ADVANCES ON MODELLING RIPARIAN VEGETATION—HYDROMORPHOLOGY INTERACTIONS

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ABSTRACT

Riparian vegetation actively interacts with fluvial systems affecting river hydrodynamics, morphodynamics and groundwater. These interactions can be coupled because both vegetation and hydromorphology (i.e. the combined scientific study of hydrology and fluvial geomorphology) involve dynamic processes with similar temporal and spatial scales. To predict and assess the consequences of restoration measures, maintenance operations or human pressures in rivers, managers and planners may wish to model these interactions considering the different and interdisciplinary implications in the fields of ecology, geomorphology and hydrology. In this paper, we review models that are currently available and that incorporate the processes that relate riparian vegetation to hydromorphology. The models that are considered include those emphasizing hydraulic-geomorphological processes (such as flow resistance, sediment transport and bank dynamics) as well as those emphasizing ecological processes (seed dispersal, plant survival, growth, succession and mortality). Models interpreting the coupled evolution between riparian vegetation and river morphology and groundwater are also presented. The aim is to provide an overview of current modelling capabilities and limitations and to identify future modelling challenges. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS: riparian vegetation; hydromorphology; modelling; REFORM project

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INTRODUCTION

Vegetation is a key element in fluvial systems, controlling river corridor form and dynamics (Figure 1). Plants actively interact with fluvial processes; their aboveground biomass can affect the flow field and sediment transport and therefore river morphological evolution, whereas their belowground biomass modifies the hydraulic and mechanical properties of the substrate and consequently the moisture regime and erodibility of the soil (Gurnell, 2014).

The interactions between vegetation and hydromorphological processes are many and complex spanning a large range of spatial and temporal scales (Camporeale *et al.*, 2013). During floods, individual plants or plant patches can trap and stabilize sediments and plant propagules, thereby promoting colonization of other plant species by building pioneer landforms. At larger scales, riparian vegetation dynamics are crucial for river planform evolution (Gurnell *et al.*, 2012). Additionally, the processes occurring at smaller scales, such as the dynamics of single patches, are probably crucial for larger scale

geomorphological phenomena (Gurnell, 2014). Importantly, vegetation and hydromorphological processes display comparable temporal dynamics; for instance fluvial erosion–sedimentation and the establishment of complete vegetation cover have similar time scales and evolution rates; therefore, they cannot be modelled separately (Camporeale *et al.*, 2013).

Riparian vegetation colonization and development is widely dominated by disturbance conditions generated by flow and flood regimes and related morphological processes (Bornette *et al.*, 2008). Within the channel, vegetation disturbance reaches a maximum, whereas this reduces on river margins where competition with other species becomes more important (Corenblit *et al.*, 2007).

Current models have been formulated either considering one-way interactions (i.e. the effects of vegetation on hydromorphological processes, or vice versa) or two-way coupled interactions. Accordingly, we distinguish the following four categories (Figure 2, 1–4):

(1) Effects of vegetation on hydromorphodynamics;

Models in this category, typically developed within the fields of geomorphology and engineering, include how vegetation affects *flow resistance*, *sediment transport* and *bank*

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Figure 1. Examples of riparian vegetation in the Cecina River (Tuscany, Italy). This figure is available in colour online at wileyonlinelibrary. com/journal/rra

dynamics (both accretion and erosion). Here, vegetation is modelled as an abiotic element, and the relevant properties are associated to the biomechanical (such as elasticity and tensile strength) and morphological plant features.

(2) Effects of hydromorphodynamics on riparian vegetation;

These effects consider ecological models aimed at evaluating the influence of hydromorphological variables on the different life stages of vegetation. Vegetation is therefore modelled as a biotic element. Processes modelled include the following: propagule *dispersal*, vegetation *recruitment*, *growth*, *succession* and *mortality*. Models related to *large wood* (recruitment, entrainment, transport and deposition) are also considered in this category.

(3) Interactions between vegetation and hydromorphodynamics;

Models here consider the *coupled evolution of vegetation pattern and river altimetric and planimetric morphology*. For instance, growth of vegetation can favour bank stability thus reducing lateral flow erosion and thereby affecting channel pattern and river morphology (Tal and Paola, 2010).

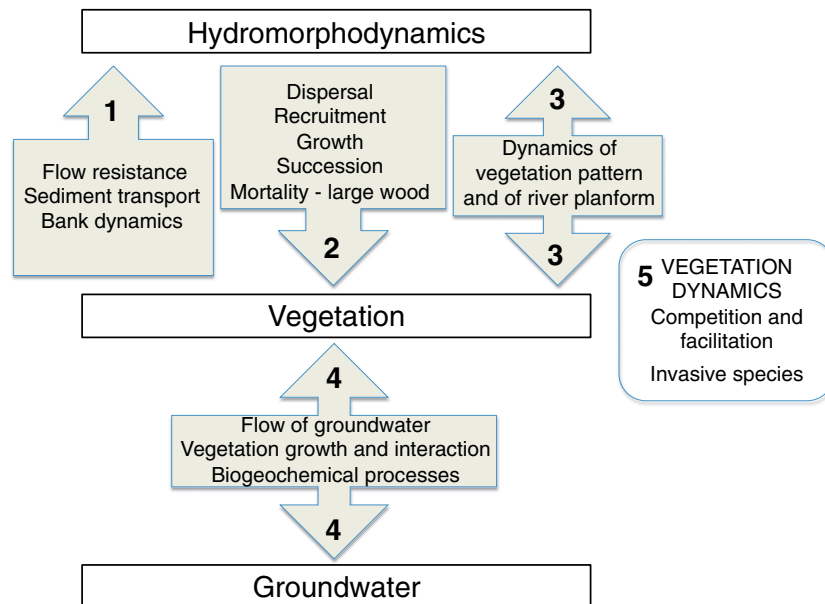(4) Interactions between vegetation and groundwater.

Figure 2. Interactions between vegetation and hydromorphology This figure is available in colour online at wileyonlinelibrary.com/journal/rra

Models of this type may emphasize groundwater-river connectivity and vegetation growth; models for *flow of groundwater*, *vegetation growth* and *biogeochemical processes*.

The aforementioned four groups of model types are complemented by a fifth group concerned with vegetation dynamics (Figure 2, topic 5). 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 and considering *invasive species*.

There have been a number of recent reviews of the effects of vegetation on various properties of fluvial systems, including considerations of hydrodynamics (Nepf, 2012), flow resistance (Aberle and Järvelä, 2013), sediment transport (Vargas-Luna *et al.*, 2015), bank stability (Pollen-Bankhead and Simon, 2010) and interactions between riparian vegetation and river hydromorphodynamics (e.g., Gurnell *et al.*, 2012; Tal and Paola, 2010; Camporeale *et al.*, 2013). Nevertheless, there is still a need to transfer this knowledge into practice by making models more available for applications in river management and restoration. Many existing models are applied to quantify a single process, but links between different components of vegetation hydromorphology interactions are still not fully acknowledged. Restoration and river-management practice needs to assess and model these interactions in order to consider their different, often interdisciplinary, implications for river ecology, geomorphology and hydrology. Accounting for these interactions is a key issue for managers because they provide insights into both the beneficial and detrimental effects of vegetation in the context of river management and restoration.

In response to this need, an extensive review of existing models relating to interactions between vegetation and fluvial processes has been conducted (Gurnell *et al.*, 2014) within the REFORM project (REstoring rivers FOR effective catchment Management; http://www.reformrivers.eu/), a collaborative EU project targeted to develop guidance and tools to make river restoration and mitigation measures more cost-effective.

This paper summarizes the main outcomes of the earlier, extensive review (Gurnell *et al.*,2014) by addressing two key questions: (i) what are the currently available models that water managers can consult, when they are developing river basin management plans, to interpret and predict the interactions between riparian vegetation and hydromorphology?; (ii) what are future research and modelling challenges?

Note that, because of space limitations, we mostly focus on modelling advances relating to riparian vegetation.

EFFECTS OF VEGETATION ON HYDROMORPHODYNAMICS

Vegetation can influence river hydrodynamics by changing the turbulent flow field and the averaged velocity profiles in comparison with those that can be commonly found in non-vegetated flows. In this way, vegetation potentially has a relevant effect on flow resistance, sediment transport and bank dynamics (Table I).

