THEME: Environment (including climate change)

TOPIC: ENV.2011.2.1.2-1 Hydromorphology and ecological objectives of WFD
Collaborative project (large-scale integrating project)
Grant Agreement 282656
Duration: November 1, 2011 – October 31, 2015

REFORM

REstoring rivers FOR effective catchment Management

Deliverable	D2.2 Part 1
Title	Influence of Natural Hydromorphological Dynamics on Biota and Ecosystem Function, Part 1 (Chapters 1 to 3 of 6)
Author(s)	A.M. Gurnell[1], M. González Del Tánago[2], M.T. O'Hare[3], M. Van Oorschot[4], B. Belletti[5], T. Buijse[4], D. García De Jalón[2], R. Grabowski[1], D. Hendriks[4], O. Mountford[3], M. Rinaldi[5], L. Solari[5], M. Szewczyk[6], A. Vargas-Luna[7] [1]QMUL [2]UPM [3]NERC [4]Deltares [5]UNIFI [6]WULS [7]Delft University of Technology (voluntary contribution)

Deliverable due date: 1 August 2014
Actual Submission date: 14 July 2014

Project funded by the European Commission within the 7th Framework Programme (2007 – 2013)
Dissemination Level

PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Summary

Background and Introduction to Deliverable 2.2. Work Package 2 of REFORM focuses on hydromorphological and ecological processes and interactions within river systems with a particular emphasis on naturally functioning systems. It provides a context for research on the impacts of hydromorphological changes in Work Package 3 and for assessments of the effects of river restoration in Work Package 4. Deliverable 2.1 of Work Package 2 proposes a hierarchical framework to support river managers in exploring the causes of river management problems and devising sustainable solutions. Deliverable 2.2 builds on the framework devised in Deliverable 2.1 by exploring published research and available data sets to more formally encompass the biota.

This report (Part 1 of Deliverable 2.2) is concerned with riparian and aquatic vegetation. It is organised into three chapters which introduce deliverable D2.2 as a whole (chapter 1); propose and support a conceptual model of vegetation-hydromorphology interactions (Chapter 2); develop the application of the conceptual model to European rivers (Chapter 3). Part 2 of Deliverable 2.2 extends the focus beyond vegetation and, within the context of the multi-scale framework, considers interactions between hydromorphology and biota more generally, including specific considerations of macroinvertebrates and fish (Chapter 4), and the role of floods and droughts as biota-shaping phenomena (Chapter 5). Lastly, part 2 presents conclusions from the whole of Deliverable 2.2 (Chapter 6).

Summary of Deliverable 2.2 Part 1.

Research Objective. Riparian vegetation is not included as a biological quality element in the Water Framework Directive, and yet research conducted over the last 20 years has clearly demonstrated that riparian vegetation has a fundamental influence on the hydromorphology of rivers and their floodplains, with a geographically more widespread impact than aquatic vegetation. This report assembles evidence from published sources and available data sets to demonstrate how vegetation interacts with hydromorphology to constrain numerous aspects of river morphology and dynamics, so providing a vital component of any river management and restoration efforts.

Methods and Results. Chapter 2 proposes a conceptual model of vegetation-hydromorphology interactions (section 2.2) that provides the underpinning for the whole of chapter 3. The literature and available data sets are exploited to place the conceptual model firmly within the context of the broader ecology of riparian and aquatic vegetation (section 2.1), and to present the modelling approaches that are currently available for exploring these vegetation-hydromorphology interactions (section 2.3).

The conceptual model assumes a naturally-functioning river-floodplain system and considers three scales of influence. *First*, the model considers how regional physical processes place constraints on the species composition of river corridor vegetation, particularly emphasising the biogeographical zone within which the river's catchment is located. *Second*, the model considers how vegetation is further constrained by longitudinal, lateral and vertical gradients in hydromorphological processes within the river corridors of a catchment, particularly by gradients of moisture availability and fluvial disturbances. Five zones of vegetation-fluvial process interaction within a river corridor are defined: perennially inundated (zone 1); fluvial disturbance dominated - predominantly coarse sediment erosion and deposition (zone 2); fluvial disturbance dominated - predominantly fine sediment deposition (zone 3); inundation dominated (zone 4); soil moisture regime dominated (zone 5). *Third*, a critical zone of vegetation-

hydromorphology interactions is defined, which bridges zones 1 to 3, and within which vegetation heavily influences the construction of landforms (e.g. river banks, islands) at the interface between the physical-process-dominated areas of the river channel and the vegetation-dominated areas of the surrounding floodplain or hillslopes.

The model is explored in a European context in chapter 3. *First* riparian and aquatic species of the 'natural vegetation' within different biogeographical zones of Europe are assembled. *Second*, a traits data base is assembled for 459 aquatic and riparian plant species that are found in association with European rivers, and two trait-based typologies are devised reflecting (a) the sediment stabilisation and (b) the sediment accumulation and channel conveyance / blockage potential of the analysed species. This is a major first step in developing methods for interpreting the hydromorphological relevance of native riparian and aquatic plant species across Europe. *Lastly*, the applicability of the conceptual model to a sample of European rivers is tested in section 3.3. It is applied to rivers located in contrasting biogeographical zones and subject to different human pressures, highlighting for the first time how different plant species and groups act as river ecosystem engineers in different river systems.

Conclusions and Recommendations. This report presents new science concepts and analyses that clearly demonstrate the importance of vegetation as a key physical control of river form and dynamics and a crucial component of river restoration. It shows how interactions between plants and hydromorphology take on different characteristics in different biogeographical settings, leading to different spatial patterns of features and temporal dynamics within zones 1 to 5 of the river corridor, and different styles of landform development within the critical interface between fluvial processes and vegetation in zones 1 to 3. Case studies illustrate how the conceptual model provides a useful multi-scale framework for understanding and interpreting vegetation-hydromorphology interactions and so supporting sustainable river restoration design and management. However, some research gaps need to be filled to permit the work to be translated into a set of simple river management tools:

1. The example applications of the conceptual model have synthesised pre-existing literature and field observations that were collected for many different scientific or management purpose. These provide a 'proof of concept' and a firm basis for recommending that new purpose-designed field research is needed to ensure the robustness and wide applicability of the model.
2. A thorough review of available modelling tools has demonstrated that the main aspects of plant-hydromorphology interactions have received attention, although many research gaps remain. However, more importantly, most existing models address narrow aspects of these interactions. More integrated modelling approaches are needed to support river and floodplain management.
3. Research is needed to assemble more comprehensive native riparian and aquatic species lists for European biogeographical zones from which a larger set of informative species traits can extend plant trait-based hydromorphological modelling.

Acknowledgements
The work leading to this report has received funding for the EU's 7th FP under Grant Agreement No. 282656 (REFORM). Many thanks to Martina Bussettini, Judy England, Angel Garcia Canton, Iain Gunn, and Fernando Magdaleno Mas for their reviews.

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1. Specification and Introduction

1.1 Tasks 2.3 and 2.4 of Work Package 2

This report describes the outcomes of tasks 2.3 and 2.4 of Work Package 2 of REFORM. The aims of these two tasks, as described in the original research proposal, were as follows:

Task 2.3: Identify linkages and interactions between hydrology and biota, and between biota and morphology (Partners: WULS, BOKU, MU, NERC-CEH, QMUL, UPM; Months1 – 33). This task explores interactions between hydrology, morphology and biota, emphasising the impact of biota on the hydromorphological properties of European rivers.

- Use the literature and data sets identified in WP1 to characterise linkages and quantify interactions between hydrology and biota and between biota and morphology.
- Establish the relation between vegetation development, river flow and alluvial groundwater characteristics, focusing on the role of vegetation in managing the high water stages in low flow periods and the mix of hydrological pathways operating across flow stages.
- Assess the evidence regarding the degree to which the natural assemblage of riparian vegetation and aquatic flora (from task 2.2) interact with sediment to construct and reinforce landforms (banks, benches, bars, islands, side channels, floodplain ponds) that provide a suite of habitats crucial to riverine ecology including the nutrition pool for plants.

Task 2.4: Establish the importance of natural dynamics for ecosystems function and ecological quality. (Partners: WULS, IGB, QMUL, NERC-CEH, UPM; Months 6 – 33). This task builds on the hydromorphological framework and understanding from Tasks 2.1 and 2.2 and the feedbacks between the biota and hydromorphology investigated in Task 2.3 to consider the impacts on biota of natural hydrology-morphology-vegetation interactions across rivers and their floodplains.

- Produce a synthesis of knowledge from WP1 and relevant case study data sets in relation to flow regimes, hydrological connectivity (surface and subsurface) and biotic responses, emphasising the relevance to European hydrological regimes and to location within the multi-scale framework devised in Task 2.1.
- Analyse relevant case study areas using contemporary and historical data to investigate the role of extreme hydrological events (flood pulsing and droughts) on river and floodplain biota.
- Synthesise the knowledge from WP1 and relevant case study data sets to assess the impact of natural morphology (i.e. habitat mosaic) and morphological dynamics (i.e. habitat turnover) on ecosystem function, particularly the response of river and floodplain biota to hydrological extremes and surface water – groundwater interactions. This task will be structured around the functional vegetation typing and multi-scale framework developed in tasks 2.1 and 2.2.

1.2 *Introduction to Deliverable 2.2*

The outputs from tasks, 2.3 and 2.4 are reported in Deliverabe 2.2, a six chapter document divided into two parts. Part 1 (this volume) contains chapters 1 to 3 and largely focuses on task 2.3. Part 2 contains chapters 4 to 6 and largely focuses on task 2.4.

Part 1 builds on REFORM Deliverable 2.1 by developing the role of vegetation as an influence on hydromorphology as well as a biological element in its own right (chapters 2 and 3). The role of both riparian and aquatic vegetation as important controls of river morphodynamics is a relatively new area of research, which has mainly developed within the last 20 years. Following an overview of the basic ecology of riparian and aquatic plants (section, 2.1), this research area is developed for REFORM through the proposal of a conceptual model of vegetation-hydromorphology interactions (section 2.2), and a thorough review of modelling approaches that can help to investigate aspects of the interaction between plants and physical processes in river environments (section 2.3). Chapter 3 then focuses on vegetation and hydromorphology in European rivers, considering the regional structure of river-related vegetation across Europe (section 3.1), a vegetation typology based on the traits of riparian and aquatic plants that are relevant to their influence on and response to hydromorphology (section 3.2). Finally section 3.3 investigates the functioning of the conceptual model described in section 2.2 across a sample of European rivers.

Part 2 of this report considers interactions between hydromorphology and biota more generally, starting in Chapter 4 with the way in which macroinvertebrates and fish are affected by hydromorphology at the range of scales incorporated within the hierarchical framework of D2.1, and then in Chapter 5 outlining floods and droughts as biota-shaping phenomena.

In developing this report, some elements of the originally-proposed work were adjusted to ensure that the report was logical and well-supported by literature and examples. The main change was to integrate the hydrological and hydraulic elements into all sections of the report, but then to highlight extreme events and hydraulic interactions in section 5. Although much relevant information was received from WP1 and also D2.1 to support the research reported in D2.2 parts 1 and 2, additional literature synthesis was necessary to support the development of the conceptual model of vegetation–hydromorphology interactions and the related synthesis of modelling approaches (chapter 2) and also to discuss responses of biota to hydromorphology at multiple scales (chapters 4 and 5). In addition, the development of the conceptual model within a European context (chapters 3, 4 and 5) depended upon new data synthesis and analysis coupled with examples drawn from the contributors' field experience and knowledge.

Deliverable 2.2 makes a significant scientific contribution to the way we conceptualise interactions between hydromorphology and ecology. It formalises two-way hydromorphology-vegetation interactions within river corridors; places these interactions within a spatially hierarchical framework as well as considering their temporal dynamics; and then considers the response of fish and macroinvertebrates to this multi-scale setting. Throughout the research for Deliverable 2.2, it has become apparent that a number of research gaps exist which require an integrated programme of research for their resolution. These research gaps are summarised in section 6.

2. Vegetation and Hydromorphology

This chapter describes the scientific context (sections 2.1 and 2.2) and modelling tools (section 2.3) that can support investigation of interactions between vegetation and hydromorphology. The conceptual model proposed in section 2.2 is placed within a European setting in chapter 3, by considering natural riparian and aquatic vegetation across Europe (section 3.1), the traits of riparian and aquatic plants that may enable them to act as physical ecosystem engineers (section 3.2), and then presenting examples of the application of the conceptual model developed in section 2.2 to some example European river systems (section 3.3).

2.1 Basic Ecology of Riparian and Aquatic Vegetation

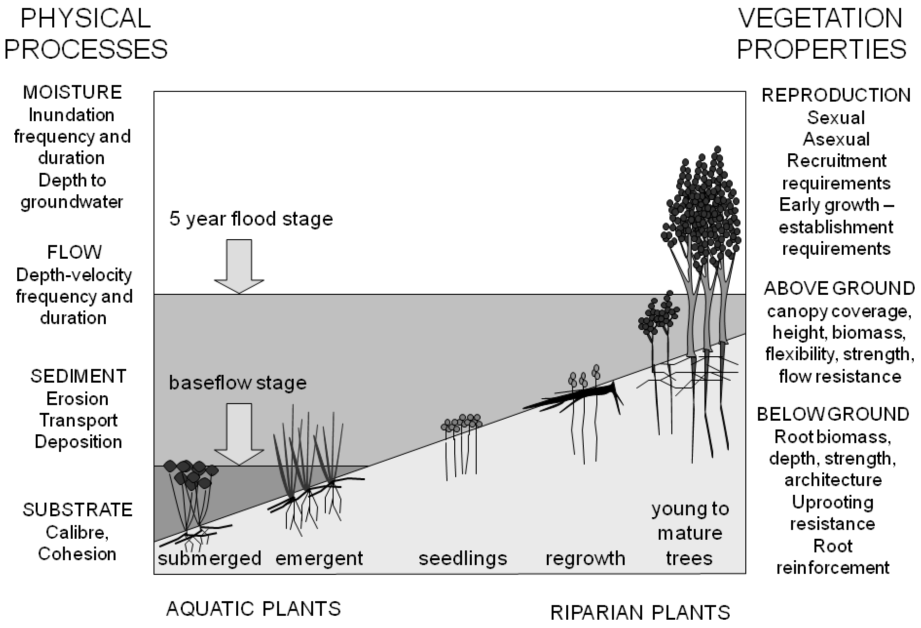
The plant species that are found thriving in and around the margins of fluvial systems are constrained by many factors that operate at different spatial and temporal scales. Ultimately climate constrains the species that are able to grow at a site, and as a result, different species of riparian and aquatic plants thrive in different environmental settings. A few of these species have the ability to colonise heavily disturbed areas of the river corridor and to grow vigorously there. For example, along the Tagliamento River, Italy, three riparian tree species dominate the riparian zone (*Alnus incana, Salix elaeagnos, Populus nigra*) with their presence and relative cover changing along the river's course as the climate shifts from Alpine in the headwaters to Mediterranean in the lower reaches. As a result, different segments of the river, located within different landscape units show different dominant riparian tree species.

Different species can take on similar functional roles in different environmental settings, and within a particular climatic context. Physical (hydrological and fluvial) processes (Figure 2.1.1A) heavily influence the survival, composition and growth performance of the riparian and aquatic plants that are present along particular river reaches. At this scale the structure and development of riparian plant communities is largely controlled by the flow regime (Pettit et al., 2001; Stromberg, 2001; Nilsson and Svedmark, 2002; Dynesius et al., 2004; Lytle and Merritt, 2004; Lite et al., 2005; Rood et al., 2003a, 2005, Bajerano et al., 2011a,b, García-Arias et al., 2012) both directly and through the cascade of physical processes that it influences, including riparian groundwater conditions and the dynamics of sediment erosion, transport and deposition. Thus, even in lakes, where marginal disturbance reflects hydrological fluctuations in lake levels rather than additional disturbances attributable to shear stresses and sediment mobilisation, distinct differences in marginal plant community structure are induced by hydrological dynamics (Figure 2.1.1B). Aquatic plants also respond strongly to fluvial controls (e.g. Riis and Biggs, 2003; Baattrup-Pedersen et al., 2006; Daniel et al., 2006), particularly flow depths, velocities and bed sediment properties, and, like riparian vegetation, have reciprocal effects on these parameters.

For the purposes of this report, the '*riparian zone / corridor*' is a transitional semi-terrestrial area that is regularly influenced by fresh water (Naiman et al., 2005), and extends from the edge of the baseflow river channel (for ephemeral rivers, the entire river bed is part of the riparian zone) to areas dominated by terrestrial communities (hillslopes, terraces, areas of the floodplain that are only flooded extremely rarely).

However, a '*functioning riparian zone / corridor'* supports riparian plant communities and so excludes areas of the natural riparian zone that are under other land cover types (e.g. agriculture, urban, transport infrastructure) or are artificially protected from flooding.

(A)



(B)

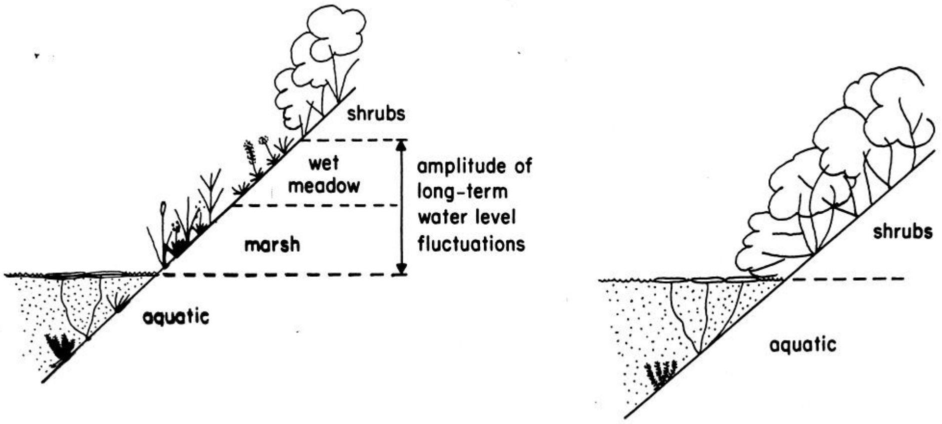


Figure 2.1.1 A Physical processes that constrain riparian and aquatic plant colonisation and growth, and the reproductive and biomechanical properties that enable plants of different species and growth stage to cope with the stresses imposed by physical processes. The relative importance of the physical processes varies from the left to right of the diagram and also through time as river stage and discharge varies (after Gurnell, 2014). B Variation in riparian plant communities depending upon water level variability in lakes: left, highly variable water level; right, stable water level (from Keddy and Fraser, 2000)

The '*aquatic zone*' corresponds to the baseflow channel. It is continuously indundated and supports aquatic plant communities, ranging from species that grow fully submerged to those that are almost entirely emergent and are found at the water's edge.

The EU Water Framework Directive requires aquatic plant communities to be monitored when assessing ecological status whereas riparian vegetation is only considered as a supporting element. As will become clear, there is an intimate relationship between both aquatic zone and riparian zone vegetation and hydromorphology under natural conditons. Therefore, the current WFD monitoring approach is likely to greatly underestimate the impact of hydromorphological alterations which is a signficant issue given the high prevalence of this type of impact across EU states.

2.1.1 Riparian plants

The entire structure and successional development of riparian plant communities along river corridors is strongly controlled by the river flow regime (Nilsson and Svedmark, 2002). Thus, Greet et al. (2011, 2013) found strong evidence for causal relations between the seasonal pattern and timing of river flows and riparian plant processes such as waterborne dispersal (hydrochory), germination and growth, which are reflected in the composition of riparian plant communities.

In addition to the predictable seasonal occurrence of low and high flows, which form part of the flow regime at a site; less predictable, short-lived flow / flood disturbances also strongly influence riparian plants. In the context of European riparian tree species, Glenz et al. (2006) present a conceptual model of how tree species respond to flooding and classify 65 tree and shrub species according to their inundation tolerance (Table 2.1.1).

High flow events not only inundate and impose drag on plants, they also erode, transport and deposit sediment, affecting the stability of the riparian substrate into which the plants are rooted, and subjecting plants to scour, excavation, uprooting and burial. As a result, the active river channel and its riparian zone show a clear structure in vegetation cover and associated landforms, which are most marked along rivers with a very strong flood disturbance regime, such as the braided Tagliamento River, Italy (Figure 2.1.2). These physical disturbances of riparian vegetation increase in severity with increasing flow depth and velocity. At the same time, mobilization and sorting of sediment can feed back into the creation of moisture extremes within riparian zones. Exposed, coarse sediment patches drain efficiently, giving rise to extreme moisture conditions ranging from waterlogged to arid as the river stage fluctuates, whereas finer exposed sediment patches are more moisture-retentive and so provide more stable moisture conditions as river stage varies.

Overall riparian corridors are heavily disturbed, extreme environments that support immense spatio-temporal variations in inundation, shear stresses, substrate calibre and dynamics, and moisture retention. As a consequence, they are characterized by complex, temporally-dynamic, spatial distributions of plant species associated with a shifting mosaic of habitat patches (Pringle et al., 1988; Stanford et al., 2005; Mouw et al., 2012), broadly reflecting relative topographic position and proximity to the main river channel (disturbance magnitude and frequency) and sediment calibre (hydrological conditions) (e.g. van Coller et al., 1997; Robertson and Augsperger 1999; Bendix and Hupp, 2000; Richter and Richter, 2000; Dixon et al., 2002; Cooper et al., 2003, 2006;

Turner et al., 2004; Friedman et al., 2006, Laterell et al., 2006; Robertson, 2006; Nakamura et al., 2007, Magdaleno et al., 2014). Biological and chemical processes that also influence the presence and abundance of riparian species are linked to and moderated by these patch environments, and also respond to larger-scale factors such as rock type, land cover and use, and the catchment species pool.

Table 2.1.1 Flood tolerance of 65 European tree and shrub species (data from Glenz et al., 2006)

Flood tolerance class	Species
Very high	Alnus glutinosa, Salix cinerea, Salix triandra, Salix viminalis, Salix elaeagnos, Salix daphnoides, Salix m. nigricans, Salix alba, Salix fragilis, Salix pentandra
High	*Alnus incana, Alnus viridis, Frangula alnus, Populus nigra, Prunus domestica, Prunus padus, Salix purpurea, Salix appendiculata, Salix caprea*
Intermediate	*Acer campestre, Ulmus minor, Lonicera xylosteum, Ligustrum vulgare, Rhamnus cathartica, Cornus sanguinea, Hipp. Rhamnoides, Fraxinus excelsior, Quercus robur, Viburnum opulus, Populus alba,,Populus tremula, Sorbus aucuparia*
Low	*Acer platanoides, Carpinus betulus, Viburnum lantana, Corylus avellana, Robinia pseudoacacia, Castanae sativa, Berberis vulgaris, Crataegus monogyna, Prunus spinosa, Tilia cordata, Ulmus glabra, Juglans regia, Aesculus hippocastanum, Malus sylvestris, Pinus sylvestris, Taxus baccata, Sorbus aria, Sambucus nigra, Betula pendula*
Very low	*Fagus sylvatica, Picea abies, Acer pseudoplatanus, Abies alba, Tilia platyphyllos, Prunus avium, Larix deciduas, Ilex aquifolium, Quercus petraea, Quercus pubescens, Juniperus communis, Crataegus laevigata, Prunus mahaleb, Amelancier ovalis*

Many riparian plant species reproduce equally effectively by both sexual and asexual means. These different reproductive strategies maximize the chances of a species surviving in the highly disturbed riparian environment. Sexual reproduction takes advantage of river flows for seed dispersal, whereas asexual reproduction takes advantage of physical damage to plants by fluvial processes. Both reproductive pathways respond differently to environmental conditions as well as displaying contrasts in initial growth performance under the same environmental conditions (e.g. Kranjcec et al., 1998; Francis and Gurnell, 2006; Francis, 2007; Moggridge and Gurnell, 2009). The propagule types (seeds, vegetative fragments) of different species have varying tolerances and growth responses to inundation and flood disturbance (Bren, 1988; Auble et al., 1994, Blanch et al., 1999, Friedman and Auble, 1999; Amlin and Rood, 2001; Pettit et al., 2001; Glenz et al., 2006; Erskine et al., 2009), and also to moisture availability (waterlogging, drought, depth to water table) in the alluvial aquifer (Amlin and Rood, 2003; An et al., 2003; Naumberg et al., 2005; Loheide and Gorelick, 2007; Imada et al., 2008; Mouw et al., 2009).

As a result of their relatively large size, and thus their ability to provide protection for and to compete strongly with other riparian species, riparian tree species are a particularly important component of riparian vegetation. Karrenberg et al. (2002)

reviewed the morphological and biomechanical characteristics and life history traits of the Salicaceae (willow and poplar species), which allow them to dominate the riparian zones of temperate rivers within the northern hemisphere. These traits relate to reproduction, germination, growth, and survival in the high flow shear stress, excavation and burial conditions that characterize riparian zones.

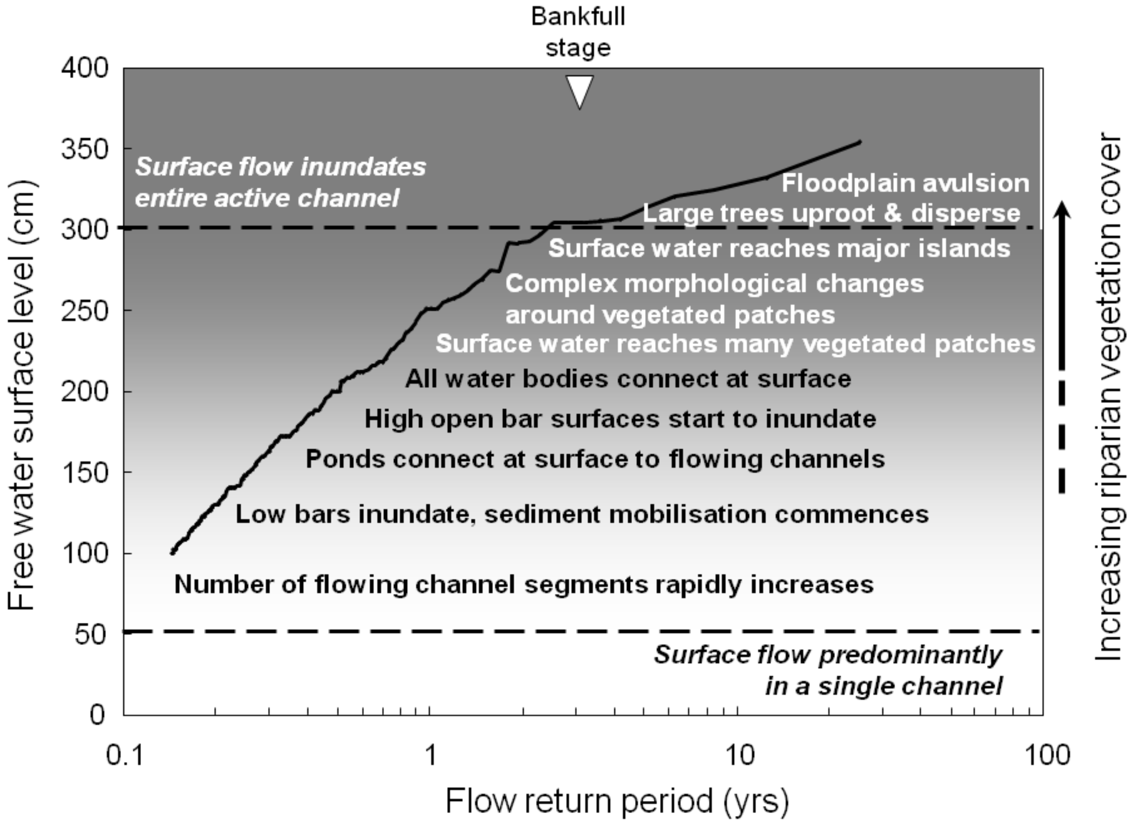


Figure 2.1.2 Association between vegetation cover, flow stage (free water surface level) and frequency (flow return period) and key physical processes within an island-braided reach of the Tagliamento River, Italy (modified from Bertoldi et al., 2009)

A particular research focus has been sexual reproduction by the riparian Salicaceae. These tree species produce enormous quantities of short-lived seeds during a very brief period of seed production. The seeds require moist, bare, alluvial sediments for germination and a gradually-falling, alluvial water table to encourage early growth. Due to the short period of seed viability, specific germination and early growth requirements, and high sensitivity of seedlings to flood or drought stress, few seedlings grow to maturity. The very close association between recruitment success and the river flow (water surface elevation) regime, allowed Mahoney and Rood (1998) to define a very simple 'recruitment box' model capable of predicting recruitment of individual riparian willow and poplar species according to the river flow regime in any particuar year (Figure 2.1.3). This model has been tested, modified, extended and calibrated by many researchers to support improved assessment and forecasting of willow and poplar recruitment in response to properties of the flow regime and alluvial sediment texture (Barsoum and Hughes, 1998; Kalischuk et al., 2001; Amlin and Rood, 2002; Guilloy-

Froget et al., 2002; Lytle and Merritt, 2004; Ahna et al., 2007; Braatne, 2007, Gonzalez et al., 2010; Merritt et al., 2010). Such models allow river flow regimes to be designed to promote recruitment of particular species in regulated river systems (e.g. Hughes and Rood, 2003; Rood et al., 2005).

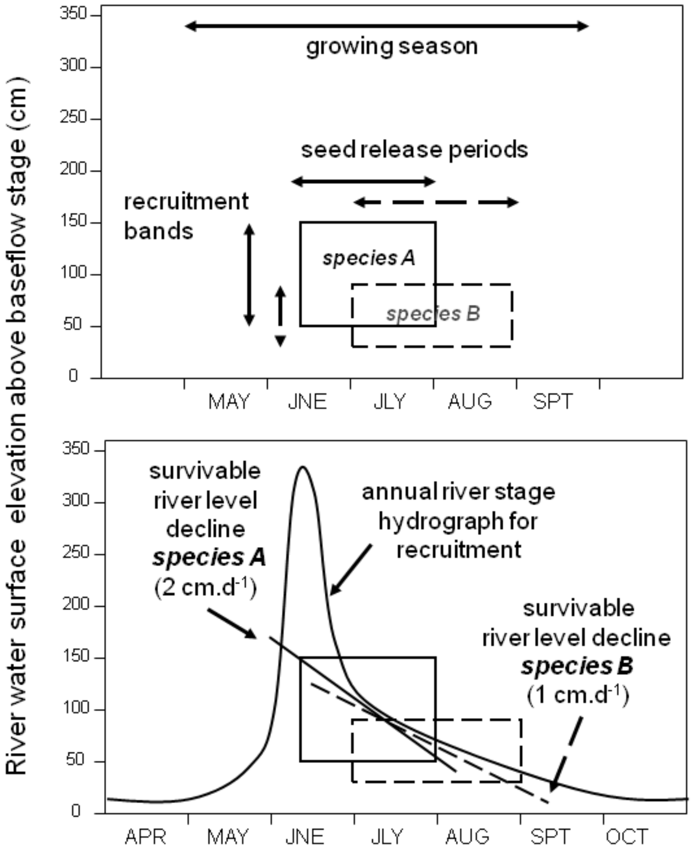


Figure 2.1.3 The recruitment box model of Mahoney and Rood (1998) applied to two hypothetical species

In addition to sexual reproduction, the Salicaceae reproduce very freely by asexual means. Small fragments, branches and entire uprooted trees are mobilised and transported during floods, and so can be produced and transported by the river at any time of the year. If these vegetative fragments are deposited on a suitable patch of moist, open alluvial sediment, they sprout quickly, anchoring themselves to the substrate through root development and providing canopy flow resistance that encourages retention and partial-burial of the plants by shallow water-bourne and wind-blown, relatively-fine, moisture-retentive sediment. The potential of these propagules to survive in the medium term is also hydrologically controlled to the extent that their site of deposition is governed by the flood stage that deposited them (the higher they are deposited within the riparian zone, the less likely that they will be disturbed as they sprout and establish), whilst their survival and growth performance is governed by the depth to the alluvial water table (the lower they are deposited within the riparian zone, the shallower the water table depth and thus the more reliable the water supply to support growth).

An ability to grow rapidly is also crucial for riparian tree survival. Riparian tree species grow rapidly in suitable environmental, particularly hydrological, conditions (García-Arias et al., 2013, 2014). For example, initial shoot growth of up to 3 $mm.day^{-1}$ in *Populus nigra, Salix alba* and *Salix elaeagnos* seedlings, 10 $mm.day^{-1}$ in cuttings, and 15 $mm.day^{-1}$ from uprooted deposited trees have been observed on the Tagliamento River (Francis et al., 2006, Moggridge and Gurnell, 2009), indicating the very rapid early development of these plants. On the same river, annual growth rates of young (3m tall) *Populus nigra* trees range from a median of 10 cm to 40 cm per year among reaches with different moisture availability, confirming the longer-term dependence of tree growth on alluvial aquifer conditions (Gurnell, 2014). Root growth is also rapid. The roots of young plants track falling water tables and root architecture is strongly influenced by groundwater levels and fluctuations (e.g. Mahoney and Rood, 1998, Kranjcec et al., 1998; Francis et al., 2005; Imada et al., 2008; Pasquale et al., 2012). Average daily increments in vertical root penetration of experimental sand and gravel substrates, under a water table decline of 3 $cm.day^{-1}$, have been observed as 27 and 20 mm, respectively, for *Salix elaeagnos,* and 15 and 10 mm, respectively, for *Populus nigra* (Francis et al., 2005).

Riparian trees also display strong morphological responses to flood flows, burial and uprooting. Young Salicaceae not only produce above- and below-ground biomass rapidly, but their stems and branches are very flexible. As they mature, some species (e.g. *Salix elaeagnos*) develop a bushy morphology, retaining stem and branch flexibility that reduces their flow resistance. Other species grow taller and develop quite rigid trunks but their canopy is elevated above ground level and thus the water surface level of most floods (e.g. *Populus nigra*). Other tall-growing species shed branches easily (e.g. *Salix fragilis*), reducing flow resistance and at the same time releasing vegetative propagules for transport downstream (e.g. Rood et al., 2003b). All species develop robust, laterally and vertically extensive root networks that strongly resist uprooting (e.g. Karrenberg et al, 2003) and whose morphology and biomass adjusts to mechanical stresses (Scippa et al., 2008). The roots anchor the plants into otherwise unstable alluvial sediments, reinforcing these sediments and any additional sediment retained within tree stands during floods. The deep root systems and the adventitious roots that are produced in response to burial are critical for preventing the trees from being undermined by bank erosion and giving them a very high tolerance to burial.

Although the Salicaceae dominate temperate riparian zones within the northern hemisphere, other widespread riparian tree species show similarly strong recruitment responses to properties of the river flow regime and related sediment dynamics, including within Europe, Alnus spp. and *Fraxinus excelsior* (e.g. Dufour and Piégay, 2008).

As a result of sensitivity to the hydrological regime, riparian vegetation composition, structure and vigour responds rapidly to flow regime changes (Nilsson and Breggren, 2000; Merritt et al., 2010; Bejerano et al., 2011a,b, 2013) as well as to the indirect hydrological consequences of river channel changes resulting from channel displacement and incision, and floodplain sedimentation (Lowry and Loheide, 2010; Loheide and Booth, 2011). The delicate balance between hydrology and riparian plants underpins the concept of riparian vegetation – flow response guilds proposed by Merritt et al. (2010). Sometimes hydrological changes result in the encroachment of river margins by native riparian species (e.g. Johnson, 1994, 1997, 2000). In other cases, native species may lose their vigour (e.g. Xu, 2007, 2009; Gonzáles et al., 2010) and may be replaced by other native or alien species that have different hydrological requirements and tolerances (e.g. Graf,1978, Katz and Shafroth, 2003; Glenn and Nagler, 2005; Lite and Stromberg, 2005; Pataki et al., 2005; Rood et al., 2010, Garófano-Gómez et al., 2011, 2013). Conversely, deliberate manipulation of flow regimes can also be used to combat invasions by alien species and to restore native riparian vegetation (e.g. Nagasaka and Nakamura, 1999; Taylor et al., 1999; Stromberg, 2001; Zamora-Arroyo et al., 2001; Nagler et al., 2005; Stromberg et al., 2007).

2.1.2 Aquatic Plants

This section focuses on aquatic macrophytes, which are simply aquatic plants that are visible to the naked eye. These species are all found within the aquatic zone of the river corridor, including both the river itself and floodplain lakes and ponds. In addition to vascular plants a number of macroalgae, mosses, liverworts and ferns are all considered to be macrophytes. It is usual for such aquatic macrophytes to be assigned to morphotypes or growth forms which reflect both the shape of the plant and its habitat (Sculthorpe,1967). Classic definitions of morphotypes include submerged, free floating, rooted with floating leaves, and emergent aquatic plants. Commonly there are also separate growth form groupings for bryophytes and sub-divisions of the submerged vegetation morophotype by leaf shape (Pieterse and Murphy, 1990): linear, broad or fine leaved. Intermediate forms make finer resolution of groupings difficult with some species even exhibiting different growth forms depending on habitat conditions. However, growth forms are crucial to aquatic macrophytes because they dictate the way in which the plant’s canopy interacts with flowing water.

Commonly, aquatic macrophyte species have a range of specialist adaptations in order to live in or near water. The submerged species are capable of accessing the relatively limited supplies of dissolved oxygen for respiration and carbon dioxide for photosynthesis by making use of short diffusion pathways, i.e. thin leaves. Many aquatic species are considered as ‘shade’ species, in that they are adapted to the low light conditions found underwater; chloroplasts are concentrated within the epidermis and photosynthesis becomes saturated at low irradiance. Emergent species are tolerant to waterlogging of their root zone, a condition which is lethal to many terrestrial species.

Although species can reproduce sexually, asexual reproduction, by fragmentation and clonal growth, is very common. Asexual reproduction is very important for expanding cover locally and for coping with major flow disturbances (Riis and Sand-Jensen, 2006). While some species are annual, many aquatic macrophyte species are perennial, usually dying back in the autumn. Many species produce dense networks of rhizomes and other storage organs that support asexual reproduction. Shoots and roots develop from nodes on the rhizomes, allowing plant stands to extend laterally during favourable conditions. Rhizomes persist through the winter, retaining and reinforcing colonised sediment. During severe floods, particularly during winter when there is negligible foliage to provide flow resistance and little root biomass (Liffen et al., 2013a), rhizome-reinforced sediment patches can become scoured or undermined, exposing rhizomes to breakage and the formation of mobile propagules that can colonise downstream sites.

The growth form of aquatic plants also reflects the ambient and extreme flow conditions within which they live. Typically rheophilic species (lovers of fast water) can live in ambient flows up to 0.75 m.s^{-1} which exert drag forces comparable to near storm conditions (Beaufort scale) in terrestrial systems. A major effect of physical forces on aquatic plants is the mechanical deformation of stems and leaves (Denny, 1988). In flowing water, submerged freshwater plants reconfigure and adopt a streamlined, compressed morphology (Sand-Jensen, 2003, O'Hare *et al*., 2007, Sand-Jensen and Pedersen, 2008). Reconfiguration serves to reduce and minimize pressure drag forces (O'Hare *et al*., 2007, Nikora, 2010). It has recently been demonstrated that aquatic plants, across a wide range of species, exhibit a trade-off between drag reduction and mechanical resistance strategies (stem and root strength) (Puijalon et al., 2011). It is also known that closely related species or the same species can inhabit areas where different strategies may be more beneficial, for example, lake versus river or winter versus summer flow conditions. A further important point is that, although many species are perennial, their annual growth cycle ensures that plants expose the lowest above-ground biomass at times of highest (winter) flows. They usually sprout in spring to achieve peak above-ground biomass in mid to late summer, when river flows and velocities are usually at their lowest, and then they die back in the autumn.

Despite the variety of conditions species can occupy, there is a surprising lack of knowledge on the morphological adaptability or otherwise of species. It can be hypothesised that macrophytes would ideally display different physical shapes to deal with the different types of drag conditions they experience. Specifically, drag forces exerted by water flow in rivers and streams require 'tensile' plants (*sensu* Nikora, 2010), which experience mainly friction drag, to be resistant against tension forces and to be flexible in order to streamline and reconfigure (O'Hare *et al*., 2007, Miler *et al.*, 2012, Figure 2.1.4). Under slower flow velocities, and in floodplain lakes, 'bending' plants (*sensu* Nikora, 2010) grow that are stiffer, have a more upright shoot morphology and are mainly affected by pressure drag (Nikora, 2010, Miler *et al*., 2012).

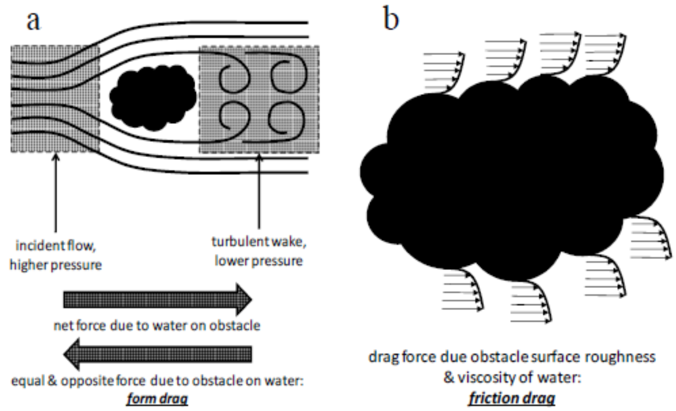


Figure 2.1.4 The flow patterns around a submerged plant

As a consequence of the fact that different plant morphologies, as well as stem and stand densities, are associated with different impacts on and interactions with the flow field (Folkard, 2009), they also display different sediment trapping and retention potentials (Sand-Jensen, 1998; Clarke, 2002; Schulz et al., 2003; Sharpe and James, 2006). Some submerged species are adversely affected by sedimentation and so they only tend to survive in locations where sediment supply is relatively low and / or where their interactions with the flow field do not support significant sediment retention. However, individuals and stands of many submerged and most emergent species form effective sediment retention structures (Cotton et al., 2006; Gurnell et al., 2006; Luhar et al., 2008; Asaeda et al., 2010; Neary et al., 2012). Whilst sediment may be resuspended (Kleeberg et al., 2010), particularly following decay of the above-ground biomass through the winter, some species develop below ground organs (roots, rhizomes etc.) within the retained sediment that both anchor the plants during the growing season and retain and reinforce the sediment through the winter (Liffen et al., 2013a).

The broader relationship between natural aquatic vegetation and its physical environment can only be understood in the context of the wider range of forces influencing plant growth in rivers. Based on Grime’s theory of community succession (Grime, 1977), Biggs (1996) developed a conceptual model of macrophyte and periphyton succession in rivers (Figure 2.1.5). The resources were assumed to be light, nutrients (N, P, C) and temperature. The disturbances, which remove biomass, were described by three factors: temporal scale hydraulics (velocity instabilities caused by floods); spatial scale hydraulics (including local turbulence and bed sediment particle size) and (in specific areas) grazing. Petts (1996) refined the flow related disturbances by setting them into the context of the hydrograph, suggesting that four flow descriptors relevant to habitat suitability were important: flood magnitude, flood duration, flood timing (through the growing season) and flood return period (frequency). On the basis of Grime’s model, Biggs (1996) predicted that no plants would grow in rivers with a high frequency of flood flows, unstable bed sediments and high, interspate water velocities, but as the severity of the hydraulic conditions decreased, periphyton would dominate, followed by bryophytes, then, at the most stable conditions, macrophytes. This is consistent with observations at the national and international scales which identify two key factors influencing aquatic macrophyte species and community distributions: alkalinity (Westlake, 1969) and a measure of disturbance, often approximated by a combination of stream power and flood magnitude and frequency (Riis and Biggs, 2003). Hence, macrophytes can be removed and periphyton dominance established simply by the development of inhospitable flow (velocity) conditions, without the need to increase nutrient input (although the biomass is likely to be much smaller when the change is induced by flow).

Although some of Biggs parameters are not incorporated, based on a national-scale, empirical analysis for British rivers, Gurnell et al. (2010) showed that the distribution of plant groups shows a strong affinity with flood discharge (Qmed is the median annual flood) and channel slope (and thus stream power, which incorporates both of these variables) (Figure 2.1.6, upper graph) and with the the calibre of the river bed material (Figure 2.1.6, lower graph). This association with hydrological and sedimentary conditions helps to explain why it has been possible to distinguish 10 classes of British river using assemblages of aquatic macrophyte species, which in turn have been shown

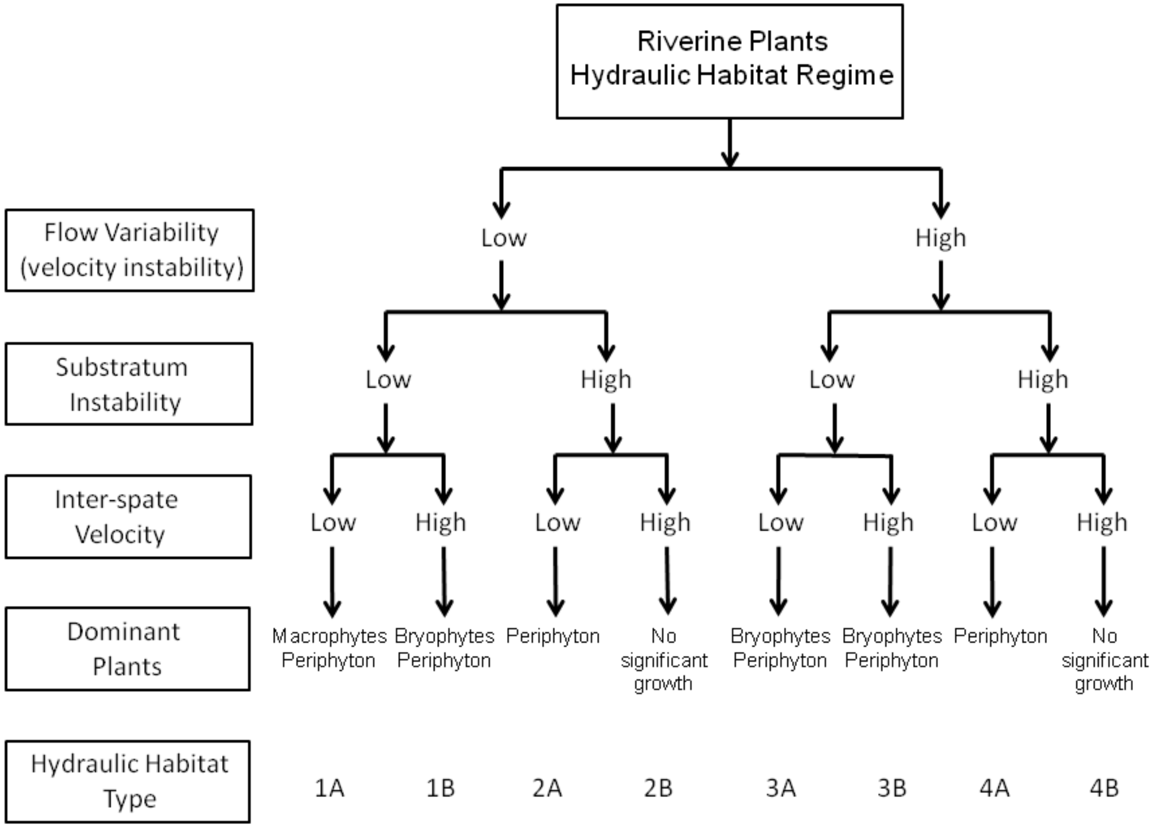


Figure 2.1.5 A concept of river sector types or categories based on the relationship between some instream vegetation and sector scale flow parameters (after Biggs, 1996).

to correspond to variations in slope, channel width and depth, substrate calibre, flow types and rock type (Holmes et al., 1998, 1999).

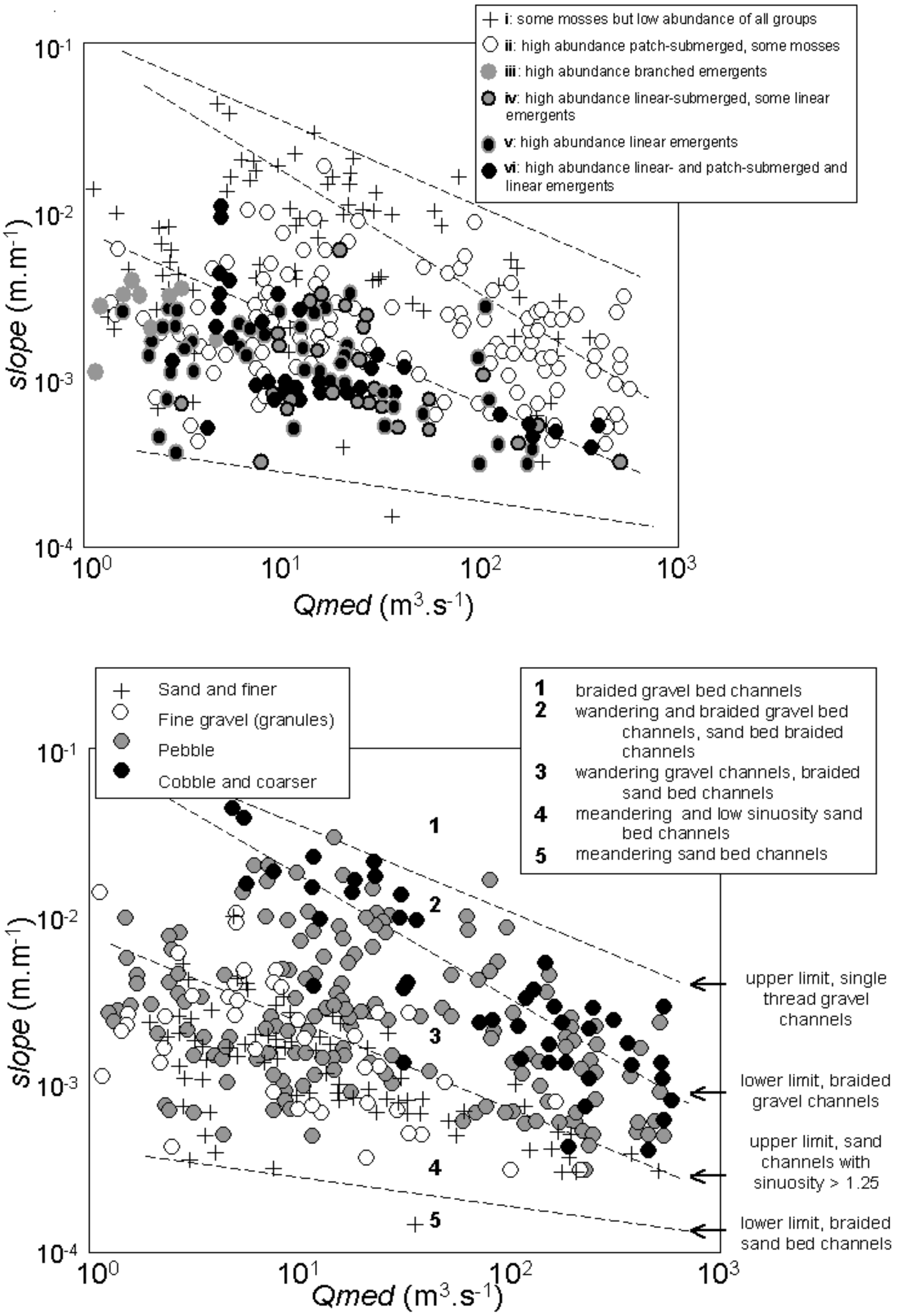


Figure 2.1.6 Associations between the median annual flood (Qmed), channel slope and groups of aquatic macrophyte morphotypes (upper graph) and bed sediment calibre (lower graph) (after Gurnell et al., 2010).

2.2 Conceptual Model of Vegetation - Hydromorphology Interactions

Riparian and aquatic plants both affect and respond to fluvial processes. Their above ground biomass modifies the flow field and retains sediment, whereas their below-ground biomass affects the hydraulic and mechanical properties of the substrate and consequently the moisture regime and erodibility of the land surface. At the same time plants are disturbed, removed and buried by fluvial processes. Thus the margins of river systems provide a critical zone where plants and fluvial processes interact to produce a diverse mosaic of dynamic landforms that are characteristic of naturally-functioning river ecosystems. It is important to understand these interactions between aquatic and riparian plants and fluvial processes, and to recognize how they contribute to trajectories of natural river change and recovery from human interventions. Such understanding is crucial to ensuring that river management and restoration work with these natural interactions so that outcomes have the best chance of being cost-effective and sustainable.

The interactions have a significant influence on river systems across space scales from individual plants to entire river corridors. Plant-scale phenomena structure patch-scale geomorphological forms and processes. Interactions between patches contribute to larger-scale and longer-term river geomorphological phenomena. Furthermore, the influence of plants varies through time as above- and below-ground biomass alter within the annual growth cycle, over longer-term growth trajectories, and in response to drivers of change such as climatic and hydrological fluctuations and extremes. Thus, although plant–hydromorphology interactions are present in all naturally-functioning systems, their nature depends on climate – biogeographical region, catchment - landscape unit – river segment, and river type contexts.

This section develops a conceptual model of plant-hydromorphology interactions, which is exlored in relation to a sample of European rivers in section 3.3. The model is built around the following spatial-scale related concepts:

1. Section 2.2.1 explains how regional physical processes place constraints (boundary conditions) around the species composition of the vegetation that may be interacting with hydromorphological processes in a particular catchment. It also introduces a hierarchy of scale-dependent hydromorphological influences on vegetation within catchments, relating to climate, moisture availability and fluvial disturbances. The hierarchy of spatial scales matches that underpinning the hydromorphological assessment methodology presented in Report D2.1.
2. Section 2.2.2 explores how vegetation is further constrained by longitudinal, lateral and vertical gradients in hydromorphological processes (section 2.2.2) within the river corridor network of a catchment. These process gradients affect the nature and extent of any ‘critical zone’ of vegetation-hydromorphology interactions within the river channel or its margins
3. The concepts of self-organisation and non-linear interactions between vegetation and physical processes within critical zones is introduced in section 2.2.3. These concepts provide a general framework in which specific vegetation – hydromorphology interactions can be considered in section 2.2.4.

4. Section 2.2.4 considers how plants, hydrological and fluvial processes interact within critical zones and how these interactions vary among rivers located in different biogeographical regions.
5. Section 2.2.5 reviews the types of pioneer landforms that may emerge as plants and physical processes interact within critical zones in different environmental settings. Pioneer landform initiation, and subsequent development or destruction affects the position, style-complexity, and dynamics of the interface between vegetation and hydromorphology, and accelerates channel changes induced by adjustments in fluvial processes.

2.2.1 Regional Context

The vegetation species and communities that may be found within river corridors are governed by a range of physical processes, which can be categorised into three broad groups: climate, moisture availability and fluvial disturbance. These processes constrain the potential species composition and vigour of vegetation that may be found at all spatial scales from biogeographical region to geomorphic unit (Table 2.2.1), and thus place physical boundaries on potential interactions between vegetation and physical processes.

2.2.1.1 Climate (Biogeographical Context)

In order to develop an appreciation of physical process–vegetation interactions and their relevance to the hydromorphology of European river systems, it is necessary to consider several biogeographical contexts that are relevant to Europe. While it would be possible to consider every one of the European biogeographical regions, for the purpose of developing one or more conceptual models, we focus on three broad biogeographical settings to illustrate the approach and examples from different European biogeographical zones are developed in section 3.3:

1. Moist Temperate (broadly corresponding to biogeographical zones 4 and 5 (the Atlantic European and Central European Biogeographic Provinces of Europe, http://www.globalbioclimatics.org/form/bg_med.htm, Rivas-Martinez et al., 2004) (Case study examples: River Frome, UK; Narew River, Poland).
2. Mediterranean (broadly corresponding to biogeographical zones 15, 16, 18, 19, 20, 21 (Mediterranean West Iberain, Betic, Murcian-Almeriensian, Mediterranean Central Iberian, Balearic-Catalonean-Provencal, Italo-Thyrrhenian, and Adriatic Biogeographic Provinces of Europe (Case study example Rivers Guadarranque and Guadalupejo, Spain).
3. The Alpine Biogeographic Province of Europe (zone 8) (Case study example: River Tagliamento, Italy).

These biogeographical settings are chosen to allow the conceptual model to incorporate cool, humid temperate and warmer, drier more seasonal climate regimes and also to consider steep, mountainous catchments with strong temperature gradients. These are three strongly contrasting environments for the development of a conceptual model and so should provide clear indications of how the model might be adapted for application within other biogeographical regions.

2.2.1.2 Moisture Availability

Once the biogeographical region has been defined, moisture availability reflects the way that the catchment and smaller spatial units translate the 'effective' precipitation regime into surface water, soil moisture and groundwater. The way in which this might control the response of aquatic and riparian vegetation and their feedbacks on river morphodynamics can be evaluated in two main ways:

(i) *With respect to the river flow regime type* (Deliverable 2.1 section 5.4.1). This indicates the reliability of flow within the river network and thus availability of moisture through the year to the river channel and its margins

(ii) *With respect to groundwater-surface water interactions*. Moisture availability is moderated at segment, reach and geomorphic unit scale by the permeability, depth and moisture dynamics in / through the river margin soils and sediments, any alluvial aquifer, and / or any underlying aquifers (e.g. shallow riparian zone groundwater – surface water interactions (GSI), GSI with a phreatic aquifer, GSI with deep (semi-) confined aquifer(s)). This segment to reach level moderation of moisture availability can be best assessed by coupling the *river type* with the appropriate seasonal GSI model (e.g. wet-temperate region, temperate wet season, temperate dry season, dry region – wet season, dry region) (see report D2.1 section 7). Further local variations in moisture availability may be reflected in local downwelling / upwelling reaches (which can be identified from well records or through low flow accretion assessments).

2.2.1.3 Fluvial Disturbances

Fluvial disturbances include inundation (depth-duration), sediment deposition (burial), shear stresses / drag imposed on plants (flow velocity gradients), and sediment erosion. These reflect the flow and sediment supply regimes to the river network and are moderated at the segment to reach scale by the valley-channel gradient, the river channel style / width (unit stream power) and they also vary across the valley bottom – floodplain.

2.2.2. Longitudinal, Lateral and Vertical Gradients

The three elements (climate, moisture availability, fluvial disturbances) accumulate to control the nature and strength of interactions between physical processes and vegetation:

1. The 'potential' vegetation composition is dictated by the biogeographical region and its potential distribution along the river system from headwaters to mouth in response to climatic gradients
2. Moisture availability controls whether a particular species can survive at a particular location and also its vigour and growth performance. In river corridors

the *vertical* depth and temporal dynamics of the water table are usually the most important hydrological variables. These are the main control on soil moisture in free-draining alluvial sediments and they vary spatially according to the structure and permeability of these sediments.

Table 2.2.1 Scale-dependent influences of water-related physical processes on vegetation.

	Climate (Biogeographical context)	**Moisture Availability (in addition to climate)**	**Fluvial Disturbance**
Region	Precipitation and Temperature (Macrobioclimates)		
Catchment	Precipitation and Temperature (Thermoclimatic belts)	Geology, Topography affecting water retention, deep percolation and aquifers	Location, Geology, Topography affecting regional features (e.g. droughts, avalanches, mudflows)
Landscape Unit	Precipitation and Temperature : Mesoclimate (Regional conditions due to Elevation, topography)	Geology, Topography and Soil condition, Land cover affecting water infiltration and moisture recharge/depletion	Magnitude, frequency and duration of water and sediment delivery to the river corridor (e.g. magnitude and frequency of droughts, avalanches, mudflows, organic debris flows)
Segment	Precipitation and Temperature :Meso-climate (Local conditions due to Elevation, topographic orientation, form and setting)	River-floodplain width, hillslope hydrology and river flow regimes. Segment-scale (alluvial aquifer) groundwater - surface water interactions (GSI)	Valley gradient and river entrenchment: river flow and sediment transport regimes (e.g. frequency and duration of floods and droughts, sediment and plant material erosion, transport, storage)
Reach	Precipitation and Temperature :Micro-climate (Local conditions due to wind, vegetation transpiration, water bodies evaporation,...	Cross sectional form and sedimentary structure, texture, permeability. Reach-scale GSI	Channel gradient, size, type – morphology, bed and bank materials(calibre, cohesion, erodibility), stream power in relation to reach-scale water, sediment, plant material dynamics
Geomorphic Unit	Precipitation and Temperature :Micro-climate (Point conditions due to vegetation shadow, water depth, updwellings, springs, velocity...	Microtopography, relative elevation, and distance relative to river bed. Sediment calibre, organic content, structure, and patch-scale GSI	3D position with respect to active channel, erosion resistance and stability.

3. Fluvial disturbances and their timing (relative to the nature and growth stage of the vegetation) provide further limits on whether the vegetation can survive. Different species have different tolerances to inundation (waterlogging) and burial, and different resistances to uprooting (stem and root strength) and undermining (root architecture and rooting depth). Therefore, species distributions reflect:

   a. The changing balance / dominance between different hydrological and fluvial processes as river confinement and gradient change from upstream to downstream (*longitudinally*) along the river

   b. The changing balance / dominance between different hydrological and fluvial processes across the river corridor (*laterally*) with increasing distance from and elevation above the low flow channel (which may flow perennially or ephemerally depending on climate / catchment context and distance longitudinally down the river)

The presence of particular plant species depends on whether all of these hydromorphological environmental conditions are suitable. Growth performance of a species is usually heavily influenced by moisture availability (the soil moisture and groundwater regime for riparian plants, the inundation regime for wetland and aquatic plants). Colonisation, establishment and survival of particular species are additionally constrained by hydrological and fluvial disturbances (inundation; drag; excavation; burial or battering from mobile sediments).

Figure 2.2.1 provides a schematic representation of how five different lateral zones within the river corridor, dominated by different hydrological and fluvial processes, may emerge along a river from steep, confined headwaters to lower gradient, unconfined floodplain reaches. In moist environments, a zone of perennially-flowing water is present in the low flow channel (zone 1, Figure 2.2.1). Beyond this, the frequency, duration and depth of inundation decreases towards the outer limits of the river corridor (floodplain / base of hillslopes). Within zone 2, inundation is most frequent, deep, and prolonged, leading to relatively high flow velocities and shear stresses and thus a high potential for the flowing water to mobilize, transport and deposit sediment and also to disturb (damage, uproot) plants. With increasing distance from the river (zone 3), inundation depth, duration and frequency decrease, reducing the potential for sediment mobilization and transport, and leading to a progressive fining of transported and deposited sediment coupled with an increase in the organic component of the deposited sediment until, in zone 4, sediment dynamics are negligible during inundation. In zone 5, which includes the most elevated areas of the river corridor, and those that are most remote from the perennial channel, inundation is extremely rare and subsurface water dynamics become the dominant control on vegetation. Within real river systems:

a these longitudinal and lateral zones are spatially irregular and patchy, reflecting the topographic and sedimentological complexity of the corridor;

b the hydrological and fluvial processes within the zones vary greatly through time;

c the boundaries of zones themselves may move in response to temporal shifts in hydrological and fluvial processes and / or shifts in the nature or vigour of the vegetation.

d Where a river is confined or partly confined by its valley, some of the outer zones may be missing (see parts marked 'confined' in Figure 2.2.1).

Figure 2.2.2 conceptualises the proportions of an unconfined river corridor that might be affected by zones 1 to 5 (Figure 2.2.2) within 7 groups of river types. These groups include river types 8 to 22 as defined in Deliverable 2.1, Table 7.2. River types 1 to 7 (Deliverable 2.1, Table 7.2) are not illustrated because they occur in confined or semi-confined situations where the width of the river corridor as well as hydrological and fluvial processes determine the presence and extent of zones 1 to 5. Note that in moist climates, high moisture availability in the least disturbed zone (zone 5), usually supports a dense vegetation cover, whereas in dry climates, this zone may suffer from a very low water table and thus low water availability and increasingly sparse vegetation cover with increasing distance from the river. In the latter case, zone 4 is likely to show the densest and most vigorous riparian vegetation cover because it gains water during dry periods through lateral seepage from the river channel or from groundwater in the alluvial aquifer below the river bed in ephemeral systems.

The river type numbers in each of the 7 groups are those defined in D2.1 section 7. Where more than one river type is listed for a group, the zone 1, 2, and 3 proportions of the river corridor width would tend to decrease as the river type number increases. As the driving variables (e.g. valley gradient, sediment calibre, flow regime, and sediment regime) vary along a river or between different rivers in the same biogeographical zone, different river types may occur, providing proportionately different lateral zone gradients (Figure 2.2.3) within which vegetation and physical processes can interact. It is important to stress once again, that the five zones and also the river planform types are not static. The zones may expand or contract as fluvial processes change and vegetation is eroded or encroaches into the more dynamic areas (zones 1, 2, 3) of the river's active corridor, and in extreme cases, these interactions may lead to a change in the river planform type.

2.2.3. Non-linear Interactions between Vegetation and Physical Processes

Thus far the discussion has implied that water-related physical processes (climate, hydrological processes, and fluvial processes) create the physical environmental envelope that controls the probable species composition of the vegetation, the growth performance of the vegetation, and the fluvial processes that limit vegetation dynamics. Reference has been made to interactions between vegetation and fluvial / hydrological processes. These interactions fluctuate through time according to the varying intensity of the fluvial / hydrological processes. They also vary through time according to the ability of the vegetation to survive disturbance by hydrological and fluvial disturbances or to recolonise areas where vegetation has died from hydrological stresses or has been removed or buried by fluvial processes.

Interactions between plants and physical processes can be so fundamental that some plant species may control key characteristics of ecosystems. In this sense the plants modify the properties of their environment and, in doing so, create new environmental conditions that can support other species. Organisms that directly or indirectly control the availability of resources by causing changes to their environment are termed 'ecosystem engineers' (Jones et al., 1994). By altering their environment these species are actively involved in 'niche construction' (Odling-Smee et al., 1996), increasing their chances of survival. By engineering the ecosystem, plants make it more resistant to modification by physical processes, and so the interaction between plants and physical processes becomes non-linear with hysteretic patterns (i.e. looped relationships, whereby, for example, vegetation can remain, once established at higher intensities of a particular process, than it shows during colonization under the same process intensity) between the two sets of variables (vegetation, physical).

A 'hot spot' or 'critical zone' for ecosystem engineering of the fluvial system by plants includes the area of the river corridor that is perennially inundated by flowing water (zone 1) and any adjacent areas that are frequently inundated and thus additionally subject to significant shear stresses and erosion and deposition of sediment (zone 2). Somewhere within these two zones is the leading edge of plant-fluvial process interactions. Here some plant species actively influence the margin between the river channel and the riparian zone and so affect channel width, channel form, channel edge dynamics and the transition from one river planform type to another. The position of the leading edge, the plant species that act as fluvial ecosystem engineers, and the landforms that they create, vary with climate (biogeographical zone, elevation etc.), moisture availability and river type.

Beyond this 'critical zone' of vegetation-fluvial process interactions, particular plant species may also interact with hydrological processes (moisture availability) and trap fine sediments (zone 3) to engineer riparian-floodplain habitats, affecting the vegetation (species, communities, age and patch structure) and micro-morphology of the land surface of zones 3 to 5.

A component of the development of vegetation patterns and associated morphological patterns within several of the zones of the river corridor, and particularly the 'critical zone' of vegetation-fluvial process interactions, is self-organisation. Self-organisation is not necessarily driven by heterogeneous environmental conditions but by interactions and feedbacks between organisms (e.g. vegetation) and the environment (e.g. the water cycle) (Scheffer et al., 2005). 'The feedback can be negative, for example when organisms deplete resources, leading to competition. Positive feedback can also occur, for example if organisms help others to survive through facilitation, by modifying the environment. If positive and negative feedbacks occur at different spatial scales (i.e. scale-dependent feedback), they might invoke regular pattern formation in ecosystems, even in the absence of environmental heterogeneity' (Rietkerk and van de Koppel, 2008, p169). In the context of vegetation-physical process interactions within river corridors, positive feedback illustrates the way in which plants can act as ecosystem engineers, whereas negative feedback reflects competition for resources such as water or nutrients. Resource scarcity (e.g. low water availability) leads to spatial reorganisation of consumers (e.g. plants) and resources (e.g. water) until resource scarcity reaches a threshold where consumers can no longer act as ecosystem engineers and the system moves to a homogenous state in which the consumer-engineers are absent (Figure 2.2.4, Rietkerk et al., 2004).

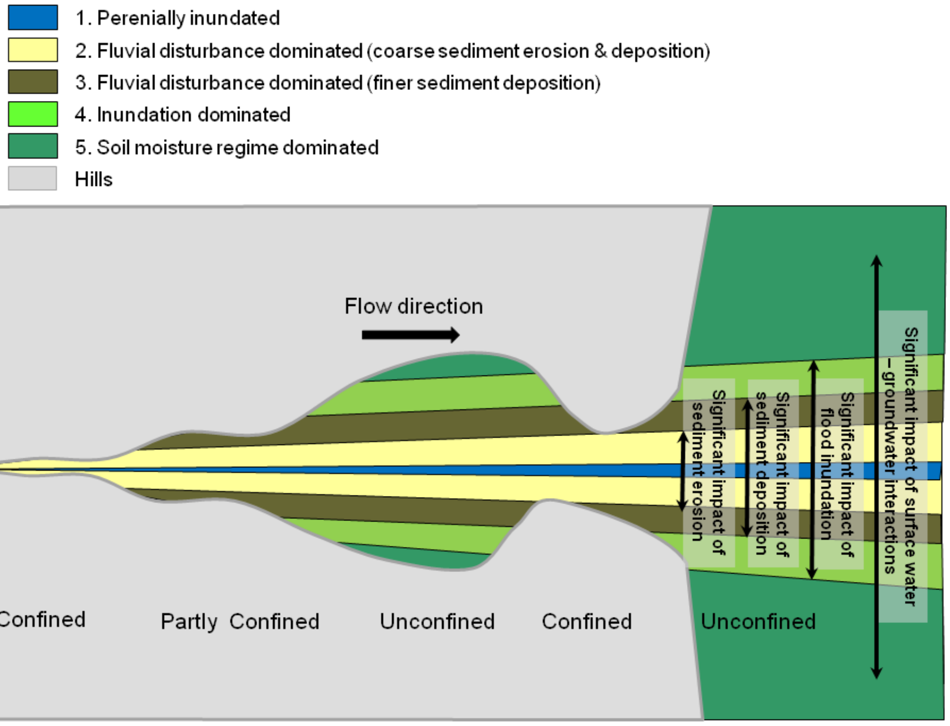


Figure 2.2.1 Longitudinal, lateral and vertical variations in the dominant hydrological and fluvial processes that influence vegetation composition, growth performance and turnover along a braided river (types 8,15) located within a valley of varying confinement.

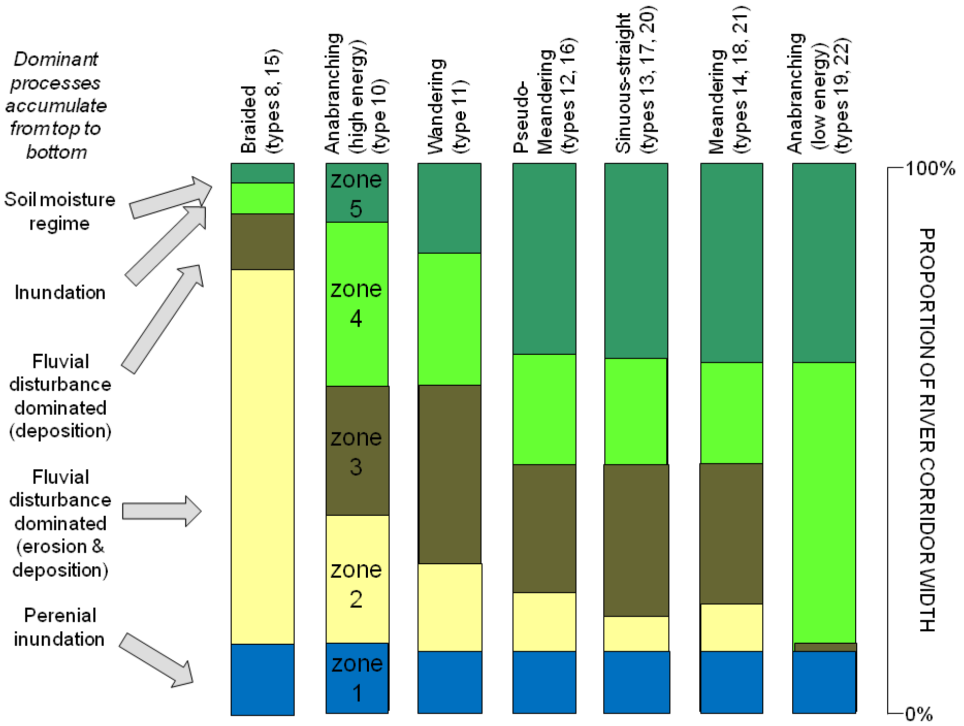


Figure 2.2.2 The relative proportions of the five river corridor lateral zones (see Figure 2.2.1 for key) where vegetation might be dominated by the different hydrological and fluvial processes in unconfined reaches subject to different river types (river type numbers refer to the types defined in D2.1, section 7).

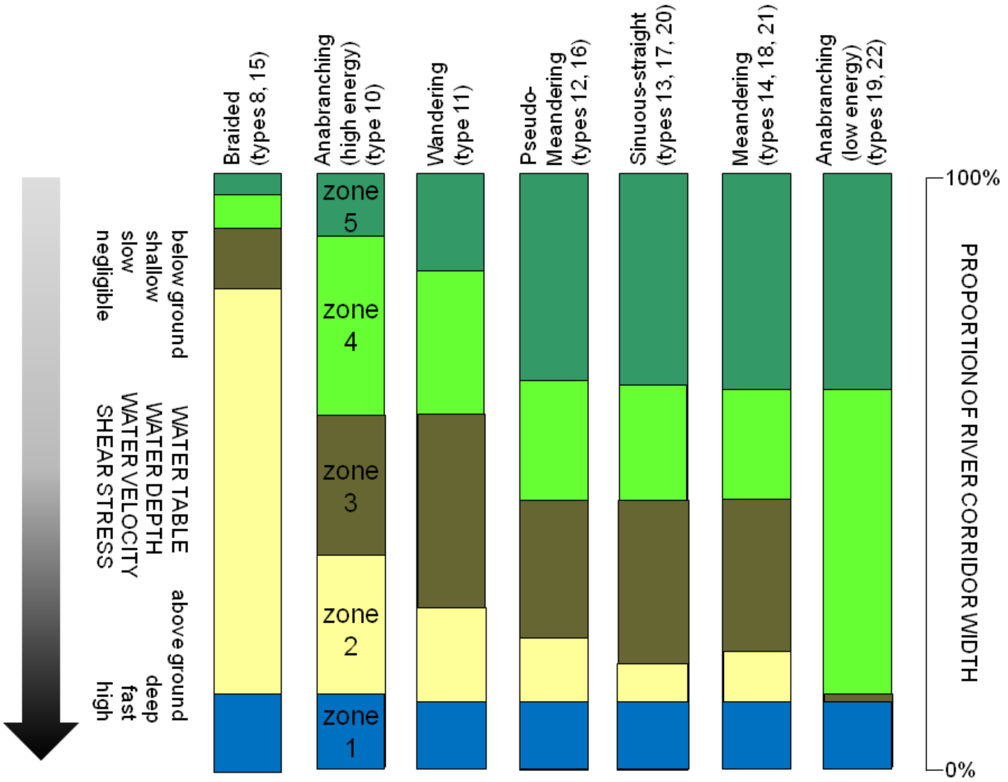


Figure 2.2.3 The hydrological and fluvial process gradients (left) that drive the lateral zonal mosaic (see Figure 2.2.1 for zone colour key, river type numbers refer to the types defined in D2.1, section 7). Note that the process gradients vary in their extent along the left vertical axis according to the river planform being considered

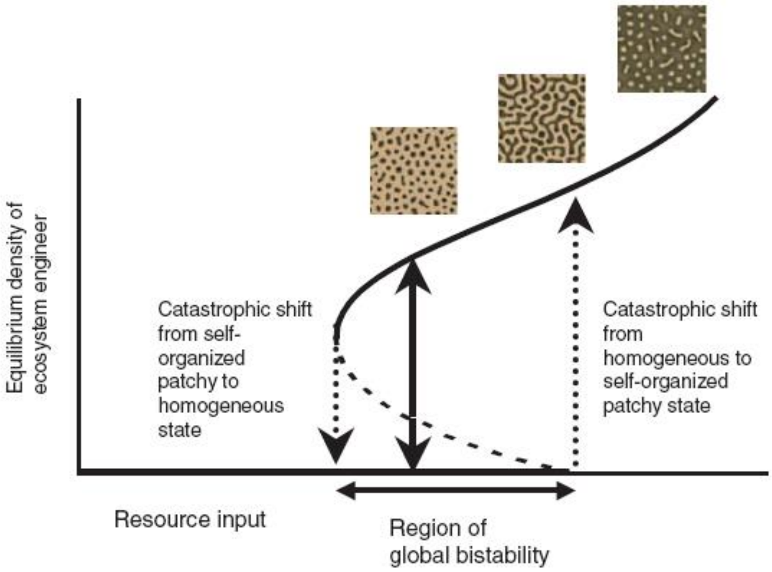


Figure 2.2.4. Ecosystems may undergo a predictable sequence of emerging self-organized patchiness as resource input decreases or increases. Thick solid lines represent mean equilibrium densities of consumers functioning as ecosystem engineers. Dotted arrows represent catastrophic shifts between self-organized patchy and homogeneous states, and vice versa. Dark colors in the insets represent high density. The range of resource input for which global biostability and hysteresis exists is between these dotted arrows. Solid arrows represent development of the system toward a coexisting self-organized patchy state or homogeneous state, depending on initial ecosystem engineer densities. (source: Rietkerk et al., 2004)

Some illustrations of hydrologically-related self organisation that may occur within the five zones of river corridors are listed in Table 2.2.2. For example, feedbacks occur between water availability and plant growth in arid areas that are relevant to zone 5 and possibly zones 4 and 3 (Figure 2.2.1) in river corridors with hot, dry climate environments, where extreme floods are rare and intervening periods of dry conditions are prolonged. In such hot, arid environments, vegetation shades the ground reducing surface evaporation and root systems encourage water infiltration into the soil such that vegetation persists once it is present but once vegetation disappears the bare soil is too hostile for recolonisation. Similarly in waterlogged peatland ecosystems, there is a positive feedback between groundwater depth and plant productivity, such that patches of highly productive plants tend to be present on locally elevated drier sites. In both arid and peatland examples, the patches of plant consumers harvest resources (water, nutrients) from their surroundings. As resource availability decreases, vegetation goes through a predictable sequence of increasing patchiness until it disappears and bare soil or a different vegetation type replaces it. Greater inputs of resources are required to reverse such transitions.

In fluvially-disturbed systems, these processes of self-organisation are accentuated by interactions between the land surface and flowing water and sediment. In general, patches with relatively high above-ground biomass (e.g. vegetated patches in dry, arid areas, vegetation tussocks and ridges in wetlands, pioneer islands on river bars, and macrophyte stands on river beds) slow flow velocities during inundation and trap transported sediments. In addition, when rainfall or overland flow occur in dry, arid areas, the vegetated patches preferentially intercept and absorb water (e.g. Wainwright et al., 2002). Constriction of flowing water between elevated patches increases flow velocities so that sediment is not deposited and these areas may be scoured. This is particularly important in zones 1 and 2, where bare areas become colonised by plants, which may subsequently develop into larger vegetated patches, elevated by sediment deposition to form pioneer landforms that may subsequently enlarge and coalesce into larger landforms. However, the rate and nature of these interactions and the associated landforms depends upon the species of plant engineers, their growth performance, and the frequency, magnitude and duration of fluvial disturbance events, all of which vary with climate / biogeographical zone, moisture availability, and river type.

2.2.4 'Critical zone' of Interactions between Plants and Fluvial Processes

With a focus on zones 1 and 2, Figure 2.2.5 provides a schematic representation of the position of a critical zone of vegetation-physical process interaction in a humid river system at the interface between the plant-dominated floodplain and the fluvial process-dominated main channel (upper graph) and how that critical zone may shift towards the floodplain in high-energy river systems and towards the channel in low energy river systems (lower graph), accompanied by a shift in the type of plant engineers from riparian to aquatic species (from Gurnell, 2014). Figure 2.2.6 provides an example of interaction between fluvial processes and riparian plants, particularly tree species, that is illustrated by a complex pattern of erosion and retention of sediment within zone 2 of the wandering River Tech, France (from Corenblit et al., 2009).

Table 2.2.2 Examples of patterned vegetation and micro- to meso-morphology (pioneer landforms) formed by self-organisation in hydrologically-related contexts.

Environmental Setting	Vegetation-Hydromorphology Interaction-Feedback Processes	Reference
Drylands (zone 5 and in some cases zones 4 and 3 in dry climate areas)	The presence of vegetation increases water infiltration (roots) and decreases soil evaporation. Vegetation extracts moisture from surrounding areas to support evapotranspiration, while differences in water infiltration reduce the supply of moisture to surrounding areas. Thus patches of vegetation persist once present, but bare soil is too hostile for recolonization once vegetation is removed.	Rietkerk et al., 2000.
	Okavango Delta: Termite mounds accumulate nutrients and become colonized by terrestrial vegetation which attracts browsers / grazers who further enrich the nutrient supply leading to island development	Gumbricht et al., 2004.
Wetlands (zones 5 and 4 in wet environments, zones 4 and 3 in less wet environments)	Mires often display hummocky / ridged patterning as a result of positive feedback between plant productivity and groundwater depth. This reflects increased production of vascular plants on drier sites.	Rietkerk et al., 2004.
	Florida Everglades: Subsurface flows of water are induced by tree evapotranspiration, which redistributes nutrients from surrounding areas towards tree islands, this increases primary productivity and peat development which increases the size and elevation of the tree islands.	Wetzel et al., 2005.
Severe fluvial disturbance dominated (zone 2 in strongly fluvially-disturbed environments)	Uprooted trees deposited on bars, sprout and produce roots, the trees are anchored by their roots and their sprouting foliage traps sediment from water and wind transport leading to island development. Flowing water is concentrated between the developing islands during floods leading to scour and vegetation removal.	Gurnell et al., 2001, 2005. Francis et al., 2009.
Submerged (zone 1)	The main mechanism for pattern formation in aquatic river vegetation is scale-dependent feedbacks between aquatic plant growth (submerged and emergent), water flow velocity and erosion and sedimentation of the river bed. Within vegetation patches, flow velocity reduction leads to sedimentation, whereas between patches flow velocity is increased resulting in less sedimentation or scour. Plant survival is increased within patches and decreased between patches.	Schoelynck et al., 2012.

The precise functioning of vegetation-fluvial process interactions is likely to vary not only with river energy but also with the biogeographical setting of the river. Figures 2.2.7 to 2.2.10 present, for different biogeographical settings (e.g. Atlantic European, Alpine, Mediterranean), schematic representations of (A) the typical average and seasonal variability in lateral moisture availability (alluvial groundwater and surface water levels, and (B) the typical lateral gradients in fluvial disturbance intensity according to river energy and whether the flow regime is ephemeral. The interactions between the hydrological processes of (A), the fluvial disturbances of (B) and vegetation, result in the the typical lateral gradients in vegetation cover and biomass shown in (C) and critical zones of vegetation – fluvial processes interactions shown in (D).

In moist climate settings (e.g. the Atlantic European and Alpine (middle and lower reaches) biogeographical zones, Figure 2.2.7), rivers generally have perennial flow regimes and plants grow freely across the moist floodplain. The critical zone shifts laterally outwards from the edges of the low flow river channel (zone 1 edge and zone 2) according to river energy and style, and vegetation cover and biomass are consistently high in zones 3, 4 and 5. In very low-energy and poorly drained conditions in moist climate settings (e.g. the Atlantic European biogeographical zone, Figure 2.2.8), vegetation-fluvial process interactions are largely confined to the perennially-flowing channel (zone 1). As a result, vegetation persists across the channel as well as the floodplain, and areas of bare sediment are confined almost entirely to gaps between aquatic plants on the river bed. In these systems, although plants provide a near-continuous cover across zones 2, 3, 4 and 5, sensitive vegetation-hydrology interactions may occur across the floodplain as plant communities interaction with high water tables and soil waterlogging associated with the groundwater regime.

In settings where floodplain moisture is more restricted (e.g. the very free-drained coarse sediment river margins and seasonal snowmelt regimes of high Alpine rivers, Figure 2.2.9, or the seasonally dry climate and river corridors of the Mediterranean biogeographical region, Figure 2.2.10), rivers with seasonally ephemeral flows become common. Strong seasonal variability in water availability results in strong vegetation-hydrology interactions in all of zones 1 to 5. These result in sparse vegetation cover in zones 4 and 5, such as across the floodplains of Mediterranean rivers and the coarse sediments of lower hillslopes of high Alpine systems, as well as strong vegetation-fluvial process interactions in zones 1 and 2 associated with the highly variable river flows.

Figure 2.2.11 illustrates patchy vegetation resulting from interactions between plants and fluvial processes within critical zones of three example rivers (River Frome, UK; River Guadarranque, Spain; River Tagliamento, Italy).

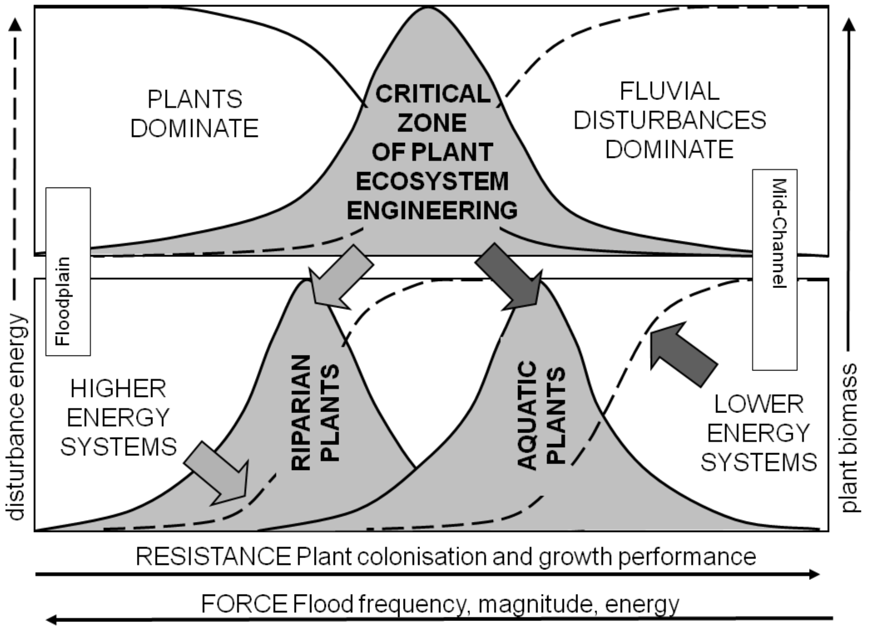


Figure 2.2.5 The location of a critical zone of plant engineering between areas dominated by fluvial disturbances and by plants (upper graph), and the potential shift in critical zone location and plant engineer type between rivers of different energy (after Gurnell, 2014).

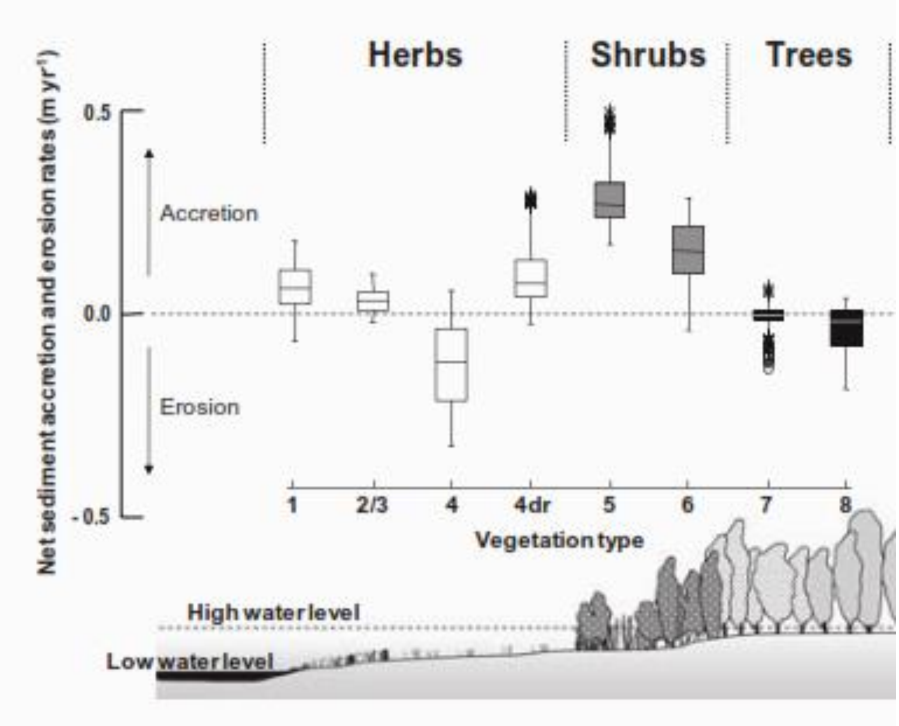


Figure 2.2.6 Transition from bare sediment to closed riparian forest between zone 1 (low flow channel) and zone 3 (tree covered area) of the wandering gravel bed River Tech, France, highlighting vegetated zones of sediment accretion within zone 2 (herbs and shrubs) (Source: Corenblit et al., 2009).

