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Impacts of riparian vegetation on hydrological processes

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Abstract:

The main impacts of riparian vegetation on hydrological processes are briefly reviewed in order to highlight needs and perspectives for research and management goals. This review is based upon three distinct influences of riparian vegetation on hydrological processes: (i) the control of runoff, i.e. the physical impact of living and dead plants on hydraulics, (ii) the impact of plant physiology on water uptake, storage and return to the atmosphere, and (iii) the impact of riparian vegetation functioning on water quality. Riparian vegetation influences runoff through complex hydraulic interactions during baseflows as well as overbank flows. The contribution of fine vegetational structures to landscape hydrological roughness needs to be considered in relation to the spatial complexity (patchiness, vertical stratification, rhizosphere) and temporal variability (phenology, succession) of plant communities. With the exception of some woody species, the uptake, storage and return of water to the atmosphere is poorly known for riparian communities, and therefore the assessment of the regional hydrological importance of the riparian corridor remains difficult to estimate. Although better understood than the above two influences of riparian vegetation on hydrological processes, there are still a number of unresolved issues concerning the role of riparian vegetation in controlling water quality. In particular, little is known about the coupling of microbial and vegetational functions in nutrient cycling and the dynamics of carbon release from coarse and fine plant debris. The influence of vegetation complexity and plant diversity on both qualitative and quantitative aspects of water cycling remains an important area for future research. Fundamental and management issues are identified in relation to the use of riparian vegetation as a model and as a tool. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS   riparian vegetation; runoff control; water consumption; evapotranspiration; water quality; river management

INTRODUCTION

Ecological properties of the vegetation colonizing riparian zones have been summarized from several perspectives (Gregory *et al.*, 1991; Malanson, 1993; Gurnell 1995; Décamps, 1997; Naiman and Décamps, 1997; Tabacchi *et al.*, 1998). Riparian plant communities were given an important role in the river continuum concept (Vannote *et al.*, 1980; Minshall *et al.* 1985). More recently, emphasis has been given to their role in intercepting cascades of water flowing from drainage basins and floodplains to main channels (Malanson, 1993). Riparian plant communities are biological processors of terrestrial–aquatic interfaces and their responses to hydrological disturbance, hydric stress and nutrient or sediment inputs from the floodplain are widely recognized (Lowrance *et al.*, 1986; Peterjohn and Correll, 1986; Cooper *et al.*, 1987; Pinay *et al.*, 1994; Gurnell, 1995; Haycock *et al.*, 1997). Despite this accumulated information, the influence of riparian plant communities on hydrological processes remains poorly understood.

This paper examines the influence of riparian vegetation on processes contributing to the water cycle in order to address theoretical and methodological difficulties in scaling up from local to regional

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environments. The paper considers: the effect of physical properties of living and dead plants on patterns of water transfer; the impact of the physiological activity of plants on the uptake, storage and return to the atmosphere of available water in riparian systems; and the role of riparian plants in controlling water quality.

RUNOFF CONTROL: THE PHYSICAL IMPACT OF LIVING AND DEAD PLANTS

Riparian vegetation and hydraulics

Assessment of the water balance in forested and/or cultivated areas has indicated the hydrological influence of vegetation at the floodplain and at the basin scale. However, riparian vegetation is likely to control many processes related to surface and subsurface flow at the local scale (Pasche and Rouvé, 1985; Bren, 1993; Piégay; 1997, Darby, 1999). Such local control reflects complex physical structures (living and dead plant structures) and hydraulic processes (flow routing and turbulence). Figure 1 identifies runoff pathways that may be affected by the physical structures of riparian vegetation. The living vegetation forms point structures with properties that change according to the season, whereas dead plant debris forms mobile, resistant (coarse woody debris) or labile (litter) structures. All of these can obstruct, divert or facilitate water flow and so they are likely to control larger scale properties of riparian zones, such as hydraulic connectivity. This means that flexibility and fragility of local vegetation should be taken into account in larger scale simulations (Kouwen and Li, 1980), although this has rarely been the case (Gourlay, 1970; Rajaratnam and Ahmadi, 1981; Ervine and Ellis, 1987; Baird and Anderson, 1992; Fathi-Maghadam and Kouwen, 1997; Thorne et al., 1998a,b). The roughness of vegetation depends on its height and stiffness coefficient, a composite parameter that includes the density, elasticity, shape and bendiness of the vegetation (Kouwen, 1988; Fathi-Maghadam and Kouwen, 1997). Thorne et al. (1997, 1998a,b) emphasize the importance of including the shape and biophysical characteristics of plant species, and also seasonal and sucessional plant dynamics in hydraulic studies of overbank flows.

The main channel: 'regular' and low flows

The role of pioneer vegetation. Vegetation interacts with hydrological processes from the earliest stages of plant succession and can have significant impacts on hydraulic processes, particularly during periods of low flow, as well as at the beginning or at the end of flood periods. The high patchiness of pioneer vegetation increases the heterogeneity of water flow patterns over sediment and vegetation mosaics, leading to the development of preferential flow pathways (Thorne et al., 1997). Furthermore, dense herbaceous vegetation locally limits infiltration of surface water into the hyporheic zone, and contributes to the trapping of fine sediments during moderately high flows. By increasing siltation over coarse sediments, pioneer vegetation also contributes to the modification of the moisture-related properties of the substrate.

Early studies indicated that plant–flow interactions change with water velocity (Ree, 1941; Eastgate, 1966), and that even continuous herbaceous vegetation can lead to patchy patterns in siltation during high water velocities (Cook and Cambell, 1939). Increasing velocity first leads to a rippled pattern in the vegetation with some turbulence, and then to flattening of plants with a reduction in turbulence. Kouwen and Li (1980) give roughness coefficients for various species of grasses. Grassy riparian areas have been observed to trap more than 50% of sediments delivered from hillslopes when overland flow depths are less than 5 cm (Magette *et al.*, 1989). This phenomenon is amplified by boundary effects within patchy vegetation of differing height and flexibility (Bromley *et al.*, 1997). Powledge *et al.* (1989) compared the maximum flow velocity on embankments. They considered two types of soil (erosion-resistant and easily eroded) and different species of grasses. With perennial grasses such as Bermuda grass, buffalo grass or Kentucky blue grass, permissible velocities ranged from 4 to 8 m s^{-1} for erosion-resistant soils and between 3 and 6 m s^{-1} for easily eroded soils. Corresponding values for annual grasses, such as Sudan grass (*Lespedeza* sp.), were 3·5 and 2·5 m s^{-1}.

