River Conservation
Challenges and Opportunities

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Chapter 9 Offprint

Between the Land and the River: River Conservation and the Riparian Zone

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Chapter 9

Between the Land and the River: River Conservation and the Riparian Zone

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The riparian zone is the transition between the land area of the catchment and the river channel. Riparian zones are areas with unique biodiversity and extremely important ecological functions, but they are currently threatened by increased human pressures. The ability of near-stream land to buffer the river channel is unique, and opportunities to rehabilitate these areas could benefit the whole river basin.

9.1. Why consider the riparian zone?

This chapter is about riparian land, the area bordering the river channel. Strictly speaking, the riparian zone includes only vegetation along the bed and banks of the river channel but in recent years the definition has extended to include the wider strip of land alongside the channel. Riparian zones are ecological boundaries, or ecotones, separating terrestrial and aquatic ecosystems. In headwater valleys, the riparian zone will be narrow, just a few metres wide at most, but lower down the river network, it can be very much wider, tens of kilometres wide on the largest rivers. Often the riparian zone is taken to be synonymous with the floodplain, the area of low-lying ground adjacent to a river, formed mainly of river sediments and subject to regular flooding. Floodplains cover an area of the order of millions of square kilometers worldwide (Tockner and Stanford 2002) and, thus, are quantitatively very important.

The idea of an *ecotone* was first proposed by Clements (1905) to denote the junction between two distinct biological communities: "*a zone of transition between adjacent ecological systems, ecotones have a set of characteristics uniquely defined by… the strength of interaction between the adjacent ecological systems*" (Holland 1988). Riparian zones fit perfectly with this definition, since they can play varied roles, shifting in time from a character that is reflective of the upland, terrestrial system, to one that may be more like the river (i.e. a conveyance system). Their position between rivers and uplands means riparian zones are effectively boundaries that can be described in terms of their permeability, width, gradient and so forth (e.g. Strayer et al. 2003). The overall biodiversity of riparian areas is extremely high, resulting from the unique combination of an ecotone between two contrasting ecosystems, from fertile soils and from the natural regime of floods and droughts (Naiman et al. 2005; Figure 9.1). In addition to the species characteristic of the interface between water and land, riparian areas often receive visitor species from the surrounding landscape, that go there to make use of the available resources or, more often, that use riparian areas as a corridor, given their spatial configuration. At the same time, riparian zones are among the most threatened ecosystems in the world, as humans also seek access to the river margins and convert fertile riparian soils for agriculture. For instance, in densely populated areas of Europe and Asia, between 60% and 99% of the entire river corridor has been converted to agricultural or urban areas (Tockner and Stanford 2002).

Figure 9.1:
A flooded varzea, *the name given to riparian forests in the Amazon basin. These forests are extremely productive and diverse*

Figure 9.2:
Riparian zones provide many ecosystem services (Table 9.1). Here, on the River Test in southern England, the riverside hay meadows provide grazing for animals and a rich habitat for flora and fauna. There is also access for anglers; this stretch of river was the birthplace of fly fishing

There is an intuitive assumption that the condition of the stream and the condition of the riparian zone are intimately linked. In general there is agreement that, for the good of the in-stream habitat, near-stream land should be maintained in as natural a state as possible. Until recently, riparian zones were thought of mainly as productive farmland or good sources of timber but their distinctive biota and apparent ability to protect the stream environment has prompted renewed interest in their broader ecological function. A good deal of specialist research has focused on the use of riparian land as an effective means of preventing diffuse pollution from farmland from reaching the river channel. As Bren (1993) points out, near-stream land is popular for all sorts of human activities – from farmland to recreation – so there is bound to be disagreement about the best use of this land (Figure 9.2).