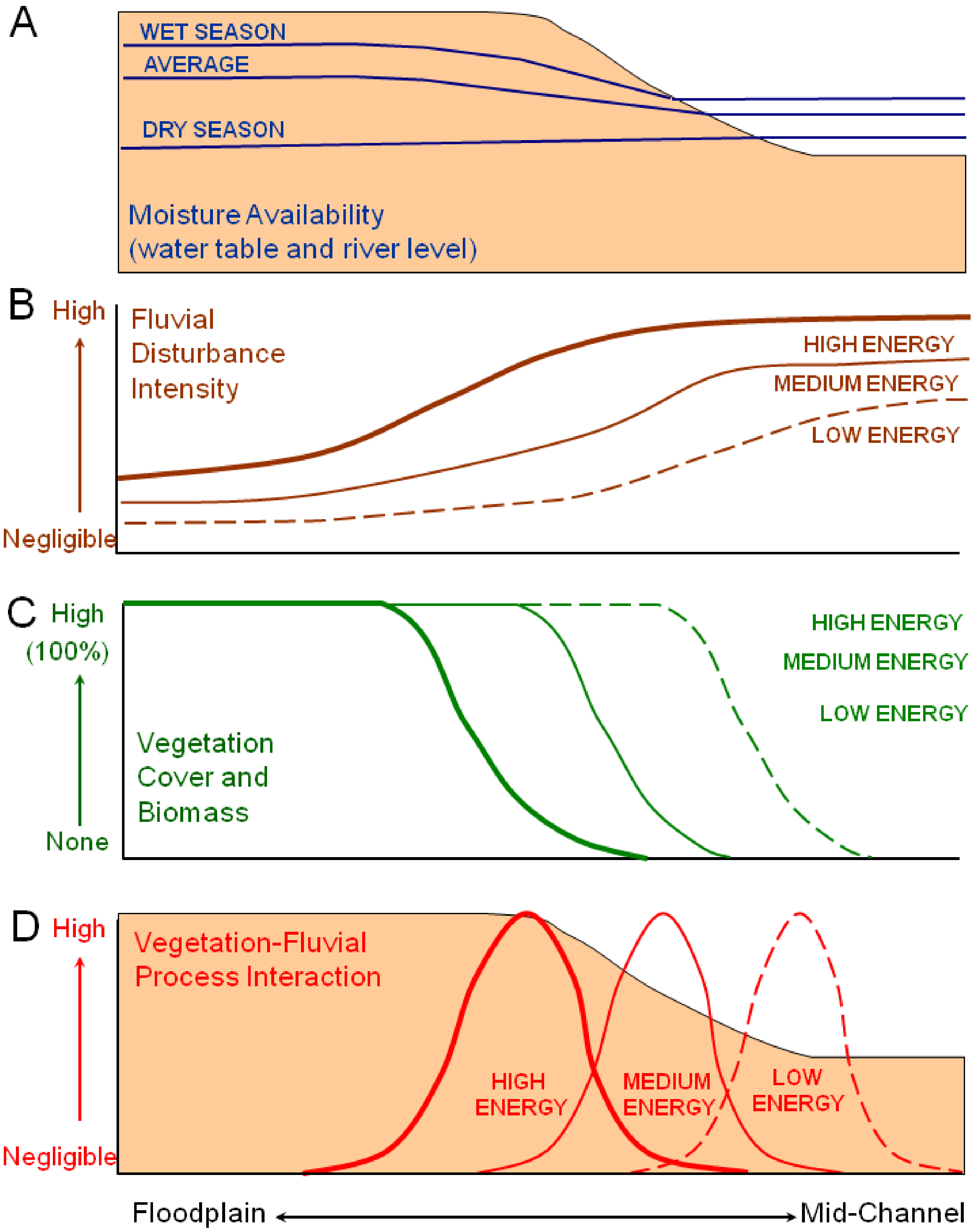


Figure 2.2.7 Schematic representation, for rivers in moist climates (e.g. Atlantic and Central European; middle-lower reaches of Alpine rivers), of lateral gradients in:

- **A. typical river and groundwater levels (average, dry season, wet season).**
- **B. fluvial disturbance intensity associated with rivers of different energy.**
- **C. vegetation cover and biomass associated with rivers of different energy.**
- **D. the position of critical zones of vegetation fluvial process interactions associated with rivers of different energy.**

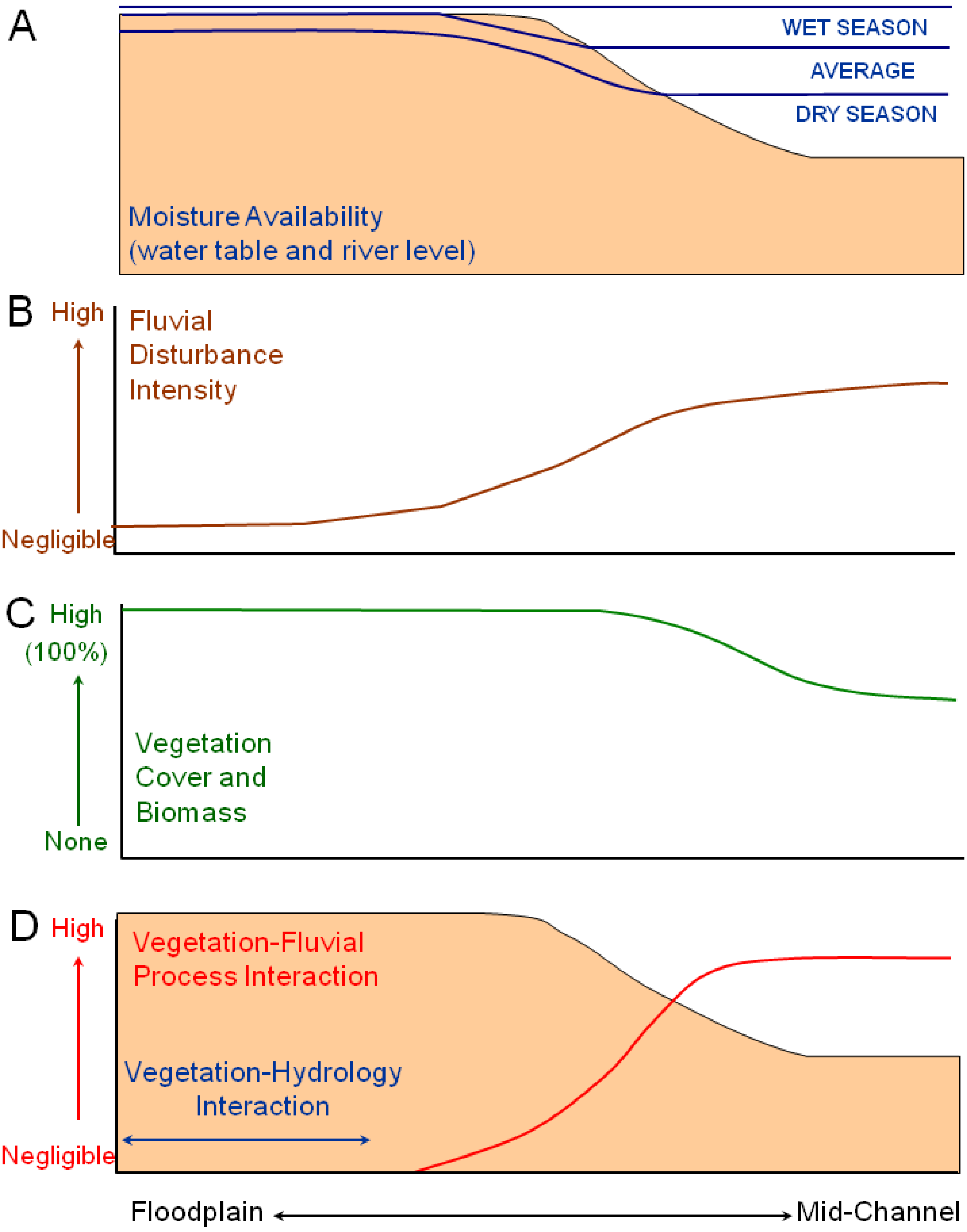


Figure 2.2.8 **Schematic representation, for very low energy, poorly-drained rivers in moist climates (e.g. Atlantic and Central European), of lateral gradients in:**

- **A. typical river and groundwater levels (average, dry season, wet season).**
- **B. fluvial disturbance intensity.**
- **C. vegetation cover and biomass.**
- **D. the position of a critical zone of vegetation fluvial process interactions and area of the river corridor affected by strong vegetation-hydrology (groundwater) interactions.**

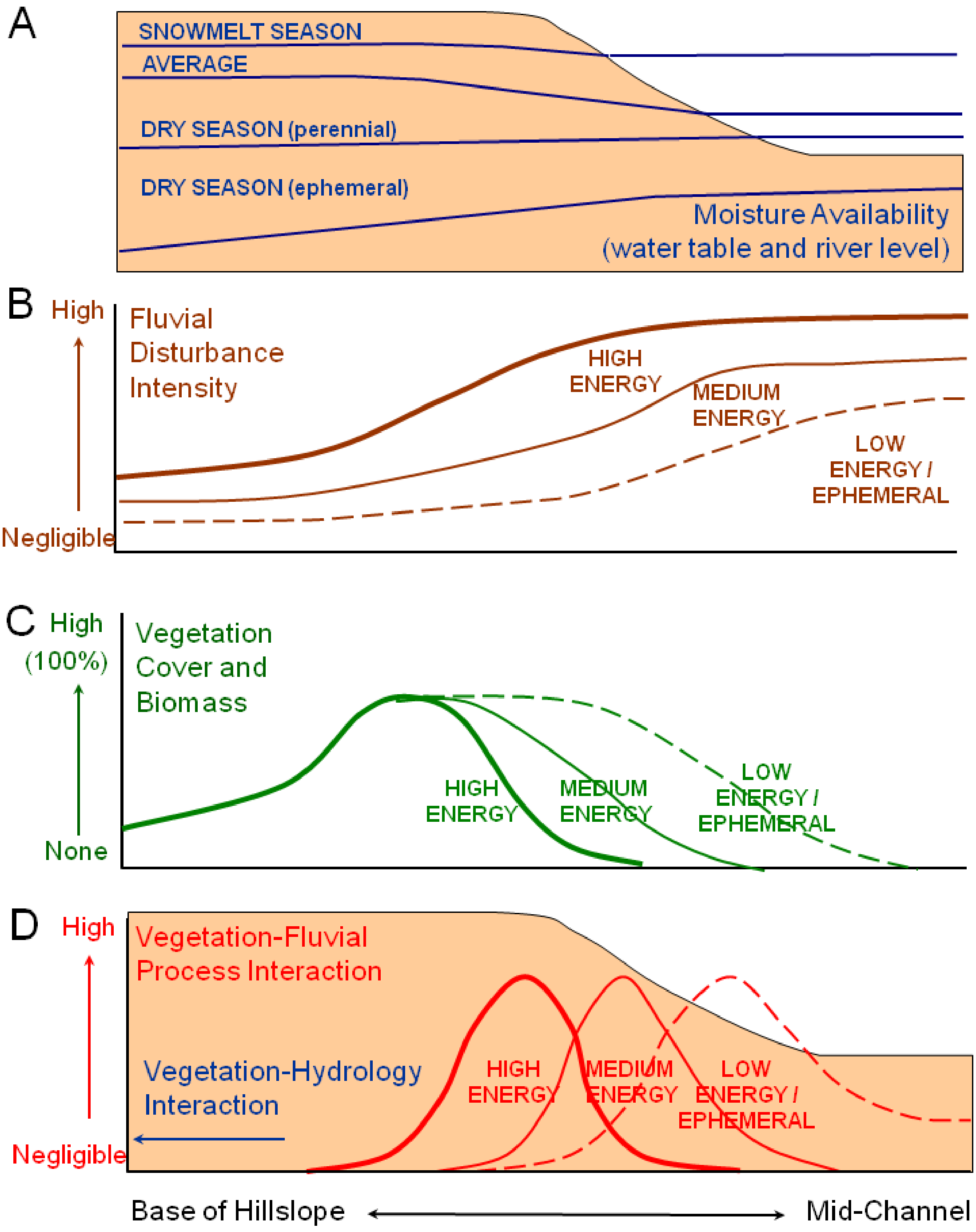


Figure 2.2.9 Schematic representation, for high Alpine rivers, of lateral gradients in:

- **A. typical river and groundwater levels (average, wet season, dry-season –perennial rivers, dry season – ephemeral rivers).**
- **B. fluvial disturbance intensity associated with rivers of different energy and flow persistence.**
- **C. vegetation cover and biomass associated with rivers of different energy and flow persistence.**
- **D. the position of critical zones of vegetation fluvial process interactions associated with rivers of different energy and flow persistence and area of the river corridor affected by strong vegetation-hydrology (groundwater) interactions.**

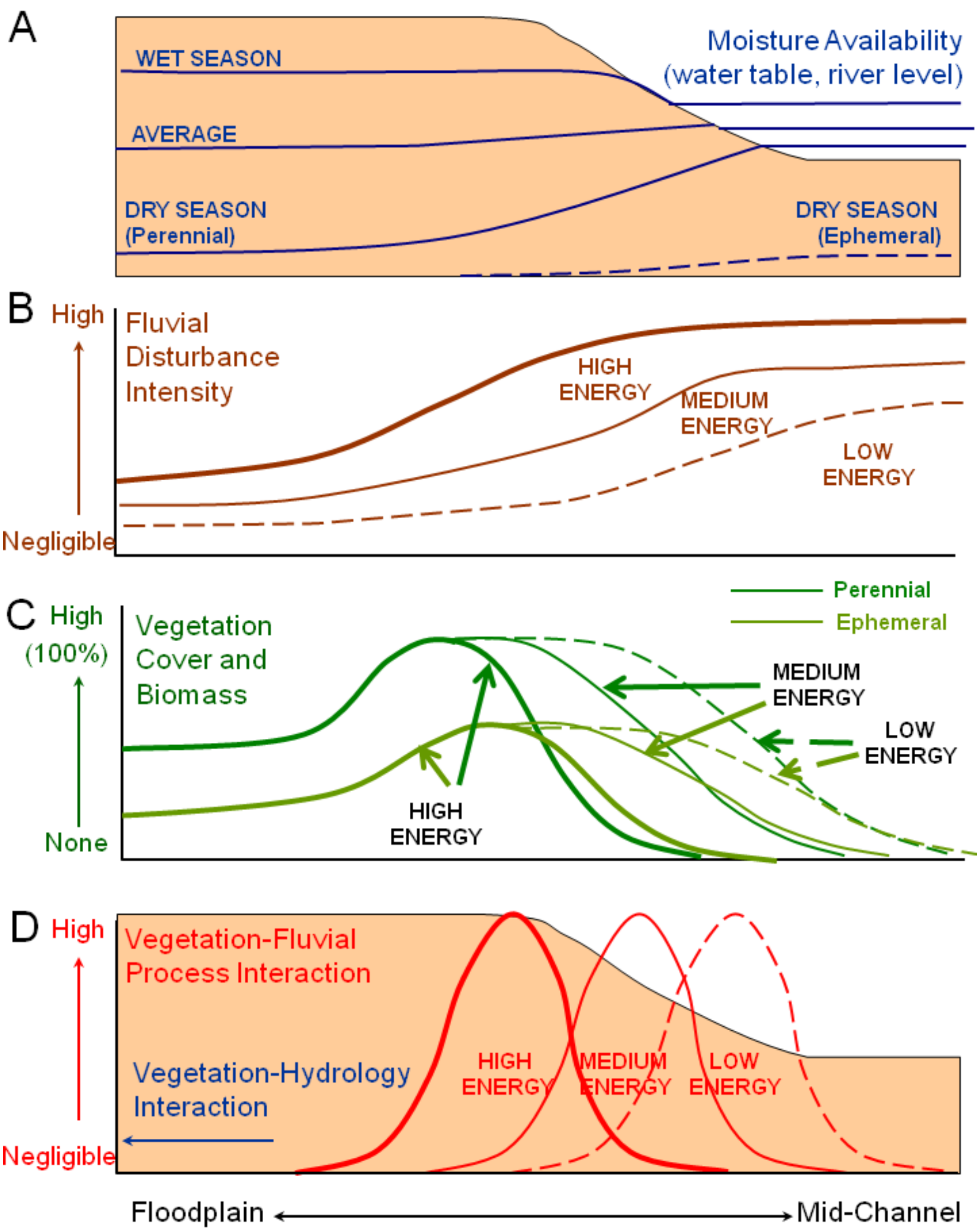


Figure 2.2.10 Schematic representation, for Mediterranean rivers, of lateral gradients in:

A. typical river and groundwater levels (average, wet season, dry-season –perennial rivers, dry season in ephemeral rivers where water table is below the channel bed).

B. fluvial disturbance intensity associated with rivers of different energy and flow persistence.

C. vegetation cover and biomass associated with rivers of different energy and flow persistence. In the case of ephemeral streams vegetation cover and biomass is reduced and occupies narrower riparian bands; aquatic plants can grow in the middle of the channel all the year in low energy rivers and at the end of wet season in medium and high energy rivers.

D. the position of critical zones of vegetation fluvial process interactions associated with rivers of different energy and flow persistence area of the river corridor affected by strong vegetation-hydrology (groundwater) interactions.

Figure 2.2.11 Examples of patchy vegetation within critical zones of vegetation-fluvial process interaction on the rivers Frome (left, submerged and emergent aquatic plants), Guadarranque (middle, riparian trees) and Tagliamento (right, riparian trees).

2.2.5 Landform construction in critical zones of vegetation-fluvial process interaction

Within the critical zone of fluvial ecosystem engineering by plants (Figures 2.2.5, 2.2.6 to 2.2.7), areas subject to self-organised patchiness (section 2.2.3) are dynamic in time and space and, as either the vegetation or the fluvial processes come to dominate, there is a transition from a patchy vegetation assemblage to either bare sediment (vegetation removed by extreme fluvial disturbances) or a more homogenous, continuous vegetation cover (vegetation expansion and succession progresses in the absence of sufficiently erosive fluvial disturbances). Furthermore, between these end points the patches either become smaller and more widely spaced (under fluvial disturbances) or grow and start to coalesce (under vegetation expansion and succession). Transitions across river corridors from more disturbed to less disturbed zones show a gradient from bare sediment through patchy vegetation to continuous vegetation cover in zones 1 to 3 (Figure 2.2.1), and transitions between river types through time, show a similar gradient or its reverse (e.g. Figure 2.2.3).

2.2.5.1 Size, Scaling and Complexity

In relation to their interactions with river flows, plants can be considered to be analogous, in many ways, to sediment particles and aggregates of particles (Table 2.2.3). The larger and denser the plant-related 'particle' the higher the shear stresses and flow velocities required for mobilisation and transport. However, plants have additional properties that affect their mobilisation, transport and deposition. They root into the substrate, making them more difficult to mobilise than mineral particles, and allowing them, despite their relatively low density and thus potential mobility, to remain in place and act as 'obstacle clasts' inducing stoss-side (upstream) and wake-tail (downstream) accumulations of other plant and sediment particles, in an analagous manner to the cluster microforms that develop around large mineral sediment particles (*sensu* Brayshaw et al., 1983). Such accumulations underpin 'pioneer landform' development associated with plants. In addition, their morphology is often more complex than mineral sediment particles, increasing their potential to snag against the river channel boundary and thus increasing their potential to be deposited. These properties allow plants to be retained in river systems more easily than sediment particles and, as a result, to act as important stabilisation and retention structures for other plant and mineral sediment particles.

Table 2.2.3 'Vegetative particles' of different size (modified from Gurnell, 2007)

Size	Small	←----------	----------	----------→	Large
Single 'particle'	Seed	Leaf, twig, root	Non-woody plant, branch	Shrub, trunk	Tree
Aggregate of 'particles'	Aggregate of mineral and organic particles including seeds	Clod of soil with contained roots or rhizomes	Non-woody plant or turf block with attached soil	Root wad of tree or shrub with attached soil	Tree with attached soil

Once mobilised, large and irregularly shaped plants or plant pieces (e.g. large wood pieces, uprooted trees, uprooted aquatic plants) can become jammed in 'small' channels, providing major features that can transform flow hydraulics and thus the retention and sorting of sediment particles and the creation of landforms through scour and deposition processes. Equally, growing plants that are 'large' relative to the size of the river channel (or individual distributary channels in multi-thread systems) can dominate flow hydraulics, sediment dynamics and channel form. Here 'small' and 'large' are relative terms, comparing the size of the vegetative particles to the size of the river channels and flow paths through which they are being transported.

In addition, for aquatic plants, Gurnell et al. (2010) identified from an analysis of information on the abundance of different morphotypes with British rivers (Figure 2.1.6), that significant cover of linear emergent and patch submerged species was limited by a combination of median annual flood discharge ($Q_{pmedian}$) and slope. Subsequent analysis of a specially collected field data set (Gurnell et al., 2013), indicated that the maximum unit stream power associated with 5% cover of the common linear emergent species, *Sparganium erectum*, was 110 $W.m^{-2}$, and with >25% cover was 60 $W.m^{-2}$. These energy thresholds are indicative of an upper limit of approximately 100 $W.m^{-2}$ beyond which aquatic plants are extremely unlikely to be significant in initiating pioneer landform construction.

2.2.5.2 Landforms associated with Plants in 'Small', 'Intermediate' and 'Large' Rivers.

The above discussion illustrates why it is important to understand the scaling between plants and the rivers with which they interact. A first step is to understand how river size has been scaled previously with respect to bed sediment. Church (1992) defined three classes of river size ('small', 'intermediate', 'large') according to relative roughness (D/d): the ratio of grain diameter of the bed material (D) and flow depth (d). He suggested that D/d is typically >1 for 'small' rivers, where individual sediment particles are significant elements of channel form; 1 > D/d > 0.1 for 'intermediate' rivers, where single aggregations of particles such as bars are major components of channel form; and D/d < 0.1, where neither individual particles nor single aggregations of particles have a major influence on channel form. Church also considered the influence of large wood in the context of these channel size classes, considering that individual wood pieces would be significant morphological elements in 'small' rivers, whereas aggregations of wood pieces (wood jams) could block rivers of 'intermediate' size. Gurnell et al. (2002) extended Church's concept, comparing the size of the vegetative particles to the size of the river channels and flow paths through which they are transported to help evaluate the storage and dynamics of wood in rivers. They considered the relative importance of hydrological properties (flow regime, sediment transport regime), wood properties (piece size, buoyancy, morphological complexity) and geomorphological properties (channel width, river type) in 'small', 'medium' and 'large' rivers, where 'small' rivers were defined as having a smaller width than the majority of wood pieces (e.g. width < median wood piece length); 'intermediate' channels had widths greater than the length of most wood pieces (e.g. width < upper quartile wood piece length); and 'large' channels had widths greater than the length of all the wood pieces delivered to them. A similar approach could be applied to all vegetative particles and, in particular, could be adapted to apply to individual plants and plant stands growing within the active channel. In this case, individual plants could form a significant component of 'small' river channels, whereas individual stands of plants could form a significant component of 'intermediate' rivers. Thus the size of channels in relation to the potential of plants species to engineer pioneer landforms is classified as 'small', intermediate' or 'large' depending on both the absolute size of the river channel and the size of the engineering plant species. The resultant landforms also differ in their character, size and frequency according to the size of the river channel and the size of the engineering plant species. Table 2.2.4 illustrates some of the pioneer landforms that may emerge from interactions between 'vegetative particles' and fluvial processes. In general, the illustrated landforms are associated with aggregations of riparian trees and wood pieces or aquatic plants, and appear within the critical zone as individual landforms in 'intermediate' size rivers and as assemblages of patch-sized features in 'large' size rivers. Based on these definitions, Figure 2.2.11 shows examples of one 'inermediate' (Guadarranque) and two 'large' rivers (Frome, Tagliamento) in the context of the influential plant species and vegetation-related landforms that are present.

2.2.5.3 Landforms associated with dead wood in rivers of different size and type

Abbe and Montgomery (2003) provide the most comprehensive attempt to classify dead wood-associated landforms based on their research on the Queets River, USA. They considered landforms associated with autochthonous and allochthonous wood both separately and in combination. The following three-fold classification of the wood jams defined by Abbe and Montgomery (2003), attempts to relate them to the channel size categorisation described in section 2.2.5.2 by Gurnell et al. (2002).

Three types of autochthonous (*in situ)* wood jams are typical of 'small' rivers and were named by Abbe and Montgomery (2003) as bank input, oblique log steps, and normal log steps.

> *Bank input jams*, as their name suggests, are simply trees or other large wood pieces that have fallen into the river from the bank, where they have remained *in situ* because of their large size relative the channel (i.e. these are 'small' river wood features). They are usually only partly located in the channel, providing the key pieces for 'partial jams' (Gregory et al., 1985), which extend part of the way across the channel, and may induce scour of pools on the river bed; erosion of the opposite river bank; and if the wood persists in the medium term, significant sediment and wood retention; and local strengthening of the river bank that can ultimately drive lateral channel migration.
>
> *Oblique and normal log steps* are also produced by tree fall with little downstream movement in 'small' rivers. However, for log step formation the large wood key piece completely spans the channel, partly or completely blocking the flow, so that mobile bed material and other wood pieces are trapped to create a step in the river bed profile. These are distinguished from *bank input jams* by the orientation of the key piece with respect to the channel plan.

Combination jams combine autochthonous and allochthonous wood. The key pieces are usually locally-produced but these jams are also characterised by large quantities of mobile wood pieces which significantly affect their form.

> *Channel spanning active / complete jams* As river channels widen and channel gradients reduce, log steps are transformed into channel spanning log jams. This transition reflects the fact that in 'intermediate' size rivers only a small proportion of wood pieces remain *in situ* while others move downstream until they become trapped by larger, channel-spanning pieces. These accumulations of wood have been classified as 'complete' and 'active' jams by Gregory et al. (1985), with active jams distinguished because they provide a sufficient flow barrier that they induce a step in the water surface profile at baseflow. Log steps not only induce steps in the bed profile through sediment retention but also through the development of downstream plunge pools and bars.
>
> As channels widen, other jam types also appear as autochthonous and allochthonous wood interact:
>
> *Valley jams* are large accumulations of wood that extend across and beyond the river channel, affecting much of the valley bottom. They occur when large trees fall and block the channel sufficiently to divert flow, leading to undermining of other trees. As a result, fallen trees become widely distributed and can trap mobile wood to form large complex jams. Land sliding and wind throw can also contribute to the initiation of valley jams. These features affect the river's long-profile and produce a complex of hydraulic habitats which may lead to wood and sediment retention, vegetation colonisation and a mosaic of aquatic and riparian landforms. Valley jams are usually characteristic of 'intermediate' rivers, although where wood supply is high (e.g. in association with catastrophic delivery from hillslopes or tributary channels), they may be observed on 'large' rivers.
>
> *Flow deflection jams* are developments of the bank input jams described above for 'small' rivers, since they are composed of key pieces delivered by local wood / tree fall that partly block the channel, coupled with large quantities of wood pieces from upstream that become braced (racked) against the key pieces, and many other smaller pieces that become jammed into this wood matrix along with sediment and seeds. These jams can be large features (associated with 'intermediate' or 'large' rivers) that deflect flows causing bank erosion and pool development; the delivery of more local wood (from bank retreat); bench development within and behind the jam; and channel migration. Vegetation colonises the benches and, if the benches persist for a sufficient time, they eventually aggrade into the floodplain.

Allochthonous jams characterise rivers of all sizes from 'small' to 'large', although jam dimensions are constrained by river channel dimensions.

> *Flood jams* are described by Abbe and Montgomery (2003) as being formed when wood accumulates beyond the river channel during floods. These jams form as wood ridges and wood piles trapped around or between standing trees. A special, large case of wood ridge development can be driven by a combination of *debris torrents* from surrounding hillslopes as well as flood delivery of wood. Similarly *wood plugs* can form, blocking the entrance to distributary channels around

islands and through the forested floodplain (see description below in relation to riparian trees).

Bench jams form where key wood pieces, oriented approximately parallel to the flow, become jammed in irregularities in the channel margins. Such jams could occur on rivers of any size, but are probably most characteristic of 'intermediate' sized channels, where they initiate a type of partial jam (Gregory et al., 1985). The key pieces create a sheltered area within the channel margins, where smaller wood pieces, sediment and seeds can accumulate, leading to wood-associated bench development, and possibly channel migration.

Bar apex jams are widespread features of 'large' rivers. They are initiated by a key piece of wood, usually an entire uprooted tree, which becomes snagged on the upstream face or crest of a mid-channel, side or point bar. The wood induces flow divergence and acceleration around the upstream-facing root wad of the tree, leading to the scour of a pool, and flow deceleration and deposition of relatively fine sediment in the form of a bar around the tree trunk. As wood pieces are trapped by the root wad, the processes of scour pool and bar development are accentuated, and seed germination on the bar gives rise eventually to the development of an island.

Meander jams develop on the outer and downstream banks of meander bends. They are formed by mobile wood becoming trapped against, within and on the bank. The trapped wood forms an erosion-resistant barrier that protects the bank and so influences the subsequent development of the river bend and is often associated with the development of deep pools in the river bed.

Counterpoint jams are not reported by Abbe and Montgomery (2003) because they form on the bends of large, low gradient meandering channels, which differ from the river channel types reported for the Queets system. On low energy, meandering systems, whole trees and large wood pieces transported from upstream accumulate in dead zones within the upstream, concave, bank of river bends. The counterpoint deposits associated with these jams are composed of fine sediment with much organic material including small wood pieces, which provide a nutrient-rich environment for seed germination and growth.

Log rafts are very large floating accumulations of wood that can block intermediate to low gradient river channels. As a result of human interventions, they are rarely observed nowadays, but have been noted in historical sources.

All of the above types are relatively stable features and usually incorporate some buried or robustly snagged key wood pieces. They can persist and enlarge over prolonged periods, and support vegetation development by acting as a seed bed for tree seedlings. However, there are a wide variety of unstable wood accumulations found in rivers that do not have the structural stability of the jams described above. These include wood deposited in loose piles and ridges along the bank edge, within the floodplain forest, and on bar tops

2.2.5.4 Landforms associated with riparian trees (a) 'Living' wood

Many riparian tree species regenerate vigorously from wood pieces. Wood capable of sprouting creates all of the features listed above in relation to dead wood. However, because of the ability of the wood to sprout, vegetation 'colonisation' of these features proceeds at a fast rate, often permitting a longer period of survival than their dead wood counterparts. There are also landforms that are specific to sprouting uprooted trees and wood pieces, and also to the growth of tree seedlings, which can be observed in rivers of all sizes. Gurnell et al. (2012) and Gurnell (2014) provide recent reviews.

Pioneer islands (e.g. Edwards et al., 1999) are initiated following bar apex jam formation with wood that sprouts. As a result of rapid vegetation regeneration, within two or three years, little evidence remains of the original key piece, but vegetated patches located on ridges of fine sediment are evident. At this stage, the pioneer islands have transformed into *building islands* (Gurnell et al., 2001), which are a product of the lateral and vertical growth of pioneer islands as vegetation traps and retains sediment and wood. In some cases, the process is further accelerated when pioneer islands coalesce. These features can form within river channels in both perennial and ephemeral river environments (in zones 1 and 2). They can also form within heavily disturbed riparian zones (zone 3), and are particularly noticeable in drier riparian environments, where part-burial of deposited wood during over-bank floods may support vegetation regeneration and the formation of distinct vegetated mounds / patches separated by areas of bare ground in zone 4.

Wood plugs form when wood accumulates at the entrance to distributary channels during flood events, particularly those that form side channels through floodplain woodland. These wood structures trap sediment and can eventually close the side channels. While such features can be composed entirely of dead wood, sprouting wood produces a more effective sealing and trapping structure, resulting in rapid channel cut-off. Furthermore, riparian trees usually form the retention structures for the wood pieces within the wood plug.

Wood cored, scroll bars are ridges that develop mainly on point bars (but counterpoint bars can also support similar ridge-type features, Page and Nanson, 1982). Although initially thought to be a result of flow-sediment interactions, Nanson (1981) recognised that they were often cored by dead wood, and it is now apparent (e.g. Gurnell et al., 2001) that their formation is widely associated with (i) the trapping and alignment of uprooted trees and wood pieces during floods to form a core for the scroll, (ii) sprouting of the wood to reinforce the scroll and induce aggradation and enlargement and (iii) eventually coalescence of the vegetated scroll bar with the active channel margin to extend the floodplain. This process is similar to pioneer and building island development but it occurs on single thread sinuous, usually meandering rivers, and causes the vegetation-banded bars described by McKenney et al. (1995). Wood is an essential component of scroll bar development in rivers with flashy flow regimes.

Seedling-induced scroll bars can be initiated by seedlings in rivers with less flashy flows but that support a more predictable annual flow regime with a distinct annual flow peak (usually the spring snowmelt peak). Sediment is trapped as the seedlings grow to form a ridge-like feature at an elevation that is sufficiently low on the point (or side) bar for the seedlings to have a sufficient moisture supply but high enough to avoid uprooting of the seedlings by flow pulses.

Seedling-induced levées form in a similar manner to seedling-induced scroll bars but at a lower elevation – close to the low flow water level. Formation at this low elevation takes advantage of the moist environment next to the low flow water level but requires minimal disturbance to avoid damage and uprooting of the seedlings. Therefore, these levée features (i) contribute to river bank formation in low-energy rivers, particularly as a part of lateral channel adjustment, or (ii) they may be indicative of rivers in transition from one style to another as a result of changes in the flow regime, or (iii) they are temporary features created during low disturbance periods, particularly in rivers close to threshold conditions between planform types.

Sprouting wood equivalents of flow deflection, bench and meander jams can be more effective in developing bench features and inducing other related landforms than their dead wood counterparts. This is because the wood can send roots into the bank toe, the jam itself and any accumulating sediments. At the same time, shoots from the wood rapidly form a vegetation canopy that can trap sediment, wood and seeds.

2.2.5.5 Landforms associated with riparian trees: Standing trees, predominantly in 'small' to 'intermediate' rivers

Individual standing trees are important for initiating landforms, particularly in 'small' to 'intermediate' rivers.

J-shaped trees and bank buttressing. Individual riparian trees can buttress the river bank with their root systems. Trees often developing J shaped trunks as a result of interaction between tree growth and bank erosion / movement, and the ability of many riparian species to produce adventitious roots can lead to roots shooting from below the J in the trunk to penetrate the river bank and bed.

Trunks, trailing branches and exposed roots can act as retention structures or key pieces in wood jams that are equivalent to those listed above as combination jams (e.g. *active, complete, valley, flow deflection jams*).

Bars, benches and islands. The hydraulic effect of living trees can lead to *lateral bar* and *bench* development, where the latter features become quickly reinforced by tree roots. Furthermore, because of the resprouting ability of many riparian tree species, new marginal and in-channel trees can sprout from trailing branches that touch the river bank or bed. These can contribute to bar, bench and island development as the new shoots grow and trap wood and sediment.

2.2.5.6 Landforms associated with aquatic plants in rivers of different size and type

Aquatic plants induce landform development in low-energy river environments. For example, Gurnell et al. (2013) estimated that landform building by the robust, linear-leaved, emergent plant, *Sparganium erectum*, in British streams, is restricted to rivers with a bank full unit stream power of less than 110 W.m^{-2} and a channel width of less than 10 m (i.e. 'small' to 'intermediate' rivers in the context of the typical size of individual aquatic plants and plant stands). Furthermore, because most aquatic plants are adversely affected by riparian shading, landform building is confined to channels where shading is low. However, within the environment of low energy, narrow, unshaded channels, interactions between aquatic plants and fluvial processes are fundamental to channel form and channel dynamics. Gurnell et al. (2012) and Gurnell (2014) provide recent reviews.

By presenting resistance to flow, submerged and emergent aquatic plants increase the retention of sediment. The extent to which they do this depends upon the hydraulic resistance of the front of the plant stand, leading to sediment accumulation within and behind the stand. Landforms associated with aquatic plants reflect a sequence of fine sediment trapping, reinforcement and aggradation, so that three types of feature can develop along river margins or within river channels. These features are (i) low amplitude mounds around the plants and below the low-flow water level; (ii) moderate amplitude mounds that extend vertically to the low-flow water level and (iii) large amplitude mounds that emerge above the low-flow water level and eventually aggrade to the level of the surrounding floodplain. The three feature types represent landform development stages, but they are distinguished by the plant species that they support. As the features evolve they trap plant propagules as well as sediment. The propagules of species appropriate to the environmental conditions provided by the feature stage develop into the vegetation cover that is present at that feature stage. Different species assemblages can result in different feature micro-topographies. Therefore, the three features and their associated plant species create distinct habitats for other species and at different flow stages.

> *Submerged shelves* (i.e. feature stage (i)) form around the base of emergent and submerged aquatic plants. They frequently form in association with stands of emergent macrophytes along channel margins, providing areas of shallow water and protecting / reinforcing the bank toe (Gurnell et al., 2006, 2014), although they can also form around both emergent and submerged plants in mid-channel locations (Cotton et al., 2006).
>
> *Emergent shelves / berms* (i.e. feature stage (ii)) are different names that have been given to similar features. They describe features that have developed to the low flow water surface level, and usually have a sharp break of slope between their vegetated surface and edges. They may occupy mid-channel locations, but most commonly occupy channel margins. The sharp break of slope between the surface and sides of these features is indicative of the interaction between the stabilising and reinforcing vegetation and erosion of the feature edges by fluvial processes. This form and the finer sediments that are incorporated distinguish these vegetation-driven features, from more rounded vegetated (side and mid-channel) bars. Vegetation plays a more passive role in bar formation than in the development of emergent shelves or berms. Because of their emergent surface, emergent shelves or berms do not support truly aquatic species, but instead are colonised by transitional and wetland species.

Vegetated benches (i.e. feature stage (iii)) have densely vegetated surfaces that lie above the low flow water level and below the level of the floodplain. They have a similar elevation range to the benches described above in relation to flow deflection jams and bench jams. Their formation is initiated by aquatic and wetland plants along small, low-gradient rivers. However, on larger, low gradient rivers, riparian trees are usually involved (dead and sprouting wood, and seedlings). At this bench stage, they support both wetland and more terrestrial species depending upon their elevation relative to the low-flow water level and thus their indundation duration and frequency. They develop preferentially but not exclusively on the inner banks of bends at point and counterpoint locations

Tussocks are micro-topographic forms associated with some species that appear during the above feature stages. These provide important hydraulic complexity when the features are inundated and distinct microhabitats within the feature.

In very low-energy environments, where the bed material is fine, vegetation is essential to landform-building and the above features are the equivalent of submerged and emergent bars in higher energy systems. If positioned appropriately within the channel, they may initiate features equivalent to mid-channel bars, side bars, point bars, and channel plugs observed in coarser sediment, higher-energy systems (Gradzinski et al., 2003).

Emergent and wetland plant induced levées. In some low-energy river systems, the above feature stages may eventually lead to significant island development, as is found in lowenergy anabranching (anastomosing) systems. The resultant islands tend to have a tabular profile covered by wetlands. Plant-fluvial process interactions across the island surfaces often result in fine sediment particles being filtered out of the flow by vegetation at the island margins. This process leads to the development of low levées around the edges of the islands.

In conclusion, the above is not an exhaustive list of the landforms that emerge as a result of interactions between plants and fluvial processes, but it provides a first attempt at a synthesis. This is a rapidly developing area of river research, but it is clear that different landforms are linked to different river types with their accompanying energy and sediment characteristics. Furthermore, different plant species act as ecosystem engineers, driving the development of these landforms in different biogeographical zones. Nevertheless, dead wood, riparian trees and aquatic plants appear to act as physical ecosystem engineers in rivers of different type and energy. Figure 2.2.12 provides a first attempts to link some of these plant-related landforms to specific positions within the cross-profiles of rivers of different style.

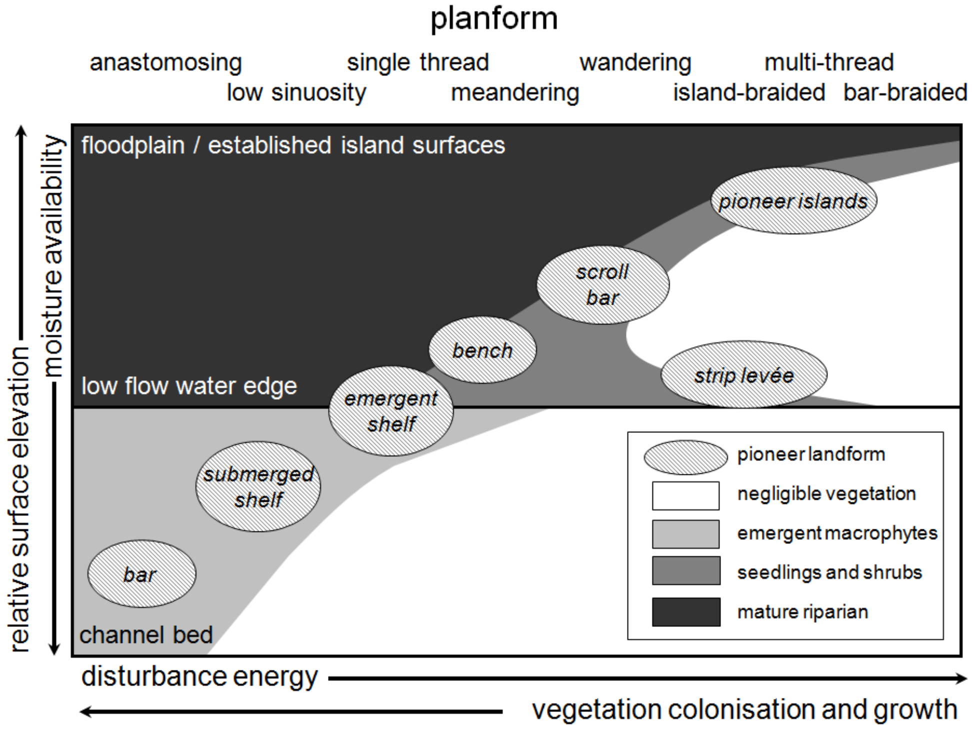
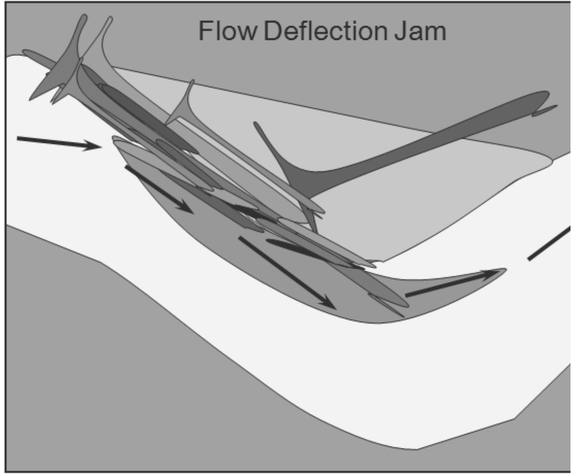
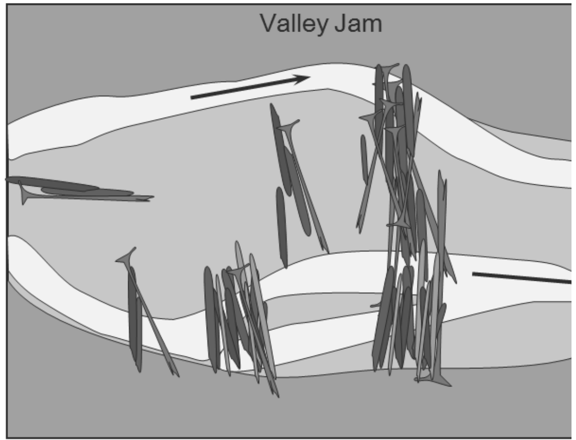
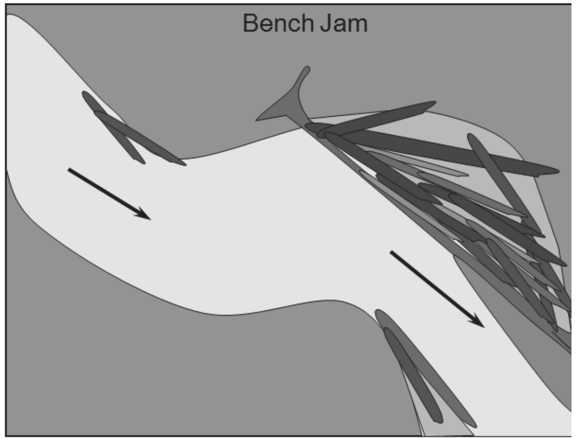


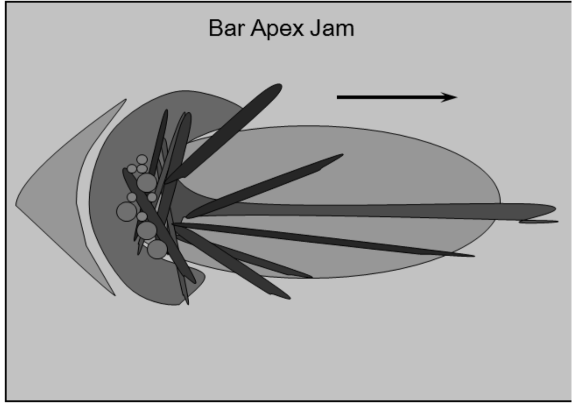
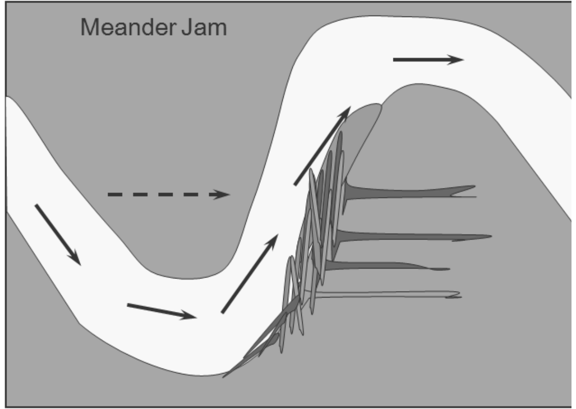
Figure 2.2.12 Expansion of zones 1 (bottom of diagram to low flow water edge) plus zone 2 (low flow water edge to edge of mature riparian vegetation) across river planform types with increasing flow energy (left to right). The ovals indicate pioneer landform types formed around patches of vegetation (Source: Gurnell, 2014)

Table 2.2.4 Some examples of vegetation-associated landforms

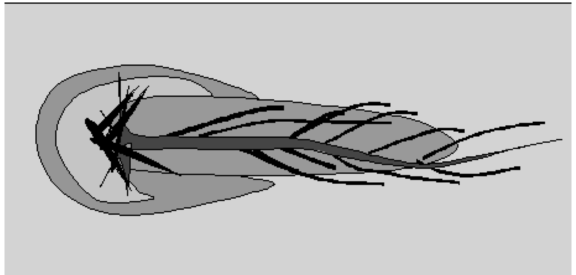
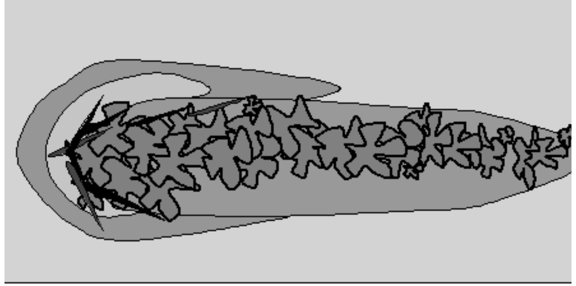
Jams produced when trees or other large wood pieces fall into the river from the bank, and remain *in situ.* Left: Bank input jam Right: Log step		
Channel spanning active (left) / complete jams (right) produced when mobile wood pieces accumulate upstream of *in situ* channel-spanning pieces, causing obstructions to flow that, in the case of active jams, induce a distinct step in the water surface profile, even at low flows		

Flow deflection jam: fallen trees deflect flow, leading to channel widening, pool development and the accumulation of fine sediment and wood in a bench-like feature behind the wood barrier		
Valley jam: very large wood jam wider than the bankfull channel width and the largest pieces of wood.		

Flood jams: Left: wood ridge Right: wood pile		
Bench jam: oblique key wood pieces are wedged into irregularities in the channel margins, creating a barrier behind which fine sediments and wood accumulate to form a bench.		

Bar apex jam: located at the upstream end and on the top of bars and formed around large wood pieces that retain fine sediment and often induce scour holes or pools at their upstream end.		
Meander jam: found on the outer margins of bends of large meandering channels where whole trees and large wood pieces jam against the downstream bank of river bends, protecting the bank from erosion and so affecting channel curvature		

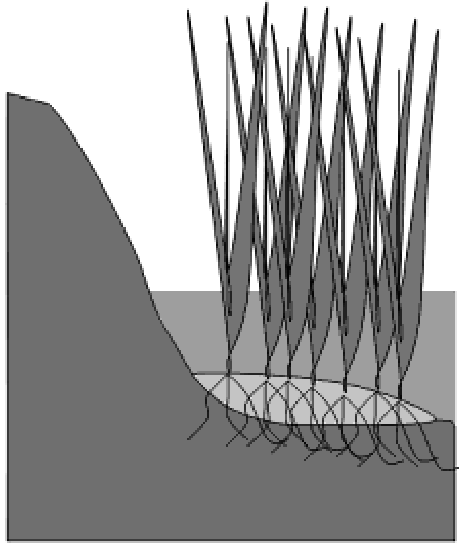
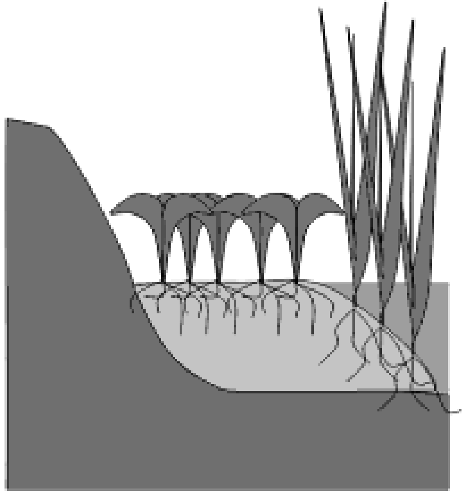
Counterpoint jam: found on the outer margins of bends of large meandering channels where whole trees and large wood pieces accumulate within a dead zone within the upstream bank of river bends. The counterpoint deposits associated with these jams are composed of fine sediment with much organic material including small wood pieces		
Left: Debris torrent in steep valley Right: Log raft – a large floating accumulation of wood that can block intermediate to low gradient river channels		

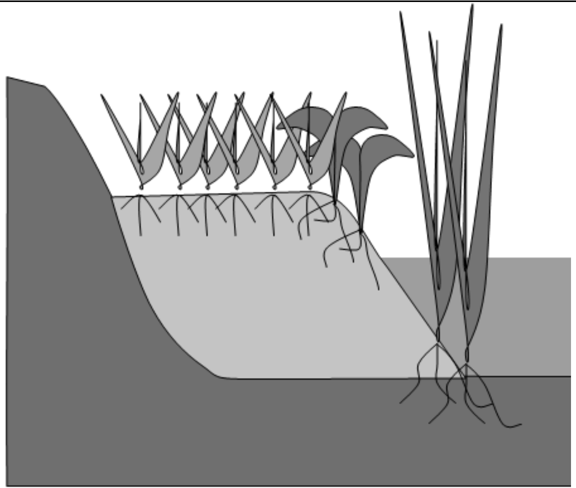
Pioneer island		
Building island		

Wood plugs in entrances to side channels		
(Sprouting) wood-cored scroll bars		

Seedling-induced levée		
J shaped trees and bank buttressing. Left: tree sprouting from the base of the bank, with roots stabilising fine sediment on the channel bed. Right: An old alder tree that originally grew on the bank. It then developed a J shape, as the bank evolved. Thick roots can be seen penetrating the water and river bed below the J, and also spreading from the rear of the trunk into the bank, where they retain a bench of sediment at a level that is below that of the surrounding floodplain (background to right).		

Tree-induced bar (left) and bench (right). In both cases the bar/bench feature is composed of fine sediment retained by tree roots.		
Branch-induced island. Left: Upstream face of island showing wood accumulation (foreground) and shrubs and 3 mature trees on the island Right: centre of island, facing upstream, showing wood and sediment accumulated around shrubs that have sprouted from branches touching the river bed		

Submerged shelf induced by aquatic plants		
Emergent shelf / berm induced by aquatic plants		

Bench induced by aquatic plants		
Left: Tussock (on emergent shelf / berm) Right: Wetland and aquatic vegetation and peat river bank		

Left: Aquatic vegetation stabilised bar Right: Island initiated by submerged aquatic vegetation (in channel in foreground - submerged aquatic vegetation trapping fine sediment to form a submerged bar / shelf)	

2.3 Advances in Modelling Vegetation-Hydromorphology Interactions

2.3.1 Introduction

Models can support river managers in the management, design and restoration of rivers. There are countless types of models ranging from simple correlative models relating several environmental variables, to species habitat suitability models, to complex 3D numerical models. The models not only vary in complexity but also in their temporal and spatial scales and application purpose. This section presents an overview of recent modelling advances that include vegetation and hydromorphology (Figure 2.3.1).

Several topics are distinguished:

(i) Effect of vegetation on hydromorphology. This includes the more complex models generally including advanced hydrology and sediment transport and simple vegetation which are mainly used for engineering purposes. It includes equations and process descriptions for flow resistance, bank erosion and bank accretion.

(ii) Effect of hydromorphology on vegetation. This includes ecological models using hydromorphodynamics as environmental variables influencing plant survival, growth, reproduction and dispersal.

(iii). Large wood. This includes models of breakage, transport and decomposition of large wood.

(iv). Interaction between vegetation and hydromorphology. This includes several models explicitly including the interaction between vegetation and hydromorphology (topics *i* and *ii* combined).

(v). Vegetation dynamics. This includes models that simulate interactions between plants and predict vegetation patterns in less disturbed environments (e.g. at higher altitudes on the floodplain) as a result of competition and facilitation processes.

(vi). Interaction between groundwater and vegetation. This includes ecohydrological models with vegetation dynamics.

Note that we have chosen to include separate sections on surface water and groundwater, although they both fall under the hydrology umbrella. The reason for this is that the groundwater models discussed here are already quite advanced and often have integrated vegetation dynamics. They also contain different vegetation processes and formulations. It is therefore convenient to describe them in a separate section.

For each topic future research and modelling challenges are listed at the end of each section. The usability of the tools for the analysis of hydromorphological pressures and design of restoration measures are presented according to topic in separate tables within Annex A.

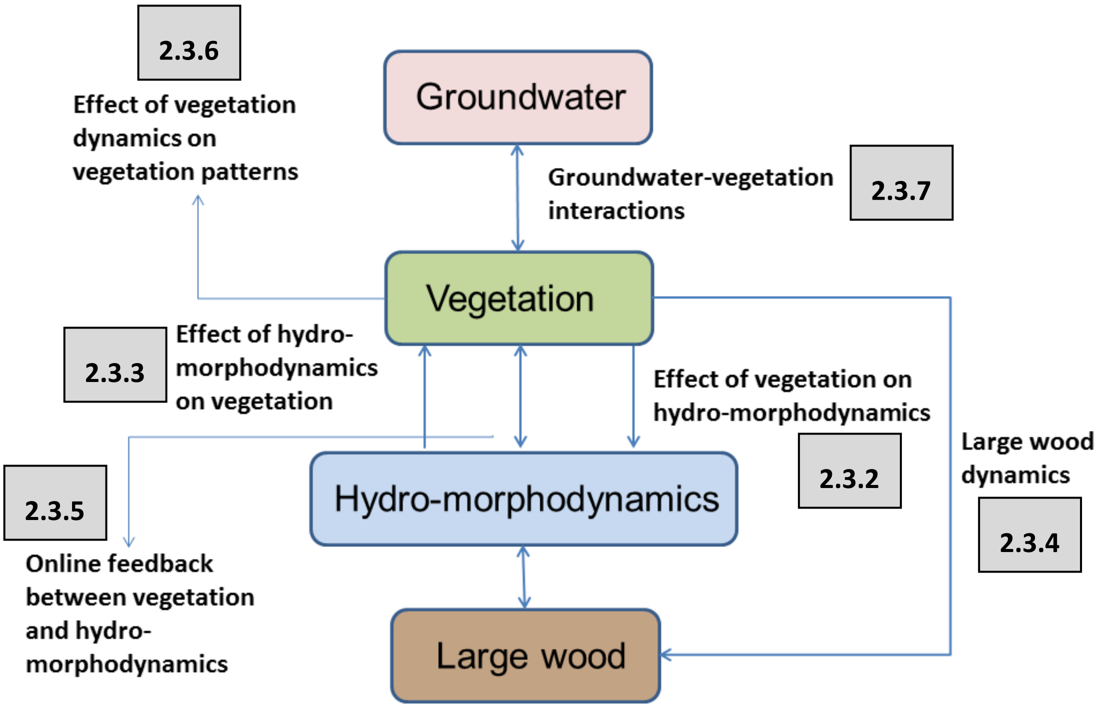


Figure 2.3.1 Flow diagram of all modelling topics that are described in this section (2.3) and their relation with hydromorphology and vegetation.

2.3.2 Effects of vegetation on hydromorphodynamics

2.3.2.1 Flow resistance

Vegetation impacts upon many aspects of rivers including surface water flow, sediment transport and channel morphology. Traditionally, hydraulic engineers have considered river vegetation in terms of its effects on water flow and flow resistance; only recently have the feedbacks between vegetation and river morphodynamics started to be acknowledged (Camporeale et al., 2013). From a hydrodynamic point of view, the presence of vegetation alters the velocity field across several scales, ranging from individual branches and leaves on a single plant to a community of plants in a patch or reach (Folkard, 2009; Nepf, 2012). At the leaf scale, local hydrodynamics is governed by boundary-layer formation on the surface. In this case, drag force is related to flexural rigidity, shape, and surface roughness of blades. At the plant scale, foliage can be a major source of drag; at the patch scale, density of vegetation plays a significant role on drag; and at the reach scale, resistance is also influenced by the planimetric distribution of vegetation within the channel.

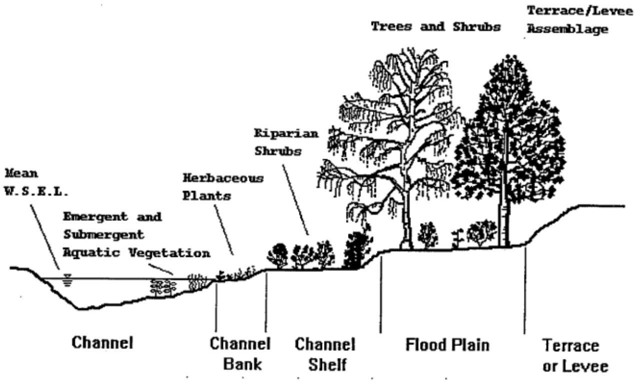


Figure 2.3.2 Examples of types of vegetation (from Craig Fischenich, 1997).

In this section, the interaction between vegetation and river flow is presented in terms of flow resistance. The focus is on the most recent models (i.e. in the last 10 years) which allow one to estimate flow resistance at the reach scale due to different types of aquatic and riparian vegetation that can be found in a river (Figure 2.3.2). Flow resistance estimations are essential in hydro-morphological models for rivers. Based on a large dataset, a recent review on flow resistance estimators in vegetated beds can be found in Vargas-Luna et al. (2014).

General background – basic equations

At the reach scale, the impact of vegetation on surface flow is generally expressed as an effect on the hydraulic roughness (Baptist et al., 2007).

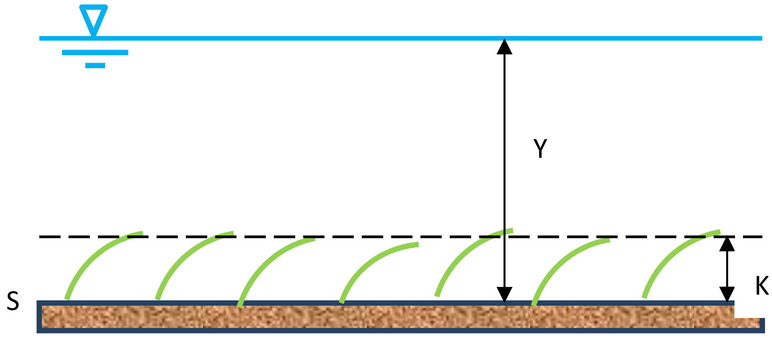


Figure 2.3.3. Sketch illustrating a channel with flexible submerged vegetation; Y is average flow depth, K is average patch height, S is bed slope.

The hydraulic roughness in vegetated flows can be interpreted by imposing the longitudinal momentum balance formulated in the case of steady and spatially averaged conditions. In particular, considering the reach scale and the case of flexible or rigid emergent vegetation, the total bed shear stress τ_t can be decomposed into the sum of two contributions: τ_b, the shear stress acting on the exposed substrate / soil surface and τ_v, the stress acting on the vegetation elements:

$$\tau_t = \tau_b + \tau_v \qquad [1]$$

τ_t is due to the component of water weight in the direction of flow taking into account the submerged portion of plant volume:

$$\tau_t = \rho g S \left(Y - m\langle V_p \rangle\right) \qquad [2]$$

where ρ = water density (Kg/m^3), g = gravity (m/s^2), S = average reach slope (-); Y = average flow depth (m), m= the number of plants per unit bed area (m^{-2}), V_p= submerged plant volume (m^3), see the sketch in Figure 2.3.3. Note that $\langle\ \rangle$ indicates spatial averaging. τ_b can be calculated as follows:

$$\tau_b = \tau_0 \left(1 - m\langle A_b \rangle\right) \qquad [3]$$

where τ_0 = shear stress on the bed surface (N/m^2), and $\langle A_b \rangle$ = average bed surface occupied by a plant (m^2). τ_v is the vegetation resistance force per unit bed area which can be expressed through the spatially averaged drag force per unit bed area as follows:

$$\tau_v = m\langle F_D \rangle = \frac{1}{2}\rho m \langle C_D A_c u_c^2 \rangle \approx \frac{1}{2}\rho m \langle C_D \rangle \langle A_c \rangle \langle u_c^2 \rangle \qquad [4]$$

where $\langle F_D \rangle$= average drag force on a plant (N); C_D = drag coefficient on a single plant (-); A_c = projected area of the plant, including the foliage, in the direction of flow (m^2); u_c = characteristics flow velocity approaching the plant (m/s). The approximation in eq. [4] has been adopted in many studies (Aberle and Järvelä, 2013).

Assuming that the parameter m is small such that $m\langle V_p \rangle << Y$ and $m\langle A_b \rangle << 1$, and dividing eq. [1] by the square of a reach-averaged flow velocity u_m (m/s) , the following equation for the total dimensionless Chezy coefficient C_t (-) can be obtained:

$$C_t = \sqrt{\frac{1}{\frac{1}{C_b^2} + \frac{1}{C_v^2}}} \qquad [5]$$

where C_b (-) is the roughness coefficient related to bed surface covered by sediment and C_v (-) expresses the resistance due to vegetation. Note C_b can easily be evaluated using the classical Strickler formula given the characteristic diameters of the grain size distribution of the bed surface.

The reach-averaged flow velocity u_m can then be calculated with the well-known Chezy equation:

$$u_m = C_t \sqrt{gYS} \qquad [6]$$

The component of flow resistance due to vegetation can be therefore expressed as:

$$C_v = \sqrt{\frac{2}{m\langle C_D \rangle \langle A_C \rangle \frac{\langle u_c^2 \rangle}{u_m^2}}} \qquad [7]$$

Equations [5]-[7] are set as the basis for estimating flow resistance in vegetated flows. In the application of eq. [7] several problems arise due to estimation of the various quantities involved (such as the drag coefficient, the flow velocity approaching the plant, the frontal plant area, especially in the case of flexible plant with the presence of foliage).

In the case of fully-submerged vegetation, flow resistance can be estimated modelling the average longitudinal flow velocity profile as composed by different layers. In the simplest case, two layers have been considered: a bottom layer with 'slow' flow inside the vegetation, and an upper layer or free water layer, above the vegetation. This approach has been adopted by many authors (e.g. Baptist et al., 2007; Luhar and Nepf, 2013; Wenxin et al., 2013), even in the case of flow resistance produced by sediment in case of macro-roughness conditions (Canovaro et al., 2007). Flow resistance is in this case given by the sum of two contributions: one due to the vegetation roughness (see eq. 5) and one related to the free water layer. The overall resistance is in this case smaller than in the case of emergent vegetation.

Flow in vegetated areas has been generally separated into i) emergent and ii) submerged conditions as the flow field changes considerably when the flow depth exceeds the height of the vegetation. Another key feature is related to the flexibility of vegetation and feedback with the flow hydrodynamics.

In the following, a brief overview is given on recent models of flow resistance in the following conditions:

1. aquatic vegetation;
2. flexible riparian vegetation;
3. rigid riparian vegetation

Aquatic vegetation

The behaviour of aquatic vegetation in the flow is rather complex and can be divided into different regimes (Figure 2.3.4): i) stems are not deflected and behave like 'rigid elements'; ii) stems vibrate and are independently waving without any organized motions; iii) stems are deflected more significantly and the coherent waving motion of vegetation is observed (i.e. Monami); iv) stems become prone therefore smoothing the bed surface. Flow resistance of grass is illustrated in the well-known retardance curves (USDA, 1947) showing the Manning coefficient for different classes of grass as a function of product of average velocity and hydraulic radius (Figure 2.3.5). The five retardance curves (A-E) shown in Figure 2.3.4 have been approximated by a set of equations by Gwinn and Ree (1980).

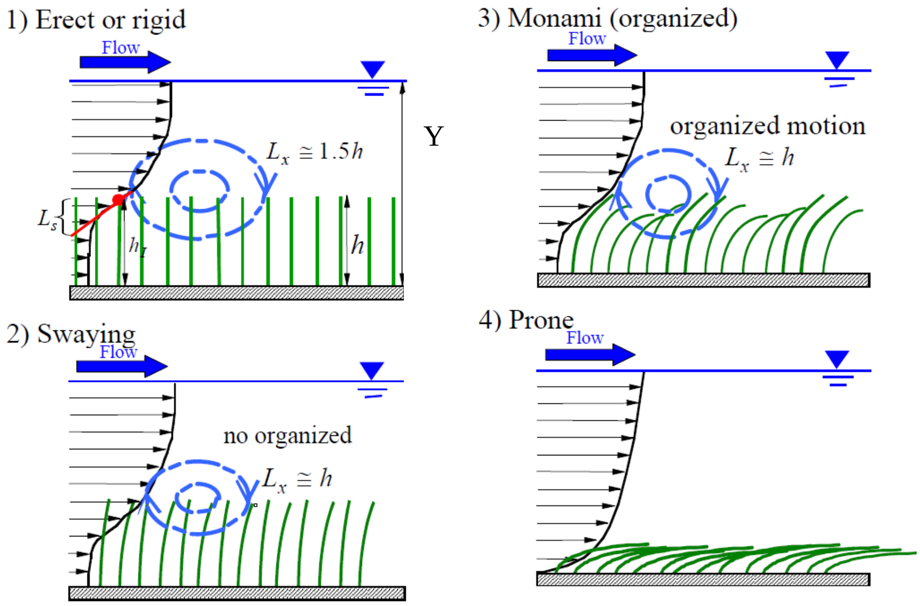


Figure 2.3.4 Vegetation configuration and average flow velocity profile (from Okamoto and Nezu, 2010).

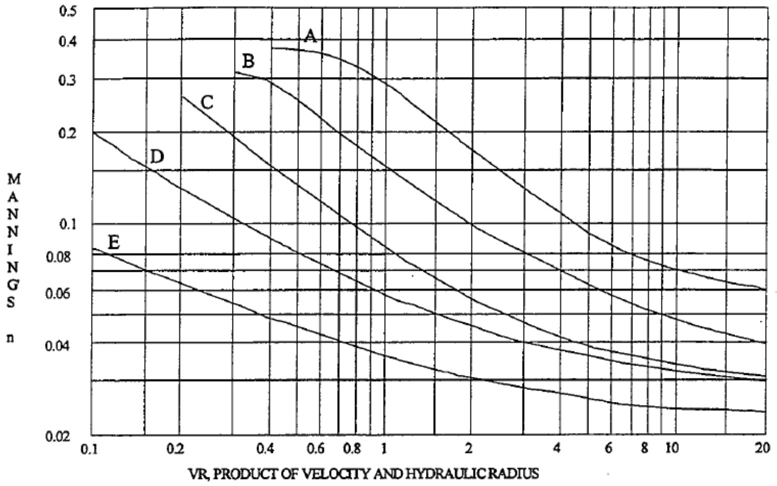


Figure 2.3.5 The n-VR relationship for different retardance classes (A-E) of grass (from Craig Fischenich, 1997).

Stem reconfiguration due to its flexibility, can reduce the flow roughness and increase velocities significantly. For instance, Luhar and Nepf (2013) show, through the interpretation of laboratory experiments, that vegetation reconfiguration, especially when the vegetation elements assume a prone position, can lead to an almost twofold increase in flow velocity compared to the case when vegetation remains undeflected and upright in flow.

Dijkstra and Uittenbogaard (2010) developed a fully mechanistic model for predicting flow velocity and plant configuration of very flexible aquatic vegetation; the model was validated by means of laboratory experiments with flexible plastic strips. A similar, though simplified, approach was later proposed by Wenxin et al. (2013) who predicted stem configuration using the theory for large-deflection cantilever beams.

Luhar and Nepf (2013), by means of mechanistic and empirical considerations, noted that at the scale of the channel reach, flow resistance due to vegetation is determined primarily by the blockage factor, B_x, which is the fraction of the channel cross-section blocked by vegetation. For a patch of height K and width w in a channel of width W and depth Y, $B_x = wK/WY$, assuming the flow velocity inside the patch of vegetation can be neglected, the authors propose the following equation of the hydraulic roughness:

$$C_t = \sqrt{\frac{2}{C_*}}\left(1 - B_x\right)^{3/2} \qquad [8]$$

where the coefficient C_* parameterizes the shear stress at the interface between vegetated and unvegetated regions, and $C_* = 0.05–0.13$, based on fits to field data.

When vegetation fills the channel width (w=W), $B_x = K/Y$ (i.e. the submergence ratio), in the case of submerged vegetation, flow resistance is given by

$$C_t = \sqrt{\frac{2}{C_*}}\left(1 - \frac{K}{Y}\right)^{3/2} + \sqrt{\frac{2}{\langle C_D \rangle a K}}\frac{K}{Y} \qquad [9]$$

where a is the frontal plant area per unit volume (m^{-1}). Eq. [9] shows a strong dependence between the flow resistance and the submergence ratio, Y/K. In particular, as Y/K increases, flow resistance decreases as a result of plant bending and submergence. This behaviour appears to be in accordance with the well-known retardance curves.

Note that equations [8]-[9] require the height of the bent vegetation layer, K, to be known. Unfortunately, the ability to predict the deflected height, K, for flexible vegetation is the limiting factor for the most of the models developed to date (Nepf, 2012). This problem was investigated by Kouwen (1992) in the case of grass; in particular, K was found to be related to the bio-mechanical properties of plants through an aggregate parameter accounting for overall canopy stiffness. Another source of uncertainty is related to the fact that vegetation parameters, such as a and K, can change in time depending on plant growth (O'Hare et al., 2010b).

Flexible riparian vegetation

For floodplain areas vegetated by shrubs or trees, the emergent flow condition (i.e. flow through the vegetation layer), is the most important condition for flow resistance (Aberle and Järvelä, 2013). In the case of flexible leafy bushes and soft-wood trees, because the contribution of leaves to drag production is significant, it appears physically sound to explicitly include a parameter describing the effect of foliage into flow resistance formulations (Aberle and Järvelä, 2013). For instance, in the case of black poplars, Västilä et al. (2011) were able to show that leaves contributed almost 90% to the total drag. Järvelä (2004) proposed the following equation:

$$C_v = \sqrt{\frac{2}{C_{D\chi} LAI \left(\frac{u_m}{u_\chi}\right)^{\chi}}} \qquad [10]$$

where Leaf Area Index (LAI) is defined as the ratio of total one-sided leave area to the downward projected area of the canopy and it is often considered as the parameter for canopy density (Jalonen et al., 2013). LAI can be determined by remote sensing or field measurements or values from the literature. Moreover, $C_{D\chi}$= species-specific drag coefficient, χ = species-specific parameter taking into account plant streamline in the flow; and u_χ is used for dimensional homogeneity. χ corresponds to the Vogel exponent in the expression to estimate the drag force on plants being $\langle F_D \rangle \propto u_m^{2+\chi}$ (note that χ=0 in the case of rigid body). An example of plant streamlining is illustrated in Figure 2.3.6. Note that flow resistance decreases (i.e. C_v increases) non-linearly with increasing flow velocity u_m due to streamlining of the plant with increasing velocity. Parameters values for using eq. [10] for different deciduous and coniferous species can be found in Aberle and Jarvela (2013), see Table 2.3.1.

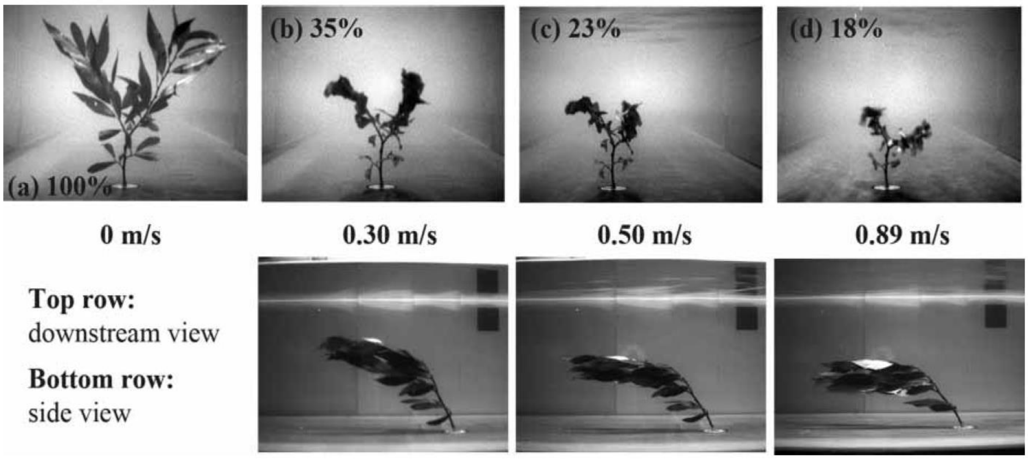


Figure 2.3.6 Behaviour of a submerged willow twig subject to various flow velocities. The % indicates the proportion of the frontal projected area compared to the erected case (from Aberle and Jarvela, 2013).

Table 2.3.1 Parameters to be used in eq. [10] for different deciduous and coniferous species (from Aberle and Järvelä, 2013).

Species	$C_{D\chi}$ (–)	u_χ (m/s)	χ (–)	LAI (–)
Deciduous plants				
Goat Willow (*Salix caprea*)[a]	0.43	0.10	−0.57	3.2
Hybrid Willow (*Salix triandra x viminalis*)[b]	0.53	0.10	−0.90	0.74–1.85
Black Poplar (*Populus nigra*)[c]	0.33	0.10	−1.03	0.95–3.25
Artificial poplar (staggered setup)[d]	0.50	0.11	−0.74	0.4–1.7
Coniferous plants				
Eastern White Cedar (*Thuja occidentalis*)[e]	0.56	0.10	−0.55	1.42
White Spruce (*Picea glauca*)[e]	0.57	0.10	−0.39	1.31
Eastern White Pine (*Pinus strobus*)[e]	0.69	0.10	−0.50	1.14
Austrian Pine (*Pinus nigra*)[e]	0.45	0.10	−0.38	1.61

[a] Järvelä (2004)
[b] Järvelä (2006)
[c] Västilä *et al.* (2012)
[d] Dittrich *et al.* (2012)
[e] Fathi-Moghadam (1996) – $C_{D\chi}$ and χ values derived by Järvelä (2004) reanalysing the original data.

Rigid riparian vegetation

In the application of eq. [7], a crucial and complex aspect is related to the determination of the drag coefficient; a relative simplification is obtained when the vegetation elements can be represented by *rigid cylinders* (see for instance the pioneering work by Petryk and Bosmajian, 1975) Note that in this case the effect of foliage is not taken into account.

(i) Emergent vegetation

In the case of a random or staggered array of rigid cylinders with uniform properties having a diameter *D* and a submerged height *h*, flow resistance can be evaluated as (Baptist et al., 2007):

$$C_v = \sqrt{\frac{2}{m\overline{C}_D \langle Dh \rangle}} \qquad [11]$$

where $\overline{C}_D$ is a bulk drag coefficient, defined as follows (Aberle and Järveä, 2013):

$$\overline{C}_D = \langle C_D \rangle \frac{\langle u_c^2 \rangle}{u_m^2} \qquad [12]$$

Note that $\overline{C}_D$ may be significantly different from $\langle C_D \rangle$ on an isolated element.

$\overline{C}_D$ describes the average drag force on a plant, in other words:

$$\langle F_D \rangle = \frac{1}{2} \rho \overline{C}_D \langle A_c \rangle u_m^2 \qquad [13]$$

$\overline{C}_D$ can be typically expressed as a decreasing function with increasing stem Reynolds number, defined as $\langle u_c \rangle D / \upsilon$ with ρ = kinematic viscosity (m^2/s), (see for instance Wu et al. 1979 presenting an aggregated vegetal drag coefficient); moreover, for the same reach-averaged velocity u_m, $\overline{C}_D$ is larger for staggered than an in-line array. Ghisalberti and Nepf (2004) evaluated the bulk drag coefficient of an emergent array of cylinders by assuming that the reduction in the drag coefficient of an individual cylinder is due entirely to the wake of the nearest upstream cylinder.

Evaluation of $\overline{C}_D$ is a difficult task, being related to the complex geometry of the plants and to the knowledge of the flow field (i.e. structure of the wake region) occurring between the plants. For these reasons, for practical applications, in recent studies $\overline{C}_D$ was simply approximated to 1 (see for instance Crosato and Saleh, 2011).

(ii) Submerged vegetation

Baptist et al. (2007) developed an analytical approach by considering the average longitudinal average flow velocity profile as composed by two layers: i) a uniform flow velocity inside the vegetation and ii) a logarithmic flow profile above the vegetation extending to the free surface.

According to this approach, the overall flow resistance can be estimated as (see also Crosato and Saleh, 2011):

$$C_t = \sqrt{\frac{1}{\frac{1}{C_b^2} + \frac{\overline{C}_D m \langle DK \rangle}{2}}} + \frac{1}{k} ln\left(\frac{Y}{K}\right) \qquad [14]$$

where k (=0.41) is the von Karman constant, and K is the vegetation height.

In equation [14], the first term on the right-hand side equals the representative roughness for partly-submerged vegetation if $Y = K$. Note that equation [14] suggests that C_t is larger than the value of C_t in the case of emergent vegetation (equation [11]), which means that fully-submerged vegetation offers smaller resistance to the flow than partly-submerged vegetation, which is in accordance with expectations.

In the application of equations [11] and [14], main vegetation characteristics such as the height, diameter and density can be evaluated using Table 2.3.2.

Examples of tools

The various formulations here presented are now applied to a simplified case represented by a compact trapezoidal cross-section and considering different combinations of vegetation (aquatic and riparian) on the bed and on the banks. The aims of this application are to evaluate the implications of different types of vegetation on: i) the equivalent Manning coefficient, and ii) the flow rating curves. This set of results can be considered as an hydraulic tool that is useful for vegetation management purposes.

Table 2.3.2. Parameters to be used in eqs. [11] and [14] (from Baptist, 2005).

Vegetation type	Diameter (m)	Density (m^{-2})	Height (m)	Drag coeff. (-)
Pioneer vegetation	0.003	50	0.15	1.8
Production grassland	0.003	15,000	0.06	1.8
Natural grassland	0.003	4,000	0.10	1.8
Herbaceous natural grassland	0.003	5,000	0.20	1.8
Creeping thistle vegetation	0.003	1,000	0.30	1.8
Dry herbaceous vegetation	0.005	46	0.56	1.8
Dewberry vegetation	0.005	112	0.50	1.8
Great willowherb vegetation	0.005	26	0.95	1.8
Herbaceous reed vegetation	0.005	32	2.00	1.8
Wet herbaceous vegetation	0.005	50	0.35	1.8
Sedges	0.006	20	0.30	1.8
Reed canary grass	0.002	200	1.0	1.8
Great bullrush	0.004	300	0.50	1.8
Cattail	0.0175	20	1.50	1.8
Reed	0.0046	80	2.50	1.8
Softwood shrub	0.034	3.8	6.0	1.5
Hardwood forest	0.115	0.2	10.0	1.5
Softwood forest	0.14	0.2	10.0	1.5

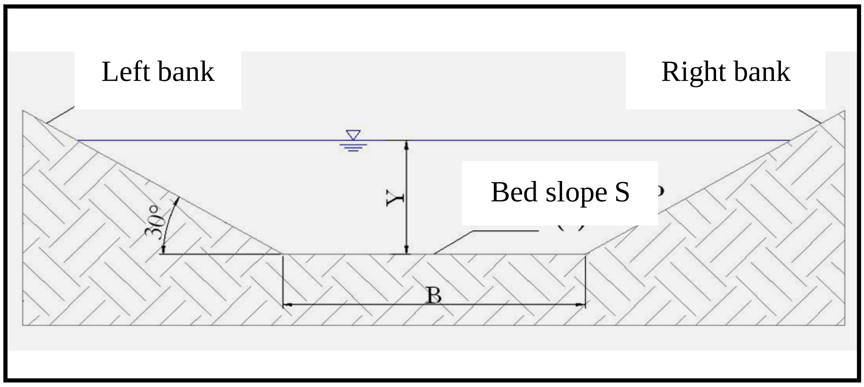


Figure 2.3.7 Case study: a compact cross-section.

The cross-section (Figure 2.3.7) has a trapezoidal shape with a bed slope equal to 0.125%, banks have an inclination of 30°, Y is the flow depth while B is the bed width. The bed is composed by loose gravel with D_{50} = 4.9 cm. The Manning coefficient due to this sediment is estimated as $n_{sediment}$=0.029 m$^{-1/3}$s, using the well-known Strickler's formula. The investigated combinations of vegetation distribution along the cross-section perimeter are illustrated in Figure 2.3.8; sediments are on the bed, while vegetation is placed on the banks (except for the case 0 where no vegetation is present in the entire cross-section). In particular, in case 1, flow resistance due to grass has been evaluated using the retardance curve method for vegetation in class C (medium vegetation such as African star, Bermuda grass, Common lespedeza about 30 cm tall) using the equations suggested by Gwinn and Ree (1980); in case 2, the resistance produced by reed and cattail was estimated using the model by Batipst et al. (2007) using the input parameter given in Table 2.3.2; in cases 3 and 4, Manning coefficients associated due to goat willows and black poplars were calculated with Järvelä (2004) using the LAI coefficient in the range suggested by the author (Table 2.3.1).

The equivalent Manning coefficient ($n_{equivalent}$) in the cross-section, accounting for different roughness on bed and banks, was calculated using Lotter method whereby the total discharge is sum of subarea discharge (see the review paper by Yen, 2002).

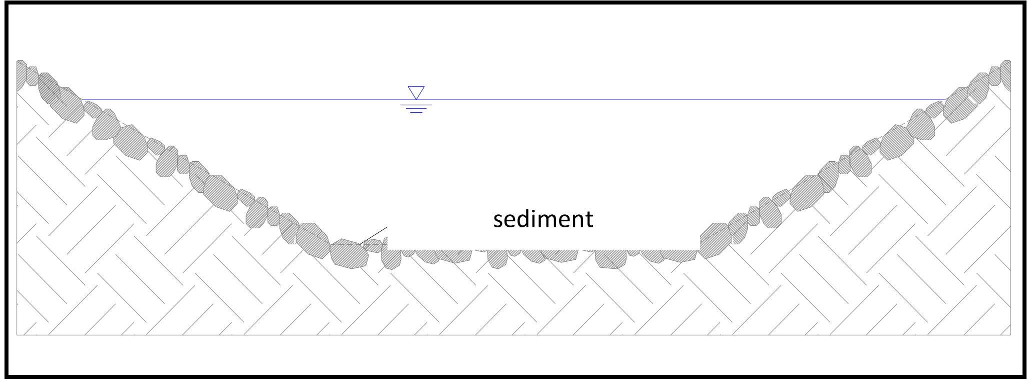
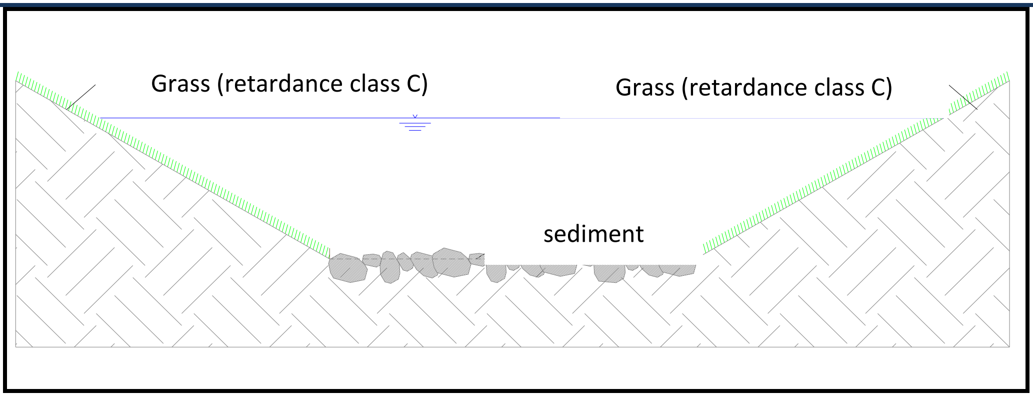
Figure 2.3.9 shows the ratio $n_{equivalent}$/ $n_{sediment}$ for the cross-sections in Figure 2.3.8; results are obtained by changing the bed width B for a given flow depth Y= 2.5 m. It appears that vegetation on the banks can greatly increase the overall roughness in the case of ‘narrow’ cross-sections; whereas, for ‘wide’ cross-sections (B about 10 times Y, in the present example) the equivalent Manning coefficient appears very similar to $n_{sediment}$, thus in these latter conditions vegetation does not produce a significant effect of flow resistance. Note that cattail and reed (case 2) give rise to a flow resistance very similar to that produced by goat willows and black poplars (case 3 and 4).

Figure 2.3.10 illustrates the flow rating curves in the different cases for a fixed bed width B = 10 m. The curves for cases 0 and 1 overlap indicating a negligible impact of this type of grass on the average flow. For a given discharge, the increase in flow depth due to other cover types, in respect to the case without vegetation, appears significant (of the order of 30%). This plot also shows that reed and cattail produce an increase of flow depth higher than black poplar.

Future research and modelling challenges

Future research is needed on the following topics:

- effect of different types and growth stages of vegetation (rigid or flexible) and different vegetation densities on flow turbulence structure and secondary currents of a stream;
- effect of plant reconfiguration with increasing flow velocity on drag;
- effect of the spatial distribution of vegetation at a reach scale on flow resistance;
- uprooting, breakage of plants during high-flow conditions may give rise to significant changes in flow resistance between the rising and falling limbs of the hydrograph;
- develop suitable parameterization to characterize different species.

Cases	***Bed***	***Banks***	***Sketch***
Case 0	*Sediment*	*Sediment* *(Strickler's formula)*	
Case 1	*Sediment*	*Grass -* *retardance class C*	

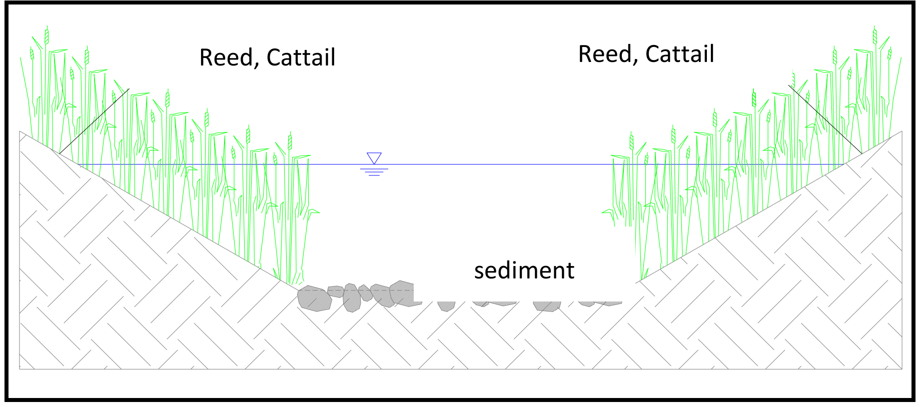
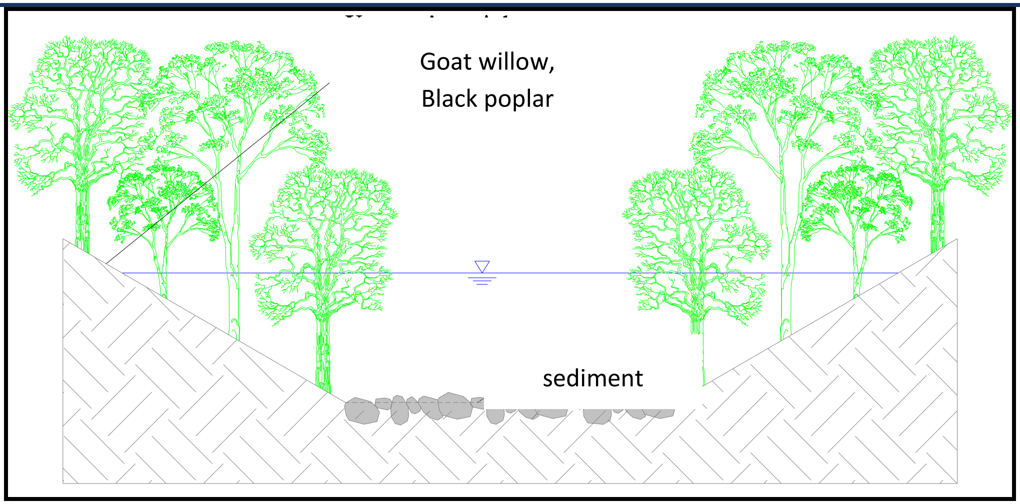
Case 2	*Sediment*	*Reed – Cattail* *(Baptist’s model)*	
Case 3	*Sediment*	*Goat willows* (Järvelä’s model, *LAI=3.2)*	
Case 4	*Sediment*	*Black poplar* (Järvelä’s model, *LAI=3)*	

Figure 2.3.8 Investigated combinations of vegetation along the wetted perimeter.

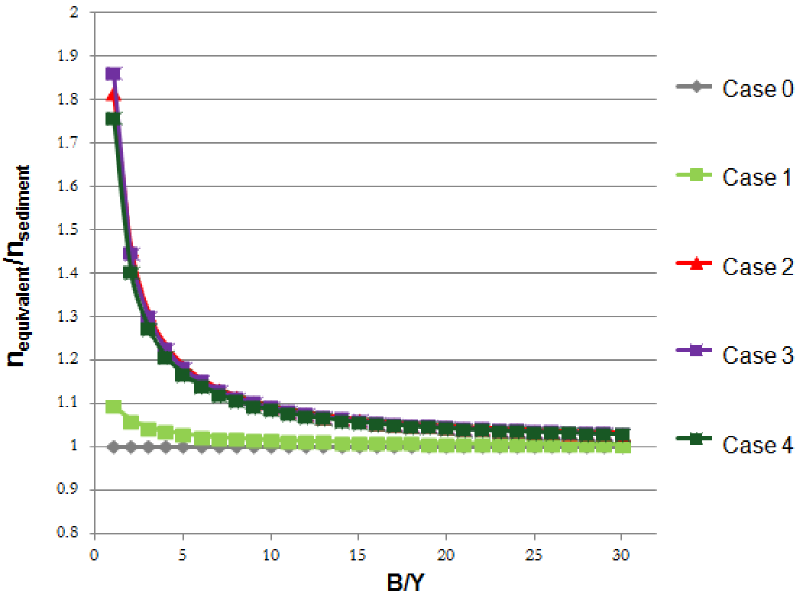


Figure 2.3.9 The equivalent Manning coefficient as a function of ratio channel bed width B over flow depth Y (Y = 2.5 m).

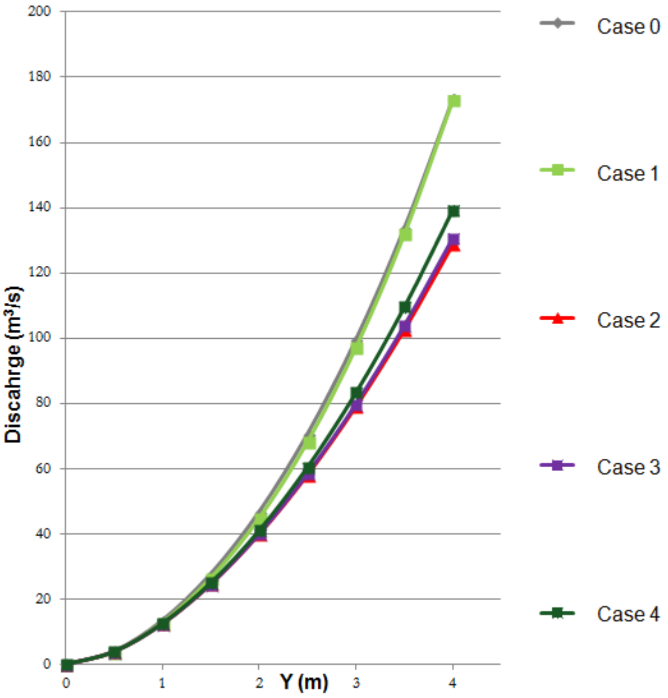


Figure 2.3.10 Flow rating curves for different cases of vegetation distribution along the wetted perimeter of the cross-section (channel width B = 10 m).

- field work measuring plant characteristics related to hydrodynamics to better calibrate model parameters.

In Annex A, Table 1 the suitability of models with flow resistance for the analysis of hydromorphological pressures or the design of restoration measures is listed.

2.3.2.2 Bank erosion

General background

The effects of vegetation on river bank processes are many and complex, and most are difficult to quantify. Vegetation can significantly affect both erosion processes and mass failures, and it is convenient to consider these effects separately.

Fluvial erosion

Fluvial erosion is frequently quantified using an excess shear stress formula such as (Partheniades, 1965):

$$E_{rf} = k_d\,(\tau_b - \tau_c)^a \qquad (1)$$

where E_{rf} (m/s) is the fluvial bank-erosion rate per unit time and unit bank area, τ_b (Pa) is the boundary shear stress applied by the flow, k_d (m^3/Ns) and τ_c (Pa) are erodibility parameters (erodibility coefficient, k_d, and critical shear stress, τ_c) and a (dimensionless) is an empirically-derived exponent, generally assumed to equal 1.0.

Problems in quantification of the rate of fluvial erosion arise from the difficulty in characterizing both the near-bank shear stress and the erodibility parameters. Over recent years, areas of major progress in quantifying near-bank shear stresses have included: (1) analytical modelling of near-bank shear stress in the presence of secondary currents (Papanicolau et al., 2007); (2) analytical models to quantify form roughness (Kean and Smith, 2006a,b) and their application to bank erosion studies (Darby et al., 2010; Nardi et al., 2013); (3) application of numerical hydrodynamic models in bank erosion studies (Rinaldi et al., 2008; Nardi et al., 2013).

Bank vegetation has potential beneficial or adverse effects on erosion processes, including: (1) reduction of shear stress by increase in roughness; (2) localized erosion related to isolated trees; (3) reduction of sediment erodibility related to root reinforcement.

Bank vegetation increases the effective roughness height of the boundary, increasing flow resistance and therefore reducing the near-bank shear stress acting on the bank surface. Various theoretical and empirical work has been dedicated to quantification and modelling the effects of vegetation on near-bank velocity and shear stress (e.g. Kouwen and Unny, 1983; Darby and Thorne, 1996a; Kean and Smith, 2004).

Spacing of trees or shrubs along the bank is important: a dense vegetation cover can protect the bank from flow scour, but an isolated tree may generate local scour and become a serious factor of bank instability (Thorne, 1990). Furthermore, vegetation cover can significantly increase the resistance to erosion (Thorne, 1990; Millar, 2000). Compared to retardance of near-bank flow, very few studies have described or attempted to quantify local scour and effects on erodibility.

Mass failures

Before discussing mechanical and hydrological effects of vegetation, it is worth reviewing the main interactions between riverbank hydrology and mass failure and their modelling, given that vegetation may have a significant impact on bank hydrological processes.

The impacts of vegetation on mass failure can then be divided into *mechanical* and *hydrological* effects, some of which are positive in terms of their impact on bank stability and some of which are negative (Rinaldi and Darby, 2008). The net change in stability induced by vegetation is, therefore, highly contingent on site-specific factors, both in terms of the characteristics of the bank (hydrology, shape, sedimentology) and the characteristics of the vegetation.

Modelling interactions between riverbank hydrology and mass failures

Riverbank retreat derives from a complex combination of various processes, where a key role is played by the interactions of groundwater and surface water. Recent progress has been made in two main research areas: the effects of hydrological factors on mass failures; and the role of subsurface flow in seepage erosion and bank stability. See Rinaldi and Nardi (2013) for a detailed recent review.

Change in pore water pressures is one of the most important factors controlling the onset and timing of bank failures (Thorne, 1982; Springer et al., 1985), and the incorporation of this aspect in bank process models is one of the major areas of recent progress. After accounting for positive pore water pressures and confining river pressures (Simon et al., 1991; Darby and Thorne, 1996b), the effects of negative pore water pressures in the unsaturated portion of the bank have been introduced in more recent bank stability analyses (Rinaldi and Casagli, 1999; Casagli et al., 1999; Simon et al., 1999, 2000). This has been achieved by introducing in bank stability studies the failure criterion for unsaturated soils of Fredlund et al. (1978):

$$\tau = c' + (\sigma - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b \qquad (2)$$

where τ = shear strength (kPa), c' = effective cohesion (kPa), σ = normal stress (kPa), u_a = pore air pressure (kPa), ϕ' = effective friction angle (°), u_w = pore water pressure (kPa) and ϕ^b = angle (°) expressing the rate of increase in strength relative to the matric suction ($u_a - u_w$).

Therefore, the distribution of pore water pressures within the bank and its variations at the scale of a single hydrograph are necessary to assess bank stability.

Groundwater flow can be modelled by using the mass conservation equation in the form extended to unsaturated conditions (Fredlund and Rahardjo, 1993):

$$\frac{\partial}{\partial x}(k_x \frac{\partial H}{\partial x}) + \frac{\partial}{\partial y}(k_y \frac{\partial H}{\partial y}) + \frac{\partial}{\partial z}(k_z \frac{\partial H}{\partial z}) + Q = \frac{\partial \theta}{\partial t} \qquad (3)$$

where H = total head (m), k_X = hydraulic conductivity in the x-direction (m/s), k_Y = hydraulic conductivity in the y-direction (m/s), k_Z = hydraulic conductivity in the z-direction (m/s), Q = unit flux passing in or out of an elementary cube (m^3/m^3s), θ = volumetric water content (m^3/m^3), and t = time (s).

A two-dimensional, finite element seepage analysis based on equation 3 is generally used in bank stability studies (e.g. Rinaldi et al., 2004, 2008; Darby et al., 2007; Luppi et al., 2009), where positive and negative pore water pressure distributions for each time step of the hydrograph are used as input data for the stability analysis.

An additional effect related to groundwater flow is the occurrence of seepage forces on bank sediment related to the hydraulic gradient. Groundwater seepage exerts forces (*SF*, force per unit volume) on bank sediment proportional to the hydraulic gradient, $\partial H/\partial y$ (Lobkovski et al., 2004; Ghiassian and Ghareh, 2008; Fox and Wilson, 2010):

$$SF = \rho g\, \partial H/\partial y \qquad (4)$$

where ρ is the fluid density (kg m^{-3}), g the gravitational acceleration (m s^{-2}), H is the total head (m), y is the distance.