The colonization of newly deposited sediments by dense herbaceous vegetation also helps to sustain high moisture levels in the upper sediment layers during dry periods as a result of the sheltering of the sediment
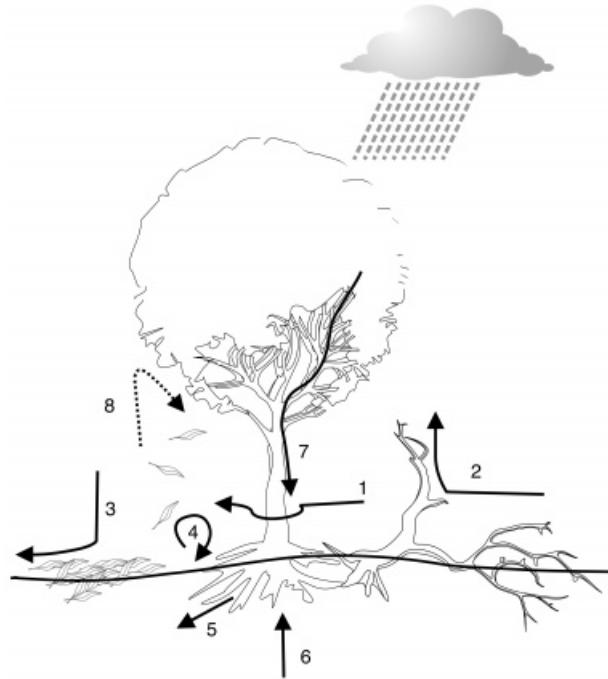
Figure 1. The main physical impacts of riparian vegetation on water cycling: 1, interaction with over-bank flow by stems, branches and leaves (turbulence); 2, flow diversion by log jams; 3, change in the infiltration rate of flood waters and rainfall by litter; 4, increase of turbulence as a consequence of root exposure; 5, increase of substrate macroporosity by roots; 6, increase of the capillary fringe by fine roots; 7, stemflow (the concentration of rainfall by leaves, branches and stems); 8, condensation of atmospheric water and interception of dew by leaves

surface by the vegetation cover and the capillarity provided by the rhizosphere. Specifically, graminoids are known to be able to develop dense rhizospheres in sediments up to 2 m deep (cf. Kutschera and Lichtenegger, 1982). Independently from any physiological lift effect, this capillarity is increased when mycorrhizal fungi colonize the roots of pioneer trees. Read (1992) calculated a mean ratio of 200 000:1 between the length of ectomycorrhizal hyphae and the length of fine roots for terrestrial forested systems, suggesting a high water absorption capability around the roots of the host by this addition to the complexity of the initial root structure. Less visible, but similar hyphal structures are known in association with endomycorrhizal fungi (Allen, 1992). Riparian areas may exhibit similar properties but almost nothing is known currently about the spatial extent of mycorrhizal fungi in riparian areas (Nakastubo *et al.*, 1994; Bialet, 1997) and some uncertainty remains about the capability of riparian ectomycorrhizae to survive under permanently flooded conditions (Nakastubo *et al.*, 1994).

The hydraulics of the entire channel can be modified drastically during both low and high flows as a result of the invasion of sand and gravel bars by pioneer trees. Such invasions can occur in response to changes in climatic conditions or following anthropogenic transformation of river regimes (river regulation by dams, pumping, diversion of the main channel, changes in the floodplain yield). The study of the Platte River, Nebraska (Johnson, 1994) illustrates the complexity of feed-back effects between hydrology, geomorphology and colonization by plants. Alterations in the river flow regime led to an invasion of the former channel by willows and poplars. Colonization by trees increased sediment retention and the flow velocity in the resulting narrowing channel. Depending on the timing of climatic and hydraulic events, further colonization within the main channel by pioneer trees could have different impacts within different stretches of the same river. Invasion processes may also result from the introduction of alien fast-colonizing plant species (Planty-

Tabacchi, 1993; Brock 1994; De Waal *et al.*, 1994; Pisek and Prach, 1994; Planty-Tabacchi *et al.*, 1996). One of the most widely cited examples of the impact of such an invasion concerns Salt Cedar in south-western USA (see Brock, 1994).

Litter mats in small streams. Small mountain streams are characterized by the abundance of litter mats that are derived from the riparian canopy. Successions of riffles and pools facilitate the accumulation of litter mats, which can then impact on flow pathways within the stream channel. Litter mats may also heavily constrain exchanges between the water within the river channel and the hyporheic zone in the river bed. Little is known of the relative importance of the hydraulic impact of litter accumulation within riparian systems. However, Chauvet (1989) and Chauvet and Jean-Louis (1988) estimated a litter production of about 5 t ha^{-1} year^{-1} in white willow forests of the middle Garonne (south-west France), whereas the biomass of the herbaceous layer (*Urtica*, *Impatiens* and *Echinocloa* stands) along the same river has been estimated to be 15 to 30 t ha^{-1} year^{-1} (Tabacchi *et al.*, unpublished data). Such large quantities of litter fall in alluvial forests can be expected to have temporary effects on water infiltration before the litter is flushed downstream during floods.

Coarse woody debris accumulations in the main channel. The qualitative impact of coarse woody debris (CWD) on stream hydraulics is well known (Harmon *et al.*, 1986; Maser and Sedell, 1994; Gurnell *et al.*, 1995). The CWD may cause water flow diversions, congestions in the main channel, reduced connectivity between the main channel and secondary waterbodies, and enhanced local erosion. In small, steep mountain streams, CWD structures can be unstable with the potential to be suddenly flushed downstream. In larger streams, accumulations occur at bridges or dams. In many parts of the world, accumulations of CWD are often removed by river managers, although it has been suggested (Bilby, 1984) that such practices could affect stream channel stability. Riparian vegetation may also act as a filter, intercepting significant amounts of litter and CWD as they drift downstream during high flows (Ehrman and Lamberti, 1992). Hickin (1984) showed that this filter effect can significantly modify the distribution of overbank flows and also may help to accelerate the stabilization of mid-channel bars by trapping sediments. The CWD and litter mats can have significant effects on water flows during low flows, especially in small streams. In addition, Ehrman and Lamberti (1992) illustrated the importance of the hydraulic impact of CWD on in-channel flows of medium-sized rivers. Comparing several (14) river systems of the world cited in the literature, Shields (1995) concluded that Manning's roughness coefficient could decrease by between 7% and 100% (average 55%) as a result of woody debris removal. Furthermore, removal along two rivers in New South Wales, Australia, resulted in a reduction of 20–30% in the Darcy–Weisbach friction factor for near-bankfull conditions and an increase of 5–20% in the bankfull discharge.