Flow resistance

Evaluation of flow resistance is typically associated to the integrated effect of hydrodynamic forces on the plants evaluated through a drag coefficient that is difficult to estimate (Aberle and Järvelä, 2013). Current models are formulated for aquatic and riparian vegetation (see review by Vargas-Luna *et al.*, 2015)

With regard to aquatic vegetation, stem bending and canopy configuration under hydrodynamic forcing is of primary importance (Nepf, 2012). Dijkstra and Uittenbogaard (2010) developed a fully mechanistic model for predicting flow velocity and plant bending of flexible aquatic vegetation. Luhar and Nepf (2013) provided a mechanistic interpretation of well-known retardance curves (USDA, 1947) by showing that the flow resistance decreases with the submergence ratio (height of deflected vegetation/flow depth).

Regarding riparian vegetation, models consider both rigid and flexible vegetation. In the rigid case, such as mature trees, vegetation elements are schematized as rigid cylinders. Current models (such as Baptist *et al.*, 2007) allow one to evaluate flow resistance both in submerged and emergent conditions as a function of density, diameter and height of the vegetation. In the case of flexible leafy bushes and softwood trees, the contribution of leaves to drag production cannot be neglected. The models by Järvelä (2004) explicitly take the effect of the foliage into account through the leaf area index. Input parameter values in Järvelä's model for different deciduous and coniferous species can be found in Aberle and Järvelä (2013).

Sediment transport

No general sediment transport models incorporating the effect of vegetation are currently available (Nepf, 2012). Various studies, typically based on laboratory observations with artificial vegetation, have explored the effect of vegetation on (i) bed load and (ii) suspended load.

Regarding bed load, various authors (e.g. Kothyari *et al.*, 2009) have found that in vegetated areas, bed, load transport rates are significantly smaller than in areas without vegetation. Bed load can be expressed using a classical power function of the excess bed shear stress (calculated taking into account the total stem drag). However, Yager and Schmeeckle (2013) found out that commonly used bed

Table I. Models for the effects of vegetation on hydromorphodynamics

Effects	Models	Key references
Flow resistance	– roughness due to aquatic vegetation	Dijkstra and Uittenbogaard (2010); Luhar and Nepf (2013)
	– roughness increase due to flexible riparian vegetation	Järvelä (2004); Aberle and Järvelä (2013)
	– roughness increase due to rigid riparian vegetation	Baptist et al. (2007)
Sediment transport	– reduction of bed load	Kothyari et al. (2009); Yager and Schmeeckle (2013)
	– turbulent flow field and suspended load	López and García (1998)
	– fine sediment trapping	Zong and Nepf (2011)
Bank dynamics (hydrological effects)	– canopy interception	Greenway (1987); Thorne (1990);
	– evapotranspiration	Simon and Collison (2002)
	– infiltration induced by root pathways	
Bank dynamics (fluvial effects)	– reduction of shear stress by increase in roughness	Thorne (1990)
	– localized erosion related to isolated trees	
	– flow deflection	
	– vegetation growth on bars	Bertoldi et al. (2014)
	– fine sediment trapping in vegetation patches	Zong and Nepf (2011)
Bank dynamics (mechanical effects)	– surcharge	Wu et al. (1979); Greenway (1987);
	– soil reinforcement by roots	Simon and Collison (2002); Pollen and Simon (2005);
	– anchoring, buttressing and soil arching, wind action	Pollen-Bankhead and Simon (2010)

load-transport equations were not able to capture the observed average-sediment fluxes unless the spatial variability in the near-bed Reynolds stress is taken into account.

Regarding suspended load, 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. Because 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. Numerical simulations of turbulent flow fields (such as López and García, 1998) show that the decrease of suspended sediment transport capacity is due to a reduction in the ability of vegetated flow (i.e. reduction of bed shear stress) to entrain sediment into suspension from the channel bottom. However, note that this is not generally true, as in real rivers flow into a vegetated area may carry sediments in suspension from upstream. Recent studies (e.g. Zong and Nepf, 2011; Ortiz et al., 2013) have emphasized the effect of the complex flow field associated with finite vegetation patches and the implications for sediment deposition, showing that vegetation may even have a destabilizing effect on the sediments (i.e. removal of fine sediments) because of high local-turbulence intensities and vertical velocity components.

Bank dynamics

River-width is a dynamic property that depends on the joint action between erosion and accretion processes occurring at opposite river banks. These adjustments are influenced by a wide range of conditions (ASCE Task Committee, 1998). Vegetation plays a key role in bank dynamics, affecting both processes of bank retreat and bank advance. Vegetation can significantly influence bank dynamics by modifying fluvial processes and affecting the mechanical and hydrological configuration of banks in various ways. In terms of fluvial processes, the main effect of reducing near-bank shear stresses can be modelled in terms of flow resistance, whereas other specific effects such as localized erosion or deposition are more difficult to account for. A change in stability due to vegetation (by means of mechanical and hydrological effects) is highly dependent on site-specific factors. The net effect of vegetative surcharge, that is, the additional weight of vegetation on the bank surface, on bank stability can be either beneficial or detrimental, 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 (Greenway, 1987; Thorne, 1990; Simon and Collison, 2002). The most important mechanical effect for both bank erosion and bank accretion is the soil strength induced by the presence of a vegetation root system. Most recent research (Pollen and Simon, 2005; Pollen-Bankhead and Simon, 2010) has shown that the previously developed model of Wu et al. (1979) tends to overestimate the additional shear strength of the roots because of 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 fibre bundle theory to account for progressive root breaking during shearing (Pollen and Simon, 2005; Pollen-Bankhead and Simon, 2010).

In terms of the influence of riparian vegetation on local-scale river bank hydrology, three main effects can be distinguished; that is, canopy interception, evapotranspiration and infiltration induced by root pathways. Although these effects are well understood at a conceptual level (e.g. Greenway, 1987; Thorne, 1990), they are in practice extremely difficult to quantify and include in existing models.

In contrast to the advances in bank erosion modelling, bank accretion modelling is still in its infancy. Some of the processes influencing bank accretion have been included in models, but there is no general physics-based model that describes this phenomenon. Most recent morphological models that consider bank accretion include vegetation effects by considering static plant properties (Nicholas, 2013; Asahi *et al.*, 2013; Eke *et al.*, 2014) or by assuming vegetation development to be described in a simplified way (Bertoldi *et al.*, 2014). In fact, it is this simplified description of the vegetation dynamics that limits the upscaling process from numerical modelling exercises to real-river applications. The sedimentation induced by vegetation has been observed in laboratory experiments (e.g. Zong and Nepf, 2011), but models estimating the effects of the fine sediment trapped in vegetation patches are still lacking.

EFFECTS OF HYDROMORPHODYNAMICS ON RIPARIAN VEGETATION

Among the several abiotic (e.g. water chemistry, light and wind) and biotic (e.g. competition, invasive species; see in the succeeding paragraphs) factors that influence riparian vegetation processes, fluvial hydrodynamics (i.e. flow and flood regime, and related processes) plays a significant role in all plant life stages, that is, dispersal, colonization, recruitment, growth, succession and mortality (Figure 3). Successful riparian plants often adopt a combination of adaptive strategies during different life stages in order to ensure their survival (e.g. high dispersal rates; adaptations to resist stress; and vegetative reproduction; Camporeale *et al.*, 2013).

Recently, several models have been developed to investigate vegetation processes in riparian systems influenced by hydromorphological processes (Table II). However, probably because of the complexity of such processes, conceptual models are still widely employed.

Vegetation dispersal

One of the main processes of vegetation dispersal within river corridors is hydrochory (dispersal by water transport).