Four primary ecological functions can be identified in the riparian zone, with a fifth to emphasise human use of riparian land (de Groot et al. 2002; de Groot 2006):

Regulation functions. These arise where stable ecosystems are able to buffer the impact of extreme hazards and provide some stability to the natural environment. They include air quality, climate, river flow, soil erosion, water purification, disease and pest control, and pollination (Table 9.1). By definition, we can expect the floodplain to be flooded on a regular basis, every year or two on average. In terms of flood protection, it is now realised that floodplains provide

Table 9.1: *Functions of natural and semi-natural riparian ecosystems and their translation to ecosystem services*

	Functions	Ecosystem processes and components	Potential ecosystem services
		Regulation function: maintenance of essential ecosystem processes	
1	Gas regulation	Role of riparian wetlands in gas exchange with the atmosphere via biogeochemical cycling (e.g. CO_2, N_2O, CH_4)	Improved air quality, prevention of climate change
2	Climate regulation	Influence of land cover on boundary layer climate	Favourable conditions for biota
3	Hazard protection	Storage of flood waters, attenuating the flood wave downstream	Downstream flood protection
4	Nutrient and pollutants regulation	Biogeochemical cycling in riparian soils; processing of pollutants derived from the surrounding terrestrial ecosystem	Protection of water resources
5	Soil protection	Role of vegetation cover in preventing soil erosion	Protection of water resources
6	Pollination	Role of biota in movement of floral gametes	Pollination of crops and wild species
		Production function: provision of natural resources	
7	Food	Conversion of solar energy into edible plants and animals	Hunting, gathering of fish, game, fruits
8	Raw materials	Conversion of solar energy into biomass for human uses	Timber for building, fuel, fodder
9	Genetic resources	Genetic material in wild plants and animals	Medicines, drugs, pharmaceuticals
10	Ornamental resources	Growth of biota with potential ornamental use	Resources for fashion, handicraft, jewellery, decoration
		Habitat function: provision of habitat for wild plants and animals	
11	Refugium function	Suitable living space for wild plant and animal species (including migrants)	Maintenance of biological and genetic diversity
12	Nursery function	Suitable reproduction habitat, both riparian and in-stream	Maintenance of commercially harvested species
		Information function: providing opportunities for cultural experiences	
13	Aesthetic experiences	Attractive landscape features with potential cultural and artistic value	Enjoyment of scenery, use of landscape in art
14	Recreation and tourism	Maintenance of landscape variety	Leisure pursuits (e.g. walking, angling)
15	Spiritual and historic information	Preservation of historic artefacts	Heritage value of natural and human features, eco-tourism

Table 9.1 *(cont.)*

	Functions	Ecosystem processes and components	Potential ecosystem services
16	Science and education	Variety in natural ecosystems with scientific or educational value	Use of riparian zones for out-of-classroom education and scientific research
	Carrier function: providing a suitable foundation for human activities and infrastructure		
17	Habitation	Providing a suitable location for human settlement and transport infrastructure including the provision of aggregate for the construction industry and locations for waste disposal	Living space; mining
18	Cultivation	Providing a suitable location for farming, commercial forestry and bio-fuels	Crop production

Source: Adapted from de Groot (2006).

important storage of flood waters. Without this (for example, if the floodplain is "protected" by levees), flood water moves quickly on, often to flood the next settlement downstream. In ecosystem terms, flood storage is a regulation function but the riparian zone fulfils other regulation functions too: for example, nutrient export may be reduced and local climate modulated. Later, we focus on biogeochemical cycling in riparian soils (e.g. nitrate, phosphate, carbon) and its dual influence on nutrient loss from the catchment area and gas exchange (e.g. nitrous oxide) with the overlying atmosphere.

Production functions. These ecosystem functions underpin the provision of natural biotic resources. These include wild plants and animals as sources of food (e.g. fish, game) and genetic resources – in some countries riparian ecosystems are an important source of medicinal compounds. Riparian land may also provide ornamental resources, items for fashion and handicraft such as wood, jewellery and flowers, and may be a rich source of timber, fuel and food for some people.

Habitat functions. In its natural state, a riparian wetland includes many specialised habitats. If riparian wetlands are intact along the entire river channel, they can also provide an important pathway for species migration.

Information functions. Natural ecosystems provide essential cultural services, contributing to human health and well-being by providing opportunities for reflection, spiritual enrichment, cognitive development, recreation and aesthetic experience. This includes the preservation of elements of landscape history. Access to floodplains for walkers and anglers is important to many people.