The riparian zone and secondary channels

The riparian corridor as a dissipative structure. Riparian vegetation, through its high hydraulic roughness and flow resistance, contributes to the dissipation of the kinetic energy of floods. According to Bren (1993), this is as a 'unique (and little explored) characteristic of riparian environments'. The role of the vegetation in determining overall roughness is of great importance. Dissipative effects of riparian vegetation during floods varies with the discharge and also appears to vary according to the width of the riparian corridor in comparison with the channel width. The patchiness of forested in comparison with non-forested areas also can be significant. It has been suggested from a long-term analysis that kinetic energy is more strongly dissipated by the riparian corridor during high-intensity–low-frequency floods than during more frequent flood events (Tabacchi, 1992). Naot *et al.* (1996) considered that for a given flood condition, vegetation has a relatively low effect on turbulence in partially vegetated channels. From a reference vegetation density of 1 (non-dimensional vegetation density), this effect was not significant up to density values of 8. With a density of 16, they observed a homogenization and attenuation of streamwise velocity and turbulent energy, whereas

with a high vegetation density (> 32), the vegetation becomes virtually impenetrable. Darby (1999) included vegetation parameters in overbank flood simulations for three different rivers with different riparian grass and/or tree covers and heights. For the River Severn, UK (5 cm high grass over the entire floodplain), he found that an increase in flexible vegetation height of 0·1 to 2·0 m (corresponding to an increase in stiffness from 0·16 to 3142 N m^{-2}) resulted in an increase of about 0·5 m in water surface elevation, representing a significant increase in flood risk. The same impact was not found for the River Idle, UK, which had the same vegetation but only on 30% of the inundated area, because the riparian zone was of limited extent in comparison to the extent of bed sediment. In the case of the Era River, Italy, where two-thirds of the floodplain was covered by trees and the remainder by grasses and reeds, the increase in elevation of the 5-year flood discharge with an increase in grass height was similar to that of the Severn (about 0·5m). However, whereas the elevation of the discharge increased with the vegetative cover for the Severn, it decreased for the Era. The elevation of the 5-year discharge decreased ($-0·75$ to $-1·25$ m at 80% according to the initial height of the vegetation) because of the presence of non flexible vegetation (trees). Of course, the reduction of discharge capacity due to vegetation is a function of the absolute size of the channel, but it is also a function of the width:depth ratio for a given absolute size. Using a stiffness of 153 N m^{-2} and a height of 0·8 m, Masterman and Thorne (1992) found that the height of grasses was reduced to 0·3 m by deflection by flowing water and that the presence of grasses induced a significant ($> 5\%$) reduction of the discharge capacity of the channel for width:depth ratios of less than 9. They then considered a seasonal change in stiffness, with 1·6 N m^{-2} in winter (typical of grasses) and 1504 N m^{-2} for fully grown conditions (typical of dense riparian stands). They estimated a reduction in discharge capacity of 2% in the former and of 38% in the latter case for a width:depth ratio of 5. With fully grown stiffness, the maximum reduction in the bankfull discharge capacity was 8% for a width:depth ratio of 20, and only 6% for a width:depth ratio of 30.

Little is known about the local influence of riparian vegetation, that is the impact of properties such as bark structure, the size and shape of stems and branches, the role of the understorey, and the interaction with litter and CWD. However, some recent studies have adopted a species-based approach, which takes into account the biological characteristics of particular plants in the computation of hydraulic parameters. For example, Rahmeyer et al. (1999) estimated stiffness index values for trees and shrubs of 2·15 E8 N m^{-2} for dogwood; 1·19 E8 N m^{-2} for blue willow; 1·50 E9 N m^{-2} for black willow, 1·92 E9 N m^{-2} for Norway maple and 5·08 E8 N m^{-2} for staghorn sumac from large flume experiments. Changes in plant density induced significant changes in the values of the index. For example, for dogwood, the index was 3·2 E8 N m^{-2} for 5·4 plants m^{-2}, whereas it was 1·02 N m^{-2} for 0·5 plants m^{-2}. Deciduous and evergreen vegetation play completely different roles according to the timing of floods. Climate controls the general nature of the vegetation stands along a river, predominantly evergreen stands being expected under extremely warm (arid, semi-arid, Mediterranean) or cold (boreal) conditions. In temperate and some tropical areas, the presence of leaves on the trees and of an active understory can have a significant impact on water flows. Event timing is the critical parameter for the hydraulic response of riparian deciduous vegetation to flood events. Both the vertical and the horizontal structures of the riparian vegetation, which are largely controlled by internal vegetation dynamics, are important for flow control. Poorly stratified and homogeneous forests (e.g., poplar plantations) have a relatively low flow resistance, whereas a number of turbulent zones can be expected in association with heterogeneous stands related to strong plant succession in disturbed areas.

The fragmentation of the riparian corridor should also be considered at the river network scale, as each disruption in the dissipation of the flood wave along a stream channel influences the flood hydrograph downstream (Archer, 1989). Figure 2 illustrates the potential hydraulic influence of three hypothetical, transverse, profiles in the riparian vegetation. A regular plant succession away from the channel results in a smooth transverse vegetation pattern, which is likely to induce relatively low turbulence and transverse hydraulic resistance. A narrow strip of trees with sharp boundaries is expected to increase turbulence at the internal and external edges, thus enhancing the resistance to flow when the water level rises. A patchy, heterogeneous vegetation profile may distribute resistance to transverse flow into a series of steps, increasing the lateral spatial extent of turbulence.
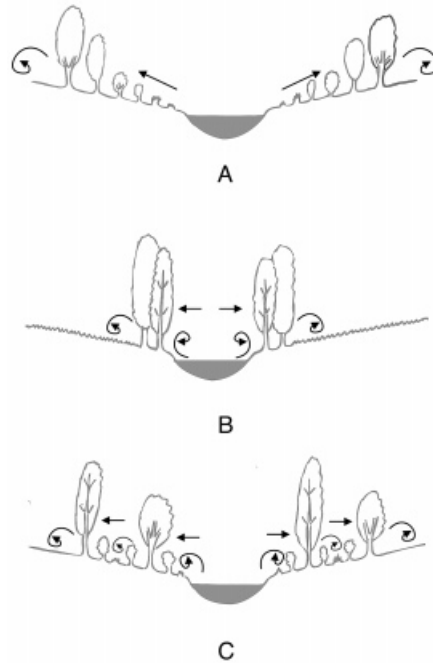
Figure 2. Hypothetical influences of riparian vegetation patterns on turbulence during overbank floods. Horizontal arrows indicate lateral resistance to flow, spiralling arrows indicate turbulences. (A) Regular transverse profile simulating progressive succession, minimal lateral resistance and minimal turbulence. (B) Sharp, dense and narrow corridor (tree line) with high lateral resistance and high turbulence at both internal and external edges. (C) Wide, heterogeneous corridor (more common profile in natural rivers), inducing a better dissipation of kinetic energy but favouring numerous small-scale turbulences