Hydraulic gradient forces can cause "pop-out" mass failure or liquefaction when upward seepage forces exceed the submerged weight of the sediment (Iverson and Major, 1986; Dunne, 1990; Budhu and Gobin, 1996; Ghiassian and Ghareh 2008; Chu-Agor et al., 2008; Lindow et al., 2009).

The movement of groundwater, in addition to changing pore water pressures or the generation of seepage gradient forces, can cause the deformation of the bank similar to fluvial erosion, and therefore promote mass failures through seepage erosion and undercutting. The first studies on groundwater seepage erosion and sapping in riverbanks were conducted by Hagerty (1991a,b), who defined 'sapping' as the process of bank collapse resulting from seepage or piping erosion, with 'piping' involving sediment erosion by macropore flow (Fox et al., 2007a,b; Wilson et al., 2007; Lindow et al., 2009).

Similar to fluvial erosion, the seepage erosion rate can be quantified using an excess gradient equation such as (Chu-Agor et al., 2009; Fox et al., 2010; Fox and Wilson, 2010):

$$E_{rs} = k_{se}\,(i - i_c)^{a} \qquad (5)$$

where E_{rs} (m/s) is the seepage erosion rate per unit time and unit bank area, k_{se} is the seepage erodibility coefficient, i is the groundwater flow gradient, i_c is the critical gradient, and a (dimensionless) is an empirically-derived exponent, reported to be 1.2 for sand and loamy sand soil (Chu-Agor et al., 2009).

Seepage erosion has received relatively less attention in the past compared to other processes of riverbank retreat, but its importance is increasingly being taken into consideration and notable recent progress has been made. Recent studies have reported in situ seepage flow and erosion measurements (Wilson et al., 2007; Fox et al., 2007b; Midgley et al., 2013), laboratory lysimeter experiments to simulate streambank undercutting by seepage flow and bank collapse (Fox et al., 2006; Wilson et al., 2007), and the numerical modelling of seepage erosion and bank instability (Fox et al., 2007a; Wilson et al., 2007; Chu-Agor et al., 2008; Cancienne et al., 2008; Lindow et al., 2009; Fox et al., 2010).

Mechanical effects of vegetation on bank stability

The two main mechanical effects of vegetation on bank stability which have received much attention are *surcharge* and *root reinforcement*, while other possible effects include *anchoring, buttressing and soil arching,* and effects related to *wind* action (Gray, 1978; Greenway, 1987; Thorne, 1990).

Surcharge refers to the additional weight of vegetation on the bank surface. The weight is calculated by multiplying the estimated volume of the tree by the wood density (depending on species). The volume of a tree is generally estimated by the following equation (De Vries, 1974):

$$V = \frac{\pi(d_1^2 + d_2^2)L}{8} \tag{6}$$

where V is the volume (m^3), d_1 is the diameter at the base (m), d_2 is the diameter at the top (m), L is the length of the trunk (m).

The net effect of vegetative surcharge can be either beneficial (increase in normal stress and therefore in the frictional component of soil shear strength) or detrimental (increasing the downslope component of gravitational force), depending on such factors as the position of the tree on the bank, the slope of the shear surface, and the friction angle of the soil (Gray, 1978; Selby, 1982).

The most important mechanical effect that vegetation has on slope stability is root reinforcement, i.e. the increase in soil strength induced by the presence of the root system. Considerable progress has recently been made in quantifying this effect (Waldron, 1977; Gray, 1978; Wu et al., 1979; Simon and Collison, 2002; Gray and Barker, 2004; Pollen et al., 2004; Pollen and Simon, 2005; Pollen, 2007; Pollen-Bankhead and Simon, 2009).

In the Waldron (1977) model, the tension developed in the root as the soil is sheared is resolved with a tangential component resisting shear and a normal component increasing the confining pressure on the shear plane. ΔS can be represented by

$$\Delta S = (\sin\theta + \cos\theta \tan\varphi)\, Tr\, (Ar/A) \tag{7}$$

where θ is the angle of shear distortion in the shear zone, φ is the soil friction angle (°), Tr is average tensile strength of roots per unit area of soil (kPa), Ar/A is the root area ratio (no units), i.e. the ratio between the cross-sectional area of the roots (Ar) and the area of the soil (A).

Sensitivity analyses carried out by Wu et al. (1979) showed that the value of the first angle term in Equation (7) is fairly insensitive to normal variations in θ and φ (40–90° and 25–40°, respectively) with values ranging from 1.0 to 1.3. A value of 1.2 was therefore selected by Wu et al. (1979) to replace the angle term, and the simplified equation becomes:

$$\Delta S = 1.2\, Tr\, (Ar/A) \tag{8}$$

Recent research (Pollen et al., 2004; Pollen and Simon, 2005) showed that the Wu et al. model tends to overestimate the additional shear strength of the roots due to the assumption that the full tensile strength of each root is mobilized during soil shearing, and that all the roots break simultaneously. Therefore, a new root reinforcement model (RipRoot) was developed based on fiber bundle theory to account for progressive root breaking during shearing (Pollen et al., 2004; Pollen, 2007; Pollen and Simon, 2005; Pollen-Bankhead and Simon, 2009).

The stabilizing effect of bank vegetation was also considered in the development of a bank stability criterion accounting for increased bank stability due to consolidation of bank sediment, cementing by fines, and binding of the sediment by root masses (Millar and Quick, 1993). This analytical approach, accounting for the effects of bank vegetation in terms of friction angle ϕ', was also used by Millar (2000) in order to assess the influence of bank vegetation on channel patterns of alluvial gravel-bed rivers. The results of this analysis suggest that bank vegetation exerts a significant and quantifiable control on alluvial channel patterns.

Hydrological effects of vegetation on bank stability

Vegetation has many effects on bank hydrology and, therefore, on bank stability. Tabacchi et al. (2000) reviewed the impacts of riparian vegetation on hydrological processes while Thorne (1990) reviewed the effects of vegetation specifically on riverbank erosion and stability, highlighting the influence of bank drainage due to the presence of vegetation on bank stability.

Vegetated banks are drier than unvegetated ones for two main reasons (Thorne, 1990; Simon and Collison, 2002): (1) canopy *interception* reduces the total volume of precipitation that infiltrates into the soil, and (2) plant *transpiration* reduces the soil water content and increases matric suction. However, vegetation may also have a detrimental hydrological effect because of the increased *infiltration* rate induced by root pathways (Simon and Collison, 2002). Hydrological effects of riparian vegetation are less well quantified than mechanical effects. Although data are available on canopy interception rates for many riparian tree species, it is more difficult to obtain data on the associated reduction of soil water content. Simon and Collison (2002) collected data on the hydrological and mechanical properties of three vegetation test plots on an unstable bank of the Goodwin Creek (Mississippi), including matric suction and pore water pressure monitoring. A key finding of this research was that the hydrological effects are as important as the mechanical effects, and can be either beneficial or detrimental, depending on antecedent rainfall. Canopy interception was negligible during the study period, accounting for only about 3 per cent of total rainfall, while pore water pressure monitoring revealed an enhanced infiltration rate via macropores, probably along root pathways. Analysis of the tensiometer values and the factor of safety before and after the period of minimum bank stability (February 2001) showed the occurrence of more adverse hydrological conditions (higher pore water pressures) under vegetation than under unvegetated soil. During these periods, hydrological effects reduced the factor of safety by 11 per cent.

The rate and amount by which plants alter the water-content distribution within a river bank also depend on many other factors related to vegetation type, soil characteristics, seasonal variations, and climatic conditions of the region. This again makes the effects of vegetation highly contingent and site-dependent, so that generalisation of results from this single study can only be attempted with extreme caution. Following the work of Simon and Collison (2002), remarkable progress has been achieved on quantification of the mechanical effects of roots (e.g. Pollen and Simon, 2005; Pollen, 2007), while there is still a need to generalize the findings of Simon and Collison (2002) by extending field measurements and the quantification of hydrological effects to a larger number of study cases.

Future research and modelling challenges

- Much progress has been made regarding the mechanical effects of riparian vegetation on bank stability (e.g. Pollen and Simon, 2005; Pollen, 2007), although measurements and the quantification of the hydrological effects of vegetation and their impact on erosion processes and bank stability are still limited (Simon and Collison, 2002). Therefore, more work is needed to better understand the hydrological effects of riparian vegetation and to incorporate them into models of bank erosion and failures.
- Modelling interactions of the various erosion processes and mass failures, and the relative role of vegetation on near-bank hydrodynamic flow conditions, erodibility parameters, and shear strength is another area of knowledge gaps, notwithstanding the recent progress that has been achieved. Existing models of bank stability and vegetation are two-dimensional, i.e. they are able to predict stability at the scale of a bank profile. It is difficult to extend results from a bank profile to a reach and account for variability of hydrodynamic, geotechnical, and vegetational conditions. This should be achieved by including vegetation into 3-D morphodynamic models.

In Annex A, Table 2 summarises the suitability of models with bank stability for the analysis of hydromorphological pressures or the design of restoration measures.

2.3.2.3 Bank accretion

General background

The morphology of an alluvial river is the result of interactions between vegetation, river flow and sediment dynamics, which includes erosion, transport and deposition. The main morphological changes in alluvial rivers are bed form evolution and corresponding river-width adjustment, by a combination of erosion and accretion of the river banks, which in turn change flow characteristics. Considering a single meander of a freely meandering river, its migration could be defined as the result of the interaction between the helical flow generated in river bends and the dynamics of river banks. Near the outer bank of erosion occurs (generated by near-bank flow and geotechnical instability), while the area close to the inner bank is dominated by deposition (due to the low flow velocities and shallow flow depth).

After decades of research, the relevance of the joint action between opposite river banks has been identified (Blench, 1969; Parker, 1978; Mosselman, 1992; Allmendinger et al., 2005). However, in most cases only erosive processes of banks are included in morphological models whereas only a coarse description of bank accretion is considered. Only when the interaction between bed topography and opposite-bank dynamics is included (notably river bank accretion), will it be possible to understand long-term equilibrium conditions for river channels such as i) determining the conditions that lead to river meandering due to the opposite-bank dynamics; ii) defining the conditions that generate transformations from meandering to braiding or vice-versa; and iii) identifying how to prevent river changes due to human interventions or climate changes.

River bank accretion is a phenomenon that acts from small scales (process scale) to large scales (reach scale), starting with the stabilization of sediment deposits on previously-formed bars. Channel margin deposits are more frequent in meandering channels than in other planforms, so these rivers generally have higher bank accretion rates.

Key factors in bank accretion

(i) General processes

Bank accretion starts with the formation of a sediment deposit which is eventually stabilized by the occurrence of several processes: mainly vegetation growth; soil compaction; and alternation of low and high flows (through the hydrologic regime and climate). The combined action between flow properties and bed material in rivers defines the sediment transport rates that drive morphological changes shaping the river bed-level. To predict bar formation is therefore the first step towards the occurrence of bank accretion (Crosato, 2008).

Stability and permanence of the deposited soil is also influenced by the presence of cohesive material, because once deposited soil consolidation increases soil resistance to erosive processes. The strengthening and stabilization of fluvial deposits are influenced by the hydrological regime, sediment transport, fine sediment processes, vegetation and climate. The interaction among all these processes allows the growth of previously-formed bars, their evolution and their final attachment to floodplains.

Flow characteristics such as magnitude, frequency, duration, timing and rate of change of the hydrological regime determine soil compaction and vegetation development, including pioneer plant growth and succession, stabilizing the deposited material (Poff et al., 1997).

(ii) Role of vegetation in bank accretion

Once established on sediment deposits, vegetation facilitates the reinforcement and construction of new landforms modifying the morphological environment. By producing additional hydrodynamic drag the new vegetation alters flow patterns and increases flow resistance, reducing the local flow velocity and the local bed-shear stress, favouring sediment trapping and deposition within the plants, and decreasing resuspension (Zong and Nepf, 2011). Some field experiences (Sand-Jensen and Mebus, 1996; van de Koppel et al., 2005; Cotton et al., 2006) and laboratory experiments (Zong and Nepf, 2010, 2011) show the effectiveness of vegetation patches in trapping and retaining fine sediment. Fine sediments trapped within vegetation patches also promote vegetation growth due to the nutrients they carry (Schulz et al., 2003) and facilitate colonization by other plant species by creating new habitats (Gurnell et al., 2012). Figure 2.3.11 shows an example of this process in a bend of a meandering stream.

The presence of vegetation favours stability of recently formed deposits by increasing the soil strength due to the mechanical reinforcement exerted by root networks including binding, tensile strengthening, and redistributing stresses (Ott, 2000; Pollen-Bankhead and Simon, 2010). Additionally, vegetation reduces erosion by covering bare soil and pore-water pressure as a result of the depletion of soil moisture by interception and evapotranspiration (Terwilliger, 1990; Pollen-Bankhead and Simon, 2010). However, the hydrological effects of vegetation may also decrease bank stability because of increased infiltration rates during rainfall events (Collison and Anderson, 1996; Simon and Collison, 2002).

Figure 2.3.11 Point bar stabilized in the Nakashibetsu River, Hokkaido (Japan) by vegetation growth and fine sediment capture. a) November 2003. b) August 2006. (Parker et al., 2011)

Modelling attempts

Scientific contributions on bank accretion in river morphodynamics mainly deal with observations, while quantitative descriptions of the evolution of bank accretion are lacking (Crosato, 2008). Some of the processes influencing river bank accretion have been included in morphological models, such as the increased roughness due to the presence of vegetation, but there is no a general model that describes this phenomenon.

Parker (1978) provided one of the first contributions to bank accretion modelling. He assumed a transverse sediment balance between accretion and erosion, including an accretion submodel caused by near-bank settling of fine sediments. By using a depth-averaged numerical model, Tsujimoto (1999) studied the effects of vegetation on bank accretion at the cross-sectional scale. Tsujimoto's model combined variable discharge and the colonization of vegetation. Nevertheless, this model does not include a bank erosion module and considers that plant properties are static in time. Bed level degradation occurs above a certain critical velocity, and then degraded areas are colonized by plants during low flows (Figure 2.3.12).

Since the majority of meander migration models only consider erosion processes, it is commonly accepted that a constant discharge (usually taken as the bankfull discharge) is sufficient to describe the natural hydrological regime. However, when the accretion process is taken into account, the seasonality of flows plays a decisive role due to the interaction between fluvial processes and vegetation development. Additionally, in this kind of model, bank advance has been taken into account classically by assuming a rate of bank advance equal to that of bank retreat on the opposite side of the channel (Ikeda et al., 1981; Crosato, 1989; Odgaard, 1989; Chen and Duan, 2006). This assumption is a basic long-term requirement for meandering rivers, but it implies that both processes work at the same speed and depend on the same factors (Crosato, 2008). Assuming also this equivalence between erosion and deposition rates, there are other modelling approaches that couple bank migration to vegetation dynamics (Perucca et al., 2006, 2007, Figure 2.3.13).

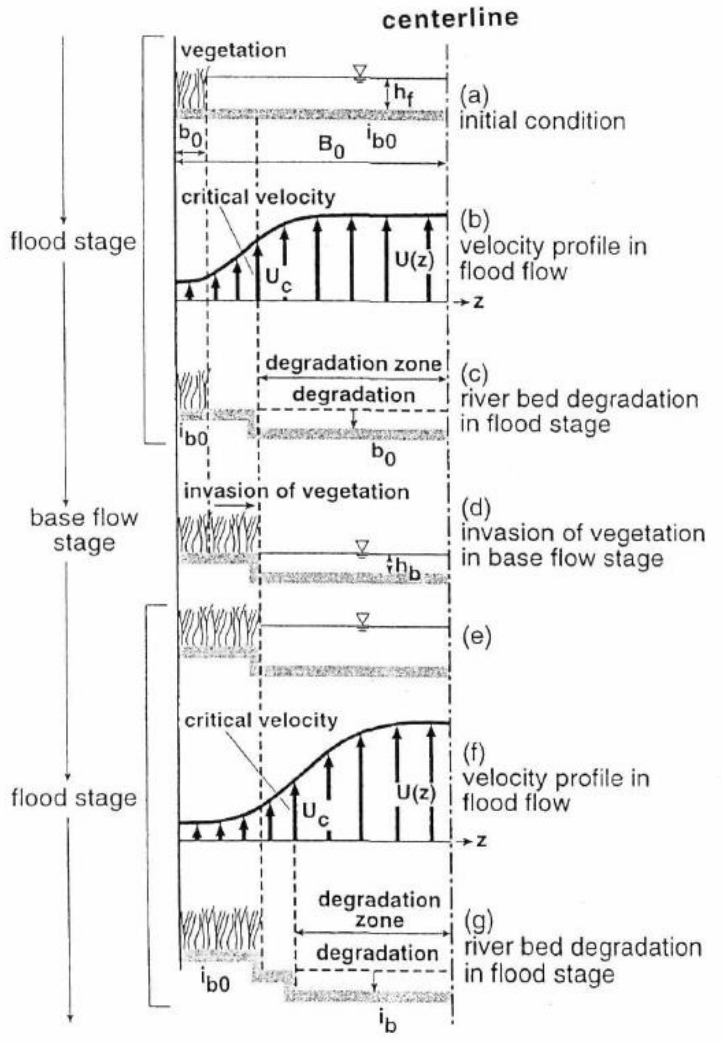


Figure 2.3.12 Schematic representation of Tsujimoto's (1999) model

In contrast, field observations have shown that erosion and accretion processes operate at very different rates and show temporal lags between them (e.g. Hobo et al, 2010; Yao et al., 2011). Figure 2.3.14 shows planimetric and width changes due to bank erosion and accretion of the Ningxia–Inner Mongolia reach of the China's Yellow River during a 50 year period.

In the case of meandering rivers, some of the more recent approaches have attempted to overcome the limitations of Ikeda et al. (1981)'s model, such as the simplified relationship that allows interaction between eroding and depositing banks defining both migration and evolution of the channel width, proposed by Parker et al. (2011). This latter model also includes the roles of slump blocks and vegetal capturing of sediment.

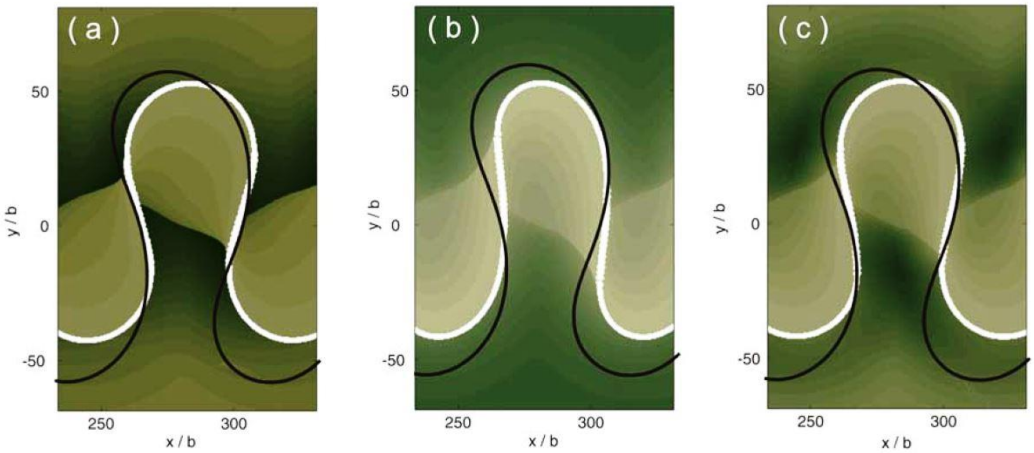


Figure 2.3.13 River planforms and corresponding vegetation patterns for transverse biomass distributions, where the main control factor is, respectively: (a) the water table; (b) floods; c) the combination of water table, floods and sedimentation. The green intensity is proportional to the vegetation biomass. The black lines indicate the planform obtained assuming a spatially constant erodibility. (Extracted from *Perucca et al.*, 2007).

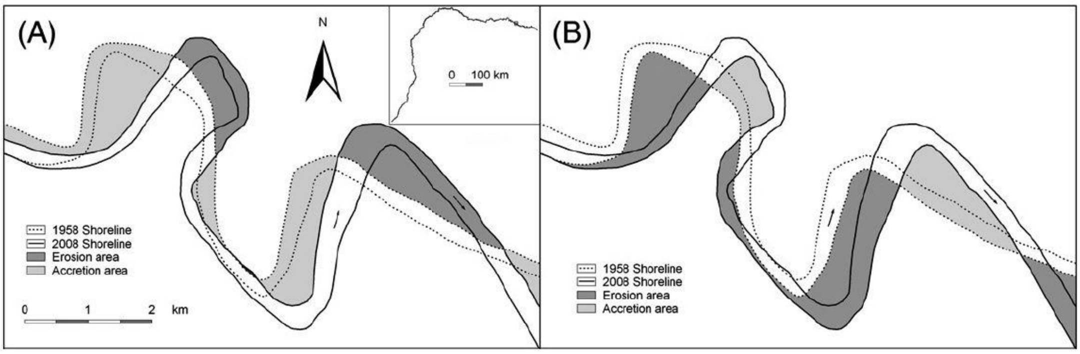


Figure 2.3.14 Bank erosion and accretion resulting in planimetric and width changes in the Ningxia - Inner Mongolia reach. Flow is left to right. Displacements observed in A) Left bank, and B) Right bank (Yao et al., 2011)

There are only a few models that consider the migration of a river as a coupled action of the eroding and depositing processes occurring at opposite banks. In relation to braided systems, a model proposed by Mosselman et al. (2000), was formulated to analyze the effects of bank stabilization. Mosselman et al. (2000) described channel migration as retreat and advance along the Brahmaputra-Jamuna River in Bangladesh, considering in both banks a submodel based on shear-stress excess of an analogous shape of the equation proposed by Osman and Thorne (1988) (see Figure 2.3.15). For the case study, they obtained good qualitative results, showing the importance of treating the erosion and accretion processes independently, however quantitative estimations deviated from observations.

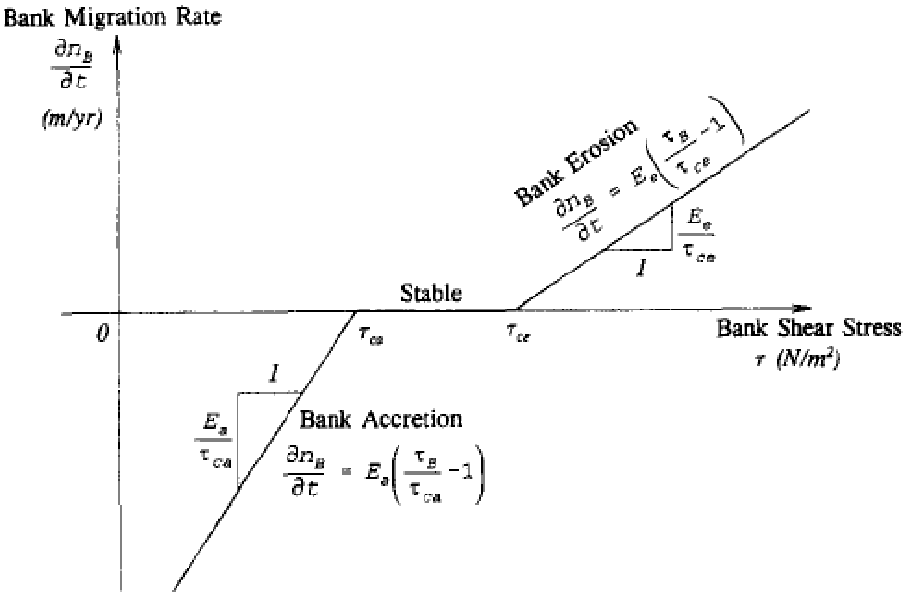


Figure 2.3.15 Schematization for bank erosion and bank accretion. (Mosselman et al. 2000)

Bank accretion is treated as bed aggradation in some existing 2D morphological models, such as Delft3D (Lesser at al., 2004); however, the effects of vegetation are not considered in this approach. There are some attempts to include erosion mechanisms in 2D morphological models, such as RIPA [developed by Mosselman (1992) and extended by Darby et al. (2002)]. However, attempts to add bank accretion in this kind of model is still lacking.

By adding channel neck cutoffs and land accretion due to vegetation development to the model proposed by Parker et al. (2011), Asahi et al. (2013) presented a computational framework that considers bank erosion and accretion simultaneously. The land is accreted to the floodplain in this model when cells are dry for a period longer than a user-defined time (See Figure 2.3.16), which means that all the vegetation processes are encapsulated in a time-dependent parameter. To date, this model is the most advanced approach that allows study of the dynamical interaction between the erosion and accretion phenomena in meandering rivers showing the relevance of variable discharges. However, this model ignores the influence and development stages of vegetation and the soil consolidation process among other relevant factors in the accretion phenomenon. Additionally, comparisons of estimates from the model with experimental or field data are lacking due to its limitation in upscaling long-term processes.

Future modelling challenges

Bank accretion modelling is still in its infancy, so there are many challenges remaining. The complexity of the processes that influence this phenomenon imposes difficulties in the modelling stages. Therefore, a clear view of each process is required to advance modelling. Our modelling recommendations relate to three main aspects: the inclusion of vegetation dynamics, the influence of the high variability of flows, and the up-scaling of the effects acting at different scales.

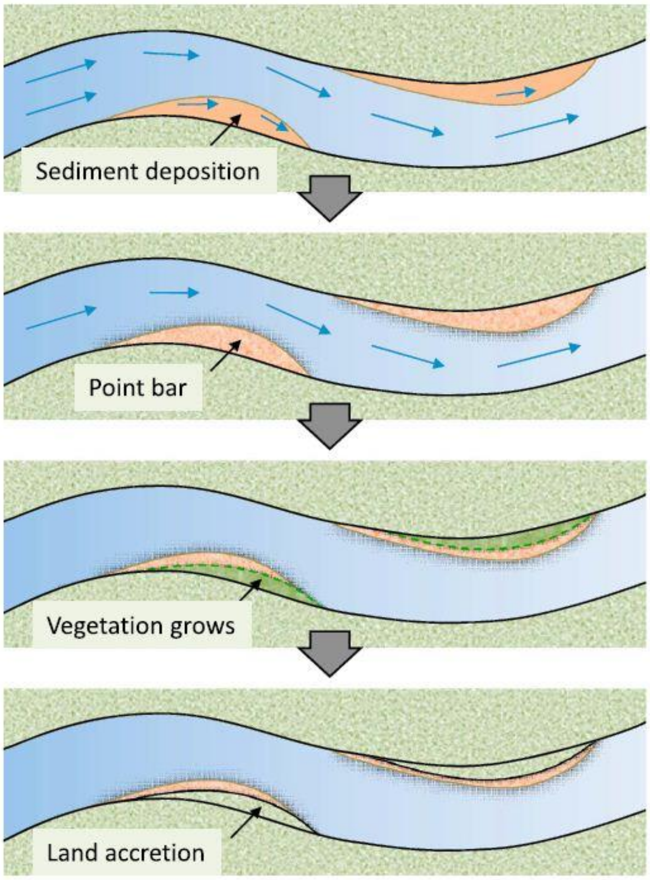


Figure 2.3.16 Land accreting process in Asahi et al. (2013)'s model.

Firstly, bank accretion models should include the effects of the presence of plants, and should consider their dynamics (colonization, survival, growth, succession, etc.) by involving their interaction with the flow and their changes over time. This aspect not only should include seasonal variations and geographical considerations, such as climate and geology, but also the effects of these processes on the groundwater distribution and on soil properties (composition, consolidation and resistance, among others). Secondly, it is necessary to include in a single framework hydrologic disturbances, morphological changes and vegetation development, allowing development timescales and the relative importance of the various components of the flow regime and its seasonal timing on the river system to be defined. Finally, river bank accretion should be understood at different scales, starting from the accretion processes that generate vertical variations within a cross section, to bank advance, observed in shifting bank lines that eventually lead to channel migration. This fact should be addressed by up-scaling processes from the short to the long term in order to reach a temporal scale of the order of several years to centuries. Timescales of bank accretion processes are highly relevant, considering their implications for vegetation development as well as the physical and mechanical transformations of soils that are due to the root effects and to consolidation processes.

In Annex A, Table 3 lists the suitability of models with bank accretion for the analysis of hydromorphological pressures or the design of restoration measures.

2.3.2.4 Effect of vegetation on sediment transport

Vegetation can drastically alter both the instantaneous and averaged flow field (Neary et al., 2012). These alterations have significant implications for sediment transport and, therefore, for bed morphology, including surface-layer sorting (Tsujimoto, 1999). In the literature, most studies focus on the implications of vegetation for river morphology while little is known about the exact influence of vegetational factors on sediment dynamics (Camporeale et al., 2013). Importantly, no general sediment transport models, incorporating the effect of vegetation, are currently available (Nepf, 2012).

In the following, a brief summary of the main findings, typically derived from laboratory observations, about the effect of vegetation on i) bed load, ii) entrainment and transport of suspended load; and iii) deposition of suspended sediment, is reported.

Regarding bed load transport, Baptist (2005) investigated, by means of laboratory experiments, the effects of *submerged flexible vegetation* on bedload transport; he found i) a reduction of the time-averaged bed shear stress, due to reduced time-averaged near-bed velocities and fluid stresses; ii) an increase of the sediment pick-up rate, due to an increased near-bed turbulence intensity. However, the primary effect was that of reduction of bed shear stress; only for short vegetation and near the threshold of motion could the increased pick-up rate become an important additional transport mechanism. Moreover, he found the sediment transport rate for a vegetated bed could be described by a common sediment transport formula, as long as the bed shear stress reduction is accounted for. These findings are substantially confirmed by other authors (e.g. Jordanova and James, 2003; Kothyari et al, 2009) in the case of sediment transport through homogeneous regions of *emergent rigid vegetation*. In particular, these investigations have shown that bed load transport rates are significantly smaller than those without the vegetation and can be expressed using a classical power function of the excess bed shear stress (i.e. of the Meyer – Peter Muller type); where the shear stress exerted on the bed was calculated by subtracting the total stem drag from the total force applied by the flow in the flow direction.

Note that the applicability of these models is confined to the range of investigated sediment size, stem diameter, and stem spacing (Järvelä et al., 2006). Moreover, regarding the bed level evolution in response to the presence of vegetation, direct measurements from a laboratory study in emergent plants have shown that the bed load transport is affected not only by the vegetation density and properties, but also by the way that its presence alters the flow conditions (Yager and Schmeeckle, 2013). Moreover, resuspension can occur in low-dense vegetation patches.

In relation to entrainment and transport of a suspended load of fine sediment (sand), numerical investigations (e.g. Lopez and Garcia, 1998; Choi and Kang, 2004) of mean flow and turbulent structure through simulated vegetation indicate the capability of current models to reproduce the suspended load observed in controlled experimental flumes. Simulations show the decrease of the suspended sediment transport capacity is due to a reduction of the ability of vegetated flow (i.e. reduction of bed shear stress) to entrain sediment into suspension from the channel bottom. However, note that is not generally true as, in real rivers, flow into a vegetated area may carry sediments in suspension from upstream; therefore, the suspended sediment transport capacity depends also on the turbulence intensity that provides the upward flow velocities that counteract gravity, irrespective of the entrainment from the bed. Crucial in the above models is an adequate modelling of the turbulent flow field; for instance, Choi and Kang (2004) showed that the isotropic turbulence model leads to an underestimation of the suspended load.

Importantly, according to Nepf (2012), in vegetated regions, the turbulence level is set by the vegetation drag and has little or no link to the bed stress. Since transport of sediment, especially suspended load, is directly linked to turbulence, the approaches and relationships developed for open-channel flows cannot be simply extended in regions with vegetation.

Regarding the deposition of suspended load, in general, sedimentation rates have been observed to increase when vegetation is present. However, this process is rather complex and affected by many factors depending on the combination of flow, vegetation (type and spatial distribution), and sediment properties (Neary et al., 2012).

Abt et al. (1994), in their pioneering contribution, investigated sediment deposition and trapment of fine sediment (D_{50} = 0.09 mm) due to the presence of an *evenly distributed submerged, flexible vegetation* (mainly Kentucky bluegrass) in a meandering laboratory flume. Vegetation induced deposition, but the process appeared to be inversely related to the blade length as relatively long blades can flatten and armour the bed. In the case of a flushing wave, the percent of sediment trapped in the bed ranged from 30 to 70 % depending on the blade length: the longer blades trapped more sediment. In addition to this, the vegetation sorted the sediment, as fines were entrained and transported while larger grains were transported as bed-load and trapped. The median size of the trapped sediment was twice that of the parent material. Cotton et al. (2006) documented the capability of in-stream macrophytes (*Ranunculus* spp.) to retain fine sediments in two river reaches in the River Frome catchment, Dorset (UK). Lower flow velocities were observed within the stands of *Ranunculus* (typically <0.1 m/s), and higher flow velocities were observed between the plants (up to 0.8 m/s) because of the constriction of flow. The low flow velocity areas promoted the deposition of fine sediment within the plant stands. The quantity of accumulated sediment was controlled by changes in sediment supply as well as the trapping efficiency of the plants.

More recently, research investigations have emphasised the effect of the complex flow field associated with *finite vegetation patches* and the implications for sediment deposition, showing that vegetation may also have a destabilising effect on the sediments (i.e. removal of fine sediments) due to high local turbulence intensities and vertical velocity components. For example, van Katwijk et al. (2010) investigated the interaction between seagrass beds and sediment dynamics, observing two opposite processes: fine sediment trapping in dense seagrass beds, and sediment resuspension due to locally enhanced turbulence in sparse beds. Elevated turbulence levels, similar to those found in open channel flow, were also observed within the leading edge of a vegetation patch by Zong and Nepf (2011), resulting in net deposition that was lower within the leading edge than in the adjacent bare bed, despite the fact that the mean flow velocity was reduced. In the case of *emergent vegetation*, Follett and Nepf (2012) documented the bed pattern near an isolated circular patch of rigid cylinders in a laboratory flume. They found that: i) the flow field at the edges of a finite patch produced erosion, associated with the removal of fine sediments, which in turn is likely to inhibit the lateral expansion of the vegetation; ii) the wake downstream of the patch was a region with predominant deposition of fine sediment transported in suspension, and it was also shaded from significant bedload transport; these conditions are likely to produce a favourable environment for plant growth.

Ortiz et al. (2013) investigated the depositional pattern of fine sediment load around an isolated circular synthetic patch of *submerged flexible vegetation*. In contrast to the case of emergent patches, no clear sediment deposition was found in the wake region. This was due to the fact that although the flow velocity was lower downstream of the patch, the submerged vegetation produced recirculation and elevated turbulent kinetic energy thus preventing fine sediment from depositing. Moreover, in this case flow was deflected not only laterally, as in the case of emergent vegetation, but also over the top of the patch, so that for the same flow conditions, submerged vegetation produced relatively weak flow acceleration at the patch edge. This investigation demonstrates the key role of turbulence in controlling deposition.

In conclusion, research on the effect of vegetation on sediment transport is needed in relation to the following topics:

- Characterization of turbulent coherent structures in mobile vegetated channels in order to understand flow conditions leading to deposition and substrate stability of a given particle size;
- The impact of spatial variability of vegetation on flow and sediment transport;
- Formulation of models for evaluating sediment transport incorporating the effect of turbulence and vegetation properties.

2.3.3 Effects of hydromorphodynamics on vegetation

2.3.3.1 Introduction

'Vegetation processes' are explored here in terms of plant life stages, i.e. dispersal related to reproduction, colonization and/or recruitment (including establishment and early survival), growth, and succession (and mortality). According to each of the stages that plants experience during their life, they adopt specific adaptive strategies which differ amongst species and also according to environmental conditions (e.g. competition, tolerance to stress, ruderal behaviour, vegetative/sexual reproduction; Grime, 1979). In rivers, successful riparian plants often adopt a combination of adaptive strategies to ensure their survival including high dispersal rates; adaptations to resist stress; and vegetative reproduction (Camporeale et al., 2013).

In summary (see section 2.2 for more detail), within fluvial systems vegetation is mainly dominated by disturbance conditions generated by floods (Bornette et al., 2008), whose dominance decreases laterally across the river corridor, being maximal at channel level and minimal on the river corridor margins, where competition with other species becomes predominant (Corenblit et al., 2007; Gurnell, 2014). The flood regime influences plants composition, distribution and structure (Bendix and Stella, 2013; Camporeale et al., 2013). Floods physically disturb vegetation, through sedimentation (i.e. plant burial), erosion and inundation effects (i.e. reduction of physiologic functions), and contribute directly to plant dispersal (i.e. hydrochory) (Bornette et al., 2008; Bendix and Stella, 2013). In fluvial systems, plants are adapted to physical disturbance by floods and develop two main kinds of biological traits (Bornette et al., 2008; Gurnell, 2014): (i) adaptations to flood duration, erosional and burial stresses through flexible stems and branches, extensive root networks, rhizomes, adventitious roots, etc.; (ii) the ability to colonise new patches and grow rapidly, by adopting both sexual reproduction (i.e. large quantities of seeds) and vegetative propagation (i.e. vegetative fragments or entire uprooted individuals). Plants are also sensitive to water-table depth variations and sediment texture in terms of soil moisture, as well as to soil chemistry in terms of mineral composition, salinity and pollutants (Bendix and Stella, 2013), and droughts (Camporeale et al., 2013).

Recently, several models have been developed to explain vegetation processes in riparian systems influenced by river hydromorphology. Probably because of the complexity of such processes, conceptual models are still widely employed. Several authors also combine classic hydraulic, hydrological models and statistical approaches (e.g. ordination techniques, regressions) to explain the vegetation patterns in relation to physical drivers. The present review includes examples of mathematical, physical and spatial (including experimental design) as well as conceptual models of vegetation processes. For each category of vegetation process a brief review of the main process principles is also provided. Finally, examples of management implications for each modelling approach are reported. The review is mainly focussed on the effects of hydromorphology on riparian vegetation processes, excluding aquatic plant vegetation types (see examples of models for these vegetation groups in Reynolds and Elliot, 2012). Riparian vegetation models often apply specifically to the Salicaceae (i.e. *Populus* spp., *Salix* spp.), which dominate riparian forest ecosystems in the temperate zone of the northern hemisphere, where most models have been developed (Camporeale et al. 2013).

2.3.3.2 Riparian vegetation dispersal

(i) Main principles

The main process of vegetation dispersal in fluvial systems is hydrochory (dispersal of plant seeds and other propagules by water) although dispersal by wind (anemochory) is also a significant process. Indeed, wind dispersal is often preferentially guided along river corridors by the valley topography and morphology of riparian canopies (Bendix and Stella, 2013). Hydrochory is maximised when flood frequency is high (Bornette et al., 2008) and during overbank floods (Nilsson et al., 2010), particularly when these events correspond to periods of seed release (e.g. Merritt and Whol, 2002; Gurnell et al., 2004). Indeed, some species (e.g. Salicaceae) synchronise their timing of seed release to benefit from environmental conditions found on the falling limb of the natural annual river flow regime (Gurnell, 2014). Transfer of plant propagules by hydrochory is moderated by channel sinuosity and roughness, including the presence of large wood (e.g. Groves et al., 2009).

(ii) Examples of modelling developments

In general vegetation dispersal models predict the spatial pattern of seed dispersal and deposition in terms of density at a given distance (e.g. Groves et al., 2009), concentration variability along river margins (e.g. Merrit and Whol, 2002) or relative amount on different riparian landforms (e.g. Steiger and Gurnell, 2002).

The earliest models addressing hydrochory used empirical approaches (e.g. Campbell et al., 2002; Levine, 2003) which did not account for the variability of the flow regime. Recently Groves et al. (2009) developed a semi-empirical model of fluvial seed density dispersal from a point source. They modelled the dispersal curve, quantified the curve empirically and then calibrated and validated the model using empirical data. The equation predicts the relative seed density deposited at X m distance from the point source (Figure 2.3.17) and has the potential to contribute to improved management and restoration efforts in riparian zones.

Merritt and Whol (2002) conducted a flume experiment which provides an empirical basis to obtain predictive models of spatial patterns of seed dispersal, based on flow regime, channel morphology and timing of seed release. The authors highlight that incorporating dispersal phenology and information regarding the biophysical environmental preferences of species of special concern may allow specific hydrograph characteristics below dams to be managed through flow release schedule design, to favour or inhibit species using hydrochory as the driver, while leaving many of the societal and economic benefits of dams uncompromised.

Other models of longitudinal dispersion in rivers exist, as for example the one developed by Tealdi et al. (2010), which concerns longitudinal dispersion in a broad sense (i.e. not only for vegetation). The authors developed a stochastic bio-hydrodynamic model which provides the probability distribution of a generic dispersion coefficient. The model is performed through four separate blocks: vegetation dynamics and characteristics, hydrology regime and hydraulic characteristics. It may allow assessment of how river management or restoration measures can impact the longitudinal dispersion along rivers.

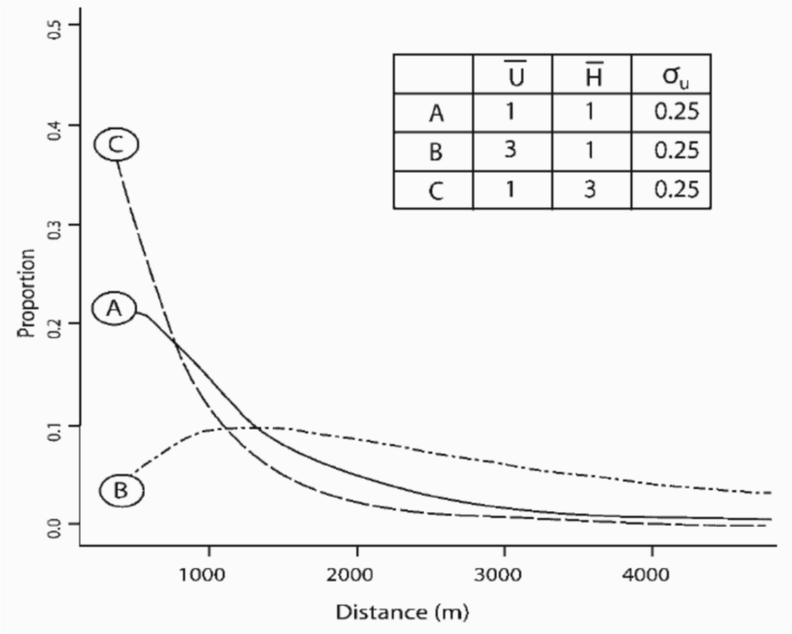


Figure 2.3.17 Modelled dispersal curves for selected parameter values: proportion, represents seed deposited; $\overline{U}$, is the geometric mean of velocity; $\overline{H}$, is the average channel depth; σ_u, is the standard deviation of ln($\overline{U}$). As $\overline{U}$ increases, the mean moves right and the tail is extended, and as $\overline{H}$ increases seeds are deposited closer to the release point. (Extracted from Groves et al., 2009)

Finally, an example of a conceptual model of plant dispersal is that of Steiger and Gurnell (2002). The authors proposed a conceptual model of the pattern of deposition of sediment mass within riparian zones in relation to flood magnitude. The model does not account directly for plant propagules, but it is assumed that these elements are part of the organic fraction of sediment deposited by floods. The authors state that deposited sediment and propagules depend on flood magnitude and on the complexity of river landforms.

Annex A, Table 4 summarises the main characteristics of the models discussed above.

2.3.3.3 Riparian vegetation recruitment, early survival and development

Main principles

The colonisation of sites depends on a combination of several factors including: river flow, mainly the flood regime; local and river reach morphology; and propagule traits. The success of early plant development also depends on the physical character of the newly colonised site and other environmental drivers such as: the presence of a bare substrate combined with the accumulation of fine sediments which retain moisture and nutrients; the topographic position of the site in terms of distance from the water table; climatic conditions during the growing season (e.g. Gurnell et al., 2002; Hervouet et al., 2011; Camporeale et al., 2013); and the flow regime. The flow regime during this early period influences initial germination or sprouting by creating favourable substrate and moisture conditions or inducing the death of young plants as a result of very rapid water table decline or excessive disturbance by flood pulses. In the case of seeds, the timing of seed release strongly influences the success of riparian vegetation recruitment, given that germination success and early seedling development of pioneer riparian tree species is related to the availability of moist, bare substrate (Gurnell, 2014). Furthermore, riparian species have differing sensitivity to hydrological processes and as a consequence the distribution of the riparian species depends on the spatial and temporal gradient of the disturbance regime (e.g. Camporeale et al., 2013). Distinctions can also be made between different reproduction strategies. For example, for the riparian Salicaceae early plant growth is faster as a result of vegetative propagation rather than from sexual reproduction. Thus early plant survival also reflects propagule type, since larger plants have the best chance of survival in disturbed riparian environments, and the critical period for plant survival is the first years when young individuals are most susceptible to being buried, eroded or desiccated (Gurnell, 2014).

Examples of modelling developments

Most models address patterns of seedling survival and growth after germination, where the latter is mainly assumed to be a function of seed dispersal (e.g. Ahn et al., 2007). In general the models predict the pattern of population dynamics in response to hydromorphological conditions. For example, Ahn et al. (2007) model vegetation recruitment through a dynamic simulation model for black willow seedling survival and early growth in relation to the flood regime, specifically flood timing and duration. They also took account of capillary water (i.e. it depends on soil type), as well as the length of the growing season and the timing of seed dispersal. The model potentially provides a framework for simulating any pioneer tree species that colonizes floodplains, when the required species-specific physiological information is available. The model may also help to prescribe management procedures to encourage or discourage colonization and growth of black willow and to predict where to plant or encourage the development of more inundation-tolerant species. In the context of dry regions, Stella and Battles (2010) and Stella et al. (2010) combined field experiments and statistical analysis (e.g. logistic regression) to derive seedling survival and growth in relation to water table stress, and so highlight the potential for a shift in riparian vegetation composition under future climate conditions or under reduced regulated river flows. Several conceptual models have also been built to understand and predict riparian plant recruitment. In particular, Mahoney and Rood (1998) developed the *recruitment box model*, which determines the stream stage patterns that 'enable successful establishment of riparian cottonwood seedlings', also integrating aspects of seedling physiology (see section 2.1 for further details). The model has been widely adopted and adapted in several contexts, as for example to prescribe flow regimes for the restoration of riparian forests in dammed rivers (e.g. Rood et al., 2003a; 2005) and to characterise three dominant tree species in a river basin in the California's Central Valley (Stella, 2005). The model can be applied to predict the effects (e.g. ecological and economic benefits) of alternative restoration strategies, or to plan how (when and where) to manage the water resource, in hydrological altered river basins.

Annex A, Table 5 summarises the main characteristics of the models discussed above.

2.3.3.4 Riparian plant growth

Main principles

Plant growth continues to be affected by river physical and hydrological drivers after the establishment phase. It is supported by the availability of moisture and nutrients, which may be facilitated through trapping and stabilisation of fine sediment by other plants (Bornette et al., 2008; Gurnell, 2014). Plants have specific adaptations and growth responses (*traits*) to meet the environmental conditions (i.e. floods and droughts) where they establish. For example, some plants ensure their maintenance after a disturbance event by clonal growth (through survival of deeply anchored roots or rhizomes; or by spreading from refuges or sprouting from vegetative propagules), whereas some plants are able to produce adventitious roots that utilize nutrients in alluvial material deposited by floods (Bornette et al., 2008). Other adaptations of growth forms to disturbance are plastic responses in terms of small size and flexible growth forms or increasing allocation of resources to anchorage.

Examples of modelling developments

There are some examples of models addressing the issue of plant growth, such as the early example for tree growth of Botkin et al. (1972), and also related with physical disturbances, such as the model for mangrove forest development along a gradient of soil salinity and nutrients by Chen and Twilley (1998), and the model for canopy-gap induced growth by Arseneault et al. (2012) for silvicultural systems. However, few concern riparian and floodplain systems and even less address individual plant growth.

One example is Pearlstine et al. (1985), who adapted a previous ecological model by Odum (1983) into a mathematical model with key processes that affect riparian plant growth (Camporeale et al., 2013). The model assumes a specific rate of riparian tree growth in optimal conditions, represented by the product of stand density (i.e. competition), temperature, shading tolerance and the position of the water table (Camporeale et al., 2013).

Another example is the model developed by Perucca et al. (2006) which describes a numerical fluid dynamic model of meander dynamics (using a shallow water equation on an erodible bed) combined with a process-based model of riparian vegetation dynamics based on the dominant or combined effect of water table oscillations, flooding and sedimentation. The model highlights the influence of river dynamics on the formation of riparian vegetation patterns, in terms of biomass density (Figure 2.3.13).

Camporeale and Ridolfi (2006) developed a stochastic model of local riparian vegetation ecosystem dynamics based on the variability of the river channel cross profile in terms of hydrology and hydraulic variability (i.e. the water level and the topographic elevation of the vegetation, respectively). They obtained an analytical expression of the probability density function of the overall vegetation biomass.

Finally, Takebayashi et al. (2006) inserted a simple rule for vegetation growth in terms of density into a mesoscale channel configuration morphodynamic model. The authors assumed linear growth starting from an initial density until it reaches a maximum density value, according to the type of vegetation.

Annex A, Table 6 summarises the main characteristics of the models discussed above.

2.3.3.5 Succession and riparian vegetation distribution

Main principles

After early plant development the creation of more stable, less disturbed areas allows vegetation to grow and establish while contributing to stabilizing these vegetated surfaces. Colonisation of bare surfaces by pioneer species is followed by succession, which involves changes in species composition and other plant community characteristics (productivity, biomass, diversity, etc.) that, if undisturbed, culminates in a mature and stable state known as *climax* vegetation (Odum, 1969). Given that river corridors are highly disturbed, unstable environments, vegetation succession is interrupted or reset by floods and droughts. Vegetation succession is accompanied by sediment retention and stabilisation through positive feedback mechanisms such that an increasingly high flood magnitude is necessary to perturb and destroy the establishing vegetated surfaces (e.g. Gurnell et al., 2002, 2004; Corenblit et al., 2007).

Examples of modelling developments

Models of vegetation succession can apply to local (i.e. site, reach or cross section) or larger (e.g. river segment, basin, region) scales.

At the *local scale*, models predict the vegetation type in terms of:

(i) riparian vegetation composition, i.e. species or vegetation/phytosociological units or plant communities;

(ii) riparian ecosystems.

An example of local scale vegetation modelling, in terms of vegetation composition, is NATLES, which predicts potential occurrence of ecological species groups and vegetation units from derived historical hydrological conditions (Runhaar, 2003). Another example is the model PREVIEW, a hydro-ecological tool which predicts vegetation development at the local scale (in terms of vegetation types) combining several river specific environmental factors: soil parameters, hydrological regime and type of management (Aggenbach and Pelsma, 2005). At the reach scale, Auble et al. (1994) describe a numerical model (hydraulic modelling combined with a cluster analysis) of vegetation changes in terms of plant communities. The aim of the model is to quantify the flood duration of distinct plant communities and to describe vegetation changes under proposed regulated flow regimes. By adopting a spatially-based approach combined with statistical relationships (e.g. GLM, Classification Trees, Boosted Trees.), Menuz (2011) predicted specific species distributions or environmental factors which promote the distribution of the species of interest. In particular the model addresses the issue of invasion by exotic species, so allowing areas susceptible to invasion and factors associated with plant invasion (e.g. nutrients, climate, forest cover, disturbance, human density) to be identified and providing preventative management recommendations.

Examples of modelling the overall riparian ecosystem include Camporeale and Ridolfi (2006), who used the results of their eco-hydrological stochastic model of riparian vegetation dynamics (in terms of biomass, see section 2.3.3.4) to analyse the effect of river hydrology and morphology on the spatial distribution of riparian vegetation across a riparian-river transect. Tealdi et al. (2011), following Camporeale and Ridolfi (2006), developed an eco-hydrological model which provided combined information on river narrowing, vegetation width and biomass variation induced by river damming, but also the consequence of vegetation modification and river narrowing on hydrological parameters and river behaviour. Similar to Menuz (2011), the CASIMIR-vegetation model employs a spatially-based approach to provide scenarios of floodplain vegetation at the reach scale under modified hydrological conditions (Benjankar et al. 2011; García-Arias et al. 2012; Rivaes et al., 2012). Lastly, Tsujimoto (1999) provides an example of physical morphodynamic modelling which includes vegetation patterns in response to flow and flood regime. The author, summarising the results of other experiments, shows how the vegetated fluvial landform pattern (island width and length) responds to several floods followed by low-flow stages, where fine sediment deposition below a dam is occurring. He also demonstrates that different island patterns occur according to the development or not of an armoured substrate.

The majority of these models can be applied to assess the impact of vegetation management; to describe natural vegetation development; and to plan riparian vegetation management in relation to hydromorphological impacts and floodplain restoration measures.

At a larger spatial scale, models mainly concern the succession of ecotypes and related parameters. Some examples are: BIO-SAFE, which provides flood prevention measures and effects on red-list species (Lenders et al., 2001); LEDESS, a decision support tool at landscape scale (Buit et al., 1998); and the probabilistic model of Franz and Bazzaz (1977) for reservoir management. An applied approach that addresses flood protection at a large scale is that of Baptist et al. (2004) for floodplain management (Cyclic Floodplain Rejuvenation, CFR) in The Netherlands. The approach combines hydraulic, sedimentation and vegetation models. In the latter, the impact of hydrology on floodplain vegetation evolution (development and succession) is assumed to be ruled by 4 input variables: (i) inundation duration (i.e. it influences species composition); (ii) the sedimentation rate (i.e. high rates may reset the succession); (iii) former land use (i.e. influence on the direction and rate of vegetation succession); and (iv) grazing by large herbivores (i.e. it creates mosaic patterns). The authors stress that floodplain rejuvenation may allow flood protection and nature rehabilitation to be combined in highly regulated rivers.

Concerning conceptual models, similar to the *recruitment box* of Mahoney and Rood (1998) for the establishment of riparian cottonwood seedlings, Kondolf and Wilcock (1996) described a conceptual model named the *Window of opportunity* which applies to mature riparian forest vegetation. The model refers to longer-term processes affecting the likely location of mature riparian vegetation. It relates relative elevation and location of successfully established riparian vegetation to scour and inundation stresses at lower elevations and to drought or desiccation stress at higher elevations. Recently, Gurnell et al. (2012) combined a numerical and a conceptual model to obtain plant distribution across a river corridor and to highlight the development of vegetation-mediated landforms (i.e. plants as ecosystem engineers), in a natural context. Finally, the six-stage Channel Evolution Model of Simon and Hupp (1986) is also relevant. Based on observations on a modified river in west Tennessee (US), the model describes river cycles of erosion, accretion, and return back to equilibrium. The cycles mainly concern geomorphic processes, but also include patterns of woody vegetation succession (Osterkamp and Hupp, 2010). Starting from the modification of the natural river channel and the removal of woody vegetation, the model highlights the establishment and the succession of different vegetation communities in relation to the evolution of geomorphic processes and forms.

Annex A, Table 7 summarises main characteristics of the models discussed above.

2.3.3.6 Population dynamics models

Several models account for all the stages of vegetation development in rivers, as for example the stochastic, density-dependent, population model of Lytle and Merritt (2004), applied to cottonwoods in the US. Lytle and Merritt's model describes, through different scenarios, how annual variation in the hydrograph affects cottonwood population dynamic in terms of mortality (i.e. via floods and droughts) and recruitment (i.e. via scouring of new habitat and seedling establishment). The model may help in planning prescribed floods by simulating how altered flow regimes might affect riparian populations. Another example is that of Van Looy et al. (2005), who combined a 2D numerical model for hydromorphology (SCALDIS; Mwanuzi and De Smedt, 1997; Mwanuzi, 1998) with vegetation data. The aim was to predict where and how vegetation patches can develop from germination to the forest phase on the basis of hydrological and morphological data. The final outputs of the modelling are temporal sequences of forest development (i.e. germination/establishing/survival/forest phase). The model can be used to assess the success of forest floodplain restoration as well as to plan restoration, by giving indications on potential sites for riparian forest development. Recently, Harper et al. (2011) combined several approaches (i.e. a patch-based model; a mechanism-based population model; a statistical analysis to rank the importance of parameters and evaluate interactions), aiming at modelling the riparian floodplain colonization and forest dynamics of the Sacramento River (California). The model simulates the interactions between floodplain topography, hydrological regime and plant demography. The result is a combination of outputs: a patch evolution map; a sub-model for plant colonization which accounts for seed release, germination, survival and mortality of seedlings, saplings and adults on each patch. The model specifically applies to a species of cottonwood present in that area, with the aim of predicting future conditions under changing climate and hydrology. The authors also include a sensitivity analysis to assess the precision of model prediction in the case of multiple-interactions.

2.3.3.7 Future modelling challenges

In the previous sections it has been shown that predicting the effects of hydromorphology on riparian communities aiming at riparian and general river management, requires integration of models of ecology, hydrology, morphology and sediment transport at scales ranging from a geomorphic unit (e.g. a gravel bar) to an entire river even an entire catchment. In the literature researchers identify some key future modelling challenges to improve the understanding of the influence of hydromorphology on riparian vegetation, that also fall within the scope of ecosystem management (e.g. Bornette et al., 2008; Osterkamp and Hupp, 2010; Camporeale et al. 2013; Gurnell, 2014), such as:

- The spatial and temporal dynamics of soil moisture and water table which influence several stages of plant development (recruitment on new sites, plant survival and growth);
- The understanding of the impact of stochastic variability of river discharge on vegetation processes and patterns;
- The development of quantitative ecological models of vegetation succession;
- The understanding of the response of different vegetation traits to a wide range of physical (fluvial) disturbances.

There is a need for models which address riparian plant growth rates at the scale of individuals (Camporeale et al., 2013; Gurnell 2014). Related to the latter point, it would be interesting, in relation to seedling survival and plant growth rate, to compare different propagule responses following disturbance (i.e. for different species and different propagule types; see the observations concerning the *Populus nigra*, showed for example by Gurnell, 2014). Another aspect is climatic change and related disturbances, which until now have received little attention in studies concerning riparian ecosystems (Osterkamp and Hupp, 2010). Finally, given that most riparian vegetation models have been developed to apply to the northern temperate zone, there is a need to extend research and modelling development into other regions and climatic contexts (Gurnell, 2014).

Appendices A, Tables 4 to 7 indicate the suitability of the discussed models including the effects of hydromorphology on vegetation (dispersal, recruitment, growth and succession) for the analysis of hydromorphological pressures or the design of restoration measures.

2.3.4 Large wood

2.3.4.1 Background

Over the last few decades, research on the role of wood in river ecosystems has become an increasingly important focus. Research on large wood and fluvial processes has included (Gurnell et al., 2002): (1) effects of wood on flow hydraulics; (2) impact of wood on the transfer of solutes, mineral sediment and organic material within the river channel and floodplain; (3) effects of wood on the geomorphology of river channels.

Analogies between wood and mineral sediment transfer (supply, mobility and river characteristics that affect retention) can provide a useful framework for synthesising current knowledge on large wood in rivers (Gurnell et al., 2002) through the investigation of wood budgets. However, the application of the budget framework for both small and large streams may prove problematic because of limitations in the current development of wood budget models (Hassan et al., 2005), which have placed most emphasis on wood recruitment (Martin and Benda, 2001; Benda et al., 2002).

Mechanisms of wood recruitment include (Benda et al., 2003): (a) chronic mortality, including blowdown, insects, pathogens, water logging, or catastrophic mortality related to single events (e.g. hurricanes); (b) wildfires; (c) bank erosion, including erosion of instream vegetated surfaces (bars or islands) and floodplain forests; (d) landslides on hillslopes connected to the stream. There are a number of less well known processes that may be regionally important, such as ice storms, ice break, dam-break floods, etc. The contribution of single processes and their relative importance to overall wood supply vary according to a number of factors including geographic region, climatic conditions, hydrologic regime, network structure, forest composition, disturbance processes and human influences.

Mutz (2003) reviewed the main hydraulic effects of wood in streams and their quantification, of which flow resistance related to wood elements has received much attention (e.g. Young, 1991; Shields and Smith, 1992; Curran and Wohl, 2003; Wilcox and Wohl, 2006; Wilcox et al., 2006).

Entrainment of wood is a difficult issue theoretically, given the complexity of interactions between wood and other elements in the channel. Theoretical wood entrainment models are based on the balance between hydrodynamic (*F*) and resisting (*R*) forces acting on individual woody elements. The drag force (F_D) is generally expressed as (Manners et al., 2007):

$$F_D = \frac{1}{2}\rho \cdot C_D A_F U^2 \qquad (1)$$

where ρ is the water density, C_D is the drag coefficient of the obstruction, A_F is the measurable frontal area of the obstruction normal to flow, U is the flow velocity.

Haga et al. (2002) developed a simplified analysis for a cylindrical wood element with a size smaller than the channel width, allowing definition of conditions for resting, rolling or sliding, and floating, as function of the non-dimensional ratio between hydrodynamic and resisting forces, and the ratio between flow depth and the diameter of a wood element.

Braudrick et al. (1997) and Braudrick and Grant (2000) carried out physical experiments on entrainment and transport of wood pieces by processes such as flotation and rolling. They introduced an analytical model that predicts the flow conditions needed to entrain individual wood pieces and then conducted flume experiments to examine wood movement as a function of flow conditions, channel morphology, and wood size input rates. They reported three distinct transport regimes: (1) uncongested, in which individual pieces move without interacting, occupying less than 10 percent of the channel area; (2) congested, in which logs move in groups, occupying more than 33 percent of the channel area; and (3) semi-congested, which is an intermediate state between the first two regimes.

A small number of studies have explored critical processes determining quantities and patterns of wood in streams, such as tree mortality, input, breakage, decomposition, mechanical breakdown, and transport. However, simulation models have been developed in recent years to explore long-term or large-scale implications of wood dynamics, with Gregory et al. (2003) providing the most recent and comprehensive review in which they compare and discuss the characteristics of 14 models (Table 2.3.3 and Table 2.3.4). The earliest wood models were mostly designed to simulate the delivery of wood to streams from adjacent riparian forests, while more recent models have attempted to describe dynamics of wood by integrating input processes, retention, decomposition, and redistribution over either long time periods and/or large portions of river networks (Bragg 2000; Beechie et al. 2000; Downs and Simon 2001; Meleason et al. 2003; Welty et al. 2002; Benda and Sias 2003). Hassan et al. (2005) reported a modified and updated version (Table 2.3.5) of the Tables developed by Gregory et al. (2003). The comparison in Table 2.3.5 is limited to variables related to wood input and output, and additionally includes the Lancaster et al. (2003) model.

A two-dimensional numerical model has been developed recently by Villanueva et al., 2014) to simulate the transport of large wood material and its effect on hydrodynamics. This deterministic model has been incorporated in the hydrodynamic model IBER in Spain, and has been used to simulate bridge clogging processes and to reconstruct wood deposition patterns, modelling the movement of individual pieces of wood with the water flow and interactions among wood pieces and with the bridge.

A GIS-based modelling approach has been developed recently by Mazzorana et al. (2010). The conceptual structure comprises: (1) criteria for the localization and classification of woody material recruitment areas and the assessment of the woody material recruitment volumes; (2) a computational procedure for woody material entrainment processes; (3) a computational scheme for woody material transport, deposition and remobilization dynamics and (4) an analysis procedure for interaction phenomena involving transported woody material occurring at critical stream configurations.

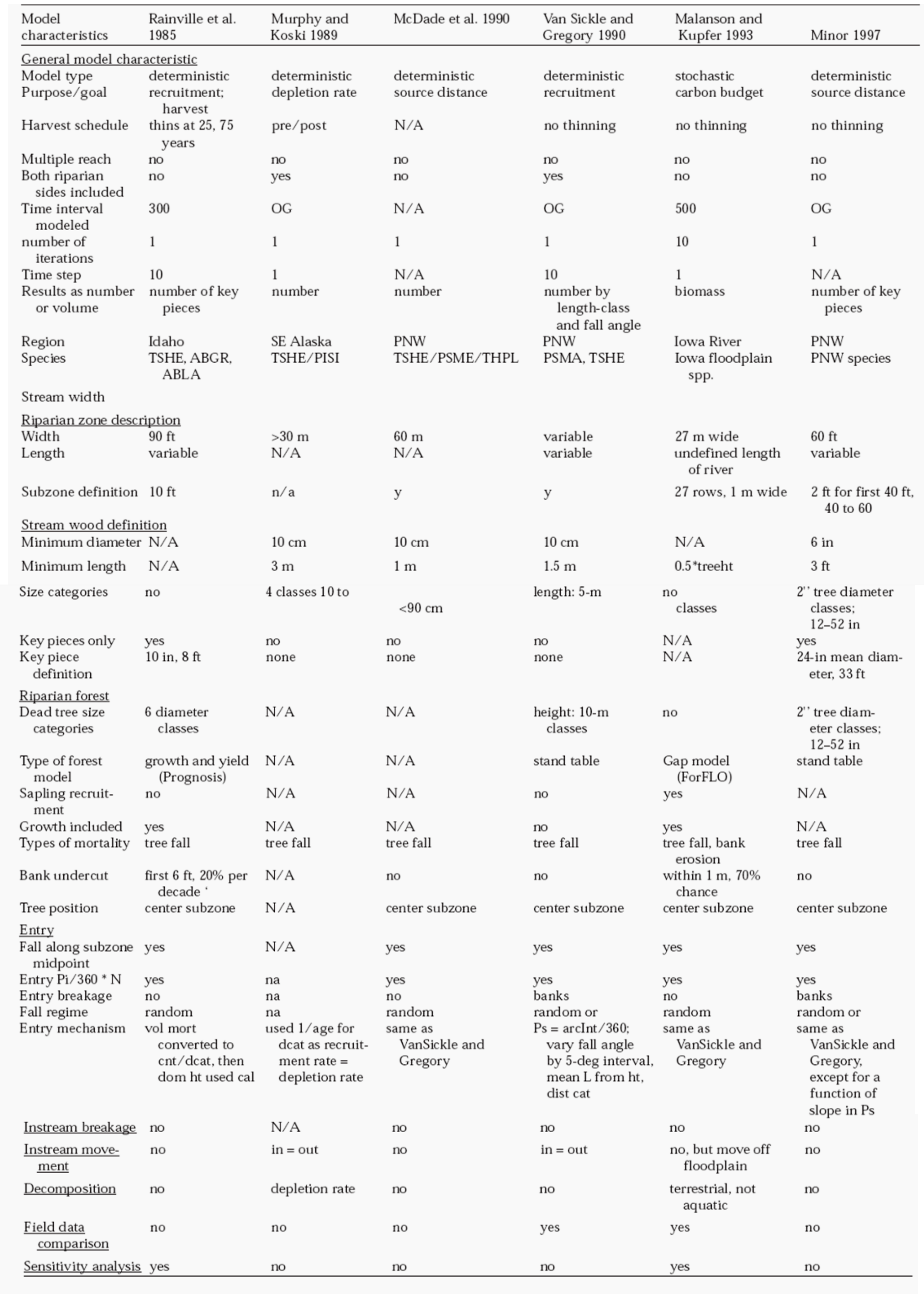
A stochastic model has also been recently developed by Eaton et al. (2012), which predicts large wood loads in a stream and the volume of sediment stored by wood. The model can be used to simulate the effects of various environmental disturbances altering wood recruitment on physical habitats.

2.3.4.2 Future modelling challenges

Modelling of single processes physical processes, their interactions, and inclusion within the context of hydrodynamic and morphodynamic models need to be expanded. Numerical models of wood dynamics are at an initial stage (e.g. Villanueva et al., 2014), and much remains to be done to fully integrate processes of wood delivery, transport and deposition with other hydrodynamic and morphodynamic processes.

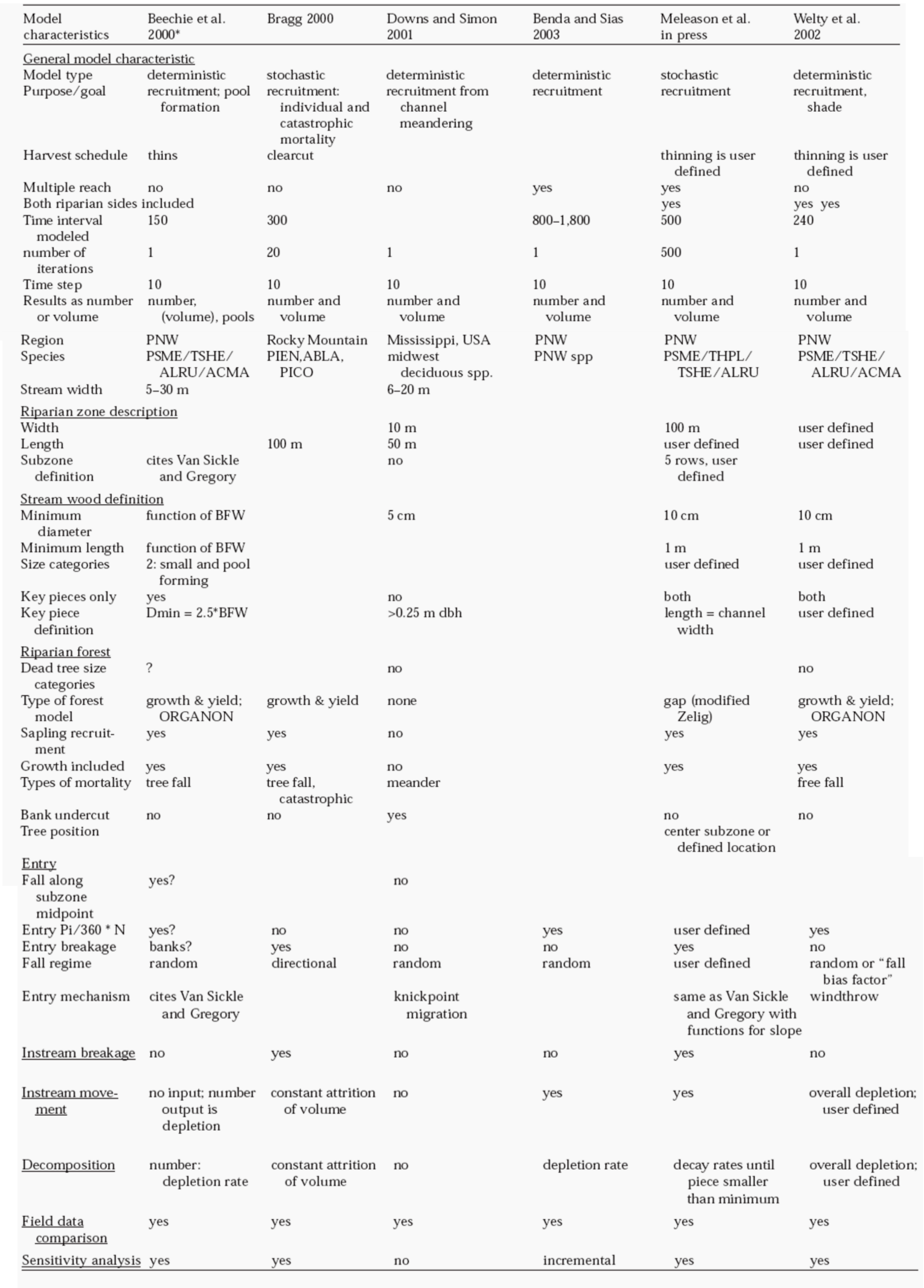
In Annex A, Table 8 summarises the suitability of the discussed models with large wood for the analysis of hydromorphological pressures or the design of restoration measures.

Table 2.3.3 A comparison of published simulation models of wood dynamics (from Gregory et al., 2003) part 1.



Model characteristics	Rainville et al. 1985	Murphy and Koski 1989	McDade et al. 1990	Van Sickle and Gregory 1990	Malanson and Kupfer 1993	Minor 1997
General model characteristic						
Model type	deterministic	deterministic	deterministic	deterministic	stochastic	deterministic
Purpose/goal	recruitment; harvest	depletion rate	source distance	recruitment	carbon budget	source distance
Harvest schedule	thins at 25, 75 years	pre/post	N/A	no thinning	no thinning	no thinning
Multiple reach	no	no	no	no	no	no
Both riparian sides included	no	yes	no	yes	no	no
Time interval modeled	300	OG	N/A	OG	500	OG
number of iterations	1	1	1	1	10	1
Time step	10	1	N/A	10	1	N/A
Results as number or volume	number of key pieces	number	number	number by length-class and fall angle	biomass	number of key pieces
Region	Idaho	SE Alaska	PNW	PNW	Iowa River	PNW
Species	TSHE, ABGR, ABLA	TSHE/PISI	TSHE/PSME/THPL	PSMA, TSHE	Iowa floodplain spp.	PNW species
Stream width						
Riparian zone description						
Width	90 ft	>30 m	60 m	variable	27 m wide	60 ft
Length	variable	N/A	N/A	variable	undefined length of river	variable
Subzone definition	10 ft	n/a	y	y	27 rows, 1 m wide	2 ft for first 40 ft, 40 to 60
Stream wood definition						
Minimum diameter	N/A	10 cm	10 cm	10 cm	N/A	6 in
Minimum length	N/A	3 m	1 m	1.5 m	0.5*treeht	3 ft
Size categories	no	4 classes 10 to	<90 cm	length: 5-m	no classes	2'' tree diameter classes; 12–52 in
Key pieces only	yes	no	no	no	N/A	yes
Key piece definition	10 in, 8 ft	none	none	none	N/A	24-in mean diameter, 33 ft
Riparian forest						
Dead tree size categories	6 diameter classes	N/A	N/A	height: 10-m classes	no	2'' tree diameter classes; 12–52 in
Type of forest model	growth and yield (Prognosis)	N/A	N/A	stand table	Gap model (ForFLO)	stand table
Sapling recruitment	no	N/A	N/A	no	yes	N/A
Growth included	yes	N/A	N/A	no	yes	N/A
Types of mortality	tree fall	tree fall	tree fall	tree fall	tree fall, bank erosion	tree fall
Bank undercut	first 6 ft, 20% per decade '	N/A	no	no	within 1 m, 70% chance	no
Tree position	center subzone	N/A	center subzone	center subzone	center subzone	center subzone
Entry						
Fall along subzone midpoint	yes	N/A	yes	yes	yes	yes
Entry Pi/360 * N	yes	na	yes	yes	yes	yes
Entry breakage	no	na	no	banks	no	banks
Fall regime	random	na	random	random or	random	random or
Entry mechanism	vol mort converted to cnt/dcat, then dom ht used cal	used 1/age for dcat as recruitment rate = depletion rate	same as VanSickle and Gregory	Ps = arcInt/360; vary fall angle by 5-deg interval, mean L from ht, dist cat	same as VanSickle and Gregory	same as VanSickle and Gregory, except for a function of slope in Ps
Instream breakage	no	N/A	no	no	no	no
Instream movement	no	in = out	no	in = out	no, but move off floodplain	no
Decomposition	no	depletion rate	no	no	terrestrial, not aquatic	no
Field data comparison	no	no	no	yes	yes	no
Sensitivity analysis	yes	no	no	no	yes	no

Table 2.3.4 A comparison of published simulation models of wood dynamics (from Gregory et al., 2003) part 2.



Model characteristics	Beechie et al. 2000*	Bragg 2000	Downs and Simon 2001	Benda and Sias 2003	Meleason et al. in press	Welty et al. 2002
General model characteristic						
Model type	deterministic	stochastic	deterministic	deterministic	stochastic	deterministic
Purpose/goal	recruitment; pool formation	recruitment: individual and catastrophic mortality	recruitment from channel meandering	recruitment	recruitment	recruitment, shade
Harvest schedule	thins	clearcut			thinning is user defined	thinning is user defined
Multiple reach	no	no	no	yes	yes	no
Both riparian sides included					yes	yes yes
Time interval modeled	150	300		800–1,800	500	240
number of iterations	1	20	1	1	500	1
Time step	10	10	10	10	10	10
Results as number or volume	number, (volume), pools	number and volume	number and volume	number and volume	number and volume	number and volume
Region	PNW	Rocky Mountain	Mississippi, USA	PNW	PNW	PNW
Species	PSME/TSHE/ALRU/ACMA	PIEN,ABLA, PICO	midwest deciduous spp.	PNW spp	PSME/THPL/TSHE/ALRU	PSME/TSHE/ALRU/ACMA
Stream width	5–30 m		6–20 m			
Riparian zone description						
Width			10 m		100 m	user defined
Length		100 m	50 m		user defined	user defined
Subzone definition	cites Van Sickle and Gregory		no		5 rows, user defined	
Stream wood definition						
Minimum diameter	function of BFW		5 cm		10 cm	10 cm
Minimum length	function of BFW				1 m	1 m
Size categories	2: small and pool forming				user defined	user defined
Key pieces only	yes		no		both	both
Key piece definition	Dmin = 2.5*BFW		>0.25 m dbh		length = channel width	user defined
Riparian forest						
Dead tree size categories	?		no			no
Type of forest model	growth & yield; ORGANON	growth & yield	none		gap (modified Zelig)	growth & yield; ORGANON
Sapling recruitment	yes	yes	no		yes	yes
Growth included	yes	yes	no		yes	yes
Types of mortality	tree fall	tree fall, catastrophic	meander			free fall
Bank undercut	no	no	yes		no	no
Tree position					center subzone or defined location	
Entry						
Fall along subzone midpoint	yes?		no			
Entry Pi/360 * N	yes?	no	no	yes	user defined	yes
Entry breakage	banks?	yes	no	no	yes	no
Fall regime	random	directional	random	random	user defined	random or "fall bias factor"
Entry mechanism	cites Van Sickle and Gregory		knickpoint migration		same as Van Sickle and Gregory with functions for slope	windthrow
Instream breakage	no	yes	no	no	yes	no
Instream movement	no input; number output is depletion	constant attrition of volume	no	yes	yes	overall depletion; user defined
Decomposition	number: depletion rate	constant attrition of volume	no	depletion rate	decay rates until piece smaller than minimum	overall depletion; user defined
Field data comparison	yes	yes	yes	yes	yes	yes
Sensitivity analysis	yes	yes	no	incremental	yes	yes

Table 2.3.5 Modified and updated versions of Tables 2.3.3 and 2.3.4 from Hassan et al. (2005)

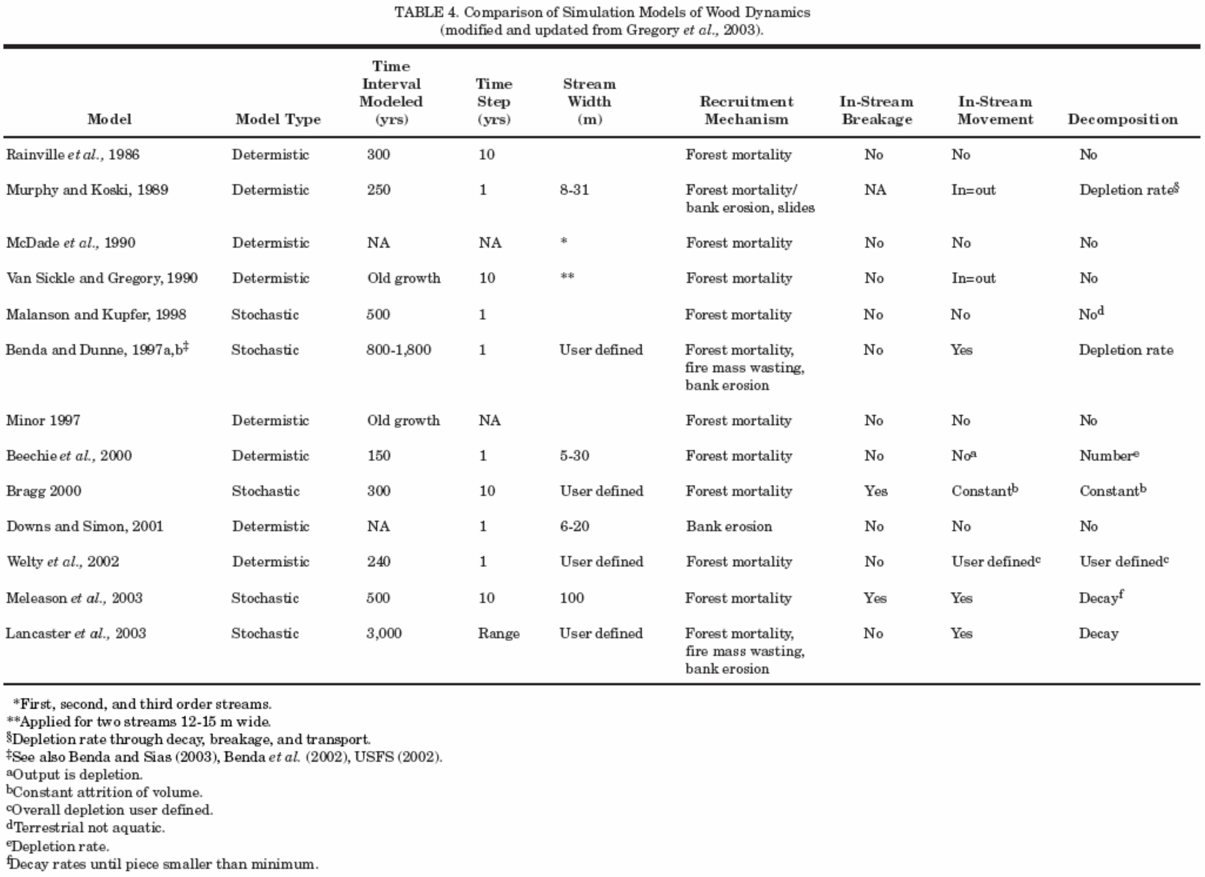


TABLE 4. Comparison of Simulation Models of Wood Dynamics (modified and updated from Gregory *et al.*, 2003).

Model	Model Type	Time Interval Modeled (yrs)	Time Step (yrs)	Stream Width (m)	Recruitment Mechanism	In-Stream Breakage	In-Stream Movement	Decomposition
Rainville *et al.*, 1986	Determistic	300	10		Forest mortality	No	No	No
Murphy and Koski, 1989	Determistic	250	1	8-31	Forest mortality/ bank erosion, slides	NA	In=out	Depletion rate§
McDade *et al.*, 1990	Determistic	NA	NA	*	Forest mortality	No	No	No
Van Sickle and Gregory, 1990	Determistic	Old growth	10	**	Forest mortality	No	In=out	No
Malanson and Kupfer, 1998	Stochastic	500	1		Forest mortality	No	No	No[d]
Benda and Dunne, 1997a,b‡	Stochastic	800-1,800	1	User defined	Forest mortality, fire mass wasting, bank erosion	No	Yes	Depletion rate
Minor 1997	Determistic	Old growth	NA		Forest mortality	No	No	No
Beechie *et al.*, 2000	Determistic	150	1	5-30	Forest mortality	No	No[a]	Number[e]
Bragg 2000	Stochastic	300	10	User defined	Forest mortality	Yes	Constant[b]	Constant[b]
Downs and Simon, 2001	Determistic	NA	1	6-20	Bank erosion	No	No	No
Welty *et al.*, 2002	Determistic	240	1	User defined	Forest mortality	No	User defined[c]	User defined[c]
Meleason *et al.*, 2003	Stochastic	500	10	100	Forest mortality	Yes	Yes	Decay[f]
Lancaster *et al.*, 2003	Stochastic	3,000	Range	User defined	Forest mortality, fire mass wasting, bank erosion	No	Yes	Decay

*First, second, and third order streams.
**Applied for two streams 12-15 m wide.
§Depletion rate through decay, breakage, and transport.
‡See also Benda and Sias (2003), Benda *et al.* (2002), USFS (2002).
[a] Output is depletion.
[b] Constant attrition of volume.
[c] Overall depletion user defined.
[d] Terrestrial not aquatic.
[e] Depletion rate.
[f] Decay rates until piece smaller than minimum.

2.3.5 Interaction between vegetation and hydromorphodynamics

2.3.5.1 Background

In the previous sections models describing the interaction between vegetation and morphodynamics were uni-directional either taking into account the effect of vegetation on morphodynamics through hydraulic resistance and bank stability, or the effect of morphodynamics on vegetation by influencing vegetation biomass or survival. Models that include the two-way interaction between vegetation and morphodynamics in an integrated, dynamic manner are scarce. Integrating ecological, hydrological and morphological processes dynamically implies that processes have to interact at appropriate temporal and spatial scales. In many models processes are averaged over time and/or space to make the computation time and complexity manageable, and depending on the desired output, certain choices for spatial and temporal scales are made. For instance, interactions between individual plants and flow will probably be modeled using a 3D model at patch scale with small grid-cells and small time steps. However, to predict long-term morphodynamic evolution at reach or region scale, a high resolution 3D model takes too much computation time, and so a 2D depth-averaged model with a coarser grid and larger time steps is a better option. To be able to predict the long-term effect of ecological restoration measures or human pressures, it is necessary to include ecological, hydrological and morphological dynamics at the appropriate scales *and* keep the computation time manageable. This poses a major challenge in modelling, but eventually these types of models will generate new hypotheses, drive new research directions, and assist water managers in selecting appropriate measures, as has been recognized by the research community (e.g. Järvelä et al., 2006; Vaughan et al. 2009; Nepf 2012; Camporeale et al. 2013; Curran and Hession 2013). A major difficulty lies in choosing the appropriate scales and averaging methods without losing vital data for processes acting at smaller scales. Another difficulty is the lack of quantitative field data for vegetation that can be used to calibrate the models or derive general response relations to morphodynamic pressures.

Recently, there have been several attempts to begin to model the physics-based interaction between vegetation and morphodynamics. Several models that explicitly take the interaction between vegetation and morphodynamics into account are discussed below. Section 2.3.5.2 describes these models and discusses the interaction processes. Two types of models are compared: cellular automata; and advanced physics-based numerical models. The difference in applicability of these models for answering different research questions is discussed in the synthesis. Section 2.3.5.3 describes knowledge gaps and important new modelling research directions, focusing on integrating realistic vegetation processes and dynamics; why these are necessary; and how they may be achieved. Finally, a condensed list is given of future modelling-research challenges.

2.3.5.2 Recent modelling advances

Below several models are discussed that include the interaction between vegetation and morphodynamics. These models can be divided in two categories: i) cellular automata and ii) advanced process-based numerical models.

Cellular automata

There is a range of cellular automata that investigate the impact of vegetation on morphodynamics (examples in Camporeale et al. 2013), but few have integrated on-line feedback.

The model of Murray and Paola (2003) investigates the effects of sediment stabilisation by vegetation roots on the channel pattern of bedload rivers. Plants can grow in cells where conditions are met until vegetation is fully developed. Vegetated cells impede sediment transport and decrease erosion. Plant mortality results from burial and scour when values exceed certain thresholds. The model results support the hypothesis that bank-stability is the main cause of single-channel stream development and that vegetation development can be sufficient to induce this (Figure 2.3.18).

Where the model of Murray and Paola (2003) could not meander due to not being able to cope with processes at longer length scales (only neighbourhood or local processes), Coulthard and Wiel (2006) and Coulthard et al., (2007) overcame this problem in their CEASAR model with an innovative method to induce meandering in cellular automata by taking curvature and longer length scales into account. CEASAR was applied to the braided Waitaki river system, New Zealand to investigate morphological development due to reduced sediment load resulting from dam construction (Coulthard et al. 2007). Vegetation could grow in cells that were not inundated and decreased the erodibility of

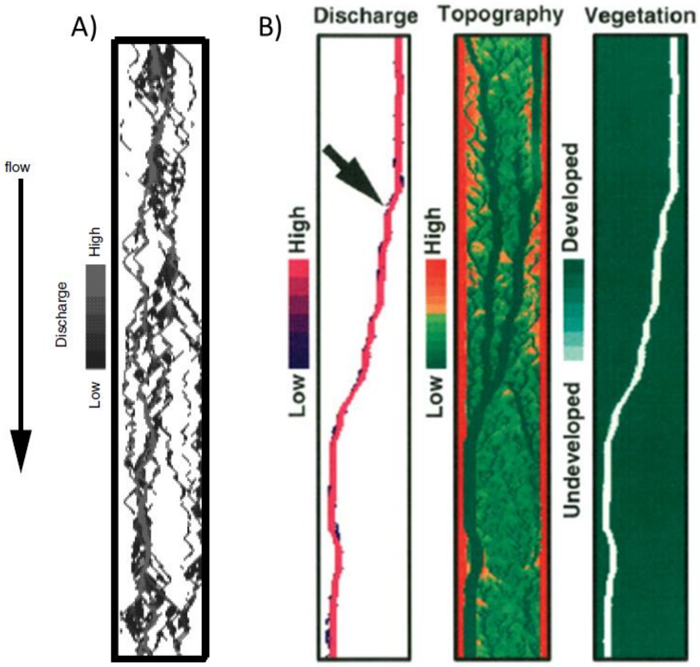


Figure 2.3.18 Model results of Murray and Paola (2003) at 110.000 iterations. A) Discharge without vegetation, B) Discharge, topography and vegetation development with vegetation. Results show that vegetation transforms the planform from a multi-thread to single-thread channel. The black arrow marks the location of minor channel migration. Figure adapted from Murray and Paola (2003).

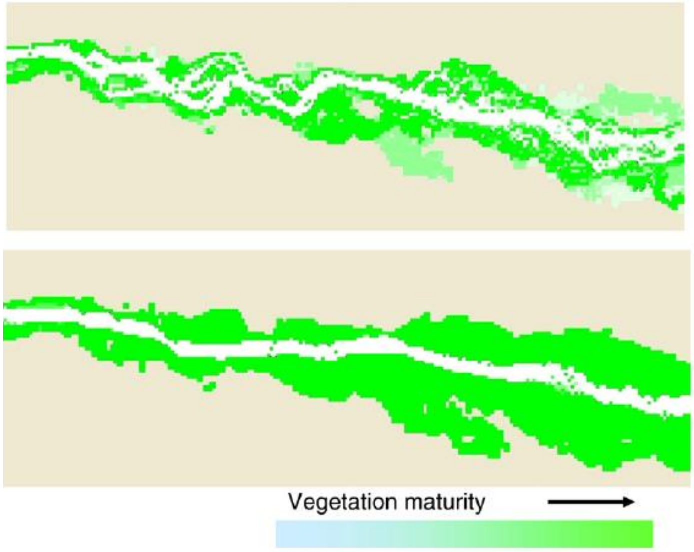


Figure 2.3.19 Model results of vegetation location and maturity with aggressive vegetation growth in the Waitaki river, NZ (from Coulthard et al., 2007). Top: results after 5 years. Bottom: results after 20 years. Vegetation growth forces the flow into one main channel thereby increasing the sediment load by incising the channel.

the riverbed. Four different (linear) vegetation growth scenarios were tested with different times for the vegetation to reach maturity. Vegetation affected the rate of lateral erosion by strengthening the river banks and riverbed. The two highest vegetation growth scenarios increased the sediment load above that prior to dam. Because high vegetation growth forced the flow into one single channel, channel incision occurred with corresponding higher sediment loads that were transported out of the system. The two scenarios with lower vegetation growth decreased the sediment load because more channels could persist and the vegetation was still able to reduce erosion with the current flow velocities (Figure 2.3.19).

The last and probably most sophisticated model in this category in terms of its representation of vegetation is the CHANGSIM (Channel Change GIS Simulation Model) model developed by Hooke et al. (2005). In this model morphology, hydrology, vegetation and groundwater are integrated. Three major vegetation types are considered: herbs, shrubs and phreatophytes (plants in continuous contact with groundwater) each of which contain four age classes. Plants can establish in cells when conditions were favourable (mainly moisture related). Presence of plants produces resistance, locally influences flow velocity and can increase sedimentation or create scour around plants. Water and sediment interact with vegetation by damaging, burying or removing it and thereby altering resources. Vegetation growth is dependent on temperature, moisture and season. Other causes of mortality implemented in the model are senescence (death due to old age) or resource stress (mainly desiccation). Vegetation spread can take place through clonal multiplication (suckers) or germination of new plants. The model was designed to simulate channel changes in ephemeral river channels and for testing the effects of changing hydrological regime and land use.

Advanced physics-based numerical models

A physically-based numerical morphodynamic model with vegetation (HSTAR - Hydrodynamics and Sediment Transport in Alluvial Rivers) was developed by Nicholas (2013). The floodplain is colonized by vegetation when the maximum inundation depth of the vegetation over a certain period does not exceed a given threshold. The effect of vegetation is a higher roughness value. Vegetation is removed by vertical erosion of floodplain cells when a velocity threshold is exceeded. Different planforms can be generated with this model and results show that vegetation has a strong effect on morphodynamics by reducing lateral migration and promoting floodplain development (Figure 2.3.20). However, the author recognizes that vegetation representation in the model is very simplistic and that the question remains whether it is sufficient for a realistic representation of river evolution.

While Nicholas (2013) does not take into account differences in vegetation density, Perucca et al., (2007) model this explicitly with different biomass density functions (Figure 2.3.21, left) combined with a dynamic meander model. Three different functions are described for three different systems. Function A resembles a semi-arid system where biomass is highest close to the channel due to higher water availability and decreases further away from the channel. Function B resembles a frequently disturbed river where biomass density is lower close to the channel due to higher disturbance and increases further away from the channel. Function C combines both functions A and B into an optimum curve highest at intermediate distance from the channel. Vegetation growth is modeled as a logistic growth function depending on the type of system (A, B or C) and the distance from the channel which determines the maximum biomass that can be reached at a certain location. Vegetation decay is modeled in the same way, but with an exponential decay curve. Vegetation biomass affects meander migration by reducing bank erodibility. Different density functions affecting bank erosion generate different meander migration and skewness compared to constant bank erosion rates (Figure 2.3.21, right).

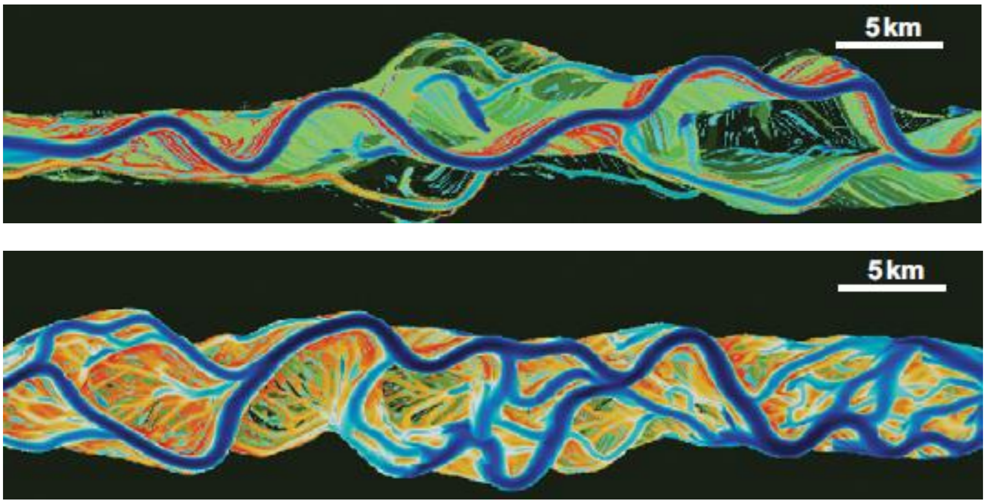


Figure 2.3.20 Channel morphology of two different scenarios with (among others) different vegetation establishment time adapted from Nicholas (2013). Top: 6 years, Bottom: 50 years. In runs where vegetation has a short establishment time, channel morphology takes on a meandering or anabranching planform. In runs with a longer establishment time the channel is more dynamic and results in a braiding planform.