In general, such models predict the spatial pattern of seed dispersal and deposition in terms of seed density at a given distance along the river from the input point (e.g. Groves *et al.*, 2009); concentration variability of seed deposition along river margins (e.g. Merritt and Wohl, 2002); a probability distribution related to a generic longitudinal dispersion coefficient (e.g. Tealdi *et al.*, 2010) or relative seed
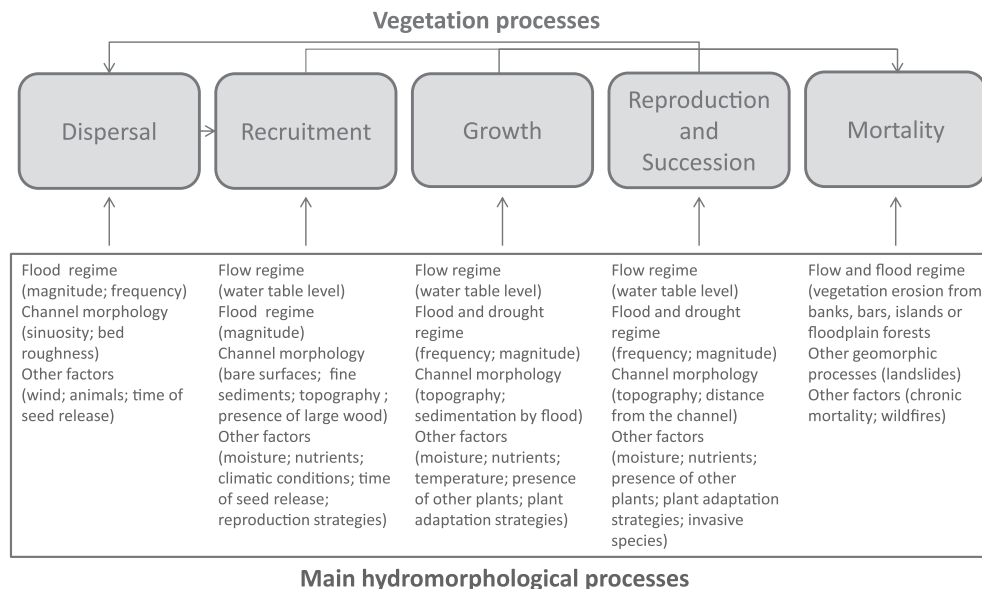

Figure 3. Effects of hydromorphological processes on riparian vegetation

Table II. Models for the effects of hydromorphodynamics on vegetation

Effects	Models	Key references
Dispersal	– spatial patterns of seeds and propagules dispersal – seed density – dispersion coefficient	Merritt and Wohl (2002); Groves *et al*. (2009); Steiger and Gurnell (2003); Tealdi *et al*. (2010)
Recruitment (survival and early development)	– seedling survival and growth – riparian vegetation composition – riparian vegetation dynamics	Mahoney and Rood (1998)
Plant growth	– plant growth rate – vegetation biomass density	Perucca *et al*. (2007)
Succession	– occurrence of specific ecological groups – vegetation types in time – vegetation width variations – spatial distribution of floodplain vegetation	Aggenbach and Pelsma, (2005); Camporeale and Ridolfi (2006); García-Arias *et al*. (2013) Lenders *et al*. (2001); Lytle and Merritt (2004); Harper *et al*. (2011)
Mortality—large wood	– recruitment – entrainment and transport – deposition	Haga et al. (2002); Braudrick and Grant (2000); Gregory *et al*. (2003); *Hassan et al*. (2005); Villanueva *et al*. (2014)

retention on different riparian landforms (e.g. Steiger and Gurnell, 2003).

Dispersion modelling has the potential to improve management and restoration efforts in riparian zones. For example, the flume experiment of Merritt and Wohl (2002) combines flow regime, channel morphology, timing of seed release and species environmental preferences, allowing the management of flow releases below dams in order to favour or inhibit species through hydrochory.

Vegetation recruitment, early survival and development

In general, these models predict the pattern of seedling survival and early growth after germination in response to hydromorphological conditions, supporting the management of riparian vegetation (e.g. encouraging/discouraging colonization and growth). One of the best known model is the *recruitment box* by Mahoney and Rood (1998) that determines the stream stage patterns that 'enable successful establishment of riparian cottonwood seedlings'. It can be applied to predict the effects of alternative restoration strategies (e.g. ecological and economic benefits) or to plan the management of hydrological altered river basins.

Plant growth

Few models address the issue of plant growth related to physical disturbances in river systems and even less address individual plant growth. In general, these models may support the understanding of the interaction between plant growth (i.e. mainly biomass) under specific hydromorphological conditions and river-channel pattern variability in space and time. For example, Perucca *et al*. (2007) combine a numerical fluid dynamic model of meander dynamics with a process-based model of riparian

vegetation dynamics (i.e. biomass density) based on the effect of water table oscillations, flooding and sedimentation.

Succession and vegetation distribution

Models of vegetation succession (i.e. the changes in species composition and other plant community characteristics such as productivity, biomass and diversity) influenced by hydromorphodynamics can apply to local (i.e. site, reach and cross section) or larger (e.g. river segment and basin) scales. At the local scale, models predict the vegetation type, in relation to flow and flood regime but also channel geometry, soil parameters, and climate and management types, in terms of the following:

(i) vegetation composition, that is, species, phytosociological units (e.g. Aggenbach and Pelsma, 2005); and
(ii) riparian ecosystems, that is spatial distribution and extent of vegetation (e.g. Camporeale and Ridolfi, 2006; García-Arias *et al*., 2013).

The majority of these models can be applied to assess the impact of vegetation management, to describe natural vegetation development and to plan vegetation management (e.g. under regulated flow regimes) and restoration measures. At a larger spatial scale, models mainly concern the succession of ecotypes and related parameters (e.g. Lenders *et al*., 2001). These models may support large scale management (e.g. reservoirs and flood prevention) in terms of floodplain vegetation evolution also including land use. Finally, several models account for all the stages of vegetation development in rivers, allowing for different scenarios of vegetation development to be investigated as well as long-term restoration or river management (e.g. Lytle and Merritt, 2004; Harper *et al*., 2011).

Mortality—large wood

The role of wood in river ecosystems has become an increasingly important focus. Analogies between wood and sediment transfer provide a framework for synthesizing current knowledge on large wood in rivers (Gurnell *et al.*, 2002) and for conceptualizing wood processes in the following categories: (1) recruitment; (2) entrainment and transport; and (3) deposition. Although these processes are conceptually well understood, most of them are difficult to quantify and include in numerical models. Furthermore, similarly to living vegetation, dead wood has a series of other effects on flow hydraulics and morphodynamic processes that need to be modelled.

Mechanisms of wood recruitment mainly include the following: (a) chronic mortality; (b) wildfires; (c) erosion of river banks or other instream vegetated surfaces (bars or islands) and floodplain forests; and (d) landslides on hillslopes connected to the stream.

Entrainment of wood is a difficult issue theoretically, given the complexity of interactions between wood and other elements in the channel. 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 a 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 and Grant (2000) developed an analytical model that predicts the flow conditions needed to entrain individual wood pieces and described three distinct transport regimes (uncongested, congested and semi-congested) based on the channel area occupied by wood elements.

Various types of simulation models with different approaches have been developed in recent years to explore long-term or large-scale implications of wood dynamics. Gregory *et al.* (2003) and Hassan *et al.* (2005) provide comprehensive reviews in which they compare and discuss the characteristics of several models. 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. The most advanced model of wood dynamics is a two-dimensional numerical model recently developed by Villanueva *et al.* (2014) to simulate the transport of large wood material, its effect on hydrodynamics, bridge clogging processes and wood deposition patterns, modelling the movement of individual pieces of wood with the water flow and interactions among wood pieces and with the bridge.

INTERACTION BETWEEN VEGETATION AND HYDROMORPHODYNAMICS

Models that include the two-way interaction between vegetation and morphodynamics in an integrated, dynamic manner are scarce. Recently, there have been several studies that model the physics-based interaction between vegetation and morphodynamics (Table III). These studies can be divided into rule-based cellular automata and, more advanced, physics-based numerical models.