Riparian vegetation and hydraulic connectivity. Owing to its natural dynamics, riparian vegetation tends to control the connectivity between the main channel and dead arms or oxbow lakes within the riparian zone (Gurnell, 1997). In some cases, ancient channels colonized by wetland vegetation may serve as preferential channels for surface and/or groundwater, especially when there are fossil pathways for groundwater consisting of coarse alluvium, the porosity of which is further increased by the rhizosphere. The hydraulic role of the later stages of riparian vegetation depends upon the density and transverse profile of successive cohorts (Figure 2). Lateral continuity in the flow structure is sustained by a homogeneous transverse succession, which minimizes edge effects and turbulences. However, this form of transverse vegetation pattern is infrequent along dynamic streams, where patchy patterns dominate. Regular profiles are only expected along margins affected by relatively low hydrological disturbance. The storage of water within the banks is another process that is important for transverse hydraulic connectivity but little is known about its control by the vegetation (Elmore and Beschta, 1987).

Effects of the rhizosphere. The rhizosphere of riparian plants modifies hydraulic conductivity of the substrate affecting soil water and groundwater flows. Deep-rooted trees improve drainage or infiltration by increasing substrate porosity and capillarity (Thorne, 1990), whereas some shallow-rooted trees and most graminoids have a dense rhizosphere, which can cause clogging of the surficial layer of the substrate, limiting or diverting water flows. Moreover, exposed roots along river banks contribute to increased turbulence within the river channel (Gregory, 1992). Using data from the Nelidovskii forest reservation, Chebotarev (1966) illustrates that forests can significantly modify the subsurface runoff as a result of the presence of organic layers and the existence of large spaces created by the extending root systems of the trees. Chebotarev cites soil moisture flow velocities of 65–85 cm day^{-1} in the upper 40 cm soil layer, and 40–70 cm day^{-1} in the

layer 40–60 cm below the soil surface. Croke *et al.* (1999) showed that the saturated hydraulic conductivity of undisturbed forest soils in the Eden Area, Australia ranged from 200 to 700 mm h^{-1}, whereas one year after logging the values declined to 70 to 350 mm h^{-1}. Stothoff *et al.* (1999) showed how the presence of vegetation along rock fissures could eliminate net infiltration as a result of both clogging and transpiration, regardless of the size of the storm, in the Yucca Mountains, Nevada. This effect may occur within the riparian zone of mountain streams or rivers affected by semi-arid and arid climates.

Fluxes between the floodplain and the river. The flood pulse concept (Junk *et al.*, 1989) emphasizes the many relationships between a river and its floodplain. These relationships include the role of riparian zones as buffers. Sediment retention is highly correlated with backwater flow patterns and depends upon vegetation cover. Usually riparian vegetation attenuates the input of water to the floodplain and delays drainage from backwaters, so facilitating exchanges between surface and groundwater beyond the riparian zone. However, longitudinal fragmentation of riparian corridors may locally increase the intensity of the river-to-floodplain pulse. By reducing the residence time of water on the floodplain and by creating shortcuts for water between river stretches, fragmentation may reduce the buffer effect of riparian zones. Conversely, the resistance to flow of the internal edge of the riparian corridor (see Figure 2) may increase the corridor effect and thus may accelerate the water velocity in the open channel. This resistance effect increases as the internal edge of the riparian vegetation becomes sharply defined and dense. Such an effect occurs where the erosion rate is so high that colonization of marginal sediment by vegetation of young and intermediate stages is impossible and where the old vegetation stands on the bank are clogged by climbing plants and shrubs.

Simplified turbulence models describe the hydraulic interaction between the main channel and its floodplain (Samuels, 1985; Wormleaton, 1986), although only sophisticated, computationally complex models (see e.g. Rodi *et al.*, 1983) provide good estimates of velocity at the edge, and even then without any reference to a given type of vegetation. Hammer and Kadlec (1986) and Pearlstine *et al.* (1985) have attempted to include Manning's coefficients for riparian vegetation, in the first example for very smooth topographic surfaces, and in the second example for a very low-gradient river. In the case of compound channels with vegetatively roughened floodplains, Pasche and Rouvé (1985) showed that the width of the vegetation zone and the slope of the bank between floodplain and main channel are only of minor importance for the control of flow resistance. The authors stated that this is not the case with uniform roughness conditions.

Physical interactions between atmospheric water and plants. The various components of rainfall and dew interception can be described as interception loss, throughfall and stemflow. This topic is reviewed extensively elsewhere (Crockford and Richardson, 2000, this issue) and so only a brief overview will be given in this paper.

Interception loss fluctuates between 12 and 50% under temperate climates, and depends mainly on the tree species and on the rainfall intensity and duration. Typical values of stemflow range from 0·6 to 15% of rainfall and depend on the stem size and on the density of the branches (Humbert and Najjar, 1992). For ecosystems linked to watersheds in South Africa, Versfeld and Van Wilgen (1986) noticed that the replacement of native vegetation by planted or alien invasive species could result in dramatic changes in the interception and runoff balance. Decreases in runoff of 52% in 29 years and 100% in 5 years could be observed after the introduction of, respectively, *Pinus patula* (Bosch 1979) and *Eucalyptus grandis* (van Lill *et al.*, 1980). Frasier *et al.* (1998) suggested that even herbaceous layers such as sedge or grass communities could control the initialization of runoff from direct rainfall, although the initial soil moisture content was more important than the structure and the height of the vegetation.

Interception by some trees, particularly conifers, can be up to five times higher for snowfall in comparison to rainfall. Although most of the snow eventually falls to the ground, intercepted snow has been observed to melt up to one or two weeks later than snow that has fallen on more open sites (Humbert and Najjar, 1992).

Mist and fog also can be intercepted by vegetation. The yield increases when trees are isolated or in small groups. This so-called horizontal precipitation has been described for dry latitude, oceanic climates where it represents the main water resource for vegetation (Cavelier and Goldstein, 1989). No data have been found for the riparian forest in the literature, but this type of moisture interception should not be neglected even under moist conditions, where daily changes in temperature are likely to lead to water condensation on the leaves, branches and trunks of the vegetation canopy.