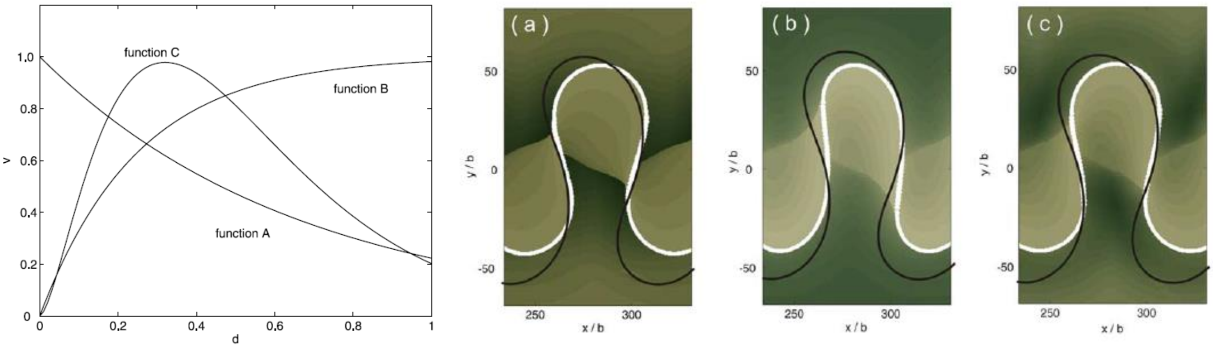


Figure 2.3.21 Vegetation density functions and river planform of Perucca et al. (2007). Left: vegetation density (y axis) functions of three different systems (A, B and C) related to distance from the channel (x axis). Right: model results of the three density functions influencing bank erosion. The black line is the resulting planform with a constant erosion rate. Results show that different vegetation densities have different effects on the planform compared to results with a constant erosion rate.

Crosato and Saleh (2011) present results of a morphodynamic model with two different vegetation densities. Vegetation can colonize new deposits in cells that are dry at a certain discharge. Morphodynamics are influenced by vegetation through increased hydraulic roughness. Simulation time was restricted to 10 years due to long computation times, but clear morphological differences appeared between the scenario with and without vegetation. Results show that including vegetation reduces a multi-thread river to a (mostly) single-thread river (Figure 2.3.22). Pioneer vegetation (lower density) was less strong in creating a meandering planform than grass vegetation (higher density) resulting in locations with more than one conveying channel. The grass vegetation was sufficient to induce a total meandering planform.

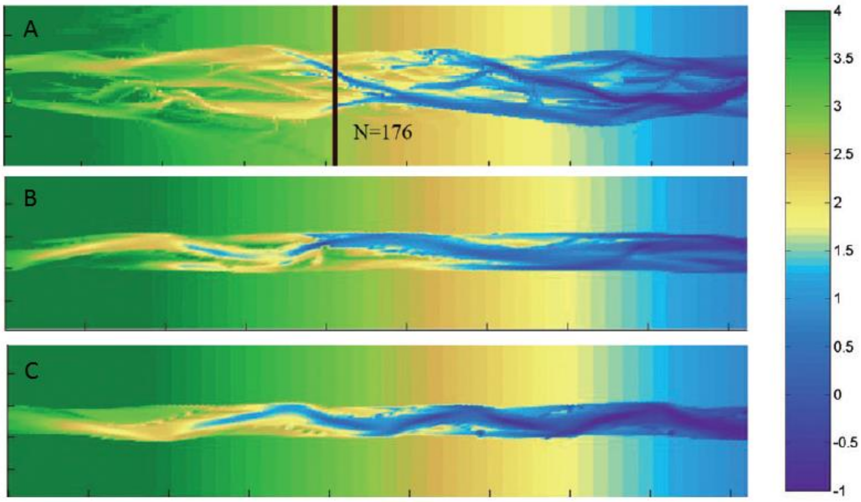


Figure 2.3.22 Results of river planform from Crosato and Saleh (2011). A: no vegetation, B: pioneer vegetation (low density), C: grass (high density). A meandering planform develops in the scenarios with vegetation.

Synthesis

From an ecological point of view the representation of vegetation in most of the discussed models is quite simplistic. Until now two different types of models have been employed to investigate the interaction between vegetation and morphodynamics: cellular automata, and more advanced numerical or meander models. Cellular automata have simplified physics and can therefore be used to make a very general exploration of river morphology evolution or pinpoint areas where more robust numerical approaches should be employed. The results are mainly qualitative and they cannot handle highly heterogeneous systems (Coulthard et al., 2007). Phenomena that play over longer length scales such as backwater effects, which influences sedimentation and erosion patterns at large length-scales, or more detailed transverse slope effects which play an important role in bank formation (Schuurman et al., 2013) are neglected in cellular automata. However, the vegetation processes in the cellular automata are currently more detailed than in the more advanced morphodynamic models. This is clearly a discrepancy and more advanced physic-based models should take advantage of this knowledge.

Since cellular automata contain highly simplified physics, phenomena at longer time scales and several local effects are not included and heterogeneous effects cannot easily be modeled. Thus, these models are unfit for the quantitative prediction of long-term ecological restoration measures or human pressures. Therefore, the discussion below focuses on possible future improvements of vegetation processes and interaction in the more robust, advanced numerical models to obtain a more realistic vegetation pattern and fluvial morphology.

2.3.5.3 Future modelling challenges

Vegetation properties

In the discussed models vegetation is represented as rigid cylinders or a certain biomass density gradient over the floodplain as opposed to the complex shapes seen in nature. Advances have been made in hydrological modelling and flume experiments to quantify the effects of more complex vegetation shapes with differing flexibility on the flow field and sediment transport (see also section 2.3.2.1 on flow resistance), but this has not yet been upscaled and integrated in reach scale models. It has been found that complex shapes (e.g. flexible plants with foliage or a dense branch structure) create different drag at different flow velocities than rigid cylinders (Whittaker et al. 2013), which would imply that implementing the effect of these detailed, flexible shapes in models will create more realistic patterns in fluvial morphology. Furthermore, the models (usually) consider only one vegetation type. Obviously in nature all kinds of vegetation types exist with different above and below ground properties. For reach scale models it is realistic to assume that the dominant vegetation types will have the largest contribution to fluvial morphology and, by integrating these, the most important vegetation structures are covered. Vegetation types can have different properties at different stages in their life cycle. As discussed above, shoot structure has an effect on the flow field and sediment transport, but the root type and architecture determines the stabilizing effect on the soil and the ability for the plant to survive dry and wet periods. For instance *Populus* species are known to have long, large taproots), which enable the tree to survive dry periods by connecting to groundwater (Wiehle et al. 2009). Different root systems have a different sensitivity for hydrological conditions and have different effects on soil stability and erodibility. By assuming different vegetation types with different above and below ground properties, the effects of vegetation on soil erodibility and hydraulic resistance in models can be refined.

Vegetation dispersal and colonization

Modelling propagule dispersal by animals, wind and water has long been an important research direction in ecology. As discussed in section 2.3.3.2, several hydrochory models have been developed, but hydrochory processes have yet to be integrated into reach-scale morphodynamic models. Nepf (2012) argues that reach scale resistance is the most important scale for water managers, and is determined by the spatial heterogeneity of vegetation. By integrating hydrochory in morphodynamic models, the dispersal and related colonisation patterns become more realistic because they then depends on flow velocities, flow direction, seed availability, seed buoyancy and stream connectivity.

Colonisation is now generally implemented as an immediate occupation of vegetation in cells where the hydrological conditions for settlement are met (Crosato and Saleh 2011; Nicholas 2013) or as a standard density function giving the same maximum density at a certain distance from the channel (Perucca et al. 2007). However, vegetation colonisation success depends on many more processes (e.g. substrate type, groundwater level, shading, competition). Integrating such factors creates a non-uniform vegetation pattern which has a different effect on fluvial morphology than a uniform vegetation pattern.

Vegetation growth and mortality

Only the model of Perucca et al. (2007) implicitly takes account of vegetation growth. Growth is expressed in biomass and only has an effect on soil erodibility. As plants grow they become more resistant to morphodynamic pressures and are therefore less easily removed. This hysteresis effect adds an extra non-linear response to the system. By including vegetation growth and expressing it as a change of certain properties (e.g. shoot height, density, and shoot length) over time and subsequently linking growth to soil erodibility, hydraulic resistance and sediment transport would be a major advance. Information on how to implement vegetation growth in cellular automata is given by Murray and Paola (2003) and Hooke et al. (2005) and could be used in other models.

Mortality could also be implemented in a more advanced way. Nicholas (2013) implements mortality as a removal of vegetation after exceeding a flow velocity threshold and Perucca et al. (2007) implicitly take mortality into account through the exponential decay function related to distance from the channel. However, vegetation mortality depends on many more processes (e.g. days of subsequent flooding, days of subsequent desiccation, scour and burial). Survival of pioneer trees for instance is very much dependent on the hydrologic regime of a specific year. In some years there is almost no successful colonisation because conditions are unfavourable and seedlings do not survive, whereas in other years there is a massive colonisation peak (van Splunder et al. 1995). So pioneer vegetation patterns are strongly dependent on timing and magnitude of the annual hydrograph, which is varies between years, strongly influencing fluvial morphology patterns. The models discussed above are first steps towards developing more (ecologically) realistic vegetation development and interaction models, but many research and modelling challenges remain:

- Include multiple vegetation types with different properties. For instance based on a functional trait set of dominant species with different above and below ground properties.
- Include vegetation dynamics or change of properties over time in direct interaction with morphodynamic processes to obtain a more realistic plant life cycle and interaction with morphodynamics.
- Implement hydrochory models to obtain a more accurate vegetation dispersal pattern
- Refine early colonization of vegetation by relating it to the type of substrate, competition, herbivory, groundwater level etc.
- Refine mortality of vegetation by including other causes of mortality like flooding, desiccation, burial and scour.
- Investigate how the dynamic interaction between vegetation and morphodynamics influences vegetation patterns and river planform at reach scale (Curran and Hession 2013).

In Annex A, Table 9a the suitability of the discussed models is listed, including the interaction between vegetation and hydromorphology for the analysis of hydromorphological pressures or the design of restoration measures. Details of the models are given in Annex A, Table 9b.

2.3.6 Vegetation dynamics

2.3.6.1 Background

Vegetation patterns

Looking at a natural functioning river, one can distinguish different types and patterns of vegetation along the floodplain (e.g. Figure 2.3.23).

Figure 2.3.23 Aerial photo of the river Allier in France showing gradients in vegetation types and patterns both laterally and longitudinally across the floodplain.

As detailed in the conceptual model (section 2.2), the location and properties of the vegetation influence morphodynamics by changing the flow pattern and reducing erosion. Close to the channel, at the lower part of the floodplain, vegetation and morphodynamics interact most frequently and this frequency decreases towards higher altitudes. With this gradient shifting from disturbed to less disturbed conditions also the dominant processes influencing vegetation patterns change. In the lower part vegetation is dominantly influenced by exogenous factors (= external disturbances, e.g. morphodynamic disturbances) and in the higher parts endogenous factors (= dynamics caused by plants themselves) begin to play a bigger role (White 1979). When morphodynamic disturbance decreases, vegetation succession can occur and the vegetation pattern can evolve from a patchy pioneer state to a more homogenous mature state (Tabacchi et al. 1998, Figure 2.3.24). The main endogenous processes that drive vegetation succession are competition and facilitation (Tabacchi et al. 1998; Brooker et al. 2007). Competition is the process of species competing for resources such as nutrients, water and light. Facilitation is the process of species supporting one another. This can be either beneficial for both parties which is also called mutualism or one species creates favorable conditions for another species indirectly, for example an ecosystem engineer actively changing its environment by trapping sediment, elevating the soil and creating less frequently flooded sites or species adding increased amounts of nitrogen to the soil which can be beneficial for surrounding plants. Each species contains a set of functional traits shaping their response to disturbances and determining their competitive and/or facilitative abilities (see section 3.2). The set of functional traits that contribute to the key events in a species life cycle is also called the 'life history strategy' of a species (Adler et al. 2014).

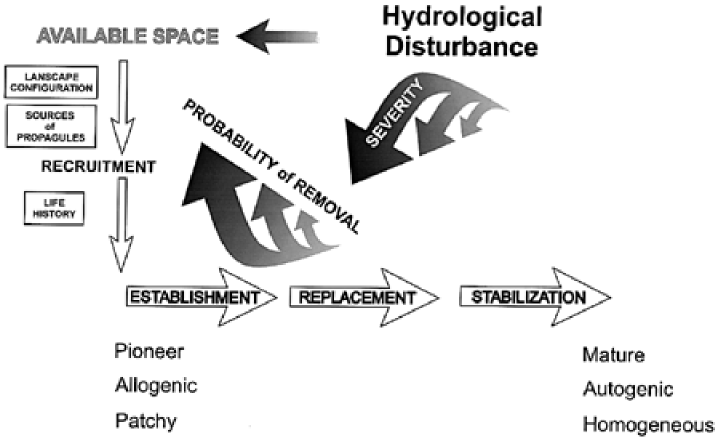


Figure 2.3.24 With decreasing disturbance and probability of removal, the vegetation pattern changes from a patchy pioneer state to a more mature homogeneous state. Figure from Tabacchi et al. (1998).

Life history strategies

Species have adapted specific life history strategies enabling them to survive in different types of habitat. Strategies include investments in growth, reproduction and survival to produce the largest possible surviving offspring. Different classifications of life history strategies have been proposed. One simple classification discriminates r and K strategies. These represent the extremes in a range of strategies that are used to generate the largest number of offspring. 'r-species' are fast growing species with a short generation time and large numbers of offspring, but low investment in defense and thereby a low survival rate. 'K-species' have a long generation time with fewer offspring but high investment in defense and therefore a higher survival rate (Southwood 1977). This is a very coarse division in the light of the very diverse plant communities observed in the field and so other theories have built on the r/K strategies by including a gradient of strategies depending on endogenous and exogenous factors. The CSR (Competitors, Stress-tolerators, Ruderals) theory (Grime, 2002) is particularly well known. Here, three main strategies are described reflecting competition which is defined as 'the tendency of neighboring plants to utilize the same quantum of light, ion of mineral nutrient, molecule of water, or volume of space'; stress which is defined as 'phenomena which restrict photosynthetic production such as shortages of light, water, mineral nutrients or sub-optimal temperatures'; and disturbance which is defined as 'partial or total destruction of the plant biomass arising from the activities of herbivores, pathogens, man and from phenomena like wind, frost, drought, soil erosion or fire' (Grime, 2002). Competitor species (C) can quickly monopolise resources and outcompete others in non-disturbed environments at intermediate levels of stress; Stress-tolerators (S) resist external disturbances well at low levels of competition and Ruderals (R) are first to colonise new areas, have short lifespans and produce many offspring at low levels of stress and competition (Figure 2.3.25). The CSR theory has been tested in various field surveys, laboratory screening, monitoring of plots and manipulative experiments and found to be applicable to vegetation in general (Hodgson et al. 1999). There is a lot more research on vegetation strategies, but it is not the goal of this section to review these, but merely to give an example for understanding the following sections.

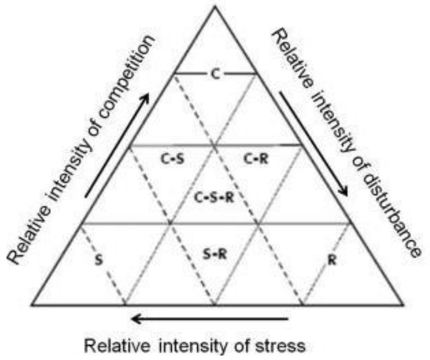


Figure 2.3.25 Life history strategies of (Grime 2002). The conceptual model describes different vegetation strategies in relation to intensity of competition, stress, and disturbance. Three primary types exist (in the corners of the triangle): Competitors (C), Stress-tolerators (S), and Ruderals (R). However, most species follow a mix of these strategies. In the diagram C-S, C-R, S-R, and C-S-R strategies are indicated with respect to the gradients of competition, stress and disturbance.

In riparian communities life history strategies are closely linked to the river's flow regime (Figure 2.3.26). Riparian species often have a set of traits that promote colonization (e.g. high seed production) and fast recovery after a disturbance event (e.g. adventitious roots). Many species adjust the timing of their seed release to the peak flow in early spring. This is a constructive strategy since falling water levels leave an optimal moist substrate behind for the germination and growth of seedlings (Greet et al., 2011; Gurnell, 2014). Because plant species have different strategies to cope with different environmental conditions, gradients of vegetation types and patterns may be observed across river floodplains.

In the following sections background, theories and hypotheses are provided in relation to competition and facilitation processes between plants and the effects of invasive species. This is followed by an overview of recent simulation models that incorporate elements of the theories, ending with a list of future research and modelling challenges. The focus of the chapter is on areas dominated by plant-plant interactions where morphodynamics do not have a significant influence and plant succession is able to take place.

2.3.6.2 Competition and facilitation

Theory

When morphodynamic disturbances become less dominant, vegetation succession can occur. Competition and facilitation are the main driving forces of vegetation succession (Tabacchi et al., 1998; Brooker et al., 2007). Examples of facilitative interactions between plants include reducing shear stress by flow blockage (Gurnell, 2014), enrichment of soil by specific plants (Brooker and Callaghan, 1998), reducing evaporation by shading, and increasing water infiltration by root systems (Rietkerk and van de Koppel, 2008). Negative interactions include competition for light, nutrients and water (Brooker and Callaghan 1998) and allelopathy (= excretion of biochemical compounds, (Muller 1966). The interplay between competition and facilitation can create spectacular regular vegetation patterns in a range of ecosystems including wetlands and tidal areas (Figure 2.3.27).

One of the explanations for regular vegetation patterns is spatial self-organisation by short-range facilitation and long-range competition (Rietkerk and van de Koppel, 2008). In close proximity of other plants, positive effects are noticeable (e.g. shading by trees preventing water loss) and this effect becomes negative at a longer distance where the benefits outweigh the costs (e.g. no shading, but increased competition for water, Figure 2.3.28).

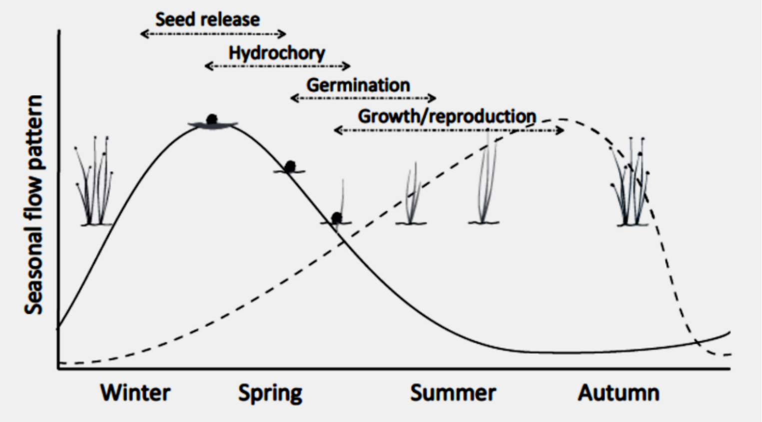


Figure 2.3.26 Conceptual model of how the life stages of riparian plants are adjusted to the annual flow regime. The solid line represents a natural flow regime with the seed release pattern coinciding with the peak flow, followed by hydrochory and deposition of seeds in appropriate conditions for germination, growth and reproduction. The dotted line represents an inverted (managed) flow regime which causes a loss of synchrony between hydrological and plant processes (from Greet et al., 2011).

Figure 2.3.27 Regular pattern formation in ecosystems. Left: *Carex stricta* tussocks in freshwater marshes in North America (van de Koppel and Crain 2006). Right: Marine benthic diatoms in the Netherlands (from Rietkerk and van de Koppel, 2008).

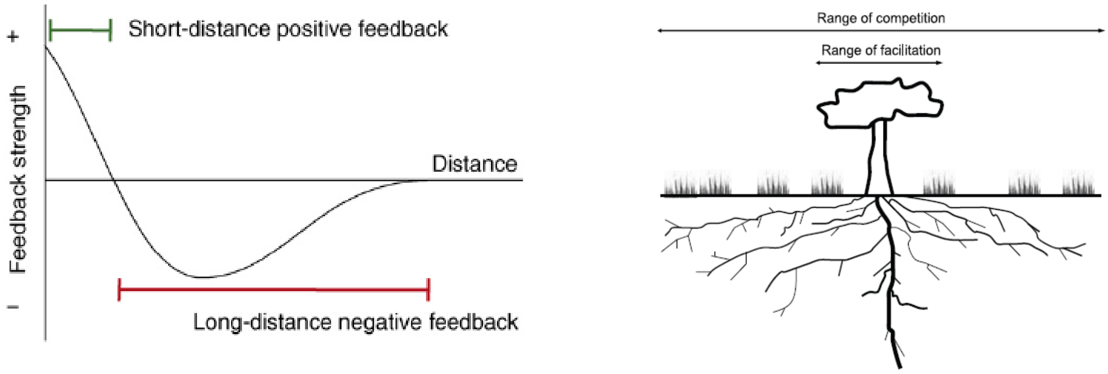


Figure 2.3.28 Left: conceptual model showing short-range facilitation long-range competition (adapted from Rietkerk and van de Koppel, 2008). Right: example of short-range facilitation by shading and long-range competition for water (from Borgogno et al., 2009).

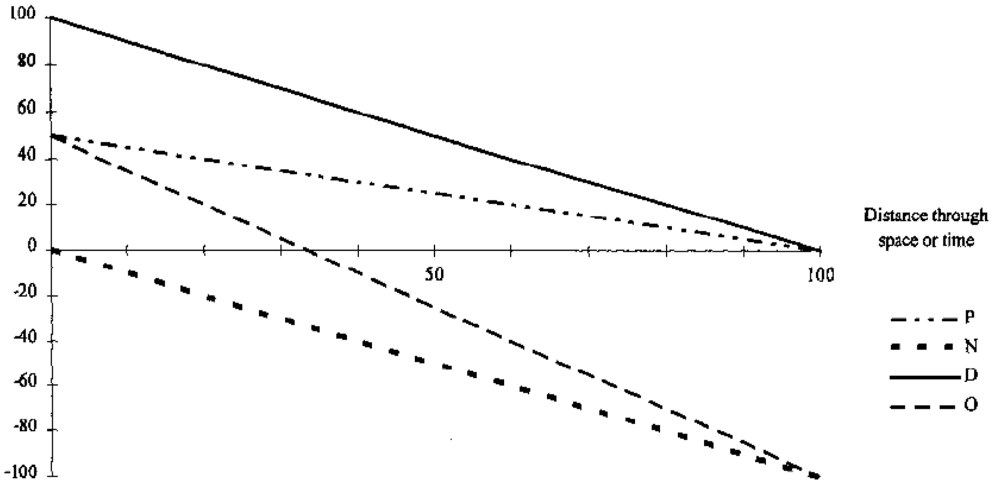


Figure 2.3.29 Conceptual model on the relation between the importance (y-axis) of positive (P) and negative (N) interactions and the net-direction of the interaction (O) on a gradient of decreasing disturbance (D). The x-axis represents time or space. For simplicity P and N are considered as directly proportional to the level of disturbance (from Brooker and Callaghan, 1998).

Under conditions of high disturbance the importance of positive interactions is greatly enhanced. Brooker and Callaghan (1998) illustrate this with a very simple (hypothetical) conceptual model (Figure 2.3.29). Where O is the observable output of the net direction of the interaction, P is the importance of the positive interaction and N the importance of the negative interaction (O=P+N). With a decreasing disturbance gradient, the importance of the positive interaction (upper half of graph) decreases, and the importance of the negative interaction (bottom half of graph) increases. This is also shown by the conceptual model of Bertness and Callaway (1994).

Facilitation may even extend the current niche of a species (Bruno et al., 2003; Travis et al., 2005), so that the species can exist outside of its predicted ranges because of these positive interactions. Grime (2002) calculated different indices of competition based on field experiments with two types of vegetation under a gradient of disturbance (grazing and trampling) and nutrient stress. Single species and mixed species plots were grown and the outputs were measured in the resulting spatial pattern (from which competitive dominance of a species can be measured) and the magnitude of reproduction. The results indicated that under disturbed or stressed conditions the importance of competition was still noticeable but its importance declined when the level of stress or disturbance increased.

The importance and frequency of facilitative interactions being higher in disturbed environments and the inverse for competitive interactions is known as the Stress-Gradient Hypothesis (SGH; Bertness and Callaway, 1994). Recently this hypothesis has been refined by several authors to take account of species life-history traits and different kinds or combinations of disturbances in different systems (e.g. Maestre et al., 2006; Holmgren and Scheffer, 2010).

In conclusion, interaction between competition and facilitation processes can create spectacular regular vegetation patterns. Facilitation is relatively more important in highly disturbed areas, whereas competition becomes more dominant in less disturbed areas.

2.3.6.3 Invasive species

Alien plant species can invade and restructure plant communities by changing the balance between competition and facilitation processes. Riparian zones are very susceptible to invasions because invasive plant propagules are easily dispersed through waterways (Grime 2002).

Areas with high human disturbance generally have a higher number of non-native species. For example, riparian areas are more prone to invaders after construction of dams which reduce or diminish flooding (Forman 2006). One theory is that a plant community becomes more susceptible to invasion when there is an increase in the amount of unused resources (Davis et al., 2000; Grime, 2002). Another theory explaining how plants can become invasive in their new range is the Enemy Release Hypothesis (EHS) which states that an exotic species can rapidly increase in distribution and abundance due to the absence of its natural enemies in the new range (Keane and Crawley, 2002). The success of invasive species in their new range might sometimes also be attributed to the new plants containing 'novel weapons' (e.g. allelopathic abilities) with which they can out-compete native species. This is known as the Novel Weapon Hypothesis (Callaway and Ridenour, 2004). It has been shown that invasive species can affect communities of plants by disturbing competition and facilitation processes (Santoro et al., 2012). Invasive species can change the dominant morphology of the plant community and thereby alter the channel morphology by increasing hydraulic roughness and trapping sediment (Tickner et al., 2001; Hoffman et al., 2008). Tickner et al. (2001) developed a conceptual framework showing how hydro-geomorphological parameters control various processes invasive species and how in turn invasive species can have a feedback on hydro-geomorphological processes (Figure 2.3.30). In some systems a monoculture of the invasive species can almost completely replace local species. Multitrophic interactions (interactions between species with different positions in the food chain, e.g. plants and animals or plants and fungi) can also increase the competitive ability of species if a positive interaction is established (e.g. mycorrhizal fungi in the root systems helping the plant with nutrient extraction while the plants gives back sugars to the fungus) thereby sometimes promoting invasive behaviour (Aschehoug et al. 2012).

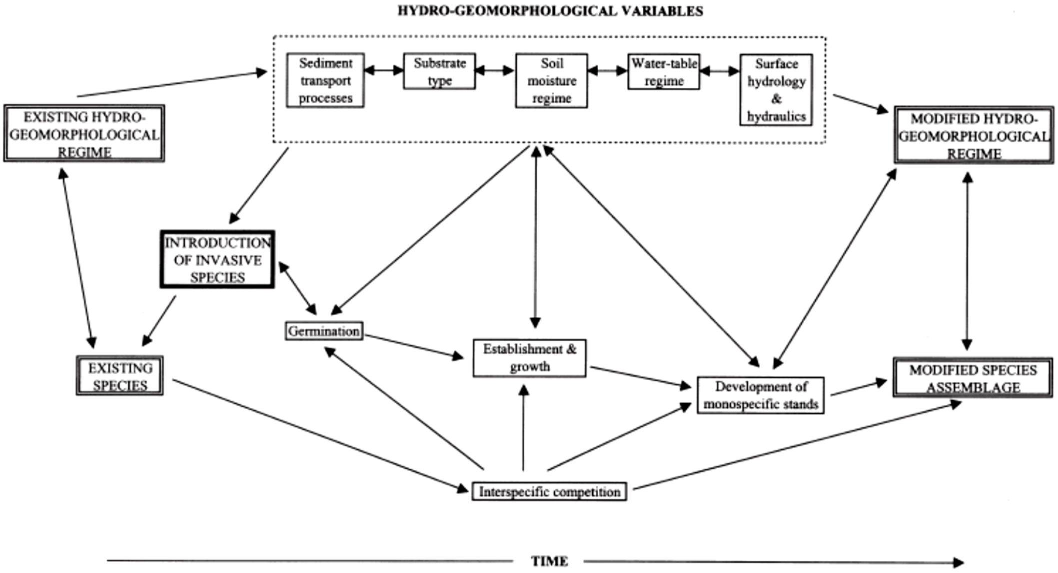


Figure 2.3.30 Conceptual model of hydrogeomorphological and ecological interactions of riparian invasions (from Tickner et al., 2001).

Non-native plant species do not always have to be a negative influence for native species. They can sometimes increase ecosystem resilience by increasing primary productivity and soil fertility, thereby increasing the tolerance ranges of native species (Richardson et al., 2007). For example, Wolkovich et al. (2009) found that litter of a non-native grass species facilitated the growth of a native shrub.

It is clear that invasions by non-native species can have a strong impact on vegetation dynamics by changing the balance between competition and facilitation processes of the native species and that management and restoration efforts have to take this into account. Water dominated systems are especially vulnerable to invasions because water forms an easy dispersal vector for invasive species.

2.3.6.4 Recent modelling advances

Several recent models have incorporated (parts of) the theories described in the previous sections to predict regular pattern formation, vegetation dynamics and the effect of invasive species on community structure. The focus in this section is on models applied in wetlands, since that is the focus of REFORM. First one model is discussed that predicts regular pattern formation in wetlands, then a range of general population dynamics models are discussed followed by models specifically developed for riparian environments. A separate section is devoted to models that include invasive species.

Models predicting regular vegetation patterns

Many deterministic and stochastic eco-hydrological models are available that predict regular vegetation pattern formation (see review by Borgogno et al., 2009). These models are mainly applicable to arid and semi-arid regions with relatively homogeneous physical and chemical conditions. One model is applied in wetlands and predicts self-organization of Carex *stricta* in relation to wrack (dead organic material) (van der Koppel et al., 2006). Empirical results show that plants are elevated by extensive root production above the soil and thereby protected against small ground-dwelling herbivores but are inhibited by the large amount of organic material they produce which reduces light or forms an impermeable layer. To investigate the mechanism behind the spatial pattern three hypotheses were tested with simulation models:

1. Small-scale competition, decreasing with distance
2. Small-scale facilitation and large-scale inhibition
3. Small-scale facilitation and intermediate-scale inhibition

Model 1 predicted homogeneous vegetation patterns, while models 2 and 3 predicted regular vegetation patterns (example result from model 3 in Figure 2.3.31). This indicates a scale-dependent feedback mechanism. A further exploration of parameter space of senescence (natural plant death) in both models indicated that model 3 was the most plausible because it never resulted in homogeneous vegetation patterns, which is in line with field observations.

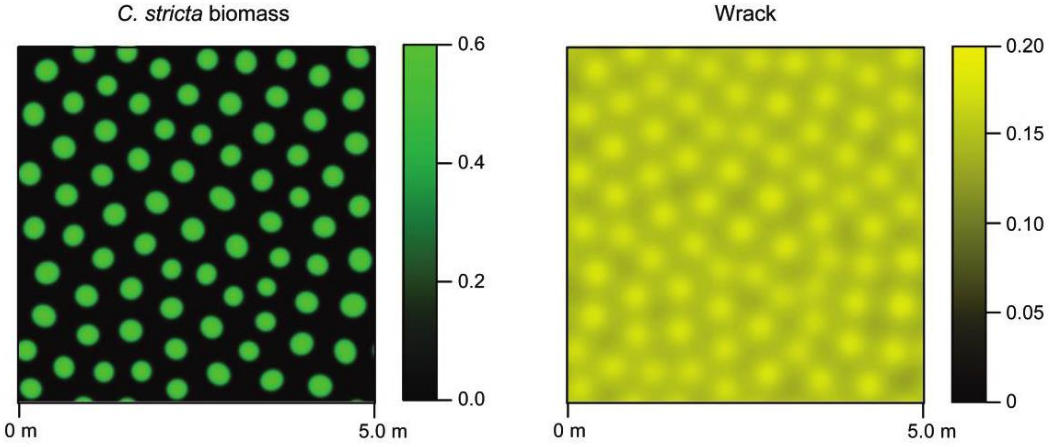


Figure 2.3.31 Spatial pattern of *Carex stricta* and Wrack resulting from model 3. The model predicts regular vegetation patterns due to small-scale facilitation and intermediate-scale inhibition (adapted from van de Koppel and Crain, 2006).

Vegetation dynamic models

General models

Evidence for the importance of facilitation in a disturbed environment is given by the model of Droz and Pekalski (2013). They constructed an individual based model with annual plant dynamics containing positive and negative interactions. The model contains two plants of the same species competing with each other (intraspecific) on a gradient of water and light. Survival, growth and seed production depend on how well conditions for resources are met. Under favorable conditions plants tend to compete more for resources resulting in isolated plants, while in harsh conditions plants tend to cluster. This result confirms the conceptual model of Brooker and Callaghan (1998) showing that the relative importance of facilitation increases when disturbance or stress increases.
The model of Travis et al. (2005) illustrates that facilitation can extend the natural range of species beyond their current niche. They model mutualists (species benefitting from each other) and cheaters (receive benefits at the costs of others but do not facilitate other species) over an environmental gradient. Two species are modelled containing mutualistic and cheater subtypes. When two mutualistic subtypes of different species interact in the same cell it is beneficial for their reproduction. Cheaters also gain reproductive advantage when interacting with a mutualist. Being a mutualist requires a cost which is expressed in a standard lower reproduction rate than the cheaters. Results show an explicit spatial segregation where (solely) mutualists can occur in harsher conditions due to positive interactions (Figure 2.3.32). Cheaters cannot sustain in this extended area because when they become dominant, the mutualists disappear and the facilitative interactions are diminished causing a retreat of the cheaters.

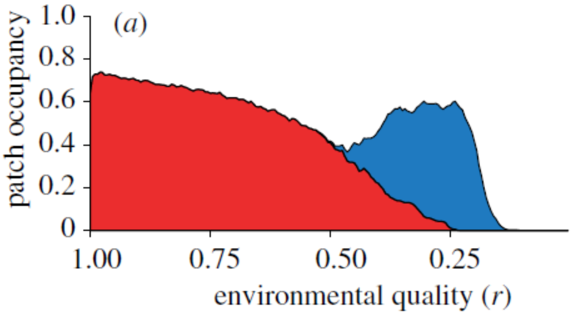


Figure 2.3.32 Spatial segregation occurs when mutualists (blue) and cheaters (red) interact over a gradient of environmental disturbance. Results show that mutualists can persist in harsher conditions (adapted from Travis et al., 2005).

Le Bagousse-Pinguet et al. (2014) found a similar result. They constructed an individual-based model to explore the impact of stress and disturbance on plant interactions thereby using the CSR concept of Grime (2002, Figure 2.3.33) and modelled species with the three primary strategies: Competitors, Stress-tolerators and Ruderals. In the model, stress and disturbance directly influenced adult survival and competition for space, and facilitation was included as a reduction of disturbance-related mortality. In the absence of facilitation, species are distributed within Grime’s CSR triangle, but with facilitation they can persist outside these ranges. Furthermore, the hotspot for species diversity shifts in situations with intense facilitation (Figure 2.3.33).

Several ecohydrological models also include vegetation competition processes in order to predict groundwater dynamics (e.g. the ecohydrological hillslope model by Brolsma et al., 2010a,b, and the SUMO module of the integrated VSD+-SUMO-NTM model by Wamelink

2007; see section 2.3.7). These models are very specific and relate plant-traits to biochemical processes.

The above modelling results show that facilitation is increased in harsh environmental conditions and that it can even increase the range of species settlement outside the predicted range.

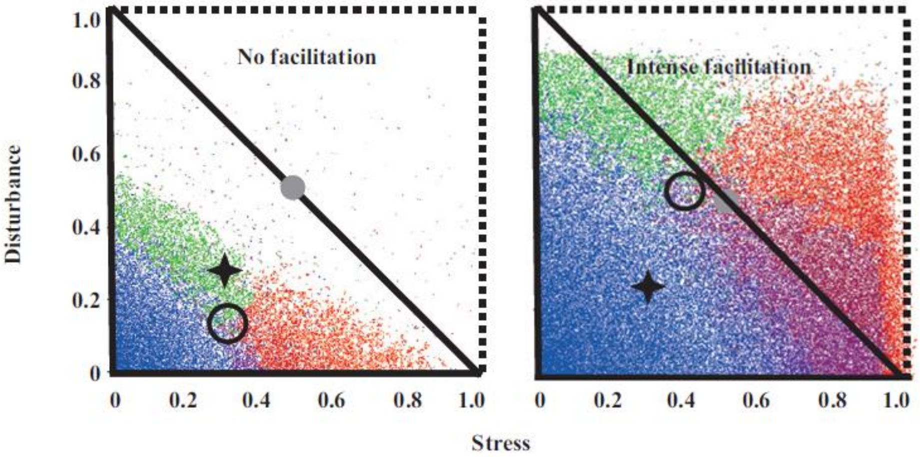


Figure 2.3.33 Model results adapted from Lebagousse *et al* (2014). Spatial distribution of plant strategies in the CSR triangle of Grime (solid lines, where the black star represents the centre of the triangle and the circle the hotspot for diversity). Blue dots are the Competitors, red dots are the Stress-tolerators, and green dots are the Ruderals (disturbance tolerators). Facilitation (right figure) extends the niche of species outside the CSR triangle.

Models in riparian zones

Only a few models including competition and facilitation are applied in riparian zones. One model showing the importance of facilitation is that of Tealdi et al. (2013). This stochastic model with long-term vegetation dynamics influenced by a hydraulic forcing includes competition and facilitation processes. Two vegetation species are considered: A) a fast growing grass or shrub growing close to the channel and B) a slower growing riparian tree. Type A has the advantage of colonising bare soil quickly but type B is able to out-compete type A in the long term. Facilitation by type A to type B is included by reducing shear stress and therefore promoting growth of type B. The results show that slow-growing species are better able to survive hydrologic stress when facilitation increases (Figure 2.3.34). The results indicate that facilitation in riparian communities is an important process influencing vegetation distribution along riparian transects.

Another model was constructed to predict which hydrological parameter is the main regulating process determining vegetation cover in the riparian zone (Ye et al., 2013). This cellular automate contains 10 herbaceous plant species interactively coupled to a hydrodynamic model to study the vegetation distribution along the Lijiang river in China. Competition is included in the model as a competitive index varying by species, based on the CSR concept of Grime (2002), according to their morphology and growth. When species interact the weakest competitor experiences reduced growth. The feedback from plants to hydrodynamics is expressed as higher roughness values. Floods in the dry and in the wet season are found to be the main regulator of vegetation cover.

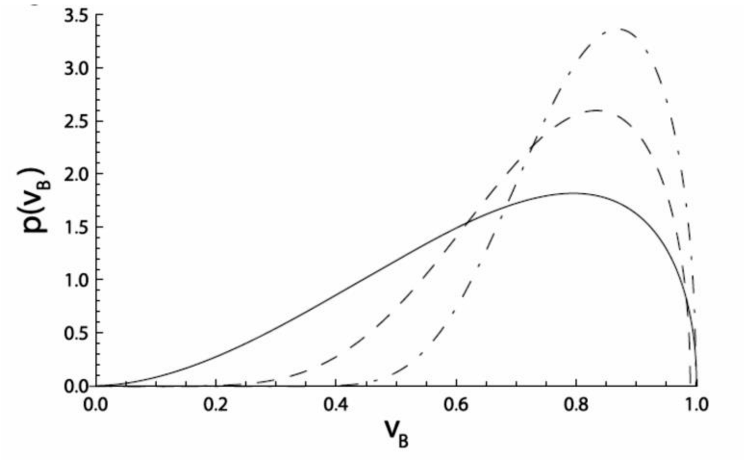


Figure 2.3.34 Probability distribution of the biomass of a slow growing species (B) with three different interaction scenarios with a fast growing vegetation type A. Solid line = no interactions, dashed line = medium facilitation by vegetation type A, dot-dashed line = maximum facilitation by vegetation type A. Results show that facilitation by type A increases the probability of increased biomass of species B.

Models including invasive species

There are many types of (conceptual) models predicting which species are likely to become invasive in new ranges, where there are suitable habitats or niches for these species (Peterson and Vieglais, 2001), how quickly invasive species spread through a region (e.g. review in Hastings et al., 2004), what the effects are on the ecosystem, and how we can mitigate these effects (Buckley et al., 2003). Here we focus on a selection of models including invasive species influencing local species community (vegetation patterns) by changing the balance between competition and facilitation processes.

The theory that the invasiveness of a plant can be promoted in its new environment by interacting with a mutualist is confirmed by the model of Xiao et al. (2012). They constructed an individual-based model describing competition for space of an invasive species with species from native areas and non-native areas under the influence of a mutualist (in this case a fungal symbiont). Relative interaction intensity indices, indicating the strength of interaction between species (negative for competition and positive for facilitation), were empirically derived and used as parameters in the model. The interaction between the invasive species and the symbiont increased dominance of the invasive plants in the scenario with non-native species but not in the scenario with native species. The authors found that effects of competitive intensity at a small spatial scale can potentially play an important role in large-scale outcomes of invasions.

Changes in resources can change the balance within a community and promote invasiveness of a species. This is shown by (Eppinga et al., 2011) who constructed an individual-based resource competition model for nutrients and light combined with litter dynamics (dead plant material which can reduce light, but also provides nutrients when decomposed). The aim of the study was to investigate the effects of an interaction between litter feedback and evolutionary change (changes in the genotype of the plant over time by adaptation to its environment, this can be expressed for instance by increased growth rate and increasing the competitive ability for light) on the competitive ability and invasion potential of a plant species. They modelled *Phalaris*, which is a strong competitor for light plus a known invader of North American wetlands, and *Carex* which is a strong competitor for nutrients growing in the same habitat as *Phalaris*. Three different scenarios were tested:

1. *Phalaris* invasion potential influenced by litter dynamics
2. The effect of evolutionary response of *Phalaris* (higher growth rate and higher C:N ratio = slower decomposition rate) on invasion potential
3. The combined effect of scenario 1 and scenario 2

Results show that the invasive effect of *Phalaris* can be increased by a combination of plant-litter feedbacks and evolutionary change which together amplify invasiveness.

A modelling study assessing the negative effect of competition by invasive species with native plants by Thomson (2005) created a matrix model to predict if invasive species are the cause of the decline of rare species in an area, and if invasive species suppress rare plants by direct competition for resources. The model is calibrated on empirical data of native plant growth of a control scenario (no removal of invasive plants from plots) and a removal scenario (invasive plants are removed from plots). Results show that removal of invasive plants does increase the growth rate of the native plant compared to the control scenario (Figure 2.3.35a), but that the growth rate is still too low for survival of the species in the long-term (Figure 2.3.35b). Furthermore, results do not support the hypothesis that resource competition was the most important mechanism behind the reduced population growth. This indicates that not only the invasive species, but also other factors (e.g. habitat fragmentation) play a role in the population decline of this species.

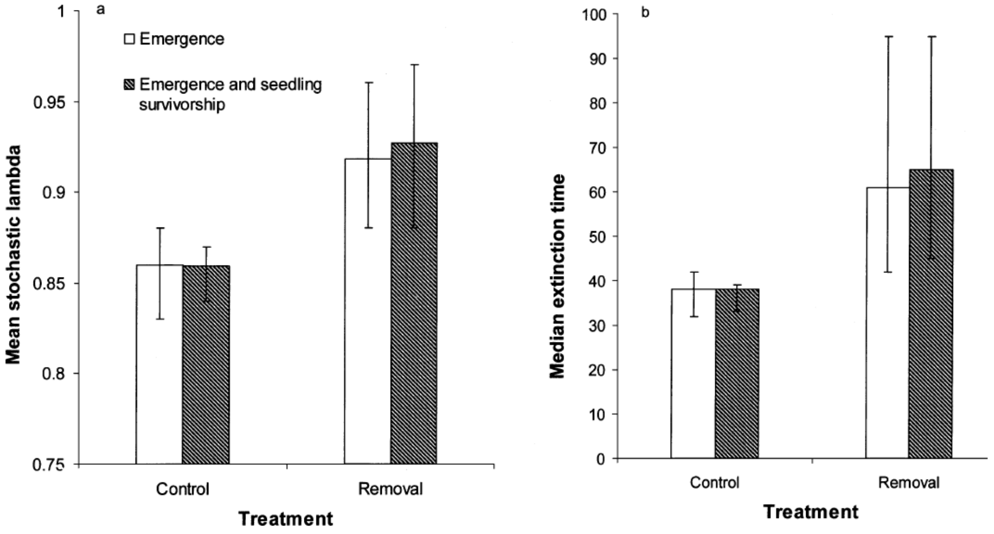


Figure 2.3.35 Effects of an invasive grass species on the mean population growth rate (a) of the native plant and the mean extinction time (b) of the scenarios with the invasive species (Control) and without the invasive species (Removal). Two different settings are tested: 1) Emergence = seedling emergence rates are affected by invasive plant and mean survival rates stays equal, 2) Emergence and seedling survivorship = both seedling emergence rates and mean survival rates are affected by invasive plants. Results show that invasive species reduce the mean growth rate of the native species and reduce the

time to extinction, but this is not the only factor causing a negative (<1) population growth and eventually extinction. (Adapted from Thomson, 2005).

How interference mechanisms (such as allelopathy) affect interactions between invasive species and native species was modelled by Allstadt et al. (2012). Interference mechanisms were modelled in trade-off with reproduction ability at the neighborhood scale. Having an interference mechanism creates competitive advantage, which is favorable for local interactions with other species, but decreases reproduction, which is unfavorable for species spread.

Three scenarios are tested:

1. The invasive species has the interference mechanism
2. The native species has the interference mechanism
3. Both invasive and native species can interfere

Modelling results indicate that individual rare invasive species do not gain advantage through interference because their rate of reproduction is too low for them to spread rapidly (because of the trade-off with reproduction). While in clustered invasive plant patches there are enough propagules to compete with native species for open sites.

The model of Goslee et al. (2001) also takes allelopathy into account. With a small scale individual-based model they simulated the importance of allelopathy and soil texture on growth, recruitment and invasion success of a non-native forb in semiarid grasslands. They found that at moderate levels of allelopathy the simulated results match the observed community composition, indicating that allelopathic interactions contribute to invasion success and influence the vegetation pattern.

2.3.6.5 Future modelling challenges

General

It is shown above that interactions between plants are dominated by competition and facilitation processes in less disturbed conditions. These interactions can for instance change the dominance of specific species by resource competition, create regular vegetation patterns by interplay between facilitation and competition, and can create settlement conditions for other species by facilitation. These processes therefore determine the vegetation patterns at the reach scale. However, the models discussed above mainly investigate the mechanisms behind competition and facilitation and how population dynamics are affected at small (abstract) spatial and temporal scales. So there is a need to upscale these processes to the reach scale. There is only a small selection of competition/facilitation models available for riparian zones and virtually none that include the effects of competition and facilitation combined with morphological development of rivers. Facilitation by ecosystem engineers (e.g. Salicaceae species) creates the 'first line of defense' against the flow on a (point) bar and is therefore an important process to take into account when modelling the interaction between vegetation and morphodynamics.

The cellular automate of (Ye et al., 2013) is quite advanced in the sense that it explicitly models the feedback between vegetation and hydrodynamics and also takes into account competition. But this model still contains simplistic hydrology and no sediment transport. Probably the most sophisticated competition processes are taken into account in groundwater models where competition for resources is linked to plant traits (e.g. root type, vegetation height, leaf type etc.) that are involved in biochemical processes (water uptake through roots, transpiration, respiration and water interception). For reach-scale hydromorphological models these processes are probably too detailed, but the idea of modelling competition and facilitation by linking these processes to plant traits might be promising. For instance, if the dominant vegetation types over the river cross-section are known, these can be translated into a functional trait set with a simple competitive index indicating which vegetation type will gain advantage over the other in a specific situation when the conditions are stable for a certain amount of time (like succession / retrogression schemes).

Therefore, the general modelling challenge is to integrate competition and facilitation processes in integrated reach scale hydro-morphodynamic models.

Based on the theories and models discussed in the previous sections, several other future (more specific) research and modelling challenges for competition and facilitation in general, and for invasive species can be distilled from the literature:

Competition and facilitation

1. Testing whether change in regular patterns can indicate loss or gain of resilience of ecosystems or act as an early warning signal (Rietkerk and van de Koppel, 2008).
2. Investigate the emergence of vegetation patterns due to stochastic factors (e.g. noise induced and random drivers, Borgogno et al. (2009).
3. Multi-scale approaches, coupling regional and local factors in all three spatial dimensions are needed to model biogeochemical and community processes within the river-riparian-upland landscape of catchments (Tabacchi et al., 2000) .
4. Include facilitative interactions along environmental gradients in space and time at local and landscape scale (Brooker et al., 2007).
5. Explore the potential for different life-history characteristics to evolve in response to the balance between facilitation and competition within a local community (Brooker et al., 2007).
6. Explore the evolutionary impact of interaction strength on an environmental gradient (Travis et al., 2005).
7. Extend spatially explicit facilitation models with properly represented facilitation described by plant ecologists (Brooker et al., 2007).
8. Explicitly distinguish between facilitation and mutualism (Brooker et al., 2007).
9. Investigate interactions in multi-species assemblages (Brooker et al., 2007).

Invasive species

1. Use process-based models with species functional traits for prediction of invasion (Catford et al., 2012).
2. Explicitly incorporate information on dispersal and adaptation (Catford et al., 2012).

3. To be more relevant for management, invasion risk models should include abundance as well as occurrence of species in models (Powell et al., 2011; Bradley, 2012).
4. Include effect of species interactions on dispersal behaviour of invasive species (Hastings et al., 2004).

In Annex A, Table 10a summarises the suitability of the discussed models with vegetation dynamics for the analysis of hydromorphological pressures or the design of restoration measures. The details of the models are given in Annex A, Table 10b.

2.3.7 Interaction between vegetation and groundwater

2.3.7.1 Background

A fundamental concept in ecohydrology is that plant physiology is directly linked to water availability, water quality and water temperature. Where there is ample water and groundwater levels are high, as in wetlands (Figure 2.3.36), plant growth is more dependent on nutrient availability. However, in semi-arid areas, like African savannahs (Figure 2.3.37), vegetation type and distribution relate directly to the amount of water that plants can extract from the soil, which is not in contact with the groundwater (saturated zone).

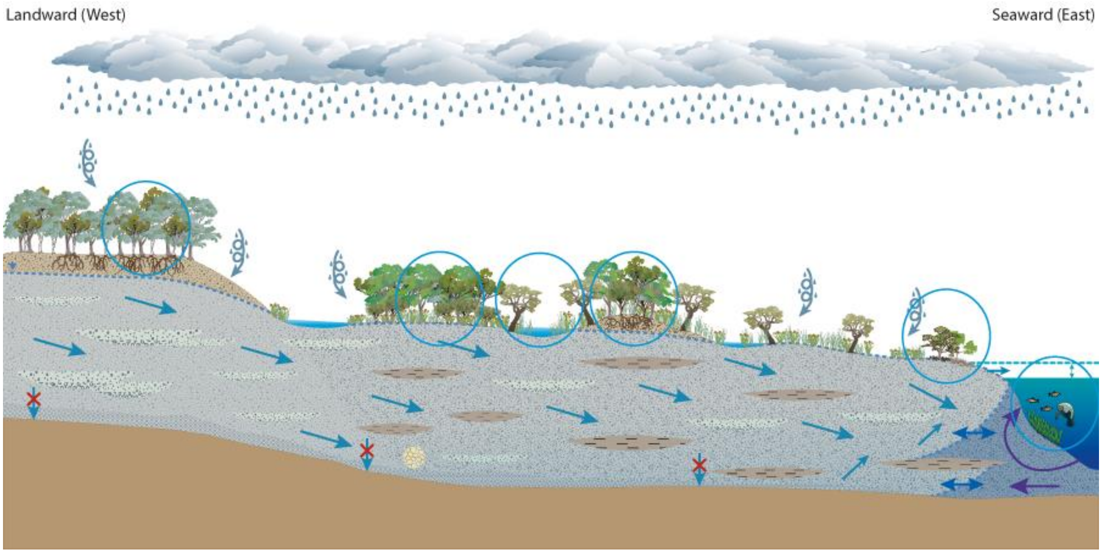


Figure 2.3.36 Schematic cross section of a groundwater dependent ecosystem (Source: http://wetland info.ehp.qld.gov.au).

Plants function best under ideal (plant specific) soil moisture conditions. Soil moisture is a general term describing the amount of water present in the vadose zone, or unsaturated portion of soil below ground. Since plants depend on this water to carry out critical biological processes, soil moisture is integral to the study of ecohydrology. Soil moisture is generally described as water content θ or saturation S. These terms are related by porosity n through the equation $\theta = n \times S$. When insufficient soil moisture is available, a water-stressed condition occurs. Plants under water stress decrease both their transpiration and photosynthesis through a number of responses, including closing their stomata.

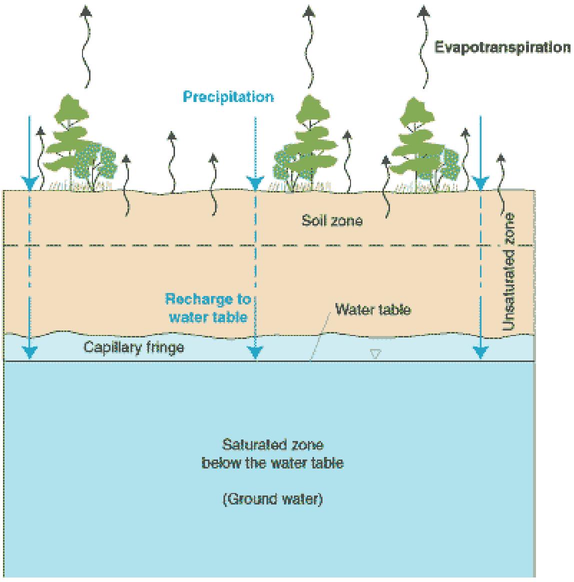


Figure 2.3.37 Schematic cross section of a rainwater dependent ecosystem, not connected to the groundwater system (Source: http://pubs.usgs.gov).

Groundwater dependent ecosystems

In addition to precipitation and inundation water, groundwater can be an important source of soil moisture. In temperate regions large areas are covered by so-called groundwater dependent ecosystems (e.g. Figure 2.3.38). In such ecosystems, the vegetation is adjusted to temporally shallow groundwater levels and dependent on the specific chemical characteristics of the groundwater. For such ecosystems, groundwater should be taken into account when modelling vegetation occurrence and patterns. Groundwater dependent ecosystems (GDEs) are simply a subset of all ecosystems which require access to groundwater on a permanent or intermittent basis to meet all or some of their water requirements so as to maintain their communities of plants and animals, ecological processes and ecosystem services (Richardson et al., 2011). Ecosystem dependency on groundwater may vary temporally (over time) and spatially (depending on its location in the landscape). GDEs may include aquifers, caves, lakes, palustrine wetlands, rivers, springs and vegetation (Figure 2.3.38).

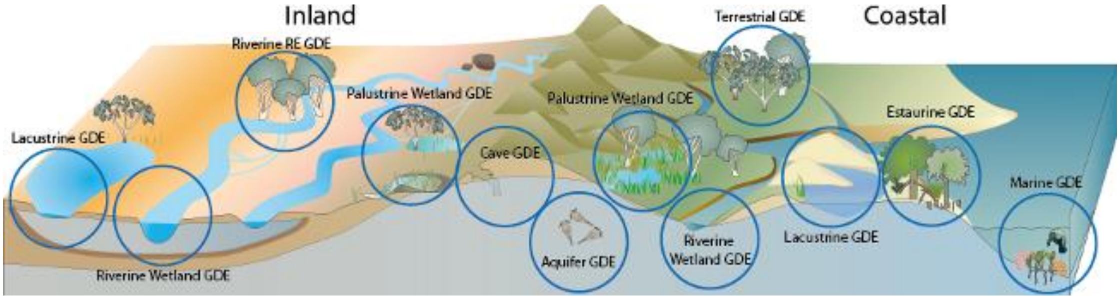


Figure 2.3.38 Schematic overview of all types of groundwater dependent ecosystems (Source: http://wetlandinfo.ehp.qld.gov.au).

Groundwater plays an important ecological role in directly and indirectly supporting terrestrial and aquatic ecosystems. Groundwater sustains terrestrial and aquatic ecosystems by supporting vegetation and providing discharge to channels, lacustrine (lake) and palustrine (marshland) wetlands, and both the estuarine and marine environment. Groundwater also plays a critical role during extended meteorologically dry periods in maintaining refuges for flora and fauna.

Importance of groundwater in riparian zones and wetlands

Riparian biota is dependent on the dynamic characteristics of the surface water regime. However, surface water only forms the visible part of a continuous hydrologic system. Riparian zones are sustained by the combination of water in the surface stream, unsaturated zone and groundwater aquifer. Water from the capillary fringe[1] of the alluvial groundwater table is the major water source for many riparian species. Lowering groundwater tables can have widespread ecologic consequences, including the conversion of perennial stream flows to intermittent flows and the alteration of vegetation composition and cover. Even short term groundwater level declines can change the distribution and abundance of riparian plant associations. Identifying the vulnerability of riparian and wetland ecosystems to anthropogenic activities and climatic variation necessitates a thorough understanding of the groundwater-surface water interactions that maintain them (Baird et al., 2005). Groundwater conditions are also important for flow dynamics and base flow in streams and rivers, thereby affecting aquatic ecology (Hendriks et al., 2014). However, in this review of groundwater – vegetation models we focus on terrestrial vegetation and the influence of groundwater on stream flow and aquatic vegetation is not taken into account.

Groundwater flow

Regional or local groundwater flow transports groundwater from one area/location to another. The groundwater flow velocity determines the residence time while the groundwater flow direction or route determines the material that the groundwater flows

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[1] The capillary fringe is the subsurface layer in which groundwater seeps up from a water table by capillary action to fill pores. Capillary action supports an unsaturated zone (or: vadose zone) above the saturated base (or: groundwater table) within which water content decreases with distance above the water table.

through. Hence, groundwater flow has a large effect on the availability and the chemical composition of the groundwater. Groundwater flow velocity and direction are determined by pressure differences and differences in permeability of the subsurface, and have a vertical and horizontal component. Vertical flow is expressed as seepage (upward) or infiltration (downward). Both the vertical and horizontal flow varies over time in velocity and direction.

2.3.7.2 Principles of groundwater – vegetation modelling

Groundwater – vegetation modelling is most frequently part of an ecohydrological model in which more site factors that affect vegetation are taken into account. An ecohydrological model inevitably contains a hydrological module as a basic element. Another necessary part is a vegetation sub-model. Also, such a model usually includes sub-models for biogeochemical cycles (carbon, nitrogen, phosphorus). The hydrological, vegetation and biogeochemical sub-models are usually coupled in order to include important interactions and feedbacks between processes, like water and nutrient drivers for plant growth, water transpiration by plants, nutrient transport by water, etc. Climate parameters are most often not modelled but used as external drivers (Krysanova et al., 1998).

Figure 2.3.39 shows the general process followed for an ecohydrological prediction by Witte et al (2008).

For areas with groundwater dependent vegetation, ecohydrological models need to include a coupling to groundwater characteristics and dynamics (Witte et al., 2008). Ecohydrological models including groundwater are often used to assess and predict the effects of a groundwater level fall on important factors and moist sites. In the schematic of Figure 2.3.40 an overview of the main negative effects of groundwater level fall is given (Witte et al., 2008).

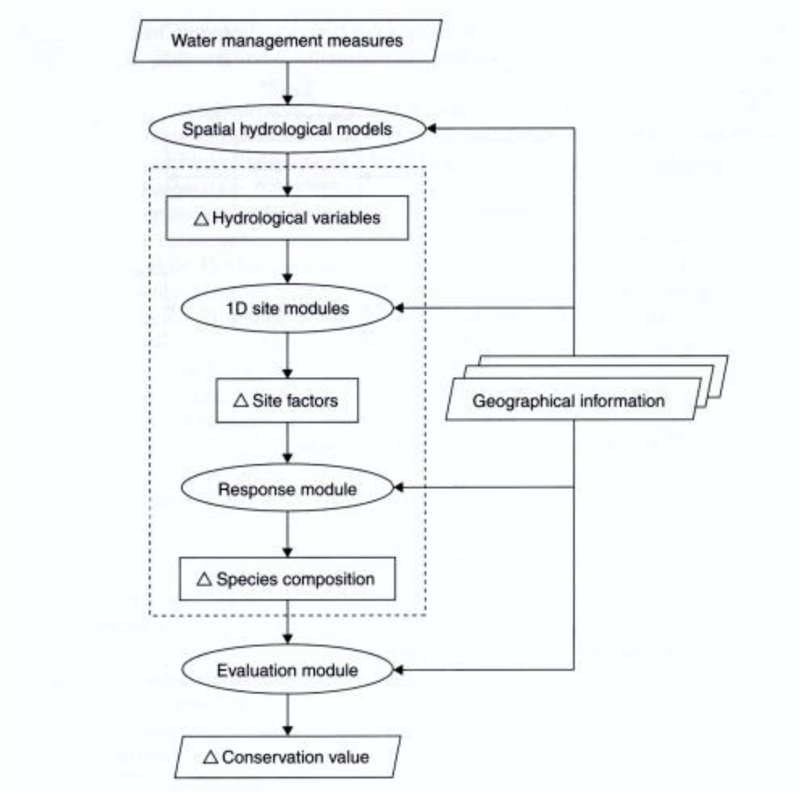


Figure 2.3.39 General process chain for an ecohydrological prediction. Input and output of data and variales are indicated by a rhombus, interim variables by a box, models and modules by an eclips, direction of flow by an arrow and change in a variable by a triangle (1D, one-dimensional) (From Witte et al., 1998).

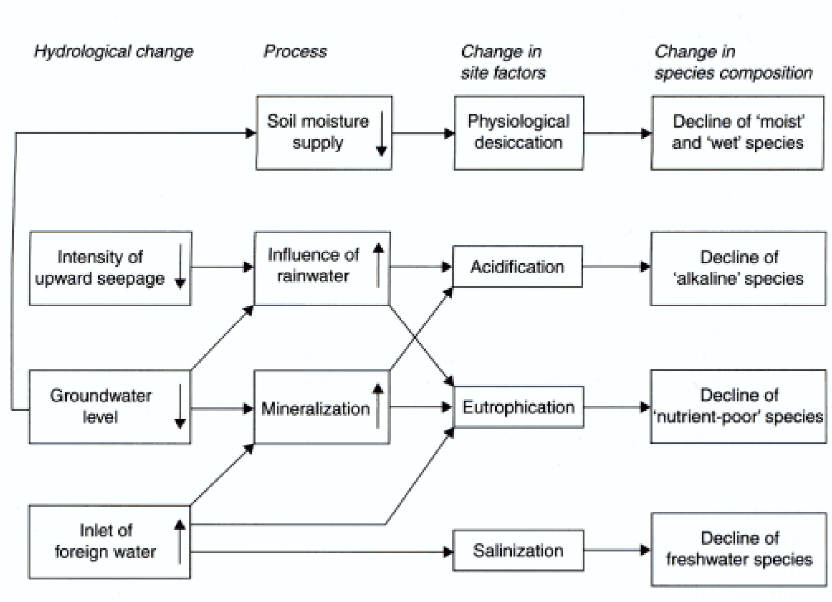


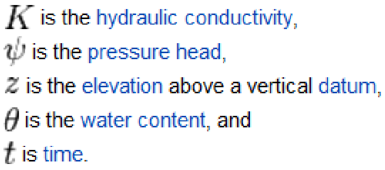
Figure 2.3.40 Main negative effects of a groundwater fall on important operational factors of wet and moist sites. Direction of change is indicated by arrows: ↑ is increase, and ↓ is decrease (From Witte et al., 2008).

Local groundwater availability

The local groundwater quantity is of importance for the plant moisture supply in the soil, the plant air supply and indirectly on the plant nutrient supply. All these processes occur in the plant root zone. The local groundwater quantity is determined by the climate (precipitation and evaporation), soil properties (porosity and permeability), and the (regional) groundwater flow. Also, the local groundwater quantity is affected by the vegetation (plant transpiration). Hence, it is important to take into account the feedback mechanisms between groundwater and vegetation. Concerning water availability in the root zone, plants can suffer both from a shortage of water (water stress) as well as from a shortage of oxygen (anaerobic or oxygen stress) that hamper their growth and occurrence (Homaee et al., 2002; Feddes et al., 1978). Current hydrological models for the unsaturated zone describe soil water flow by solving the Richards' equation, which includes a sink term that represents water uptake by plant roots[2]:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial \psi}{\partial z}+1\right)\right]$$

where:



K is the hydraulic conductivity,
ψ is the pressure head,
z is the elevation above a vertical datum,
θ is the water content, and
t is time.

Different procedures for the simulation of root water uptake exist (Bartholomeus et al., 2008). A well-known and frequently used procedure to simulate root water uptake, is the reduction function of Feddes et al. (1978). Current hydrological models that include the Feddes-function, such as SWAP (Kroes et al., 2008) and HYDRUS (Sˇimu˚nek et al., 2005), compute root water uptake by multiplying potential transpiration (which is determined by meteorological conditions and crop type) with a sink term variable for root water uptake *F* (Figure 2.3.41). Depending on soil water pressure head *h*, *F* corrects for conditions that are either too dry, or too wet. Root water uptake decreases linearly between pressure head h_2 and the anaerobiosis point h_1 due to oxygen stress in wet situations.

On the dry side of the Feddes function, root water uptake decreases linearly between pressure head h_3 and wilting point[3] h_4 due to water stress. The following sections give more information on water tress and oxygen stress.

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[2] Richards equation is equivalent to the groundwater flow equation, which is in terms of hydraulic head (h), by substituting h = ψ + z, and changing the storage mechanism to dewatering.

[3] Wilting point (WP) is defined as the minimal point of soil moisture the plant requires not to wilt. If moisture decreases to this or any lower point a plant wilts and can no longer recover its turgidity when placed in a saturated atmosphere for 12 hours. The physical definition of the wilting point (symbolically expressed as θpwp or θwp) is defined as the water content at −1500 J/kg of suction pressure, or negative hydraulic head.

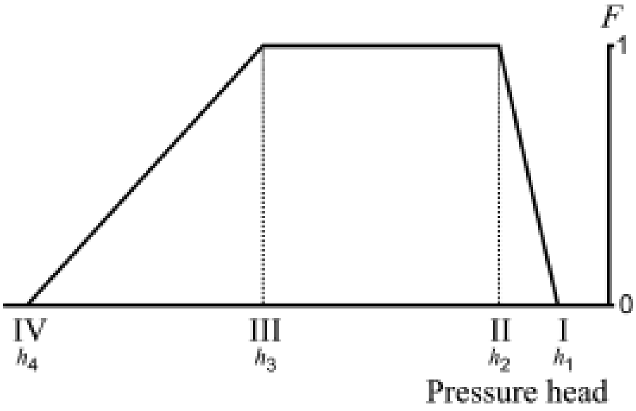


Figure 2.3.41 Sink term variable F as function of pressure head h according to Feddes et al. (1978). Root water uptake reduces linearly from III (h3) to IV (h4) due to moisture stress, as well as from th ecritical values II (h2) and I (h1), due to oxygen stress. In between II and III, root water uptake is optimal (F=1) (From: Bartholomeus et al., 2008).

Water stress

Several empirical groundwater head-dependent root water uptake reduction functions have been developed that can are used to simulate the effect of shortage of water (water stress) on plant transpiration (*a(h)*). The most common formulation of this reduction term was developed by Feddes et al. (1978):

$$\alpha(h) = \frac{h - h_4}{h_3 - h_4}$$

in which *h* is soil water pressure head, h_3 soil water pressure head threshold value, and h_4 soil water pressure head at wilting. Alternatively, Van Genuchten (1980) proposed:

$$\alpha(h) = \frac{1}{[1 + (h/h_{50})^p]}$$

in which h_{50} is the soil water pressure head at which *a(h)* is reduced by 0.50. Dirksen and Augustijn (1988) and Dirksen et al. (1993) modified the equation by Van Genuchten by the assumption that root water uptake is not reduced above a threshold value of soil water pressure head *h**, and introduced:

$$\alpha(h) = \frac{1}{1 + [(h^* - h)/(h^* - h_{50})]^p}$$

Homaee (1999) introduced a second threshold value and replaced h_{50} with *h*max and proposed:

$$\alpha(h) = \frac{1}{1 + (1 - \alpha_0)/\alpha_0[(h^* - h)/(h^* - h_{\max})]^p}$$

in which h_{max} is the soil water pressure head beyond which the changes of h no longer influence the relative transpiration significantly, and *a(h)* is the relative transpiration at h_{max}. Similar to Van Genuchten (1980), he further assumed that the dimensionless exponent *p* is crop, soil, and climate specific and proposed:

$$p = \frac{h_{\max}}{h_{\max} - h^*}$$

The advantage of such so-called macroscopic approaches is that it does not require complete insight in the physical process of root water uptake and, therefore, eliminates the need for soil and plant parameters that are difficult to obtain. However, such an empirical approach still needs to be calibrated for different plants and different climatic conditions (Homaee et al., 2002).

Oxygen stress

Feddes et al. (1978) indicated that a fixed anaerobiosis point h_2 , identical for all environmental conditions, may be inappropriate, because pressure heads do not provide direct information on the aeration status of the soil. A detailed analysis of this wet side of the Feddes function has however never been performed. In 2008 Bartholomeus et al. a proposed a model to compute plant oxygen stress based that includes both oxygen consumption of plant roots described by plant physiological processes and oxygen transport to plant roots described by physical laws. They argued that these plant physiological and soil physical processes should be considered simultaneously, as the oxygen transport (ad 1) is determined by oxygen consumption and vice versa (Bartholomeus et al., 2008).

SWAP

Soil Water Atmosphere Plant (e.g. Feddes et al., 1978; Van Dam et al., 1997; Van Dam and Feddes, 2000) is a model that describes the transport of soil water as dependent upon climate, vegetation characteristics, soil characteristics and groundwater regime. SWAP has already been linked to various models for crop growth, vegetation development, and soil chemistry. It contains feedbeack mechanisms between vegetation and soil (e.g. vegetation extracts water from the soil for transpiration; transpiration and vegetation cover are reduced when the soil dries up). The soil characteristics of SWAP however cannot change, as soil development is not a part of the present SWAP version

SWAP simulates transport of water, solutes and heat in unsaturated/saturated soils, integrating the Soil-Atmosphere-Plant System. The model is designed to simulate flow and transport processes at field scale level, during growing seasons and for long term time series. The bottom boundary is located in the unsaturated zone or in the upper part of the groundwater and describes the interaction with regional groundwater.

SWAP applies Richards' equation integrally for the unsaturated-saturated zone, including possible transient and perched groundwater levels. In this zone the transport processes are predominantly vertical; therefore SWAP is a one-dimensional, vertical directed model. The flow below the groundwater level may include lateral drainage fluxes, provided that these fluxes can be prescribed with analytical drainage formulas (Kroes et al., 2008).

Local groundwater quality and temperature

In addition to availability the chemical composition and temperature of groundwater are important for vegetation development and occurrence of plant types (Klijn, 1989). Concerning water quality, the most important aspects are nutrient richness, salinity, lime content (hardness), pH, iron content, oxygen content, and water contamination. The chemical composition of the water is, besides the composition at time of infiltration, determined by the characteristics of the subsurface through which the water flows as well as by the time during which the water remains in subsurface (the residence time). This residence time is important for the establishment of a chemical equilibrium of the groundwater.

Groundwater is often characterised by reference water types based on Piper-diagrams, Stiff-diagrams or Collins-diagrams. Van Wirdum (1980) introduced the 'ecological classification' in which characteristic ion compositions are related to the origin of residence time of groundwater. Van Wirdum distinguishes three main reference types based on the ion ratio and the electrical conductivity:

- Atmocline water, characterised by large similarity to rain water (short residence time after infiltration of rain water): ion poor, low electrical conductivity, low salinity, high acidity, oxygen rich.
- Lithocline water, characterised by large similarity to composition of subsurface and deeper groundwater (long residence time after infiltration): ion rich, high electrical conductivity, neutral or basic, oxygen poor.
- Thalassocline water, characterised by large similarity with sea water: ion rich, very high electrical conductivity, high salinity, basic.

Groundwater indicator values (Ellenberg)

Another option to link groundwater and soil moisture availability to vegetation and plant functioning is the use of indicator values for moisture availability and nitrogen, salinity, and alkalinity of soil moisture. Ellenberg (1979, 1991) developed a system of indicator values of characteristics/parameters of site types in central Europe, based on numourous field studies of plants and ecosystems. In this 'Ellenberg indicator system' moisture conditions are classified in 12 indicator values, 9 indicator values for nitrogen content, 9 indicator values for salinity, and 9 indicator values for alkalinity that cover the moisture availability for all plant species in the central Europe.

A combination of the classes of all parameters results in a matrix, each of which represents a certain site type. On the basis of Ellenberg's indicator values, ecological species groups are assinged to each site type. Furthermore, each site type is given a potential conservation value, calculated only once from the number of highly valued species in the corresponding ecological group. To facilitate predictions, the class boundaries have also been defined in physical terms. The boundary between 'wet' and 'moist' for example, corresponds to an average groundwater level of 20 cm below the surface. Computed changes in site factors may bring about the crossing of class boundaries and, as a result, a new site type with its associated new potential conservation value (Witte et al., 2008).

Sources of groundwater input

When coupled with models of wetland or riparian ecology and with sufficient field monitoring, regional models can be used for predicting the vulnerability of wetland and riparian habitat to water table decline and the future status of created or restored ecosystems (Baird et al., 2005). Groundwater models can also aid in the quantification of basin or reach scale water requirements for key habitat types in riparian landscape.

Non-stationary, spatially distributed groundwater models (e.g. MODFLOW) that combine information on groundwater depths, soil and subsurface properties, and meteorological information are used to simulate groundwater levels and groundwater flow for larger areas. In many cases these models are coupled to unsaturated zone models that simulate water use and transpiration by plants. In some models, the groundwater quality and the chemical processes are also taken up (e.g. MT3D).

If spatially distributed groundwater models are not available, it is also possible to take groundwater into account in a more simplified way. Most common options are:

- One dimensional water balance models that calculate the height of the groundwater table. Water is added by precipitation, while evapotranspiration (including interception) and drainage remove water from the system.
- Information on local groundwater quantity is available through data bases of local soil and groundwater characteristics that are dived into classes. For the Netherlands this can be found in the 'LKN files' (soil types) and the 'grondwatertrappen' (classes of groundwater depths). From such information, water availability throughout the year can be derived.
- Local measurements of groundwater level, pressure head and groundwater quality.

2.3.7.3 Recent modelling advances

This section contains an overview of available groundwater – vegetation models. First an explanation is given of the different types of models: correlative, mechanistic and semi-mechanistic. After that an overview of the various mechanistic and semi-mechanistic models is given. In Annex A, Table 11 lists the characteristics and possible applications (hydromorphological pressures and restoration design) for all relevant models.

Model types: correlative or (semi-)mechanistic

Ecohydrological models can roughly be classified into three types (Figure 2.3.42: (i) correlative models, (ii) mechanistic models with causal relationships, and (iii) semi-mechanistic models, which contain both correlative and causal relationships (Witte et al., 2008).

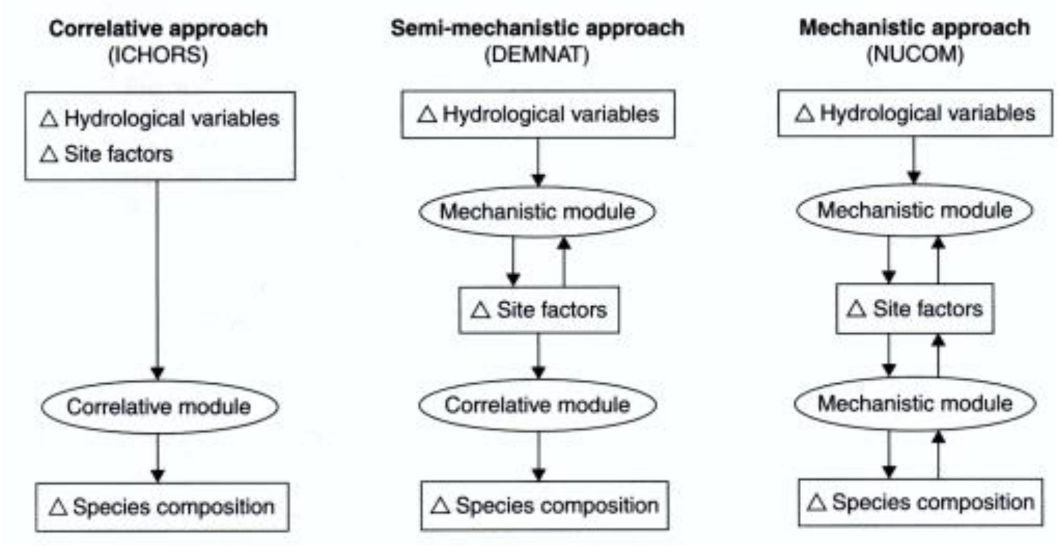


Figure 2.3.42 Three types of ecohydrological models, differing in the causality of the modelled relationships. Examples are given in parentheses (From Witte et al., 2008; adapted from Runhaar, 1999).

Correlative models

The basic feature of a correlative approach is that it considers the ecosystem as a black box: the occurrence of species is statistically correlated with a broad spectrum of site factors, irrespective of their supposed ecological importance. Completely correlative approaches do not exist, however one will always try to select site factors (among which groundwater quantity and quality) that are expected to have at least some ecological meaning. The adjective 'correlative' has a relative meaning, to distinguish between 'more correlative' and 'more mechanistic'. With 'more correlative' models, probablity functions are based on logistic multiple regressions (or response functions) on data concerning vegetation characteristics and the relevant site factors obtained by data collection in the study area. Because of their back-box character, for each region a special version of the model is made, with unique occurrence probability functions (Witte et al., 2008).

In many cases ecohydrological models serve as decision support tools in water management. Witte et al. (2008) state that a correlative approach is especially usefull in an initial stage of research, to reveal unknown relationships in a specific area. Correlative models have the disadvantage of accidental and apparent results. For areas in which the site factors that determine plant species are already sufficiently known, Witte et al. (2008) advise against the use correlative models.

Examples of a (relatively) correlative approach are ICHORS (Influence of Chemical and Hydrological factors On the Response of Species; Barendrecht, 1991), HYVEG (Hydrology-VEGetation; Noest, 1994), and ITORS (Influence of Terrestrial site conditions On the Response of Species; Ertsen, 1998). Because correlative models are very location-specific these examples are not further explained.

Mechanistic models

A mechanistic model contains causal relationships that are well known from experimental studies or that have been derived theoretically. Like 'correlative', the adjective 'mechanistic' also has a relative meaning, since any model will always contain processes that to a certain degree have been lumped (Witte et al., 2008). With mechanistic modelling the processes that take place in nature are simulated. This method is preferred in scientific work. Moreover, mechanistic modelling may be the only solution to long-term predictions by taking into account the history and feedback mechanisms of the ecosystem. The practical value of mechanistic models is often limited, due to the high demand for input data and the simplificantions with respect to local situations (Witte et al., 2008).

Semi-mechanistic models

Most *ecohydrological models* are of a semi-mechanistic approach, whereby the species composition of the vegetation is regarded as a function of a limited number of site factors. The site factors are expected or have been proved to have the largest influence on the species composition of the vegetation. This approach is partly mechanistic and partly correlative. How environmental changes influence site factors such as moisture regime and nutrient availability is – as far as is possible and practical – modelled in a mechanistic way, on the basis of present knowledge of the processes that take place in soil and groundwater. The relationship between site factors and species composition, however, is determined in a correlative way (Witte et al., 2008).

In most cases, semi-mechanistic approaches are preferred, in which site factors are modelled in a mechanistic way as far as is possible. Any correlative relationships between site and vegetation should be based on ecological knowledge. For example: the fraction of hygrophytes (plants that grow in wet or waterlogged soil) should be correlated with the groundwater level (as a measure of 'moisture regime'), or the fraction of alkaline vegetation species should be correlated with the soil pH (as a measure of 'acidity') (Witte et al., 2008).

Mechanistic model examples

PROBE

With the PROBE approach (Witte et al., 2006; Witte et al., 2007a) an additional functional layer of traits is modelled (grey box in Figure 2.3.43), which is disposed between the environment and the type of vegetation. The traits layer has several scientific advantages, for instance enabling feedback mechanisms, and 'habitat filtering'. Also, introduction of new vegetation types is possible without making changes to the model structure. The probability of occurrence of vegetation types is calculated as a function of plant characteristics. The method uses a file with almost forty vegetation surveys. With density functions the Bayesian chances of the occurrence of vegetation types are predicted for a given combination of plant characteristics.

The first PROBE model was built for non-groundwater dependent vegetation types in the dune area of the Netherlands. For PROBE-2, the model was extended to other habitats, including groundwater dependent vegetation types. The reaction of the vegetation to the moisture condition (water stress and oxygen stress) is not, as in most of the models, directly related to the depth of the groundwater table, but on the availability of water and oxygen in the root environment (Bartholomeus, 2010). The routine to calculate water and oxygen stress is integrated into the hydrological model SWAP (Soil Water Atmosphere Plants) and needs the same input data as SWAP (see section 2.3.7.2).

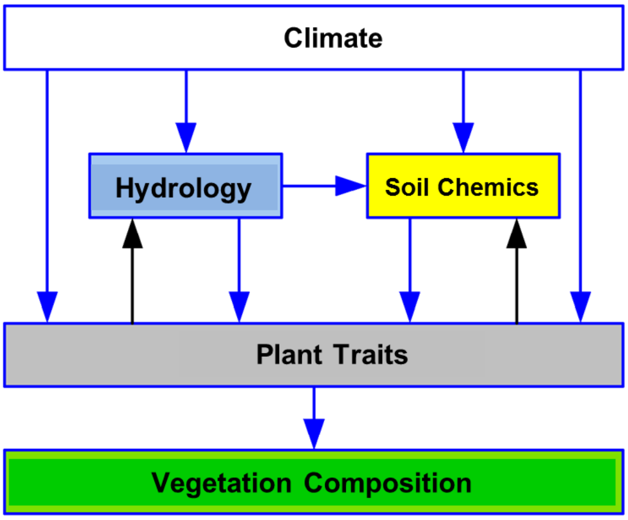


Figure 2.3.43 Schematic of the work flow in the PROBE model.

NUCOM

The fully process-based model NUCOM was first developed by Van Oene et al. (1999) for sandy areas in the Netherlands with low groundwater tables. The first versions did not include groundwater, because they were developed for ecosystems without groundwater dependent vegetation. In 2001 NUCOM was extended for wetter ecosystems including groundwater dependent vegetation (Van Oene and Berendse, 2001). Also, NUCOM-BOG was developed, which focuses on temperate peat bogs (see below).

NUCOM models the effects of climate change on carbon and nitrogen cycling and ecosystem productivity, plant competitive relations and plants species composition of communities. Interactions between vegetation and soil dynamics are modelled at the ecosystem scale. Characteristic for the model is the feedback between effects of changed soil organic matter and the effects of changed plant species composition on soil organic dry matter dynamics (Van Oene and Berendse, 2001).

The hydrology module of NUCOM calculates water fluxes in the unsaturated and saturated root zone assuming a one-dimensional (vertical) direction of these fluxes. The process description is based on the SWAP model (see section 2.3.7.2). The processes including in NUCOM are soil evaporation, plant transpiration, rainfall interception, soil water flow, and capillary effects from groundwater to soil moisture (Van Oene and Berendse, 2001).

NUCOM-BOG

NUCOM-BOG is a landscape scale process-based model that describes vegetation, carbon (C), nitrogen (N), and water dynamics in temperate peat bogs in response to climatic changes over tens to hundreds of years. The vegetation is described in terms of Sphagnum mosses; graminoids, ericaceous dwarf shrubs, and birch trees which compete with each other for light and nitrogen. The model includes vegetation-soil feedbacks, such as the effects of plant species groups on nutrient mineralization rates and soil moisture. NUCOM-BOG uses a monthly time step for the C and N balances (including calculations of plant growth and mineralization of soil organic matter) and a quarter monthly time step for the water balance (including calculations of evapotranspiration). Monthly temperature, precipitation, and potential evapotranspiration data, as well as annual atmospheric CO2 concentration and N deposition, are required as inputs to the model (Heijmans et al., 2008, Heijmans et al., 2013).

In bog ecology, the height of the groundwater table relative to the moss surface is considered an important factor. NUCOM-BOG accounts for changes in the water balance in order to calculate the height of the groundwater table. Water is added by precipitation, while evapotranspiration (including interception) and drainage remove water from the bog ecosystem. Evapotranspiration depends on the relative abundance of the mosses and vascular plants, as the peat mosses contribute more to the vegetation’s water loss than vascular plants. The term ‘drainage’ represents surface run-off and lateral outflow of water through the living moss layer. Vertical drainage is assumed to be negligible (Heijmans at al., 2008).

Riparian zone model: RIP-ET and PRE-RIP-ET

Baird et al. (2005) introduced an innovative groundwater-vegetation modelling approach for riparian zones. Evapotranspiration from riparian/wetland systems is modelled in a manner that more realistically reflects plant ecophysiology and vegetation complexity (model programs RIP-ET and PRE-RIP-ET). The single, monotonically increasing evapotranspiration flux curve in traditional (MODFLOW) groundwater models is replaced with a set of ecophysiologically based curves, one for each plant functional group present. For each group, the curve simulates transpiration declines that occur both as water level declines below rooting depths and as water rise to levels that produce anoxic soil conditions. Accuracy is further improved by more effective spatial handling of vegetation distribution, which allows modelling of surface elevation and depth to water for multiple vegetation types within each large model cell. When combined with vegetation mapping and a supporting program (RIP-GIS), RIP-ET also enables predictions of riparian vegetation response to water use and development scenarios. The RIP-GIS program links the head distribution from MODFLOW with surface digital elevation models, producing moderate- to high-resolution depth-to-groundwater maps. Together with information on plant rooting depths, these can be used to predict vegetation response to water allocation decisions.

Ecohydrological hillslope model

Brolama and Bierkens (2007) developed a quasi 2-dimensional hydrological model to investigate and quantify the influence of slope angle, precipitation input and vegetation composition on the hydrological system. Figure 2.3.44 gives a schematic overview of this model. Hydrology is modelled as a 2-dimensional model of saturated-unsaturated flow along a slope using Richards’ equation. This hydrological model aims to describe the flow of water along a hillslope. The simplified model consists of two coupled zones: a root zone where trees abstract their water and a groundwater zone. Flow in the groundwater zone is horizontal only and a vertical exchange flux exists between the root zone and the groundwater zone. The model was used for assessments of the effect of hydrology and climate on vegetation and vegetation competition (Brolsma et al., 2010a, 2010b, and 2010c).

The link between groundwater and vegetation consists of this vertical flux between groundwater and the root zone. The magnitude of the flux is dependent on the groundwater depth and the root water uptake due to the water demand of the plants. Root water uptake occurs from the rootzone and depends on its matric potential and is modelled using the Feddes et al. (1978) root water uptake reduction function for oxygen stress. Water stress and its effects are modelled according to Porporato et al. (2001), who designed a method to calculate water stress in which static and dynamic stress are distinguished. Static stress gauges the “state of stress” of a plant at a given time, while dynamic stress is a measure of total stress that a plant has experienced over a prolonged period of time taking into account the frequency and the mean length of the water stress period that a plant has experienced during a growing season.

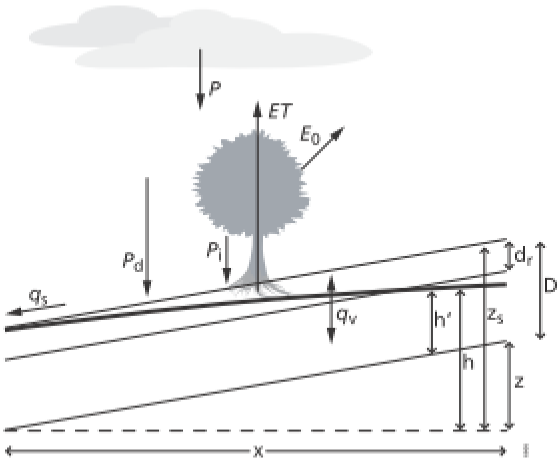


Figure 2.3.44 Schematic overview of the groundwater – vegetation model for hillslopes by Brolsma et al. (2007).

Semi-mechanistic models

DEMNAT

A good example of the semi-mechanistic approach is DEMNAT (Dose-Effect Model for terrestrial NATure), a national prediction model meant for analysing the effects of water management in ecosystems (e.g. Witte, 1992; Van Ek et al., 2000). DEMNAT is a practical model suited to national-scale applications and generates results that have to be interpreted as ‘best professional judgement’ given the current state of knowledge and availability of data. With DEMNAT it is possible to compute the ecological effects of changes in hydrology. Hydrological changes that can be evaluated include changes in: mean spring-groundwater level, upward seepage, water level of small surface waters, and the inlet of river water into local systems. Ecological effects are expressed as changes in the botanical quality (completeness) of 18 ecotopes. Only plant species are considered because these organisms most closely express changes in hydrology. A conservation valuation module may be used to weight the ecological effects according to the importance of the ecotopes for nature conservation in the Netherlands. DEMNAT consists primarily of three modules: a geographical schematization of ecosystems, a set of dose-effect functions, and a conservation valuation module (Van Ek, et al., 2000). Figure 2.3.45 shows the process diagramm for a DEMNAT prediction of change in nature value as a results of water management interventions.

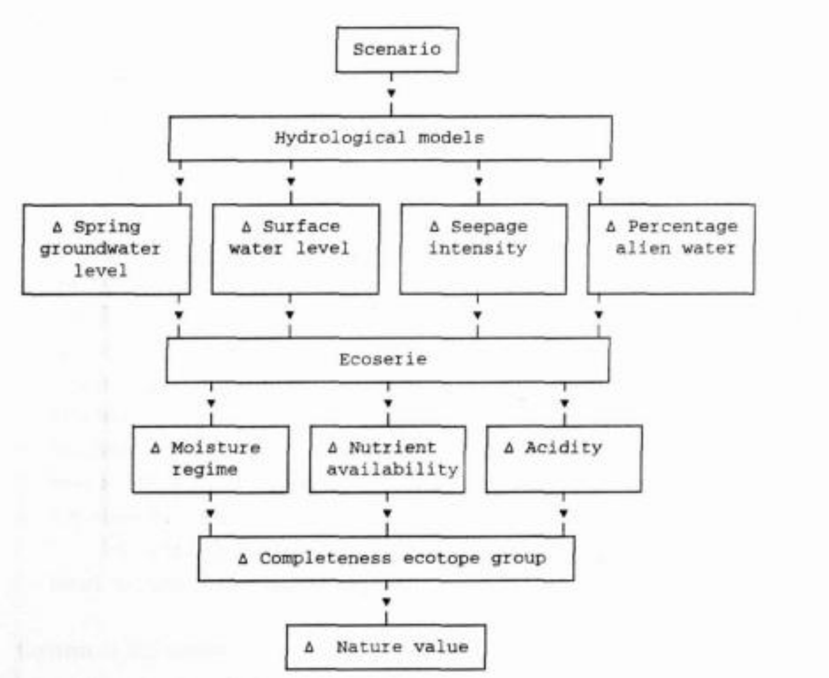


Figure 2.3.45 Process diagram for a DEMNAT-2 prediction. Changes indicated with 'Δ'. (From: Witte et al., 2008).

DURAVEG

DURAVEG is a practical ecohydrological effect program based on changes in groundwater level regime. The model is developed and tuned to a spatially distributed groundwater model. It contains a database (reference matrix) with (time series of) ecohydrological boundary conditions for many vegetation types occurring in the Netherlands. Time series of groundwater conditions in an average wet year and an average dry year of a location or area, are compared with the reference matrix to determine the specific habitat. During this procedure the soil composition is taken into account. For a full prediction of vegetation species, the following additional parameters can be incorporated:

- Seepage, infiltration, inundation
- Rain water lenses
- Contribution of deep groundwater to seepage
- Nutrient content
- Land use
- Influence of salt or brackish water

DURAVEG determines the most likely vegetation type for the calculated groundwater regime. The results are visualized as maps of target vegetation types (Source: factsheets Royal Haskoning, the Netherlands).

INFORM

The model INFORM (Hens et al., 2011) can be used for evaluation of the ecology of river valleys, inundation areas and riparian zones. Besides vegetation, the effects of water management on macro fauna are provided. The model is based on system blocks (see Figure 2.3.46) and structured according to the following impact pathway:

discharge → inundation water → groundwater → soil → biotics

Along this impact pathway, the direct effects of inundations on the ecology as well as the effects of morphology on river water level are incorporated. The indicator values by Ellenberg et al. (1991) are used to predict the occurrence of vegetation. The INFORM model gives a rating of the expected ecological changes after water management interventions, taking into account the rules and regulations.

The system block groundwater combines all system components that are required for the determination of the groundwater surface and their processing to groundwater-surface distances. Stationary groundwater levels can be calculated based on hydrological maps, river water level and information on aquifer thickness, permeability and groundwater recharge using analytical formulae. Short-term groundwater level fluctuations cannot be simulated with this GRUNVER component. Another option is to import the results of a (spatially distributed, non-stationary) groundwater model into the groundwater block of the INFORM model GRUNMOD (Gieble et al., 2011). Although groundwater is not fully coupled, the output of a spatially distributed groundwater model (e.g. MODFLOW) can be validated in the output of the INFORM model. Finally, based on the groundwater surface calculated by GRUNDVER or GRUNDMOD, the groundwater-surface distance for the affected study area is made on the basis of a digital elevation model (DEM).

VSD+-SUMO-NTM

In the coupled model VSD+-SUMO-NTM, soil processes (VSD+, previously: SMART), vegetation processes and succession (SUMO) and are coupled to a prediction of the ‘potential floristic diversity’ based on habitat characteristics (NTM). For the simulation of soil processes and biomass development of natural vegetation, the model chain VSD+-SUMO-NTM has been developed. VSD+-SUMO is a dynamic process model that describes annual changes in soil processes and vegetation growth. VSD+ is the soil module and SUMO the vegetation module, which are fully coupled. NTM is a static module that calculates the potential nature value for both groundwater dependent and groundwater independent vegetation types.