Cellular automata

There is a range of cellular automata that investigate the impact of vegetation on morphodynamics (e.g. review in Camporeale *et al.*, 2013). However, few studies have integrated the on-line feedback between vegetation and morphodynamics. One of the first integrated models was constructed by Murray and Paola (2003). They investigated the effect of sediment stabilization by vegetation roots on channel pattern. The model results support the hypothesis that bank-stability is the main cause of single-channel development and that vegetation development can be sufficient to induce this response. The lack of meandering behaviour in this model due to the inclusion of only local processes was overcome by Coulthard and Van de Wiel (2006) and Coulthard *et al.* (2007) in their Cellular Automaton Evolutionary Slope And River (CEASAR) model by including curvature and longer length scales. This model was applied

Table III. Models for the interactions between vegetation and hydromorphodynamics

Effects	Models	Key references
Bed dynamics	– plant biomass dynamics and bar dynamics	Bertoldi *et al.* (2014)
Planform dynamics	– bank stability, vegetation colonization and vegetation removal	Crosato and Saleh (2011); Nicholas (2013)
Meander migration	– bank erosion and plant biomass	Perucca *et al.* (2007)
Channel pattern migration	– bank stability, vegetation colonization, growth and mortality	Murray and Paola (2003); Coulthard *et al.* (2007); Hooke *et al.* (2005)

to investigate morphological development because of reduced sediment load resulting from dam construction (Coulthard *et al.*, 2007). Different vegetation growth-rate scenarios were tested affecting the rate of lateral erosion by strengthening the river banks and riverbed. High vegetation-growth rates forced the flow into a single channel and caused channel incision by increasing the sediment load, while in scenarios with low vegetation-growth rates, multiple channels could persist; decreasing the sediment load. Probably the most extensive cellular automate was constructed by Hooke *et al.* (2005). In this model, morphology, hydrology, different vegetation types and groundwater were integrated. The model was designed to simulate channel changes in ephemeral river channels and for testing the effects of changing hydrological regime and land use.

Cellular models are often relatively easy to set up, do not require large quantities of input data and can perform fast calculations. However, these models have simplified physics and cannot cope with highly heterogeneous systems (Coulthard *et al.*, 2007). This means that processes on longer length scales, like backwater effects influencing sedimentation and erosion processes or more detailed transverse slope effects, playing an important role in bank formation (Schuurman *et al.*, 2013), are neglected. Nevertheless, cellular automates can be useful tools in making a general exploration of river morphology evolution and, for instance, to pinpoint areas where more advanced numerical models should be employed.

Physics-based numerical models

Crosato and Saleh (2011) were one of the first to test the effect of vegetation on river planform with an advanced physics-based numerical model. In each year, vegetation colonized dry cells and increased the roughness value. Nicholas (2013) created a model that was able to produce a range of river planforms. Vegetation was included in the same manner as in Crosato and Saleh (2011), but here, it could also be removed by vertical erosion. Both studies described earlier show that dense or fast vegetation development can create a single-thread channel as opposed to a multi-thread or braided river. The model constructed by Perucca *et al.*, (2007) contains different vegetation biomass-density functions representing different climatic zones. The maximum biomass of the vegetation depends on the distance from the channel and affects bank erosion rates. Results show how different vegetation density functions generate different meander bend skewness and migration. However, contrary to the models of Crosato and Saleh (2011) and Nicholas (2013), this model does not incorporate sediment transport. Therefore, morphological development was not tested. A recently developed model-coupling vegetation biomass dynamics with advanced morphodynamics was created by

Bertoldi *et al.*, 2014. Here, aboveground and belowground vegetation properties actively influence morphodynamics. Vegetation biomass can increase over time, and vegetation can die through uprooting.

While cellular automata generally contain dynamic vegetation processes like vegetation growth rates and mortality, these processes are surprisingly neglected in most advanced numerical models. However, numerical models contain more sophisticated physics-based calculations than cellular automata.

All of the models discussed earlier contain elements that could contribute to an advanced, fully coupled ecohydromorphodynamic model with correct morphological and vegetation length and timescales, including the following: (i) advanced morphodynamics as presented in Crosato and Saleh (2011) and Nicholas (2013), (ii) ecological processes as described in the cellular automates and (iii) appropriate vegetation timescales as included by Bertoldi *et al.* (2014). However, several building blocks are still missing.

VEGETATION DYNAMICS

Riparian vegetation shows a gradient of interaction with morphodynamics, with the highest degree of interaction close to the channel. At higher altitudes, where there is less morphodynamic disturbance, vegetation succession occurs, and the vegetation pattern evolves from a patchy pioneer state to a more homogenous mature state (Tabacchi *et al.*, 1998). Here, internal plant processes, as opposed to morphodynamic processes, begin to play a more dominant role (White, 1979). The main processes that drive vegetation succession are competition and facilitation. 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, also called mutualism, or one species creates favourable conditions for another species indirectly. An example of the latter is an ecosystem engineer that actively changes its environment by trapping sediment, elevating the soil and creating less frequently flooded sites, or that adds nitrogen to the soil, benefitting surrounding plants (Tabacchi *et al.*, 1998; Brooker *et al.*, 2007). Each species has a set of functional traits that contribute to key events in its life cycle, thereby shaping its response to disturbances and determining its competitive and/or facilitative abilities (Adler *et al.*, 2014). The interplay between competition and facilitation can create spectacular regular vegetation patterns in a range of ecosystems including wetlands and tidal areas. One of the explanations for regular vegetation patterns is spatial self-organization by short-range facilitation and long-range competition (Rietkerk and van de Koppel, 2008). Research has also shown that facilitation is relatively more important in highly disturbed areas, whereas

competition becomes more dominant in less disturbed areas (Brooker and Callaghan, 1998; Bertness and Callaway, 1994; Grime, 2002).

Alien-plant species can invade and restructure plant communities by changing the balance between competition and facilitation processes (Santoro *et al.*, 2012). Invasive species can change the dominant morphology of the plant community and eventually alter channel morphology by increasing hydraulic roughness and trapping sediment (Tickner *et al.*, 2001; Hoffman *et al.*, 2008). Riparian zones are especially susceptible to invasions because invasive plant propagules are easily dispersed through waterways (Grime, 2002).

There are many deterministic and stochastic eco-hydrological models available that predict regular vegetation pattern formation (review in Borgogno *et al.*, 2009; Table IV). However, most of these models are applied in arid or semi-arid regions. One example of a model applied in a wetland is used to explain the regular vegetation pattern of Carex *stricta* (Van de Koppel and Crain, 2006). The study shows that short-range facilitation and intermediate-range competition is the responsible mechanism for creating these regular patterns: on the one hand, by elevation of plant patches through extensive root growth, providing protection against herbivores and, on the other hand, through shading of these roots, limiting plant growth. A model showing that the relative importance of facilitation increases when disturbance or stress increases was developed by Droz and Pękalski (2013). In the model, plants clustered in harsh conditions, while under favourable conditions, plants showed an increased competition for resources. Other models have illustrated that facilitation can even extend the natural range of species beyond their current niche (Travis *et al.*, 2005; Le Bagousse-Pinguet *et al.*, 2014).

Only a few models that include both competition and facilitation have been applied in riparian zones. One model showing the importance of facilitation is that of Tealdi *et al.* (2013). The results show that slow-growing species are better able to survive hydrologic stress when facilitation

increases. These 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 was the main regulating process determining vegetation cover in the riparian zone (Ye *et al.*, 2013). Competition was included in the model as a competitive index varying between species, according to their morphology and growth. The feedback from plants to hydrodynamics was expressed as higher roughness values. It was found that floods were the main regulator of vegetation cover.

Several models include invasive species and their influence on the 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 (i.e. an interaction that is beneficial for both species) was confirmed by the model of Xiao *et al.* (2012). The authors found that the effects of competitive intensity at a small spatial scale can potentially play an important role in large-scale outcomes of invasions. Modelling has also demonstrated that shifts in resources can change the balance within a community and promote invasiveness of a species (Eppinga *et al.*, 2011). This model combines a resource competition model for nutrients and light with litter dynamics. Results show that the invasive effect can be increased by a combination of plant-litter feedbacks and evolutionary change that together amplify invasiveness. Interference mechanisms of plants, such as excretion of biochemical compounds to gain competitive advantage (i.e. allelopathy), can affect interactions between invasive species and native species. In the model of Allstadt *et al.* (2012), interference mechanisms were modelled as a trade-off with reproduction ability. Modelling results indicate that individual alien species do not gain advantage through interference because their rate of reproduction is too low for them to spread rapidly, but where they occur in clustered plant patches, there are enough propagules to compete with native species for

Table IV. Models for vegetation dynamics

Effects	Models	Key references
Regular vegetation pattern formation	– short-range facilitation, – long (or intermediate)- range competition	Borgogno *et al.* (2009); Van de Koppel and Crain (2006)
Plant clustering or increased competition	– facilitation and competition under disturbance gradient	Droz and Pękalski (2013)
Niche extension, survival	– facilitation	Travis *et al.* (2005); Le Bagousse-Pinguet et al. (2014); Tealdi *et al.* (2013)
Vegetation cover, promoted invasiveness	– competition	Ye *et al.* (2013); Xiao *et al.* (2012); Eppinga *et al.* (2011)
Clustering, competitive advantage, invasion success	– interference mechanism– reproduction trade-off	Allstadt *et al.* (2012); Goslee *et al.* (2001)

open sites. The model of Goslee *et al.* (2001) also takes allelopathy into account. The importance of allelopathy and soil texture on growth, recruitment and invasion success of a non-native forb was modelled 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.