Carrier functions. Most human activities (e.g. housing, transport) require space and a suitable foundation to support the associated infrastructure; most of these activites involve complete destruction of the original ecosystem. Floodplains have always provided humans with living space and today, in towns and cities, they continue to provide flat ground for housing, industry and transport. This space is so valuable in monetary terms that its fundamental nature gets forgotten, until the next flood that is. In many places, floodplains are also a convenient source of aggregate for the construction industry, an activity that again conflicts directly with habitat conservation (Chapter 3). Farming can also be included in this category, given that farmland is clearly different from the natural ecosystem it has replaced. The soil is often very fertile, particularly when the water table has been lowered by land drainage. Intensive farming for the production of food, fibre, timber and, increasingly, bio-fuel is likely to compete with habitat functions: a more varied landscape which includes woodland and wetlands will have much higher biodiversity than arable land. Traditional low-intensity farming methods such as hay meadows are valued for their rich flora, and farmers may be paid to conserve them.

It has been estimated that these functions of floodplains are responsible for more than 25% of all the terrestrial ecosystem services, despite floodplains covering only 1.4% of the land surface area (Tockner and Stanford 2002).

9.2. Hydrology of the riparian zone

Given their location (adjacent to the river channel) and topography (often a wide, flat area), riparian zones are more often than not likely to have high water tables, even if the substrate is permeable. Very low gradients across the floodplain help to sustain waterlogged conditions, especially where the floodplain is wide or the alluvial sediments are of low permeability. Often, the riparian zone is so poorly drained that peat deposits have accumulated, adding to its poorly drained condition still further. Inputs of water to the riparian zone can originate both from the catchment area adjacent to the riparian zone and from the river channel, as well as from precipitation (Box 9.1). In headwater valleys, the main direction of water movement will be from land to river channel but further downstream there is more of a balance between these sources of water.

9.2.1. Flow paths and the residence time of water within the riparian zone

In headwater tributaries the riparian zone may be very narrow or non-existent, so that the opportunity for the riparian zone to buffer the impact of terrestrial runoff will be minimal. In the middle sections of the stream network, the presence of floodplains provides the potential for buffering runoff from the catchment as well as providing storage for flood waters. In lowland reaches there may be very wide floodplains with no connectivity between "upslope" areas and the river.

In *headwater catchments* slopes are intimately coupled to streams; the predominant direction of water movement is towards the stream (Burt et al. 2010). There

Box 9.1

The water balance of the riparian zone

The water balance of the riparian zone may be defined in terms of the inputs and outputs to the area (Burt et al. 2010):

Inputs

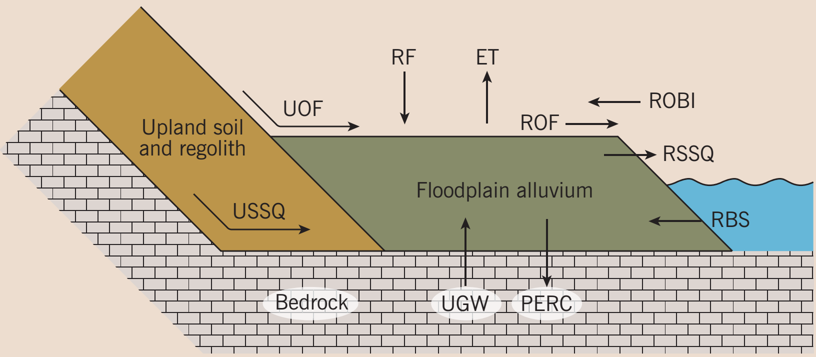
a. Overland flow from the terrestrial ecosystem upslope (UOF)
b. Subsurface flow from upslope (USSQ)
c. Precipitation directly on to the riparian zone (RF)
d. Groundwater discharge from local aquifers into the riparian zone (UGW)
e. Seepage from the river channel through the bank (RBS)
f. Overbank flooding from the river to the floodplain surface (ROBI)