VSD+ uses the water balance of hydrological models (precipitation, evapotranspiration, seepage groundwater flux in root zone) as well as soil moisture and temperature for the calculation of reduction factors for soil mineralisation and de-nitrification (Bonten et al., 2010). VSD+ imports the nutrient and litter uptake from SUMO. VSD+ exports the nutrient availability to SUMO and calculates the pH and nitrogen levels. These are converted to Ellenberg indicator values and used as import in NTM.

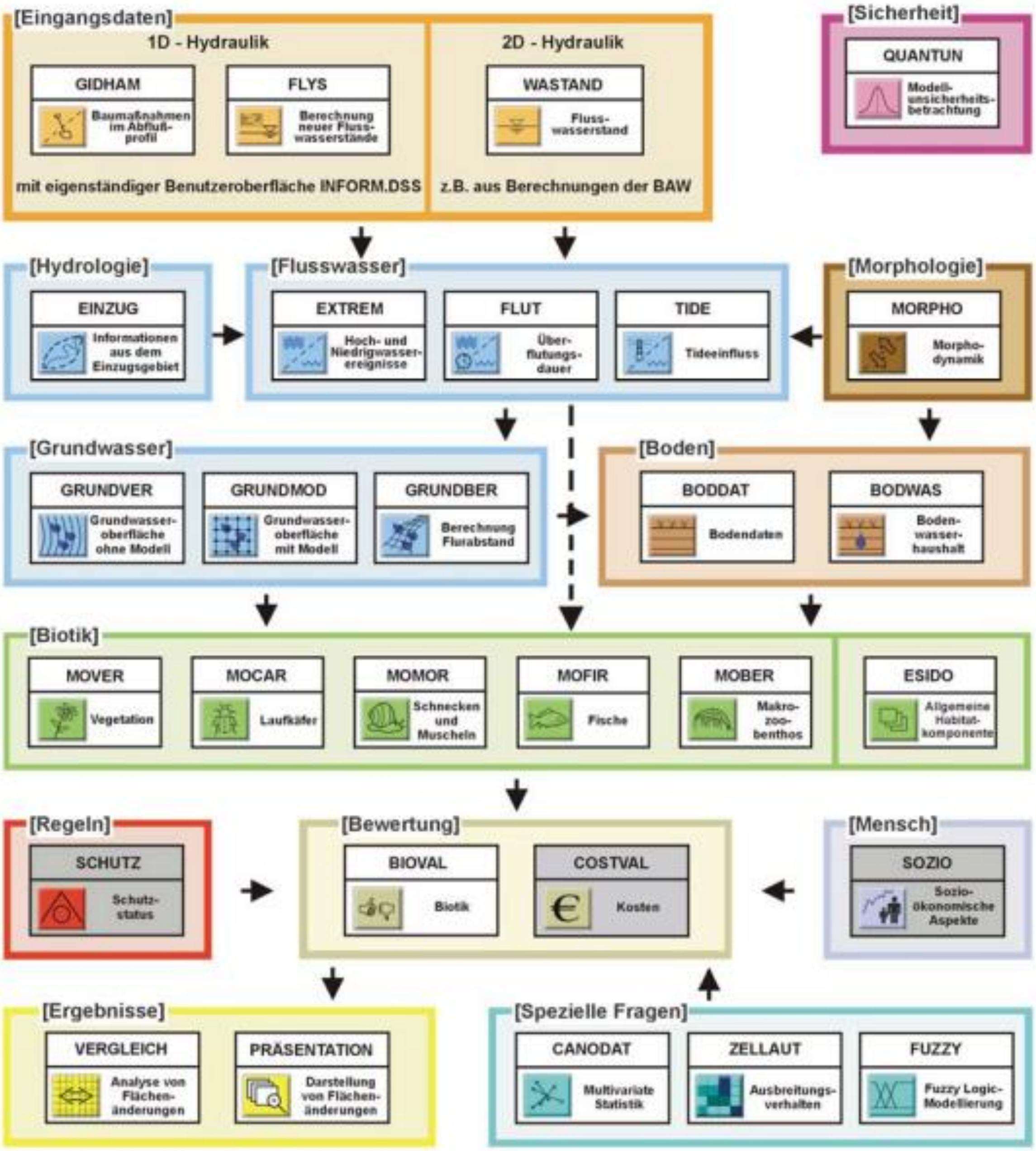


Figure 2.3.46 System blocks and components of the INFORM model.

SUMO2, like VSD+, (Berendse, 1994; Wamelink et al., 2005, Wamelink, 2007) is a process-oriented model that simulates vegetation succession and biomass production for time steps of one year. The biomass development is simulated for five functional vegetation types (FT), herbs and grasses (1), dwarf shrubs (2), shrubs (3), and two tree species (4 and 5). The five FT compete with each other for nitrogen (including nitrogen deposition), light, and moisture. Competition for nitrogen is based on the relative biomass present in the roots of the FT. Competition for light is simulated as a result of the height and the leaf biomass of the FT. Actual biomass growth of each FT is the result of a reduction of the maximum growth by moisture, nitrogen and light availability. The biomass can also be reduced as a result of management. SUMO2 requires information on soil type and groundwater level, the initial vegetation type and the management.

NTM3 (Wamelink et al., 2003) is a regression model based on the criteria of the red list, i.e. the rarity, the temporal trend and the size of the distribution area of each species. It is a regression model that predicts the potential floristic diversity at given values of the soil characteristics nitrogen availability, soil pH and moisture availability. The nitrogen availability and soil pH are simulated by VSD+, the moisture availability as spring groundwater level is derived from a hydrological map. A nature conservation value (NCV) has been assigned to the vascular plant species occurring in The Netherlands, based on the red list criteria, rarity, temporal trend and size of the distribution.

The model chain VSD+-SUMO-NTM requires gridded groundwater table information as input. This information can be derived from measurements or spatially distributed models. For example, in a national scale application of SMART-SUMO-NTM by Wamelink et al. (2009), gridded information with 250x250 m grid cells of groundwater levels were used for this purpose.

SWIM model coupled to simplified groundwater model

SWIM (Soil and Water Integrated Model) is a proces-based continuous-time semi-distributed ecohydrological model, interating hydrological processes, vegetation, nutrients (nitrogen and phosphorus) and sediment transport at the river basin scale. Its spatial disaggregation scheme has three levels: basin, sub-basins and hydrotopes within sub-basins (Krysanova et al., 1998). SWIM is based on the basin scale eco-hydrological model SWAT (Soil and Water Assessment Tool, Srinivasan and Arnold, 1994) and the nitrogen transport model MATSALU (Krysanova et al., 1998). Arnold et al. (1993) first coupled a simplified groundwater module (Smedema and Rycroft, 1983) with SWAT to predict monthly surface and base flow. This simplified groundwater model was also integrated in SWIM by Hatterman et al. (2005) and was developed further in order to have a better representation of groundwater dynamics and allow for automatic calibration. The application of a fully distributed physics based three-dimensional hydrological model was impossible because of limits in data availability and computation resources. Daily groundwater dynamics (water levels and discharge) are modeled on a meso-scale and can be parameterized using physically meaningful data (Smedema and Rycoft, 1983). Figure 2.3.47 gives a flow chart of the SWIM model, integrating hydrological processes, nitrogen, phosphorus and crop/vegetation growth.

The module representing crops and natural vegetation is an important interface between hydrology and nutrients. A simplified EPIC approach (Williams et al., 1984) is included in SWIM for simulating arable crops and aggregated vegetation types using specific parameter values for each crop type. Vegetation in the model affects the hydrological cycle by the cover-specific retention coefficient, impacting surface runoff and indirectly influencing the amount of transpiration, which is simulated as a function of potential evapotranspiration and leaf area index (Krysanova et al., 2005).

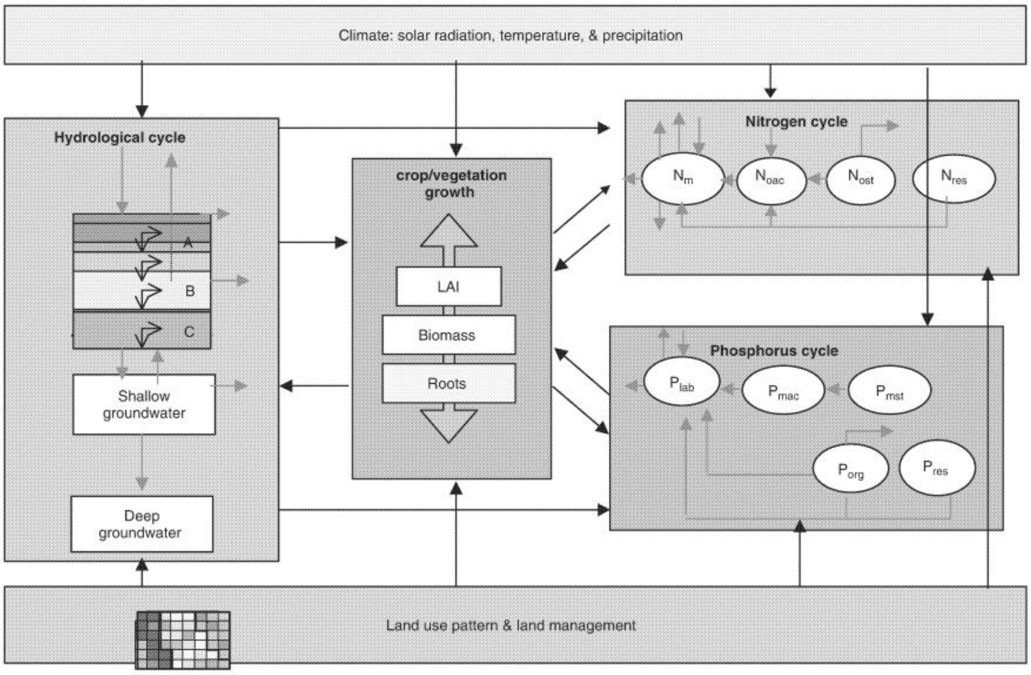


Figure 2.3.47. Flow chart of SWIM, integrating hydrological processes, nitrogen, phosphorus, crop/vegetation growth at river basin scale (From Krysanova et al., 1998).

WAFLO, MOVE and NICHE

Some older ecohydrological models developed in the Netherlands that combine groundwater and vegetation are WAFLO, MOVE and NICHE. The Water-FLOra model (WAFLO; Gremmen et al., 1990) was the first Dutch ecohydrological model. It evaluates the increase in groundwater extraction in the Pleistocene parts of the Netherlands. It comprises both a response module and an evaluation module and it contains 'if-then' expert rules applied to the indicator values of Ellenberg (1979). The Model for the Vegetation (MOVE; Latour and Reiling, 1993) uses the method of Ter Braak and Gremmen (1987) for its response model. This method combines the statistical approach of ICHORS (correlative approach) with the indicator values of Ellenberg (1991). Lastly, the "Nature Impact assessment of Changes in Hydro Ecological systems" model (NICHE; Meuleman at al., 1996) uses more detailed geographical information and makes predictions for phyto-sociological vegetation types instead of ecosystem types.

2.3.7.4 Future modelling challenges

From this review it becomes clear that in the Netherlands, a country with a large area of groundwater dependent vegetation, ecohydrological modelling including groundwater - vegetation coupling is undertaken relatively often and with different model types. As a result, the status of groundwater - vegetation coupling in ecohydrological modelling is more advanced in the Netherlands. In Germany and the United States, models exist that also integrate groundwater and vegetation (respectively, INFORM, SWIM and RIP-ET), whereas in other countries the relation is not (yet) coupled in models, and the general practice is to run groundwater models, after which the ecological implications of changes in water level model results are assessed separately with eco-hydrological models.

Wider application of coupled groundwater – vegetation models

A next step would therefore be to investigate the possibility and need to apply the method of coupled groundwater - vegetation modelling in other countries and regions. Ideally, this would be done with open source tools for model coupling in which model components for groundwater, unsaturated zone and vegetation are connected. With such an open source tool, existing models for groundwater, unsaturated zone and vegetation could be used.

For the purpose of coupled groundwater – vegetation modelling it is important that floral data bases of present and desired vegetation types are generated, including the plant traits related to groundwater. For the Netherlands and Germany such information is available and generic relations have been deducted that are used in the coupled groundwater – vegetation models. It is likely that a lot of floral information is also available for other countries.

Suitable model types

In section 2.3.7.3 the different types of coupled models are described (correlative, mechanistic and semi-mechanistic). Overall, it can be concluded that semi-mechanistic models are most suitable for medium to large scale ecohydrological studies that focus on the occurrence and development of vegetation types under specific (changing) environmental conditions. Both correlative models and fully mechanistic models are more suited to local studies. Correlative models are fully based on the relations between plants and environmental factors from local research and the validity of scaling up such relations is often very uncertain. However, the information collected for such correlative models can be used to generate floral data bases of larger regions. Fully mechanistic models contain many model parameters and require very detailed information on characteristics of the plant and its' environment. These models are usually used to study the functioning of a specific vegetation type or ecosystem or to study a specific aspect. However, the information that is collected for such purposes can be used also to generate floral data bases of larger regions.

Improve model principles for effect of wetting

Concerning the basic principles of groundwater – vegetation modelling, additional research on oxygen stress resulting from wetter conditions is required. Especially in the wet conditions near rivers (e.g. riparian zones, flood plains), an increase of groundwater levels is a conceivable scenario after changes in land use or hydromorphology. Simple relations between oxygen stress and plant functioning (Feddes, 1978) that are currently used in models are likely to reduce the quality of model predictions of the effects of wetting on vegetation. Bartholomeus et al. (2008) argued that for this purpose both plant physiological and soil physical processes should be considered simultaneously.

In Annex A, Table 11a summarises the suitability of the discussed models with groundwater – vegetation interaction for the analysis of hydromorphological pressures or the design of restoration measures. The details of the models are given in Annex A, Table 11a (for semi-mechanistic models) and Annex A, Table 11b (for mechanistic models).

2.3.8 Synthesis

A broad range of modelling topics that include vegetation and hydromorphodynamics have been discussed in this section (2.3) and Annex A, Tables 1 to 11 provide summaries in the form of fact sheets relating to all topics including the modelled processes, input and output variables, spatial scale of application and whether the models can be used for the analysis of hydromorphological pressures and/or help in the design of restoration measures.

Many research and modelling challenges have been identified, containing several overarching points. For models to be of use for water managers and to assist in the reach scale analysis of rivers, it is important that the location of vegetation development can be predicted and its interaction with hydromorphodynamics is realistically included. Until now these 2D reach-scale hydromorphological models lack the appropriate vegetation dynamics and properties. Therefore it is necessary to investigate and include the reaction of (dominant) vegetation types to hydromorphological variables (in terms of dispersal, colonisation, growth and mortality) and use this information to refine vegetation processes, many of which are incorporated in the conceptual model proposed in section 2.2. This can be partly achieved by integration of knowledge from other areas of expertise. In groundwater models for instance a lot of information on biochemical processes in plants is included, which can be used to predict sensitivity of species groups to dry or wet conditions. Furthermore, integrating more complex vegetation shapes as opposed to rigid (or flexible) cylinders can greatly improve flow resistance predictions.

Several modelling areas are still in their infancy (e.g. the effects of bank accretion due to vegetation and the hydrological effects of vegetation on bank stability), while other areas are very advanced (groundwater models with vegetation dynamics and 2D or 3D hydromorphological models). Such advances in modelling are crucial to complement field observations, laboratory experiments and developing integrating concepts to provide more scientifically-informed, sustainable solutions for river management and rehabilitation.

3. Natural Vegetation and the Hydromorphology of European Rivers

3.1 Europe's River Vegetation

3.1.1 Introduction

This account of European river vegetation began as a systematic review of the main approaches to river habitat classification employed in Europe, cataloguing all those types described within the EUNIS/CORINE and Natura 2000 systems as occurring in undisturbed (natural or semi-natural) rivers and their riparian zones (Davies et al 2000; European Communities, 1991, 1992, European Commision 2007). The full review is comprehensive, covering all relevant EUNIS/CORINE and Natura 2000 systems and is included as Annex B to this report. What follows here is a brief overview highlighting the main vegetation types by bioregion. The vegetation types chosen for review are considered to be of direct relevance to hydromorphological processes and, therefore, they also equate to a functional typing of riparian and aquatic vegetation.

Because this report emanates from REFORM's Work Package 2, which emphasises 'natural' rivers, the habitat types included in this account frequently have some nature conservation designation and in their intact state are no longer the most widespread aquatic and riparian types in much of the intensively developed parts of Europe. Much river vegetation in these highly populated areas can be linked to natural types documented in the EU27 Interpretation Manual (European Commission 2007), but as clearly degraded versions lacking sensitive species and/or dominated by species tolerating eutrophic and disturbed situations. For example, the central aquatic type in Natura 2000 (**3260** Water courses of plain to montane levels with the *Ranunculion fluitantis* and *Callitricho-Batrachion* vegetation) may be found in residual forms dominated by *Potamogeton pectinatus* and *Zannichellia*, or with prominent invasive alien species (*Elodea* spp. *etc.*), (Dawson et al., 1999) Similarly, the hydrophilous tall herb fringe communities found from the plains up to the montane level (type **6430**) and above is replaced by tall-herb vegetation of *Urtica, Rumex* and invasive *Impatiens glandulifera*. Within intensively developed Europe, natural riparian woodlands (type **91E0** Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior*) is represented by patchy relic clumps of *Salix* and *Populus*, often planted, and in some areas accompanied by invasive *Acer negundo* etc. Such degraded river systems are the focus of REFORM's Work Package 3. The degraded states for aquatic and riparian vegetation, outlined above, might well have profoundly different roles in hydro-morphological processes than the natural habitats targeted by Natura 2000.

This theme within the REFORM programme examines vegetation types and habitats designated under European legislation on the assumption they represent the *de facto* natural condition, in effect that such 'natural' vegetation types were once widely spread in the Continent. Natural condition can be interpreted as reference condition (*sensu* Water Framework Directive). There has been detailed discussion regarding how to set reference conditions for European rivers which is beyond the scope of this study, but which in general uses a mixture of evidence to set targets which reflect pre-industrial conditions (Hering et al 2010, Muxika 2007). Under the Water Framework Directive emphasis is placed on instream vegetation (macrophytes) as a Biological Quality Element while riparian vegetation *per se* is not a BQE, despite its intimate relationship with riverine processes. This reflects the established position, at the time the legislation was written, of considering primarily instream degradation, particularly water quality as the major impact to freshwaters. New evidence from the EU member states suggests hydromorphological degradation is likely to be as important as water quality degradation (European Environment Agency, 2013). To reflect this change in perception we have taken an inclusive approach to riverine vegetation which covers both instream and riparian vegetation. It should be noted that while physical modifications to rivers accelerated during the industrial revolution, there is a long history of physical river adaptation across Europe with signficant changes observed during the agricultural revolutions of the 1700s and earlier, which lead to extensive drainage.

What follows is not an in-depth analysis of what the reference condition should be in terms of riverine vegetation, which has already been established for instream vegetation anyway, it is a review of what natural riverine vegetation in Europe is considered to be for conservation purposes. In this regard it provides a starting point for the discussion of reference condition for riparian vegetation and its role in hydromorphological processess.

The description of vegetation structure is arranged by the biogeographic regions used by the European Environment Agency in Natura 2000 (Habitats and Birds Directives) and depicted in Figure 3.1.1. This account eschews the phytosociological nomenclature but does retain the habitat names used in the key sources (Table 3.1.1). The original catalogue was comprehensive, including all described habitats that might occur within rivers or their riparian zones. The present account focuses on those habitat types that are especially relevant to REFORM, but including not only those types that are widespread over several biogeographic regions, but also those that are confined to a single region. Most attention is given to the more extensive biogeographic regions (Boreal, Atlantic, Continental, Alpine and Mediterranean) which are described systematically, though reference is made to the much more restricted Arctic, Black Sea, Pannonian and Steppic regions. The river and riparian habitats of the Pannonian region are similar to those of the Continental region, whereas the Black Sea region shows some similarities to the Mediterranean region in its range of habitats. The Anatolian and Macaronesian regions are omitted from this account.

Table 3.1.1 Some key source-works on the classification of European river vegetation

Council Directive (1992) 92/43/EEC on the conservation of natural habitats and of wild fauna and flora, O.J. L206,22.07.92

Davies, C.E. and Moss, D. (2000). *EUNIS Habitat Classification*. Final ITE Report on behalf of the European Environment Agency.

Devillers, P. and Devillers-Terschuren, J. (1996). *A classification of Palaearctic habitats*. Council of Europe, Strasbourg: Nature and environment, No 78.

European Commission (2007). *Interpretation Manual of European Union Habitats - EUR27.* DG Environment - Nature and Biodiversity

European Communities (1991). *Habitats of the European Community. CORINE biotopes manual, Volume 2.* Luxembourg: Commission of the European Communities.

European Communities (1992). *Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora.* Official Journal of the European Communities, L206.

European Environment Agency 2013, European waters — current status and future challenges Synthesis , Copenhagen Denmark.

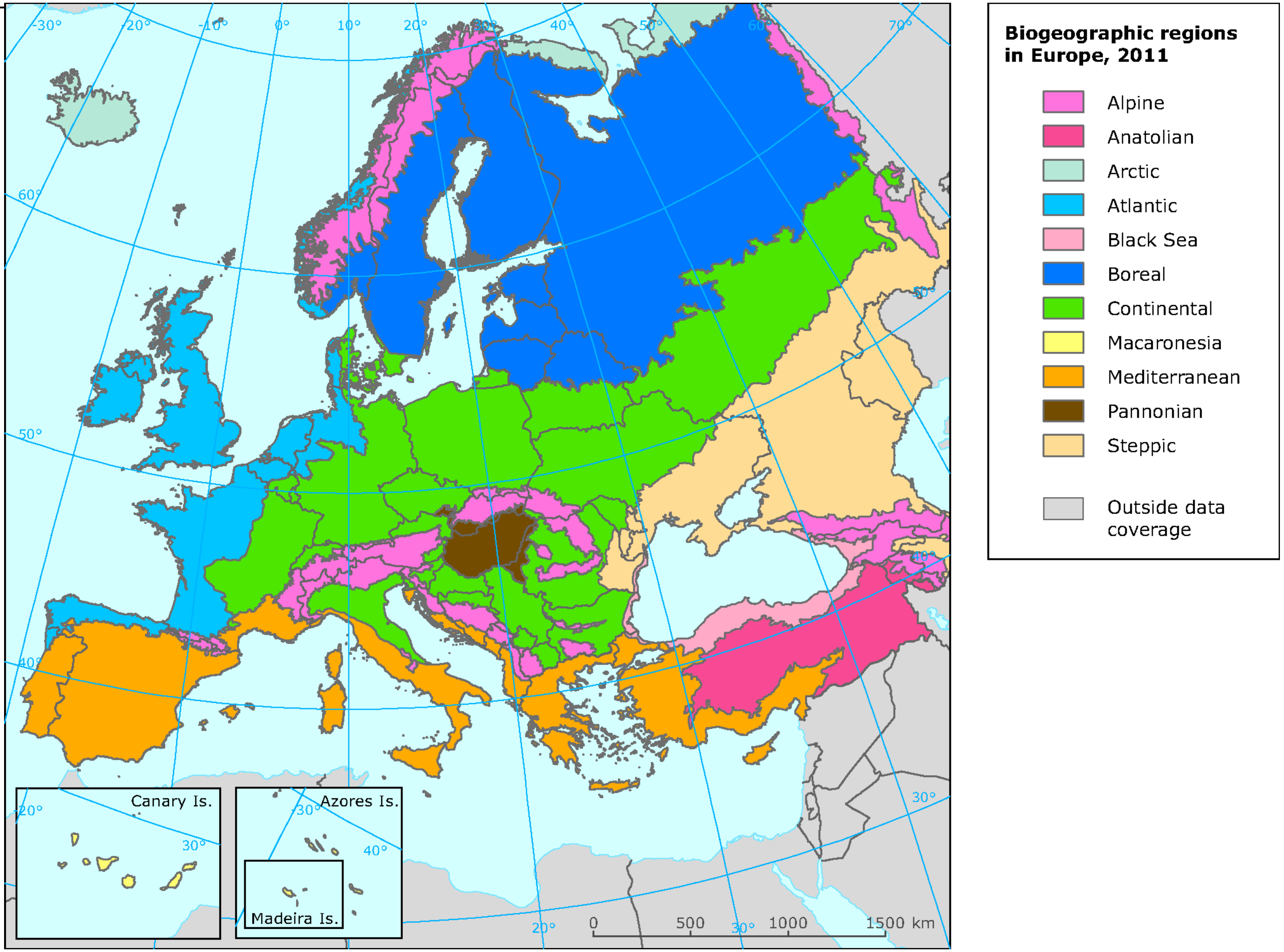


Figure 3.1.1 Broad scale biogeographic regions of Europe (source: EEA).

3.1.2 Boreal Biogeographical Region

The largest biogeographical region of Europe, with a cool and mainly continental climate, the Boreal, is Europe's forest region par excellence, overwhelmingly coniferous though with deciduous trees becoming prominent in more species-rich forests further south. The rivers of the Boreal (e.g. Figure 3.1.2) are prone to heavy floods in spring and early summer, following the melting of the winter snow; in winter the rivers have low-flow or are frozen. Most rivers are quite fast-flowing and short, with small catchments.

Figure 3.1.2 Boreal river bank © University of Umeå website.

Aquatic vegetation

The aquatic vegetation of non-alpine rivers in the Boreal zone comprises specifically northern habitats (Natura 2000 type **3210** Fennoscandian natural rivers) but gives way southward to a type that is widespread over much of Europe (**3260** Water courses of plain to montane levels with the *Ranunculion fluitantis* and *Callitricho-Batrachion* vegetation). The Fennoscandian rivers are natural or near-natural with nutrient-poor water, much dynamic variation and water levels varying by up to 6 m during the year (being highest in the spring). The conditions within the Scandinavian and Russian taiga eco-regions are unique to this part of Europe. The rivers have very little truly aquatic plants, although mosses are locally important, with beds of the sedge *Carex aquatilis* and the bur-reed *Sparganium glomeratum* in bays and backwaters. While bryophytes are known to have little influence on either sediment stability or bed roughness both *Carex* spp. and *Sparganium* species can locally stabilise sediments and impede flow (Suren et al., 2000). The more southern type (**3260**) has altogether more diverse and luxuriant aquatic vegetation often dominated by water-crowfoots (*Ranunculus*), pondweeds (*Potamogeton*), water-starworts (*Callitriche*) or aquatic mosses. There is considerable variation in vegetation composition depending on the pH and nutrient levels in the water.

Herbaceous riparian vegetation

This may also be divided into a specifically Boreal habitat (Natura 2000 type **6450** Northern boreal alluvial meadows) and the widespread type **6430** (Hydrophilous tall herb fringe communities of plains and of the montane to alpine levels) which occurs in the southern Boreal (as well as adjacent biogeographic regions). Clearly northern boreal alluvial meadows extend beyond the strictly riparian, but do include vegetation fringing large rivers with quiet sections that are frozen every winter and flood the riparian zone and beyond in the spring. In the emergent zone the dominant is usually horsetail (*Equisetum fluviatile*), giving way to sedges (*Carex acuta* or *C. aquatilis*) in the regularly-flooded riverside meadows. Hydrophilous, tall herb, fringe communities are variable in composition, often with species typical of nitrophilous situations, and may occur as a marginal zone between the river and either woodland or grassland/wetland. Typical species include wetland tall-herbs such as *Aegopodium, Epilobium hirsutum, Filipendula ulmaria, Senecio fluviatilis* and *Urtica dioica*, and the growth is often shrouded in climbers such as *Calystegia sepium*. This fringing vegetation can be viewed as having an important role in fluvial geomorphological processes where it acts to stabilise the river bank and the adjacent floodplain. Although herbaceous, many of the species are perennial and provide significant stability in the critical transitional zone between river and bank. During flood events these species tend to be relatively disturbance tolerant with above ground biomass flattening and drag reduction as a result. The transition from the lowlands to the montane zone may be indicated by the importance of *Adenostyles*. Conversely, tidal or saline water in the coastal zone may have *Althaea officinalis* as the typical tall-herb, although this variant is probably absent from the Boreal zone. In the far south of the Boreal zone, especially where the riparian zone is grazed and manured, shorter flood swards with low grasses, sedges, rushes and herbs can replace the tall-herb habitat (*e.g. Agrostis stolonifera, Alopecurus geniculatus, Carex hirta, Juncus inflexus, Potentilla anserina* and *Rumex crispus*).

Riparian woodlands

In the Boreal zone riparian woodlands are typically dominated by *Fraxinus excelsior* and *Alnus glutinosa* (Natura 2000 type **91E0**), although such formations become more extensive in the Atlantic and Continental regions, growing on heavy soils that are periodically inundated by the annual rise of the river. These woodlands have a herbaceous layer with many of the same species as present in the hydrophilous tall-herb fringes (type **6430**). Elsewhere in the Boreal zone, riparian willow formations become dominant on river banks with periodic flooding. Tree-willows may predominate in the south and shrubby species further north, notably *Salix daphnoides* in Fennoscandia. On river outwash gravel and at higher altitudes, *Myricaria germanica* may accompany the willows. These woodland species are considered to be crucially important to fluvial geomorphological processes.

3.1.3 Alpine Biogeographical Region

The Alps and, to a lesser extent, the other main European pmountain ranges are the source of some of the major European rivers, fed by springs and, more locally, glaciers. Extreme climatically with a short growing season, the rivers have often been dammed for the production of hydro-electric power. More natural watercourses are fast flowing with a rocky or stony bed and banks, with highest flows in the spring and early summer, following the snowmelt (Figure 3.1.3).

Figure 3.1.3 Typical subalpine stream in Făgăraș, Romania © Owen Mountford, CEH.

Figure 3.1.4 *Myricaria germanica* scrub (with *Chamerion dodonaei*) on shingle banks by a montane river below Piatra Craiului, Romania © Oliviu Pop

Aquatic vegetation

Truly aquatic vegetation is uncommon in alpine rivers, other than Bryophyta. However, the shores and riparian zone of rivers in the mountains have several distinctive assemblages of woody and/or herbaceous plants. Locally in the larger rivers of the Alpine zone, variants of the widespread type **3260** occur as submerged cover, especially where the water is oligotrophic and often acid. Typical species include *Myriophyllum alterniflorum, Potamogeton polygonifolius, Callitriche hamulata* and *Littorella uniflora*.

Herbaceous riparian vegetation

The most distinctively alpine type of herbaceous riparian vegetation is characterised within the Natura 2000 type **3220** (Alpine rivers and the herbaceous vegetation along their banks). Such pioneer communities are open with a mix of herbaceous and slightly woody plants (often strictly alpine) and colonise the gravel beds of streams with an alpine, summer-high, flow regime. Classic dominant species include low willowherbs (*Chamerion fleischeri*) and the colonial grass *Calamagrostis pseudophragmites*. Where the vegetation is more nutrient-rich and lush, often adjacent to montane forests, variants of the type **6430** hydrophilous tall-herb fringes are found, especially those with low birch (*Betula*) bushes and the tall-herb *Adenostyles*.

Riparian woodlands

In the alpine region, riparian woodlands are typically variants of the widespread **91E0** *Alnus- Fraxinus* habitat, but typically dominated by the Grey Alder (*Alnus incana*) with an understory of tall colonial grasses, e.g. *Calamagrostis varia.* Two alpine habitats (Natura 2000 types **3230** and **3240**) are structurally intermediate between woodlands and riparian herbaceous vegetation, comprising a mixture of low shrubs and tall, often strictly montane or alpine, herbs. The communities have low shrubby pioneers invading gravel deposits along alpine streams with a high summer flow and rich in fine silts. Particular variants may be dominated by *Myricaria germanica* (Figure 3.1.4) or by willows, notably *Salix elaeagnos* but also *S. purpurea* ssp. *gracilis*, *S. daphnoides* and *S. nigricans.* The spiny thicket-forming shrub *Hippophae rhamnoides* can also dominate these gravel bars and shores.

3.1.4 Atlantic Biogeographical Region

This region is characterised by a mild climate and high precipitation, resulting in good conditions for farming and, locally, a high human population. The region is quite varied topographically, resulting in rivers that may have rapid upland reaches with stony beds as well as more sedate slow-flowing lowland reaches. These rivers may bear large sediment loads, we well as nutrients and, locally, pollution from the more-intensively developed catchment. The variety of topography, geology and cultivation leads to a range of river clarities and trophic levels (Holmes et al 1998). Most Atlantic biogeographic region rivers are regulated to a greater or lesser extent. Rivers originating within the region are usually short, though longer rivers with their sources in the Continental (and Alpine) regions pass through this biogeographic region, discharging into the northeast Atlantic Ocean or North Sea. The river and riparian habitats of this biogeographic zone are almost all widespread in Europe, occurring also in the Continental biogeographic region and frequently in the (southern) Boreal, the Pannonian and less arid parts of the Mediterranean regions.

Aquatic vegetation

Variants of Natura 2000 type **3260** (Water courses of plain to montane levels with the *Ranunculion fluitantis* and *Callitricho-Batrachion* vegetation) are widespread in the Atlantic region. Such diverse submerged or floating vegetation grows in rivers with slow to moderately rapid flows and with the lowest levels during summer (in contrast to the Alpine region). The usual dominants are *Ranunculus* spp., *Potamogeton* spp., *Callitriche* spp. and/or aquatic mosses, but there are distinctive mixtures of plants found where the water is a) acid oligotrophic; b) lime-rich oligotrophic; c) mesotrophic; or d) eutrophic*.* The dominants are often colonal with feathery, linear or broad but thin leaves. In calcareous systems in-stream vegetation can produce prodigious biomass and cover entire channels, impeding flow (Figure 3.1.5, O'Hare et al 2010a)

Figure 3.1.5 Channel dominated by *Ranunculus penicillatus* in the Atlantic Biogeographic region. River Rye, England UK

Herbaceous riparian vegetation

The Natura 2000 type **6230** (Hydrophilous, tall herb) is also very variable in this region, forming a fringe between the river and adjacent terrestrial habitats. Amongst the most typical species are *Calystegia sepium, Eupatorium cannabinum, Epilobium hirsutum, Urtica dioica, Filipendula ulmaria*, *Angelica sylvestris* and the reed-like grass *Phalaris* *arundinacea*. These form a tall floriferous mixture of graminoids and broad-leaved herbs. Especially distinctive variants are dominated by the huge round leaves of *Petasites hybridus*, and *Althaea officinalis* formations occur on of the banks of brackish rivers. As mentioned in the description of the Boreal region, regularly inundated, grazed and fertile shores are typified by shorter grasses (*Agrostis stolonifera, Alopecurus geniculatus*) and forbs reflecting nutrient-rich situations (*Rumex crispus* and *Ranunculus repens*). Where the banks of the river are muddy and nitrogen rich, the Natura 2000 type **3270** (rivers with muddy banks with *Chenopodion rubri* p.p. and *Bidention* p.p. vegetation) can occur, forming an annual pioneer nitrophilous vegetation of the lush broad-leaved herbs.

Riparian woodlands

The most important natural types of woodland along rivers are again the Natura 2000 type **91E0** (Alluvial forests of *Alnus glutinosa* and *Fraxinus excelsior*) and its related gallery forests of willows (*Salix* spp.). They are found by rivers in the lowlands and hills on periodically inundated clay soils rich in alluvial deposits over a herbaceous layer of substantial tall herbs such as *Filipendula ulmaria, Angelica sylvestris, Rumex sanguineus* and sedges (*Carex* spp.). Several sub-types are described, including some that are characteristic of parts of the Atlantic region. *Alnus-Fraxinus* woods of springs and the rivers arising from them, often with low tussocks of the sedge *Carex remota* in the ground layer, whilst other types of *Alnus-Fraxinus* with different understory cover are typical of fast-flowing rivers. A particular variant of the willow galleries where *Salix triandra* and *S. viminalis* are prominent is found principally in the Atlantic and Continental regions.

3.1.5 Continental Biogeographical Region

Most of the larger rivers in Europe cross this region, including some that are highly regulated with drained floodplains. The situation broadly resembles that of the Atlantic region, although the climate pattern is distinctly different with lower rainfall and more seasonal extremes. River flows are moderate but often with huge volumes of water due to size of the catchment areas. EEA data for 1995 for river flow estimate that one-fifth of the total average annual run-off for Europe is carried to the sea by rivers originating in this region. The river and riparian habitats of the Continental region share many features with those of the Atlantic region, and attention is paid here principally to any differences in character between the two regions.

Aquatic vegetation

Habitats and communities are essentially the same as those described for the Atlantic region.

Herbaceous riparian vegetation

These fringing communities are also largely identical with those found further west in Europe.

Riparian woodlands

The region contains most of the remaining European floodplain forests (Figure 3.1.6). The *Alnus-Fraxinus* woodlands (e.g. Figure 3.1.7) and riparian *Salix* fringes are closely related to those from the Atlantic and southern Boreal regions, although variants, where these trees are accompanied by elm (*Ulmus* spp.) and/or *Prunus padus,* become prominent in those parts of Europe that are distant from the ocean and the Mediterranean sea.

A forest type of great importance for biodiversity is confined to this biogeographic region, namely the Natura 2000 type **91F0** (riparian mixed forests of *Quercus robur*, *Ulmus laevis* and *U. minor*, *Fraxinus excelsior* or *F. angustifolia* along the great rivers).

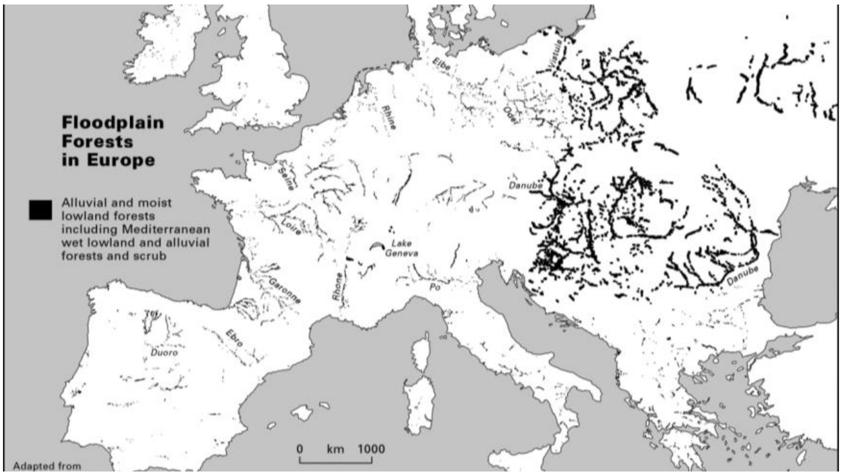


Figure 3.1.6 Map of remaining European floodplain forests (based on data from UNEP – World Conservation Monitoring Centre in UNEP–WCMC, 2000 and Girel *et al.*, 2003; in Hughes *et al* 2008, 2012)

Figure 3.1.7 Riparian *Alnus glutinosa* woodland with *Matteuccia struthiopteris* in the Continental biogeographic region, near Brașov, Romania © Oliviu Pop.

These forests occur on recent alluvial deposits within the floodplains of the Rhine, Danube, Emst, Elbe, Saale, Weser, Loire, Rhône-Saône systems and to some extent parts of northeast Italy (including the Po and its tributaries) and north Greece. These hardwood forests are liable to flooding by the river or, locally, following the raising of the water table. As the habitat name indicates, the forest has a diverse range of dominant trees, as well as a complex and rich ground flora.

Other riparian forests occur in the transition between the Continental and Mediterranean regions, including the *Salix alba* and *Populus alba* gallery woodland, which are quite widespread as fringing tree zones in parts of Central Europe (Natura 2000 type **92A0**). In addition, because the definition of the Continental region includes part of the Apennine mountains in Italy, some montane riparian shrub communities may be relevant.

3.1.6 Mediterranean Biogeographical Region

In many respects this region if the most biodiverse in Europe, and certainly has the greatest variety of natural river and woody riparian habitats that are confined to a single biogeographic region. There are relatively few large rivers originating in this region, although several with their origins elsewhere discharge into the Mediterranean biogeographical region. The longest wholly Mediterranean rivers are in the Iberian peninsula (e.g. Guadalquivir). Many Mediterranean and most Iberian rivers have low annual volume and irregular regimes, and several characteristic river habitats in this region have intermittent flows. The fluvial regime typically has an extended summer period of low water. Many watercourses have reduced flows due to water extraction for irrigation. For a detailed description of the composition and distribution of riparian stands trhoughout Spain, see Lara et al. (2004) and Garilleti et al. (2012).

Aquatic and sub-aquatic vegetation

Three distinctive Natura 2000 river types are found through much of the Mediterranean region, with variation depending on whether the rivers flow constantly or intermittently. Type **3250** comprises constantly flowing rivers (but with a low summer level) where gravel deposits are colonised by *Glaucium flavum etc.* The second habitat of constantly flowing rivers (type **3280**) occurs below hanging curtains of *Salix alba* and *Populus alba* (see riparian woodland type **92A0** below) where the wet alluvial banks of larger rivers are covered in a mixture of nitrophilous annual and perennial grasses and sedges, e.g. *Paspalum paspaloides*, *P. vaginatum*, *Polypogon viridis* and *Cyperus fuscus.* The final habitat (**3290**) has a similar vegetation of grasses and sedges to the latter but occurs by intermittently flowing rivers without the associated *Salix/Populus* curtain. The river flow is interrupted and the bed dry for at least part of the year (either completely or with some residual pools).

Herbaceous riparian vegetation

In contrast to the aquatic and woody riparian categories, there is limited evidence of any distinctive Mediterranean natural herbaceous riparian habitats, but rather variants on more widespread forms. The riparian zone of Mediterranean rivers does have numerous distinctive herbaceous species, however.

Riparian woodlands

In addition to the ubiquitous riparian willow formations, five Natura 2000 habitats are confined (or largely confined) to the Mediterranean region. The willow formations include particular assemblages of narrow-leaved Salix species in the hills and mountains around the Mediterranean (*Salix triandra, S. viminalis* and *S. purpurea* are prominent). The remaining five types often show marked local variation, and a very rich flora.

The most widespread habitat is the type **92A0** (*Salix alba* and *Populus alba* galleries) which dominate the riparian forests of the Mediterranean and Black Sea basins. Variants range also into the Continental and Black Sea biogeographic regions, as well as parts of the Pannonian and possibly Steppic regions. In addition to the nominate species, *Salix fragilis* is a common dominant whilst numerous other trees occur locally, leading to sub-types such as the Mediterranean Riparian *Populus* forests, Mediterranean Riparian *Ulmus* forests, Mediterranean riparian *Fraxinus* woods and Hop-Hornbeam (*Ostrya*) galleries.

The distinctive riparian formations on intermittent Mediterranean watercourses with *Rhododendron ponticum*, *Salix* and others (Natura 2000 type **92B0**) are much more limited in extent and occur as either relict galleries of alder (*Alnus cordata* and *A. glutinosa*) in deep, steep-sided valleys; mixtures of *Rhododendron, Frangula alnus* and a rich understory fern community; or riparian galleries of the endemic birch *Betula parvibracteata.* Different variants are found in Greece, Italy, Cévennes, Corsica, Iberia, and Greece.

Two highly restricted riparian forest types are placed with the Natura 2000 type **92C0** depending on whether they are dominated by *Platanus orientalis* (Greece, southern Balkans and Sicily) or *Liquidambar orientalis* (Rhodes and Anatolia only – hence outwith the defined scope of this account). The Oriental plane woods (*Platanus orientalis*) occur as gallery forests along rivers (including temporary ones) and in gorges. The forests colonise poorly stabilised alluvium by large rivers, gravel/boulder deposits of permanent/temporary torrents, spring basins and particularly in the bottom of steep, shady gorges. A wide variety of trees accompany *Platanus* (*Salix* spp., *Alnus glutinosa*, *Celtis*, *Cercis*, *Populus* spp., *Juglans regia*, *Fraxinus ornus* as well as the shrubs *Vitex agnus-castus*, *Nerium oleander* etc*.* The ground flora is very rich with many herbs, grasses, mosses, lichens and ferns (among which *Pteridium aquilinum* is often abundant).

The type **92D0** (Southern riparian galleries and thickets *Nerio-Tamaricetea* and *Securinegion tinctoriae*) is usually dominated by *Tamarix*, *Nerium* and *Vitex* along permanent or temporary streams and wetlands in both the warmer parts of the Mediterranean zone and in south-western Iberia. Related habitats are found by stream sides and in coastal localities of the Pontic and Steppic regions of western Eurasia, as well as in North Africa. In addition to the typical form of this habitat (widespread throughout the Mediterranean basin), particular variants are found in south and south-west Spain, dominated by *Securinega tinctoria, Prunus lusitanica* and *Viburnum tinus* or *Frangula, Myrica gale, Salix atrocinerea* and *S. salvifolia*.

The most restricted of all the riparian woodland types are the groves of *Phoenix* species (Natura 2000 type **9370**). Two palms species are involved, both endemic to small areas: *Phoenix theophrasti* is found on Crete (and in adjacent Anatolia) whereas *P. canariensis* is confined to the Macaronesian region. On Crete, the palm groves are restricted to damp sandy coastal valleys, forming a quite extensive forest at Vai (where palms are accompanied by a thick shrubby undergrowth of *Nerium oleander*) and in *ca* 4 other smaller coastal groves. Though included as a natural habitat the *Phoenix* groves are prone to disturbance from tourism and from fire.

3.1.7 Conclusions

Current status

This review focuses on the natural condition of river systems. Unlike instream vegetation riparian vegetation has not been subject to detailed survey and inventory during the installation of monitoring programmes for the Water Framework Directive. Therefore, there are no large datasets to describe in detail its current condition and the deterioration it has suffered. From GIS analysis of broad landuse classifications we are aware that there is significant human alteration of riparian zones and their vegetation across Europe (Clerici et al 2013). The distribution of sites designated under the EC Habitats and Species Directives give us some insight into the location of remnant areas of high quality riparian vegetation (Figure 3.1.8). It is noteworthy that the most common vegetation type designated under the Habitat and Species Directives is **91E0** (Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior*). A total of 5610 sites (21% of all designated sites) have this vegetation type abeit the representivity (quality) of the community is not always pristine. It is clear, however, from this review of the natural vegetation of European rivers, that this vegetation in its natural state has been heavily modified or significantly reduced in much of its range. The general pattern where montane and boreal systems appear less impacted than other biogeographic zones is consistent with evidence on the multiple pressures suffered by more lowland rivers, rivers in the south of Europe and rivers in areas of dense population (Schinegger et al. 2012).

Hydromorphological implications

From a hydromorphological perspective the reduction in riparian tree cover, especially the once widespread riparian floodplain forests, is especially noteworthy. In contrast to the current agricultural vegetation of floodplains, these forests would have presented large ‘roughness’ elements which would have impeded flood flows and created a very different interaction between floodplain and river than is evident today.

The alterations to herbaceous riparian flora are more subtle with a shift in assemblage structure toward species advantaged by nutrient-rich growing conditions. A detailed analysis of the traits of the plant species involved would reveal the changing interaction with hydromorphology. It is predicted that more competitive species (*sensu* Grime et al 1988) are expected to dominate (e.g. *Urtica dioica*) at high biomass. The associated reduction in species richness, it can be argued, could theoretically reduce system resilience to disturbance, including hydromorphological disturbance.

Figure 3.1.8 A map of sites designated across Europe with Habitat 91E0 (Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior*)

The degradation of instream vegetation is likely to have system-specific interactions which are dealt with in detail in REFORM's WP3 (see Deliverable 3.1 for an overview). They range from increases in instream biomass and associated change in channel roughness / blockage factors and sediment stabilisation.

Reference condition - historical perspective

Across most member states the approach to reference condition for rivers has to been to choose rivers which equate to a pre-industrial or pre-1800s condition. This approach has been informed through our knowledge of nutrient and toxic pollution which became dramatically more intense during the industrialisation period with consequent impacts on freshwater biota. Hydromorphological alterations to rivers also increased dramatically during this period with channelization for navigation and the building of reservoirs associated with the industrial revolution. However, it is important to note that agricultural improvements preceded these by up to a century. Large scale drainage programmes of wetland areas to bring them into agricultural production significantly altered the interactions between river and floodplain, while evidence suggests that changes in ploughing practices in the early middle ages resulted in changes in river style (Macklin et al., 2010).

Future considerations

In the context of l ong term change, the process of setting reference conditons for hydromorphologically-relevant riverine vegetation groups requires careful consideration. In sections 2.1 and 2.2, the important role of vegetation in river hydromorphological processes was highlighted as well as its relationship with river style. Emphasis was placed on the importance of processes. It is clear therefore that two kinds of targets could exist for reference conditon, a purely ecological one which focuses on restoring the flora of rivers and one which re-instates processes. Both are valid. In reality the two targets are so intimately interconected that it is reasonable to consider achieving both targets simultaneously.

In section 3.2, we explore the relationship between European vegetation and physical processes by using pant traits to explain their role, with the aim of highlighting the physical roles of natural riverine vegetation and allowing standards to be developed for restoration.

3.2 The hydromorphologically relevant traits of European river vegetation

3.2.1 Introduction

REFORM focuses on improving the science behind river restoration, with Work Package 2 aiming to create a fluvial geomorphological typology for European rivers (Deliverable 2.1) and to relate that to the natural functioning of vegetation within river systems as both a respondent to and an influence on hydrology and fluvial geomorphology (Deliverable 2.2). The work description requires a functional typing of riparian and aquatic vegetation.

3.2.1.1 The concept

A database has been produced for European riverine vegetation which lists traits that are relevant to a plants’ function in relation to fluvial geomorphological and hydrological processes. The database forms the core of the functional typology that is developed in this section (3.2). Previously functional typologies have been limited to ecological function, here the typology focuses on the interaction between plants and physical processes.

The means by which vegetation may influence fluvial geomorphology were previously identified in broad terms in chapter 2 of this report. The typology groups plants into those that are likely to have a functionally important role (ecosystems engineers) and those of less significance.

The plants can be grouped by biogeographic regions, which differ in their riverine plant assemblages (Section 3.1), and by their likely vertical zonation relative to the river, which determines how frequently they are inundated and therefore the frequency and type of interaction they have with physical processes.

The typology uses a suite of traits to type the vegetation and uses those traits that directly influence physical processes, such as a plant’s ability to stabilise sediment, but it also includes other traits which are relevant to biotic processes such as nutrient preferences. As vegetation links physical and biotic processes so too does it introduce biological complexity (Figure 3.2.1). As biotic processes in rivers are highly modified by humans, this approach has the potential to help us understand how multistressors influence natural physical - vegetation interactions. This is the approach being taken in REFORM's Work Package 3, Deliverable 3.2.

Such an approach has not been taken before, so detailed information is provided on its construction, limitations and scope for future development.

3.2.1.2 Background

Vegetation influences the boundary conditions of rivers where the water interfaces with sediment and rock. Here plants can slow water and trap sediment with their canopy, and stabilise sediment with their roots. These influences are mediated by the characteristics or traits of the vegetation. Here we review and investigate the traits of the natural riverine vegetation of Europe, considering their role in physical and ecological processes.

In the last two decades there has been an increasing awareness of the role of vegetation in physical processes and this has been reflected in a surge of scientific papers which demonstrate the role of vegetation in instream and riparian physical processes. Recent work in the REFORM project builds on emerging conceptual models (e.g. Gurnell 2012, Gurnell 2014).

These models emphasise the importance of ecosystem engineering by vegetation, where the succession of vegetation following a disturbance has a direct impact on the hydromorphology. They identify a link between where the plant grows, its growth form (emergent, submerged, riparian, etc.), and its intensity of interaction with fluvial geomorphological processes.

These models also highlight the importance of species traits, in particular their ability to colonise disturbed habitats through competitive establishment strategies which can include fast growth rates, asexual reproduction from fragments, tolerance to burial, and strong root systems.

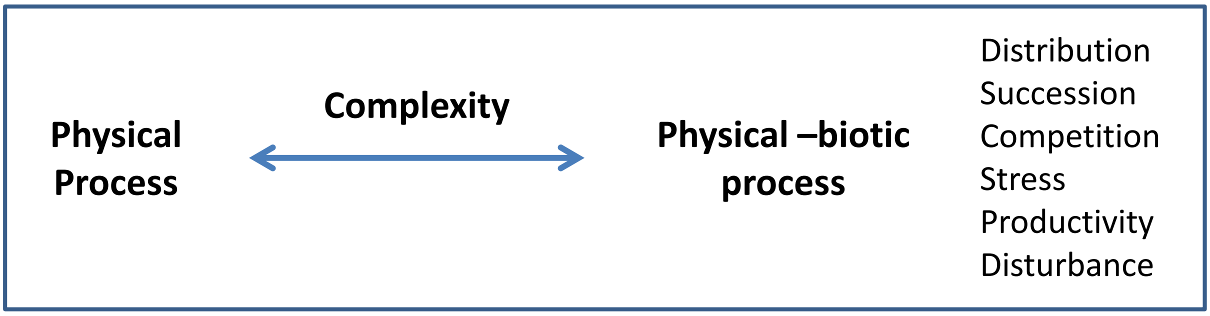


Figure 3.2.1 The role of vegetation in physical processes in rivers introduces complexity, which requires consideration of the feedback of biotic processes on physical processes.

3.2.1.3 Why a trait based approach?

To date, there has not been a comprehensive review of the traits presented by riverine species in the context of their hydromorphological role, although see Willby et al. (2000) for a detailed examination of the ecological traits of European macrophytes. In REFORM we have used an inclusive concept of 'riverine vegetation' which moves away from the restrictive aquatic macrophyte concept to include riparian vegetation and species of southern Europe that are associated with rivers in arid regions. As this has not been previously used as an approach there is a significant gap in the literature.

Traits can be grouped into broad categories: those that directly influence fluvial geomorphology, such as a plant's ability to stabilise sediment; and those traits that influence a plant's likelihood of influencing fluvial geomorphology, such as their tolerances for soil moisture/water level and their general habitat preferences.

Traits should if possible also include information on plant strategy where it is relevant, for example, if a species is likely to make an effective colonist of disturbed riverine habitat. Fluvial geomorphologists see rivers as dynamic and view vegetation in a similar fashion, so if it is possible to indicate whether a species is indicative of a climax flora or a transition flora it would be useful. Some passing consideration should be given to traits which are not species specific but could be relevant, such as age in the case of trees.

Riparian vegetation has recently been grouped into a series of guilds which are considered to function as 'super-species' in response to flow (Merritt et al., 2010). They include life-history, reproductive strategy, morphology, fluvial disturbance and water balance guilds which share complimentary traits. Many of Merritt and co-workers guild characteristics not only distinguish the response of plants to fluvial processes but, given the intimacy of the interaction, they will also encapsulate guilds of vegetation which engineer physical processes, although this was not the original aim of their study. The guilds of Merritt et al. (2010) are conceptual and condense existing knowledge on riparian vegetation rather than providing an actual classification of vegetation.

There are detailed studies relating vegetation roughness to the biomechanics of plants (e.g. Petryk and Bosmajian, 1975; Naden et al.; 2006) as well as water velocity and depth (e.g. Garton and Green, 1983). These methods are not widely used in industry practice, possibly because detailed plant information is required and also because dynamically linking the roughness to the velocity and depth calculation is challenging. Where these methods are adopted, they tend to be by-hand calculations for each flow depth.

A channel's resistance to water flow is varied by plants growing within its margins (Pitlo and Dawson 1990). The variations are rarely quantified making it challenging to estimate the conveyance of a channel with certainty. Traditionally most resistance advice in the literature (Cowan, 1956; Chow, 1959) is expressed in terms of Manning's n. These n-values take all aspects of resistance into account including turbulence due to boundary friction, lateral shear and secondary circulations. Some of these approaches provide advice for vegetated channels (e.g. Cowan, 1956; Garton and Green, 1983) including broad vegetation categories such as no vegetation, dense weeds etc (Gordon et al., 1992). These broad categories do not take account of differences in interactions with flow between species (Sand-Jensen, 2003; O'Hare et al., 2007). The categories are based on few data; only single roughness values or ranges are provided with no statistical error or uncertainty measure (standard error or standard deviation). There is the potential to improve and simplify these roughness values.

3.2.2 Methods

3.2.2.1 Species considered

In selecting species that are relevant to REFORM, no consideration was given to the availability of trait data for these species. It was considered best to assemble the list of species first so that any missing traits could be added once available. Species selection was based on the following criteria:

- Aquatic species that occur, at least occasionally, in flowing water
- Species which are emergent or river bank species either as their primary or as a frequent habitat cited in the standard floras.
- Species included as dominants or characteristic of the various riparian and aquatic habitats and UK National Vegetation Classification (NVC) types included in the Pan-European classification (section 3.1).
- Species identified as riparian species from the Habitats Directive (true aquatic/riparian only), from Ellenberg F moisture values, Ciocârlan or BIOFLOR.
- Species which, based on the experience of botanists with field experience in north west Europe, eastern Europe and Iberia, should be termed riparian.
- Plants of high altitude stream-sides
- Species that are very rare but which nonetheless are found on some river-bank sites

Based on the above criteria, a total of 459 species were included in the analyses.

3.2.2.2 Traits considered

Ideal traits

The traits available in the botanical literature were not defined with physical processes in mind. Despite this, many of them are relevant and applicable to such processes. The traits available to this project are reviewed in section 3.2.2.3. However, first, a list of ideal traits is presented and their purpose is discussed. Many of these traits can be measured and quantified in a manner suitable for modelling purposes, e.g. flexibility, drag etc. However such quantified traits are often not available in trait datasets but surrogates can be used; for example, plant height can be substituted for plant size. As there are caveats which must be enforced with this approach, it is important to distinguish between what is an ideal trait and what is available. Pre-existing trait databases were used with the UK-based PLANTATT as a starting point. The first step was to remove irrelevant species. Non-UK species were then added and additional traits taken from Ellenberg (1988), Ciocârlan, or BIOFLOR.

Form

Aquatic macrophytes have developed a range of adaptation strategies against mechanical stresses imposed by flowing water (Bornette and Puijalon 2011, Puijalon et al. 2011). A trade-off between avoidance and tolerance strategies, mitigated through high flexibility (i.e. low flexural rigidity) and high tensile strength (i.e. high breaking force), respectively, has been suggested for submerged macrophytes, and evidence has been provided that this depends on plant growth form (Puijalon et al. 2011). The importance of plant morphotypes for plant distribution and composition of riverine plant communities has been shown to be related to physical conditions, e.g. multi-scale channel morphology (Riis et al. 2000, Gurnell et al. 2010). Furthermore, specific plant communities and the morphologies of macrophyte patches and patch mosaic patterns influence spatial sedimentation processes (Clarke 2002, O'Hare et al. 2011, Pollen-Bankhead et al. 2011) and hence both submerged and emergent macrophytes can act as ecosystem engineers (*sensu* Jones et al., 1994). It can be hypothesised that river and lake macrophytes would ideally display different physical shapes to deal with the different types of flow conditions they experience. Specifically, drag forces exerted by water flow in rivers and streams may lead to the selection of tensile plants sensu Nikora (2010), which experience mainly viscous drag and are thus resistant against tension forces, being flexible in order to streamline and reconfigure to avoid/minimise pressure drag (O'Hare et al. 2007, Miler et al. 2012). Under slower flow velocities, bending plants *sensu* Nikora (2010) prevail, having a more upright shoot morphology and being mainly affected by pressure drag (Nikora 2010, Miler et al. 2012).

Perennation / Winter biomass

Whether or not a plant is perennial can be interpreted as a measure of the need for the plant to re-establish itself in a riverine situation each year and also, in combination with its woodiness, to impede flow throughout the year. Re-establishment is directly related to the plant's potential tolerance to disturbance and in many situations it can be considered a good strategy to overwinter as seed or propagule. In combination with this, plants which are perennial but subject to seasonal senesce, so little canopy is left to impede flow or protect sediment, can be viewed as a subset of perennial species.

Whether a plant provides a constant presence or is only present for parts of the year has a significant influence on its interactions with physical processes. If the plant is absent in winter it cannot block flow and it cannot stabilise sediment. Therefore, perrenation is important as riparian plants can be annual with no overwintering presence of any significance, or alternatively some riparian plants are perennial and are crucial for stabilising sediment (e.g. river banks).

For woody perennial plants, their ability to carry leaves during winter (evergreens) is likely to contribute to form drag. This relationship is poorly quantified for tree - water interactions, although data is available for some species interactions with fluid air flows. Many herbaceous species which are perennial, whether instream or riparian, senesce or die-back at the onset of winter. This is a natural processes and the dead material may wash out quickly or remain to interact with fluvial processes.

Strategy

Grime 1977 defines three fundamental strategies for established plants. These are Competitors (C) which exploit low stress and low disturbance, Stress tolerators (S) which are found at high stress - low disturbance, and Ruderals (R) which are found in low stress and high disturbance. These are considered as evolutionary extremes along two gradients: habitat duration, habitat productivity. Few species exhibit pure CSR strategies with most exhibiting secondary strategies which are a combination (e.g. CR, SR, etc.: for further explanation see section 2.3.6.1).

Disturbance in this context is defined as anything which removes plant biomass, while stress is anything which limits dry matter production by a plant. These traits are relevant because rivers exhibit gradients in flood disturbance and productivity. Flood disturbance is related to flood magnitude, duration and specific energy, which is governed by channel / floodplain gradient and width, and it also provides a conceptual framework within which fluvial processes can be placed in the wider context of ecological processes relating to disturbance and productivity. A plant strategy is not a true trait in terms of being a measurable plant characteristic, but it is shorthand for a combination of traits. Grime’s group examined a suite of traits, subjecting species to a battery of tests to confirm their strategy and the relevance of those traits. It should be noted that Grime’s strategy approach is somewhat controversial but it does provide a useful conceptual framework.

Establishment

How plants establish after a disturbance such as a flood, where space has opened up, is the first stage of the succession process. Key to establishment is the plants ability to first get to the site and then to reproduce. Hydrochory is the ability of a plant to have its propagules transported by water and vegetative reproduction is the ability of the plant to reproduce from propagules that are parts of the plant. Willows and poplars classically re-establish from fragments, rooting from nodes. This response is closely related to their ability to respond to burial. Many aquatic plants will also reproduce from fragments.

As part of their establishment strategy, many plants grow clonally from a mother plant, which produces daughters to colonise locally. This can allow a plant to establish large clumps and thereby quickly stabilise sediment. *Sparganium erectum* is a classic example of a species which exhibits these characteristics: its ecosystem engineering role is described in detail in section 2.2.

Environmental Envelope

The ‘environmental envelope’ defines the area of Europe where particular plants can be found. Although not directly related to function it does prescribe the outer limits of the areas within which particular plants can operate and also has some relationship with the type of rivers they tend to occupy. Section 3.1 describes the riverine flora of Europe by broad biogeographic region and whilst many species are widespread there are distinct regional differences.

Ellenberg values

These can be considered as an extension of the environmental envelope but in this case along gradients of productivity (Ellenberg N) and moisture (Ellenberg F). The Ellenberg F values are especially relevant to physical processes as they discriminate species which are found in water from those that are rooted in water, and from those that occupy a gradient in soil moisture from wet to dry soil. The Ellenberg values have been criticised as being subjective since they are based on expert judgement to some degree rather than empirical observation. However, they have found widespread practical application in modelling tools (e.g. MULTIMOVE) and in progressing understanding of riverine plant trait-habitat relationships (Cavalli et al., 2014).

Dominance / Cover

The amount of a particular plant in a river or on a river bank also determines how important its role is in physical processes. For example the greatest uncertainty in channel conveyance estimates for vegetated channels is the effect of the amount and variability of the vegetation (O'Hare 2008). Dominance is the ability of a plant to have the highest biomass / cover of any species present. The amount of plant material is usually recorded in field surveys and is not indicated in trait datasets because it is fundamentally a site specific measurement. However there is some evidence that the ability of a plant to dominate a site is related to how widespread the plant is at national scales (Riis and Sand-Jensen, 2002). This evidence is as yet insufficient and requires further research. Field observations would suggest that it is not unusual to find river sites dominated by particular species. For example, in the UK *Ranunculus penicillatus* is likely to be the most dominant instream species where it is present. Unfortunately, dominance and cover values are not recorded in trait data sets.

The traits investigated in this research are summarised in Table 3.2.1.

Table 3.2.1 A list of traits which determine a plant's ability to influence fluvial geomorphological and hydrological processes, the processes they affect and the availability of the trait

Trait Type	Trait	Distribution	Succession	Channel Blockage	Sediment deposition	Disturbance tolerance	General Availability	Sources used	Description of actual trait used
Form	morphotype	X		X	x	x	Available for aquatic macrophytes only	Expert judgement by REFORM partners.	
	Size			X	x	X	Available as height or length or categorical data	PLANTATT	Height/length
	flexibility			X	x	x	Rarely quantified but measurement techniques are described	PLANTATT	Woodiness categories converted to 1-3 scale, 1=herbaceous 2=semi-woody 3=woody
	Stem strength			X	X	x	As described for previous trait		No surrogate
	Root strength					X	As described for previous trait		No surrogate

Trait Type	Trait	Distribution	Succession	Channel Blockage	Sediment deposition	Disturbance tolerance	General Availability	Sources used	Description of actual trait used
Form (ctd.)	Root type				X	X	Present in species descriptions and collated for this project	various	Roots in categorical form: adventitious, fibrous, tap or other
Winter biomass	Perenniation		X	X	X	X	Available for many species but not collated	PLANTATT	Categorised as perennial, biennial, annual
	Senescence			X	X	X	Rarely reported		No surrogate
Grime Strategy	CSR		X				Strategy quantified for species in UK examined experimentally by Grime et al 1998.		
Establish-Ment	Hydrochory		X			X	Patchy information available		
	Clonal growth		X			X	Available in various forms in trait databases	PLANTATT	Based on the clone 1 trait. Local dominance by rapid clonal growth all turned to 1 upto node1 node1=2, node2 =3, Rhiz1=2, Rhiz2=3, root=3, stol1=2, Stol2=3, Tip=3

Trait Type	Trait	Distribution	Succession	Channel Blockage	Sediment deposition	Disturbance tolerance	General Availability	Sources used	Description of actual trait used
Establish-ment (ctd.)	Vegetative reproduction		X			x	Available in various forms in trait databases		
Environ-mental Envelope	Latitude	X					Geographic ranges often described by biogeographic region but not collated systematically and quantitatively		
	Longitude	X					As above		
	Altitude	X					As above		
Ellenberg	F	X					Readily available for many species	PLANTATT, Ciocârlan or BIOFLOR.	No substitution
	N	X					As above	PLANTATT, Ciocârlan or BIOFLOR.	No substitution
Dominance							Not available in trait datasets		

3.2.2.3 Typology construction

In constructing a typology, we considered three processes: sediment stabilization; sediment deposition; and channel conveyance / blockage. These were the processes which could be best described using available traits. Channel blockage and sediment deposition are both influenced by similar traits so were grouped together to create a single typology. A second dichotomous trait key was created for sediment stabilization.

In practice species were grouped by traits using a species-by-traits matrix in Excel. The environmental envelope data (species ranges etc) was included in the traits matrices but not included in the two typologies directly, with the exception of Ellenberg F values. This approach allowed the environmental envelope data to be applied once the functional typology was created.

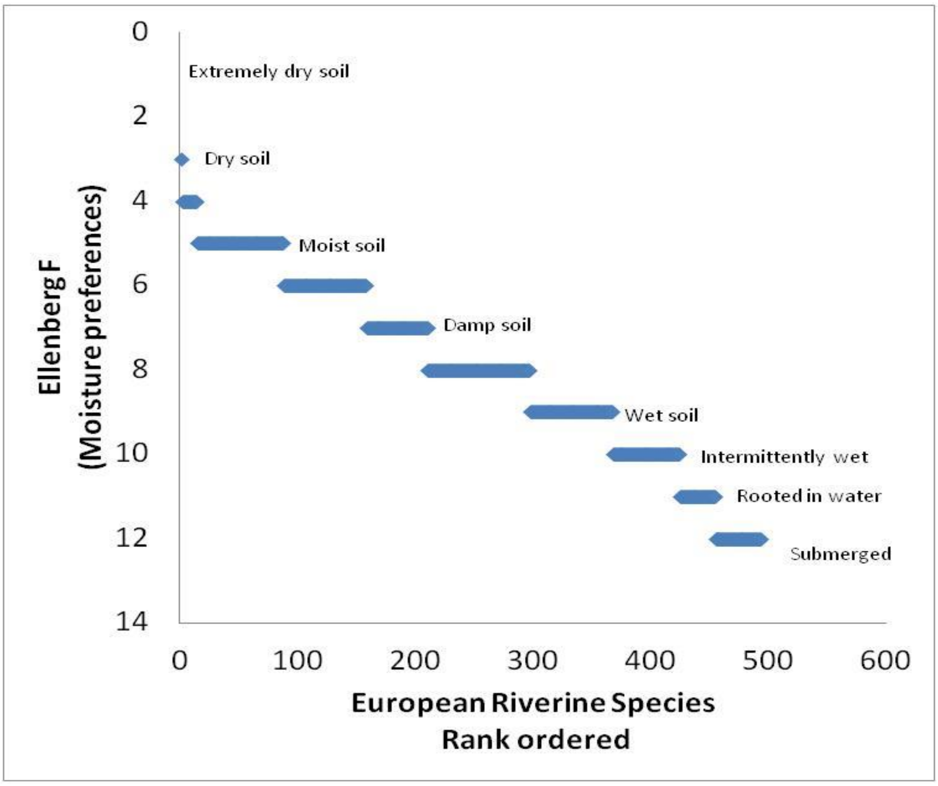


Figure 3.2.2 European riverine species placed in rank order by their Ellenberg F values, which indicate preference for soil moisture. The length of the blue bars indicates the number of species at each Ellenberg F value.

The role that plants have is determined by their proximity to the river. Ellenberg F moisture values give us an indication of where the plants grow in relation to the water table (Figure 3.2.2). They have been incorporated into the typology for flow conveyance and sediment accumulation (see below) but they have been simplified to distinguish only between instream and marginal vegetation as one group and riparian vegetation as another group.

In section 2.2.3, hotspots of vegetation-fluvial process interactions are discussed. Zone 1 (permanently inundated) and Zone 2 (frequently inundated) equate to Ellenberg F values of 12 and 11-10, respectively. Zones 3 to 5 can be broadly considered to relate to a vegetation gradient from Ellenberg F values 9 to 1. A simplistic equating of ellenberg F values between 9 - 1 must be considered very carefully in terms of the river style and the surrounding terrestrial habitat type. It must be remembered that Ellenberg F values relate to soil moisture. The situation on a high energy gravel bed river is very different from the riparian gradient in a lowland area. Even in Scotland which has 1500 to 3000 mm rainfall a year, riparian gravel bars can produce very well drained conditions which favour species of lower Ellenberg values. Equally the general condition of riparian flora and the gradients in soil moisture they represent differ with aridity. Mediterranean rivers and their flora are very different from those at higher latitudes.

3.2.3 Results - The Typologies

3.2.3.1 Sediment stabilisation

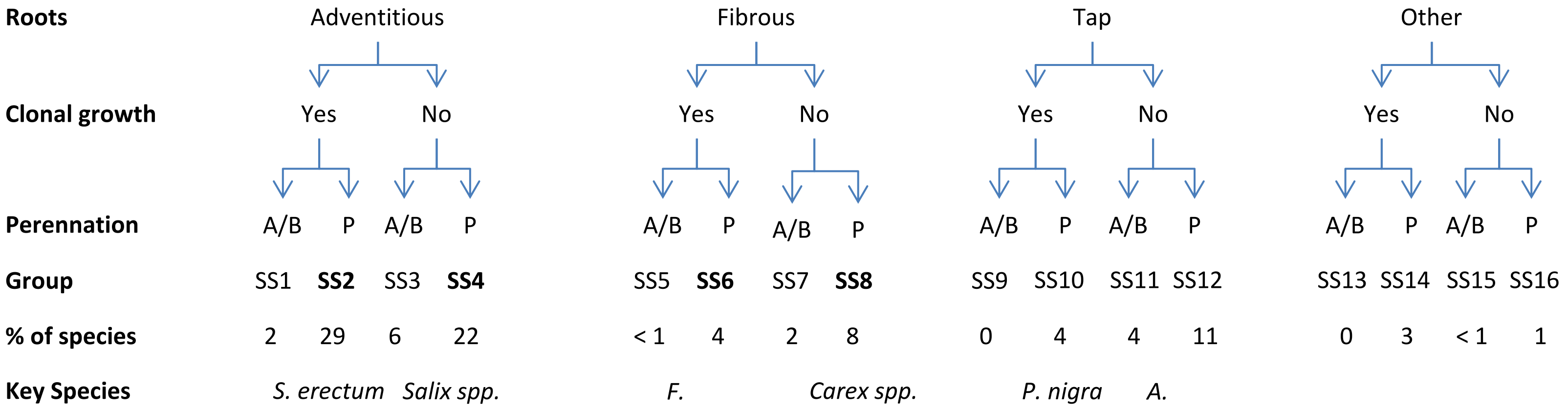
Figure 3.2.3 illustrates the dichotomous key that was developed, based on expert judgment, to place species in groups based on traits relevant to sediment stabilisation. The traits used for this typology were root type, clonal growth and perennation. A data base of species traits used in the typology can be found in Annex C. Clonal growth reflects the plant’s ability to spread locally and rapidly. While trait datasets contain much information on seed dispersal, which is also important, there is little information to indicate if seed can contribute to local dominance. Those species which are annual or biennial can be assumed to have only a short term role in sediment stabilization (i.e. a seasonal role only), while those that are perennial are relevant over longer time periods.

The most important groups (SS2, SS4, SS6 and SS8) are highlighted in bold in Figure 3.2.3); all are perennial and have either adventitious or fine roots. These are also amongst the most common type of plants within the data set. The combination of SS2 and SS4, both of which are perennial with adventitious roots, includes over 51% of species. Figure 3.2.4 illustrates some species that fall into some of the most important groups.

Tap roots might be considered less useful in stabilising sediment than those roots which bind sediment - the fibrous and adventitious types. However, tap roots may penetrate shear planes in river banks, helping to stabilize them. Furthermore, for tree species a tap root may be a primary type of root but typically it is augmented by strong lateral fibrous roots which have a sediment binding capacity. Equally, as can be seen in Figure 3.2.3, group SS12 is effective at stabilizing the sediment surface but vulnerable to incision and undermining by lateral erosion of river banks.

Those species which could only have their roots categorised as ‘other’ (groups 13-16), require further examination to determine their role. A wide range of species occur within the adventitious rooted perennial groups including key marginal and submerged macrophyte species; e.g. *Juncus* spp., *Eleocharis* spp., *Equiseteum* spp., *Petasites* spp., *Elodea* spp., *Potamogeton* spp..

Sediment Stabilisation



Roots	Adventitious				Fibrous				Tap				Other			
Clonal growth	Yes		No		Yes		No		Yes		No		Yes		No	
Perennation	A/B	P	A/B	P	A/B	P	A/B	P	A/B	P	A/B	P	A/B	P	A/B	P
Group	SS1	**SS2**	SS3	**SS4**	SS5	**SS6**	SS7	**SS8**	SS9	SS10	SS11	SS12	SS13	SS14	SS15	SS16
% of species	2	29	6	22	< 1	4	2	8	0	4	4	11	0	3	< 1	1
Key Species		*S. erectum*		*Salix spp.*		*F.*		*Carex spp.*		*P. nigra*		*A.*				

Figure 3.2.3 The dichotomous key used to place species in groups based on their traits relevant to sediment stabilisation.

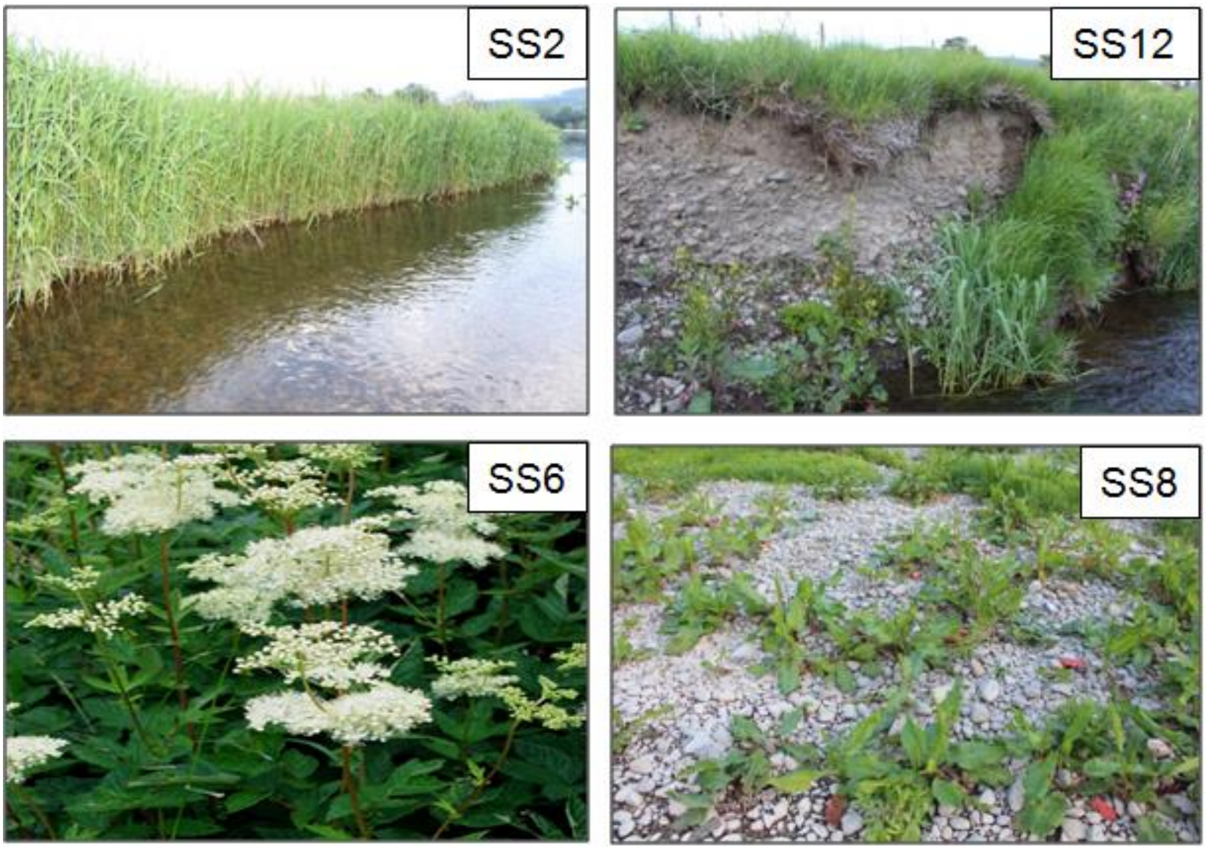


Figure 3.2.4 Photographs illustrating species in some of the key groups, SS2 *Phalaris arundinacea,* SS6 *Filipendula ulmara,* SS8 *Rumex* spp. and SS12 *Poa* spp.

3.2.3.2. Sediment accumulation and channel conveyance / blockage

This section of the typology focuses on the influence vegetation can have on channel conveyance/ blockage and sediment accrual. Not all possible permutations of traits were commonly found. Herbaceous species dominated with few woody species. Most common were medium sized herbaceous species with this grouping representing 45% of species analysed. The typology related to sediment accumulation and channel conveyance / blockage is presented in Figure 3.2.5. Species representative of two of the types are illustrated in Figure 3.2.6. A data base of species traits used in the typology can be found in Annex C.

In general small species irrespective of whether or not they are herbaceous or woody are likely to have a limited influence on channel conveyance at base flows and also under flood flows where the riparian zone is inundated. Small stiff species, if present in abundance, could have a cumulative impact.

Medium sized species form the bulk of the riverine vegetation. Instream they can be key determinands of water depth, especially in channels with benign growing conditions such as those which are calcareous and groundwater fed. Batrachian *Ranunculus* species can easily occupy 80% of channel width and increase Manning’s n roughness by 0.6 compared to unvegetated channels (O’Hare et al 2010). As herbaceous perennials or

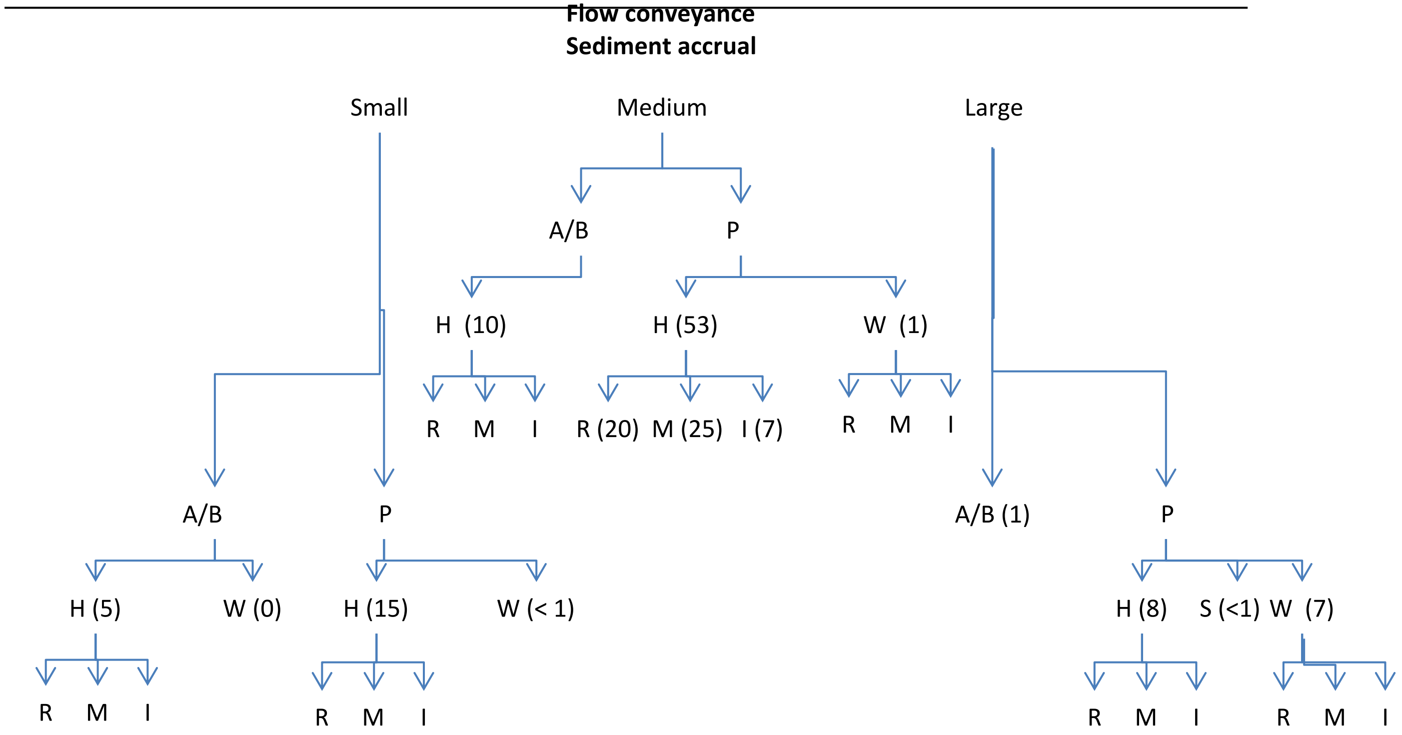


Figure 3.2.5, The dichotomous key used to place species in groups based on their traits relevant to sediment accrual and channel blockage / flow conveyance. The first level is size (small < 0.3m, medium , 1.5m and large > 1.5m in height or length); then perennation (A/B annual/biennial, P perennial), the next is woodiness, a surrogate for flexibility (H herbaceous, W woody) finally the Ellenberg F values are interpreted as (R riparian < 9, M marginal 10-11, I instream 12). The numbers in brackets give the % of species in each major grouping, where species refers to those where a full suite of traits was available for this analysis, N = 469.

Figure 3.2.6 Photographs illustrating two key groups relevant to sediment accrual and channel blockage / flow conveyance. Left: Large perennial woody marginal species such as *Salix spp.*. Right: large herbaceous perennial instream species, *Ranunculus penicillatus*.

annuals the instream flora typically exerts a seasonal influence only although those species with overwintering roots can stabilize sediment while not impeding flow during the winter period (e.g. *S. erectum*).

In the marginal and riparian zones, medium sized species are of critical importance in determining the channel resistance. Their size means they are likely to be at least partially submerged during floods. As the majority are herbaceous species, they can be expected to be reasonably flexible, although some are stiff but not as stiff as woody species. As herbaceous species they leave litter over winter if they are not perennial, and this can impede flow. Unlike instream species this litter is less frequently washed out and will accumulate if it does not decompose.

Large species are almost all perennial and can be either herbaceous or woody. It is only in this group that woody species are as well represented as herbaceous species. This is not surprising as tall plants require stiff stems to support their canopies and woody tissue provides this. As the large woody species are riparian or marginal, and not typically found instream, they only interact with flood flows. The taller parts of the canopy will rarely interact with flood waters unless the plants are uprooted. As stiff structures in the floodplain they act to capture debris during floods which can increase their form drag below the water. This has not been quantified but can on occasion be substantial leading to the development of wood jams.

3.2.3 Discussion

The typology presented in this section (3.2) types plants by traits into practical groups which allow for the rapid assessment of the physical functioning of the flora. Below we discuss its potential practical application, links to modelling and possible further refinements.

3.2.3.1 Practical application

In practice most field studies of the role of vegetation in physical processes have been case studies based on detailed information collected at particular sites. The transfer of knowledge between sites can be facilitated in the future by using the river typology under development here in REFORM (Deliverable 2.1). In addition it should also be possible to classify botanical survey data from detailed study sites into trait groups using a simple tool based on the trait matrix.

Equally the approach of analysing botanical survey data opens up the possibility for physical scientists to make use of data from purely ecological studies and marry it with widely available physical data on river systems such as slope, channel width, discharge, bed material etc. Suitable survey data includes the Water Framework Directive monitoring data, which provides a massive resource across Europe. To date that data has focused on macrophytes (instream and marginal) vegetation although in some countries information on riparian species is routinely collected as well (e.g. Denmark). What is especially important about these botanical surveys is that they typically contain information on the abundance of the individual species. This in combination with trait grouping can give the hydromorphologist a strong impression of the potential role of vegetation at particular sites.

3.2.3.2 Links with modelling

Through the analysis of traits we have identified species and groups which have the potential to play an active role in physical processes of different types, linked broadly to sediment stabilisation, sediment accumulation or flow impedance / conveyance. Section 2.3 reviews advances in Modelling Vegetation-Hydromorphology Interactions using similar processes; bank accretion, bank erosion and flow resistance. As they stand, the models for these processes use vegetation data recorded with varying degrees of refinement. Fundamentally though, most models focus on particular plant characteristics, which are traits in effect, such as the stabilising influence of roots on sediment (Pollen-Bankhead et al., 2011). This is an area of multi-disciplinary research where there is active interest in aligning trait based approaches with fundamental physical modelling approaches. The development of the models is being driven in a bottom up fashion by hydraulics specialists focusing on fundamental physics but this is being mediated by the realities of ecological variability. The need for scientific development in this area is already recognised by the EU, which has funded training of new scientists under the HYTECH project. This project addresses Hydrodynamic Transport in Ecologically Critical Heterogeneous Interfaces. REFORM maintains close communication with HYTECH.

3.2.3.3 Further refinements

The application of the approach demonstrated here is limited by the availability of suitable traits. In this regard it is important to caution the user regarding the limitations of the approach as it stands. They should confirm / ground truth the expression of traits at their study sites. Our understanding of plant-hydromorphological interactions is rudimentary and care should be taken to confirm the actual role of vegetation. For example we have identified particular groups of traits that are likely to be especially significant in sediment accrual. Much of the research on the role of vegetation in riparian physical processes highlights the importance of ecosystem engineering species, such as *Populus nigra* or *Sparganium erectum* (Gurnell, 2014; Liffen et al., 2011, 2013a,b). Often these are the species which initiate landform change and cause new sedimentary structures to develop. They are pioneer species which facilitate other species by creating new habitat. Critical to initialisation is sediment accrual. The species highlighted in our typology under sediment accrual have the capacity to engineer habitat. One key point however is that some species, which are included in the typology, may also function to accumulate sediment in a manner that is not covered by the typology. During flood events these tree species up root and form obstacles in the channel around which flows slow and in turn sediment deposits. Their drag while standing is relatively low compared to when they are uprooted. This mechanism is illustrated in Table 2.2.4 as the development of a ‘pioneer island’.

Detailed information on traits has proven useful in hydromorphological studies already; in particular the application of broad morphotypes to the study of channel conveyance (McGahey et al., 2006, 2008). Further studies have helped to refine which traits are important, particularly in relation to morphology, and the trade-off in plant structures between stem breaking strain and drag reduction, which is especially important for conveyance and channel blockage (Albayrak et al., 2012; Puijalon et al., 2005). The robustness of a trait based approach is dependent on more fundamental science as championed in the studies referenced above. Equally important are the advances in our conceptual understanding of the interaction between plants and physical processes as outlined in chapter 2 which will help steer further developments.

This deliverable focuses on natural processes however it is worth noting that a traits based approach has been taken in Work Package 3 of REFORM to help us understand the impact of multiple stressors on riverine vegetation (see Deliverable 3.2). As Figure 3.2.1 illustrates, physical processes can be influenced by a variety of biotic processes some of which are in turn influenced by humans. In a series of field studies it has previously been demonstrated that channel blockage by instream vegetation is exacerbated by eutrophication which increases the biomass of the blocking vegetation (O’Hare et al. 2010 a and b). Initial results from research conducted in Work Package 3 indicate that the distribution of traits in Danish rivers is heavily influenced by eutrophication and hydromorphological alteration (Cavalli et al., 2014). These trait shifts have implications for physical processes as species are favoured which can reproduce from meristems and can dominate sites by producing significant biomass.

3.3 Examples of Vegetation-Hydromorphology Interactions in different Biogeographical Settings

3.3.1 Introduction

Section 3.3 investigates the applicability of the conceptual model described in section 2.2 to a sample of European Rivers. The model considers three spatial scales, which map onto those of the hierarchical framework of Deliverable 2.1:

1. The characteristics of the biogeographical *region* of the river *catchment* and, in large, topographically-complex catchments, the contained *landscape units*, that dictate the climate, moisture availability, fluvial disturbance and also the plant species that are present.
2. Longitudinal, lateral and vertical gradients in moisture availability and fluvial disturbances that are found within *segments* to *reaches* of the river corridor as represented by the distribution of the five zones described in section 2.2.2.
3. The 'critical zone' that comprises zones 1 and 2 and the character and dynamics of the interface between them at the *reach* to *geomorphic and hydraulic unit* scales, including the vegetation-related landform types that are present. Since the influence of individual plants and plant stands varies with the size of the river, consideration of river size is introduced at this spatial scale as well as the plant species that are instrumental in landform development.

The conceptual model is explored for one or more reaches of the River Frome, UK (section 3.3.2), the Tagliamento River, Italy (section 3.3.3.), the Guadarranque and Guadalupejo Rivers, Spain (section 3.3.4), and the River Narew, Poland (section 3.3.5). Table 3.3.1 provides some summary information for these rivers including the biogeographic region and subregion (source: http://www.globalbioclimatics.org) in which they are situated; the average rainfall, air temperature, and flow regime of the investigated segments; and the river types (from Deliverable 2.1, chapter 7), their gradients and bed material calibre.

In section 3.3.6 an overview is provided of the variations encountered in braided river characteristics in south east France, which includes pats of several biogeographic regions and subregions (source: http://www.globalbioclimatics.org) including region 5 (Central European) subregion a (Subatlantic); region 7 (Cévenno-Pyrenean) subregions d (Cévennean) and e (Auvergnean); region 8 (Alpine) subregions a (Mediterranean Alpine) and b (Western Alpine); and region 19 (Balearic-Catalonian-Provencal) subregion b (Occitanian-Provencal).

This section (3.3) concludes with a synthesis concerning the application of the conceptual model of vegetation-hydromorphology interactions and further research needs (section 3.3.7).

Table 3.3.1 Typical characteristics of the four river systems that investigated in this report section (3.3)

	Frome	Tagliamento headwaters	Tagliamento mid-reaches	Tagliamento lower reaches	Guadarranque mid and lower reaches	Guadalupejo mid and lower reaches	Narew upper reaches
Biogeographic region	4 - Atlantic European	8 - Alpine	8 - Alpine	9 – Appenino-Balkan	15-Mediterranean West Iberian	15-Mediterranean West Iberian	5 – Central European
Biogeographic subregion	c - Britannic	d – Eastern Alpine	d – Eastern Alpine	b - Padanian	a - Luso-Extremadurense	a - Luso-Extremadurense	C – Hemiboreal Baltic
Mean annual rainfall (mm)	750	1700	2000	1300	650	650	580
Mean daily air temperature (°C)	11.2	9.5	10.5	12.5	20	20	7
Mean daily air temperature coolest, warmest month (°C)	6.4, 17.1	-1.5, 19.0	0.5, 20.0	3.0, 22.0	5.5, 35.0	5.5, 35.0	-2, 18
Flow Regime	Perennial superstable	Snow + Rain	Perennial Flashy	Perennial Flashy Intermittent	Intermittent Flashy	Intermittent Runoff / Flashy	Snow + rain
River Types	13 /17 Sinuous 19 Anabranching 18 Meandering	6 Plane Bed 8 Braided	13 Sinuous - Straight 8 Braided 10 Anabranching	8 Braided 10 Anabranching 12 Pseudo-meandering 14 Meandering	7 Straight-sinuous 11 Wandering	11 Wandering	22 Anabranching
Bed material (for above river types)	Gravel–Sand Gravel–Sand Gravel–Sand	Boulder–Cobble–Gravel Cobble–Gravel–Sand	Cobble–Gravel–Sand Cobble–Gravel–Sand Cobble–Gravel–Sand	Gravel–Sand Gravel–Sand Gravel–Sand Gravel–Sand	Cobble, gravel,	Cobble, Gravel	Sand
~Slope (for above river types)	≥0.003 0.002-0.003 ≤ 0.002	0.008-0.108 0.001-0.032	0.0004-0.011 0.0006-0.012 0.0016-0.0092	<0.001-0.008 <0.001-0.005 <0.001-0.005 <0.001-0.005	0.04-0.07	0.01 – 0.04	0.0002
Confinement (for above river types)	Unconfined Unconfined Unconfined	Confined Partly Confined	Confined Partly Confined Partly Confined	Partly/Unconfined Unconfined Unconfined Unconfined	Confined/Partly confined	Unconfined	Unconfined

3.3.2 The River Frome, Southern England

3.3.2.1 Region to Reach Context

Regional and Catchment Setting

The regional setting of the River Frome is summarised in Table 3.3.1. The Frome is located in the Britannic subregion of the Atlantic European biogeographical region of Europe (source: http://www.globalbioclimatics.org), and so it has a mild climate with average daily air temperature of 11.2 ^{o}C and an average annual rainfall of 750 mm.