Although vegetation dynamics begin to play a more prominent role in less disturbed areas of the floodplain, they have a strong effect on the development of vegetation patterns. Interaction between plants 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. Therefore, implementing vegetation dynamics in morphodynamic models could be a valuable addition in predicting how vegetation patterns will evolve in times of fewer disturbances and which plant morphologies will prevail.

INTERACTION BETWEEN VEGETATION AND GROUNDWATER

Plant physiology is directly linked to the availability, the chemical composition and the temperature of soil moisture in the unsaturated zone. Vegetation functions best under plant-specific ideal soil-moisture conditions. Plants under water stress or oxygen stress decrease both their transpiration and photosynthesis through a number of responses, including closing their stomata (e.g. Feddes *et al.*, 1978; Homaee *et al.*, 2002; Bartholomeus *et al.*, 2008). Each plant species also functions best under plant-specific optimum soil water quality (most importantly, salinity, nutrient availability and acidity) and temperature conditions (Klijn, 1989; Van Wirdum, 1980; Witte *et al.*, 2008).

Ecosystems that require access to groundwater on a permanent or intermittent basis to meet all or some of their water requirements to maintain their ecosystems, such as

wetlands, lakes, rivers, riparian zones, springs, lakes, caves and aquifers, are called groundwater-dependent ecosystems (Richardson *et al.*, 2011). In such ecosystems, groundwater is an important source of soil moisture available for plants. In general, vegetation extracts water from the upper aquifer, the phreatic aquifer, of which the unsaturated zone forms the top layer. The availability and chemical composition of this groundwater depends on the climate (precipitation and evaporation), the (regional) groundwater flow, and the chemical composition of the rocks and sediments in the subsurface. The local groundwater level and composition is also affected by the plant transpiration. Hence, besides (variations in) groundwater characteristics, it is important to take into account the feedback mechanisms between groundwater and vegetation by integrating groundwater dynamics (quantity and quality) in an eco-hydrological model.

When coupling vegetation models to groundwater dynamics (Table V), it is preferred to use non-stationary, spatially distributed groundwater models that combine information on groundwater depths, soil and subsurface properties, and meteorological information to simulate groundwater levels and groundwater flow (e.g. Modular Three-Dimensional Finite-Difference Groundwater Flow Model (MODFLOW); McDonald and Harbaugh, 2003). Ideally, a groundwater model is used that includes groundwater quality and the chemical processes in the groundwater (e.g. MT3D; Zheng, 1990). However, if spatially distributed groundwater models are not available, it is also possible to take groundwater into account in a more simplified way by using one-dimensional water balance models, databases with spatially distributed information on soil types and classes of groundwater levels, or local groundwater measurements.

Various vegetation models that have a coupled groundwater module exist. Some of these coupled eco-hydrological models are mechanistic models, which simulate processes based on causal relationships (Witte *et al.*, 2008). Mechanistic eco-hydrological models for groundwater dependent ecosystems often include the Soil–Water–Atmo-

Table V. Models for the interactions between vegetation and groundwater

Effects	Models	Key references
Flow of groundwater	– MODFLOW: groundwater levels and flow	McDonald and Harbaugh (2003)
Vegetation growth	– DEMNAT—Dutch national eco-hydrological prediction	Witte (1998); Van Ek *et al.* (2000)
	– ecohydrological hillslope model	Brolsma and Bierkens (2007)
	– NUCOM	Van Oene and Berendse (2001)
	– PROBE	Witte *et al.* (2007)
	– RIP-ET module for riparian zones and wetlands	Baird *et al.* (2005)
	– SWIM	Krysanova *et al.* (1989)
	– VSD + −SUMO−NTM	Berendse (1994); Wamelink (2007); Bonten *et al.* (2010)
Biogeochemical processes	– MT3D	Zheng (1990)

sphere–Plant (SWAP) model (e.g. Van Dam *et al.*, 1997; Van Dam and Feddes, 2000). SWAP describes the transport of soil water as dependent upon climate, vegetation characteristics, soil characteristics and groundwater regime and contains feedback mechanisms between vegetation and soil (moisture). The lower boundary describes the interaction with regional groundwater (Kroes *et al.*, 2008). Groundwater-vegetation models that include a SWAP module are the Probability Based Ecological target (PROBE) model (Witte *et al.*, 2007), Nutrient cycling and competition (NUCOM) model (Van Oene and Berendse, 2001), and the ecohydrological hillslope model (Brolsma and Bierkens, 2007). The RIParian EvapoTranspiration package (RIP-ET) module, for riparian zones and wetlands, offers another integrated groundwater-vegetation modelling approach (Baird *et al.*, 2005): evapotranspiration is modelled by using detailed information on groundwater level and topography and by replacing the evapotranspiration flux curve often incorporated in groundwater models with a set of eco-physiologically based curves for plant functional groups.

Other eco-hydrological models with coupled groundwater-vegetation modules adopt a semi-mechanistic approach, whereby groundwater and soil moisture availability are often linked to vegetation and plant functioning by indicator values. How environmental changes influence site factors such as moisture regime and nutrient availability is—as far as possible —modelled in a mechanistic way. The relationship between site factors and species composition, however, is determined in a correlative way (Witte *et al.*, 2008). An example is the Dutch national eco-hydrological prediction model Dose-Effect model for terrestrial NATure (DEMNAT) that is based on geographical schematization of ecosystems, dose-effect functions and a conservation valuation module (e.g. Witte *et al.*, 1992; Van Ek *et al.*, 2000). Another example is the SWIM model (Krysanova *et al.*, 1989) that integrates hydrological processes, vegetation, nutrients (nitrogen and phosphorus) and sediment transport at the river-basin scale. Various other semi-mechanistic models are (partly) based on the Ellenberg indicator values: INFORM (Hens *et al.*, 2011) and VSD + −SUMO−NTM (e.g. Berendse, 1994; Wamelink, 2007; Bonten *et al.*, 2010). The Ellenberg indicator values system (Ellenberg *et al.*, 1991) is based on information of the groundwater-related parameters moisture availability and nitrogen, salinity and alkalinity of soil moisture of site types in central Europe, acquired during numerous field studies of plants and ecosystems.

FUTURE RESEARCH AND MODELLING CHALLENGES

In general, more efforts are required to fully integrate models for vegetation dynamics in hydromorphological models considering the two-way coupled interactions at various flow conditions and at various spatial scales (from a geomorphic unit, e.g. a bar, to an entire river and even an entire catchment). These models should not only take into account seasonal variations and geographical considerations, such as climate and geology, but also take into account the effects of soil properties and of groundwater distribution. More specifically, the following topics need to be further explored for modelling purposes.

The hydraulics of vegetated flow does not fully consider the impact of different vegetation properties (flexibility, density, foliage, spatial distribution) on turbulent flow structures and secondary currents. This has relevant implications in the evaluation of flow resistance and sediment transport which are now estimated using average flow quantities through empirical parameters that are difficult to quantify (such as the drag coefficient). Moreover, uprooting and the breakage of plants during high flow conditions may give rise to significant changes in the flow field and sediment transport between the rising and falling limbs of the hydrograph.

More research is needed to understand the impact of stochastic variability of river discharge and of groundwater flow (spatial-temporal dynamics of soil moisture and of water table) on vegetation processes and pattern evolution. Additional research on oxygen stress resulting from wet conditions is required (Bartholomeus *et al.*, 2008) to improve groundwater-vegetation modelling.

There is also a requirement for the development of quantitative ecological models for the following: (i) hydrochory, to obtain a more accurate pattern of vegetation dispersal; (ii) early colonization of vegetation, by relating it to the type of substrate, competition, herbivory and groundwater level; (iii) plant growth rates at the scale of individuals; (iv) vegetation succession; and (v) mortality of vegetation by including other causes of mortality like flooding, desiccation, burial and scour.

Additionally, there is a need to understand response of vegetation traits to physical disturbances. For instance, it would be of interest to compare the seedling survival and plant growth rate of different species of propagules following a disturbance. Indeed, riparian vegetation models often apply specifically to the Salicaceae (i.e. *Populus* spp., *Salix* spp.), living in the temperate zone of the northern hemisphere, where most models have been developed. Field research and model development needs to be extended to other regions and climatic contexts (Gurnell, 2014).