Outputs

a. Overland flow from the riparian zone to the river (ROF)
b. Subsurface discharge from the riparian zone to the river (RSSQ)
c. Evaporation from the riparian zone (ET)
d. Percolation from the riparian zone into aquifers below (PERC)

Any difference between input and output must, by definition, involve a change of water storage within the riparian zone (ΔS). The water balance may therefore be expressed as follows:

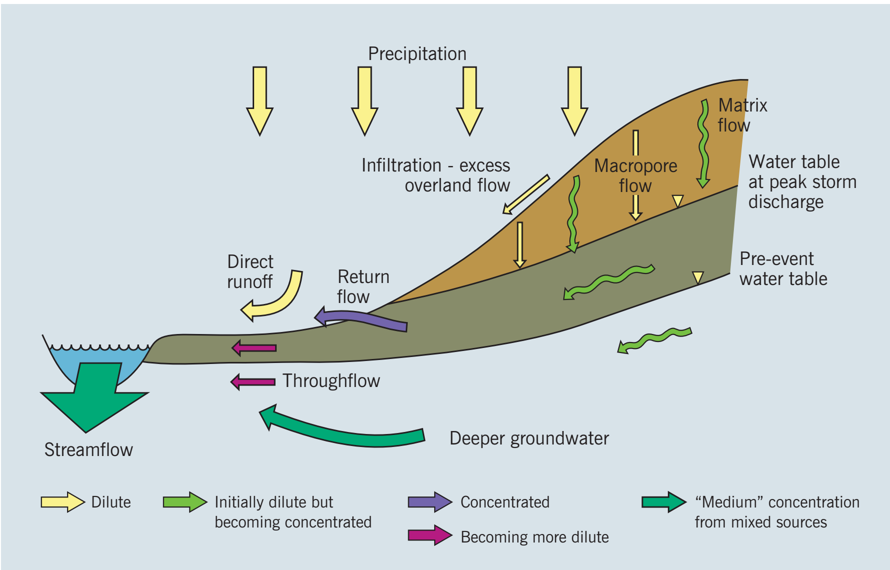
$$UOF + USSQ + RF + UGW + RBS + ROBI - ROF - RSSQ - RET - PERC \pm \Delta S = 0$$



may or may not be a narrow riparian zone with the potential to provide some protection for aquatic ecosystems, but hydrological conditions in the near-stream zone are predominantly controlled by inflows from upslope. Figure 9.3 provides a schematic representation of hillslope flow processes and associated nitrate transport. It shows how water flowing rapidly across upslope soils remains dilute whereas water flowing more slowly through soil and bedrock is much more likely to become concentrated. In relation to nitrate, the riparian zone may protect the stream: waterlogged soils favour anaerobic processes like denitrification, with nitrate being reduced to nitrous oxide or dinitrogen gas and thereby permanently removed from the river basin. However, the same conditions may favour release of other nutrients e.g. phosphate, so that riparian zones may not buffer all pollutants to the same degree. Surface runoff on farmland may erode soil; this may be deposited in the riparian zone, depending on its width and the type of vegetation cover found there.

In the *middle reaches* of a river basin floodplains are wider and there can be inputs to the riparian zone from both hillslopes and the river channel (see Box 9.1). Bank storage is an important process during flood events, both seepage through the bank and overbank flooding from the river to the floodplain surface. Hillslope discharge to the riparian zone dominates during non-flood periods. In temperate zones, the main emphasis has been on buffering as water moves from upslope areas (usually farmland), across the riparian zone to the

Figure 9.3: *Hillslope runoff pathways and associated nitrate transport*



Source: Burt and Pinay (2005).

stream; there is a relatively small buffering capacity for water moving out of the channel during floods. However, in semi-arid areas, water movement out of the channel is a much more important source of water compared to temperate areas (Harms and Grimm 2008).