The River Frome and its catchment are fully described in the Annex Volume of 'Catchment Case Study Applications' of Deliverable 2.1. According to the Water Framework Directive typology, the Frome has a medium-sized, lowland, calcareous catchment (catchment area = 459 km^2, mean elevation = 108 m), and a groundwater dominated 'perennial superstable' flow regime. These characteristics support a moist river corridor that is subject to a high water table and relatively subdued fluvial disturbances

Longitudinal, Lateral and Vertical Gradients

The bed material throughout the Frome catchment is gravel and sand. The river types that are present are sinuous (types 13, 17), meandering (type 18) and low energy anabranching (type 19). Interpreting the river corridor based on Figures 2.2.1 and 2.2.2, these river types combined with the groundwater-driven flow regime would be expected to support extensive areas of floodplain under zones 5 (soil moisture regime dominated) and 4 (inundation dominated). Sinuous and meandering river types would be expected to show small but significant areas of floodplain and river margin under zone 3 (fluvial disturbance dominated – fine sediment deposition) and even smaller areas under zone 2 (fluvial disturbance dominated – coarse sediment erosion and deposition) at the edges of zone 1 (perennially inundated). Low energy anabranching river types would be expected to show very small areas of zone 3 close to the zone 4 and 5 margin, with negligible presence of zone 2.

Unfortunately, as fully discussed in the Annex Volume of 'Catchment Case Study Applications' of Deliverable 2.1, the entire river corridor of the River Frome is highly managed, with intensive agriculture often coupled with systems for floodplain drainage, extending across the floodplain almost to the edge of the prerennially inundated channel. As a result, only small patches of land survive that could be classified as representative of zones 4 and 5, typically sections of abandonned and silted channel that have not been drained and that persist as 'islands' of wetland surrounded by agricultural land. However, a part of one reach (reach 4) retains an essentially undrained floodplain covered by vegetation that is subject to minimal management. This low energy anabranching section shows extensive areas characteristic of zones 4 and 5, forming a potential reference for restoration of other floodplain areas of the catchment (Figure 3.3.1). Tussocks are a characteristic growth form for some grasses in the wettest areas of zone 4. These are pillar-like structures of organic material that raise plants above the surrounding waterlogged areas and often provide colonisation sites for other species that require moist conditions but cannot tolerate waterlogging. In this part of reach 4, Zone 3 forms a narrow band immediately adjacent to the river channels, because fine flood-transported sediment is deposited close to river channels as overbank flows penetrate the densely vegetated floodplain surface. Zone 2 is confined to marginal bars and other depositional features within the river channel.

Elsewhere along the Frome, naturally functioning zones 4 and 5 are largely absent or survive as small disconnected patches and, at a maximum, zone 3 is restricted to the immediate channel margins where a narrow border of riparian trees and herbaceous vegetation is often present that grades into emergent macrophytes at the bank toe. Thus the ‘critical zone’ of interaction between vegetation and fluvial processes (zone 2) is largely confined to the low flow channel.

Figure 3.3.1 A part of reach 4 of the River Frome where the floodplain still supports wetland vegetation (grassland and floodplain woodland) that depends on a perennially high water table (image from Google Earth).

Critical zone of interaction between vegetation and fluvial processes

Average main channel width for the 17 reaches of the River Frome, defined in the Annex Volume of Catchment Case Studies of Deliverable 2.1, ranges from 3.1 to 7.7 m in landscape unit 1 (headwater reaches 1 to 4), through 10.0 to 29.4 m in landscape unit 2 (reaches 5 to 11) (headwaters) to 15.5 to 23.7 m in landscape unit 3 (reaches 12 to 17). Considering scaling with respect to riparian trees, wood and aquatic plants, these channel widths indicate ‘small’ to ‘intermediate’ channels in the context of wood and trees and ‘intermediate’ to ‘large’ channels in the context of aquatic plants. Thus individual plants and plant stands of both riparian and aquatic vegetation have the potential to significantly influence river channel morphology.

In relation to riparian trees, all channels are sufficiently narrow, for toppled trees to span the channel and thus for major wood jams to form (i.e. an ‘intermediate’ channel, where a single aggregation can significantly affect channel form), and in landscape unit 1 and in many reaches of landscape units 2 and 3, the channel is sufficiently narrow for individual riparian trees or the largest pieces of wood to have a major influence on channel form (i.e. channels are ‘small’ in relation to tree size).

In relation to aquatic plants, single plant stands could be large enough to influence local channel form in the headwaters (i.e. ‘intermediate’ channels in relation to aquatic macrophytes), whereas in most of the main channel, a few to many plant stands would be needed before there could be a significant effect on channel morphodynamics (i.e. 'large' channels in relation to aquatic macrophytes).

Main channel gradients are low (0.010 to 0.003 in landscape unit 1; 0.004 to 0.002 in landscape unit 2; 0.003 to 0.001 in landscape unit 3) and $Q_{pmedian}$ values are 0.62, 11.71 and 20.72 $m^3.s^{-1}$ at gauging stations located, respectively, in these three landscape units. These place the entire river network within the area of the graphs of $Q_{pmedian}$ against slope illustrated in Figure 2.1.6 that is characterised by pebble - fine gravel - sand and finer bed material and can support very high abundances of linear emergent and both linear- and patch-submerged aquatic plant morphotypes. Therefore, there is considerable potential for aquatic macrophytes to influence channel form.

Unfortunately, because the riparian zone is highly managed in the Frome catchment there is only partial riparian corridor function, at best, and a poor, severely degraded wood budget in all reaches downstream from reach 6. As a result, there are few locations within the Frome river network where riparian trees can be seen interacting freely with fluvial processes. One exception is the channel and floodplain along the upstream part of reach 4. Part of this length of the river (the central part shown in Figure 3.3.1) was straightened when an embanked railway line was built in the mid-19th century, and its lateral movement on the left bank is constrained by the embankment. Here, riparian woodland is well developed and both trees and large wood are influencing channel development. In addition, aquatic 'weed' cutting has been widely practiced in the Frome catchment until recently. Nevertheless, interactions between aquatic plants and fluvial processes can be observed more widely along the Frome because of the ability of aquatic macrophytes to recover very rapidly following management.

3.3.2.2 Influence of riparian trees and wood on river morphology in the critical zone

Despite the highly managed nature of the riparian corridor, the River Frome is bordered in many reaches by an irregular line of riparian trees, and occasionally by a wider band of riparian woodland. Riparian trees are usually managed to some extent (e.g. large wood removal, pruning). However, in the upstream part of reach 4 (Figure 3.3.1), a band of essentially unmanaged riparian woodland borders the river. The main riparian tree species present in this part of reach 4 are *Alnus glutinosa, Salix caprea, Salix fragilis, Salix triandra,* and *Salix viminalis.* In some locations more terrestrial tree and shrub species also interact with the river, including *Acer campestre, Corylus avellana, Fraxinus excelsior*, and *Prunus spinosa*. Observations in this upstream part of reach 4 provide an indication of how unmanaged trees and wood might influence channel form and dynamics of the River Frome in sections where the channel is 'small' in relation to height of the mature riparian trees along the banks (channel bankfull width ranges from 3.8 to 7.8m).

The upstream section of reach 4 was straightened during the 19th century in association with the construction of a large railway embankment (located on the left bank of the river – the right side of each of the maps in Figure 3.3.2). From field evidence, the river banks appear to have been reinforced in some sections with wood (Figure 3.3.3) and in a few local patches with harder reinforcement (e.g. brick). Much of this reinforcement probably dates back to the time when the railway embankment was constructed.

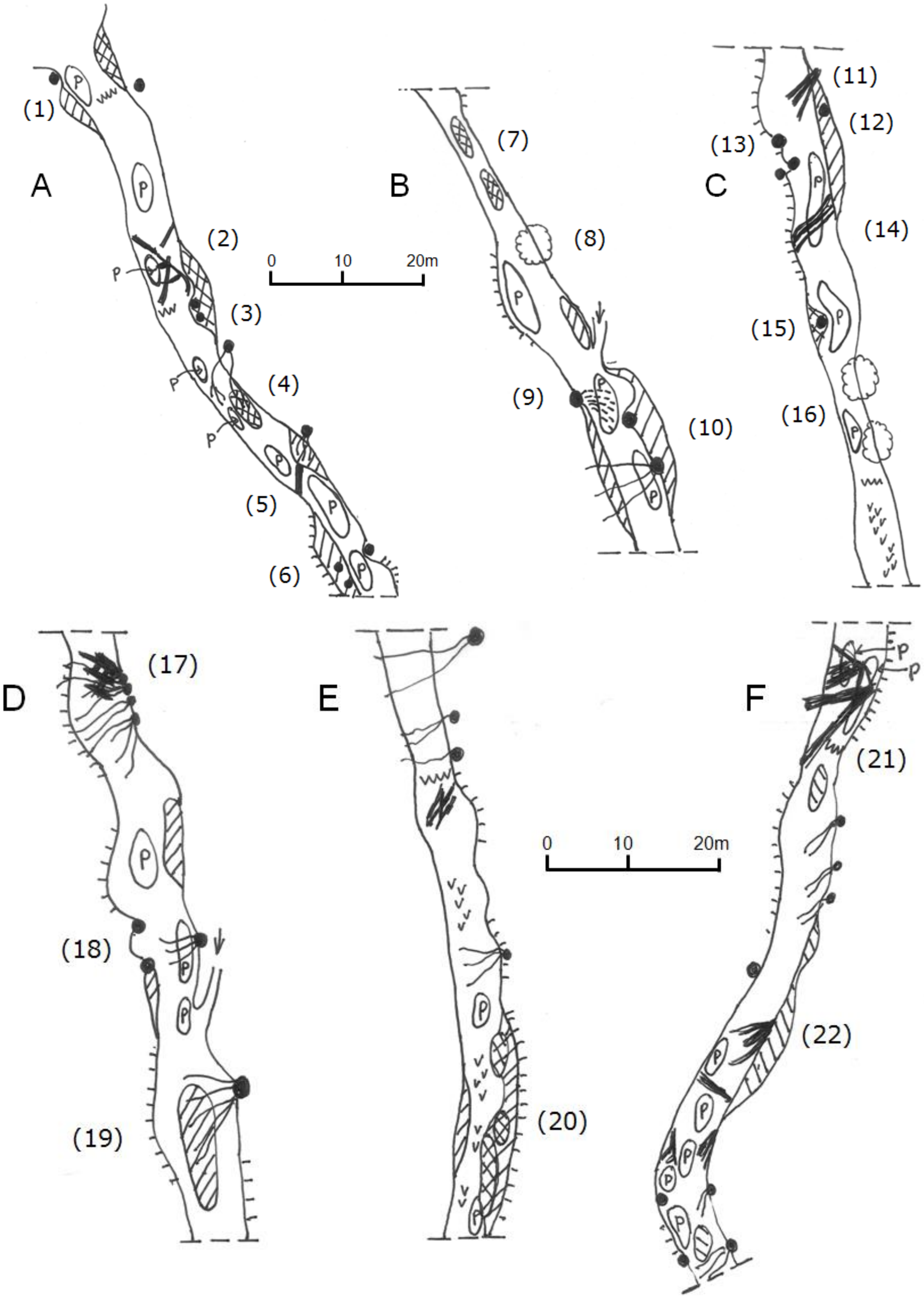


Figure 3.3.2 (continued on next page)

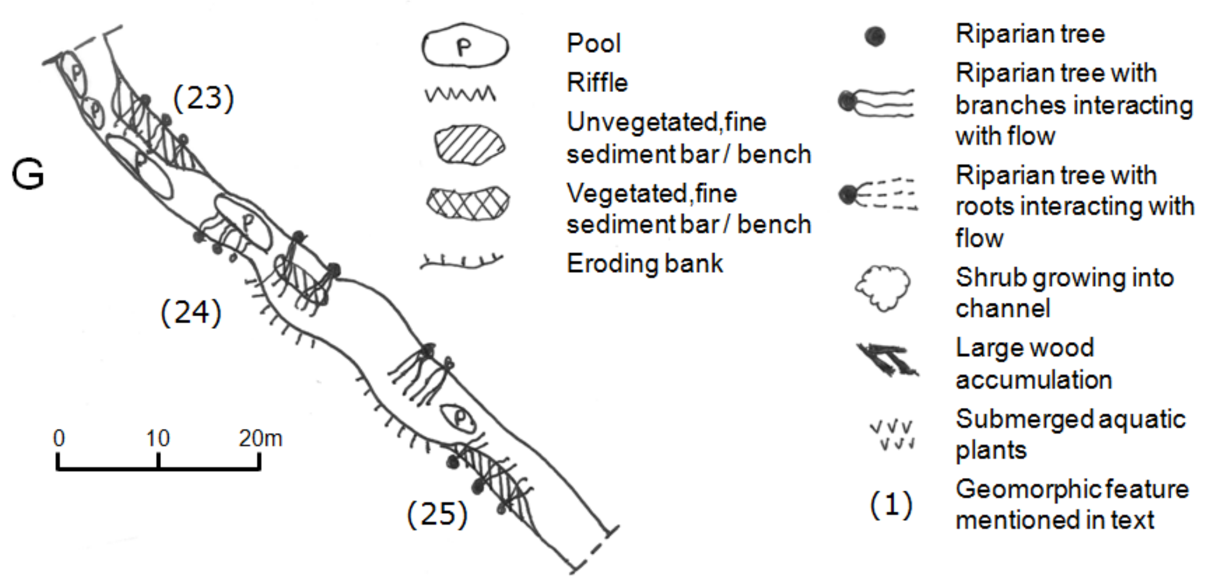


Figure 3.3.2 Geomorphological sketches of sections A (upstream) to G (downstream) of the upper part of reach 4 of the River Frome (flow direction is from the top to the bottom of each sketch)

Figure 3.3.2 shows geomorphological maps of seven contiguous sections of the upstream part of reach 4. The sections are illustrated in an upstream to downstream sequence (A to G, Figure 3.3.2), with the direction of flow running from the top to the bottom of each map. The maps were constructed using a base map of the bank lines surveyed by the Ordnance Survey. The Ordnance Survey bank lines showed some curvature in their planform, but the field mapping revealed considerable greater variation in channel width and bank plan curvature that could be attributed to both bank construction and erosion.

The field survey revealed that, although the gravel river bed is occasionally exposed, much of the bed in this part of reach 4 is buried by sand and silt deposits, and this finer sediment is apparent in many of the landforms that are present.

Predominantly dead wood features include small log steps (Figure 3.3.2: features 5 and 14), a complete jam (Figure 3.3.2: 2), an active jam (Figure 3.3.2: 21; Figure 3.3.4), and several flow deflection jams (Figure 3.3.2: 11, 17, 22) which are all characteristic of ‘small’ to ‘intermediate’ sized channels.

There are also many features linked to standing riparian trees and ‘living’ (sprouting) wood. Dense areas of exposed roots (Figure 3.3.2: 9; Figure 3.3.5) and branches (Figure 3.3.2: 19; Figure 3.3.6) trail into the channel, forming jam-like and bar features, respectively. In section G, trailing branches, leaning trees and adventitious roots contribute to the development of lateral bars, submerged shelves and benches comprised of fine sediment (Figure 3.3.2: 23, 24, 25; Figures 3.3.6 and 3.3.7), which, combined with intervening areas of eroding banks, are leading to the development of a more sinuous channel planform. Bank instability is indicated in section G by numerous leaning and J-shaped trees (Figure 3.3.7).

Several other sections of the river support large riparian trees that are buttressing the river bank and leading to the development and, through root reinforcement, the retention of fine sediment benches (Figure 3.3.2: 1, 3, 6, 19, 10, 12, 13, 15, 18; Figure 3.3.8). In many cases, these trees appear to grow out of the bank face, with the upper part of their J-shaped trunk growing vertically, and with adventitious roots growing vertically downwards from the base of the trunk's 'J' shape into the channel bed. At the same time, other adventitious roots grow horizontally into the bank face, reinforcing bench features (Figure 3.3.9). In several locations, shrubs are also growing into the channel, retaining sediment and wood, and narrowing the channel (Figure 3.3.2: 8, 16).

One of the most striking features of the maps in Figure 3.3.2 is the widespread occurrence of lateral bars and benches, comprised of fine sediment and usually associated with riparian trees. In addition, immediately upstream of the active jam (Figure 3.3.2: 21) in section F is a complex of vegetated and unvegetated bench and bar / ridge features (Figure 3.3.10). Individual, steep-sided, fine sediment bars / ridges (both unvegetated and vegetated) occur elsewhere, for example, just upstream of the confluence of small side channels in sections B and D, and also in the middle of the channel in section B (Figure 3.3.2: 7; Figure 3.3.11). Although the origin of these features is unclear, they appear to result from a combination of smaller pieces of sprouting wood and aquatic plants. A complex of these features (Figure 3.3.2: 20) is comprised of scroll-like vegetated ridges, with intervening, lower areas that are exposed at baseflow. The lower areas are most likely reinforced by tree roots and probably act as flood channels when high flows are elevated upstream of the active jam. The jam certainly supports complex flow pathways, which have resulted in the scour of pools under the jam, and these flow pathways may propagate upstream during flood-ponding to create the feature complex at (Figure 3.3.2: 20). A similar explanation could be proposed for the scroll-like unvegetated ridges observed at the two minor stream confluences.

Figure 3.3.3 Remnants of wooden bank reinforcement

A final vegetation-related feature is an island in section A (Figure 3.3.2: 4, Figure 3.3.12). This feature appears to have developed around branches that trail into the channel. The island is comprised of large quantities of wood and silt that have been trapped by the young trees that have sprouted from the branches where they touched the channel bed. The accumulation of wood and sediment around the sprouting branches has raised the surface of the island to the level of the surrounding floodplain.

In conclusion, although planform recovery is very slow in this ‘small’, low energy, upstream part of reach 4, individual trees and wood accumulations are driving the recovery by providing flow obstructions, and retaining and root-reinforcing fine sediment. In many cases, trees and wood and trees are acting together to build landforms and induce channel morphological change.

Figure 3.3.4 Active wood jam: Above – upstream third of jam; Middle – central part of jam; Below – downstream third of jam.

Figure 3.3.5 A jam created by tree roots.

Figure 3.3.6 Leaning trees trapping wood and rooting into the channel bed

Figure 3.3.7 Leaning and J-shaped trees inducing lateral bar development (left)

Figure 3.3.8 Fine sediment bench protected by a flow deflection jam and riparian trees

Figure 3.3.9 Alder tree buttressing river bank. Note the old roots growing downward from the base of the 'J' shaped trunk of the tree, and also into the river bank to support a bench that is significantly lowered than the flood plain at the rear of the photograph.

Figure 3.3.10 Side channels in the form of vegetated ridges (to left and in the middle distance) separated by low areas that are above the low flow water level. The river bank is on the extreme right of the photograph

Figure 3.3.11 A vegetated mid-channel bar of fine sediment.

Figure 3.3.12 The centre of an island created by tree branches touching the channel bed and sprouting. Note the large quantities of wood trapped in between the shrubs

3.3.2.3 Influence of aquatic plants on river morphology in the critical zone

As a result of the generally sparse riparian woodland along the Frome, providing limited shade to the channel, and also the low energy of the river, aquatic plants are abundant in many reaches. Two species that are particularly widespread and that have the ability to trap significant quantities of fine sediment are the emergent, linear species, *Sparganium erectum,* and the patch-forming, submerged species, *Ranunculus penicillatus.* By mid-summer, these plants are present in very high abundances in many reaches (e.g. Figure 3.3.13) and have an enormous effect on water velocity and depth.

Gurnell et al. (2006) investigated the impact of aquatic plant growth on flow velocity and depth at the reach scale within sections of reaches 5 and 6. They classified combinations of point velocity measurements at 0.6 channel depth measured at the same grid of locations during baseflow on four occasions during the summer growing season (early March, mid April, early June, Late August). Five classes of velocity behaviour were identified: 1 – lowest sustained velocities through the four measurement periods; 2 – intermediate and declining velocity through the four measurement periods; 3 – Initially high velocities followed by a sharp fall to low velocities through the four measurement periods; 4 – Initially lowest velocities followed by a sharp increase through the four measurement periods; 5 – Highest sustained velocity through the four measurement periods. Figure 3.3.13 illustrates the growth of aquatic plants in one of the studied reaches during the four occasions when measurements were collected. Figure 3.3.14 shows the spatial distribution of the velocity classes across the two studied reaches in comparison with water depth, the abundance of *Ranunculus penicillatus* and the abundance of other aquatic macrophytes (mainly *Sparganium erectum*) during observation period 4 (late August). Other macrophytes show highest abundance along the channel margins where water depth is low and velocity class 1 predominates. *Ranunculus penicillatus* shows highest abundance in mid-channel locations where water depths are intermediate and velocity classes are highly variable. In particular, velocity class 1 is typical at the centre of plant stands. Velocity classes 2, 3 and 4 occur at stand margins, illustrating the way in which velocities are reduced (classes 2 and 3) as the plant stands extend; inducing increased velocities in the gaps between the plants (class 4). Velocity class 5 is confined to those areas of the channel where no aquatic plants are present.

Surface bed material calibre remained coarse throughout all four measurement periods in channel areas subject to velocity class 5, and fine in all areas subject to velocity class 1. Velocity classes 2, 3 and 4 showed progressive fining of sediment on the bed surface as the plant canopies developed. The greatest depths of fine sediment were consistently found in those areas of the channel under velocity class 1, where 'other macrophytes' were most abundant. From these observations, it is apparent that all aquatic plants have a significant effect on flow velocity as their foliage develops through the summer growing season. However, fine sediment is only consistently retained in areas where 'other macrophytes' are present close to the channel margins. This suggests that, although *Ranunculus penicillatus* and 'other macrophytes' growing within the central area of the channel, have a strong influence on the magnitude and spatial pattern of flow velocities, and as a consequence, retention of fine sediment, this fine sediment is not retained through the winter. Significant fine sediment is only retained in association with 'other macrophytes' growing towards the edges of the channel margins, where *Sparganium* *erectum* predominates. Thus the 'critical zone' of plant-fluvial processes interactions (zone 2) is mainly confined to the submerged and emergent margins of the channel. Of course, these observations relate specifically to the main channel of the Frome in reaches 5 and 6. In upstream reaches and lower energy side channels, fine sediment retained by all aquatic plants may remain through the winter, extending the critical zone to the entire channel bed. For example, some of the fine sediment bars described in reach 4, may be associated, at least in part, with sediment retention by *Ranunculus penicillatus.*

In the studied sections of reaches 5 and 6, stands of *Sparganium erectum* appear to be an important component of channel margin migration. Figure 3.3.15 illustrates (a and b) fine sediment retained by the roots and rhizomes of *Sparganium erectum.* These photographs were taken in early spring when the leaves of the plants were just starting to appear. *Sparganium erectum* tends to grow in fairly shallow water (typically up to 1m deep; Haslam, 2005), and in relatively deeper channels, it tends to be confined to the margins. Thus it is most effective at trapping fine sediment to form submerged shelves that eventually aggrade to form side bars and then benches as the sediment features are colonised by more terrestrial species. Figure 3.3.15 d shows the early emergence of a large *Sparganium erectum* reinforced shelf, whereas Figure 3.3.15 c shows a mid-channel bar reinforced by *Sparganium erectum.* Figure 3.3.15 e shows the same bar in mid-summer and Figure 3.3.15 f shows a *Sparganium erectum*-reinforced bar which has trapped fragments of willow that is sprouting. This is an example of how *Sparganium erectum*-reinforced features can support colonisation by other plants which can sustain fine sediment retention, surface aggradation, and, in this case, the gradual evolution of the vegetated bar to form an island.

Overall, aquatic plants in general, and linear emergent plants such as *Sparganium erectum* in particular, are very effective physical ecosystem engineers in low energy, narrow rivers like the Frome. They support channel migration by aggrading the bank toe, and they also support channel division through island development.

Figure 3.3.13 The studied section of reach 6 in early March (top left), mid April (top right), early June (bottom left), and late August (bottom right).
Note: in mid April, the early growth of *Ranunculus penicillatus* (below the water surface in the foreground) and *Sparganium erectum* (a small stand emerging through the water surface towards the right side of the channel in the middle distance); by late August, the stands of *Sparganium erectum* are occupying almost 25% of the channel width.

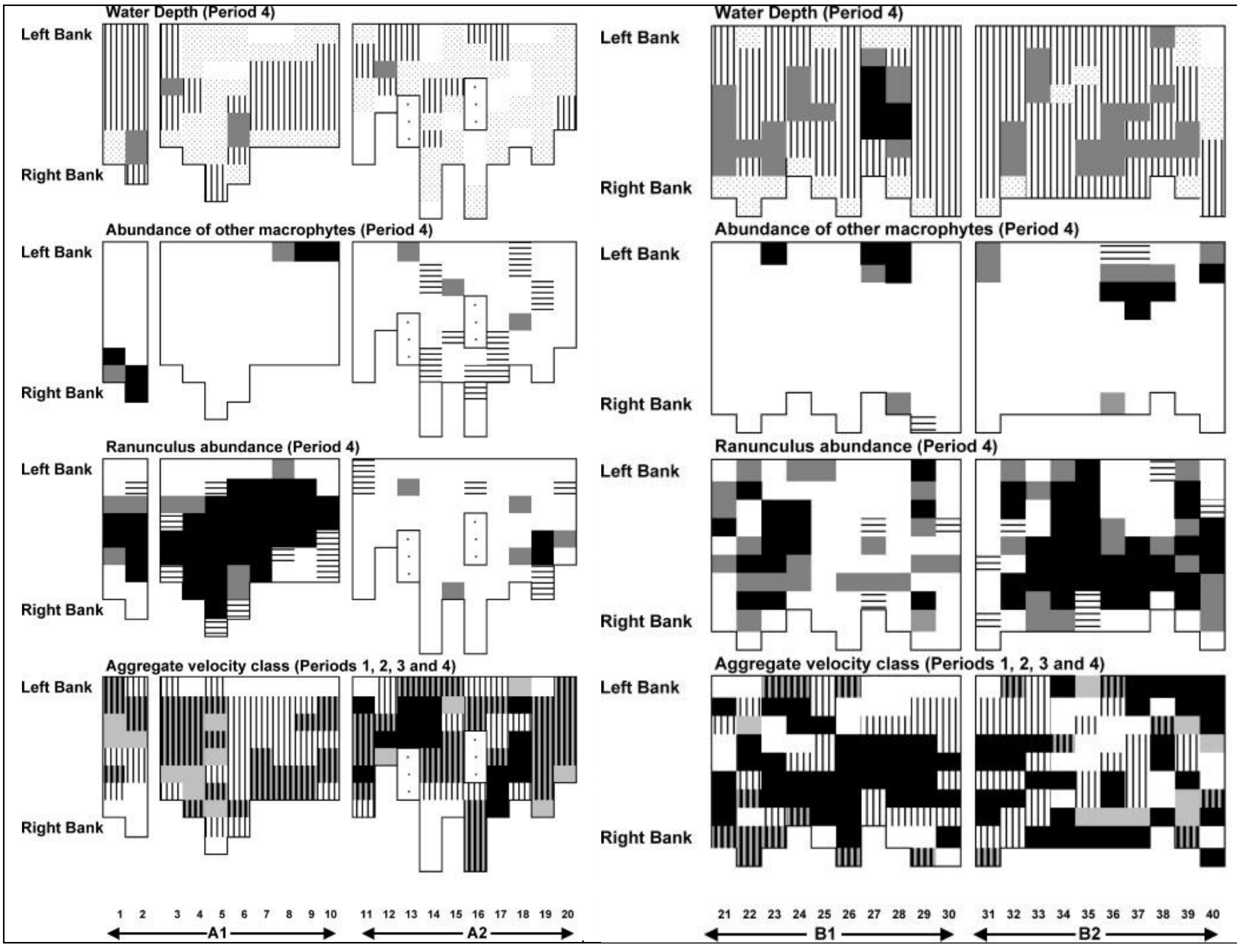


Figure 3.3.14 The spatial distribution (in the studied sections of reach 5 (left) and reach 6 (right) of water depth, *Ranunculus penicillatus* abundance, and the abundance of other macrophytes in late August in comparison with the velocity classes estimated from four sets of measurements spread through spring and summer

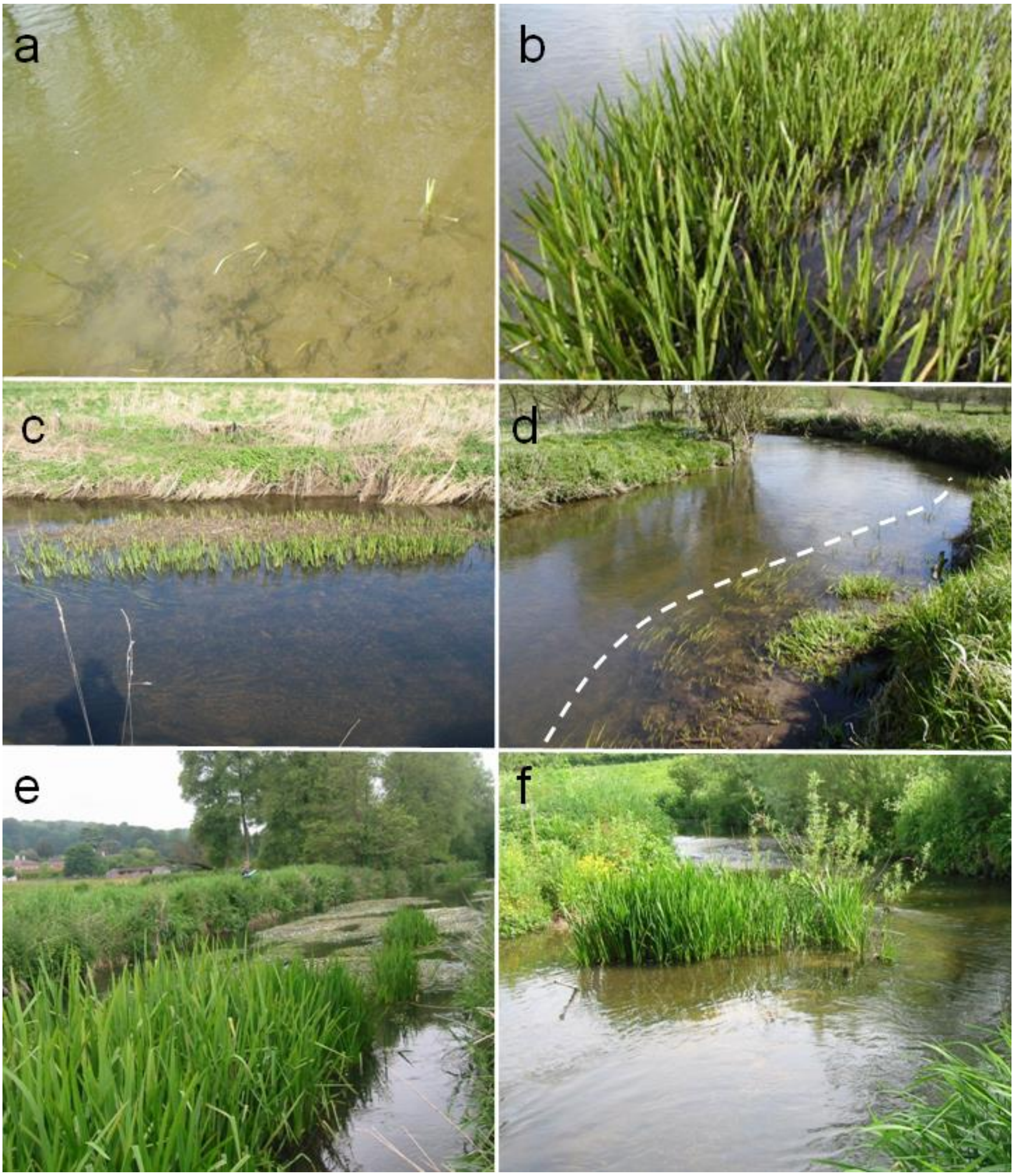


Figure 3.3.15

(a) and (b): Submerged shelf of fine sediment reinforced by *Sparganium erectum* roots and rhizomes with early (a) and developing (b) *Sparganium erectum* shoots.

(c) and (d): Two landforms developing as a result of fine sediment retention by *Sparganium erectum* – a bar (c) and shelf-berm-bench (d – the dashed white line indicates the edge of the shelf).

(e) *Sparganium erectum* in full foliage on the bar shown in (c)

(f) A bar of fine sediment reinforced by *Sparganium erectum.* The bar has trapped some 'living wood' that has sprouted to produce a young willow, showing the early stages of island development.

3.3.3 The River Tagliamento, Northern Italy

3.3.3.1 Region to Reach Context

Regional and Catchment Setting

The regional setting of the Tagliamento River is summarised in Table 3.3.1. According to the Water Framework Directive typology, the Tagliamento has a large, highland catchment of mixed geology (catchment area = 2580 km^2, mean elevation = 987 m, Tockner et al., 2003). In relation to the hierarchical framework (Deliverable 2.1), the catchment contains five landscape units, six segments and 57 reaches. The catchment is located within the Eastern Alpine subregion of the Alpine biogeographical region of Europe in its headwaters and middle reaches, and the Padanian subregion of the Appenino-Balkan biogeographical region of Europe in its lower reaches (source: http://www.globalbioclimatics.org). In the upper, middle and lower reaches, respectively: mean annual rainfall is 1700, 2000, and 1300 mm; and the flow regime is snow+rain, perennial flashy, and perennial flashy – intermittent.

Longitudinal, Lateral and Vertical Gradients

Bed material fines downstream along the main stem of the Tagliamento from boulder-cobble-gravel in the headwaters, to cobble-gravel-sand in the middle reaches, and gravel-sand in the lower reaches. River types are plane bed and braided (types 6, 8) in the headwaters, sinuous-straight, braided, and high-energy anabranching (types 13, 8, 10) in the middle reaches, and braided, high-energy anabranching, pseudo-meandering, meandering in the lower reaches (types 8, 13, 12, 14). Although river gradient decreases down the main stem, there are strong local variations that are often associated with a change in confinement and also a transition between river types, leading to widely varying presence of zones 3 to 5 as illustrated in the conceptual diagram of Figure 2.2.1.

Along most of the middle and lower reaches and in wider sections of the headwater reaches, the river is bordered by a floodplain that is composed of deep, free-draining alluvial deposits. Wherever the river is unconfined or partly confined, and thus a floodplain is present, riparian woodland borders the river. This rarely extends across the entire floodplain, but gives way to pasture in the upper catchment and mixed or cultivated agriculture in the middle and lower catchment with lateral distance from the active channel(s).

Tree species within the riparian woodland vary between the river’s source (approximately 1500 m.a.s.l.) and mouth. Karrenberg et al. (2003) surveyed samples of five 50 m^2 vegetated patches located within the active channel and spaced every 10 km along the main stem to 130 km from the river’s source (65 patches). They found a downstream reduction in woody species richness and average patch age (Figure 3.3.16 A), with distinct variations in the basal area of the woody species along the river (Figure 3.3.16 B). Nine woody species dominated at least one of the surveyed patches (assessed from total basal area of trees > 1.3m tall): *Populus nigra* (28 patches), *Alnus incana* (13), *Salix elaeagnos* (9), *S. alba* (4), *S. purpurea* (3), *S. triandra* (3), *S. daphnoides* (2), *Pinus sylvestris* (2), *Cornus sanguinea* (1). *Alnus incana* and *Salix elaeagnos* dominated the headwaters, whereas *Populus nigra* dominated along the middle and lower reaches (Figure 3.3.16 C).

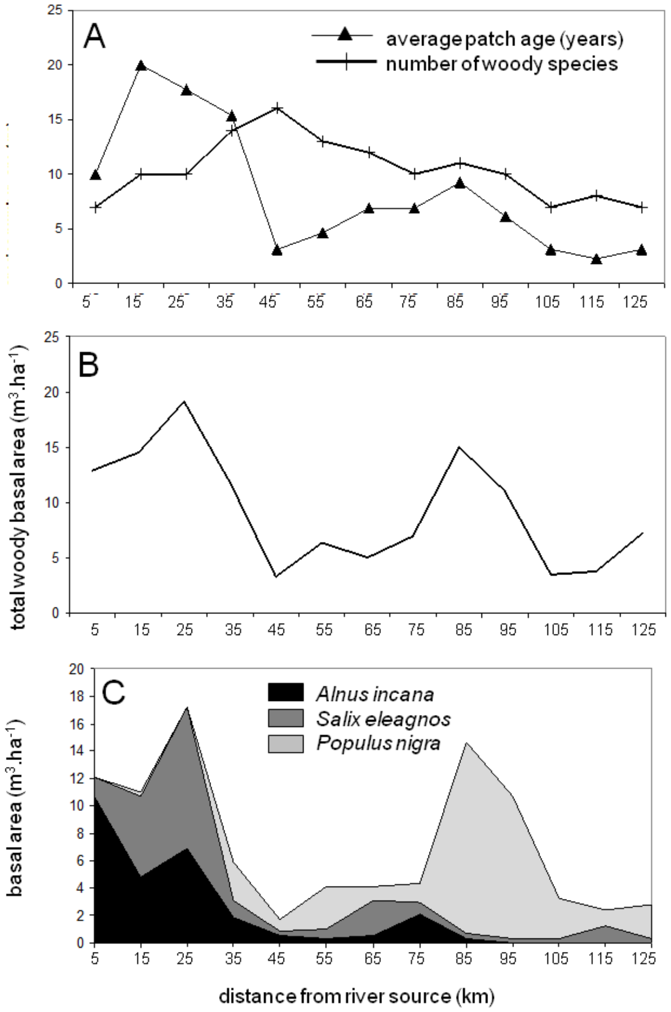


Figure 3.3.16 Characteristics of woody vegetation at 10km intervals along the Tagliamento main stem. At each site, measurements were obtained within 5 x 50 m^2 plots located on vegetated patches within the active tract (data from Karrenberg et al., 2003). (A) average age of oldest tree within each of the 5 plots and number of woody species present, (B) basal area of all woody species;(C) basal area of A.incana, S. elaeagnos and P. Nigra. (source: Gurnell, in press)

Populus nigra and the willow species (*S. alba*, *S. daphnoides*, *S. elaeagnos*, *S. purpurea*, *S. triandra*) regenerate freely from deposited uprooted trees and wood fragments, whereas *Alnus incana* regenerates less readily. This partly explains the transition from predominantly dead wood deposited within the river's active channel in the headwater reaches to wood capable of regeneration ('living' wood) in the middle and lower reaches (Gurnell *et al.*, 2000, Figure 3.3.17). In addition, some of the largest dead uprooted trees and logs in the headwaters are from coniferous species, which do not regenerate from deposited wood.

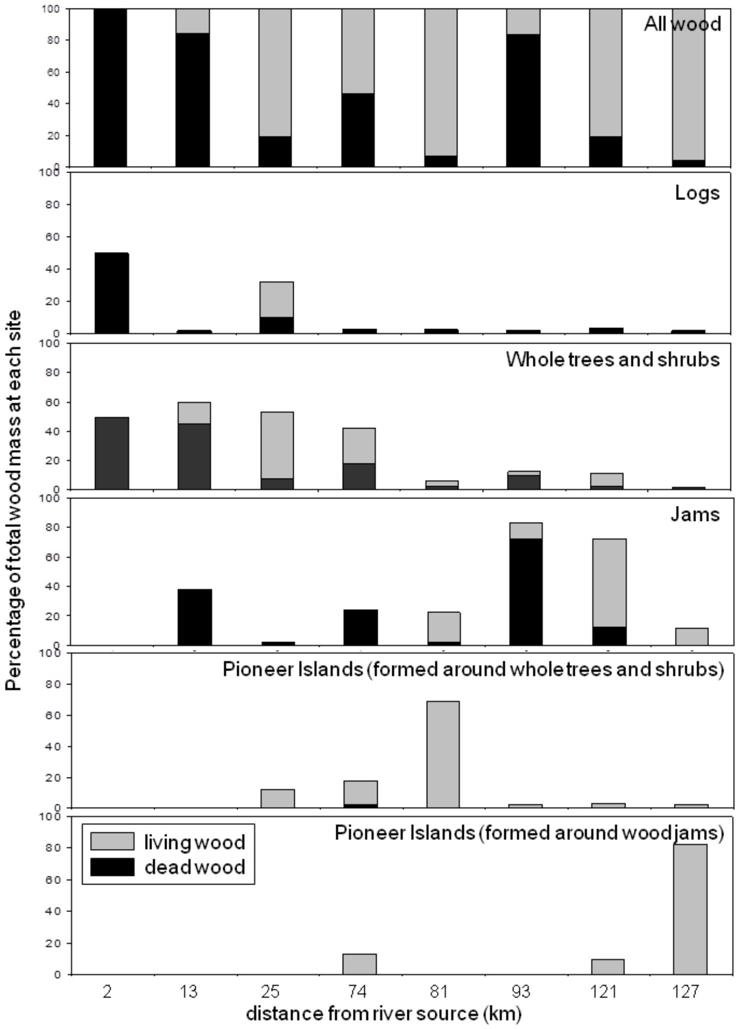


Figure 3.3.17 Percentage of the deposited wood biomass exposed on the surface of the active channel bed that is dead (black) or sprouting / alive (grey) at eight sites along the Tagliamento main stem. Data are presented for the total exposed wood biomass (top) and for different components of the wood biomass, illustrating a downstream trend in the proportions of the wood according to type and whether dead or sprouting. (Data from Gurnell et al., 2000; diagram from Gurnell, in press)

The alluvial deposits underlying the active channel and floodplain support alluvial aquifers with highly dynamic water tables which reflect the flashy flow regime. River flows often cease during summer in one part of the lower reaches, resulting in an intermittent flow regime as the water table falls below the level of the river bed. The high-energy, flashy flow regime, coupled with the highly dynamic alluvial water table, provide a very disturbed environment for vegetation along the entire main stem. In reaches where the water table tends to remain relatively high, extensive areas of zone 4 and 5 exist, representative of high soil moisture levels (zone 5) and extensive areas that are subject to quite frequent inundation (zone 4) (e.g. Figure 3.3.18). In reaches where the water table drops several metres below the ground surface for significant periods, zone 5 is quite arid as a result of the free-draining gravel-sand substrate and zone 4 is indistinguishable from zone 5 because of low soil moisture levels between floods. Zones

1 to 3 are quite extensive for all river types, reflecting the flashy, high-energy flows and the plentiful cobble and finer sediments that are available for fluvial transport.

Figure 3.3.18 illustrates a partly confined reach where groundwater upwelling maintains relatively high, and sustained water table levels in the alluvial aquifer. Interactions between woody vegetation, large wood and fluvial processes have resulted in the development of a morphologically complex floodplain since the 1940s and as a result, a series of parallel overlapping zones comprised of a mixture of the zones 1 to 5 defined in Figure 2.2.1. In essence, part of zone 2 in the 1940s evolved into zone 3 by the 1980s and has functioned as a mixture of zones 3, 4 and 5 since the 1990s (Zanoni et al., 2008).

Figure 3.3.18 A partly confined reach of the Tagliamento illustrating the overlapping distribution of zones 1 to 5 created by evolution of the channel and floodplain over the last 70 years.

Because of the current complex morphology, zone 5 dominates across the contemporary floodplain that is covered by riparian woodland but it coexists with extensive patches of zones 3 and 4, particularly close to the current active channel. Zone 5 is comprised of the higher floodplain patches, where high soil moisture levels sustain the riparian woodland, whereas zones 3 and 4 are comprised of depressions left by old side channels. Some of these (zone 3) are gradually silting up. This process is patchy and is often accelerated by wood that floats in during floods forming blockages (jams and plugs) in these linear depressions. While deposition is marked in some depressions (i.e. zone 3), other depressions receive little sediment but support ponds and wetlands sustained by floodwater and high water table levels.

Within the currently active channel, the main braid channels (zone 1) are bordered by dynamic gravel bars, the highest of which become colonised by vegetation (zone 2). As the vegetation interacts with fluvial processes, the bar surface aggrades to form pioneer and building islands (zone 2) which stabilise and aggrade to floodplain level (zone 3 patches of established islands within zone 2).

The Tagliamento is a highly dynamic river with changes driven by the interactions between vegetation and fluvial processes. As a result, the mosaic of vegetated patches are highly dynamic within zone 2 and are associated with a highly dynmaic and complex margin with zone 3. This is illustrated in Figures 3.3.19 and 3.3.20, where a sequence of classified satellite images show variations in vegetation extent within the active channel since the 1980s for two different reaches of the river, one in the headwaters (Figure 3.3.19) and one in the middle reaches (Figure 3.3.20).

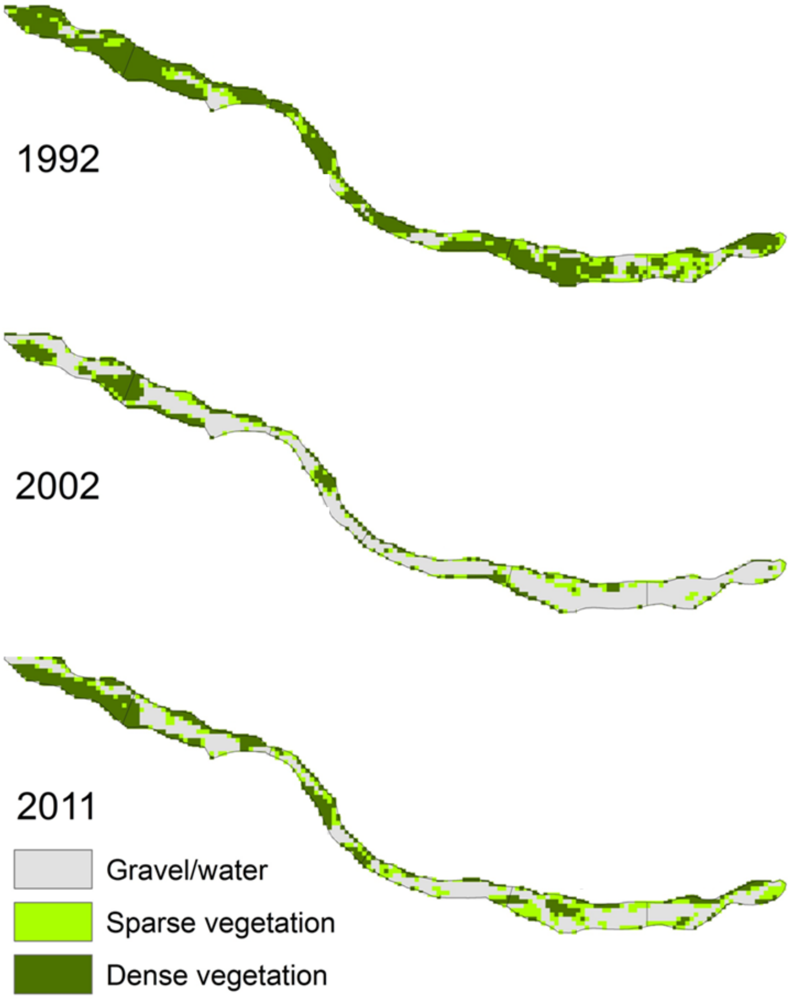


Figure 3.3.19 Variations in the extent of dense (closed canopy) and sparse vegetation patches within the active channel of the Tagliamento River, between 9 and 15 km from its source, based on the analysis of Thematic Mapper data (for details, see Henshaw et al., 2013).

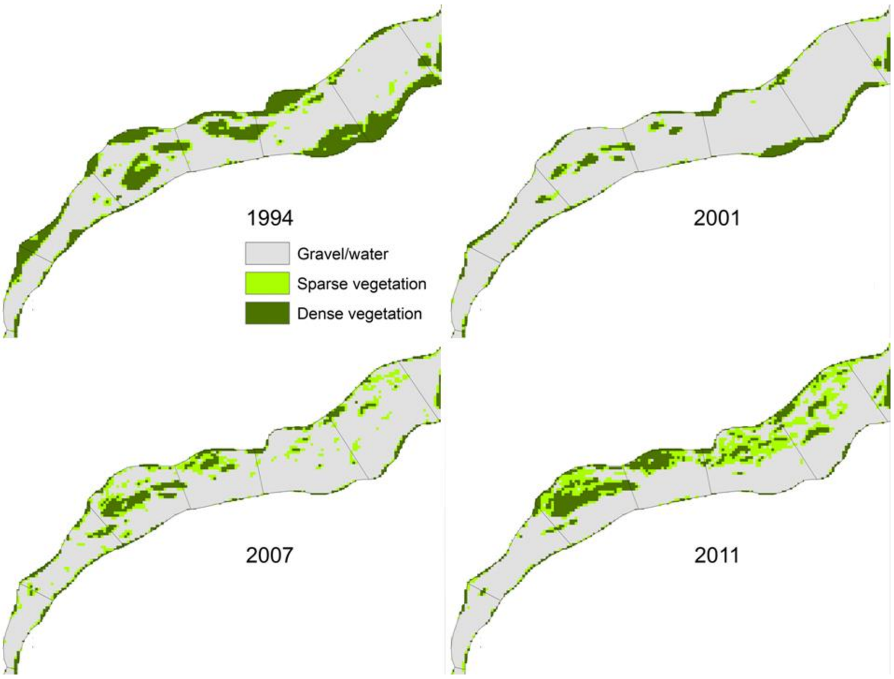


Figure 3.3.20 Variations in the extent of dense (closed canopy) and sparse vegetation patches within the active channel of the Tagliamento River, between 77 and 83 km from its source, based on the analysis of Thematic Mapper data (for details, see Henshaw et al., 2013).

Critical zone of interaction between vegetation and fluvial processes

The active channel width of the main stem averages 416 m and ranges from 5 to 1810 m. The active width exceeds 100 m for 69% of the main stem length, making it a 'large' channel with respect to riparian trees, wood and aquatic plants. The high energy of the river prevents the establishment of aquatic plants within the main channel, although they are observed occasionally in side channels within the riparian woodland that borders the river for most of its ca. 170 km length. Although wood is harvested from the main channel, much remains on the river bed as a consequence of high wood delivery from the flashy flow regime interacting with the riparian woodland along the channel margins and the numerous islands that are present. Section 3.3.3.2 provides details of the many ways in which riparian trees and wood interact with fluvial processes within the critical zone between zone 1 and the margins of zone 3 along the main stem of the Tagliamento River.

3.3.3.2 Influence of riparian trees and wood on river morphodynamics

As noted above, there are strong contrasts in the environmental setting along the Tagliamento River. The most important implication of these contrasts for hydromorphology are (a) transitions along the entire river length in the dominant tree species and the related transition from dead wood to living wood, accompanied by sediment fining and an increase in the availability of sand and finer sediments downstream, (b) local changes in the growth performance of the dominant tree species, and the relevance of (a) and (b) for (c) the mainly multi-thread planform which varies from braided to high energy anabranching according to wooded island extent (this excludes single thread reaches in very confined mountainous sections and a meandering planform in the most downstream part of the main stem).

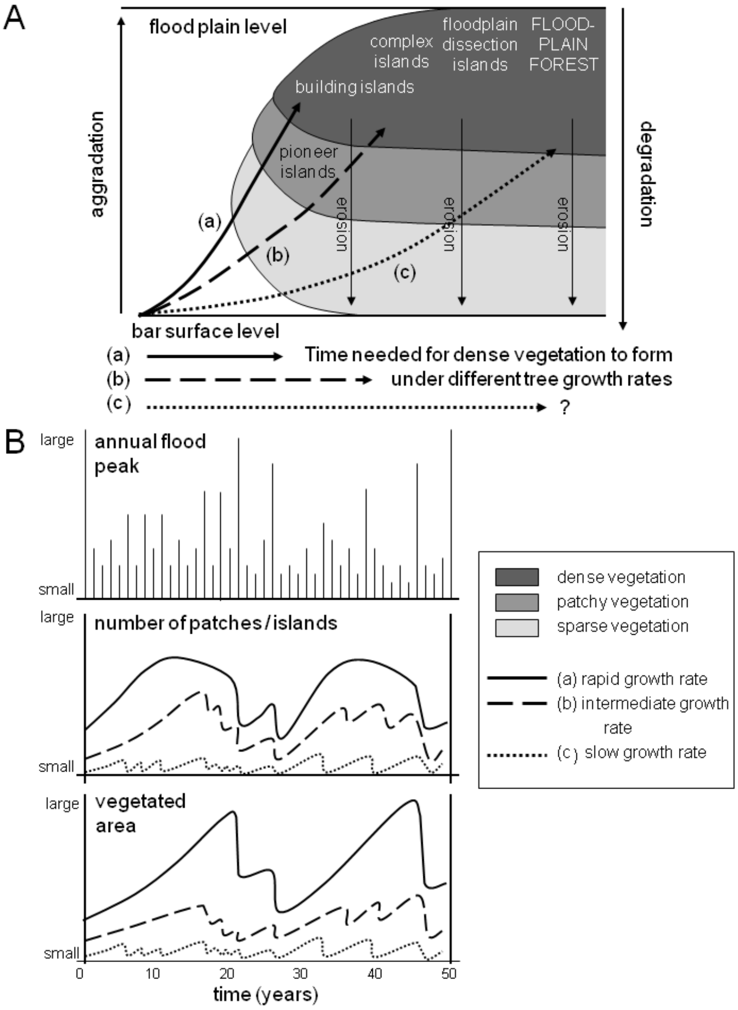


Figure 3.3.21 Conceptual model of island development (after Gurnell et al., 2001). (A). Different rates of aggradation and island development (from bare bar surface through pioneer, building and established island development) according to different growth trajectories a, b, and c (for explanation see text). (B). Changes in the number and area of islands under each of the three vegetation growth trajectories (a, b, c) in response to the same sequence of annual floods. (Source: Gurnell, in press)

Wood has been shown to be an crucial element in island and floodplain development along the Tagliamento River (Gurnell et al., 2001). A conceptual model of island development (Figure 3.3.21) proposes that three broad categories of tree-related roughness elements contribute to the initiation of island development (seedlings, dead wood, and 'living' (regenerating) wood). These are incorporated in three trajectories of vegetation growth (Figure 3.3.21 A) on bar surfaces. Trajectory (c) is initiated by germination of seeds dispersed across open gravel bar surfaces. Trajectory (b) is initiated by seed germination and/or regeneration from small pieces of living wood that accumulate with finer sediments in the lee of large dead wood accumulations. Trajectory

(a) is initiated by regeneration from large living pieces of wood (often entire uprooted trees). All three trajectories involve interaction between woody vegetation and fluvial processes. Trajectory (a) involves the most rapid rates of vegetation growth, retention / aggradation of finer sediment, and development of root-reinforced, vegetated landforms. Trajectory (c) shows the slowest rates of vegetation growth, sediment retention and landform development.

Given the different rates of vegetation development that may occur under the three trajectories following large flood disturbances (Figure 3.3.21 B), the model proposes that trajectory (c) is very unlikely to lead to the development of islands. This is because the relatively slow growing dispersed seedlings are easily uprooted or buried by fluvial processes before they are able to develop into substantial plants. However, during a recent period of several years without floods, levée-like structures of fine sediment accumulated around seedlings growing along braid channel edges in some reaches, indicating that in lower-energy river environments, tree seedling growth is capable of initiating pioneer, ridge-like landforms, and in some channels, these might take the form of scrolls or benches. Trajectory (a), which supports the most rapid vegetation growth, is most likely to resist flood disturbance and trap sediments to support rapid pioneer island development and coalescence to form building islands and, eventually, established islands (Figure 3.3.21 A). Trajectory (b) has an intermediate chance of contributing to established island development rather than succumbing to removal of the vegetated patches and landforms by fluvial processes (Figure 3.3.21 A and B). The relative success of the three trajectories in contributing to island development, and thus the spatial distribution of zones 1 to 3, reflects their different rates of initial above- and below-ground vegetation growth, and thus their ability to trap and stabilise finer sediment, and to resist erosion / removal by fluvial disturbances. The same trajectories contribute to the expansion of building and established islands, and also to islands that become dissected from the floodplain, leading to the production of complex islands (Figure 3.3.21 A).

In the headwaters of the Tagliamento where dead wood dominates, trajectory (b) underpins vegetation and island development. Dead wood accumulates on the highest bar surfaces during floods, where it snags and accumulates around roughness elements, such as the breaks of slope at bar top margins, areas of larger clasts, and existing vegetation patches. Fine sediment is scarce and easily mobilised by high energy river flows in the headwaters. However, obstructions such as large wood accumulations provide lee-side shelter where fine sediments and seeds can accumulate, providing both a fine substrate and shelter suitable for seeds to germinate and establish. If the seedlings are not severely disturbed during their first few years of growth, they form a patch of vegetation that can develop into an island. Once initiated, islands extend upstream by trapping wood that shelters new seedling growth and downstream where the island itself provides shelter in which fine sediment and seeds can accumulate. Developing islands divide high river flows, induce scour and trap wood along the island margins, and thus increase the local relative relief of the island surface with respect to the surrounding bars. This process is similar to that of bar apex jam formation described by Abbe and Montgomery (2003), and it can lead to quite rapid island development, particularly when the relative relief of the active channel is disrupted by landslides, which deposit major roughness elements in the form large clasts (boulders) and piles of sediment. Figure 3.3.19 illustrates high island cover (1992), low island cover (2002) and recovery over 9 years from the low island cover (2011), based on the analysis of Thematic Mapper data (Henshaw et al., 2013) for a 6 km long reach, which is confined by steep mountain hillslopes, and is located 9-15 km from the river's source at an average elevation of 741 m. The images are bounded by the maximum lateral extent of bare gravel found at any time between 1984 and 2012 and so they illustrate how the extent of zones 1 and 3 and the intervening critical zone has fluctuated They illustrate the variable extent and rate of recovery of islands in this headwater location, and as a result, how the reach fluctuates between a braided and high-energy anabranching river type as islands develop and are eroded by extreme flow events. Landslides periodically contribute large amounts of sediment to the active channel in the upstream (left) 2 km of the reach and between 4 and 5 km from the upstream end of the 6 km reach.

In the central and lower reaches of the Tagliamento, 'living' wood underpins island development and dynamics (Gurnell et al., 2001, 2005). This part of the river is dominated by braided and high-energy anabranching river types, with the active channel reaching a maximum width of 1800 m and typically achieving a width of over 900 m. Analysis of Thematic Mapper again illustrates how dynamic vegetation and bare gravel / water cover have been in the area occupied at some point by bare gravel since 1984 (Figure 3.3.20). In this part of the river, trajectory (a) characterises vegetation-hydromorphology interactions, with the dominant riparian species, *Populus nigra,* playing a key role. Vegetation cover regenerates extremely rapidly in many parts of the middle and lower reaches of Tagliamento, with the full sequence of pioneer island development around individual deposited trees, followed by enlargement and coalescence to produce building and eventually established islands within a few years. For example, Figure 3.3.20 illustrates a time of high island cover (1994), which was before two large floods in 1996 and the largest flood peak (in 2000) in the 30 years of daily stage records. Apart from a very brief flash flood in 2004, there were no major flood peaks between 2000 and 2011, and during this 10 year period, rapid island development has occurred and, since 2007, widespread coalescence, reflecting the conceptual pattern for trajectory (a) (Figure 3.3.21 B). Again, it is clear from Figure 3.3.20 how spatially dynamic zones 1 to 3 and the intervening critical zone are as a result of vegetation-fluvial process interactions.

A major environmental constraint on the initiation and development of islands is the active channel width, particularly where the channel is confined, since width combined with channel gradient, affects the energy per unit channel width (unit stream power) for any given discharge. In narrow confined reaches of the Tagliamento such as the Pinzano gorge (river km 83, width ca 130 m), even modest (frequent) floods have very high energy and so islands cannot establish. However, this is not a significant constraint throughout much of the middle and lower reaches of the Tagliamento. A more widespread constraint is the regeneration success and rate of growth of deposited trees and wood fragments. By restricting growth rate measurements to samples of 20 individuals of a single species (*Populus nigra*), each approximately 3m tall, and located on bar tops at 15 different locations along the river (Figure 3.3.22), it is possible to observe clear spatial trends in growth rates of *P.nigra*. These spatial contrasts largely reflect moisture availability in the alluvial aquifer. The different growth rates established for the same sites in different years (2005 and 2010) reflect temporal contrasts in moisture availability, since river flows were higher with more frequent flow pulses between 2007 and 2010 than between 2003 and 2005, ensuring the maintenance of

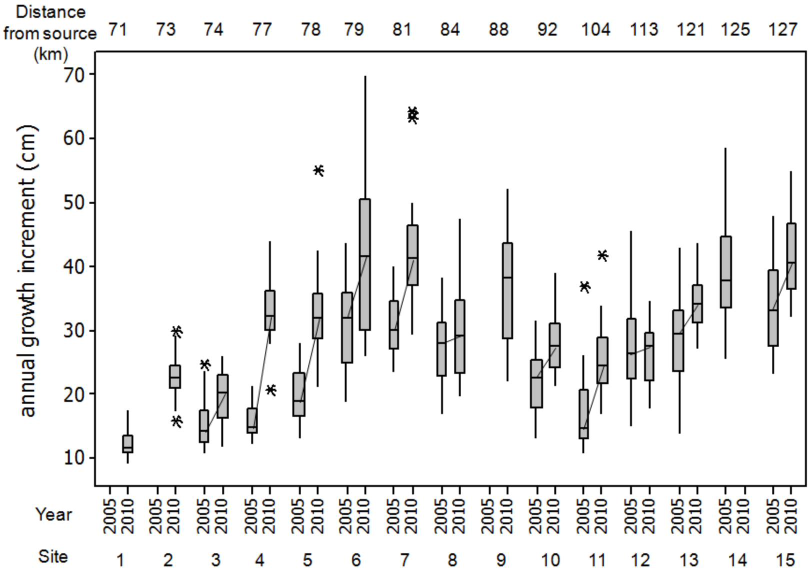


Figure 3.3.22 Box and whisker plots of the annual growth increments, measured in 2005 and 2010, of samples of twenty 3 m tall *P. nigra* located at fifteen sites along the Tagliamento between 71 and 127 km from the river's source (source Gurnell, in press).

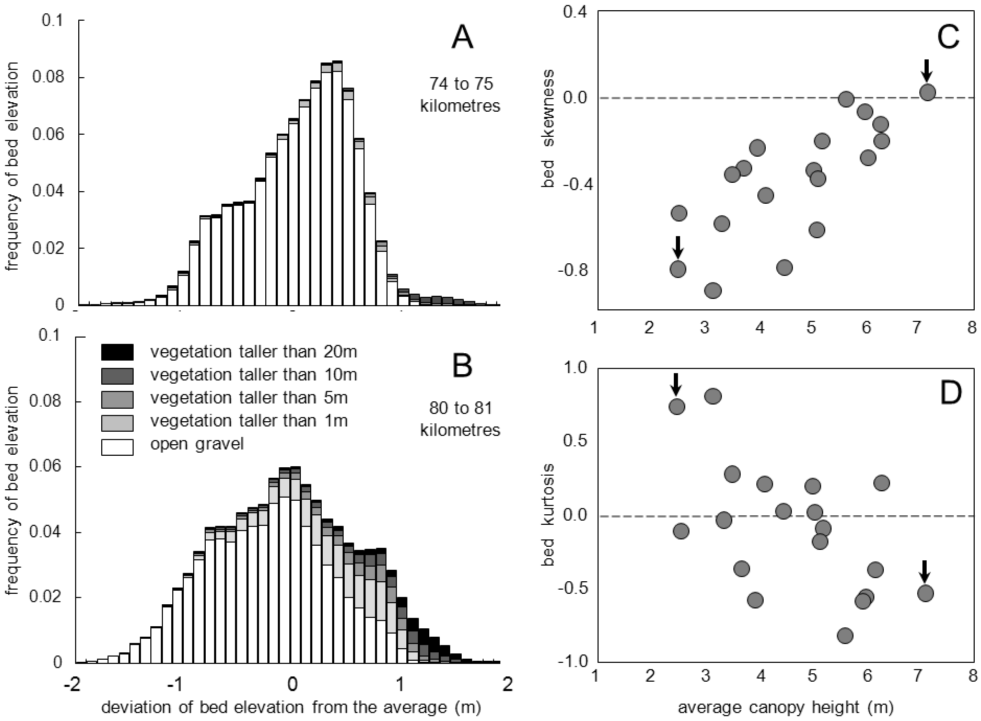


Figure 3.3.23 Left: .Frequency distributions of river bed elevation within 1km segments of the active tract of the Tagliamento River between 68 and 89 km, in the most heavily (A) and least heavily (B) vegetated segments. The bars in (A) and (B) are subdivided according to the proportion of grid cells at that elevation that are bare gravel (vegetation shorter then 1m), or under vegetation taller than 1, 5, 10 and 20m. Right: Relationships between average vegetation canopy height in nineteen 1 km segments of the Tagliamento River between 68 and 89 km and the skewness (C) and kurtosis (D) of the frequency distribution of river bed elevation (data from Bertoldi et al., 2011b, source: Gurnell, in press).

higher water table and moisture levels in the alluvial aquifer for the years preceding the 2010 measurements. Within the parts of the middle and lower reaches illustrated in Figure 3.3.22, island development and dynamics are most marked where the growth rates are highest (Gurnell, in press).

In summary, the Tagliamento illustrates the crucial importance of large wood for pioneer island development within the critical zone. The development and enlargement of islands is accompanied by the development of a suite of related habitats that would not otherwise be present on the braid bars. Furthermore, differences in the area and development of vegetated patches (islands) are associated with differences in the morphology of the river bed (Bertoldi et al., 2011) as represented by the kurtosis and skewness of the bed elevation frequency distribution (Figure 3.3.23). In this river setting, significant tree management and wood removal would threaten island dynamics and the availability of related habitats, and would have implications for river bed morphology and the predominant river types that are present.

3.3.4. The Rivers Guadarranque and Guadalupejo, South-Western Spain

The Guadarranque and Guadalupejo rivers are two medium-sized tributaries of the Guadiana River which enter the main river on its right bank in the central part of the Basin, between the Cijara and García-Sola reservoirs in Extremadura, South-West Spain (Figure 3.3.24).

Figure 3.3.24. Location of the Guadarranque and Guadalupejo catchments in the Guadiana Basin.

3.3.4.1. The Guadarranque River

Regional and Catchment Context

The Guadarranque catchment is located within the Western Mediterranean biogeographical region, with mean annual rainfall between 650 and 800 mm and mean annual temperature around 20ºC. According to the Water Framework Directive (WFD) typology, the Guadarranque has a medium-size (287 km^2), mountain, siliceous catchment, with an altitudinal range between 1430 m (highest elevation at the catchment divide) and 360 m (lowest elevation of the river at its confluence with the Guadiana River). Slates and quartzites and shrub-forest land cover more than 80 % of the area. The Guadarranque valley corresponds to a synclinal formation and is relatively straight, narrow and V-shaped along its length.

In relation to the hierarchical framework (Deliverable 2.1) the catchment contains two landscape units. Landscape unit 1, is located in the upper part of the catchment. It has steep hillslopes covered by native forest ('dehesas' of *Quercus ilex*) and contains a single homogenous steep river segment (0.07 average slope) of approximately 5 km in length, which is 12 % of the entire river length. The valley in this part of the river is strongly confined and the bed of the channel is formed of coarse, colluvial material (boulders and cobbles) with frequent rock outcrops. Landscape unit 2 occupies the rest of the catchment and contains a single river segment 36.5 km in length (there are no significant tributaries), representing the remaining 88% of the entire river length. The valley in this landscape unit alternates between a confined and partly confined cross profile. Along the segment of landscape unit 2, five river reaches have been differentiated, reflecting small local expansions and constrictions of the valley which determine the formation of small, local, discontinuous floodplains. All of these reaches show high slope values ranging between 0.041 and 0.067. In these reaches, the bed material is mostly cobbles with gravel and sand.

There is only one gauging station on the Guadarranque River and this is located near its confluence with the Guadiana River. Daily discharge data are available from 1968-1990 and 2003-2009. Figure 3.3.25 shows the Mediterranean hydrologic regime of the river, which according to the methodology proposed in D.2.1. Annex C may be classified as 'intermittent flashy'. Water is most available during the rainy season (November to March) but river flows decrease sharply in the warmer months and the river dries out in most years. The main flood period is frequently in January, and is moderately predictable. Base flow is very low and the average number of zero days extends to nearly two months.

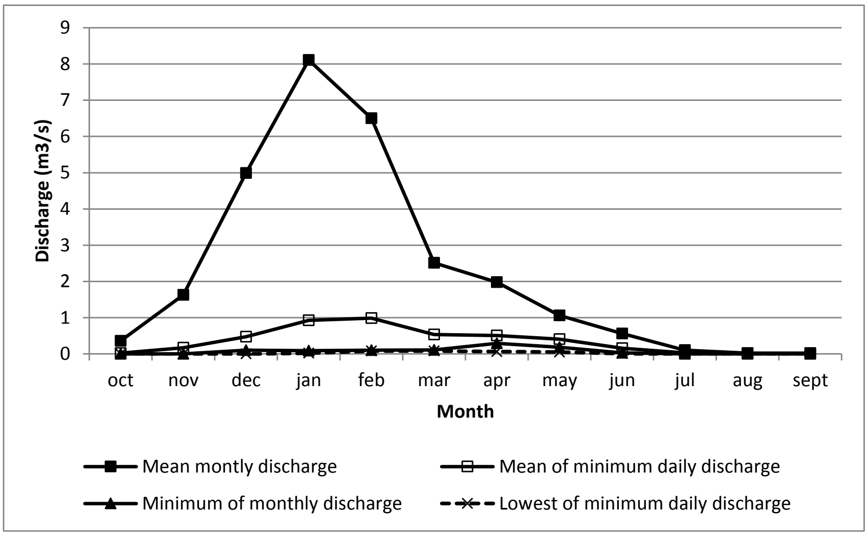


Figure 3.3.25 Flow regime characteristics of the Guadarranque river (Cijara, 1969-1989),

Longitudinal, Lateral and Vertical Gradients

The geological context of the river and the rather homogeneous geomorphological features of the Guadarranque valley create a relatively smooth longitudinal bed profile. A similar size of bed material (mostly cobbles and gravel) is observed along the river channel from the source to the mouth (Figures 3.3.26 to 3.3.29). A similar planform typology is also exhibited along the length of the river. Applying the river types described in Deliverable 2.1, river type 5 (straight-sinuous, boulder-cobble bed) is observed throughout landscape unit 1 and types 7 (straight-sinuous, gravel-sand bed) and 11 (wandering, gravel-sand) are observed in landscape unit 2. Because of the valley confinement of the active channel and floodplain, there is negligible alluvial material stored in the valley, and there is no evidence of an alluvial aquifer or permanent groundwater.

The same plant formations are present as a narrow continuous mixed gallery of *Salix salvifolia* and *Fraxinus angustifolia* from the upper parts of the river to the lower reaches near the confluence with the Guadiana River. Alternate patches of *Alnus glutinosa* and *Salix fragilis* at the river banks and *Flueggea tinctorea* at the floodplain pockets are also frequently observed. The confined nature of the valley results in a narrow river corridor, typically 20 to 30 m on each side of the active channel along most of the river length. This leads to compression of the lateral zones illustrated in Figures 2.2.1 and 2.2.2. Taking into account the reduced soil water availability for vegetation growth, zone 5 of the conceptual model hardly exists. Furthermore, channel morphology and entrenchment strongly limit the lateral dimensions of zones 2, 3 and 4. Zones 2 and 3 are undifferentiated, containing the same species and both located at the river banks, and zone 4 only exists at local expansions of the valley floor where occasional inundation over small floodplain pockets may occur (Figure 3.3.30).

Figure 3.3.26 Upper part of the Guadarranque river (landscape unit 1) showing the willow gallery of Salix salvifolia with Fraxinus angustifolia.

Figure 3.3.27 Middle parts of the Guadarranque river

Figure 3.3.28 Lower parts of the Guadarranque river with frequent rockoutcrops in the channel and similar riparian vegetation formations to the upper reaches

Figure 3.3.29 Lower parts of the Guadarranque river showing the coarse bed material present along the entire river

Figure 3.3.30 Riparian corridor of the lower Guadarranque river showing vegetation in zones 2+3 (yellow color) and 4 (orange color)

In terms of aquatic plants, due to the coarse size of the bed substratum and frequent rock outcrops along the entire river, which reflect the steepness of the channel and high energy of floods, aquatic vegetation is nearly absent. Only very local stands of Carex, Juncus and Cyperus are observed at the river banks of the upper reaches. The shade effect of the relatively high riparian gallery covering the river channel and the low mineralized waters from natural runoff represent additional limitations on submerged or bank-attached macrophyte growth inside the channel.

Influence of riparian trees and wood on river morphology in the critical zone

Within landscape unit 1, the average main channel width is approximately 5-10 m, which represents a ‘small’ channel in the context of the riparian trees and wood that drive vegetation-fluvial process interactions.

Along this upper part of the river, it is bordered by a relatively dense willow gallery of *Salix salvifolia,* externally bordered by *Fraxinus angustifolia.* Riparian trees cover most of the narrow steep channel (average slope 0.07) and so have considerable potential to influence channel form (Figure 3.3.31a). Local masses of *Juncus* sp. and *Carex* sp. may also act to stabilize the river bed, locally retaining some fine sediment, diverting water flowing along the channel, and stabilizing the bed at high flows (Figure 3.3.31b). These vegetation effects are reinforced by occasional rocky outcrops among a coarse substratum with cobbles and boulders.

Within landscape unit 2, which represents the middle and lower reaches of the river, average main channel width ranges from 16-18 m in the upper section and 20-25 m downstream to the mouth. With respect to riparian trees and wood these values indicate ‘intermediate’ channels. The riparian corridor is mostly covered by a narrow gallery dominated by *Fraxinus angustifolia* and *Salix salvifolia* with patches of *Alnus glutinosa* towards the inner parts close to the water’s edge, and bushes of *Fluggea tinctoria* towards the outer area of discontinuous floodplain. According to the size of the tree species, the channel is sufficiently narrow to be partly or fully bridged by toppled trees and is subject to major wood jams that may have a significant influence on channel form.

The river is confined within a narrow valley for most of its length, and in some reaches, in addition to the impact of dry climatic conditions, the riparian vegetation is significantly impacted by extensive grazing by both wild (deer) and domestic animals (goats), reducing the density, vigour and recruitment of the main species, and leading to a reduction in the potential for trees and wood to be delivered to the river channel (Figure 3.3.32a). Nevertheless, periodic, torrential precipitation events produce flash floods which erode the channel banks, exposing tree roots, inducing the fall of older trees and the formation of wood jams (Figure 3.3.32b).

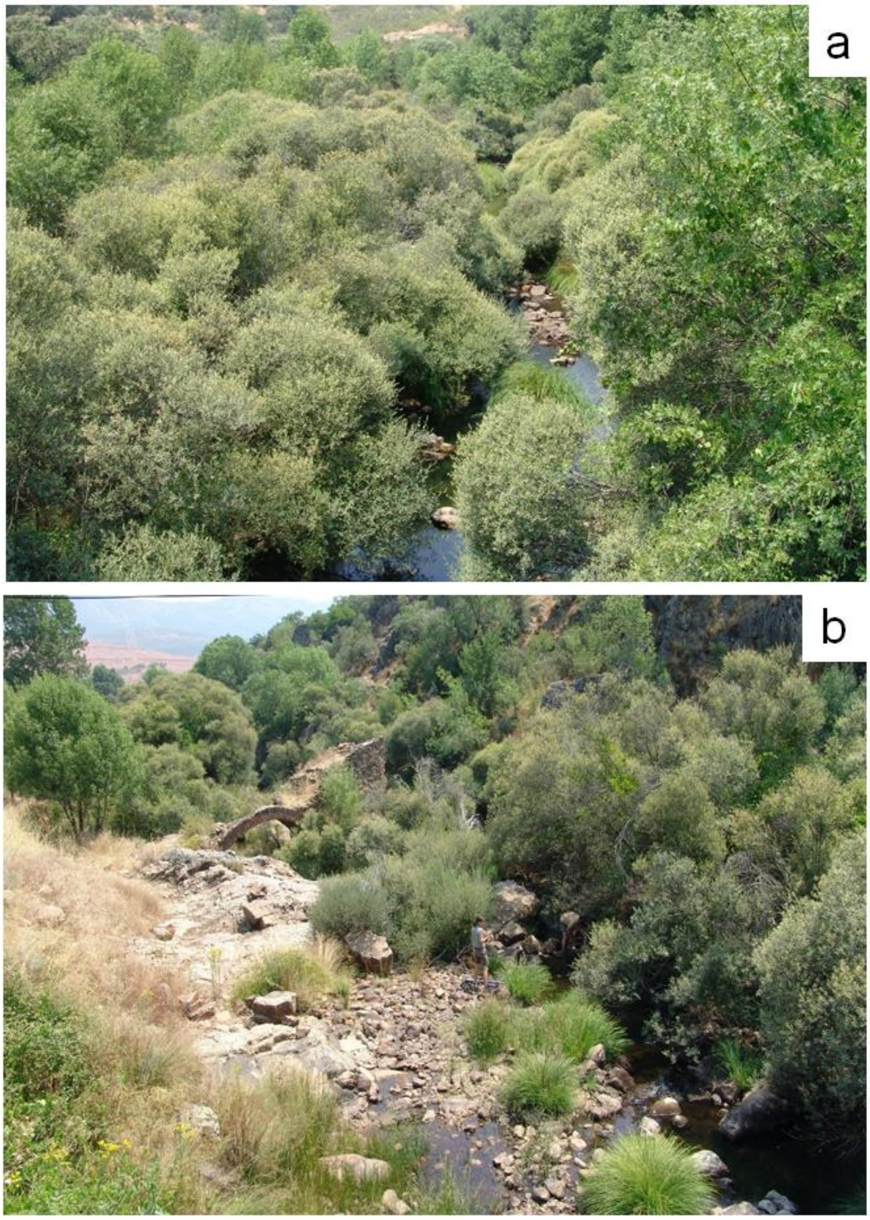


Figure 3.3.31. Upper part of the Guadarranque river (landscape unit 1).
a) Willow gallery of *Salix salvifolia* with *Fraxinus angustifolia* covering the channel and conditioning morphological processes;
b) presence of macrophytes (*Carex, Juncus*) in open shallow sections anchoring the substratum.

In summary, interactions between vegetation and fluvial processes are apparent widely within zones 2 and 3 along the Guadarranque river, but are very compressed as a consequence of valley confinement (see Figure 3.3.30). Channel morphology (i.e. effective channel width) and hydraulic conditions (i.e. water velocity, roughness) are influenced by riparian vegetation. In the upper parts of the river within landscape unit 1, continuous willow formations of *Salix salvifolia* and local masses of *Carex* anchor the channel banks and represent major elements of channel roughness during floods, determining flow deflection and division. Within landscape unit 2, trees on the river banks, notably *Fraxinus angustifolia* and *Alnus glutinosa,* confer cohesion and strength to riparian soils and represent an essential element to maintain channel morphology and bank forms (Figure 3.3.33a). During floods, these riparian trees act as strong structures against the erosive forces of river flows and retain large quantities of wood (Figure 3.3.33b), which contribute to energy dissipation by friction and to reduction of the effective cross section promoting jams and over-bank flooding (Figure 3.3.33c). In the case of the Guadarranque river, the riparian vegetation is not actively managed and wood is not harvested or removed. However, overgrazing reduces riparian vegetation biomass and recruitment, and Mediterranean climatic conditions may accelerate wood decomposition and mineralization. These factors should be considered as important characteristics that differentiate this river’s biogeomorphological environment from others across different biogeographic regions of Europe.

Figure 3.3.32 Middle and lower parts of the Guadarranque river (landscape unit 2)

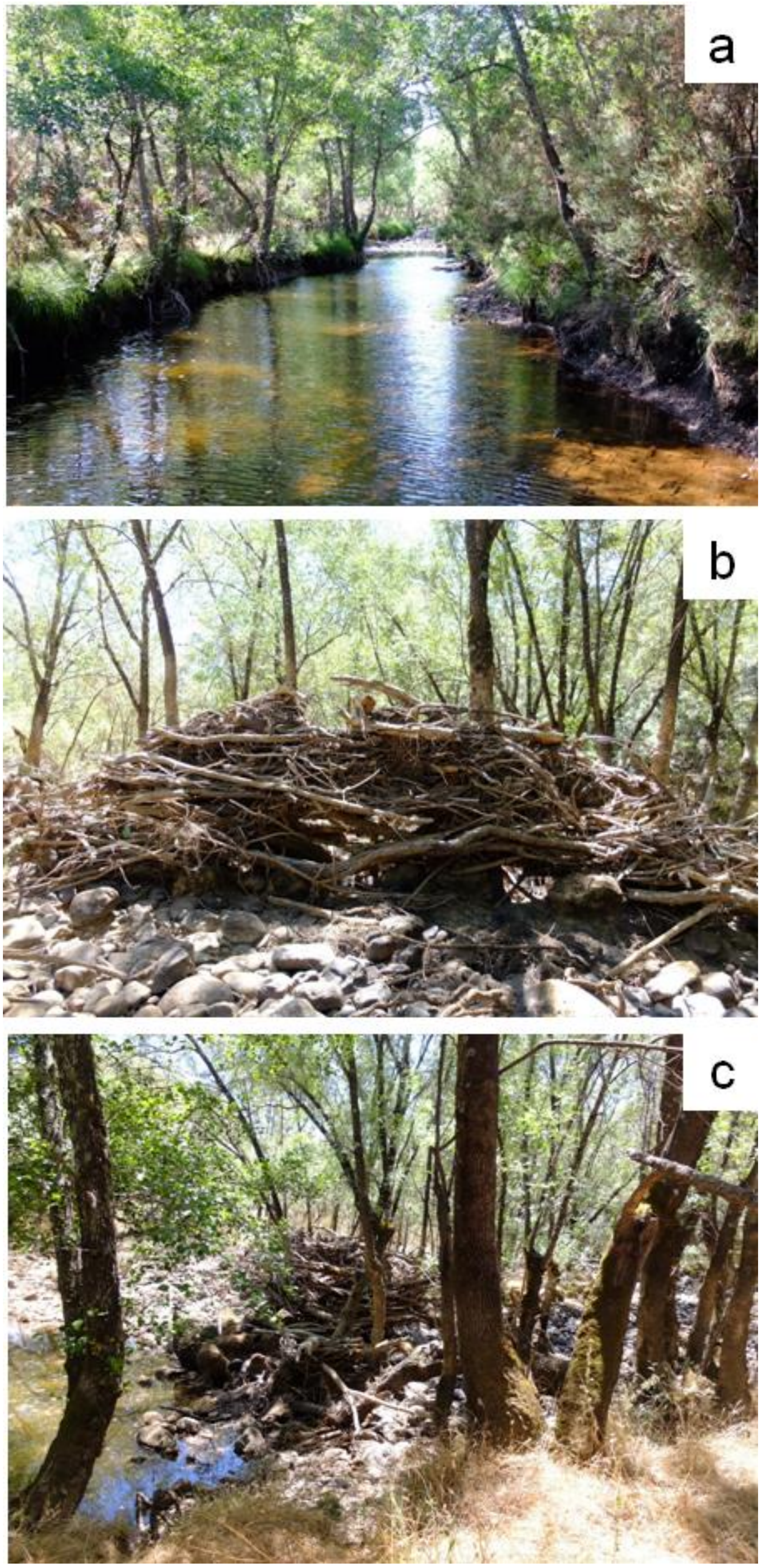


Figure 3.3.33 Different effects of vegetation-water and sediment flows interactions in the Guadarranque river.

3.3.4.2 The Guadalupejo River

Regional and Catchment Context

The Guadalupejo is located in the same biogeographical region as the Guadarranque and experiences similar precipitation and temperature regimes. The catchment is also medium sized (416 km^2) according to the WFD, and the altitudinal range is also similar, between 1350 m and 355 m. In relation to the hierarchical framework (Deliverable 2.1), two landscape units have been differentiated within the catchment. Landscape unit 1 occupies the upper third part of the catchment (35% of the area) and is dominated by Precambric slates with a mixed forest and arable land cover. It contains one relatively steep (average slope 0.09) river segment, running along a confined and relatively narrow valley. Landscape unit 2 occupies the rest of the catchment (65 %) representing the middle and lower sections of the river, and is mainly underlain by sedimentary rocks with extensive alluvial deposits along the main unconfined valley. Landscape unit 2 contains two river segments defined by the confluence of the Silvadillo River, with longitudinal slopes of 0.04 upstream and 0.01 downstream.

The flow regime is perennial in landscape unit 1 and becomes intermittent runoff/flashy downstream when water infiltrates through the alluvial deposits along the river in landscape unit 2. Within this second landscape unit, there are distinct variations in water table depth. In the upstream sections the water table is deeper with respect to the average channel bed elevation resulting in isolated pools and a dry river bed during a large part of the year. Further downstream flowing water is sustained in the channel for a greater length of time although the channel dries out during the driest period (Figure 3.3.34). The highest flows occur in December and the frequency of floods is relatively high. At the gauging station located in the lower sector of the river, base flows are higher than in the Guadarranque River and the number of zero days is significantly smaller (typically 4 to 5 days - less than a week). Coarse bed material (pebbles and gravel) predominates along the entire river. River types mostly correspond to type 7 (straight-sinuous) within the upper part of the river in landscape unit 1 and type 11 (wandering) within landscape unit 2, with some braided and island braided planforms (types 8 and 9) in the lower sectors of some tributaries.

Although the river Guadalupejo is located in the same geographical context (i.e. climate, geology and land cover) as the Guadarranque River, important differences in channel morphology and riparian vegetation interactions are observed, most of them reflecting differences in valley features.

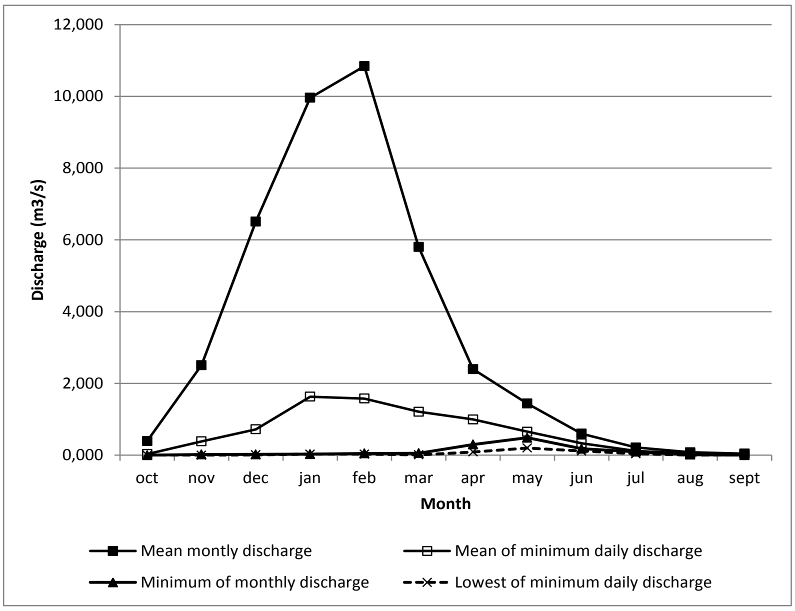


Figure 3.3.34 Flow regime characteristics of the Guadalupejo river (Valdecaballeros, 1972-1985)

Longitudinal, Lateral and Vertical Gradients

Changes in the geological context and valley features along the Guadalupejo River lead to a longitudinal zonation pattern, supporting differences in channel morphology and dimensions, flow conditions and riparian corridor features. In the upper parts of the river within landscape unit 1, the valley is confined and the channel is relatively narrow (8-10 m) and flows perennially. Under these conditions, a dense, relatively tall (>20 m height) and narrow gallery of *Populus alba* with *Fraxinus angustifolia, Alnus glutinosa, Salix fragilis* and *Salix atrocinerea* completely overhangs the channel (Figure 3.3.35). Towards landscape unit 2, along with a distinct geology, the valley widens gradually and the channel width increases significantly. Upstream of the confluence with small tributaries that deliver large quantities of coarse sediments to the main channel, the Guadalupejo has a short reach of flowing lentic waters that are densely covered by macrophytes (Figure 3.3.36). Immediately downstream the channel widens significantly and presents a wandering morphology, with multiple dry channels bordering large accumulations of coarse alluvial material from the local eroded plateaus. Within this relatively deep coarse cobble and gravel layer, runoff mostly infiltrates resulting in a dry channel with isolated pools. Soil moisture is a major limiting factor for vegetation growth and riparian species are very scarce. In the middle part of the river (segment 1 of landscape unit 2), the riparian corridor is mostly dominated by *Flueggea tinctorea* and no other riparian vegetation exists (Figures 3.3.37 and 3.3.38). Towards the lower parts of the river, especially downstream of the confluence with the Silvadillo stream, the discharge and soil moisture within the riparian zone increases, allowing a dense, tall gallery (> 15 m) dominated by *Fraxinus angustifolia* with *Populus nigra, Salix salvifolia* and dense masses of *Flueggea tinctorea* to be maintained (Figure 3.3.39).

Lateral gradients within the river corridor are mainly due to different hydrologic conditions, with permanent water located within the channel but very sharp gradients of soil moisture towards the borders. Strong vertical gradients are also observed; from isolated pools temporarily connected with groundwater to completely dry bank tops, which effectively become recent terraces with vegetation that is not related to the river system.

According to these physical and hydrological gradients, the species composition and coverage of the riparian vegetation varies significantly along the Guadalupejo river. Following the conceptual model presented in 2.2.2., different vegetation bands may be recognized according to channel morphology and water availability. The confined nature of the valley within landscape unit 1 leads to compression of the lateral zones, but the zones are better developed and more readily recognized in the unconfined lower reaches within landscape unit 2. Along the upper part of the river, dimensions of vegetation bands are strongly controlled by channel morphology and only zones 2 and 3 exist, mainly formed by *Populus alba* and *Fraxinus angustifolia*. Within landscape unit 2, two types of conditions may be found. In the driest parts, water availability is the main limiting factor and only zone 2 exists, but in this case with *Flueggea tinctorea* colonizing a relatively broad area (Figure 3.3.40). In the more humid reaches vegetation bands are more fully developed, with a wider and denser zone 2 with *Flueggea tinctorea*, followed by a narrow band including zone 3, 4 and 5 all together, dominated by *Salix, Populus* and *Fraxinus,* which connects with the xeric soils of the surroundings (see Figure 3.3.39).

Figure 3.3.35 Upper part of the Guadalupejo river showing a dense tree gallery of Populus alba and Fraxinus angustifolia covering the entire channel.

Figure 3.3.36 Short reach below the sector shown in Figure 3.3.35 where the channel is fully covered by macrophytes.

Figure 3.3.37 River Guadalupejo at landscape unit 2 with severe water availability restrictions for riparian vegetation growth.

Figure 3.3.38 River Guadalupejo showing the dry coarse bed material where dispersed bushes of *Flueggea tinctorea* grow within zone 2.

Figure 3.3.39 Lower parts of the Guadalupejo river where water emerges and a riparian corridor of woody vegetation exists. Lateral and temporal gradients of moisture and flood disturbance allow submerged macrophytes to grow in the channel, bushes of *Flueggea tinctorea* on the coarse substratum near the banks (zone 2) and a tree gallery of *Populus alba* and *Fraxinus angustifolia* at the distal parts of the channel (zone 4 and 5).

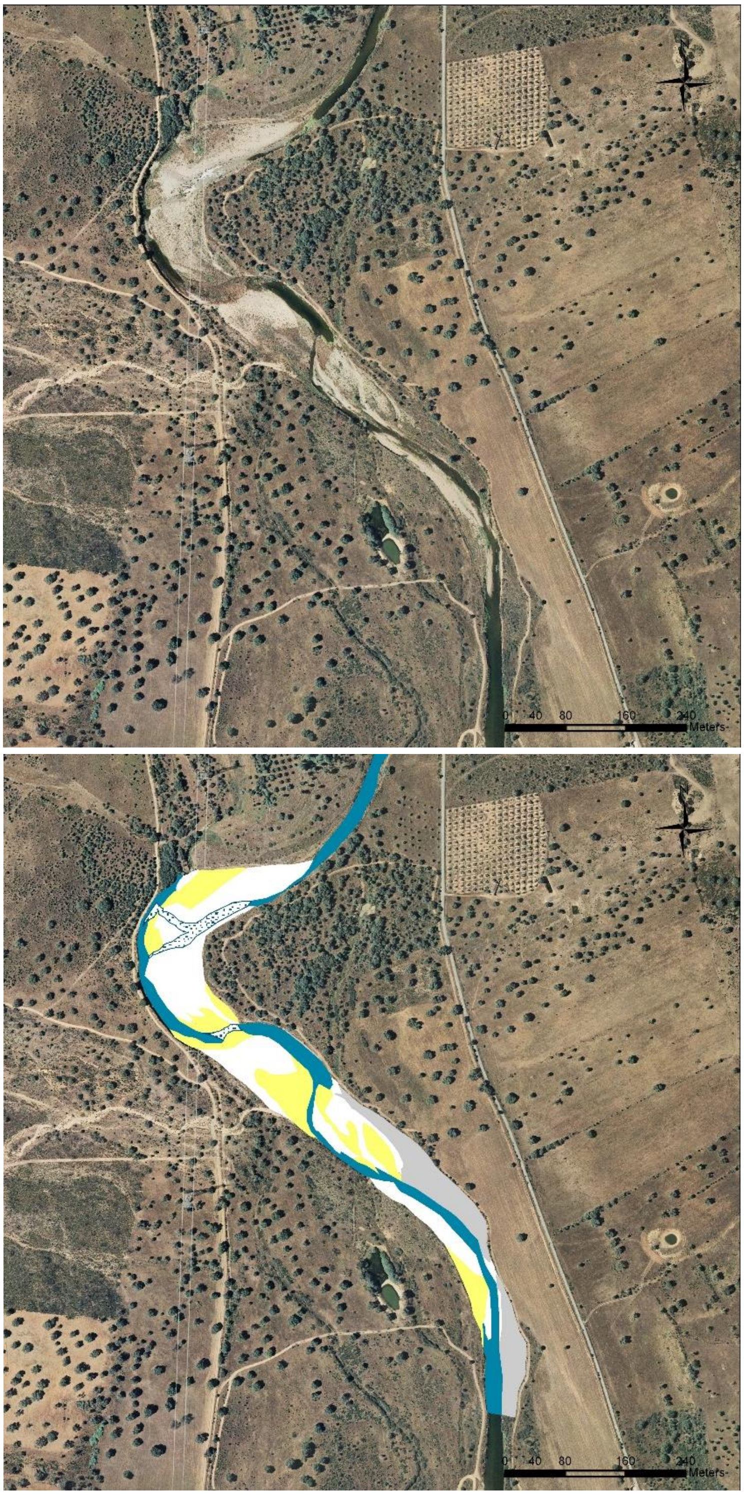


Figure 3.3.40. Upper segment of the Guadalupejo river on landscape unit 2. Interpretation of landcover types within the channel where isolated pools (solid blue colour) and dry channels (dotted blue colour) may be identified around bare gravels (white colour) and areas with disperse colonization of Flueggea tinctorea (yellow colour). Grey areas at the channel banks correspond to dry terraces desconnected from the channel (see Figures 3.3.37 and 3.3.38 from the same reach).