PHYSIOLOGICAL IMPACT OF RIPARIAN PLANTS ON WATER PROCESSING

Water processing

The storage and use of water by plants in riparian zones also affects the hydrological regime of rivers and, therefore, affects downstream riparian areas (Malanson, 1993). The water cycle in riparian zones depends on three linked areas: water uptake and/or absorption of the soil humidity by plants; water storage in different parts of plants; and the return of water to the atmosphere by evaporation.

Water sources

Uptake is difficult to separate from evaporation, but our focus here is on the various sources of available water (Figure 3): precipitation, atmospheric humidity, floods, soil moisture, and groundwater. A major problem is to identify the dominant source of water and to establish whether uptake patterns are stable through time.

Water intercepted from humidity in the atmosphere, notably mist or fog, has to condense and drip to the ground in order to be taken up by the vegetation. Water derived from direct interception probably does not exceed a few per cent of the total plant uptake. The use of soil water by vegetation appears to largely determine the ecological and hydrological outcome of plant growth. However, the origin of soil water in a floodplain varies widely, being a dynamic combination of rainfall, river and groundwater. River water,
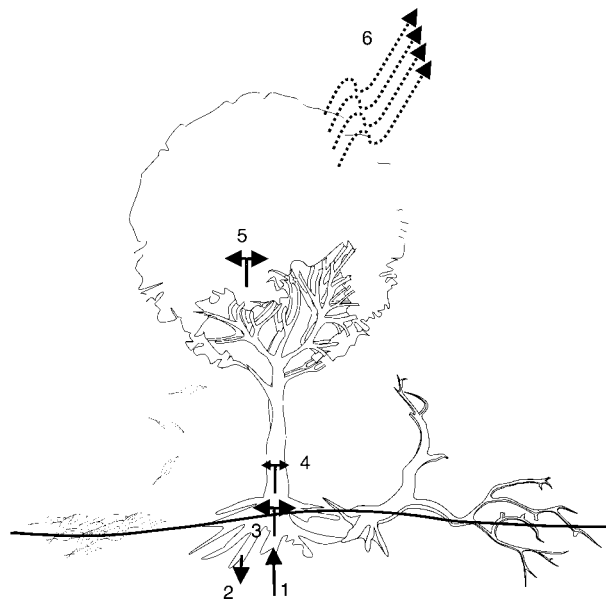

Figure 3. The main physiological impacts of riparian vegetation on water cycling: 1, hydraulic lift; 2, hydraulic redistribution; 3, water storage in large roots; 4, water storage in the stem; 5, water storages in branches and leaves; 6, evapotranspiration

particularly floodwater, combines water from different sources, as can be seen from its varying chemical composition, physical appearance and anoxic influence on the vegetation. The isotopic composition of water obtained from riparian sap cores indicates a close hydrological linkage between river, ground and soil water during the growing season (Busch *et al.*, 1992). Only rarely, as in the case of semi-arid areas, does groundwater and river water not mix freely in the riparian zone, so that old trees a few metres from the river depend on deep groundwater sources (Dawson and Ehleringer, 1991). Evidence of water transfer from deep soil layers to overlying dry soil by plant root systems, termed 'hydraulic lift' (Richards and Cadwell, 1987), strongly suggests that plants initiate a vertical uplift of water beyond that attributable to capillarity. In addition, soil water can be actively transferred downwards from surface to deeper soil horizons by plant roots in addition to the influence of gravity. This reverse phenomenon allows a 'hydraulic redistribution', which maintains root viability, facilitates root growth in dry soils and modifies resource availability (Burgess *et al.*, 1998). Dendrohydrology can aid the identification of water source uptake by woody taxa over consecutive growing seasons, because cellulose hydrogen is derived entirely from the water that is taken up by the roots (White *et al.*, 1984).

Water storage

Water that is taken up by vegetation is not returned instantaneously to the atmosphere. A large amount of water is stored. For example, Penka (1991) found that *Impatiens parviflora* D.C. has the greatest water content of the herb layer in Morovia during early June, with water accounting for 97·8% of the fresh weight of the stems and 94·2% of the weight of leaves. Three months later percentages were still 92·2% and 89·6%, respectively. For *Urtica dioica*, water content was 87·6% in the stem and 85·9% in the leaves in June, and 84·6% and 80·1%, respectively, three months later. Differences of up to 10% in water content are commonly observed between different riparian herb species and diurnal variability in water content can be of the order of 2 to 3%. There is a general decrease of up to 5% in the water content of herbs during the growing season, but because of plant growth (e.g. from 16 to 38 cm for the *Impatiens* and from 40 to 80 cm for the *Urtica*), the total amount of water stored in living vegetation increases.

Penka (1991) found that the water content in the shrub layer was generally lower than in the herb layer, and was similar in the stem and leaves at the beginning of the season. Thus, water content was 75·8% in the stem and 75·4% in the leaves of *Ulmus carpinifolia* in June, but 55·2% and 65·3%, respectively, at the end of September. Most species exhibited a decrease in water content during the growing season, which was lower in the stem (-20 to -30%) than in the leaves (-10%). Water content was similar in the stems and in the leaves of the tree layer, and changes were more limited during the season: fluctuations ranged from 54% to 58% in *Quercus*, and from 58% to 67% in *Fraxinus*.

Measurements made from 60 leaves of each of the dominant planted poplar clones in the Garonne valley in France show a highly significant difference in leaf water content, further illustrating the complexity of water storage in riparian trees. Values of 78·0% and 68·6% water content were observed at 1130 hours in early May for *I45/51* and *I214*, respectively (Muller *et al.*, *unpublished results*). During severe water stress conditions, as for example in July, leaf water content can be reduced by 8% for *I45/51* and by 4% for *I214*, which is considered as more resistant to drought. A severe drought can even provoke an early leaf fall. Poplar trees can mobilize water in woody tissues during water stress (Jacquiot, 1970). According to Chararas (1972), the I214 poplar maintains a higher osmotic pressure in the leaves than in the cortical tissues (17·2 and 10·9 atmospheres, respectively). The difference of 6 to 7 atmospheres is observed when poplars are growing in good physiological conditions. During water stress or in response to disease both values increase, but especially the osmotic pressure in the cortical tissues, so that the difference can be reduced to only 1 or 2 atmospheres.