In *large river basins* the floodplain becomes an important source of runoff in its own right and there is little influence from the surrounding catchment area. Drainage of the riparian zone to allow more intensive agriculture encourages subsurface flow and may increase nutrient leaching as a result. Water draining through the soil can by-pass most of the riparian zone via ditches and drains, much reducing the opportunity for buffering processes to operate. For example, it is thought that rising nitrate concentrations in many rivers in the UK in the 1960s and 1970s were in part caused by extensive land drainage programmes at that time, much of which involved drainage of floodplains (Burt et al. 2008). This was compounded by the fact that land use changed from low-intensity grazing to high-intensity arable farming, with ploughing annually and high rates of fertiliser application.

9.2.3. Hydrological variability and disturbance as drivers of change in the riparian zone

Fluvial processes shape the form of river channels over the long term (decades to centuries) through processes of erosion and deposition (Chapter 3). The familiar example of a migrating meander illustrates how these slower geomorphic processes influence riparian zones: on the outside edge of the meander, trees succomb to the flow even as new substrate for seedlings is deposited on the opposite, aggrading the bank. Successional processes of vegetation growth integrate with the dynamic change in river channel form, creating complex patterns in substrate (soil, sediment) and biota upon which biogeochemical processes play out.

On ecological time scales, individual floods are disturbances that contribute to the geomorphic landscape evolution, but also are important drivers of change in riparian structure and function. Floods can uproot trees, carve out river banks, deposit thick layers of sediment in some areas and scour others. They will generally produce a rise in water table within floodplains and may displace riparian groundwater, causing pre-event soil water to mix with river water. Rising water tables can promote soil microbial activity by alleviating water limitation. The channel and the riparian zone differ in their resilience to flood disturbance (Fisher et al. 1998); in general, riparian zones are less likely to be altered by all but the largest floods compared to the stream channel which will be regularly disturbed. On the other hand, because they often are dominated by long-lived organisms (trees), when flood destruction occurs, they will re-establish more slowly.

Drying also is a disturbance to riparian zones; indeed, the prevalence of seasonal drying may limit the extent of riparian zones to larger streams, particularly in arid, semi-arid, or Mediterranean climates. Stream drying during regional droughts can decimate riparian forests when the water table falls below the reach of riparian vegetation during long periods. It follows that any propensity for climate change towards warmer and drier conditions, i.e. increasing evaporation losses relative to rainfall input, will pose a threat to riparian habitats.

The particular pattern of seasonality in flow, differences between peak and low flow, timing and magnitude of floods, and duration of extreme low flows comprises the hydrological regime. Hydrological regimes differ among climatic regions (Chapter 2) and it is important to understand not just the impact of an individual disturbance but of the entire regime. In the arid South West of the USA, mineralization of organic matter is a major source of available nitrogen, subsidized by input of nitrogen from floods. Baseflow inputs are most likely removed by rapid denitrification at the stream-riparian edge, while higher rates of flood supply exceed the capacity of this "filter" (Schade et al. 2002). Year-to-year hydrological variability is very high and results in multi-year differences in the abundance of a shrub, *Baccharis salicifolia*, that colonizes the parafluvial zone (nearest-stream portion of the riparian zone). Because *B. salicifolia* roots alter subsurface organic matter content and flow patterns, these difference between years translate to strong impacts on nitrogen biogeochemistry.

A complex set of interactions governs the hydrological disturbance regime in any catchment. Floods are not easily predicted simply from rainfall amount and intensity; the permeability of soils, antecedent conditions (how long since it last rained), soil and vegetation type, temperature, and so forth all contribute (Chapter 2). Thus, it is clear that hydrological regimes are likely to be altered under global climate change, although we are far from being able to generate predictions with high confidence. With changing hydrological regimes, we expect to see changes in the character and biogeochemical dynamics of riparian ecosystems.

9.3. Biogeochemical cycling in the riparian zone

Riparian zones have long been under human pressure because of conflicting interests associated with the use of near-stream land. The fundamental role of these wetlands in the functioning of river ecosystems has been ignored until relatively recently (Burt et al. 2010). Even though ecologists have been interested for decades in spatial transitions from one biological community to another, and how their proximity affects the functioning of each zone, science and management have been disconnected (Grimm et al. 2003). The importance of the riparian zone ecotone as a "buffer" against high sediment and nutrient (nitrogen and phosphorus) fluxes from land to the sea via riverine transport has been recognized in terms of diffuse pollution control (Peterjohn and Correll 1984).