With regard to riparian pattern dynamics, until now, competition and facilitation processes are generally not included in advanced physics-based models. Therefore, the main challenge is to integrate the existing knowledge on competition and facilitation, including the effect of invasive species, from previous modelling advances and conceptual models at different spatial and temporal scales into future numerical models.

Concerning dead vegetation and large wood, numerical models of wood dynamics are at an initial stage (e.g. Villanueva *et al.*, 2014), and much remains to be carried out to fully integrate processes of wood delivery, transport and deposition with other hydrodynamic and morphodynamic processes.

Additional research is required on how the dynamic interaction between vegetation and morphodynamics influences vegetation patterns and river planform at the reach scale. Of particular relevance is the process of bank dynamics (accretion and erosion). More work is needed to better understand the hydrological effects of riparian vegetation and to incorporate them into models of bank erosion and bank accretion. Also, modelling interactions among the various processes of erosion and mass failures, and the relative role of vegetation on near-bank hydrodynamic flow conditions, erodibility parameters and shear strength is another area where knowledge is limited. Existing models of bank stability and vegetation are two-dimensional, and it is difficult to extend results from a bank profile to a reach and account for variability of hydrodynamic, geotechnical and vegetation conditions. This should be achieved by including vegetation and bank erosion processes into 3D morphodynamic models. The formulation of a physics-based model for quantifying bank accretion is also required, by including the effects of vegetation, discharge variability and fine sediment processes.

CONCLUSIONS

Modelling the interactions between vegetation and hydromorphology requires interdisciplinary research incorporating the fields of plant ecology, geomorphology and hydrology.

Many models have been already formulated to provide an interpretation of the interactions between vegetation and hydrodynamics, morphodynamics and groundwater. Recent models describing the coupled evolution between vegetation dynamics and river altimetric and planimetric evolution (e.g. Bertoldi *et al.*, 2014; Crosato and Saleh, 2011) can predict the response of a river to human pressures such as the implementation of restoration measures and maintenance operations, in an extremely schematic but quantitative way. However, despite the enormous advances of the last decade, the complexity of the involved processes mean that current modelling capabilities are very uneven. For example, quantitative, advanced mathematical models have been formulated in vegetation hydrodynamics (Nepf, 2012); while conceptual models are still employed for evaluating the interactions between hydromorphodynamic variables and plant life development. In addition to this, modelling of other processes, such as sediment transport in vegetated areas or bank accretion, are still in their infancy as they are not yet completely understood.

Actually, there is still much to be learnt about the interactions between plants and hydromorphology (Gurnell, 2014), and we suggest that, in particular, more research is needed to improve the current modelling capabilities on the following topics:

- interaction between vegetation and flow turbulent structures and implications in sediment transport;
- interaction between river bank accretion and vegetation dynamics, discharge variability and fine sediment processes;
- coupling between processes of wood delivery, transport, deposition and river morphodynamic evolution;
- inclusion of vegetation evolution in relation to its direct interaction with morphodynamic processes;
- inclusion of the effects of hydromorphology on riparian communities;
- coupling of competition and facilitation processes in integrated reach scale hydromorphodynamic models; and
- coupling of groundwater dynamics with eco-hydrological models.

REFERENCES

Aberle J, Järvelä J. 2013. Flow resistance of emergent rigid and flexible floodplain vegetation. *Journal of Hydraulic Research* **51**(1): 33–45.

Adler PB, Salguero-Gómez R, Compagnoni A, Hsu JS, Ray-Mukherjee J, Mbeau-Ache C, Franco M. 2014. Functional traits explain variation in plant life history strategies. *PNAS* **111**: 740–745.

Aggenbach CJS, Pelsma TAHM. 2005. Hydro-ecological assessment of vegetation of Dutch river habitats. *Large Rivers, 15, Archiv für Hydrobiologie Suppl* **155**(1-4): 199–210.

Allstadt A, Caraco T, Molnár F, Korniss G. 2012. Interference competition and invasion: spatial structure, novel weapons and resistance zones. *Journal of Theoretical Biology* **306**: 46–60.

Asahi K, Shimizu Y, Nelson J, Parker G. 2013. Numerical simulation of river meandering with self-evolving banks. *Journal of Geophysical Research: Earth Surface* **118**: 2208–2229.

ASCE Task Committee on Hydraulics, Bank Mechanics, and Modelling of River Width Adjustment. 1998. River width adjustment. I: processes and mechanisms. *Journal of Hydraulic Engineering* **124**(9): 881–902.

Baptist MJ, Babovic V, Rodríguez Uthurburu J, Keijzer M, Uittenbogaard RE, Mynett A, Verwey A. 2007. On inducing equations for vegetation resistance. *Journal of Hydraulic Research* **45**(4): 435–450.

Baird KJ, Stromberg JC, Maddock T. 2005. Linking riparian dynamics and groundwater: an ecohydrologic approach to modeling groundwater and riparian vegetation. *Environmental Management* **36**(4): 551–564.

Bartholomeus RP, Witte JPM, van Bodegom PM, van Dam JC, Aerts R. 2008. Critical soil conditions for oxygen stress to plant roots: substituting the Feddes-function by a process-based model. *Journal of Hydrology* **360**: 147–165

Berendse F. 1994. Competition between plant populations at low and high nutrient supplies. *Oikos* **71**: 253–260

Bertness MD, Callaway R. 1994. Positive interactions in communities. *Trends in Ecology and Evolution* **9**: 191–193.

Bertoldi W, Siviglia A, Tettamanti S, Toffolon M, Vetsch D, Francalanci S. 2014. Modeling vegetation controls on fluvial morphological trajectories. *Geophysical Research Letters* **41**: 7167–7175. DOI: 10.1002/2014GL061666.

Bonten L, Posch M, Reinds GJ, 2010. *The VSD + Soil Acidification Model - Model Description and User Manual*. Alterra and CCE, Wageningen and Bilthoven.

Borgogno F, D'Odorico P, Laio F, Ridolfi L. 2009. Mathematical models of vegetation pattern formation in ecohydrology. *Reviews of Geophysics* **47**: RG1005. DOI: 10.1029/2007RG000256.

Bornette G, Tabacchi E, Hupp C, Puijalon S, Rostan JC. 2008. A model of plant strategies in fluvial hydrosystems. *Freshwater Biology* **53**(8): 1692–1705.

Brolsma RJ, Bierkens MFP. 2007. Groundwater-soil water-vegetation dynamics in a temperate forest ecosystem along a slope. *Water Resources Research* **43**: W01414. DOI: 10.1029/2005WR004696.

Braudrick CA, Grant GE. 2000. When do logs move in rivers? *Water Resources Research* **36**: 571–583.

Brooker RW, Callaghan TV. 1998. The balance between positive and negative plant interactions and its relationship to environmental gradients : a model. *Oikos* **81**: 196–207.

Brooker RW, Maestre FT, Callaway RM, Lortie CL, Cavieres LA, Kunstler G, Liancourt P, Tielbörger K, Travis JMJ, Anthelme F, Armas C, Coll L, Corcket E, Delzon S, Forey E, Kikvidze Z, Olofsson J, Pugnaire F, Quiroz CL, Saccone P, Schiffers K, Seifan M, Touzard B, Michalet R. 2007. Facilitation in plant communities: the past, the present, and the future. *Journal of Ecology* **96**: 18–34.

Camporeale C, Ridolfi L. 2006. Riparian vegetation distribution induced by river flow variability: a stochastic approach. *Water Resources Research* **42**(10): W10415.

Camporeale C, Perucca E, Ridolfi L, Gurnell AM. 2013. Modelling the interactions between river morphodynamics and riparian vegetation. *Reviews of Geophysics* **51**. DOI: 10.1002/rog.20014.

Corenblit D, Tabacchi E, Steiger J, Gurnell AM. 2007. Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: a review of complementary approaches. *Earth Science Reviews* **84**: 56–86.

Coulthard TJ, Hicks DM, Van de Wiel MJ. 2007. Cellular modelling of river catchments and reaches : advantages, limitations and prospects. *Geomorphology* **90**: 192–207.

