegetation plays key role in anabranching.	Segment.	Tooth & Nanson, 1999.
Macrofauna depends on physical conditions.	Reach.	Vannote et al., 1980.
Increased bank resistance due to vegetation cover frustrates meandering.	Reach.	Gregory & Gurnell, 1988
Vegetation affects erosion and bank retreat.	Reach.	Abernethy & Rutherford, 1998.
Cow grazing reduces vegetation cover and decreases erosional resistance.	Reach	Trimble & Mendel, 1995.
Log and debris dams create new physiotopes.	Ecotope.	Gregory, 1992; Brown, 1997.
Distribution of plants depends on physical environment.	Ecotope.	Gurnell, 1997.
Riparian zones affect land-water interaction.	Ecotope.	Goodwin et al., 1997; Gregory et al., 1991.
Floodplain forests affect geomorphology through overbank flow.	Ecotope.	Piégay, 1997.
Grass enhances deposition and retains sediment.	Ecotope.	Abt et al., 1994.
Submerged vegetation affects turbulence and sediment transport.	Ecotope.	Li & Shen, 1973; Nakagawa et al., 1992; Tsujimoto, 1999.
Physical factors directly determine mesohabitats	Eco-element	Newson & Newson, 2000.

Table 2 gives a rough rating of the biogeomorphological influence for different scale levels. So far, the magnitude of influence is not yet quantified. This first attempt is based on the number of references found in the literature for each scale level and the importance for mutual interactions as indicated by the authors. In this table, the space scale indicates the longitudinal size of the system and the time scale is defined as the persistence of geomorphic features.

Table 2. Biogeomorphological influence for scale levels.

Level	Space scale (m)	Time scale (y)	Biogeo-morphology influence
River basin	10^5-10^7	10^3-10^5	--
Segment	10^5-10^6	10^2-10^3	-
Reach	10^3-10^5	10-10^2	+
Ecotope	10-10^3	1-10	++
Eco-element	1-10	0.1-1	+

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