9.3.1. The riparian zone as conduit

Riparian zones, the land areas bordering the river channel, have unique biodiversity and extremely important ecological functions

Given their location alongside rivers, during flood events riparian zones receive large amounts of dissolved and particulate organic matter and nutrients from upstream. In headwater locations, riparian zones are subject to large subsurface nitrate inputs from the adjacent uplands (Peterjohn and Correll 1984), while in larger rivers, significant amounts of sediment, organic matter and nutrients are deposited during overbank flood events. River floodplains are recognized as important storage sites for sediments and associated nutrients mobilized from upstream catchments during floods (Walling and He 1998). The recycling and storage of sediment deposits in floodplains are largely depend on the hydrological connectivity between the river and its floodplain, i.e. existence of side channels and oxbows, as well as of the magnitude, frequency and duration of floods. Collectively, these factors create a mosaic of geomorphic surfaces that influence the spatial pattern and successional development (series of vegetation community from pioneer grass, to soft and hard wood) of riparian vegetation (Salo et al. 1986). The fluxes of matter mediated via surface connectivity have the potential to control gaseous nitrogen loss via denitrification by controlling the rate of nitrate delivery. This has been shown for pools in the Danube River (Welti et al. 2012) and in other smaller European floodplains (Pinay et al. 2007). In riparian zones and floodplains well connected to the river, the pattern of surface and subsurface flow provides large potential for nitrogen retention and removal which contributes to reduction of natural diffuse pollution (Burt and Pinay 2005).

The high productivity measured in floodplains is mainly a function of the abundant matter supplied by the drainage basin as well as the co-existence of aerated (oxic) and non-aerated (anoxic, reduced) conditions in its soils and sediments (Brinson et al. 1984). In many parts of the world, floodplains sustain high food production for the local population. For instance, flood events in a given year increase the fish yield the following year in various large rivers such as the Danube, the Kafue, the Niger and the Shire rivers (Welcomme 1995). Sediment and nutrient deposits on the Ganges and the Brahmaputra floodplain mean soils can sustain up to three rice crops a year in Bangladesh.

9.3.2. The riparian zone as a barrier

The use of natural buffer zones to protect fresh water from pollution has attracted considerable interest. It is now recognized that riparian zones along streams can mitigate diffuse pollution by nitrate input from upland areas. Two processes are involved in this regulation: plant uptake, which provides temporary storage, and denitrification, which represents a permanent sink for nitrogen since nitrate ultimately is transformed to a gaseous form and lost from the river ecosystem completely (see Haycock et al. 1997; and Burt et al. 2010 for reviews).

There is an intuitive assumption that the condition of the stream and the condition of the riparian zone are intimately linked

Efficiency of nitrogen cycling and retention, the processes which contribute to diffuse pollution control in river ecosystems, is correlated with the length of contact between water and sediment in stream or between wetland and upland. This positive relationship occurs both in the main channel itself and in the riparian and floodplain zones (Hill 1979; Jones and Holmes 1996; Valett et al. 1996). The duration of contact between water and these substrates controls the biological use and thereby the total amount of nitrogen processed. The frequency, duration, timing and intensity of floods also directly affect nitrogen cycling in alluvial soils by controlling the period during which soils will be saturated with water and therefore will lack aeration. This soil saturation with water can result from flooding but may simply reflect the slow rate of drainage across the flat riparian zone. Flooding duration is controlled by local topography: low areas are flooded more often and for longer than higher ones. Biogeochemical processes involved in nitrogen cycling are sensitive to whether the soil contains free oxygen or not (Hefting et al. 2004). For example, organic nitrogen can be transformed into ammonia by both aerobic and anaerobic ammonification processes in oxic or anoxic conditions respectively, whereas the nitrification process, which requires free oxygen in the environment, can only occur in aerated soils or sediments. As a consequence, under permanently anoxic conditions, mineralisation of organic nitrogen results in the accumulation of ammonium. Other processes, such as nitrate dissimilation or denitrification, are anaerobic and require saturated soils to operate. Therefore, the end products of nitrogen cycling in riparian soils are controlled by the moisture regime (i.e. water table level), with important implications for floodplain productivity and management.