Diurnal fluctuations in the water content of plants are partly a result of delays in water extraction from the soil. Root absorption does not react instantaneously to evapotranspiration demand as water is first supplied by the tissues. At the end of the day, transpiration stops but roots can still extract water to supply the tissues. About 15 to 22% of daily water consumption seems to be directed to this process in oak (Cermak *et al.*,

1982), larch and fir (Schulze *et al.*, 1985), and pine (Loustau *et al.*, 1996). Variations in the girth of trees, measured by a microdendrometer, gives an indication of the hydration and water storage in trunks. Two parts of trees control this mechanism: short-term variations are achieved within living tissues like the cambium and phloem, whereas long-term variations are achieved by the sap wood in the trunk, branches and larger roots (Granier and Aussenac, 1988). However, about 90% of the water stored in *Larix* and used over a 24-h period seemed to be mobilized from the tree crown and only 10% from the trunk (Schultze *et al.*, 1985).

The return of water to the atmosphere

Potential evapotranspiration may be estimated using empirical equations based on climatic parameters (net radiation, heat balance, air temperature, dew point, etc.). It gives a theoretical indication of the flow of water to the atmosphere when the soil surface is well covered by vegetation with a good water supply. The potential evapotranspiration, needs to be adjusted to reflect true evapotranspiration rates, especially when the environment is complex.

In floodplain forests, evapotranspiration rates are usually close to the potential evapotranspiration rate. Busch *et al.* (1992) found, from a regression analysis, that on average evaporation from soil and from woody taxa (*Salix*, *Populus* and *Tamarix*) did not appear to differ greatly. In Morovia, the total daily transpiration of adult trees, estimated from trunk sap flow measurements, was strongly correlated with the potential evapotranspiration rate, and, to a lesser extent, with the global radiation and the mean daily air temperature (Cermak, 1991). Weaker correlations were observed at the beginning and at the end of the growing season, that is times when the canopy is not fully developed or during leaf fall. In the same area, the actual and the potential evapotranspiration were found to remain equal during the growing season, despite strong monthly fluctuations and insufficient rainfall (Zidek, 1991). From April to September, monthly precipitation could account for only 94%, 14%, 87%, 55%, 57% and 38% of the evapotranspiration, respectively. The rest, a total of 256 mm (45% of the total requirements), was provided by groundwater, illustrating that floodplain trees transported water from the water table to the atmosphere through transpiration, with a positive effect on the mesoclimate of the area, which is otherwise relatively dry with low precipitation.

The vertical and horizontal structure of riparian vegetation influences water consumption. Penka (1991) showed that the herb layer accounted for less than 3% of the potential evapotranspiration, the shrub layer about 9%, and the tree layer about 88%, for a total mean daily consumption of 4·4 mm. Evapotranspiration varies (both seasonally and diurnally) according to the local environment, as well as to plant species and community structure. For example, during a two week period at the beginning of the growing season, lime commenced transpiration first, followed by oak and lastly ash (Cermak, 1991). At the end of the season, lime ceased transpiration last, with oak one week before and ash three weeks before. Thus the duration of transpiration in a growing season varied between 180 and 200 days according to the species, and differences could be observed from one year to another with, for example, a range of 14 days for oak. In addition, transpiration was not stable throughout the season. Both the magnitude and timing of the maximum transpiration rate varied with the species, and the duration of the daily transpiration was 15 h in May or June but only 8 h in October.

It is difficult to compare the water consumption of riparian trees, particularly when measurements have not been taken in the same environment or during the same year. In addition, it is unclear which is the most appropriate index for comparing trees (height, diameter, active sapwood area, leaf area, dry matter, canopy volume or some other parameter). Measurements made by Cermak (1991) during a growing season showed that the daily water consumption of a 33-m-high oak tree was on average 174 kg day^{-1} tree^{-1}, with a daily maximum of 460 kg day^{-1} tree^{-1}. In comparison, in the same area, the average daily water consumption for a 34-m-high ash tree was 73 kg day^{-1} tree^{-1}, with a daily maximum of 203 kg day^{-1} tree^{-1}, that is less than half the consumption of the oak. The total water consumption by oak during three consecutive years showed large fluctuations and was evaluated as 20·2, 39·1 and 21·7 m^3 tree^{-1}, respectively. However, surprisingly, the maximum daily water consumption did not occur in the most moist year but in a climatically drier one. This

probably reflects improved aeration in the soil around the roots in comparison with an excessively moist year.

Early studies indicated that the absorption of water by poplars could be considerably higher than for other species (FAO, 1980). For example, the mean daily water absorption, expressed in cubic centimetres per gram of leaf dry matter, was 20·6 for the pedunculated oak and 50·4 for poplar. High transpiration rates have been reported for poplar (Pallardy and Kozlowski, 1981) and willow (Hall et al., 1998). However, viewed from the perspective of sap transport per square centimetre of sapwood, phreatic softwood trees do not seem to take up an abnormal volume of water. Wullschleger et al. (1998) give values ranging from 0·078 to 0·881 l day^{-1} cm^{-2} sapwood area for water consumption of woody plants. Values are high for *Salix matsudana* (0·811) and *Populus x euramericana* (0·820) species, but values are still higher for other non-softwood species (e.g. *Larix gmelinii*, 0·881) or similar tropical trees (e.g. *Eperua purpurea*, 0·776 and *Ocotea* sp., 0·723). From our own first sap flood measurements, taken during the summer period, we have found smaller values of sap flux density than those reported above for *Populus*, but similar values between the clone *I45/51* of *P. x euramericana* and *P. nigra*. The high total water consumption of these trees is attributable to the large sap wood area of these softwood trees (the non conductive heartwood remains very small). Invading species can strongly alter the water balance in riparian areas by consuming the water from the soil and from the saturated zone. Salt cedars are well known to dramatically affect the riparian zone they invade in many ways, including imposing exceptional water consumption and loss rates (Busch et al., 1992; Truman, 1996).

The riparian environment also affects the water balance of the surrounding area. In absorbing energy for evaporation, it adds moisture to the air. The effect of the stream itself on local humidity may be fairly small, depending on its size and velocity, but it is likely that humidity is high within and downwind of the riparian forest. This phenomenon is often referred to as the 'oasis effect', and has been noted primarily in association with bodies of open water.