Coulthard TJ, Van de Wiel MJ. 2006. A cellular model of river meandering. *Earth Surface Processes and Landforms* **31**: 123–132.

Crosato A, Saleh MS. 2011. Numerical study on the effects of floodplain vegetation on river planform style. *Earth Surface Processes and Landforms* **36**: 711–720.

Dijkstra JT, Uittenbogaard RE. 2010. Modeling the interaction between flow and highly flexible aquatic vegetation. *Water Resources Research* **46**: W12547. DOI: 10.1029/2010WR009246.

Droz M, Pękalski A. 2013. Model of annual plants dynamics with facilitation and competition. *Journal of Theoretical Biology* **335**: 1–12.

Ellenberg H, Weber HE, Dull R, Wirth V, Werner W, Paulissen D. 1991. *Zeigerwerte von Pflanzen in Mitteleuropa (Scripta Geobotanica; 18). 3. verbess. und erw. Aufl. 248 S., 38 Abb*. Verlag Erich Goltze KG: Göttingen. ISBN 3-88452-518-2.

Eke E, Parker G, Shimizu Y. 2014. Numerical modeling of erosional and depositional bank processes in migrating river bends with self-formed width: morphodynamics of bar push and bank pull. *Journal of Geophysical Research: Earth Surface* **119**(7): 1455–1483.

Eppinga MB, Kaproth MA, Collins AR, Molofsky J. 2011. Litter feedbacks, evolutionary change and exotic plant invasion. *Journal of Ecology* **99**: 503–514.

Feddes RA, Kowalik PJ, Zaradny H. 1978. Simulation of field water use and crop yield. *Simulation Monographs*. Centre for Agricultural Publishing and Documentation: Wageningen, Netherlands; 189.

García-Arias A, Francés F, Ferreira T, Egger G, Martínez-Capel F, Garófano-Gómez V, Andrés-Doménech I, Politti E, Rivaes R, Rodríguez-González PM. 2013. Implementing a dynamic riparian vegetation model in three European river systems. *Ecohydrology* **6**(4): 635–651.

Goslee S, Peters DP, Beck K. 2001. Modelling invasive weeds in grasslands: the role of allelopathy in Acroptilon repens invasion. *Ecological Modelling* **139**: 31–45.

Greenway DR. 1987. Vegetation and slope stability. In: Anderson MG, Richards KS (eds). *Slope Stability*. Wiley and Sons: New York; 187–230.

Gregory SV, Meleason MA, Sobota DJ. 2003. Modelling the dynamics of wood in streams and rivers. In: Gregory SV, Boyer KL, Gurnell AM (eds). *The Ecology and Management of Wood in World Rivers, American Fisheries Society, Symposium 37*, American Fisheries Society Symposium: Bethesda, Maryland; **37**: 315–335.

Grime JP. 2002. *Plant Strategies, Vegetation Processes, and Ecosystem Properties*, 2nd ed. John Wiley & Sons: Chichester.

Groves JH, Williams DG, Caley P, Norris RH, Caitcheon G. 2009. Modelling of floating seed dispersal in a fluvial environment. *River Research and Applications* **25**(5): 582–592.

Gurnell AM, Piégay H, Swanson FJ, Gregory SV. 2002. Large wood and fluvial processes. *Freshwater Biology* **47**(4): 601–619.

Gurnell AM, Bertoldi W, Corenblit D. 2012. Changing river channels: the roles of hydrological processes, plants and pioneer landforms in humid temperate, mixed load, gravel bed rivers. *Earth Science Reviews* **111**: 129–141.

Gurnell AM. 2014. Plants as river ecosystem engineers. *Earth Surface Processes and Landforms* **39**(1): 4–25.

Gurnell AM, Gonzàlez Del Tánago M, O'Hare MT, van Oorschot M, Belleti B, García De Jalón D, Grabowski R, Hendricks D, Mountford O, Rinaldi M, Solari L, Szewczyk M, Vargas-Luna A. 2014. Influence of Natural Hydromorphological Dynamics on Biota and Ecosystem Function. *Deliverable 2.2, Part 1, of REFORM* (REstoring rivers FOR effective catchment Management), a Collaborative project (large-scale integrating project) funded by the European Commission within the 7th Framework Programme under Grant Agreement 282656.

Haga H, Kumagai T, Otsuki K, Ogawa S. 2002. Transport and retention of coarse woody debris in mountain streams: an *in situ* experiment of log transport and a field survey of coarse woody debris distribution. *Water Resources Research* **38**: WR001123.

Harper EB, Stella JC, Fremier AK. 2011. Global sensitivity analysis for complex ecological models: a case study of riparian cottonwood population dynamics. *Ecological Applications* **21**(4): 1225–1240.

Hassan MA, Hogan DL, Bird SA, May C., Gomi T, Campbell D. 2005. Spatial and temporal dynamics of wood in headwater streams of the Pacific Northwest. *Journal of American Water Resources Association* **41**(4): 899–919.

Hens T., Hutterman C., Rosenzweig S. 2011. Integriertes Flussauenmodell INFORM – ein Modellsystem zur ökologischen Modellierung an Bundeswasserstraßen. In: Strobl J, Blaschke T, Griesebner G. *(Hrsg.) (2011): Angewandte Geoinformatik 2011*. Wichmann Verlag: Berlin.

Hoffman JD, Narumalani S, Mishra DR, Merani P, Wilson RG. 2008. Predicting potential occurrence and spread of invasive plant species along the North Platte River, Nebraska. *Invasive Plant Science and Management* **1**: 359–367.

Homaee M, Feddes FA, Dirksen C. 2002. Simulation of root water uptake II. Non-uniform transient water stress using different reduction functions. *Agricultural Water Management* **57**: 111–126.

Hooke JM, Brookes CJ, Duane W, Mant JM. 2005. A simulation model of morphological, vegetation and sediment changes in ephemeral streams. *Earth Surface Processes and Landforms* **30**: 845–866.

Järvelä J. 2004. Determination of flow resistance caused by non-submerged woody vegetation. *Journal River Basin Management* **2**(1): 61–70.

Klijn F. 1989. Landschapsecologische kartering Nederland: grondwaterrelaties. Toe-lichting bij het databestand "grondwaterrelaties" van het LKN-project. Stiboka-rapport nr. 2107

Kroes JG, Van Dam JC, Groenendijk P., Hendriks RFA, Jacobs CJ. 2008. SWAP version 3.2, theory description and user manual. *Alterra Report 1649*. Wageningen University and Research Centre: Wageningen.

Krysanova V, Meiner A, Roosaare J, Vasilyev A. 1989. Simulation modelling of the coastal waters pollution from agricultural watershed. *Ecological Modelling* **49**: 7–29.

Kothyari UC, Hashimoto H, Hayashi K. 2009. Effect of tall vegetation on sediment transport by channel flows. *Journal of Hydraulic Research* **47**(16): 700–710. DOI: 10.3826/jhr.2009.3317

López F, García M. 1998. Open-channel flow through simulated vegetation: suspended sediment transport modeling. *Water Resources Research* **34**(9): 2341–2352. DOI: 10.1029/98WR01922.

Le Bagousse-Pinguet Y, Maalouf JP, Touzard B, Michalet R. 2014. Importance, but not intensity of plant interactions relates to species diversity under the interplay of stress and disturbance. *Oikos* **123**(7): 777–785.

Lenders HJR, Leuven RSEW, Nienhuis PH, De Nooij RJW, Van Rooij SAM. 2001. BIO-SAFE: a method for evauation of biodiversity values in the basis of political and legal criteria. *Landscape and Urban Planning* **55**(2): 121–137.

Lytle D, Merritt D. 2004. Hydrologic regimes and riparian forests: a structured population model for cottonwood. *Ecology* **85**: 2493–2503.

Luhar M, Nepf H. 2013. From the blade scale to the reach scale: a characterization of aquatic vegetative drag. *Advances in Water Resources* **51**: 305–316.

Mahoney JM, Rood SB. 1998. Streamflow requirements for cottonwood seedling recruitment—an integrative model. *Wetlands* **18**: 634–645.

McDonald MG, Harbaugh AW. 2003. The History of MODFLOW. *Ground Water* **41**(2): 280–283. DOI: 10.1111/j.1745-6584.2003. tb02591.x

Merritt DM, Wohl EE. 2002. Processes governing hydrochory along rivers: hydraulics, hydrology, and dispersal phenology. *Ecological Applications* **12**: 1071–1087.