It is important to underline that the capacity of riparian zones to retain and remove nitrogen does not apply to other types of pollutants. It is especially clear, for instance, that the role of riparian forests in controlling phosphorus pollution has been often overestimated. Phosphorus is mainly transported by surface flow and its permanent removal from riparian wetlands can only be achieved by plant harvesting since it does not have any gaseous form. Phosphorus is somewhat less mobile than nitrate, forming insoluble complexes, but under anoxic conditions phosphorus goes back into solution. Thus, riparian zones may become sources of soluble phosphorus for the adjacent stream under flooded conditions. This limits their role on phosphorus flux control (Uusi-Kamppa et al. 1997).

9.3.3. Hot spots and connectivity at the landscape scale

Riparian zones represent an important interface between the terrestrial and aquatic environments and can exert significant controls on water quality. They are typically areas of topographic convergence with high upslope contributing area and low slope which promote the development of near-surface saturation and enhanced denitrification. In addition, the combination of reduced slope and increased heterogeneity due to the presence of trees and rough grass can enhance deposition of soil eroded in adjacent fields and the removal of associated organic matter and nitrogen from runoff (Burt and Pinay 2005).

Nevertheless, factors accounting for the pollution retention capacity of riparian zones are diverse, and the performance of a buffer zone within a catchment is difficult to predict (Haycock et al. 1997). Indeed, the transfer of nitrogen within the drainage basin and its transformation within riparian zones varies widely in response to local environmental conditions. For instance, Pinay et al. (1998) examined the buffering capacities of different riparian vegetation (natural riparian forest, 3- and 15-year-old poplar plantations, and a wet meadow) on non-point source nitrogen pollution along a 7th-order reach of the Garonne River in south west France. They found that the role of riparian zones was marginal. In an urban study, Roach and Grimm (2011) compared denitrification among habitats of a constructed stream-pond-floodplain complex in south western USA, and found that denitrification in grassy floodplains that were periodically inundated or irrigated removed nearly all of the nitrogen added by fertilisation, but that denitrification in the ponds was limited by nitrate diffusion through the sediment and in the streams by a small areal extent. This designed floodplain thus provided nitrogen removal service within the larger urban landscape. In a pan-European study evaluating the role of small forested and meadow riparian zones, Sabater et al. (2003) found that the rates of biological uptake and denitrification of nitrogen were controlled by local hydrological conditions and nitrate load rather than by broad differences in climate among sites. The large variability of nitrate export rates from small headwater basins is a sure sign that nitrate retention processes are very active at some sites but completely absent in others (Burt and Pinay 2005). These two last studies point to the high degree of variability among sites and a limited predictive capacity based upon broad-scale drivers.

Given the high heterogeneity at the local scale (topography, soil, vegetation cover, etc.), it is difficult to extrapolate site specific *in situ* evaluation of nitrogen buffering capacity of riparian zones at larger scales, i.e. 1 to 100 km^2. This intermediate catchment size is also the scale where models linking percentage of land use to nutrient fluxes tend to fail (Strayer et al. 2003). However, this is an important management scale where socio-economical drivers such as crop production and landscape aesthetics meet. An alternative approach to tackling this scaling issue could be to consider that riparian zones represent a particular type of biogeochemical hot spot where hydrological flow paths converge with high concentrations of substrates (such as soil carbon and nitrogen) essential for microorganisms. These "coupled" solutes are transported to the riparian zones which show disproportionately high reaction rates relative to the surrounding matrix (McClain et al. 2003). Therefore, evaluation of nitrogen retention and removal at the drainage basin level could be done by considering the likelihood of a given land use and land cover arrangement hosting biogeochemical hot spots.