Influence of riparian trees and wood on river morphology in the critical zone

Although the river Guadalupejo is located in the same geographical (i.e. climate, geology and land cover) context of the Guadarranque River, important differences in channel morphology and riparian vegetation interactions are observed which seem to be derived from differences in valley features (confinement, sediment transport and storage and sediment size) which create also significant differences in water availability for vegetation growth.

Within landscape unit 1 the main channel width ranges between 13 and 23 m which represents an 'intermediate' channel in relation to the potential influence of trees and wood and a 'large' channel for aquatic plants. Relatively continuous formations of willows (*Salix salvifolia*) with *Fraxinus angustifolia* and *Alnus glutinosa* also dominate large parts of the channel and represent physical controls on lateral channel adjustments during floods (see Figure 3.3.41). This vegetation supplies woody material to the river, which is transported and deposited on the floodplain of downstream reaches, where its interactions with river morphology are more evident. The shadow effects of the woody gallery together with the high energy of the river within this steep landscape unit 1 (channel gradient 0.09) prevents the establishment of aquatic plants in this fully covered river reach.

As described in the previous section, within landscape unit 2 the valley becomes unconfined, the river corridor enlarges and water infiltrates into the alluvial aquifer and disappears from the river channel for most of the year. The main channel width increases to between 25 and 80 m in the upstream sector, above the confluence of the Silvadillo tributary, and to between 40 and 150 m downstream. These channel widths represent 'intermediate' to 'large' channels in the context of the riparian trees and wood that are present. Riparian vegetation is strongly controlled by the availability of soil moisture and so is present in discontinuous stands or dispersed individuals according to local phreatic features. Along the upstream sector of landscape unit 2, bush formations of *Flueggea tinctorea* extend over the enlarged channel. These easily persist though floods events offering significant flow resistance (Figure 3.3.42a,b). Downstream and along the widest channel cross sections, large deposits of coarse bed material (pebbles and gravels) form a highly permeable river bed with negligible moisture retention capacity to support vegetation establishment (Figure 3.3.42c). The effects of overgrazing are also apparent in these locations where 'green' material is very scarce during the dry season. In the lower sectors of landscape unit 2 the water table becomes shallower and vegetation reappears. Forest stands of *Salix salvifolia, Fraxinus angustifolia* and occasionally *Alnus glutinosa* anchor the river banks and supply woody material to the channel (Figure 3.3.43a). In the lower reaches of the Silvadillo river, dense galleries of *Alnus glutinosa* with *Fraxinus angustifolia* exist in some of the channel branches (Figure 3.3.43b), providing significant flow resistance during floods (Figure 3.3.43c).

In summary, riparian vegetation exerts an important effect on river morphology in the Guadalupejo river by several means, (1) reinforcing soil strength and stabilizing river banks (Figure 3.3.44a), (2) dissipating flood energy and promoting woody debris trapping and sediment deposition (Figure 3.3.44b) and (3) supplying wood that is large enough to create islands and jams (Figure 3.3.44c).

Nevertheless, the Guadalupejo river represents an example of severe conditions in terms of climate and soil moisture availability for riparian vegetation growth. At the same time, recurrent flash floods impose fluvial disturbance conditions which periodically reset vegetation establishment. Finally, other external pressures such as overgrazing by wild and domestic animals contribute to limiting the influence of vegetation on river morphodynamics.

The presence of *Flueggea tinctorea*, which is the dominant or single species in the driest reaches of the Guadalupejo river, is an indicator of current hydromorphological conditions. This species is very well adapted to dryness and flooding and it is not as heavily impacted by overgrazing as other woody species because it has spiny branches and small leaves. It predominates mainly in the wider depositional reaches where coarse and very permeable river beds are dominated by fluvial disturbance, but where soil moisture is reduced most of the time. In this sense, *Flueggea tinctorea* could be considered as performing a similar function to species such as *Salix elaeagnos* or *Salix purpurea*, which are found in other torrential Mediterranean rivers but where water availability is higher. This illustrates the conceptual model explained in section 2.2, since this species is representative of the critical zone of vegetation – fluvial process interactions (see Figure 2.2.10) which frequently represent a large proportion of the unconfined braided-wandering type reaches of the Guadalupejo river within landscape unit 2.

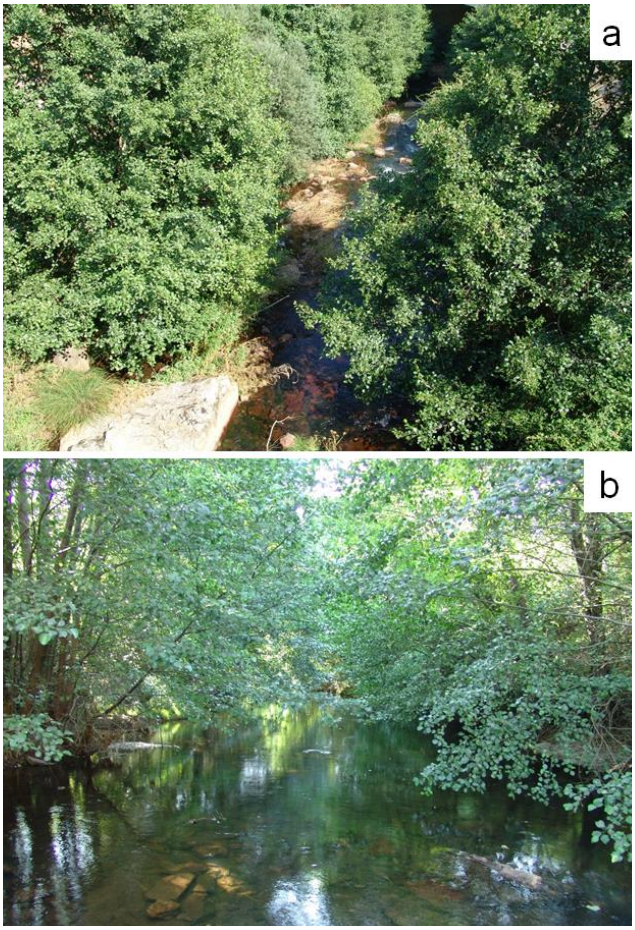


Figure 3.3.41 Upper part of the Guadalupejo river within landscape unit 1.

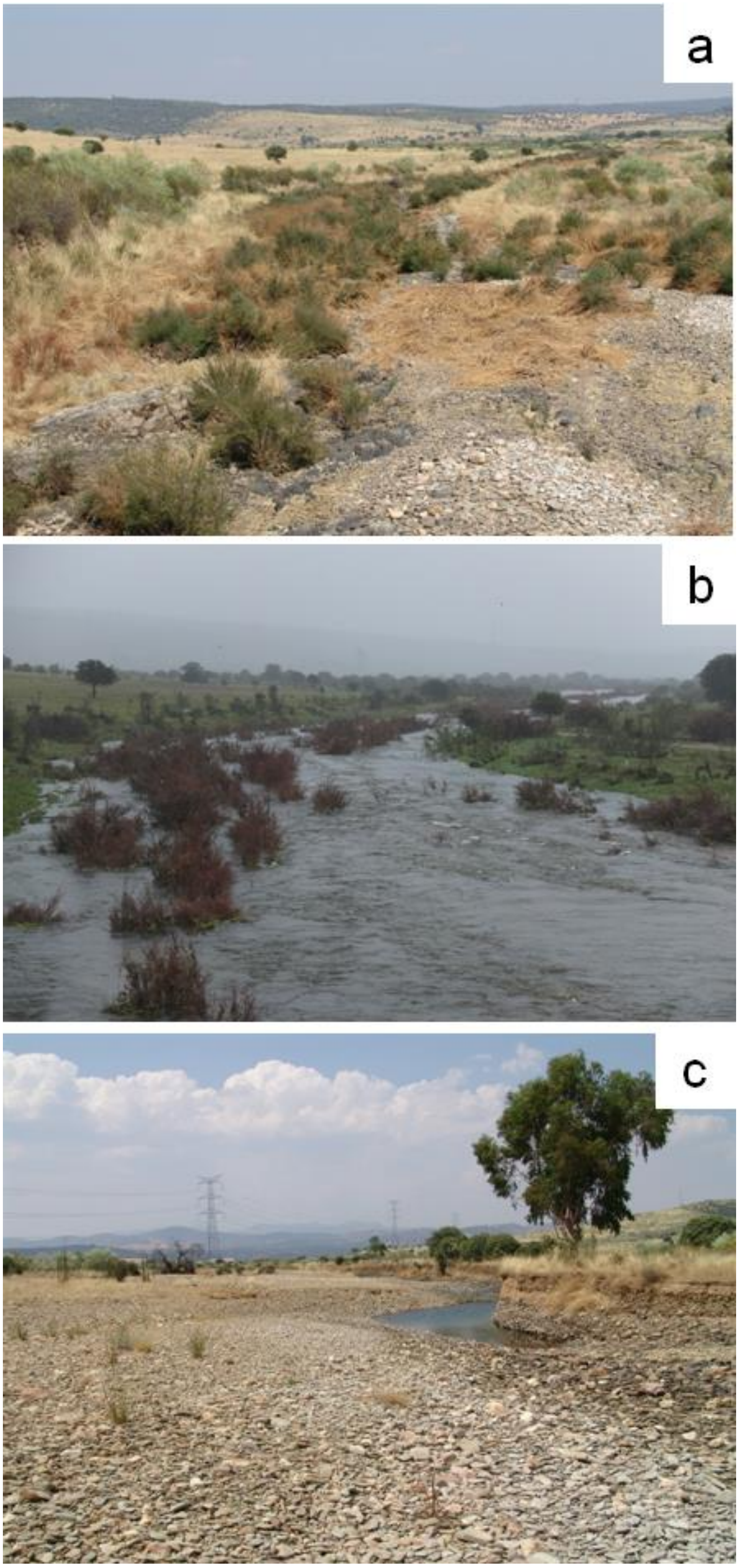


Figure 3.3.42 River Guadalupejo at landscape unit 2. Upper sector with Flueggea tinctorea formations in (a) dry and (b) flood conditions, and (c) wider and drier sectors a short distance downstream.

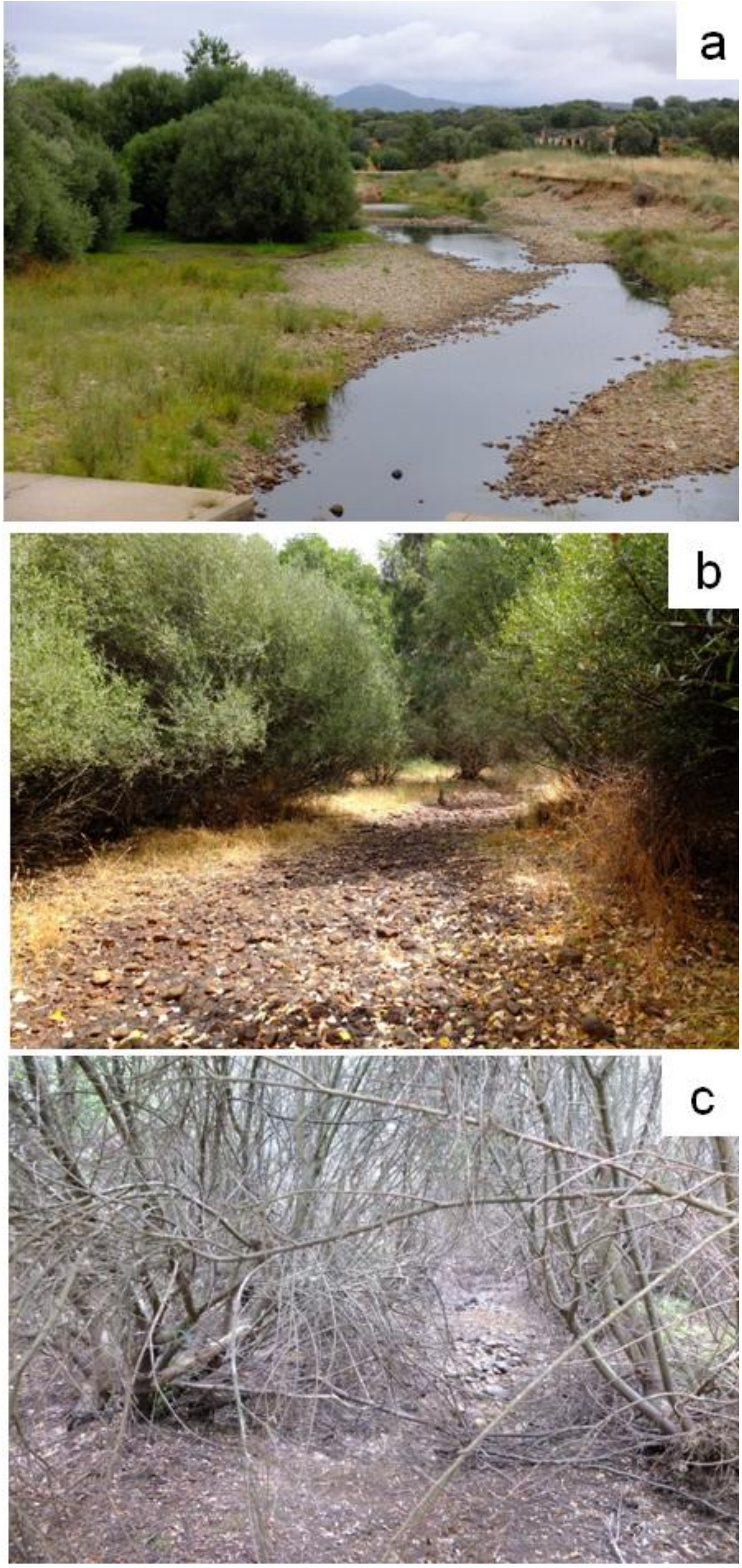


Figure 3.3.43 Riparian vegetation structure of a) the Guadalupejo river, lower sector of landscape unit 2; and (b, c) the Silvadillo river inside lateral channels.

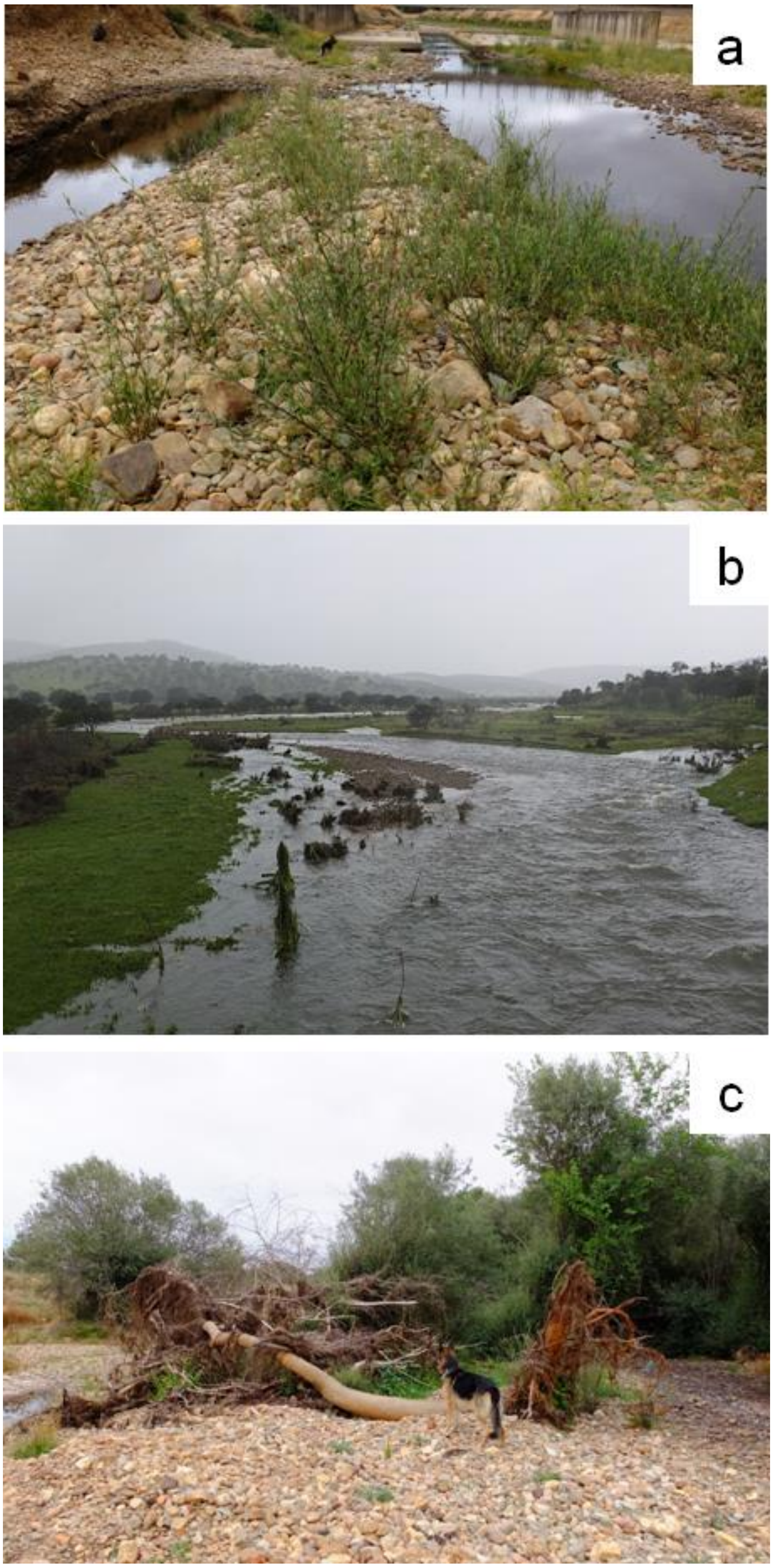


Figure 3.3.44 Riparian vegetation interactions with river morphodynamics in the Guadalupejo river: a) quick willow regeneration stabilizing sediment deposits b) dissipating flood energy promoting gravel deposition and c) wood supply representing big roughness elements within the channel.

3.3.4.3 Influence of aquatic plants on river morphology in the critical zone of the Guadarrangue and Guadalupejo rivers

In the Guadarranque river aquatic plants are nearly absent, basically due to the morphological conditions of the valley which determine a steep and narrow channel with high energy and very coarse bed material, including frequent rocky outcrops. Additionally, the presence of a tree gallery along the channel banks that completely shades the water surface may act as another limiting factor for the development of submerged or emergent macrophytes communities.

Aquatic plants are present in certain reaches of the Guadalupejo river during short periods and where enough water is available. In these local reaches (e.g. upper and lower parts of landscape unit 2) masses of *Ranunculus* and several emergent macrophytes grow very densely and quickly in the middle of the channel due to favorable conditions of light and temperature (Figure 3.3.45). These plant formations represent an essential element of channel roughness and have strong control on water velocity and stream power although for only short distances. The interaction of plants with hydraulic conditions is very strong in this case, influencing river morphology by inducing widening and shallowing processes and sedimentation of much finer material.

Figure 3.3.45 Masses of Ranunculus growing in the middle of the Guadalupejo channel having strong interactions with hydraulic conditions.

3.3.5 The Narew National Park, Poland: Vegetation-hydromorphology interactions in a low energy anabranching river

3.3.5.1 Regional and Catchment Setting

The River Narew is located in the Hemiboreal Baltic subregion of the Central European biogeographical zone ((source: http://www.globalbioclimatics.org). In the upper reaches of the River Narew, Poland, one reach retains a near-natural, multi-thread planform which falls within river type 22 (unconfined, sand bed, low energy anabranching; see Deliverable 2.1, chapter 7). This river type would once have been common across much of the north European plain and also in very low gradient areas of the UK and Eire, but in most locations such rivers have been transformed into relatively straight, predominantly multi-thread systems through channel realignment coupled with land drainage for agriculture. Indeed the River Frome (section 3.3.2) is likely to have supported a similar river type prior to forest clearance and agricultural development. Therefore, this reach of the Narew provides an opportunity to consider the hydromorphology of this river type under relatively natural conditions.

3.3.5.2 Longitudinal, Lateral and Vertical Gradients

Within the Narew National Park, the anabranching river system displays a predominantly sand bed with peat forming the banks. The river beds have extremely low gradient (~0.0002, Klimaszewski, 1981; Gradziński, 2004) supporting a perennial presence of water within the network of channels even at times of low flow, low flow velocities, and weak rates of drainage from the floodplain to the river.

Peat development and the associated wetland vegetation across the floodplain depend entirely upon maintenance of a high water table by reliable river flows (Banaszuk, 1996). It is believed that the multi thread channel pattern, which evolves by avulsion, separation and reconnection of channels, probably predates the development of floodplain peat deposits (Banaszuk, 1996). The low valley gradient and wide, relatively flat, valley floor facilitate quite even flooding across the floodplain, with water surface levels typically elevated between 0.2 and 1.0 m above the bankfull level. Floods are most frequent in spring (February to early May) and are usually driven by snowmelt. Flooding is more frequent and lasts longer in the upstream part of the reach, where the total channel width and thus the conveyance offered by the river channels is lower than in the downstream part (Mioduszewski et al., 2004). This hydrological difference is reflected in a broad change in the distribution of vegetation communities between upstream and downstream (Figure 3.3.46).

Based on the stratigraphy of the hydrogenic soils, four stages of valley paludification and related vegetation processes have been reconstructed, illustrating the great age of the valley wetlands (Okruszko and Oświt, 1973, Churski, 1973). During the first stage, muds accumulated in the valley bottom, aggrading its surface. This was followed during stage II by peat accumulation from 4.5 thousand years ago and the development of a vegetation cover comprised of willow shrubs and rushes, such as *Phragmites australis*, *Equisetum fluviatile*, *Menyanthes trifoliata* and many species of sedge (*Carex* spp.). Stage III involved the accumulation of sedge peat, commencing ca. 2.5 thousand years ago. During this period, the prevalent plant community in the valley was *Caricetum elatae.* The low level of decomposition of the peat indicates the highest paludification of the valley in that period. Stage IV persists to the present and is characterised by gradual drying. During this period, the character of the floodplain / valley bottom has evolved to reflect spatial variations in the intensity of surface flooding (Banaszuk, 2004; Okruszko and Oświt, 1973; Okruszko, 1983).

As illustrated in Figure 2.2.2 for rivers of type 22, the majority of the river corridor falls within zones 4 and 5, with only a narrow margin of zone 3 adjacent to the permanently inundated, perennially-flowing river channels. This structure is reflected in the above-described sequence of peat development, which has resulted in a complex of vegetation communities that respond to inundation (zone 4) but are differentiated by the persistence of soil waterlogging between floods. Two ecological sequences have been identified by Oświt (1973), permanently boggy and periodically boggy, representing communities that are largely located within zones 4 and 5.

3.3.5.3 Response of the vegetation to hydrology in zones 4 and 5

The permanently boggy sequence within zone 4 is located preferentially in the downstream section of the National Park and includes:

tall helophyte communities of the alliance *Phragmition*,

tall sedge community of the slender tufted sedge *Caricetum gracilis typicum*,

tall sedge community of the tufted sedge *Caricetum elatae*,

tall sedge community of the fibrous tussock sedge *Caricetum appropinquatae*,

sedge-moss community of lesser tussock sedge *Caricetum diandrae*.

These communities are typical for the Uhowo-Rzędziany area for sites characterised with slight fluctuations in water table levels, and in association with the near river zone communities of the *Phragmition* alliance and *Caricetum gracilis typicum*. In the sites located closer to the peripheries of the valley, where flooding is less frequent, shallower and of shorter duration (zone 4 to 5 transition), *Caricetum appropinquatae* is found. In the peripheries of the valley supplied with subterranean waters (zone 5), there are moss-sedge communities, such as *Caricetum diandrae*.

The periodically boggy sequence (zone 5) includes:

Glycerietum maximae and *Phalaridetum arundinaceae*,

dried tall sedge community of the slender tufted sedge *Caricetum gracilis* with species from the *Agropyro-Rumicion* alliance,

meadows of *Molinio-Arrhenatheretea* class.

The periodically boggy sequence communities occur in places with high water level fluctuations, in conditions of more intense drying and aeration of the superficial soil layer, both in the peat covered valley sections where the paludification process has stopped as well as in the areas where it was never significant.

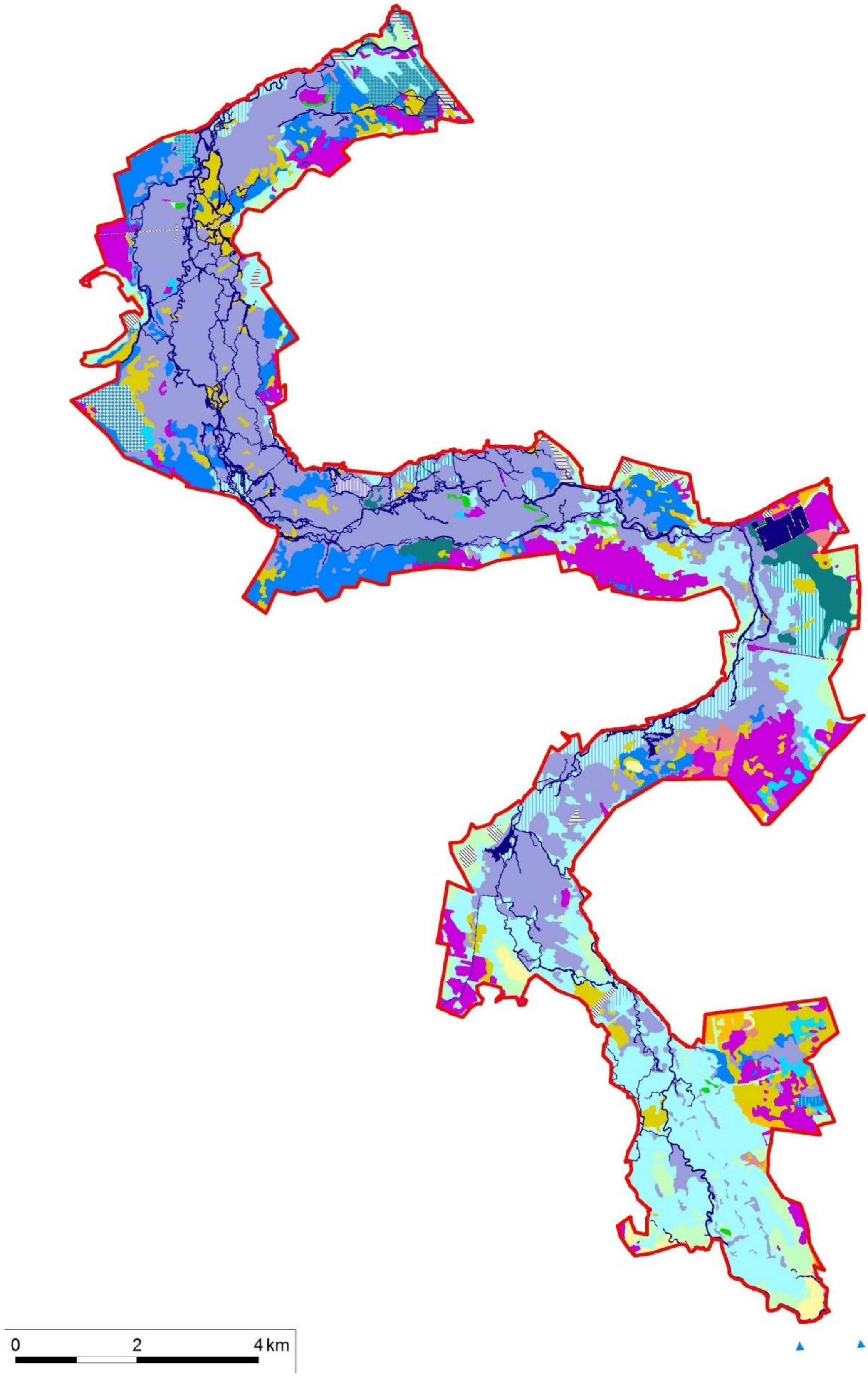


Figure 3.3.46. Map of vegetation communities in the Narew National Park. The river flows from the bottom to the top of the Figure (i.e. from south to north). The map legend is on the following page.

Legend for Figure 3.3.46.

🟪 Phragmition and tall sedge communities with Phragmites australis
🟦 Caricetum elatae
▤ Caricetum elatae with nitrophilous species
🟦 Caricetum appropinquatae
🟦 Caricetum gracilis typicum
🟦 Phalaridetum arundinaceae, Glycerietum maximae and Caricetum gracilis
▤ Phalaridetum arundinaceae, Glycerietum maximae and Caricetum gracilis with nitrophilous species
▥ mosaic of Phragmitetum australis and Caricetum elatae
▥ mosaic of Phragmitetum australis, Phalaridetum arundinaceae and Glycerietum maximae
▥ mosaic of Phalaridetum arundinaceae, Glycerietum maximae and Caricetum gracilis typicum
▥ mosaic of Caricetum elatae and Caricetum appropinquatae
▦ mosaic of Phragmitetum australis, Phalaridetum arundinaceae, Glycerietum maximae and Caricetum elatae
▦ moaic of Caricetum elatae, Caricetum appropinquatae and tall sedge communities with Phragmites australis
▦ tall sedge communities with Phragmites australis and nitrophilous species
🟥 Scheuchzerio-Caricetea nigrae
🟩 Molinio-Arrhenatheretea
🟨 Koelerio glaucae-Corynephoretea canescentis, Nardo-Callunetea
🟨 Salicetum pentandro-cinereum, Betulo-Salicetum repentis
🟪 Alnetea glutinosae, Alno-Ulmion
🟩 Carpinion betuli
🟧 Peucedano-Pinetum

▨ others
🟦 water

〰 Narew National Park border

source: Szewczyk 2008

Not only the pattern (Figure 3.3.46) but also the dynamics of the plant communities in the Narew valley are determined largely by hydrological processes including the duration of flooding and / or the rate of movement of groundwater and the proximity of the water table to the ground surface. Although now curtailed, cutting and grazing has for a long time limited the process of vegetation succession and supported the prevalence of non-forest rush and sedge communities, particularly tall sedge communities (mainly the tufted sedge community *Caricetum elatae*). The latter community is found in the zone of surface flooding (zone 4), but in areas of smaller water table fluctuations than, for example, *Caricetum gracilis*, and in areas of low flow velocity during continuous flooding (Okruszko and Oświt, 1973). Assuming that the *Caricetum elatae* is the initial ecosystem with a long-term flooding preference (zone 4), four directions of succession can be observed within the marsh areas of the Narew valley over recent decades.

1. The expansion of reed. Communities with a greater fraction of *Phragmites australis* have been formed mainly in the area originally covered by *Caricetum elatae* and *Caricetum gracilis typicum*. Currently, the process of reed expansion takes place also in the periodically boggy sequence communities (Szewczyk, 2008). During the 1980's the patches of flora formed by sedges and reed were considered to be a stage in the secondary succession process of the sedge communities resulting from discontinuation of mowing and they were included into the *Magnocaricion* (Bartoszuk, 1996). When the reeds become denser inland, they are classified as the *Phragmitetum australis*.
2. The expansion of communities from the periodically boggy sequence, *Caricetum gracilis* in its various forms, *Phalaridetum arundinaceae* and *Glycerietum maximae,* into *Caricetum elatae* sites. The broad ecological amplitude of the *Caricetum gracilis*, especially in relation to humidity and fertility of the soil, results from the properties of this acute sedge, which is usually found in eutrophic sites, on mineral and peat soils, in periodically flooded sites. The slender tufted sedge communities are found mainly in eutrophic sites, usually on organic soil that is frequently highly mineralised or mineral-organic. Thus, the expansion of *Caricetum gracilis* in place of *Caricetum elatae* indicates an increase in the fluctuation of groundwater levels and of the site trophism (Nowiński, 1967; Okruszko and Oświt, 1973).
3. In the marsh areas, development of willow shrubs and alder trees, constituting the initial stage of forest communities. This is occurring mostly within the edge zone of the valley among permanently boggy sequence communities (both *Magnocaricion* and sedge-moss communities). The development of shrubs and alder forests correlates with a decrease in the area of the *Scheuchzerio-Caricetea* class communities within the last 50 years, including phytocenoses of the *Caricetum diandrae* which were found in the valley in the 1960s as narrow bands along the edges (Okruszko and Oświt, 1973), and in the last ten years their sites have not been confirmed (Szewczyk, 2008). The succession process towards shrubs is noted to a much smaller extent in the central zone of the valley which is strongly influenced by river waters (Szewczyk, 2008).
4. Succession of the tufted sedge community *Caricetum elatae* towards communities from the *Scheuchzerio-Caricetea nigrae* class, resulting from flooding and decreased water mobility, with a concurrent water supply from the surrounding hillslopes. This

succession from the permanently boggy sequence takes place locally and does not cover larger areas of the park (Szewczyk, 2008).

The presented directions of changes of the wetland plant communities are strictly connected with the valley's hydrology. Within the last 40 years, the changes in vegetation indicate increased fluctuations of groundwater levels during the growing season and increased mobility of waters within the river channels, as well as discontinuation of the mowing-grazing economy in the valley (Szewczyk, 2008).

3.3.5.4 Critical Zone of interaction between vegetation and fluvial processes

In this reach of the Narew, true two-way interactions between vegetation and hydromorphology are confined to the permanently inundated river channels and their immediate margins. Thus zones 1 to 3 are largely confined to the areas occupied by the channel threads of this low energy anabranching system and the zones are essentially superimposed upon one another. The river's sand-bed restricts its ability to create geomorphic features without the stabilising influence of vegetation. Thus plants are absolutely crucial to river morphodynamics. Plants provide the peat material from which the floodplain and channel banks are constructed. Plants reinforce these organic river banks; encroach into and narrow channels; colonize the channel bed; and induce local channel shallowing (Gradzinski et al., 2003). Submerged and emergent aquatic plants, such as *Sagittaria sagittifolia* and *Nuphar lutea* colonise river channel beds, whereas emergent species, such as *Phragmites australis*, colonise the river banks. Colonisation, stabilisation and aggradation of river channel bed and margins by aquatic plants (notably the emergent macrophyte, *Sparganium erectum*) contribute to bar formation and so are the main processes by which vegetation contributes to evolution of this anabranching system. Vegetated bar formation is the main process that induces channel change, including narrowing and avulsion. Gradzinski et al., (2003) identified six bar types (mid-channel, side, point, concave bank, lingoid and plug) that are induced by aquatic plants. Development of these six bar types and channel blockage induced by aquatic plants elevates water surface levels, which in turn induces avulsions that create new channels.

Although the area within the National Park is now protected so that vegetation-hydromorphology interactions can operate freely, there has been a decrease in the amplitude of floods in recent years as a result of flow regulation. Ice flows are also diminishing and will probably decrease further under projected climate changes. These hydrological changes have implications for the frequency of flooding across zone 4, with a likely adjustment of the spatial extent of vegetation communities across zone 5 (which may enlarge) and zone 4 (which may get smaller). They also have significant implications for the anabranching channel pattern, since the creation of new channels will become increasingly unlikely, and thus the spatial dynamics and internal functioning of zones 1 to 3 is likely to become severely impacted.

3.3.6 The case of the braided reaches at the regional scale of the Rhone river, South-East of France

3.3.6.1 Regional and Catchment Setting

The regional perspective presented in this section through an investigation of the entire Rhone basin, illustrates how rivers of a particular planform (braided) may vary in their characteristics across different biogeographical regions and subregions, reflecting a number of factors, not least the variations in hydromorphological processes and vegetation.

The French Rhone basin, located in the South-East of France, is characterized by several braided reaches, which have survived the widespread disappearance of braided rivers that occurred during the 20th century (Figure 3.3.47). Braided reaches are mainly located on left bank tributaries of the Rhone River, particularly in the alpine area, where the density of braided reaches is the highest in Europe (Habersack and Piégay, 2007).

As noted in the introduction to section 3.3, the Rhone basin includes parts of several biogeographic regions and subregions (source: http://www.globalbioclimatics.org) including region 5 (Central European) subregion a (Subatlantic); region 7 (Cévenno-Pyrenean) subregions d (Cévennean) and e (Auvergnean); region 8 (Alpine) subregions a (Mediterranean Alpine) and b (Western Alpine); and region 19 (Balearic-Catalonian-Provencal) subregion b (Occitanian-Provencal). Figure 3.3.48 refers to the hydro-ecoregions of France, which show that the Rhone basin coincides with four level 1 hydro-ecoregions: the Internal (2), the Northern (5) and the Southern Alps (7) hydro-ecoregions and the Mediterranean (6) hydro-ecoregion. Thus, it includes several different climate contexts, including semi-continental, high-mountain, and Mediterranean climates.

The Rhone basin is also located in an area of geological transition between the Jurassic and Alpine mountains and the more recent deposits from the late Tertiary and the Quaternary (Bravard, 2009).

3.3.6.2. Characteristics of the investigated reaches

Following Belletti et al. (2013), 53 braided reaches were selected for analysis from the four main hydrographical basins in the Rhone basin. Four are located in the ‘Upper Rhone’ basin, 15 in the ‘Middle Rhone’ basin, 9 in the Isère River basin, 23 in the Durance River basin and 2 in the Var River basin (Figure 3.3.49a). The reaches were selected so that their length was at least 20 times the width of the active channel (AC: the area occupied by water channels and bare sediments, Toone et al., 2014). The average reach length was 2458 m (minimum 986 m, reach 7; maximum 7259 m, reach 52) (Figure 3.3.49b). These selected reaches encompass a large range of geomorphologic contexts (Figure 3.3.49b): the average upstream catchment area is 658 km^2 (minimum 37 km^2, reach 20; maximum 12972 km^2, reach 52); the average altitude is 708 m (minimum 75.3 m, reach 46; maximum 1787 m, reach 6); the mean slope is 13.9 m km^{-1} (minimum 2.3 m km^{-1}, reach 52; maximum 52.5 m km^{-1}, reaches 7); the mean floodplain width is 694 m (minimum 59.9 m, reach 7; maximum 7749.5 m, reach 52).

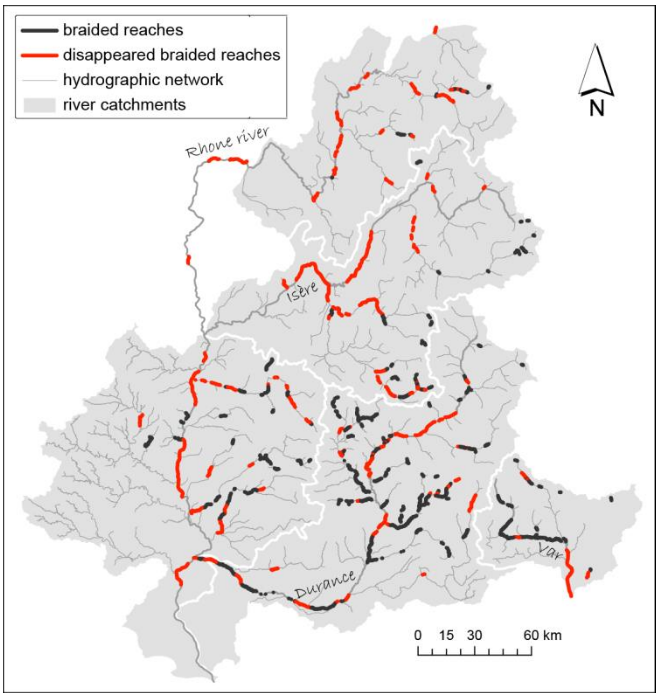


Figure 3.3.47 Spatial distribution of the sectors where the braided pattern disappeared and the sectors that are still braided across the Rhone catchment. (Modified from Piégay et al., 2009).

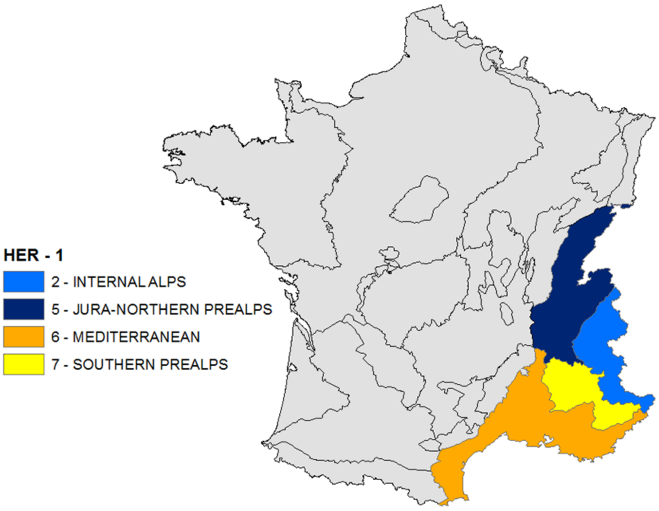
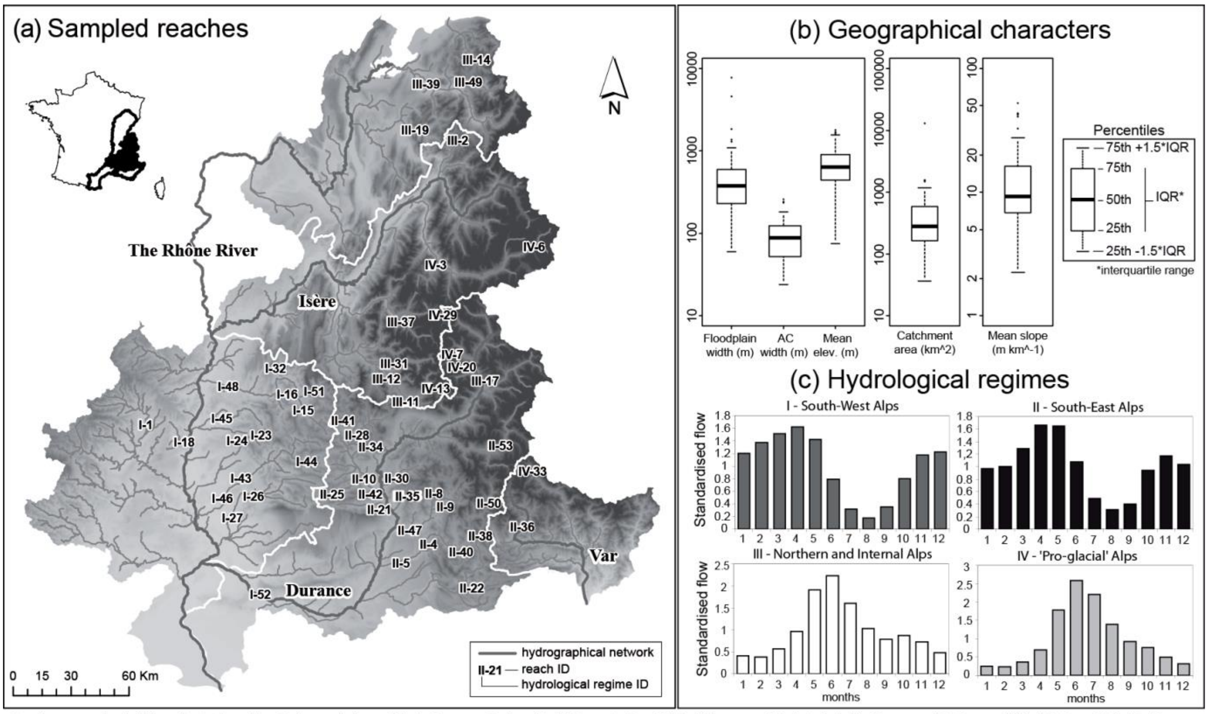


Figure 3.3.48 Hydro-ecoregions of the French Rhone basin.

The reaches are also exposed to varied climate conditions and hydrological regimes: from snow and glacier melt regimes (high mountains) to Mediterranean regimes (most of the southern reaches) (Figure 3.3.49c). Additionally, the Mediterranean reaches could be split into two sub-climatic areas (Guiot, 1986; Figure 3.3.50): a more humid area in the western part, belonging to the Rhone river corridor and the right-side tributary of the Durance River, one of the greatest tributaries of the Rhone; and a drier area in the eastern part, belonging to the left tributaries of the Durance river. As a consequence, at any given time each reach can be exposed to several, contrasting controlling factors. For example Figure 3.3.51 shows for each reach the time that has passed (i.e. number of months) since the last 10-year return period flood, relative to the most recent available orthophotos; in general, reaches in the south-eastern part of the study area underwent a 10-year flood more recently than other reaches.



Reaches name: 1 - Ardèche_dis; 2 - Arrondine; 3 -Arvan; 4 - Asse_BM; 5 - Asse_av; 6 - Averole; 7 - Bans; 8 - Bes_Bl; 9 - Bléone_am; 10 - Buëch_L; 11 - Drac_am; 12 - Drac_middle; 13 - Drac_Noir; 14 - Dranse; 15 - Drôme_dis; 16 - Drôme_LenD; 17 - Durance_A; 18 - Escoutay; 19 - Fier; 20 - Fournel; 21 - Jabron_2; 22 - Jabron_3; 23 - Lez_A; 24 - Lez_L; 25 - Méouge; 26 - Ouvèze_am; 27 - Ouvèze_av; 28 - PetitBuëch; 29 - Romanche; 30 - Sasse; 31 - Seveirasse; 32 - Sure; 33 - Tinée; 34 - TrtDeMaraise; 35 - Vanson; 36 - Var; 37 - Véneon; 38 - Verdon; 39 - Arve_dis; 40 - Asse_Blieux; 41 - Buëch_dis; 42 - Buech_A; 43 - Eygues_milieu; 44 - Eygues_R; 45 - Roubion; 46 - Aigue_C; 47 - Bléone_av; 48 - Drôme_Liv; 49 - Giffre; 50 - Verdon_dis; 51 - Bes_Dr; 52 - Durance_O; 53 - Ubaye.

Figure 3.3.49 (a) Study area, (b) geographical, and (c) hydrological characters of the 53 selected reaches. In panel (c), a monthly index is calculated as the ratio between the average monthly flow and the average annual flow, calculated for the set of stations for each geographical area. (From Belletti et al., 2013).

Human influence has also differed over time between the reaches and the different geographical areas in which they are located. In particular northern reaches have been strongly impacted by direct human actions since the 1950s (Peiry et al., 1994) including the construction of bank protection, dams and weirs for energy production, stabilization of longitudinal profiles, the introduction of torrent control works, and gravel mining. In the southern part of the study area the human impact has been mainly indirect and can be often attributed to land use changes at several scales, in particular the reforestation of catchments and riparian areas following their abandonment, as well as the introduction of torrent control works and other actions related to flood protection (e.g. Gautier, 1994; Landon and Piégay, 1999a; Liébault and Piégay, 2002).

All of these factors are influential in the different width evolution patterns observed over time. Reaches in the northern part of the study area have strongly narrowed compared to southern reaches and compared to their width in the 1950s (Figure 3.3.52).

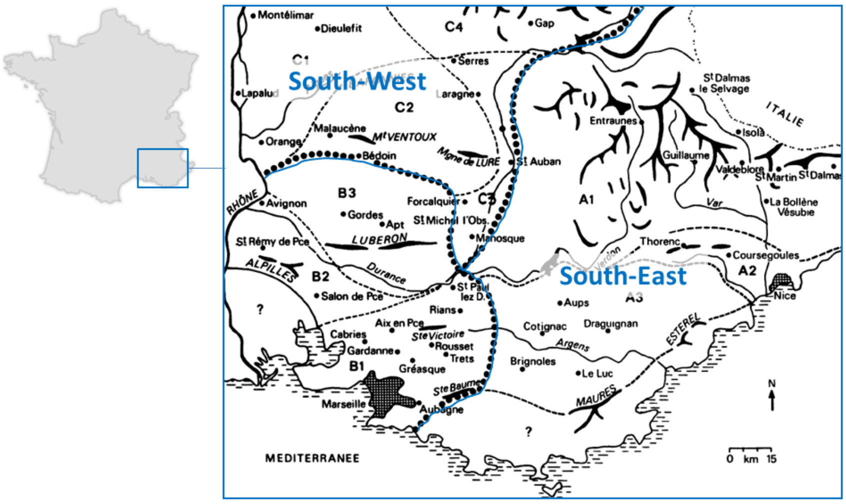


Figure 3.3.50 The two sub-climatic Mediterranean areas of the Rhone basin (Modified from Guiot, 1986).

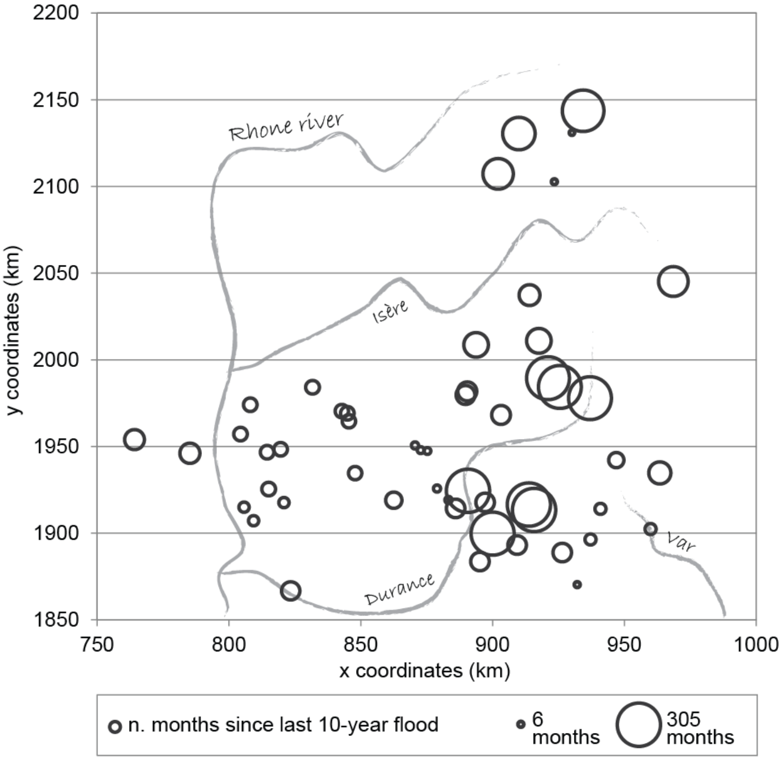


Figure 3.3.51 The flood regime history of 53 reaches: the number of months since the last 10-year return period flood. The number of months is referred to the most recent available orthophotos. (Data from Belletti et al., 2013).

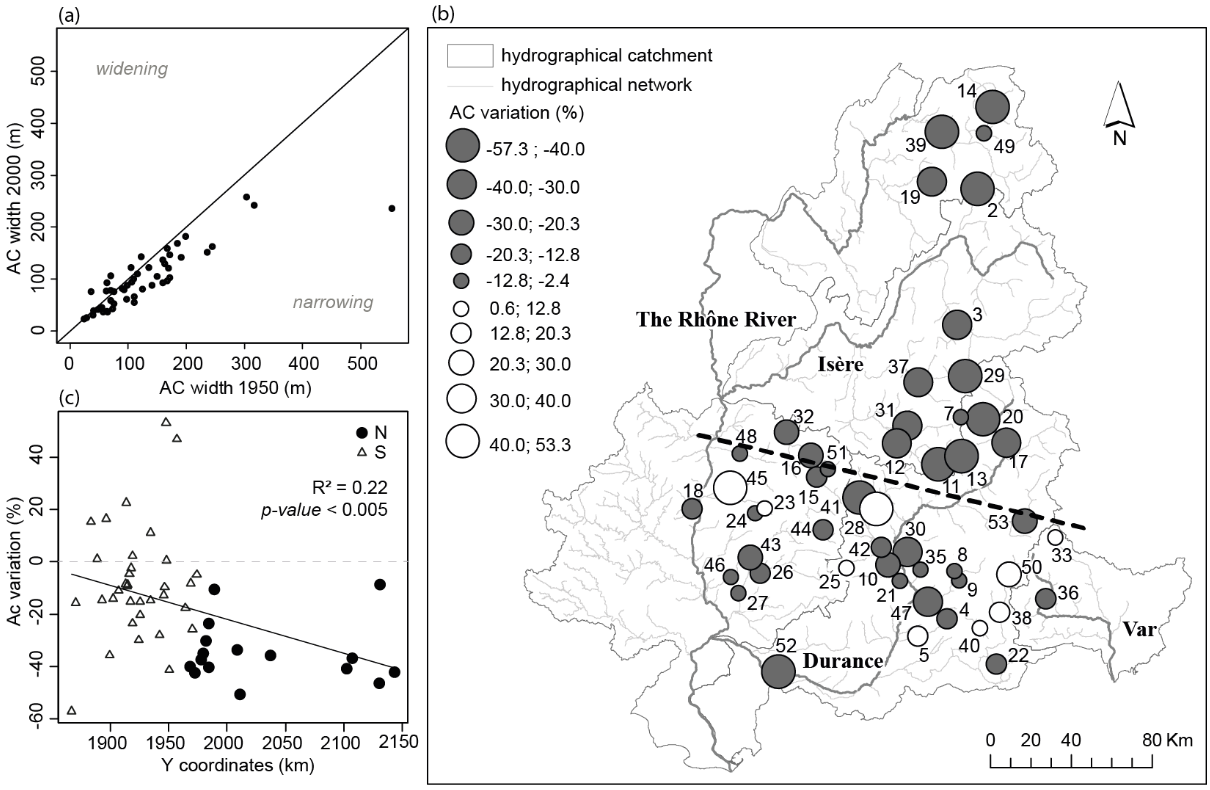


Figure 3.3.52 (a) Evolution of active channel width between the 1950s and the 2000s. (b) Spatial distribution of the active channel width evolution between the 1950s and the 2000s in the overall study area; dotted line represents the north-to-south gradient of the active channel lateral evolution. (c) Spatial distribution of the active channel width evolution between the 1950s and the 2000s according to the north-to-south coordinates (km), showing the position of northern and southern reaches along the spatial gradient; dotted line identifies widened versus narrowed reaches. From Belletti et al. (2013).

3.3.6.3 Riparian vegetation

The selected braided reaches are surrounded mainly by near-natural vegetated areas (50.5% of the reaches), following by agricultural areas (47.1% of the reaches); and only a small number are urbanized (2.4% of the reaches) (Figure 3.3.53).

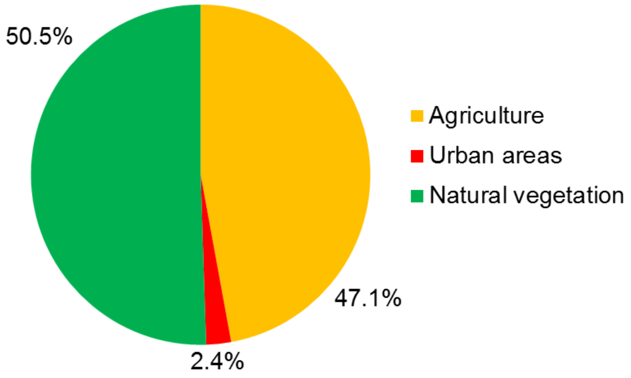


Figure 3.3.53 The land use surrounding the selected braided reaches.

Figure 3.3.54 Examples of the main river types for the 53 selected reaches. From left to right: wandering (type 11), island braided (type 9) and braided (type 8).

According to the typology proposed in Deliverable 2.1, chapter 7, the selected reaches mainly belong to the following river types (Figure 3.3.54):

- 10 reaches belong to type 8 (braided);
- 34 reaches belong to type 9 (island braided);
- 9 reaches belong to type 11 (wandering).

From Figure 3.3.54, it is clear that zones 1 (perennially inundated), 2 (fluvial disturbance dominated – coarse sediment erosion and deposition) are present within the active channel, and that the sparsely and more heavily vegetated patches within the active channel correspond to a transition between zones 2 and 3 (Fluvial disturbance dominated – finer sediment deposition). However the distribution of zones 3, 4 (inundation dominated) and 5 (soil moisture regime dominated) within the riarian woodland along the active channel margins is unclear and is highly variable among the investigated reaches.

Tree species within the riparian woodland vary among the rivers. Concerning the northern reaches, the Arve river for example is characterized by meso-hygrophilous formations (*Fraxinus* sp., *Alnus incana*) in the riparian areas, whereas *Salix purpurea*, *S. elaeagnos* and *S. daphnoides* dominate in the most active areas of the active channel (ONF, 2005). The riparian zone of the Giffre river, located in the northern alps, is characterized by a high species diversity (Piégay, 1995): *Alnus incana* dominates the riparian area with the presence of some individuals of *Picea abies*; the most marginal parts of the riparian areas are composed of *Alnus glutinosa*, *Alnus incana* and *Quercus pedunculata*; *Alnus incana* dominates the tree layer on islands, where also a high pioneer species diversity is observed (*Salix* sp., *Populus nigra*, locally also *Fraxinus excelsior* and several herbaceous species). In the southern part of the study area, the Drome reaches (Dufour, 2005) are characterized by: several pioneer species in the active channel; species like *Salix elaeagnos*, *Salix purpurea* and *Populus nigra* in the moors; the post-pioneer alluvial forests is characterized by the presence of Fraxinus sp. and *Populus nigra*, with the local presence of *P. alba* and *Acer* sp.; the xerophilous areas are dominated by herbaceous species and *Populus nigra*; willow plantations are also present, mainly in the downstream reaches (*Salix alba*). Another example is the Eygues river (Pautou et al., 2003; Landon and Piégay, 1999b): the riparian corridor here is composed of formations of *Populus nigra* and *Alnus glutinosa*, where the first dominates in the active channel (gravel bars and islands) combined with shrubs of *Salix* sp., and the latter dominates in the marginal riparian zones combined with *Populus nigra*. Individuals of *Robinia pseudoacacia* are also extensively present. Oak formations are present at the margins of the riparian area. Concerning the mountain reaches, Pautou et al. (2003) report the composition of the riparian area of the Ubaye river: alder formations dominate the riparian area in combination with ash and pinewood; in the most active parts of the active channel *Salix* sp. dominates; the less active and highest parts of the active channel (i.e. most stable islands) are mainly composed by alders, pinewoods, *Hippophae rhamnoides*, with the sporadic presence of *Salix* sp.

3.3.6.4 Critical Zone of interaction between vegetation and fluvial processes

Islands are the main geomorphic features resulting from interaction between vegetation and fluvial processes within zones 2 and 3 of the investigated braided reaches. Figure 3.3.55 displays the island characteristics of the 53 reaches obtained from aerial orthophotos of the 2000s, in terms of their island proportion, island density and proportion of mature islands (modified from Belletti et al., 2013). Reaches are grouped following their geographic position in the Rhone basin and according to climatic characteristics. The Figure displays the difference in island density and proportion (both total and concerning mature vegetated islands) between the northern/internal alps, high mountains and southern (Mediterranean) reaches, as well as between the south-western and south-eastern reaches. In particular it shows that the northern/internal alps and mountain reaches are more vegetated and support mature islands compared to southern Mediterranean reaches. Between the south-west and south-east of the study area the difference is mainly in terms of island density (higher in the first case).

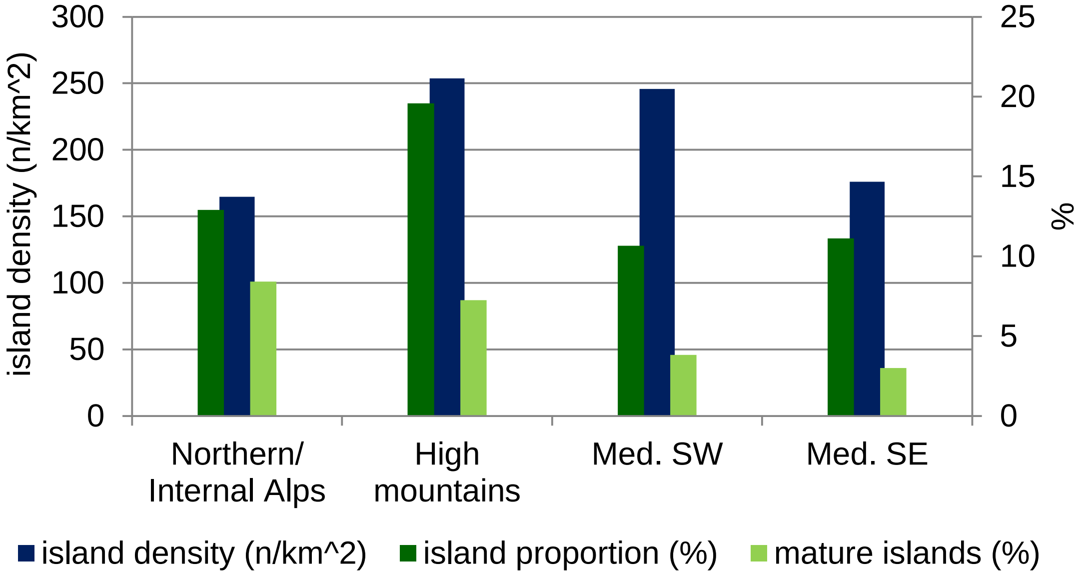


Figure 3.3.55 Island characteristics of the 53 selected reaches: island density (n km^{-2}), total island and mature island proportions (%). Reaches are grouped following their geographic position in the Rhone basin and according to the climatic characteristics. Data are obtained from Belletti et al. (2013).

As noted above, there are strong contrasts in the environmental setting within the Rhone catchment. The most important implication of these contrasts for hydromorphology are related to the geographical setting because of the large spatial scale (Figures 3.3.49 to 3.3.52): (a) between the northern and the southern parts of the study area in terms of hydrological regime, climatic conditions and active channel width evolution; (b) between the south-western and the south-eastern parts of the study area in terms of climatic (i.e. more humid versus dryers climate) and hydromorphological (i.e. slope, altitude, upstream sediment availability) conditions (Belletti et al., 2013).

These contrasted environments have also shown different fluvial vegetation patterns and the development of vegetation-mediated geomorphic units since the 1950s (Figures 3.3.56 and 3.3.57). In general all the reaches have displayed an increase in island density over time (Figure 3.3.56), although island proportion has remained quite constant between the two dates (Figure 3.3.56). Concerning island composition, a large number of reaches experienced a reduction in mature islands, in favor of the development of pioneer islands, and these changes mainly concerned reaches located in the south-western part of the study area, and reaches that underwent a 10-year flood recently (Figure 3.3.57). On the other hand, mountain and northern reaches recorded a significant increase of mature islands (Figure 3.3.57).

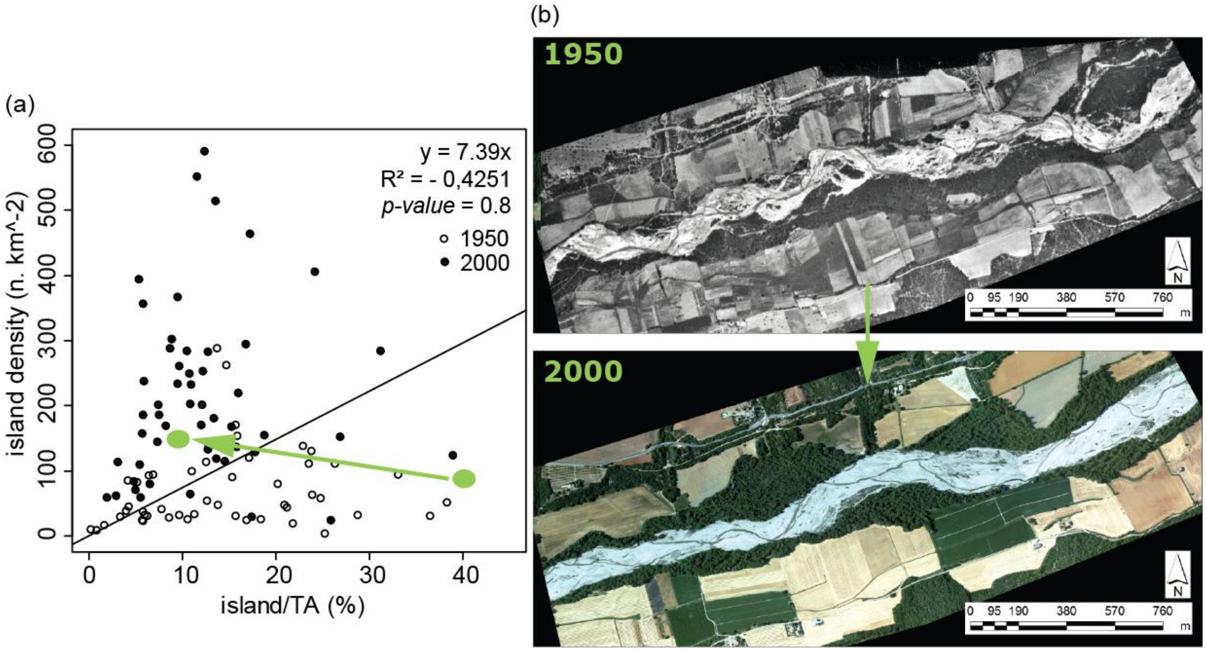


Figure 3.3.56 Island characteristics evolution: (a) the relationship between island density and island proportion is mapped for the 1950s and the 2000s—the intercept of the model is equal to 0; (b) example of a reach on the Asse river (reach n. 5), showing the reach pattern (i.e. river type) change from island braided to braided. (Modified from Belletti et al., 2013).

3.3.6.5 Conclusions

This regional analysis demonstrates how vegetation-fluvial process interactions within the critical zone, even within river reaches of the same type and subject to the same set of vegetation-mediated geomorphic units, can vary greatly through time and across space as controlling factors change. Such factors may reflect broad environmental controls such as climate, geology, flow regime and vegetation composition, but these are confounded by the multitude of human pressures, which may themselves map onto the broad environmental controls.

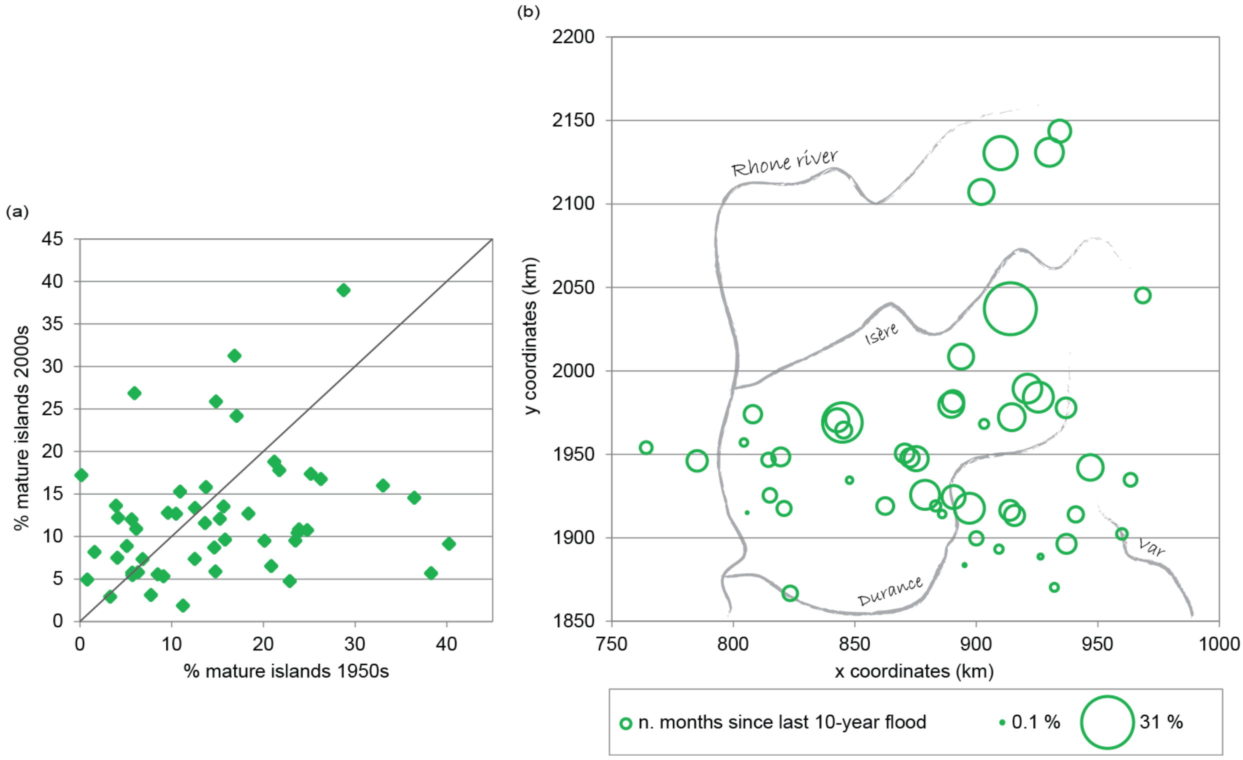


Figure 3.3.57 Island composition evolution and characteristics of the 53 selected reaches: (a) evolution of mature island proportion between the 1950s and the 2000s; (b) spatial distribution of mature islands (2000s) in the Rhone basin. Data are from Belletti et al. (2013).

3.3.7 Progress in developing and applying a conceptual model of vegetation-hydromorphology interactions to European rivers.

3.3.7.1 Conceptual Model

The conceptual model proposed in section 2.2 assumes a naturally-function river-floodplain system and contains three spatially hierarchical elements.

> *First*, the model considers how regional physical processes place constraints (boundary conditions) around the species composition of the vegetation that may be present along river corridors and that may interact with hydromorphological processes in a particular catchment. The biogeographical region within which a catchment is located is emphasised, since this links climate to biota.
>
> *Second*, the model considers how vegetation is further constrained by longitudinal, lateral and vertical gradients in hydromorphological processes within the river corridor network of a catchment, notably by gradients of moisture availability and fluvial disturbances. Five zones of potential vegetation-fluvial process interaction are defined: perennially inundated (zone 1); fluvial disturbance dominated - predominantly coarse sediment erosion and deposition (zone 2); fluvial disturbance dominated - predominantly fine sediment deposition (zone 3); inundation dominated (zone 4); soil moisture regime dominated (zone 5).
>
> *Third*, a critical zone of vegetation-hydromorphology interactions is defined, which bridges zones 1 to 3, and within which vegetation-mediated landforms occur at the interface between the fluvial-process dominated areas of the active channel and the vegetation-dominated areas of the surrounding floodplain / terraces / hillslopes.

3.3.7.2 Applying the conceptual model to European plants and rivers

In section 3, the conceptual model is applied to European rivers by:

(i) Focusing on a simplified (broad scale) set of European biogeographical regions and attempting to summarise the key riparian and aquatic species of the 'natural vegetation' that may be present. This challenging task draws on a wide range of sources. Unlike instream vegetation, riparian vegetation has not been subject to detailed survey and inventory during the installation of monitoring programmes for the Water Framework Directive, and so there are no large datasets to describe in detail its current condition and the deterioration it has suffered. Therefore, the analysis and descriptions provided in section 3.1 form a new perspective on the natural vegetation of European rivers and their riparian margins.

(ii) Another completely new analysis is presented in section 3.2. Here a traits data base is assembled for 459 native aquatic and riparian plant species that are found in association with European rivers. The species included in the data set are constrained by the traits information that could be assembled for them, and furthermore, the traits that could be assembled constrained the detail of the analysis that was feasible. Nevertheless, two trait-based typologies are devised reflecting (a) the sediment stabilisation potential and (b) the sediment accumulation and channel conveyance / blockage potential of the analysed species. This is a major first step in developing methods for interpreting the hydromorphological relevance of native riparian and aquatic plant species across Europe.

(iii) Section 3.3 provides a first test of the applicability of the conceptual model to a sample of European rivers. It is applied to rivers located in contrasting biogeographical zones (Table 3.3.1) and subject to different human pressures. These applications are all highly informative, showing the potential of the conceptual model to support scientific understanding of the different river systems, to aid interpretion of the key processes that are operating, and to aid evaluation of the degree to which the five zones are degraded or have been removed by human activities.

3.3.7.3 Example applications of the conceptual model

Brief summaries are provided below of observations resulting from the application of the conceptual model to a sample of European rivers, illustrating its utility for improving scientific understanding of the vegetation-mediated, hydromorphological function of rivers and thus for improving river restoration design.

The River Frome, southern England (a low energy, mainly anabranching river system located in the Atlantic European biogeographical region).

In this river system, zones 4 and 5 are no longer functioning (they have been almost completely replaced by agricultural land use), and zones 2 and 3 are highly restricted in space. Nevertheless, a range of landforms indicative of strong vegetation-hydromorphologv interactions are present along the entire river. These are particularly evident in relation to aquatic vegetation but less so for riparian vegetation, which is heavily managed. Nevertheless, there are locations where 'reference processes' of riparian vegetation-hydromorphology interaction can be observed that are highly relevant to restoration design elsewhere within the catchment.

The Tagliamento River (a mainly braided and high energy anabranching river system located mainly in the Alpine biogeographical zone but with its lower reaches in the Appenino-Balkan region)

Analysis of vegetation-hydromorphological interactions on this river focuses on two near-naturally functioning reaches. There is some hydropower development, torrent stabilisation, and gravel mining along the Tagliamento, but the level of impact of these activities on the two selected reaches is very small. The case study illustrates the crucial importance of large wood for pioneer island development on this river system. The development and enlargement of islands is accompanied by the development of a suite of related habitats that would not otherwise be present on the braid bars. Furthermore, differences in the area and development of vegetated patches (islands) are associated with differences in the morphology of the entire river bed. Distinct differences in the growth performance of riparian trees are associated with the depth to the water table. Changes in depth to the alluvial water table, for example resulting from increased flow regulation, ground water abstraction, or channel bed incision due to gravel mining of the channel bed, are likely to have very significant impacts on the complexity and form of the braid plain. Changes in water table depth and the growth performance of riparian trees affect the character of the riparian woodland (zones 3 to 5); the supply of wood to the active channel (zones 1 to 3); and thus the formation of islands and floodplain. A widespread fall in the water table could lead to a change from a high energy anabranching river type to braided river type, whereas an increase in the elevation of the water table level could lead to more intensive anabranching and eventually a single thread meandering / sinuous river type. Significant tree management, including clear-cutting of the riparian forest and wood removal from the active channel would threaten island dynamics and the availability of related habitats, and could lead to flood plain 'unravelling' with a widening of the braided channel. Thus the morphology and plant ecology of zones 2, 3 and 4 are all highly susceptible to any of the above-stated human activities, as are the beneficial flood alleviation effects of the flood plain forest, and, in an extreme case of deforestation, the extent of the agricultural floodplain beyond the forest.

The Rivers Guadarranque and Guadalupejo, South-Western Spain (two mainly confined single-sinuous to wandering rivers located in the Mediterranean, West Iberian biogeographical region)

Both of these rivers are subject to a dry Mediterranean climate, have intermittent flashy runoff regimes, and steep, mainly confined valleys. As a result, zones 1 to 4 are highly laterally compressed in most reaches. In this dry environment, the availability of water is crucial for vegetation development. Water is focussed in the confined valley bottoms and its availability depends on climate and valley features.

Zone 1 (perennially inundated) only exists in a few places. One short reach of the Guadalupejo River maintains perennially flowing water which supports a dense growth of aquatic macrophytes. Elsewhere, zones 2 to 4, which are occasionally flooded, are distinguished from zone 5 by their relatively more abundant vegetation and zone 2 occupies the entire river bed with riparian shrubs and clump-forming *Carex* and *Juncus* providing bed roughness elements. The character of the zone 2 to 3 transition varies enormously depending upon moisture availability, with dense galleries of riparian trees stabilising the river channel margins and trapping sediments to build distinct river banks in relatively moist reaches, whereas in drier reaches the transition from active channel to floodplain is gradual, and the floodplain is marked by widely dispersed shrubs of *Flueggea tinctorea*. This illustrates the importance of vegetation for building river banks and near-river floodplain surfaces in the transition from zone 2 to 3. Zone 4 overlies zones 2 and 3 in most places, in that inundation, whether or not it is associated with sediment erosion and deposition, is an important water source for the vegetation. Vegetation is irrigated by inundation, and inundation also contributes to recharging the riparian aquifer and increasing soil moisture storage, which sustains the vegetation between floods.

Because vegetation is so important for river bank formation and floodplain stabilisation, the vigour of the vegetation in this very dry environment has a fundamental influence on river and floodplain morphology. In North America, flood plain unravelling (conversion from a narrow single thread river with vegetated margins / floodplain to a wider multi-thread braided river) has been observed to result from overgrazing (Griffin and Smith, 2004; Smith, 2004), illustrating the likely sensitivity of these dry Spanish river corridors to heavy grazing. It is also very apparent that the influence of valley features on water availability and fluvial disturbance results in very different but equally sensitive vegetation patterns at the reach scale within the same biogeographic region and with similar conditions at catchment scale.

The Narew River, Poland (a low energy anabranching reach of the river located within the Narew National Park and in the Central European biogeographical region)

The studied reach of the Narew is near-natural in terms of its vegetation and channel morphodynamics, although until recently there was some cutting and grazing sufficient to arrest vegetation succession. Nevertheless, this reach of the Narew provides an opportunity to consider the hydromorphology of a once widespread but now rare river type under relatively natural conditions.

Apart from the areas immediately adjacent to and within the anabranching channels, vegetation in the river corridor falls within zones 4 and 5. The patterns and dynamics of the plant communities are determined largely by hydrological processes: notably the duration of flooding, the rate of movement of groundwater; and the proximity of the water table to the ground (peat) surface. This makes the extent and character of these zones and their vegetation communities highly sensitive to the river flow regime.

Zones 1 to 3 are largely confined to the areas occupied by the channel threads and are essentially superimposed upon one another. The river's sand-bed restricts its ability to create geomorphic features without the stabilizing influence of vegetation. Thus plants are absolutely crucial to river morphodynamics. Plants provide the peat material from which the floodplain and channel banks are constructed. Plants reinforce the organic river banks; encroach into and narrow channels; colonize the channel bed; and induce local channel shallowing. Colonization, stabilization and aggradation of the river channel bed and margins by aquatic plants, contributes to bar formation, which is crucial to the evolution of this anabranching system.

In all, the Narew anabranching system and its floodplain depend on vegetation, which in turn is dependent upon hydrological processes. Although the area within the National Park is now protected so that vegetation-hydromorphology interactions can operate freely, there has been a decrease in the amplitude of floods in recent years as a result of flow regulation. In addition, ice flows are diminishing and will probably decrease further with climate change. These hydrological changes have implications for the frequency of flooding across zone 4, with a likely adjustment of the spatial extent of vegetation communities across zone 5 (which may enlarge) and zone 4 (which may get smaller). They also have significant implications for the anabranching channel pattern, since the creation of new channels will become increasingly unlikely, and thus the spatial dynamics and internal functioning of zones 1 to 3 is likely to become severely impacted.

Braided rivers of south-west France

This regional assessment does not constitute a detailed examination of vegetation-hydromorphology interactions, but it illustrates how braided rivers take on different levels of anabranching (i.e. show different levels of island-braiding) across a large area that extends over several biogeographical regions. This regional analysis demonstrates how vegetation-fluvial process interactions within the critical zone (across zones 2 and 3), even within river reaches of the same type and subject to the same set of vegetation-mediated geomorphic units, can vary greatly through time and across space as controlling factors change. Such factors may reflect broad environmental controls such as climate, geology, flow regime and vegetation composition, but these are confounded by the multitude of human pressures, which may themselves map onto the broad environmental controls.

3.3.7.4 Concluding points.

This report has developed a range of themes that relate to the rapidly developing field of fluvial biogeomorphology. Most research in this interdisciplinary field has evolved since 2000, and so it can be described as new and fast-breaking science. Given this brief history, it is scarcely surprising that the various sections of this report present truly new results but also leave a range of important research gaps. While we are confident that the conceptual model provides a useful multi-scale framework for understanding and interpreting vegetation-hydromorphology interactions in a way that can support sustainable river restoration design and management, research gaps need to be filled before the work can be translated into a set of simple tools for river management, namely:

1. The conceptual model needs to be refined to make it more robust following its proper application to a range of European rivers. To achieve this, the application of the conceptual model must involve collection of new purpose-specific field observations. The examples presented here have synthesised pre-existing literature and field observations that were collected for many different scientific or management purposes. They have provided a 'proof of concept' and a firm basis for recommending that new purpose-specific field research is needed.
2. The thorough review of available modelling tools has also demonstrated that all of the different aspects of plant-hydromorphology interactions have received attention from modellers, although many research gaps remain. However and more importantly, most of the models only address narrow aspects of this interaction. More integrated modelling approaches are needed to better support understanding and the development of tools suitable for integrated management.
3. Although we have made significant advances in synthesising information on the natural riparian and aquatic vegetation of European rivers, and in assembling species traits that are relevant to vegetation-hydromorphology interactions, more research is needed to add to the work that has been presented in this report. This includes both the assembly of information on native riparian and aquatic species (and their abundance) for European biogeographical regions and also the extraction of a larger set of informative species traits.

Overall, this report has gone a long way towards demonstrating the importance of understanding vegetation as a key physical control of river morphodynamics, and thus a crucial component of river restoration. We have also shown how interactions between plants and hydromorphology take on different characteristics in different biogeographical settings, leading to different spatial distributions and temporal dynamics of zones 1 to 5, and different styles of landform development within the critical interface between fluvial processes and vegetation within zones 1 to 3. These long-overlooked dynamics need serious research and management attention, and riparian vegetation needs to be more formally incorporated into the Water Framework Directive. We hope that we have provided a useful framework for advancing this field.

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Annexes

Annex A: Summary tables of models described in section 2.3

Table 1. **Summary of model characteristics on vegetation and flow resistance**	
Processes	Flow hydrodynamics in terms of hydraulic roughness in vegetated flows
Type of models	Semi-empirical equations for the estimation of flow resistance to be inserted in 1D-2D hydro-morphodynamic models
Model Input	Vegetation characteristics (geometry, density), flow conditions (water discharge, water surface slope)
Underlying equations	Flow resistance for aquatic flexible vegetation (Nepf, 2013), flow resistance for riparian flexible vegetation (Aberle and Järvelä, 2013), flow resistance for riparian rigid vegetation (Baptist, 2007)
Model Output	Flow resistance induced by vegetation (aquatic and riparian), rigid and flexible, submerged/ unsubmerged
Spatial scale of application	Reach scale

Suitability for analysis of hydromorphological pressures

	YES	NO
1. Water abstractions		X
2. Flow regulations	X	
3. River fragmentation		X
4. Morphological alterations	X	

Suitability for helping with restoration design

	YES	NO
1. Water flow quantity improvement		X
2. Sediment flow quantity improvement		X
3. Flow dynamics improvement	X	
4. Longitudinal connectivity improvement		X
5. River bed depth and width variation improvement	X	
6. In-channel structure and substrate improvement		X
7. Riparian zone improvement	X	
8. Floodplain-, off-channel, -lateral connectivity-, habitat improvement		X

Software packages

Delft3D (download page: http://oss.deltares.nl/web/delft3d/download)

Table 2. Summary of model characteristics on vegetation and bank stability

Processes	Root reinforcement, surcharge
Type of models	Numerical 2D model of bank stability including some of the effects of vegetation, numerical 2D groundwater flow modelling
Model Input	Bank geometry (bank slope, height, profile), flow conditions (shear stress, water surface elevation), groundwater flow conditions (water table elevation, negative pore water pressure distribution), bank material (shear strength, critical shear stress, erodibility coefficient), bank vegetation (tensile strength-root diameter relation, root-area ratio, weight)
Underlying equations	*General equations for fluvial erosion:* boundary shear stress equation, bank erosion rate (Partheniades, 1965) *General equations for bank stability:* shear strength of saturated (Mohr-Coulomb) or unsaturated soil (Fredlund et al., 1978), factor of safety equation (Limit Equilibrium Method) *General equations for groundwater flow:* darcy law, mass conservation extended to unsaturated conditions (Fredlund and Rahardjo, 1993) *Equations for root reinforcement:* root reinforcement (Wu et al., 1978), progressive breaking by the RipRoot model (Pollen and Simon, 2005)
Model Output	Bank stability, bank geometry, rate of bank retreat, amount of bank erosion products
Spatial scale of application	Bank profile - site

Suitability for analysis of hydromorphological pressures

	YES	NO
1. Water abstractions		X
2. Flow regulations	X	
3. River fragmentation		X
4. Morphological alterations	X	

Suitability for helping with restoration design

	YES	NO
1. Water flow quantity improvement		X
2. Sediment flow quantity improvement		X
3. Flow dynamics improvement	X	
4. Longitudinal connectivity improvement		X
5. River bed depth and width variation improvement	X	
6. In-channel structure and substrate improvement		X
7. Riparian zone improvement	X	
8. Floodplain-, off-channel, -lateral connectivity-, habitat improvement		X

Software packages

The most commonly used and most advanced model explicitly accounting for *root reinforcement* is the Bank Stability and Toe Erosion Model (BSTEM) developed by the USDA-ARS (Simon et al. 2000; Simon and Collison 2002; Pollen-Bankhead and Simon, 2009).
Download at: http://ars.usda.gov/Research/docs.htm?docid=5044
In BSTEM, root reinforcement is simulated by the RipRoot model (Pollen and Simon, 2005; Pollen-Bankhead and Simon, 2009), which is a global load-sharing fiber-bundle model. It explicitly simulates both the snapping of roots and the slipping of roots through the soil matrix, by determining the minimum applied load required to either break each root or pull each root out of the soil matrix. As the strength of each root is removed from the fibre bundle, the load is redistributed to the remaining roots according to the ratio of the diameter of each root to the sum of the diameters of all the intact roots. RipRoot builds on earlier work by Waldron (1977) and Wu et al. (1979).