Murray AB, Paola C. 2003. Modelling the effect of vegetation on channel pattern in bedload rivers. *Earth Surface Processes and Landforms* **28**: 131–143.

Nepf H. 2012. Hydrodynamics of vegetated channels. *Journal of Hydraulic Research* **50**(3): 262–279.

Nicholas AP. 2013. Modelling the continuum of river channel patterns. *Earth Surface Processes and Landforms* **38**(10): 1187–1196.

Ortiz AC, Ashton A, Nepf H. 2013. Mean and turbulent velocity fields near rigid and flexible plants and the implications for deposition. *Journal of Geophysical Research - Earth Surface* **118**: 2585–2599. DOI: 10.1002/ 2013JF002858.

Perucca E, Camporeale C, Ridolfi L. 2007. Significance of the riparian vegetation dynamics on meandering river morphodynamics. *Water Resources Research* **43**: W03430.

Pollen N, Simon A. 2005. Estimating the mechanical effects of riparian vegetation on streambank stability using a fiber bundle model. *Water Resources Research* **41**: W07025.

Pollen-Bankhead N, Simon A. 2010. Hydrologic and hydraulic effects of riparian root networks on streambank stability: is mechanical root-reinforcement the whole story? *Geomorphology* **116**(3-4): 353–362.

Richardson E, Irvine E, Froend R, Book P, Barber S, Bonneville B. 2011. *Australian Groundwater Dependent Ecosystems Toolbox Part 1: Assessment Framework*. National Water Commission. Canberra.

Rietkerk M, van de Koppel J. 2008. Regular pattern formation in real ecosystems. *Trends in Ecology and Evolution* **23**: 169–175.

Santoro R, Jucker T, Carboni M, Acosta ATR. 2012. Patterns of plant community assembly in invaded and non-invaded communities along a natural environmental gradient. *Journal of Vegetation Science* **23**: 483–494.

Simon A, Collison A. 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. *Earth Surface Processes and Landforms* **27**: 527–546.

Schuurman F, Marra WA, Kleinhans MG. 2013. Physics-based modelling of large braided sand-bed rivers: bar pattern formation, dynamics, and sensitivity. *Journal of Geophysical Research: Earth Surface* **118**: 1–19.

Steiger J, Gurnell AM. 2003. Spatial hydrogeomorphological influences on sediment and nutrient deposition in riparian zones: observations from the Garonne River, France. *Geomorphology* **49**: 1–23.

Tabacchi E, Correll DL, Hauer R, Pinay G, Planty-Tabacchi A-M, Wissmar RC. 1998. Development, maintenance and role of riparian vegetation in the river landscape. *Freshwater Biology* **40**: 497–516.

Tal M, Paola C. 2010. Effects of vegetation on channel morphodynamics: results and insights from laboratory experiments. *Earth Surface Processes and Landforms* **35**: 1014–1028. DOI: 10.1002/esp.1908.

Tealdi S, Camporeale C, Perucca E, Ridolfi L. 2010. Longitudinal dispersion in vegetated rivers with stochastic flows. *Advances in Water Resources* **33**(5): 562–571.

Tealdi S, Camporeale C, Ridolfi L. 2013. Inter-species competition–facilitation in stochastic riparian vegetation dynamic. *Journal of Theoretical Biology* **318**: 13–21.

Tickner DP, Angold PG, Gurnell AM, Mountford JO. 2001. Riparian plant invasions: hydrogeomorphological control and ecological impacts. *Progress in Physical Geography* **25**: 22–52.

Thorne CR. 1990. Effects of vegetation on riverbank erosion and stability. In: Thornes JB (Ed). *Vegetation and Erosion*, Wiley: Chichester; 125–144.

Travis JMJ, Brooker RW, Dytham C. 2005. The interplay of positive and negative species interactions across an environmental gradient: insights from an individual-based simulation model. *Biology Letters* **1**: 5–8.

USDA (U.S. Dept. of Agriculture). 1947. Handbook of channel design for soil and water conservation. USDA, Washington DC, Soil Conservation Service Report TP-61.

Van Dam JC, Huygen J, Wesseling JG, Feddes RA, Kabat P, van Walsum PEV, Groenendijk P, van Diepen CA. 1997. Theory of SWAP version 2.0. Simulation of water flow, solute transport and plant growth in the Soil–Water–Air–Plant environment. Report 71, Department of Water Resources, Wageningen Agricultural University, Tech. Docu. 45, DLO Winand Staring Centre, Wageningen, the Netherlands.

Van Dam JC, Feddes RA. 2000. Numerical simulation of infiltration, evaporation and shallow groundwater levels with the Richards equation. *Journal of Hydrology* **233**(1–4): 72–85

Van de Koppel J, Crain CM. 2006. Scale-dependent inhibition drives regular tussock spacing in a freshwater marsh. *The American Naturalist* **168**: E136–E147.

Van Ek R., Witte JPM, Runhaar J, Klijn F, 2000. Ecological effects of water management in the Netherlands: the model DEMNAT. *Ecological Engineering* **16**: 127–141.

Van Oene H, Berendse F. 2001. Predicting responses of ecosystem processes to climate change and nitrogen deposition; in: long-term effects of climate change on biodiversity and ecosystem processes, Dutch national research programme on global air pollution and climate change. Report no.: 410200089.

Van Wirdum G. 1980. Eenvoudige beschrijving van de water-kwaliteitsverandering gedurende de hydrologische kringloop ten behoeve van de natuurbescherming. *CHO/TNO rapporten en nota's* **5**: 118–143.

Vargas-Luna A, Crosato A, Uijttewaal WSJ. 2015. Effects of vegetation on flow and sediment transport: comparative analyses and validation of

predicting models. *Earth Surface Processes and Landforms* **40**(2): 157–176. DOI: 10.1002/esp.3633.

Villanueva VR, Castellet EB, Diez-Herrero A, Bodoque JM, Sanchez-Juny M. 2014. Two-dimensional modelling of large wood transport during flash floods. *Earth Surface Processes and Landforms* **39**(4): 438–449.

Wamelink GWW. 2007. Simulation of vegetation dynamics as affected by nitrogen deposition. Pons & Loyen, Wageningen. PhD thesis.

White PS. 1979. Pattern, process, and natural disturbance in vegetation. *The Botanical Review* **45**: 230–299.

Witte JPM. 1998. *National water management and the value of nature*. PhD Thesis, National Water Wageningen Agricultural University. The Netherlands.

Witte JEM, Klijn E, Claessen EAM, Groen CLG, van der Meijden R. 1992. A model to predict and assess the impacts of hydrologic changes on terrestrial ecosystems in The Netherlands, and its use in a climate scenario. *Wetlands Ecology and Management* **2**(1/2): 69–83.

Witte JPM, de Haan M, Hootsmans MJM. 2007. PROBE: een ruimtelijk model voor vegetatiedoelen. *Landschap* **24**: 77–87

Witte JPM, Runhaar J, van Ek R. 2008. Ecohydrological modelling for managing scarce water resources in a groundwater dominated temperate system. In: Harper DM, Zalewski M, Pacini N. *Ecohydrology: Processes, Models and Cases Studies*. CABI: Cambridge, MA, USA.

Wu TH, McKinnell WP, Swanston DN. 1979. Strength of tree roots and landslides on Prince of Wales Island, Alaska. *Canadian Geotechnical Journal* **16**(1): 19–33.

Xiao S, Callaway RM, Newcombe G, Aschehoug ET. 2012. Models of experimental competitive intensities predict home and away differences in invasive impact and the effects of an endophytic mutualist. *The American Naturalist* **180**: 707–718.

Yager EM, Schmeeckle MW. 2013. The influence of vegetation on turbulence and bed load transport. *Journal of Geophysical Research - Earth Surface* **118**: 1585–1601. DOI: 10.1002/jgrf.20085.

Ye F, Chen Q, Blanckaert K, Ma J. 2013. Riparian vegetation dynamics: insight provided by a process-based model, a statistical model and field data. *Ecohydrology* **6**: 567–585.

Zheng C. 1990. MT3D: a modular three-dimensional transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems, report to the Kerr Environmental Research Laboratory, US Environmental Protection Agency, Ada, OK.

Zong L, Nepf H. 2011. Spatial distribution of deposition within a patch of vegetation. *Water Resources Research* **47**: W03516.