IMPACTS OF RIPARIAN PLANTS ON WATER QUALITY

Riparian vegetation as source, sink and filter

The role of riparian zones as nutrient filters for water flowing from agricultural watersheds to rivers is well known (Karr and Schlosser, 1978; Peterjohn and Correll, 1984). Many recent reviews of the topic (e.g., *Ambio*, 1994; Collier et al., 1995; Lowrance et al., 1995; Haycock et al., 1997) have emphasized the management issues of this important ecological property of riparian zones. Riparian plants directly take up and store nutrients, and they also provide organic matter to autotrophic nutrient transformers. In both cases, the resulting nutrient uptake influences water quality. However, nutrients are also released with the decomposition of dead plants, contributing to the modification of runoff quality. Riparian vegetation also controls water quality by exuding various organic and mineral components. The leaching of organic or mineral products at the surface of living vegetation provides potential additional effects on water quality. Figure 4 illustrates the main potential impacts of riparian vegetation on water chemistry.

Riparian vegetation and nutrient cycling

Owing to its high productivity in comparison with many other communities, riparian vegetation participates first in the nutrient uptake from soil and groundwater through its own growth. A second influence of riparian vegetation on nutrient cycling is through indirect processes. Two of these processes seem to have significant impacts on water quality. The first is the increase of organic matter inputs for heterotrophic organisms such as denitrifying bacteria. Under temperate climates with winter floods, the indirect role of riparian plants in microbial uptake of nutrients appears to be complementary to the direct uptake during the growing season. The second indirect role of riparian vegetation consists of the symbiotic association of plants and microbes such as mycorrhizal fungi or root symbiotic nodosities (cf. Allen, 1992; Nakastubo et al., 1994; Bialet, 1997; Stacey and Keen, 1997). These symbiotic associations increase the
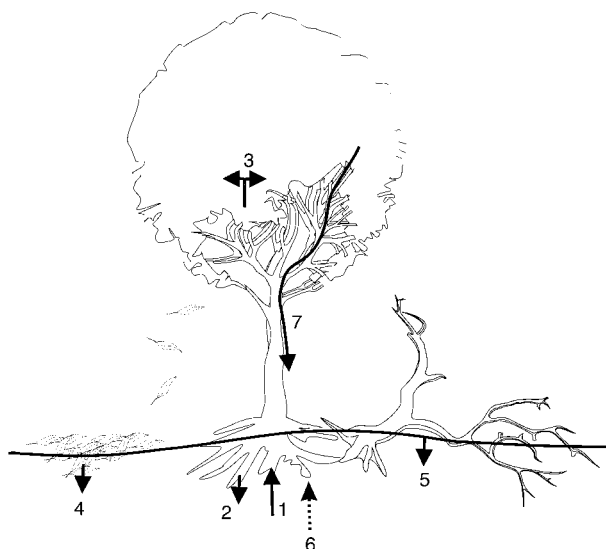
Figure 4. The main impacts of riparian vegetation on water quality: 1, direct nutrient uptake; 2, root excretions; 3, storage and concentration of mineral and organic components; 4, fast decomposing organic matter release from litter; 5, slow decomposing organic matter release from woody debris; 6, indirect uptake through symbiotic associations (bacterias and fungi); 7, leaching of pollutants and natural compounds at the surface of the plant

nutrient uptake efficiency by increasing the volume and surface of interaction between the plant and the physical environment, and additionally enabling plants to use forms of nutrients indirectly, such as atmospheric nitrogen, carbohydrates or ammonia.

Nutrients stored in living vegetation are released subsequently during the decomposition of organic matter. This aspect is a major biogeochemical process in wetlands (Jordan *et al.*, 1989). The role of riparian buffer strips in relation to nitrogen has been well studied (Peterjohn and Correll, 1984; Groffman *et al.*, 1992; Pinay *et al.*, 1994; Daniels and Gilliam, 1996). As suggested by Cole (1981), the nitrogen uptake in riparian areas is usually limited by the resource. Indeed, this author showed that black poplar trees (*Populus nigra* L.) can take up more than 50% of artificial fertilization rates as high as 400 kg N ha^{-1} year^{-1}, whereas they assimilate only 16 kg N ha^{-1} year^{-1} in natural conditions. O'Neil and Gordon (1994) have demonstrated the high capacity of nitrogen filtering by planted Carolina poplars (*Populus x canadensis*), which are able to store large amounts of nitrogen in their roots.

The vegetational cycling process seems to be particularly complex for phosphorus, which can be easily trapped by physical processes in the riparian zone, which acts as a sink. Phosphorus may be released directly in available forms and may directly enrich runoff waters. Usually, the direct transport of phosphorus from sediments involves different forms, which are processed during their transport by shallow groundwater. Another part of biologically available phosphorus is intercepted by plants and is released later during decomposition. However, the biological role of the vegetation in phosphorus cycling in riparian areas seems to be minor in comparison with the one provided by the physical buffer effect (Naiman and Décamps, 1997). As suggested by Pinay *et al.* (1995) and Tabacchi *et al.* (1998), dead organic matter provided by plants is likely to have a complementary effect to substrate waterlogging on redox potential. Therefore riparian vegetation is here also indirectly involved in the control of many biogeochemical processes capable of modifying runoff water quality. Leaching of litter may also have a significant impact on the quantity of nitrogen and phosphorus provided to runoff waters (Berg and Staaf, 1981).

Dead riparian vegetation as a source of carbon

Organic components are released at various rates during decomposition, according to the main process involved (physical leaching, active microbial decomposition, etc.) and to the initial nature of the dead organic matter. Leaves and stems of herbs are likely to decompose rapidly in comparison with the trunks and branches of trees (Jordan *et al.*, 1989; Berg *et al.*, 1996). However, slow decomposition rates have been observed for leaves of evergreen species and for species containing a high concentration of tannic components.

Highly complex organic compounds become unstable and disintegrate mechanically and chemically after plant death. Biopolymers (e.g. polysacharides, proteins, nucleic acid) are attacked by micro-organisms and are broken down to soluble compounds. Part of the decay products are oxidized to form CO_2 and H_2O, some of which are used to build up new living organic material by the organisms living on them; other parts polymerize and form heterogeneous random polymers, i.e. humic and fulvic substances. With the molecular weight and the degree of cross linkage increasing, these large molecules become insoluble and look like gels, terminating the process of diagenesis of organic matter. The process during which further changes in the composition of organic matter occurs as a result of burial has been termed katagenesis (Deines, 1980). During this process, groups of the organic compounds are lost, CO_2 and H_2O are produced, and at the same time hydrocarbons are formed. Their production decreases towards the final stages of katagenesis during which more and more methane evolves.