Table 3. Summary of model characteristics on vegetation and bank accretion	
Processes	River bank advance due to accretion processes
Type of models	Semi-empirical equations for the estimation of bank advance to be inserted in 1-2D hydro-morphodynamic models.
Model Input	Hydrological regime, soil properties vegetation characteristics (variable in time)
Underlying equations	**-**
Model Output	Cross-sectional changes, bankline advance
Spatial scale of application	Cross-sectional scale, reach scale

Suitability for analysis of hydromorphological pressures	YES	NO
1. Water abstractions		X
2. Flow regulations	X	
3. River fragmentation		X
4. Morphological alterations	X	

Suitability for helping with restoration design	YES	NO
1. Water flow quantity improvement		X
2. Sediment flow quantity improvement		X
3. Flow dynamics improvement	X	
4. Longitudinal connectivity improvement		X
5. River bed depth and width variation improvement	X	
6. In-channel structure and substrate improvement		X
7. Riparian zone improvement	X	
8. Floodplain-, off-channel, -lateral connectivity-, habitat improvement	X	

Software packages
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Table 4. Summary of model characteristics on vegetation dispersal

Processes	Vegetation dispersal
Type of models	Empirical and semi-empirical approaches, flume experiments, bio-hydrodynamic models, conceptual models
Model Input	Flow regime, variability of the flow regime, flood magnitude, channel morphology, hydraulic characteristics, seed dispersal phenology
Underlying equations	-
Model Output	Spatial patterns of seeds and propagules deposition and dispersal, Seed density, Dispersion coefficient
Spatial scale of application	Reach scale, Channel/floodplain cross section

Suitability for analysis of hydromorphological pressures

	YES	NO
1. Water abstractions		X
2. Flow regulations	X	
3. River fragmentation	X	
4. Morphological alterations	X	

Suitability for helping with restoration design

	YES	NO
1. Water flow quantity improvement	X	
2. Sediment flow quantity improvement		X
3. Flow dynamics improvement	X	
4. Longitudinal connectivity improvement	X	
5. River bed depth and width variation improvement		X
6. In-channel structure and substrate improvement	X	
7. Riparian zone improvement	X	
8. Floodplain-, off-channel, -lateral connectivity-, habitat improvement		

Software packages

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Table 5. Summary of model characteristics on vegetation recruitment

Processes	Riparian vegetation recruitment (i.e. seed and propagule survival and early development)
Type of models	Dynamic simulation models, Field experiments, Statistical analysis (e.g. logistic regression), Conceptual models
Model Input	Flooding regime, Hydrological regime, Water table dynamic, Specie-specific physiological information (e.g. timing and duration of seed dispersal, tolerance to inundation)
Underlying equations	**-**
Model Output	Seedling survival and growth, riparian vegetation composition and vegetation dynamics
Spatial scale of application	Local/site scale, landform/patch scale, reach scale, riparian corridor scale

Suitability for analysis of hydromorphological pressures

	YES	NO
1. Water abstractions	X	
2. Flow regulations	X	
3. River fragmentation		X
4. Morphological alterations	X	

Suitability for helping with restoration design

	YES	NO
1. Water flow quantity improvement	X	
2. Sediment flow quantity improvement		X
3. Flow dynamics improvement	X	
4. Longitudinal connectivity improvement		X
5. River bed depth and width variation improvement		X
6. In-channel structure and substrate improvement		X
7. Riparian zone improvement	X	
8. Floodplain-, off-channel, -lateral connectivity-, habitat improvement	X	

Software packages
STELLATM (v.8.1.1): Richmond and Peterson (1997)

Table 6. Summary of model characteristics on vegetation growth

Processes	Plant growth
Type of models	Ecological model (mathematical); process-based model; stochastic model (analytical)
Model Input	Stand density; temperature; shading tolerance; position of the water table; variability of the water table level; floods; sedimentation; river channel cross profile and variability
Underlying equations	**-**
Model Output	Plant growth rate; vegetation biomass density
Spatial scale of application	Local (riparian zone; individuals)

Suitability for analysis of hydromorphological pressures

	YES	NO
1. Water abstractions	X	
2. Flow regulations	X	
3. River fragmentation	X	
4. Morphological alterations	X	

Suitability for helping with restoration design

	YES	NO
1. Water flow quantity improvement	X	
2. Sediment flow quantity improvement	X	
3. Flow dynamics improvement	X	
4. Longitudinal connectivity improvement	X	
5. River bed depth and width variation improvement	X	
6. In-channel structure and substrate improvement	X	
7. Riparian zone improvement	X	
8. Floodplain-, off-channel, -lateral connectivity-, habitat improvement	X	

Software packages

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Table 7. Summary of model characteristics on vegetation succession

Processes	Riparian vegetation succession
Type of models	Hydro-ecological model; numerical model; fluid dynamic models; process-based model; spatially-based approach
Model Input	Historical hydrological conditions ; soil parameters; type of management; flood regime; hydrological regime; groundwater level dynamic; variability of the topographic cross-profile; hydraulic variables; vegetation maps; floodplain topography; physical variables (and their spatial distribution)
Underlying equations	**-**
Model Output	Occurrence of specific ecological groups; vegetation types (units, communities) in time; species distribution; significant environmental factors distribution (e.g. related to the issue exotic species); river-vegetation interactions; vegetation width variations; river morphological changes (e.g. width variation, meander dynamic); spatial distribution of floodplain vegetation
Spatial scale of application	Local scale: site; reach scale; river cross-section; vegetation unit scale. Large scale: floodplain scale; landscape and regional scales

Suitability for analysis of hydromorphological pressures

	YES	NO
1. Water abstractions		X
2. Flow regulations	X	
3. River fragmentation		X
4. Morphological alterations	X	

Suitability for helping with restoration design

	YES	NO
1. Water flow quantity improvement	X	
2. Sediment flow quantity improvement		X
3. Flow dynamics improvement	X	
4. Longitudinal connectivity improvement		X
5. River bed depth and width variation improvement	X	
6. In-channel structure and substrate improvement	X	
7. Riparian zone improvement	X	
8. Floodplain-, off-channel, -lateral connectivity-, habitat improvement	X	

Software packages

BIO-SAFE: Lenders et al. (2001)
CASIMIR-vegetation: e.g. Rivaes et al. (2012)
LEDESS: Buit et al. (1998)
NATLES: Runhaar J. (2003)
PREVIEW (Predicting Vegetation in Escavated Winterbeds): Aggenbach and Pelsma (2005)

Table 8. Summary of model characteristics on large wood

Processes	Several fundamental wood processes are represented only in few models. Delivery from adjacent riparian forests generally is modelled as direct mortality and fall, windthrow, bank undercutting, or an overall composite mortality of all of these sources. Two models (Benda and Dunne, 1997a,b; Lancaster et al., 2003) incorporate four processes (tree mortality, fire, bank erosion, and mass wasting) to predict wood input to streams. Only one model (Meleason et al., 2003) simulates the breakage of trees as they fall into streams and breakage of wood as it is subsequently transported. Most models also combine the processes of decomposition, breakage, and export into an overall depletion estimate.
Type of models	Deterministic or stochastic. Most of the existing models are deterministic models that produce single estimates of outcomes with no variance. Disturbance processes in most wood models are simulated based on fixed scenarios of long-term disturbance events. In contrast, three models are stochastic models based on probabilities of selected wood processes and rates of processes.
Model Input	Extremely variable, including wood species, riparian zone description, stream wood size, etc.
Underlying equations	Extremely variable
Model Output	Variable, including recruitment and stream wood quantity, depletion rate, in-stream movement and travel distance, etc.
Spatial scale of application	Reach to overall stream length

Suitability for analysis of hydromorphological pressures

	YES	NO
1. Water abstractions		X
2. Flow regulations		X
3. River fragmentation		X
4. Morphological alterations		X

Suitability for helping with restoration design

	YES	NO
1. Water flow quantity improvement		X
2. Sediment flow quantity improvement		X
3. Flow dynamics improvement		X
4. Longitudinal connectivity improvement		X
5. River bed depth and width variation improvement		X
6. In-channel structure and substrate improvement	X	
7. Riparian zone improvement	X	
8. Floodplain-, off-channel, -lateral connectivity-, habitat improvement	X	

Software packages

Oregon State University STREAMWOOD

Table 9a. Summary of model characteristics on vegetation interaction with hydromorphology			
Processes	Hydrology, morphological development, vegetation development and interaction		
Type of models	2D numerical models, cellular automata		
Model Input	Discharge, parameters for vegetation colonisation, growth and mortality		
Underlying equations	Equations for water flow, sediment transport, vegetation roughness, bank strength		
Model Output	River planform, vegetation pattern, vegetation biomass		
Spatial scale of application	Reach scale		
Suitability for analysis of hydromorphological pressures			
		YES	NO
1. Water abstractions		X	
2. Flow regulations		X	
3. River fragmentation		X	
4. Morphological alterations		X	
Suitability for helping with restoration design			
		YES	NO
1. Water flow quantity improvement		X	
2. Sediment flow quantity improvement		X	
3. Flow dynamics improvement		X	
4. Longitudinal connectivity improvement		X	
5. River bed depth and width variation improvement		X	
6. In-channel structure and substrate improvement		X	
7. Riparian zone improvement		X	
8. Floodplain-, off-channel, -lateral connectivity-, habitat improvement		X	
Software packages			
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Table 9b. Detailed characteristics of models on vegetation – hydromorphology interactions

Reference	Vegetation influences Morphodynamics	Morphodynamics influences vegetation	Other vegetation processes	Spatial scale	Temporal scale
(Murray & Paola 2003a)	-Increase bank strength -Impedance sediment transport	- Colonization on dry areas - Mortality by scour or burial	- Plant growth	-Reach size: 3 km x 250 m -Cell size 5 x 5 m.	1000 days
(Coulthard *et al.* 2007)	-Decreased erosion	-Colonization on dry areas	- Plant growth	-Reach size 4 x20 km - Cell size 50x50m	20 years
(Hooke *et al.* 2005b)	-Higher roughness	- Colonization based on moisture - Growth influenced by moisture, flow velocity and water depth -Mortality due to flow velocities, water depth, burial and desiccation		-Reach length 100 m, - Cell size 30x30 cm	10 years
(Nicholas 2013b)	-Higher roughness -Reduced bank erosion	-Colonization based on water levels -Mortality due to bank erosion		-Reach size maximum 50 x 20 km -Cell size ranging from 10 x 5 to 80 x 40 m	Ranging from 20 to 500 years
(Perucca *et al.* 2007)	-Reduced bank erosion	-Biomass density development in relation to channel distance	- Plant growth - Plant decay	Reach size: 3 x 1 km Cell size: 0.1 x 0.1 m	Variable
(Crosato & Saleh 2011a)	-Higher roughness values	-Colonization based on water levels	- Different vegetation types	-Reach size 6500 x 100 m	10 years

Table 10a. Summary of model characteristics on vegetation dynamics

Processes	Competition, facilitation, plant growth, plant dispersal, colonisation, mortality
Type of models	Individual-based , patch occupancy, cellular automata, matrix models
Model Input	Various plant characteristics, resources, disturbance gradient
Underlying equations	Various
Model Output	Vegetation patterns, plant biomass, plant abundance, patch occupancy, plant distribution
Spatial scale of application	Generally patch scale (1-5 m^2)

Suitability for analysis of hydromorphological pressures

	YES	NO
1. Water abstractions		X
2. Flow regulations		X
3. River fragmentation		X
4. Morphological alterations		X

Suitability for helping with restoration design

	YES	NO
1. Water flow quantity improvement		X
2. Sediment flow quantity improvement		X
3. Flow dynamics improvement		X
4. Longitudinal connectivity improvement		X
5. River bed depth and width variation improvement		X
6. In-channel structure and substrate improvement		X
7. Riparian zone improvement	X	
8. Floodplain-, off-channel, -lateral connectivity-, habitat improvement	X	

Software packages

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Table 10b. Detailed characteristics of models on vegetation dynamics

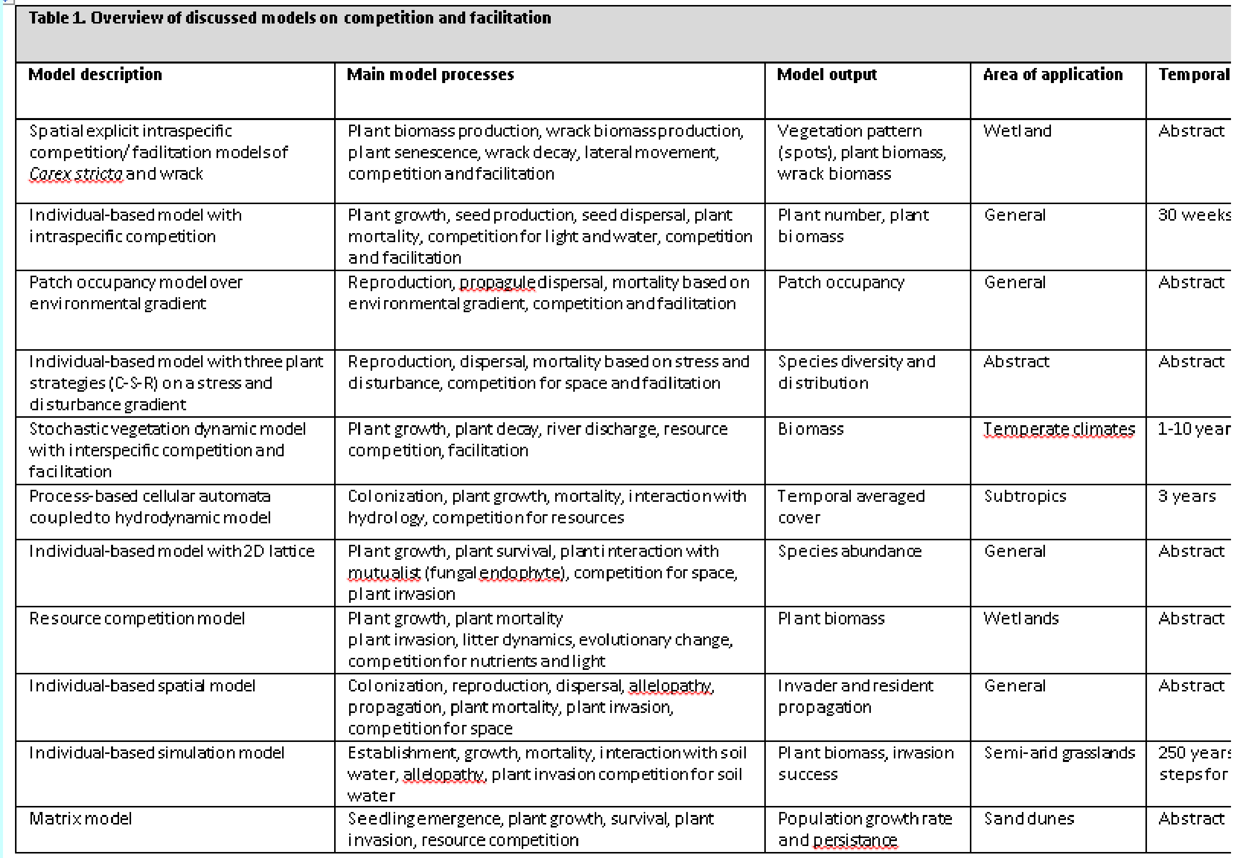

Table 1. Overview of discussed models on competition and facilitation

Model description	Main model processes	Model output	Area of application	Temporal
Spatial explicit intraspecific competition/facilitation models of *Carex stricta* and wrack	Plant biomass production, wrack biomass production, plant senescence, wrack decay, lateral movement, competition and facilitation	Vegetation pattern (spots), plant biomass, wrack biomass	Wetland	Abstract
Individual-based model with intraspecific competition	Plant growth, seed production, seed dispersal, plant mortality, competition for light and water, competition and facilitation	Plant number, plant biomass	General	30 weeks
Patch occupancy model over environmental gradient	Reproduction, propagule dispersal, mortality based on environmental gradient, competition and facilitation	Patch occupancy	General	Abstract
Individual-based model with three plant strategies (C-S-R) on a stress and disturbance gradient	Reproduction, dispersal, mortality based on stress and disturbance, competition for space and facilitation	Species diversity and distribution	Abstract	Abstract
Stochastic vegetation dynamic model with interspecific competition and facilitation	Plant growth, plant decay, river discharge, resource competition, facilitation	Biomass	Temperate climates	1-10 year
Process-based cellular automata coupled to hydrodynamic model	Colonization, plant growth, mortality, interaction with hydrology, competition for resources	Temporal averaged cover	Subtropics	3 years
Individual-based model with 2D lattice	Plant growth, plant survival, plant interaction with mutualist (fungal endophyte), competition for space, plant invasion	Species abundance	General	Abstract
Resource competition model	Plant growth, plant mortality plant invasion, litter dynamics, evolutionary change, competition for nutrients and light	Plant biomass	Wetlands	Abstract
Individual-based spatial model	Colonization, reproduction, dispersal, allelopathy, propagation, plant mortality, plant invasion, competition for space	Invader and resident propagation	General	Abstract
Individual-based simulation model	Establishment, growth, mortality, interaction with soil water, allelopathy, plant invasion competition for soil water	Plant biomass, invasion success	Semi-arid grasslands	250 years steps for
Matrix model	Seedling emergence, plant growth, survival, plant invasion, resource competition	Population growth rate and persistance	Sand dunes	Abstract

Table 11a. Summary of model characteristics on vegetation interaction with groundwater

Processes	Flow of groundwater, vegetation growth and interaction, biogeochemical processes
Type of models	Mechanistic and semi-mechanistic
Model Input	Meteorological conditions, soil parameters, vegetation parameters, ecohydrological model, morphology, land use, nutrients
Underlying equations	Various
Model Output	Vegetation occurrence, vegetation development, vegetation succession, vegetation distribution, vegetation development
Spatial scale of application	From field scale to ecosystem scale

Suitability for analysis of hydromorphological pressures

	YES	NO
1. Water abstractions	X	
2. Flow regulations	X	
3. River fragmentation	X	
4. Morphological alterations	X	

Suitability for helping with restoration design

	YES	NO
1. Water flow quantity improvement	X	
2. Sediment flow quantity improvement	X	
3. Flow dynamics improvement	X	
4. Longitudinal connectivity improvement	X	
5. River bed depth and width variation improvement	X	
6. In-channel structure and substrate improvement	X	
7. Riparian zone improvement	X	
8. Floodplain-, off-channel, -lateral connectivity-, habitat improvement	X	

Software packages

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Table 11b. Detailed characteristics of semi-mechanistic groundwater – vegetation models

Model Characteristics	**DEMNAT**	**VSD+-SUMO-NTM**	**DURAVEG**	**INFORM**	**SWIM coupled to groundwater model**
creator/institute	Deltares	Alterra	RoyalHaskoning	BfG	PIK-Potsdam
purpose / goal	effects of water management changes on terrestrial vegetation (time horizon: 20 years)	longstanding effects of atmospheric deposition, management interventions, etc.	ecohydrological effect program based changes in groundwater level regime	evaluation of (effects of water management on) the ecology in flood plains	regional impact assessment climate change and land use
model type	semi-mechanistic	semi-mechanistic	semi-mechanistic	semi-mechanistic	semi-mechanistic
ecotope(s)	14 groundwater (semi-)dependent terrestrial ecosystems, 4 aquatic ecotopes	groundwater dependent and groundwater independent ecotopes	groundwater dependent and groundwater independent ecotopes temperate sea climate	river valleys, inundation areas and riparian	groundwater dependent and groundwater independent ecotopes
region	Netherlands (NW Europe?)	Netherlands (NW Europe?)	Netherlands (NW Europe?)	Germany (NW Europe?)	Germany (NW Europe?)
spatial scale	local to national scale, gridded	local to national scale, gridded (e.g. 250x250m)	local to regional scale, gridded	riparian zone to river valley	basin, sub-basins and hydrotopes within sub-basins
temporal scale	annual	annual	annual	??	days?
input parameters	moisture regime, nutreint availibility, acidity	soil moisture, temperature, nutrient- and litter production	meteo-conditions, soil characteristics, moisture conditions	soil characteristics, surface water and inundation, moisture conditions, morphology	land use and management, climate data, soil characteristics, moisture conditions, elevation
groundwater	groundwater: hydrogeological information of the area or output of spatially distributed groundwater models	spatially ditributed data: water balance of hydrological models	groundwater: output of spatially distributed groundwater models	groundwater: hydrogeological information of the area or output of spatially distributed groundwater models	simplified groundwater model: groundwater dynamics (water levels and discharge) on a meso-scale parameterized using physical data
link groundwater - vegetation	dose-effect functions	Ellenberg indicator values	database (reference matrix) with (time series of) ecohydrological boundary conditions	Ellenberg indicator values	vegetation type specific parameter values (EPIC approach)
model output	(changes in) botanical quality (or completness) of the 18 ecotopes	soil processes, vegetation growth and vegetation succession	most likely vegetation type for the calculated groundwater regime	occurrence of vegetation types	prediction of crop growth, vegetation growth in flood plains
reference	Witte (1998), Van Ek et al. (2000)	Wamelink et al. (2003), Wamelink et al. (2009), Berendse (1994), Wamelink et al. (2005) Wamelink (2007)	Factsheets RoyalHaskoning	Hens et al. (2011), Gieble et al. (2011)	Krysanova et al. (1989), Krysanova et al. (2005), Hatterman et al. (2005)
website	https://publicwiki.deltares.nl/display/KRWGR/DEMNAT		www.modelwalhalla.nl/wiki/pub/Tools/TriwacoFLAIRS/Triwaco4_-g-_Duraveg_ecologische_effectvoorspellingsmodule.pdf www.modelwalhalla.nl/wiki/pub/Tools/TriwacoFLAIRS/Triwaco4_-g-_Duraveg_ecologische_effectvoorspellingsmodule_poster.pdf		

Table 11c. Detailed characteristics of mechanistic groundwater – vegetation models

Model Characteristics	PROBE	NUCOM(-BOG)	RIP-ET and PRE-RIP-ET	Ecohydrological hillslope model
creator/institute	KWR	WUR	University of Aizona	UU
purpose / goal	effects of climate change on vegetation and competition	longstanding effects of climate change on effects of climate change on nutrient cycling, vegetation development, plant competition, carbon sequestration	predict vegetation response to water allocation decisions	influence of slope angle, precipitation input and vegetation composition on the hydrological system and effect of hydrology and climate on vegetation, vegetation competition
model type	mechanistic	mechanistic	mechanistic	mechanistic
ecotope(s)	groundwater dependent and groundwater independent ecotopes	groundwater dependent and groundwater independent ecotopes: forest, heather, dunes and bogs	groundwater dependent ecosystems on riparian zones	groundwater dependent ecosystems on hillslopes
region	Netherlands (NW Europe?)	Netherlands, NW Europe	Semi-arid basins Arizona	NW Europe
spatial scale	field scale	ecosystem scale (NUCOM-BOG: landscape scale)	local scale, gridded (riparian zones)	local scale
temporal scale	??	montly (NUCOM-BOG: decades to centuries)	years?	years to centuries
input parameters	meteo-conditions, soil temperature, soil moisture, soil composition, plant traits	climate, CO2 concentration, atmospheric deposition, soil parameters, moisture conditions, vegetation parameters	plant rooting depths, land surface elevation, moisture conditions, initial plant composition and distribution, vegetation parameters	Climatic forcing, interception and evapotranspiration, moisture conditions, soil parameters, root zone thickness, vegetation parameters
groundwater	SWAP model	SWAP model	moderate- to high-resolution depth-to-groundwater output of spatially distributed groundwatermodels	2-dimensional model of saturated-unsaturated flow along a slope
link groundwater - vegetation	water stress and oxygen stress of plant traits (Feddes functions)	water stress and oxygen stress of vegetation types in ecosystem (Feddes functions)	ecophysiologically based evapotranspiration curves, one for each plant functional group present	water stress and oxygen stress
model output	occurrence of vegetation types	long term vegetation succession for plant species typical for ecosystems	vegetation development of plant functional groups in riparian zones	vegetation distribution and abundance
reference	Witte et al. (2006), Witte et al. (2007a)	Van Oene (1999), Van Oene and Berendsen (2001), Van Oene et al. (2001) Heijmans et al. (2008) and Heijmans et al. (2013)	Baird et al. (2005)	Brolsma et al. (2007), Brolsma et al (2010a), Brolsma et al (2010b), Brolsma et al (2010c)
website	www.kwrwater.nl/klimaat_natuur/probe_benadering/ www.nrel.colostate.edu/projects/century/MANUAL/html_manual/man96.html			

Annex B: Riparian and Aquatic Plant Communities of Europe

This annex contains tables of aquatic (Table 1) and riparian (Table 2) vegetation types which are considered natural and may therefore indicate natural hydrological and fluvial geomorphological conditions. The vegetation communities are taken from EUNIS / PHYSIS and the Natura 2000 (N2K) coding systems.

Table 1: Aquatic Vegetation Types

A first attempt at a Pan-European classification of aquatic vegetation likely to occur in rivers under natural geomorphic conditions. The classification is based on EUBIS/PHYSIS or a Natura 2000 description.

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EUNIS / PHYSIS code	EUNIS / PHYSIS Sub-code	N2K code	EUNIS / PHYSIS or N2K description	Geographic extent
n/a		3210	Fennoscandian natural rivers [N2K manual page 44]. Defined as "Boreal and hemiboreal natural and near-natural river systems or parts of such systems containing nutrient-poor water. The water level shows great amplitude, up to 6 m during the year. Especially during the spring, the water level is high. The water-dynamics can vary and contain waterfalls, rapid streams, calm water, and small lakes adjacent to the river. The water erosion causes a higher amount of nutrients towards the river-mouth, where sedimentation starts. In higher levels the rivers are characterised by great, very cold water flows, coming from glaciers, deep snow-beds and large snow-covered areas in mire- and woodlands. In addition the water surface in placid river sections is frozen to ice every winter. These circumstances create ecosystems unique to this part of Europe. [Mainly Scandinavian and Russian taiga eco–region	boreal
C2.2			**Permanent non-tidal, fast, turbulent watercourses**	

EUNIS / PHYSIS code	EUNIS / PHYSIS Sub-code	N2K code	EUNIS / PHYSIS or N2K description	Geographic extent
	C2.2/P-24.12		Epirhithral and metarhithral streams (mountain streams)	
	C2.2/P-24.13		Hyporhithral streams (lower reaches of mountain sections)	
		3220	Alpine rivers and the herbaceous vegetation along their banks [N2K manual page 44 – equivalent to PHYSIS 24.221 and 24.222].	Alpine Bio-geographic region
	P-24.221		· Open assemblages of herbaceous or suffrutescent pioneering plants, rich in alpine species, colonising gravel beds of streams with an alpine, summer-high, flow regime, (Epilobion fleischeri p.)	· formed in northern boreal and lower Arctic mountains, hills and sometimes lowlands, as well as in the alpine and subalpine zones of higher, glaciated, mountains of more southern regions, sometimes with abyssal stations at lower altitudes (Epilobion fleischeri p.)
	P-24.222		Open or closed assemblages of herbaceous or suffrutescent pioneering plants, colonising, within the montane or sub-montane levels, gravel beds of streams with an alpine, summer-high, flow regime, born in high mountains (Epilobion fleischeri p., Calamagrostion pseudophragmitis).	[Includes eco-regions of a) Scandinavian montane birch forest & grasslands; b) Alps conifer & mixed forests; c) Carpathian montane coniferous forests; d) Pyrenees conifer & mixed forests; and maybe e)Dinaric Mountains mixed forests; and f) Urals Montane tundra & taiga]
	P-24.223	3230	Alpine rivers and their ligneous vegetation with Myricaria germanica [N2K Manual page 45 – equivalent to PHYSIS 24.223 x 44.111]. Communities of low shrubby pioneers invading the herbaceous formations of 24.221 and 24.222 on gravel deposits rich in fine silt, of mountain and northern boreal streams with an alpine, summer-high, flow regime. Myricaria germanica and Salix spp. are characteristic (Salici-Myricarietum	Eco-regions presumably as for type 3220
	P-24.224	3240	Alpine rivers and their ligneous vegetation with Salix elaeagnos [N2K Manual page 46 – equivalent to PHYSIS	Salix elaeagnos is confined to Pyrenees, Alps, Carpathians, Apennines and Dinaric

EUNIS / PHYSIS code	**EUNIS / PHYSIS Sub-code**	**N2K code**	**EUNIS / PHYSIS or N2K description**	**Geographic extent**
			24.224 x 44.112]. Defined as: Thickets or woods of, among others, Salix spp., Hippophae rhamnoides, Alnus spp., Betula spp., on stream gravels of mountain and northern boreal streams with an alpine, summer-high, flow regime. Formations of Salix elaeagnos, Salix purpurea ssp. gracilis, Salix daphnoides, Salix nigricans and Hippophae rhamnoides of higher gravel shoals in Alpine and peri-Alpine valleys	mountains – so assume relevance to those eco-regions
	P-24.225	3250	Constantly flowing Mediterranean rivers with Glaucium flavum. [N2K Manual page 46 – equivalent to PHYSIS 24.225]. Defined as: Communities colonising gravel deposits of rivers with a Mediterranean, summer-low, flow regime, with formations of the Glaucion flavi. [	Various eco-regions – see EEA map
	P-24.4	3260	Water courses of plain to montane levels with the Ranunculion fluitantis and Callitricho-Batrachion vegetation [N2K manual page 46 – equivalent to PHYSIS 24.4]. Defined as: Water courses of plain to montane levels, with submerged or floating vegetation of the Ranunculion fluitantis and Callitricho-Batrachion (low water level during summer) or aquatic mosses. [Widespread through Atlantic and Continental and at least the southern Boreal biogeographic regions (probably further afield but certainly from Ireland to Romania and north to Sweden) – including many eco-regions]	Widespread
	C2.2/P-24.41(p)		Acid oligotrophic vegetation of fast-flowing streams ***	
	C2.2/P-24.42(p)		Lime-rich oligotrophic vegetation of fast-flowing streams ***	
	C2.2/P-24.43(p)		Mesotrophic vegetation of fast-flowing streams ***	
	C2.2/P-24.44(p)		Eutrophic vegetation of fast-flowing streams ***	
C2.3			**Permanent non-tidal, slow, smooth-flowing**	

EUNIS / PHYSIS code	EUNIS / PHYSIS Sub-code	N2K code	EUNIS / PHYSIS or N2K description	Geographic extent
			watercourses	
	C2.3/P-24.14		Epipotamal streams	
	C2.3/P-24.15		Metapotamal and hypopotamal streams	
	C2.3/P-24.43(p)		Mesotrophic vegetation of slow-flowing rivers ***	
	C2.3/P-24.44(p)		Eutrophic vegetation of slow-flowing rivers ***	
C2.4			**Tidal rivers, upstream from the estuary**	
	C2.4/P-13.11		Brackish water tidal rivers	
	C2.4/P-13.12		Freshwater tidal rivers	
	C2.4/P-24.43(p)		Mesotrophic vegetation of tidal rivers ***	
	C2.4/P-24.44(p)		Eutrophic vegetation of tidal rivers ***	
C2.5			**Temporary running waters (wet phase)**	
	P-24.52	3270	Rivers with muddy banks with Chenopodion rubri p.p. and Bidention p.p. vegetation [N2K manual page 46 – equivalent to PHYSIS 24.52]. Defined as: Muddy river banks of plain to sub-montane levels, with annual pioneer nitrophilous vegetation of the Chenopodion rubri p.p. and the Bidention p.p. alliances. During the spring and at the beginning of the summer, sites look like muddy banks without any vegetation (develops later in the year). If the conditions are not favourable, this vegetation has a weak development or could be completely absent. [Distribution probably similar to 3260 though possibly absent from the Boreal biogeographic region	Widespread

EUNIS / PHYSIS code	EUNIS / PHYSIS Sub-code	N2K code	EUNIS / PHYSIS or N2K description	Geographic extent
	P 24.53	3280	Constantly flowing Mediterranean rivers with Paspalo-Agrostidion species and hanging curtains of Salix and Populus alba [N2K Manual page 47 – equivalent to PHYSIS 24.53]. Defined as: Nitrophilous annual and perennial grass and sedge formations of the alluvial banks of large Mediterranean rivers, with Paspalum paspaloides, P. vaginatum, Polypogon viridis (= Agrostis semiverticillata), Cyperus fuscus, and hanging curtains of Salix spp and Populus alba	Assume in all/most eco-regions within this Mediterranean biogeographic region]
	P-24.53 & P-24.16	3290	Intermittently flowing Mediterranean rivers of the Paspalo-Agrostidion [N2K manual page 46 – equivalent to PHYSIS 24.16 and 24.53]. Defined as: Intermittently flowing Mediterranean rivers with Paspalo-Agrostidion communities. They correspond to the river type 24.53, but with the particularity of an interrupted flow and a dry bed during a part of the year. The bed of the river can be completely dry or left with some pools	Assume in all/most eco-regions within this Mediterranean biogeographic region]
	C2.6		Films of water flowing over rocky watercourse margins	

Table 2: Riparian Vegetation Types

The focus for this table is on (semi-) natural woody vegetation, though some attention is paid to herbaceous vegetation where that might exist naturally in an undisturbed floodplain. Especially in the upland and montane areas, many different types of forest may be found directly adjacent to rivers and overlapping with the riparian zone.

EUNIS / PHYSIS code	EUNIS / PHYSIS Sub-code	N2K code	EUNIS / PHYSIS or N2K description	Geographic extent
53.1			**Reed beds (Phragmition australis and Scirpion maritimi)**	
	53.11		Common Reed-beds (Phragmitetum etc) – 3 subdivisions	
	53.12		Common Clubrush beds (Scirpetum lacustris)	
	53.13		Reedmace beds (Typhetum angustifoliae and Typhetum latifoliae)	
	53.14		Medium-tall Waterside Communities. Ten subdivisions, most characterised by a single major dominant Sagittaria sagittifolia (and Sparganium emersum), Sparganium neglectum, Sparganium erectum, Acorus calamus, Butomus umbellatus, Oenantho-Rorippetum amphibae community, Equisetum fluviatile, Sium latifolium, Hippuris vulgaris, and Eleocharis palustris	
	53.15		Reed sweet-grass beds (Glycerietum maximae)	
	53.16		Reed Canary-grass beds (Phalaridetum arundinaceae)	
	53.17		Halophile club-rush beds (Scirpion maritimi)	
53.2			**Large sedge communities (Magnocaricion)**	
	53.21		Large Carex beds. Ten major subdivisions (some of which further split) with man dominants for those most likely to occur in riparian zone being Carex acuta, C. acutiformis, C. riparia, C. rostrata, C. vesicaria, C. elata, C. paniculata etc	
	53.22		Tall galingale beds (Cyperetum longi – mainly Mediterranean)	mainly Mediterranean
53.3			**Fen-sedge beds (Cladietum marisci i.a.) at land-building zone of calcareous lakes in north and general watersides in Mediterranean.**	
	53.33		Riparian Cladium beds is the most typical type by rivers, and mainly in Mediterranean region.	mainly in Mediterranean region

EUNIS / PHYSIS code	EUNIS / PHYSIS Sub-code	N2K code	EUNIS / PHYSIS or N2K description	Geographic extent
*****53.4**			**Small reed-beds of fast-flowing waters (Glycerio-Sparganion). Formations of smaller helophytes found throughout Europe. Typical dominants include Glyceria fluitans, G. notata, G. nemoralis, G. declinata, Leersia oryzoides, Catabrosa aquatica, Sparganium neglectum, S. microcarpum, Nasturtium officinale, N. microphyllum, Veronica beccabunga, V. anagallis-aquatica, Apium nodiflorum and Berula erecta at banks of small rivers.**	
53.5			**Tall rush swamps (Agropyro-Rumicion crispi p). See also 37.2 Eutrophic Humid grasslands**	
53.6			**Riparian cane formations. Two types of Mediterranean region**	
	53.61		Ravenna Cane communities. Dominants Imperata, Saccharum spp, Arundo plinii	
	53.62		Provence Cane beds dominated by long-introduced Arundo donax	
37.1		**6410**	**37.1: Meadowsweet stands and related communities (Filipendulion ulmariae. Defined as: hygrophile tall herb strips of fertile alluvial stream banks, often dominated by Filipendula ulmaria, and tall herb stands (F. ulmaria, Angelica sylvestris) colonising humid hay meadows and pastures after more or less long discontinuation of mowing or grazing; characteristic species are Filipendula ulmaria, Achillea ptarmica, Angelica sylvestris, Cirsium palustre, Deschampsia cespitosa, Epilobium hirsutum, Geranium palustre, Veronica longifolia, Scutellaria hastifolia, Eupatorium cannabinum, Lysimachia vulgaris, Lythrum salicaria, Phalaris arundinacea, Persicaria bistorta and Valeriana officinalis. When occurring as a hygrophile tall herb strip, this habitat type is of central importance to REFORM *** Molinia meadows on calcareous, peaty or clayey-silt-laden soils (Molinion caeruleae) [N2K manual page 76 – equivalent to PHYSIS 37.31]. Defined as: Molinia meadows of plain to montane levels, on more or less wet nutrient poor soils (nitrogen, phosphorus). They stem from extensive management, sometimes with a mowing late in the year or, they correspond to a deteriorated stage of draining peat bogs. Sub-types:**	**[Widespread through Atlantic and Continental and at least the southern Boreal biogeographic regions (probably further afield but certainly from Ireland to Romania and north to Sweden) – including many eco-regions]**
	37. 311		·: on neutro-alkaline to calcareous soils with a fluctuating water table, relatively rich in species (Eu-molinion). The soil is sometimes peaty and becomes dry in summer.	

EUNIS / PHYSIS code	EUNIS / PHYSIS Sub-code	N2K code	EUNIS / PHYSIS or N2K description	Geographic extent
	37.312:		· on more acid soils of the Junco-Molinion (Juncion acutiflori) except species-poor meadows or on degraded peaty soils.	
		6430	Hydrophilous tall herb fringe communities of plains and of the montane to alpine levels [N2K manual page 78 – equivalent to PHYSIS 37.7 and 37.8]. Defined as:37.7: Wet and nitrophilous tall herb edge communities, along water courses and woodland borders belonging to the Glechometalia hederaceae and the Convolvuletalia sepium orders (Senecion fluviatilis, Aegopodion podagrariae, Convolvulion sepium, Filipendulion). [Distribution likely to similar to 6410 – see also Alpine Bio-geographic region]According to CORINE/PHYSIS, this watercourse veil and shady woodland edge type may be divided into 37.71 Watercourse Veils and 37.72 Shady woodland edge fringes. Only the former is especially relevant to REFORM***. Watercourse veils comprise screens or veils of perennial tall herbs, small bushes and lianas lining lowland watercourses (and often have many ruderal and invasive alien plants). Type includes those alliances underlined above and may be further subdivided:	
	37.711:		Angelica archangelica fluvial communities. Angelica archangelica ssp littoralis formations of great formation of great northern rivers, presently rare & threatened.	
	37.712:		Angelica heterocarpa fluvial communities. Angelica heteropcarpa formations of the tidal estuaries of the Loire, the Charente and the Gironde [Species is a rare and very narrow endemic of south-western France]	very narrow endemic of south-western France
	37.713:		Marsh Mallow screens. Althaea officinalis formations of river banks and marsh edges, particularly on somewhat saline soils ***	
	37.714:		Butterbur riverine communities. Formations of Petasites hybridus and Cirsium oleraceum of the banks of small streams *** [Also locally by large rivers]	
	37.715:		Mixed riverine screens. Formations of Senecio fluviatilis, Calystegia sepium, Eupatorium cannabinum, Epilobium hirsutum, Sonchus palustris, Urtica dioica and others species, lining lowland watercourses ***	

EUNIS / PHYSIS code	EUNIS / PHYSIS Sub-code	N2K code	EUNIS / PHYSIS or N2K description	Geographic extent
37.2		**6440**	**Eutrophic humid grasslands. Includes the N2K Manual type 6440 Cnidion dubii (see below under Continental biogeographic region) but also Molinetalia, Calthion palustris, Bromion racemosi, Deschampsion cespitosae, Juncion acutiflorae, Agrostietalia stoloniferae and Agropyro-Rumicion p. Most of these occur in meadows developed on moderately to very nutrient-rich, alluvial or fertilised, wet or damp swards, often inundated at least in winter, and relatively lightly mowed or grazed – in lowland, collinar and montane western and Central Europe, south to western Iberia [Hence occurring in Atlantic, Continental and parts of Mediterranean biogeographic regions]. Although all types listed in CORINE biotopes manual may be found in the riparian zone, the following are especially typical:**	
37.24			**Flood swards and related communities. Agropyro-Rumicion crispi p. Defined as: grasslands of occasionally flooded river and lake banks, of depressions where rain water collects, of disturbed humid areas and pastures submitted to intensive grazing**	
	37.241:		Tall rush pastures. Rush (Juncus effusus, J. conglomeratus, J. inflexus) colonies of intensively grazed pastures	
	***37.242 :		Creeping bent and tall fescue swards. Flood swards with Agrostis stolonifera, Carex hirta, Schedonorus arundinaceus, Juncus inflexus, Alopecurus geniculatus, Rumex crispus, Mentha longifolia, M. pulegium, Potentilla anserina, P. reptans and Ranunculus repens.	
38.2		**6510**	**Lowland hay meadows (Alopecurus pratensis, Sanguisorba officinalis) [N2K manual page 80 – equivalent to PHYSIS 38.2]. Defined as: Species-rich hay meadows on lightly to moderately fertilised soils of the plain to sub-montane levels, belonging to the Arrhenatherion and the Brachypodio-Centaureion nemoralis alliances. These extensive grasslands are rich in flowers and are not cut before the grasses flower and then only one or two times per year. CORINE/PHYSIS subdivides the type into three, none of which is strictly riparian or confined to floodplains**	**Distribution similar to 6410 and in the Continental biogeographic region as far as Nn Italy]**

EUNIS / PHYSIS code	EUNIS / PHYSIS Sub-code	N2K code	EUNIS / PHYSIS or N2K description	Geographic extent
	38.31	6520	Mountain hay meadows [N2K manual page 81 – equivalent to PHYSIS 38.31]. Defined as: Species-rich mesophile hay meadows of the montane and sub-alpine levels (mostly above 600 metres) usually dominated by Trisetum flavescens and with Heracleum sphondylium, Viola cornuta, Astrantia major, Carum carvi, Crepis mollis, C. pyrenaica, Bistorta major, (Polygonum bistorta), Silene dioica, S. vulgaris, Campanula glomerata, Salvia pratensis, Centaurea nemoralis, Anthoxanthum odoratum, Crocus albiflorus, Geranium phaeum, G. sylvaticum, Narcissus poeticus, Malva moschata, Valeriana repens, Trollius europaeus, Pimpinella major, Muscari botryoides, Lilium bulbiferum, Thlaspi caerulescens, Viola tricolor ssp. subalpina, Phyteuma halleri, P. orbiculare, Primula elatior, Chaerophyllum hirsutum and many others. [Possibly of marginal relevance, although the UK variant (NVC MG3) certainly does occur in the floodplain locally –]	distribution straddles Atlantic, Continental and Alpine biogeographic regions and numerous eco-regions
		7210	Calcareous fens with Cladium mariscus and species of the Caricion davallianae [N2K manual page 86 – equivalent to PHYSIS 53.3]. Defined as: Cladium mariscus beds of the emergent-plant zones of lakes, fallow lands or succession stage of extensively farmed wet meadows in contact with the vegetation of the Caricion davallianae or other Phragmition species [Cladietum marisci (Allorge 1922) Zobrist 1935	Distribution similar to 6410
54.3				
		7240	Alpine pioneer formations of Caricion bicoloris-atrofuscae [N2K manual page 88 – equivalent to PHYSIS 54.3]. Defined as: Alpine, peri-Alpine and northern British communities colonising neutral to slightly acid gravelly, sandy, stony, sometimes somewhat argilous or peaty substrates soaked by cold water, in moraines and on edges of springs, rivulets, glacial torrents of the alpine or sub-alpine levels, or on alluvial sands of pure, cold, slow-flowing rivers and calm backwaters. A permanent or continuous soil frost over a long period is essential for the existence of this habitat type. Low vegetation composed principally of species of Carex and Juncus (Caricion bicoloris-atrofuscae).	Confined to Arctic, Boreal and Alpine biogeographic regions, though rarely on higher mountains in Atlantic

EUNIS / PHYSIS code	EUNIS / PHYSIS Sub-code	N2K code	EUNIS / PHYSIS or N2K description	Geographic extent
	41.24	9160	Sub-Atlantic and medio-European oak or oak/hornbeam forests of the Carpinion betuli [N2K manual page 108 – equivalent to PHYSIS 41.24] Defined as: Forests of Quercus robur (or Quercus robur and Q. petraea) on hydromorphic soils or soils with high water table (bottoms of valleys, depressions or in the vicinity of riparian forests). The substrate corresponds to silts, clayey and silt-laden colluvions, as well as to silt-laden alterations or to siliceous rocks with a high degree of saturation. Forests of Quercus robur or natural mixed forests composed of Quercus robur, Q. petraea, Carpinus betulus and Tilia cordata. Hyacinthoides non-scripta is absent or rare.	Apparently occurring in Continental, eastern part of Atlantic and southern portion of Boreal biogeographic regions
44.9			**Alder, willow and bog-myrtle swamp woods. This main category includes some Natura 2000 types of restricted distribution (see type 9080 in Boreal region below). The more widespread types include:**	
	44.91		Alder swamp woods. Woods and scrubs of marshy ground, waterlogged for most of year, colonising fens and marshy or permanently inundated alluvial terraces of rivers. 3 main subdivisions, one of which is further subdivided into 2 sub-units. ***	Atlantic and Continental regions, as well as Boreal etc.
	44.92		Mire willow scrub (Salicion cinereae). Willow dominated formations with Salix aurita, S. atrocinerea, S. cinerea, S. pentandra, Frangula alnus and Betula humilis of fens, marshy floodplains and fringes of lakes and ponds. 4 sub-divisions.	
	44.93		Swamp bog-myrtle scrub. Myrica gale thickets of fringes of fens, drying fens and nascent or regenerating bogs of middle Europe, mostly characteristic of the Atlantic sector.	middle Europe, mostly characteristic of the Atlantic sector.

EUNIS / PHYSIS code	EUNIS / PHYSIS Sub-code	N2K code	EUNIS / PHYSIS or N2K description	Geographic extent
	44.A1 - 44.A4	91D0	91D0 * Bog woodland [N2K manual page 111 – equivalent to PHYSIS 44.A1 to 44.A4]. Defined as: Coniferous and broad-leaved forests on a humid to wet peaty substrate, with the water level permanently high and even higher than the surrounding water table. The water is always very poor in nutrients (raised bogs and acid fens). These communities are generally dominated by Betula pubescens, Frangula alnus, Pinus sylvestris, Pinus rotundata and Picea abies, with species specific to bogland or, more generally, to oligotrophic environments, such as Vaccinium spp., Sphagnum spp., Carex spp. [Vaccinio-Piceetea: Piceo-Vaccinienion uliginosi (Betulion pubescentis, Ledo-Pinion) i.a.]. In the Boreal region, also spruce swamp woods, which are minerotrophic mire sites along margins of different mire complexes, as well as in separate strips in valleys and along brooks. Sub-types:	
	· 44.A 1:		Sphagnum birch woods. Three subdivisions.	
	· 44.A 2:		Scots pine mire woods. Almost confined to north and east Germany	
	· 44.A 3:		Mountain pine bog woods. Alps, Jura and higher Hercynian ranges of Germany	
	· 44.A 4:		Mire spruce woods [Mainly in Boreal biogeographic region]. Two subdivisions	
44.1			**/PHYSIS type 44.1 comprises the Riparian Willow formations, of which several subdivisions are described under N2K types – subdivisions of this riparian type are listed under the relevant biogeographic region(s). They are all united by being Salix spp brush or aborescent formations, lining flowing water and submitted to periodic flooding.**	
	44.12		44.12: Lowland, collinar and Mediterraneo-montane willow brush: linear shrubby willow formations of river banks in plains, hills and low mountains of middle Europe and the Mediterranean region, with Salix triandra, S. viminalis and S. purpurea.	
			There are 7 sub-divisions which are simply listed under below or under other biogeographic regions if more restricted.	
			· 44.121: Almond willow-osier scrub (Salicetum triandro-viminalis) – Continental and Atlantic	

EUNIS / PHYSIS code	**EUNIS / PHYSIS Sub-code**	**N2K code**	**EUNIS / PHYSIS or N2K description**	**Geographic extent**
		9.10E +01	Alluvial forests with Alnus glutinosa and Fraxinus excelsior (Alno-Padion, Alnion incanae, Salicion albae) [N2K manual page 113 – equivalent to PHYSIS 44.3, 44.2 and 44.13]. Defined as: Riparian forests of Fraxinus excelsior and Alnus glutinosa, of temperate and Boreal Europe lowland and hill watercourses.44.3: Alno-Padion); riparian woods of Alnus incanae of montane and sub-montane rivers of the Alps and the northern Apennines (44.2: Alnion incanae); arborescent galleries of tall Salix alba, S. fragilis and Populus nigra, along medio-European lowland, hill or sub-montane rivers (44.13: Salicion albae). All types occur on heavy soils (generally rich in alluvial deposits) periodically inundated by the annual rise of the river (or brook) level, but otherwise well-drained and aerated during low-water. The herbaceous layer invariably includes many large species (Filipendula ulmaria, Angelica sylvestris, Cardamine spp., Rumex sanguineus, Carex spp., Cirsium oleraceum) and various vernal geophytes can occur, such as Ranunculus ficaria, Anemone nemorosa, A. ranunculoides, Corydalis solida. This habitat includes several sub-types:	of temperate and Boreal Europe lowland and hill watercourses
	44.31		· ash-alder woods of springs and their rivers (44.31: Carici remotae-Fraxinetum) – type is subdivided into 5 units by CORINE-PHYSIS distributed by small streams in Atlantic, sub-Atlantic and sub-Continental Middle Europe	small streams in Atlantic, sub-Atlantic and sub-Continental Middle Europe
	44.32		· ash-alder woods of fast-flowing rivers (44.32: Stellario-Alnetum glutinosae) – said to occur by CORINE/PHYSIS hills of northern and western Europe (assume Atlantic and Boreal)	hills of northern and western Europe (assume Atlantic and Boreal)
	44.33		· ash-alder woods of slow-flowing rivers (44.33: Pruno-Fraxinetum, Ulmo-Fraxinetum) – subdivided into 2 units by CORINE-PHYSIS and found in central and locally western Europe (Atlantic but mainly Continental)	central and locally western Europe (Atlantic but mainly Continental)
	44.21		montane grey alder galleries (44.21: Calamagrosti variae-Alnetum incanae Moor 58	
	44.22		· sub-montane grey alder galleries (44.22: Equiseto hyemalis-Alnetum incanae Moor 58)	
	44.13		· white willow gallery forests (44.13: Salicion albae)	

EUNIS / PHYSIS code	**EUNIS / PHYSIS Sub-code**	**N2K code**	**EUNIS / PHYSIS or N2K description**	**Geographic extent**
	?		· Spanish types belong to alliance Osmundo-Alnion (Cantabric-Atlantic & SE Iberia peninsula)	[Distribution may be partly inferred from description of sub-types, but clearly found throughout the Atlantic, Continental, Alpine biogeographic regions, as well as parts of the Mediterranean, Pannonian and Boreal regions
	44.34		type 44.34: Northern Iberian Alder galleries. Various communities and sub-divided into 3 major units and two sub-units with Alnus glutinosa and Fraxinus excelsior. Includes Pyrenees (Alpine region) and Galicia (Atlantic region)	Includes Pyrenees (Alpine region) and Galicia (Atlantic region)
	44.12		44.12: Lowland, collinar and Mediterraneo-montane willow brush types	atlantic
	44.125		· 44.125: Cantabrian willow scrub (Salicetum cantabricae) – Cordillera Cantabrica	atlantic
		6450	Northern boreal alluvial meadows [N2K manual page 79]. Defined as: Along large rivers with placid river sections which are frozen every winter, the type is affected by flooding in spring. The traditional management as hay meadows has usually ceased. Type includes areas that are not yet severely overgrown with trees and bushes [Mainly Scandinavian and Russian taiga eco–region]	Mainly Scandinavian and Russian taiga eco–region

EUNIS / PHYSIS code	EUNIS / PHYSIS Sub-code	N2K code	EUNIS / PHYSIS or N2K description	Geographic extent
		6530	6530 Fennoscandian wooded meadows [N2K manual page 81]. Defined as: A vegetation complex consisting of small copses of deciduous trees and shrubs and patches of open meadows. Ash (Fraxinus excelsior), birch (Betula pendula, B. pubescens) and Quercus robur, Tilia cordata, Ulmus glabra or Alnus incana are the common tree species. Nowadays very few areas are managed but traditionally these areas were managed by a combination of raking, hay-cutting, grazing of grassland and pollarding or lopping of trees. Species-rich vegetation complexes with rare and threatened meadow species and well developed epiphytic flora of mosses and lichens are characteristic. Many threatened species preferring old pollarded deciduous trees of semi-open habitats occur. The habitat type includes managed areas and overgrown areas with old pollarded or lopped deciduous trees. The type does not include abandoned meadows being invaded by trees. [Presumably as 6450 – this habitat type is probably rare in the riparian/floodplain zone]	Presumably as 6450 – this habitat type is probably rare in the riparian/floodplain zone
	N2K manual page 104 – equivalent to PHYSIS 44.9112, 44.915, 44.A14 (1997 version	9080	9080 *Fennoscandian deciduous swamp woods [N2K manual page 104 – equivalent to PHYSIS 44.9112, 44.915, 44.A14 (1997 version)]. Defined as: Deciduous swamps are under permanent influence of surface water and usually flooded annually. They are moist or wet, wooded wetlands with some peat formation, but the peat layer is usually very thin. Ash (Fraxinus excelsior) in the hemi-boreal zone and black alder (Alnus glutinosa) reaching the middle boreal zone are typical tree species. Grey alder (Alnus incana), silver birch (Betula pubescens) and willows (Salix spp.) are also common. A mosaic of patches with different water level and vegetation is typical for the type. Around the tree stems are small hummocks, but wet flooded surfaces are dominant. Deciduous swamp woods are most common in Finland in the south-western archipelago and other coastal areas. On the mainland they are rare. In Sweden they are common throughout the whole region. [Eco-regions include Scandinavian and Russian taiga and Baltic mixed forests	[Eco-regions include Scandinavian and Russian taiga and Baltic mixed forests

EUNIS / PHYSIS code	**EUNIS / PHYSIS Sub-code**	**N2K code**	**EUNIS / PHYSIS or N2K description**	**Geographic extent**
	37.8 & 37.7	6430	Hygrophilous perennial tall herb communities of montane to alpine levels of the Betulo-Adenostyletea class. 6430 Hydrophilous tall herb fringe communities of plains and of the montane to alpine levels [N2K manual page 78 – equivalent to PHYSIS 37.7 and 37.8]. Defined as:	Probably includes eco-regions of a) Scandinavian montane birch forest and grasslands; b) Alps conifer & mixed forests; c) Carpathian montane coniferous forests; d) Pyrenees conifer and mixed forests; and possibly e)Dinaric Mountains mixed forests]
	44.12		44.12: Lowland, collinar and Mediterraneo-montane willow brush types	mediterranean
	44.124		· 44.124: Ibero-montane willow scrub (Salicetum triandrae-elaeagni) – Pyrenees, Iberian Range and Sierra Nevada (thus also Mediterranean region)	mediterranean
	37.23	6440	6440 Alluvial meadows of river valleys of the Cnidion dubii [N2K manual page 78 – equivalent to PHYSIS 37.23]. Defined as: Alluvial meadows with natural flooding regime belonging to the Cnidion dubii alliance, under continental to subcontinental climatic conditions. [	Principally in Germany, Czech Republic, Slovakia, Hungary, Poland and into Romania – Eco-regions include Central European mixed forests (and into Western too) and Pannonian mixed forests]
	44.4	91F0	Riparian mixed forests of Quercus robur, Ulmus laevis and Ulmus minor, Fraxinus excelsior or Fraxinus angustifolia along the great rivers (Ulmenion minoris) [N2K manual page 114 – equivalent to PHYSIS 44.4]. Defined as: Forests of hardwood trees of the major part of the river bed, liable to flooding during regular rising of water level or, of low areas liable to flooding following the raising of the water table. These forests develop on recent alluvial deposits. The soil may be well drained between inundations or remain wet. Following the hydric regime, the woody dominated species belong to Fraxinus, Ulmus or Quercus genus. The undergrowth is well developed.	

EUNIS / PHYSIS code	EUNIS / PHYSIS Sub-code	N2K code	EUNIS / PHYSIS or N2K description	Geographic extent
	44.41		· 44.41: Rhine, Danube, Emst, Elbe, Saale, Weser, Loire and Rhône-Saône systems	· 44.41: Rhine, Danube, Emst, Elbe, Saale, Weser, Loire and Rhône-Saône systems
	44.42		· 44.42: Residual fragments in the same systems	as for 44.41
	44.43		· 44.43: Sub-Mediterranean regions of SE Europe (Balkanic) – sub-units in NE Italy and Nn Greece	· 44.43: Sub-Mediterranean regions of SE Europe (Balkanic) – sub-units in NE Italy and Nn Greece
	44.44		· 44.44: Po and its tributaries	· 44.44: Po and its tributaries

EUNIS / PHYSIS code	EUNIS / PHYSIS Sub-code	N2K code	EUNIS / PHYSIS or N2K description	Geographic extent
	41.2A	91L0	Illyrian oak–hornbeam forests (Erythronio-Carpinion) [N2K manual page 117 – equivalent to PHYSIS 41.2A]. Defined as: Forests of Quercus robur or Q. petraea, sometimes Q. cerris, and Carpinus betulus on both calcareous and siliceous bedrocks, mostly on deep neutral to slightly acidic brown forest soils, with mild humus in the SE-Alpine-Dinaric region, West- and Central Balkans extending northwards to Lake Balaton mostly in hilly and sub-montane regions, river valleys and the plains of the Drava and Sava. The climate is more continental than in sub-Mediterranean regions and warmer than in middle Europe; these forests are intermediate between oak-hornbeam woods (e.g. 9170) of central Europe and those of the Balkans and merge northwards into the Pannonic oak woods (91G0). They have much higher species richness than the Central European oak woods. Outliers of these forests also occur in Frioul and the northern Apennines. [Though centred in the Continental biogeographic region of Serbia, Croatia and Bosnia-Herzegovina, this type clearly enters the Alpine and Pannonian regions, and the outliers are in the Mediterranean region]	SE-Alpine-Dinaric region, West- and Central Balkans extending northwards to Lake Balaton mostly in hilly and sub-montane regions, river valleys and the plains of the Drava and Sava. The climate is more continental than in sub-Mediterranean regions and warmer than in middle Europe; these forests are intermediate between oak-hornbeam woods (e.g. 9170) of central Europe and those of the Balkans and merge northwards into the Pannonic oak woods (91G0). They have much higher species richness than the Central European oak woods. Outliers of these forests also occur in Frioul and the northern Apennines. [Though centred in the Continental biogeographic region of Serbia, Croatia and Bosnia-Herzegovina, this type clearly enters the Alpine and Pannonian regions, and the outliers are in the Mediterranean region]

EUNIS / PHYSIS code	**EUNIS / PHYSIS Sub-code**	**N2K code**	**EUNIS / PHYSIS or N2K description**	**Geographic extent**
	44.162 & 44.6	92A0	92A0 Salix alba and Populus alba galleries [N2K manual page 128 – equivalent to PHYSIS 44.141, 44.162 and 44.6]. Mostly found in Mediterranean biogeographic region (see below) – certainly it reaches its greatest diversity there	Mostly found in Mediterranean biogeographic region (see below) – certainly it reaches its greatest diversity there
	37.4	6420	6420 Mediterranean tall humid herb grasslands of the Molinio-Holoschoenion [N2K manual page 78 –equivalent to PHYSIS 37.4]. Defined as: Mediterranean humid grasslands of tall grasses and rushes, widespread in the entire Mediterranean basin, extending along the coasts of the Black Sea, in particular in dunal systems [P	Passes from Mediterranean region into Black Sea region – covering numerous eco-regions – may be mostly coastal rather than riparian]
	44.12		PHYSIS 44.12: Lowland, collinar and Mediterraneo-montane willow brush types	
	44.122		· 44.122: Mediterranean purple willow scrub (Saponario officinalis-Salicetum purureae) – Southern France, Mediterranean eastern Spain and south to Rio Seguara basin (Italy)	Southern France, Mediterranean eastern Spain and south to Rio Seguara basin (Italy)
	44.123		· 44.123: Balkanic purple willow scrub (various communities with Salix purpurea and other willows)	Balkans?
	44.124		· 44.124: Ibero-montane willow scrub (Salicetum triandrae-elaeagni) – Pyrenees, Iberian Range and Sierra Nevada (thus also Alpine region)	Pyrenees, Iberian Range and Sierra Nevada (thus also Alpine region)
	44.126		· 44.126: Iberian sage-leaved willow scrub (Salicetum purpureo-salvifoliae) – Central and southern Iberia	Central and southern Iberia
	44.127		· 44.127: Pedicellated willow scrub – subdivided into 4 types confined to a) Andalusia; b) Sardinia; c) Sicily; and d) Calabria	a) Andalusia; b) Sardinia; c) Sicily; and d) Calabria
	44.142		44.142: Olive-leaved and ashy willow riparian woods (Rubo corylifolii-Salicetum atrocinereae and Viti-Salicetum atrocinereae) which occurs with four variants from central and southern Iberia via Sardinia to Italy and Greece	from central and southern Iberia via Sardinia to Italy and Greece
	44.162 & 44.6	92A0	***92A0 Salix alba and Populus alba galleries [N2K manual page 128 – equivalent to PHYSIS 44.141, 44.162 and 44.6]. Defined as:	

EUNIS / PHYSIS code	**EUNIS / PHYSIS Sub-code**	**N2K code**	**EUNIS / PHYSIS or N2K description**	**Geographic extent**
	44.141		· Riparian forests of the Mediterranean and Black Sea basins dominated by Salix alba, Salix fragilis or their relatives (44.141)	[Distribution may be partly inferred from description of types, but clearly found throughout the Continental, Black Sea, Mediterranean and Black Sea biogeographic regions, as well as parts of the Pannonian and possibly Steppic region]
	44.6		· Mediterranean and Central Eurasian multi-layered riverine forests with Populus spp., Ulmus spp., Salix spp., Alnus spp., Acer spp., Tamarix spp., Juglans regia, Quercus robur, Quercus pedunculiflora, Fraxinus angustifolia, Fraxinus pallisiae, lianas. Tall poplars, Populus alba, Populus caspica, Populus euphratica (Populus diversifolia), are usually dominant in height; they may be absent or sparse in some associations which are then dominated by species of the genera listed above (44.6). Type is subdivided by CORINE/PHYSIS into 4 major units:	Mediterranean and Central Eurasian
	44.61		o 44.61: Mediterranean Riparian poplar forests – further subdivided into five major units in Iberia, Provence/Languedoc, Corsica/Sardinia, Italy and Greece (Greek stands are themselves classified into four minor sub-units)	Mediterranean
	44.62		o 44.62: Mediterranean Riparian Elm forests	Mediterranean
	44.63		o 44.63: Mediterranean Riparian Ash woods: further subdivided into six units distributed from Iberia (3 units) through southern France and northern Italy (1 unit) to Adriatic Italy and Sicily (1 unit) and Greece (1 unit)	Mediterranean
	44.64		o 44.64: Hop-Hornbeam galleries: Ostrya dominated and only in SE France	SE France
	44.52 & 44.54	92B0	92B0 Riparian formations on intermittent Mediterranean watercourses with Rhododendron ponticum, Salix & others [N2K manual p. 128: equivalent to PHYSIS 44.52 & 44.54]. Types:	

EUNIS / PHYSIS code	**EUNIS / PHYSIS Sub-code**	**N2K code**	**EUNIS / PHYSIS or N2K description**	**Geographic extent**
	44.52		· Distinctive, relict thermo- and meso-Mediterranean alder galleries of deep, steep-sided valleys, with Rhododendron ponticum ssp. baeticum, Frangula alnus ssp. baetica, Arisarum proboscideum and a rich fern community including Pteris incompleta, Diplazium caudatum, #Culcita macrocarpa (44.52).	
	44.54		· Relict Betula parvibracteata riparian galleries. The dominant species, an extremely local endemic, is accompanied by Myrica gale, Frangula alnus, Salix atrocinerea, Galium broterianum, Scilla ramburei (44.54) [Found in Montes de Toledo only]	Found in Montes de Toledo only]
			CORINE/PHYSIS lists in addition to these N2K types the following further units:	
	44.51		· 44.51: Southern Black Alder galleries in Italy, Cévennes, Iberia and Greece (4 sub-units)	Italy, Cévennes, Iberia and Greece
	44.53		44.53: Corsican Black and Cordate Alder galleries (2 sub-units both in Corsica	Corsica
		92C0	92C0 Platanus orientalis and Liquidambar orientalis woods (Plantanion orientalis) [N2K manual page 129 – equivalent to PHYSIS 44.71 and 44.72]. Defined as: Forests and woods, for the most part riparian, dominated by Platanus orientalis (oriental plane) or Liquidambar orientalis (sweet gum), belonging to the Platanion orientalis alliance. Sub-types:	
	44.71		· 44.71: Oriental plane woods (Platanion orientalis) Forests of Platanus orientalis.	

EUNIS / PHYSIS code	**EUNIS / PHYSIS Sub-code**	**N2K code**	**EUNIS / PHYSIS or N2K description**	**Geographic extent**
	44.711		o 44.711: Helleno-Balkanic riparian plane forests. Platanus orientalis gallery forests of Greek and southern Balkanic watercourses, temporary rivers and gorges; they are distributed throughout the mainland and archipelagos, colonising poorly stabilised alluvial deposits of large rivers, gravel or boulder deposits of permanent or temporary torrents, spring basins and particularly, the bottom of steep, shady gorges, where they constitute species-rich communities. The accompanying flora may include Salix alba, S. elaeagnos, S. purpurea, Alnus glutinosa, Celtis australis, Cercis siliquastrum, Populus alba, P. nigra, Juglans regia, Fraxinus ornus, Alnus glutinosa, Crataegus monogyna, Cornus sanguinea, Ruscus aculeatus, Vitex agnus-castus, Nerium oleander, Rubus spp, Rosa sempervirens, Hedera helix, Clematis vitalba, Vitis vinifera ssp sylvestris, Ranunculus ficaria, Anemone blanda, Aristolochia rotunda, Saponaria officinalis, Symphytum bulbosum, Hypericum hircinum, Melissa officinalis, Calamintha grandiflora, Helleborus cyclophyllus, Cyclamen hederifolium, C. repandum, C. creticum, Galanthus nivalis ssp reginae-olgae, Dracunculus vulgaris, Arum italicum, Biarum tenuifolium, Brachypodium sylvaticum, Dactylis glomerata and may be rich in mosses, lichens and ferns, among which Pteridium aquilinum is often abundant. Various associations have been described reflecting regional and ecological variation in composition of the under-growth. Plane tree galleries are particularly well represented along the Ionian coast and in the Pindus; other important local complexes exist in Macedonia, in Thrace, around the Olympus massif, in the Pelion, in the Peloponnese, particularly in the Taygetos, where luxuriant gorge forests reach 1300m, in Euboea and in Crete; local, distinctive, representatives occur in other Aegean islands e.g. Rhodes, Samos, Samothrace, Thasos. Restriction to gorges is increasingly pronounced towards the south.	Greece & Baltics
	44.712		o 44.712: Hellenic slope plane woods. Platanus orientalis woods on colluvions, detritus cones, ravine sides or other poorly stabilised substrates, of Greece.	greece

EUNIS / PHYSIS code	EUNIS / PHYSIS Sub-code	N2K code	EUNIS / PHYSIS or N2K description	Geographic extent
	44.713		o 44.713: Sicilian plane tree canyons. Relict Platanus orientalis-dominated or P. orientalis -rich galleries of the Cassabile, the Anapo, the Irminio and the Carbo rivers, in the Iblei range of south-eastern Sicily, of the gorge of the Sirmeto, in the vicinity of the Nebrodi. Some of these formations, in particular, in the gorges of the Cassabile and of the Anapo, are true plane tree woods. Others, such as on the Sirmeto, are Populus alba, Fraxinus angustifolia, Salix spp. formations with Platanus orientalis; as they grade into each other, and because of the very isolated occurrence, and great biogeographical and historical interest of Platanus orientalis in Sicily, they are all listed here. Plane tree woods have had a much greater extension in Sicily and probably in Calabria. A large forest has, in particular, existed on the Alcantara, where the species is now extinct.	sicily
	44.72		· 44.72: Sweet gum woods. Riverine forests dominated by the Tertiary relict Liquidambar orientalis, with very limited range in south Asia Minor and Rhodes.	south Asia Minor and Rhodes
	44.721		o 44.721: Rhodian sweet gum woods. Liquidambar orientalis gallery forest of the Petaloudhes Valley, on Rhodes, with poorly developed undergrowth and a ground layer dominated by Adiantum capillus-veneris in damp areas. This forest constitutes the only European formation of this species and harbours the unique, concentrated aggregation of Jersey Tiger Moths, Panaxia quadripunctaria.	Petaloudhes Valley, on Rhodes
	44.81 to 44.84	92D0	92D0 Southern riparian galleries and thickets (Nerio-Tamaricetea and Securinegion tinctoriae) [N2K manual page 130 – equivalent to PHYSIS 44.81 to 44.84]. Defined as: Tamarisk, oleander, and chaste tree galleries and thickets and similar low ligneous formations of permanent or temporary streams and wetlands of the thermo-Mediterranean zone and south-western Iberia, and of the most hygromorphic locations within the Saharo-Mediterranean and Saharo- Sindian zones. Includes formations of Tamarix smyrnensis (syn. Tamarix ramosissima) of stream sides and coastal localities of the Pontic and Steppic regions of western Eurasia. The formations with Tamarix africana should not be taken into account.	
	44.81		· 44.81: Oleander (Nerium), Chaste-tree (Vitex) and Tamarix galleries. 3 units defined by the dominant shrub, with Tamarix galleries being further sub-divided into 4 major sub-units and 4 subsidiary units. Throughout Mediterranean region	mediterranean

EUNIS / PHYSIS code	EUNIS / PHYSIS Sub-code	N2K code	EUNIS / PHYSIS or N2K description	Geographic extent
	44.82		· 44.82: South-western Iberian tamujares: characterised by Securinega tinctoria and found in southern Spain and southern Portugal.	southern spain and portugal
	44.83		· 44.83: Oretanian lauriphyllous galleries: Montes de Toledo (southern Spain) only – Prunus lusitanica and Viburnum tinus.	southern spain
	44.84		· 44.84: Oretanian bog myrtle & willow scrub: Montes de Toledo (southern Spain) only – Frangula, Myrica gale, Salix atrocinerea, S. salvifolia.	southern spain
		9370	9370 * Palm groves of Phoenix[N2K manual page 133 – equivalent to PHYSIS 45.7]. Defined as: Woods, often riparian, formed by the two endemic palm trees, Phoenix theophrasti and Phoenix canariensis.· The palm groves of Crete are restricted to damp sandy coastal valleys; they include the extensive forest of Vai, where the luxuriant palm growth is accompanied by a thick shrubby undergrowth rich of Nerium oleander, and about four other smaller coastal groves, notably on the south coast of the prefectorate of Rethimnon (Plakias etc).· The Canarian palm groves are mostly characteristic of the bottom of barrancos and of alluvial soils, below 600 metres; particularly representative examples are found at Fragata, Maspalomas and Barranco de Tirajana in the Gran Canary, Valle Gran Rey in La Gomera, Masca in Ténérife and Brena Alta in La Palma.[Geographical range clearly indicated in description of the sub-types]	Fragata, Maspalomas and Barranco de Tirajana in the Gran Canary, Valle Gran Rey in La Gomera, Masca in Ténérife and Brena Alta in La Palma.[Geographical range clearly indicated in description of the sub-types]

Annex C: Hydromorphology-related traits of some European Riparian and Aquatic Plants

Taxon name	Predominant root type	Height /length cm	Perennation	Woodiness	Geomorph - Clone1	Ellenberg F
Aconitum napellus	tap	100	3	1	2	7
Acorus calamus	adventitious	112	3	1	3	10
Adiantum capillus-veneris	adventitious	30	3	1	0	7
Aegopodium podagraria	adventitious	100	3	1	3	5
Agrostis canina	adventitious	60	3	1	3	7
Agrostis gigantea	adventitious	80	3	1	3	5
Agrostis stolonifera	adventitious	45	3	1	3	6
Alisma gramineum	adventitious	30	3	1	0	11
Alisma lanceolatum	adventitious	100	3	1	0	10
Alisma plantago-aquatica	adventitious	100	3	1	0	10
Alliaria petiolata	tap	120	2	1	0	6
Allium scorodoprasum	adventitious	80	3	1	1	6
Allium ursinum	adventitious/contractile	45	3	1	0	6
Alnus glutinosa	tap	2000	3	3	0	8
Alnus incana	tap	2000	3	3	0	7
Alopecurus aequalis	adventitious	40	1	1	0	9
Alopecurus borealis	adventitious	50	3	1	1	9
Alopecurus geniculatus	adventitious	40	3	1	3	7
Anemone nemorosa	adventitious	23	3	1	2	
Angelica sylvestris	tap	200	3	1	0	8
Apium graveolens	adventitious	80	2	1	0	8
Apium inundatum	adventitious	50	3	1	1	10
Apium nodiflorum	adventitious	100	3	1	1	10
Apium repens	adventitious	15	3	1	3	9
Asplenium scolopendrium	adventitious	60	3	1	0	5
Azolla filiculoides	simple	1	3	1	1	11
Baldellia ranunculoides	adventitious	20	3	1	0	10
Barbarea stricta	tap	100	2	1	0	7
Barbarea vulgaris	fibrous/tap	90	2	1	0	6
Berula erecta	adventitious	100	3	1	1	10
Betula pubescens	tap	2000	3	3	0	7
Bidens cernua	fibrous	67	1	1	0	9
Bidens tripartita	fibrous	67	1	1	0	8

Taxon name	**Predominant root type**	**Height /length cm**	**Perennation**	**Woodiness**	**Geomorph - Clone1**	**Ellenberg F**
Bolboschoenus maritimus	adventitious	100	3	1	2	10
Brachypodium sylvaticum	fibrous	95	3	1	1	5
Brassica nigra	tap	150	1	1	0	5
Brassica rapa	tap	100	1	1	0	5
Butomus umbellatus	adventitious	150	3	1	3	11
Calamagrostis canescens	adventitious	120	3	1	3	9
Calamagrostis epigejos	adventitious	200	3	1	3	7
Calamagrostis purpurea	adventitious	150	3	1	3	8
Callitriche brutia	adventitious	25	1	1	3	10
Callitriche hamulata	adventitious	80	1	1	3	11
Callitriche hamulata sens.lat.	adventitious	25	1	1	3	10
Callitriche hermaphroditica	adventitious	50	3	1	1	12
Callitriche obtusangula	adventitious	60	3	1	1	11
Callitriche platycarpa	adventitious	15	1	1	3	10
Callitriche stagnalis	adventitious	15	1	1	3	10
Callitriche stagnalis sens.lat.	adventitious	15	1	1	3	10
Callitriche truncata	adventitious	20	1	1	0	12
Caltha palustris	fibrous	40	3	1	0	9
Calystegia sepium	adventitious	200	3	1	3	8
Campanula latifolia	tap	120	3	1	0	5
Cardamine amara	fibrous	50	3	1	2	9
Cardamine flexuosa	fibrous	50	3	1	0	7
Cardamine hirsuta	fibrous	30	1	1	0	5
Cardamine impatiens	fibrous	80	2	1	0	5
Cardamine pratensis	fibrous	60	3	1	0	8
Carex acuta (gracilis)	adventitious	120	3	1	3	9
Carex acutiformis	adventitious	150	3	1	3	9
Carex appropinquata	fibrous	80	3	1	1	9
Carex aquatilis	fibrous	110	3	1	3	10
Carex canescens	fibrous	50	3	1	2	9
Carex distans	adventitious	72	3	1	1	6
Carex disticha	adventitious	90	3	1	3	8

Taxon name	Predominant root type	Height /length cm	Perennation	Woodiness	Geomorph - Clone1	Ellenberg F
Carex elata	fibrous	95	3	1	1	10
Carex elongata	adventitious	80	3	1	1	8
Carex hostiana	adventitious	57	3	1	1	9
Carex laevigata	adventitious	120	3	1	1	8
Carex lasiocarpa	adventitious	120	3	1	3	10
Carex nigra	adventitious	70	3	1	3	8
Carex otrubae	fibrous	100	3	1	1	8
Carex paniculata	fibrous	150	3	1	1	9
Carex pendula	fibrous	150	3	1	1	8
Carex pseudocyperus	fibrous	90	3	1	1	9
Carex recta	fibrous	85	3	1	3	9
Carex remota	fibrous	67	3	1	1	8
Carex riparia	adventitious	130	3	1	3	9
Carex rostrata	adventitious	100	3	1	3	10
Carex strigosa	adventitious	72	3	1	1	8
Carex sylvatica	fibrous	70	3	1	1	5
Carex vesicaria	fibrous	120	3	1	2	10
Carex vulpina	fibrous	100	3	1	1	9
Carum verticillatum	tap	60	3	1	0	8
Catabrosa aquatica	adventitious	72	3	1	3	9
Ceratophyllum demersum	absent	100	3	1	1	12
Ceratophyllum submersum	absent	100	3	1	1	12
Chenopodium glaucum	tap	50	1	1	0	6
Chenopodium rubrum	tap	70	1	1	0	7
Chrysosplenium alternifolium	adventitious	20	3	1	3	8
Chrysosplenium oppositifolium	adventitious	15	3	1	3	9
Cicerbita alpina	tap	130	3	1	3	6
Cicuta virosa	adventitious	150	3	1	0	10
Circaea alpina	adventitious	30	3	1	3	7
Circaea alpina x lutetiana (C. x intermedia)	adventitious	45	3	1	3	6
Cirsium heterophyllum	adventitious	120	3	1	2	6
Cirsium palustre	tap	175	2	1	0	8
Cirsium tuberosum	tap	80	3	1	0	6
Cirsium vulgare	tap	150	2	1	0	5
Cladium mariscus	adventitious/fibrous	200	3	1	2	10
Claytonia sibirica	adventitious	40	1	1	0	7
Clematis vitalba	adventitious	3000	3	3	0	4
Cochlearia pyrenaica	adventitious	30	2	1	0	7
Conium maculatum	tap	250	2	1	0	5
Convallaria majalis	adventitious	25	3	1	3	5

Taxon name	Predominant root type	Height /length cm	Perennation	Woodiness	Geomorph - Clone1	Ellenberg F
Cornus sanguinea	fibrous	400	3	3	3	5
Crassula aquatica	adventitious	8	1	1	0	9
Crassula helmsii	adventitious	30	3	1	1	10
Crataegus monogyna	fibrous	1000	3	3	0	5
Crepis mollis	tap	60	3	1	0	5
Crepis paludosa	tap	80	3	1	0	7
Cuscuta europaea	absent	2	1	1	3	7
Cyperus fuscus	adventitious	20	1	1	0	8
Cyperus longus	adventitious	100	3	1	2	9
Dactylis glomerata	fibrous	120	3	1	1	5
Deschampsia cespitosa	adventitious	150	3	1	1	6
Dipsacus pilosus	tap	150	2	1	0	6
Dryas octopetala	adventitious	10	3	3	3	4
Dryopteris cristata	adventitious	60	3	1	0	9
Eleocharis acicularis	adventitious	10	3	1	3	10
Eleocharis austriaca	adventitious	60	3	1	3	9
Eleocharis palustris	adventitious	60	3	1	3	10
Eleocharis parvula	adventitious	8	3	1	3	9
Eleogiton fluitans	adventitious	45	3	1	1	11
Elodea canadensis	adventitious	300	3	1	1	12
Elodea nuttallii	adventitious	300	3	1	1	12
Elymus caninus	adventitious	110	3	1	1	6
Epilobium alsinifolium	adventitious	20	3	1	2	9
Epilobium anagallidifolium	adventitious	10	3	1	2	8
Epilobium brunnescens	fibrous	4	3	1	3	8
Epilobium ciliatum	adventitious	75	3	1	0	6
Epilobium hirsutum	adventitious	150	3	1	3	8
Epilobium obscurum	adventitious	75	3	1	0	8
Epilobium palustre	adventitious	60	3	1	2	8
Epilobium parviflorum	adventitious	75	3	1	0	9
Epilobium roseum	adventitious	75	3	1	0	8
Epilobium tetragonum	adventitious	75	3	1	0	7
Equisetum arvense	adventitious	90	3	1	3	6
Equisetum	adventitious	100	3	1	3	10

Taxon name	Predominant root type	Height /length cm	Perennation	Woodiness	Geomorph - Clone1	Ellenberg F
fluviatile						
Equisetum hyemale	adventitious	100	3	1	3	7
Equisetum palustre	adventitious	60	3	1	3	8
Equisetum pratense	adventitious	60	3	1	3	7
Equisetum ramosissimum	adventitious	120	3	1	3	4
Equisetum sylvaticum	adventitious	90	3	1	3	8
Equisetum telmateia	adventitious	180	3	1	3	8
Equisetum variegatum	adventitious	60	3	1	3	8
Erigeron acris	fibrous	50	1	1	0	5
Eupatorium cannabinum	adventitious	150	3	1	2	8
Euphorbia cyparissias	tap	40	3	1	3	3
Euphorbia hyberna	tap	52	3	1	0	5
Euphrasia arctica	adventitious	30	1	1	0	5
Euphrasia rostkoviana	adventitious	35	1	1	0	5
Festuca altissima	fibrous	120	3	1	1	5
Festuca ovina	fibrous	43	3	1	1	5
Ficaria verna	adventitious	25	3	1	1	6
Filipendula ulmaria	fibrous	120	3	1	3	8
Fraxinus excelsior	tap	2500	3	3	0	6
Fritillaria meleagris	adventitious	30	3	1	0	8
Gagea lutea	contractile	25	3	1	1	6
Galanthus nivalis	contractile	22	3	1	1	6
Galium aparine	tap	150	1	1	0	6
Galium boreale	tap	45	3	1	3	5
Galium palustre	tap	75	3	1	2	9
Geranium pratense	adventitious	100	3	1	0	6
Geranium robertianum	fibrous	50	2	1	0	6
Geranium sylvaticum	adventitious	70	3	1	0	5
Geum rivale	adventitious	50	3	1	0	7
Glaucium flavum	tap	90	3	1	0	5
Glaux maritima	tap	30	3	1	3	7
Glechoma hederacea	adventitious	30	3	1	3	6
Glyceria declinata	fibrous	60	3	1	3	9
Glyceria fluitans	fibrous	95	3	1	3	10
Glyceria fluitans x notata (G. x pedicellata)	adventitious/fibrous	95	3	1	3	10
Glyceria maxima	adventitious/fibrous	200	3	1	3	10

Taxon name	Predominant root type	Height /length cm	Perennation	Woodiness	Geomorph - Clone1	Ellenberg F
Glyceria notata	adventitious	95	3	1	3	10
Groenlandia densa	adventitious	65	3	1	1	12
Gymnocarpium dryopteris	adventitious	35	3	1	3	5
Hedera helix	adventitious	3000	3	3	3	5
Helminthotheca echioides	fibrous	80	1	1	0	5
Heracleum mantegazzianum	tap	350	2	1	0	6
Heracleum sphondylium	tap	175	2	1	0	5
Hesperis matronalis	fibrous	100	3	1	0	7
Hierochloe odorata	adventitious	55	3	1	3	9
Hippophae rhamnoides	fibrous	300	3	3	3	5
Hippuris vulgaris	adventitious	100	3	1	3	10
Hottonia palustris	adventitious	120	3	1	1	11
Humulus lupulus	fibrous	450	3	1	3	7
Hydrocharis morsus-ranae	adventitious	50	3	1	2	11
Hydrocotyle ranunculoides	adventitious	40	3	1	1	10
Hydrocotyle vulgaris	adventitious	20	3	1	3	8
Hymenophyllum tunbrigense	adventitious	8	3	1	2	6
Hymenophyllum wilsonii	adventitious	10	3	1	2	5
Hypericum androsaemum	adventitious	80	3	3	0	6
Hypericum canadense	adventitious	20	1	1	0	9
Hypericum elodes	adventitious	40	3	1	3	10
Hypericum hirsutum	adventitious/tap	100	3	1	0	5
Hypericum tetrapterum	adventitious/tap	60	3	1	2	8
Hypericum undulatum	adventitious	60	3	1	2	8
Impatiens capensis	adventitious	60	1	1	0	9
Impatiens glandulifera	adventitious	200	1	1	0	8
Impatiens noli-tangere	adventitious	60	1	1	0	7
Impatiens parviflora	adventitious	100	1	1	0	5
Imperatoria ostruthium	tap	100	3	1	0	5
Iris pseudacorus	adventitious	150	3	1	3	9
Isoetes echinospora	adventitious	15	3	1	0	12

Taxon name	Predominant root type	Height /length cm	Perennation	Woodiness	Geomorph - Clone1	Ellenberg F
Isolepis cernua	adventitious	15	1	1	0	8
Isolepis setacea	adventitious	15	1	1	0	9
Juglans regia	tap	2400	3	3	0	4
Juncus acutiflorus	adventitious	100	3	1	3	8
Juncus alpinoarticulatus	adventitious	30	3	1	2	9
Juncus ambiguus	adventitious	17	1	1	0	8
Juncus articulatus	adventitious	60	3	1	3	9
Juncus balticus	adventitious	45	3	1	3	8
Juncus bufonius	adventitious	25	1	1	0	7
Juncus conglomeratus	adventitious	100	3	1	1	7
Juncus effusus	adventitious	120	3	1	1	7
Juncus filiformis	adventitious	30	3	1	1	9
Juncus inflexus	adventitious	90	3	1	1	7
Lactuca saligna	tap	75	1	1	0	4
Lamium album	adventitious	60	3	1	3	5
Lathraea squamaria	parasitises roots of woody plants	30	3	1	0	6
Lathyrus palustris	tap	120	3	1	3	9
Leersia oryzoides	adventitious	90	3	1	3	9
Lemna gibba	simple	0.5	3	1	1	11
Lemna minor	simple	0.4	3	1	1	11
Lemna minuta	simple	0.3	3	1	1	11
Lemna trisulca	simple	1	3	1	1	12
Leucojum aestivum	contractile	60	3	1	1	9
Leucojum vernum	contractile	30	3	1	1	6
Limosella aquatica	fibrous	6	1	1	3	8
Limosella australis	fibrous	4	1	1	3	9
Littorella uniflora	adventitious	10	3	1	3	10
Lotus pedunculatus	tap	60	3	1	0	8
Lupinus polyphyllus	tap	150	3	1	0	5
Luronium natans	adventitious	50	3	1	3	11
Luzula sylvatica	adventitious	80	3	1	2	5
Lycopus europaeus	adventitious	100	3	1	2	8
Lysichiton americanus	contractile	110	3	1	2	9
Lysimachia nemorum	adventitious	20	3	1	3	7
Lysimachia nummularia	adventitious	5	3	1	3	7
Lysimachia punctata	adventitious	120	3	1	2	6
Lysimachia thyrsiflora	adventitious	70	3	1	3	10
Lysimachia vulgaris	adventitious	105	3	1	3	9

Taxon name	Predominant root type	Height /length cm	Perennation	Woodiness	Geomorph - Clone1	Ellenberg F
Lythrum salicaria	tap	120	3	1	0	9
Matteuccia struthiopteris	adventitious	60	3	1	0	8
Melissa officinalis	tap	60	3	1	2	5
Mentha aquatica	adventitious	90	3	1	3	8
Menyanthes trifoliata	adventitious	150	3	1	3	10
Mimulus	adventitious/fibrous	50	3	1	3	9
Mimulus guttatus	adventitious/fibrous	50	3	1	3	9
Mimulus guttatus x luteus (M. x robertsii)	adventitious/fibrous	50	3	1	3	8
Mimulus luteus	adventitious/fibrous	50	3	1	3	9
Minuartia stricta	tap	10	3	1	0	9
Molinia caerulea	fibrous	130	3	1	1	8
Montia fontana	adventitious	20	1	1	2	9
Myosotis laxa	fibrous	40	1	1	0	9
Myosotis scorpioides	adventitious/fibrous	57	3	1	2	9
Myosotis secunda	adventitious/fibrous	55	3	1	2	9
Myosotis stolonifera	adventiuous/fibrous	20	3	1	2	9
Myosoton aquaticum	adventitious/fibrous	100	3	1	2	8
Myrica gale	cluster (proteoid)	150	3	3	3	9
Myriophyllum alterniflorum	adventitious	120	3	1	1	12
Myriophyllum spicatum	adventitious	250	3	1	1	12
Myriophyllum verticillatum	adventitious	300	3	1	1	12
Myrrhis odorata	tap	180	3	1	0	6
Narcissus pseudonarcissus	adventitious	35	3	1	1	5
Nardus stricta	fibrous	40	3	1	1	7
Nasturtium microphyllum	adventitious	60	3	1	3	10
Nasturtium officinale	adventitious	60	3	1	3	10
Nasturtium officinale sens. Lat.	adventitious	60	3	1	3	10
Noccaea caerulescens		40	3	1	0	4
Nuphar lutea	adventitious	150	3	1	2	11
Nuphar pumila	adventitious	150	3	1	2	11
Nymphaea alba	adventitious	150	3	1	2	11
Nymphoides peltata	adventitious	200	3	1	1	11
Oenanthe aquatica	adventitious	150	1	1	0	10
Oenanthe crocata	tap	150	3	1	0	9
Oenanthe	tap	80	3	1	0	9

Taxon name	**Predominant root type**	**Height /length cm**	**Perennation**	**Woodiness**	**Geomorph - Clone1**	**Ellenberg F**
fistulosa						
Oenanthe fluviatilis	adventitious	100	3	1	3	10
Oenanthe lachenalii	tap	100	3	1	0	8
Oenanthe silaifolia	tap	100	3	1	0	9
Oenothera biennis	tap	100	2	1	0	4
Oreopteris limbosperma	adventitious	90	3	1	0	6
Orobanche reticulata	parasitises roots of thistles	60	2	1	0	6
Orthilia secunda	fibrous	5	3	1	2	5
Osmunda regalis	adventitious	160	3	1	0	9
Oxyria digyna	fibrous	30	3	1	0	6
Pentaglottis sempervirens	tap	100	3	1	0	5
Persicaria amphibia	adventitious	200	3	1	3	10
Persicaria bistorta	tap	80	3	1	2	7
Persicaria hydropiper	fibrous	75	1	1	0	7
Persicaria lapathifolia	adventitious	100	1	1	0	6
Persicaria maculosa	fibrous/tap	80	1	1	0	6
Persicaria minor	fibrous	40	1	1	0	8
Persicaria mitis	fibrous	75	1	1	0	8
Persicaria vivipara	adventitious	30	3	1	2	6
Petasites albus	adventitious	70	3	1	3	5
Petasites fragrans	adventitious	30	3	1	3	5
Petasites hybridus	adventitious	120	3	1	3	7
Petroselinum segetum	tap	100	2	1	0	5
Peucedanum officinale	tap	200	3	1	0	5
Phalaris arundinacea	adventitious	200	3	1	3	9
Phegopteris connectilis	adventitious	40	3	1	3	6
Phleum alpinum	adventitious	50	3	1	2	5
Phragmites australis	adventitious	270	3	1	3	10
Phyteuma spicatum	tap	80	3	1	0	5
Pilularia globulifera	adventitious	10	3	1	3	10
Pinguicula lusitanica	adventitious	3	3	1	0	8
Pinguicula vulgaris	adventitious	8	3	1	0	8
Plantago major	adventitious/fibrous	15	3	1	0	5

Taxon name	**Predominant root type**	**Height /length cm**	**Perennation**	**Woodiness**	**Geomorph - Clone1**	**Ellenberg F**
Poa humilis	adventitious	30	3	1	3	6
Poa palustris	fibrous	100	3	1	1	9
Poa trivialis	adventitious	70	3	1	1	6
Polemonium caeruleum	adventitious	90	3	1	0	5
Polygala amarella	tap	10	3	1	0	6
Polygonatum verticillatum	adventitious	80	3	1	3	5
Polystichum aculeatum	adventitious	60	3	1	0	5
Polystichum setiferum	adventitious	120	3	1	0	5
Populus alba	tap	2000	3	3	3	6
Populus alba x tremula (P. x canescens)	tap	3000	3	3	3	6
Populus nigra sens.lat.	tap	3000	3	3	3	8
Populus tremula	tap	2000	3	3	3	5
Potamogeton acutifolius	adventitious	100	3	1	1	12
Potamogeton alpinus	adventitious	280	3	1	1	12
Potamogeton berchtoldii	adventitious	60	3	1	1	12
Potamogeton coloratus	adventitious	70	3	1	1	11
Potamogeton compressus	adventitious	90	3	1	1	12
Potamogeton crispus	adventitious	150	3	1	3	12
Potamogeton filiformis	adventitious	30	3	1	3	12
Potamogeton friesii	adventitious	150	3	1	1	12
Potamogeton gramineus	adventitious	80	3	1	1	12
Potamogeton gramineus x lucens (P. x zizii)	adventitious	120	3	1	1	12
Potamogeton gramineus x perfoliatus (P. x nitens)	adventitious	250	3	1	1	12
Potamogeton lucens	adventitious	250	3	1	1	12
Potamogeton natans	adventitious	100	3	1	1	11
Potamogeton nodosus	adventitious	250	3	1	1	12
Potamogeton obtusifolius	adventitious	190	3	1	1	12
Potamogeton pectinatus	adventitious	230	3	1	3	12
Potamogeton perfoliatus	adventitious	300	3	1	1	12

Taxon name	**Predominant root type**	**Height /length cm**	**Perennation**	**Woodiness**	**Geomorph - Clone1**	**Ellenberg F**
Potamogeton polygonifolius	adventitious	70	3	1	1	10
Potamogeton praelongus	adventitious	300	3	1	1	12
Potamogeton pusillus	adventitious	70	3	1	1	12
Potamogeton rutilus	adventitious	45	3	1	1	12
Potamogeton trichoides	adventitious	100	3	1	1	12
Potentilla anserina	adventitious/tap	25	3	1	3	7
Potentilla fruticosa	adventitious	100	3	3	0	6
Primula vulgaris	fibrous	15	3	1	0	5
Prunus lusitanica	adventitious/fibrous	800	3	3	0	5
Prunus padus	adventitious/fibrous	1500	3	3	0	6
Pseudorchis albida	adventitious/tap	20	3	1	0	5
Pteridium aquilinum	adventitious	150	3	1	3	5
Pulicaria dysenterica	adventitious/fibrous	80	3	1	3	7
Quercus robur	tap	3000	3	3	0	5
Ranunculus acris	fibrous	75	3	1	0	6
Ranunculus aquatilis	adventitious/fibrous	90	1	1	0	11
Ranunculus aquatilis sens.lat.	adventitious/fibrous	90	1	1	0	11
Ranunculus circinatus	adventitious	75	3	1	1	12
Ranunculus flammula	adventitious	50	3	1	2	9
Ranunculus fluitans	adventitious	300	3	1	1	12
Ranunculus hederaceus	adventitious	23	1	1	0	10
Ranunculus lingua	adventitious	120	3	1	3	10
Ranunculus omiophyllus	adventitious	25	1	1	0	10
Ranunculus peltatus	adventitious	90	1	1	0	11
Ranunculus penicillatus	adventitious	180	3	1	1	12
Ranunculus repens	adventitious	60	3	1	3	7
Ranunculus sceleratus	adventitious	60	1	1	0	8
Ranunculus trichophyllus	adventitious	60	1	1	0	12
Rhinanthus minor	semi parasitic on roots of grasses	50	1	1	0	5
Ribes alpinum	fibrous	200	3	3	0	5
Ribes nigrum	adventitious/fibrous	200	3	3	0	9
Ribes rubrum	fibrous	200	3	3	0	7
Ribes spicatum	fibrous	200	3	3	0	6

Taxon name	Predominant root type	Height /length cm	Perennation	Woodiness	Geomorph - Clone1	Ellenberg F
Rorippa amphibia	adventitious	120	3	1	2	10
Rorippa palustris	tap	60	1	1	0	8
Rorippa sylvestris	tap	60	3	1	2	8
Rubus saxatilis	adventitious	40	3	1	3	5
Rumex aquaticus	tap	180	3	1	0	9
Rumex conglomeratus	tap	60	3	1	0	8
Rumex crispus	tap	100	3	1	0	6
Rumex hydrolapathum	tap	200	3	1	0	10
Rumex longifolius	tap	120	3	1	0	6
Rumex maritimus	tap	40	1	1	0	9
Rumex obtusifolius	tap	100	3	1	0	5
Rumex palustris	tap	60	3	1	0	8
Rumex pseudoalpinus	tap	70	3	1	0	6
Rumex sanguineus	tap	60	3	1	0	7
Ruscus aculeatus	adventitious	77	3	3	2	5
Sagina procumbens	tap	20	3	1	0	6
Sagina saginoides	tap	10	3	1	0	7
Sagittaria sagittifolia	adventitious	95	3	1	1	11
Salix alba	adventitious	2500	3	3	0	7
Salix arbuscula	adventitious	70	3	3	0	5
Salix aurita	adventitious	250	3	3	0	8
Salix caprea	adventitious	1000	3	3	0	7
Salix cinerea	adventitious	800	3	3	0	8
Salix fragilis	adventitious	1500	3	3	0	8
Salix myrsinifolia	adventitious	300	3	3	0	8
Salix pentandra	adventitious	700	3	3	0	8
Salix phylicifolia	adventitious	400	3	3	0	8
Salix purpurea	adventitious	300	3	3	0	9
Salix triandra	adventitious	1000	3	3	0	8
Salix viminalis	adventitious	600	3	3	0	8
Samolus valerandi	fibrous	45	3	1	0	8
Sanguisorba officinalis	tap	120	3	1	0	7
Saponaria officinalis	tap	90	3	1	3	5
Saxifraga aizoides	adventitious	20	3	1	3	9
Saxifraga hirculus	adventititous	20	3	1	2	9
Saxifraga hirsuta	adventitious	30	3	1	2	7
Saxifraga oppositifolia	adventitious	3	3	1	3	6
Saxifraga spathularis	adventitious	40	3	1	2	8
Saxifraga	adventitious	20	3	1	0	8

Taxon name	Predominant root type	Height /length cm	Perennation	Woodiness	Geomorph - Clone1	Ellenberg F
stellaris						
Schedonorus arundinaceus	fibrous	125	3	1	1	6
Schoenoplectus lacustris	adventitious	210	3	1	2	11
Schoenoplectus tabernaemontani	adventitious	150	3	1	2	10
Schoenoplectus triqueter	adventitious	125	3	1	2	10
Scirpus sylvaticus	adventitious	120	3	1	2	8
Scrophularia auriculata	tap	120	3	1	0	8
Scrophularia nodosa	tap	100	3	1	0	6
Scrophularia umbrosa	tap	100	3	1	0	9
Scutellaria galericulata	adventitious	50	3	1	2	8
Sedum villosum	fibrous	10	3	1	0	9
Selaginella selaginoides	adventitious	9	3	1	2	7
Senecio aquaticus	tap	80	2	1	0	8
Senecio fluviatilis	tap	150	3	1	3	8
Senecio smithii	tap	100	3	1	0	7
Sibthorpia europaea	adventitious	5	3	1	3	7
Silaum silaus	tap	100	3	1	0	5
Silene dioica	fibrous/tap	90	3	1	0	6
Silene uniflora	adventitious	28	3	1	0	6
Sium latifolium	fibrous	200	3	1	0	10
Solanum dulcamara	adventitious	225	3	2	3	8
Solidago canadensis	fibrous	200	3	1	2	5
Solidago gigantea	adventitious/fibrous	200	3	1	2	5
Solidago virgaurea	adventitious/fibrous	70	3	1	0	5
Sonchus arvensis	tap	150	3	1	3	6
Sonchus palustris	tap	250	3	1	0	8
Sorbus arranensis	adventitious	750	3	3	0	4
Sorbus aucuparia	adventitious	1500	3	3	0	6
Sorbus pseudofennica	adventitious	700	3	3	0	4
Sparganium angustifolium	adventitious	100	3	1	3	11
Sparganium emersum	adventitious	60	3	1	3	11
Sparganium erectum	adventitious	150	3	1	3	10
Sparganium natans	adventitious	50	3	1	3	11
Spiranthes romanzoffiana	tap	25	3	1	0	8
Spirodela	simple	0.8	3	1	1	11

Taxon name	**Predominant root type**	**Height /length cm**	**Perennation**	**Woodiness**	**Geomorph - Clone1**	**Ellenberg F**
polyrhiza						
Stachys palustris	adventitious	100	3	1	3	8
Stachys palustris x sylvatica (S. x ambigua)	adventitious	100	3	1	3	6
Stachys sylvatica	adventitious	100	3	1	3	6
Stellaria neglecta	tap	80	1	1	0	7
Stellaria nemorum	adventitious	60	3	1	2	6
Stellaria uliginosa	fibrous	40	3	1	2	8
Stratiotes aloides	adventitious	50	3	1	2	11
Subularia aquatica	adventitious	6	1	1	0	11
Symphytum officinale	tap	135	3	1	0	7
Symphytum tuberosum	tap	55	3	1	0	6
Tamus communis	tap	400	3	1	0	5
Tanacetum vulgare	fibrous	120	3	1	2	6
Taraxacum	tap	30	3	1	0	5
Tellima grandiflora	tap	70	3	1	0	8
Tephroseris palustris congesta	fibrous	100	3	1	0	9
Teucrium scordium	adventitious	55	3	1	3	8
Thalictrum alpinum	fibrous	15	3	1	3	7
Thalictrum flavum	fibrous	100	3	1	0	8
Thalictrum minus	fibrous	70	3	1	3	4
Thelypteris palustris	adventitious	100	3	1	3	8
Tolmiea menziesii	adventitious	70	3	1	0	6
Trichomanes speciosum	adventitious	35	3	1	2	7
Trifolium medium	adventitious/tap	45	3	1	0	4
Trifolium squamosum	adventitious/tap	40	1	1	0	6
Triglochin maritima	adventitious/fibrous	55	3	1	2	7
Triglochin palustris	fibrous	55	3	1	3	9
Trollius europaeus	fibrous	60	3	1	0	7
Typha angustifolia	fibrous	300	3	1	3	10
Typha latifolia	fibrous	275	3	1	3	10
Ulmus glabra	fibrous	3000	3	3	0	5
Ulmus minor	fibrous	100	3	3	0	6
Urtica dioica	adventitious	150	3	1	3	6
Utricularia	absent	60	3	1	1	12

Taxon name	**Predominant root type**	**Height /length cm**	**Perennation**	**Woodiness**	**Geomorph - Clone1**	**Ellenberg F**
australis						
Utricularia vulgaris sens.lat.	absent	100	3	1	1	12
Utricularia vulgaris sens.str.	absent	100	3	1	1	12
Valeriana officinalis	fibrous	175	3	1	0	8
Verbena officinalis	fibrous	67	3	1	0	5
Veronica anagallis-aquatica	adventitious	50	1	1	2	10
Veronica beccabunga	adventitious	45	3	1	2	10
Veronica catenata	adventitious	50	1	1	2	10
Veronica filiformis	adventitious	5	3	1	3	6
Veronica montana	adventitious	15	3	1	3	6
Vicia cracca	adventitious	120	3	1	2	6
Viola canina	adventitious	18	3	1	0	4
Viola hirta	adventitious	15	3	1	0	4
Viola persicifolia	adventitious	25	3	1	0	8
Wahlenbergia hederacea	adventitious	5	3	1	3	8
Wolffia arrhiza	absent	0.1	3	1	1	11
Zannichellia palustris	adventitious	50	3	1	1	12