The amount of coarse particular organic matter (CPOM) provided by the vegetation varies with the type of vegetation and the size of the stream. In small streams, the amount can be as high as 1 kg of ash-free dry mass per square metre (Weigelhofer and Waringer, 1994). However, a large part of this CPOM is likely to be removed by floods and its decomposition is aquatic. In addition to CPOM, riparian vegetation contributes significant amounts of dissolved organic matter (DOM). Water quality may be modified by DOM coming from the unsaturated or the saturated zones of the riparian soils (Neal *et al*. 1990). Depending on soil type and climate, storms can cause sudden amounts of hydrophobic organic acids in groundwater (McLain and Richey, 1996).

Excretion, exudation and leaching from living plants

Little is known about the impact of plant excretion in riparian systems but some examples provide evidence for significant impacts of alien plants on water quality (e.g. Berry, 1970; Wiesenborn 1996). Brock (1994) highlights the success of the invasion of riparian zones in south-west USA by salt cedars and the ability of these shrubs to exude salts. In addition to the various ions that are excreted (chlorine, carbonate, sodium, potassium, bromine, calcium, nitrate, magnesium and sulphate), salt cedars are also believed to exude allelopathic substances such as flavenol bisulphates and bisulphate-glucuromides (Harbourne, 1975). Other plant species are well known to excrete similar allelopathic substances (phenols, tannins, alcaloïds). The impact of these compounds on water quality should not be ignored. Sanchez-Perez (1992) indicates that leaf and stem leaching by rainfall may have a significant impact on water quality dynamics. In addition to components derived from the plant, atmospheric pollutants trapped by the vegetation canopy also can be transported to the soil and to the groundwater. For example, the deposition of sulphates, under the canopy can be 1·5 to six times greater than rates outside of the forest. The dry atmospheric deposits also can provide important amounts of sulphates and nitrogen, whereas the leaf canopy is mainly responsible for the increase in cations such as potassium, calcium and magnesium.

CONCLUSIONS: FUNDAMENTAL AND MANAGEMENT ISSUES

In relation to the three main groups of impacts of vegetation on hydrological processes that have been discussed above, several knowledge gaps appear to exist in the context of the riparian zone and its potential importance at both local and regional scales. It is clear that research is needed to fill these gaps in knowledge

or at least conceptual and methodological improvements are required in existing research in order to support sustainable management practises. There is a major requirement for improved knowledge of the physical impact of plants on hydraulic phenomena, and, in particular, for the development of modelling approaches that incorporate the complexity of the riparian vegetation structure. In addition to the fact that local (i.e. at the scale of metres) interactions between plant structures and geomorphological processes may result in major larger scale patterns (i.e. at the scale of hundreds of metres), roughness estimates need to include not only rigid structures but also flexible structures, which are likely to change with time and hydrological disturbance intensity. This means that hydraulic modelling needs to interface with biological approaches by including representations of the physiognomic diversity and phenology of natural plant communities, and even by incorporating successional patterns to drive long-term and regional studies. Plant biologists and hydrogeomorphologists would also benefit from this new direction, for instance in predicting plant dispersal and physiological response, or early transitions between erosional and depositional phases. However, such an approach still requires empirical roughness measurements, which are difficult to assess at the regional scale, particularly because the physiognomic complexity of natural riparian stands is high and is variable in space and time.

In relation to plant physiology, very little is know about the water requirements and consumption of riparian species. Water resources are extremely variable within the riparian zone, and plant adaptation to this variability results in a high diversity of patterns and behaviour. Recent studies on the impact of biological diversity on emergent properties of the ecosystem (such as overall plant production) have shown that high diversity promotes temporal stability in biological functions. At the moment, the only available data for riparian zones concerns man-influenced, homogeneous woody communities (poplar plantations, coppiced willows, etc.). Comparisons between these homogeneous, managed riparian stands and diverse, natural stands would greatly improve our knowledge of the role of functional and physiognomic diversity of riparian plant communities on their efficiency to store or to transfer water. The specific characteristics of the riparian zone, such as its structure, soil-water conditions or microclimate, would also need to be taken into account.

As a result of the recent focus on improved, integrated management of drainage basins, the impact of riparian vegetation on water quality seems to be the most fully understood of the three aspects discussed in this paper. However, recent studies show that three main problems remain unsolved. The first is the coupling between microbial and vegetational activity for nutrient filtering with respect to local groundwater pathways, to plant phenology and competition, and to local 'external' factors such as the climatic setting and the level of interaction between river and groundwater. The second problem concerns the release of organic matter to the stream from living and dead plants. It is likely that excretion from living plants plays at least a minor role at the regional scale, but there is a lack of research to support this hypothesis at present. Although the role of CWD in habitat creation has been emphasized over the past decade, little is known about its complementary role in relation to fast- and slow-decomposing organic matter and the provision of carbon to the riparian zone and to river systems. The third problem is the role of plant diversity in the control of nutrient dynamics at the river–floodplain interface. In relation to physiological water use by plants, the spatial and functional diversity of riparian plant communities may increase the efficiency and the stability of the riparian ecotone in processing nutrients from upstream to downstream and from the floodplain to the river. Specific research studies are needed with respect to this issue.

A major problem that remains at the end of this analysis is the difficulty of scaling up plant–hydrology interactions. Scale-independent tools, such as geographical information systems, still wait for conceptual, scale transfer functions to efficiently model regional patterns from field data, but this problem is not confined to the plant–hydrology interaction problem in the context of riparian systems.

All the problems mentioned above are relevant to management (Petts, 1990; Brookes, 1995; Collier *et al.*, 1995; Brown *et al.*, 1997; Haycock *et al.*, 1997). The need for effective management of water quality, water routing and water resources increases significantly with the ecological consequences of human activities. Despite their apparently small size at the regional scale, riparian ecosystems and their biological components

perform a major functional role in interfacing many of the physical components involved in water cycling. Indeed, the importance of riparian vegetation may have been underestimated for some central hydrological processes. Increasingly stream managers include riparian vegetation as an important parameter in their planning. Currently there is a clear trend towards the use of riparian vegetation as a tool for managing and restoring stream ecosystems. Riparian systems are changing due to resource use and structural alteration by humans (e.g. river regulation, agriculture, forest fragmentation, plant introduction, etc.). However, the majority of restoration efforts using riparian plants seek to mimic natural structures or to replace artificial mineral structures by biological material. The future direction is probably to insist on self-sustainable management (Gardiner, 1995), taking into account the needs of the different species but also the vegetation dynamics and behaviour of plants in the face of hydrological and geomorphological constraints. In this paper, the pressing need for improved knowledge of the impacts of riparian vegetation on hydrology has been highlighted. This represents the complementary approach to a rational use of this biological tool. One challenge for the near future would be a consistent and stronger linkage between studies in riparian ecology and in environmental physics.

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