9.3.4. Contrasting cases: temperate, arid, and arctic riparian zones

The previous overviews mainly describe general hydrological and biogeochemical conditions that typify riparian zones of temperate regions. In other regions, seasonality of the hydrological cycle and ecosystem processes yields patterns in riparian biogeochemistry that contrast from the general, moderately moist ("mesic") model. Here, we discuss riparian zones that differ from this general model. Patterns observed in these special cases may also pertain to temperate riparian zones under conditions that differ from normal, including drought or urbanization.

Drylands. Temperate rivers tend to receive water from the aquifers and from multiple subsurface sources, and therefore, are called "gaining" rivers, as the discharge they transport tends to increase downstream. In contrast, rivers in dry areas are called "losing" rivers, as they tend to lose water to local aquifers and to the riparian zone. The direction of this flow has consequences for both hydrology and biogeochemistry. Riparian zones along losing reaches have deeper groundwater tables than those along gaining reaches, and surface flow is often intermittent or ephemeral. Overall, water availability is much lower in the riparian zones adjacent to losing reaches. As a consequence of the scarcity of water, riparian vegetation is less dense and rates of soil microbial activity are water limited; thus the capacity for nutrient retention is much lower in riparian zones along losing compared to gaining reaches (Harms et al. 2009).

Although water is scarce for much of the year in arid regions, large floods occur from time to time. Because the soils, devoid of much vegetation, have low infiltration capacity, the heavy rainfall falling during a storm quickly reaches the stream. This results in inputs of water from up-basin tributaries (often ephemeral washes), overbank floods that inundate the riparian zone, and a rapid rise of the water table. Because soluble materials can build up in soils during long dry periods, inputs to the riparian zone are accompanied by high loads of dissolved and suspended materials from the uplands and "flushing" of solutes derived from riparian soils. Sediments may be physically entrained or trapped by riparian biota, whereas increased water availability combined with increased availability of nutrients can promote biological uptake and removal of carbon and nutrients. However, during very large floods the residence time of water and substrates in riparian zones may be insufficient to allow significant biological activity, and most of the nutrients are exported. Conversely, in locations where there is prolonged inundation, this may also suppress biological uptake due to declining oxygen levels and substrate availability. Thus, the size and timing of water inputs to riparian zones of drylands has strong consequences for biogeochemical activity (Harms and Grimm 2012).

Floodplains are estimated to be responsible for more than 25% of terrestrial ecosystem services despite covering only 1.4% of the land surface area

Permafrost-influenced catchments. Permafrost is ground that remains frozen throughout the year, and is common at high latitudes or high elevations. During summer, the soil surface can thaw (the thawed soil is known as the *active layer*), but the deep soil layers remain frozen. Catchments dominated by permafrost have unique hydrological templates that have consequences for the biogeochemistry of riparian zones. Permafrost restricts deeper percolation of soil water, preventing growth of plant roots and fostering little microbial activity. Water moving from upslope areas via riparian zones to the stream flows through the active layer.

Thaw dynamics play a dominant role in the hydrology and biogeochemistry of permafrost-influenced catchments. Early in the snowmelt period, soil thaw is minimal, and solutes and water in the snowpack are exported from the riparian zone. However, some time later the upper organic soil horizons, which are typically composed of living mosses, begin to thaw, and thus provide strong potential for retention and removal of nutrients. As the soils continue to thaw, flow paths may be disconnected from surface organic horizons, and flow is routed through deeper, mineral soils. These soils may strongly adsorb organic molecules, but provide a weak sink for inorganic solutes. In sum, seasonal patterns in thaw depth and water table elevation in riparian soils contribute to strong seasonality in solute export.

Spatial extent of permafrost and the rate of seasonal thaw of soils respond strongly to the thermal regime. In regions with discontinuous permafrost in the Northern Hemisphere, south- and west-facing catchments tend to have less permafrost. Similarly, where permafrost is continuous, deeper active layers form in catchments that receive greater solar input. Permafrost extent and depth of thaw have consequences for the residence time of water in the riparian subsurface. Water can infiltrate thawed soils, which provide a reservoir for water storage, and the riparian zone contributes more strongly to mitigating peak flows and material fluxes during storms where thaw depth is greater.

Riparian zones in permafrost regions are particularly prone to bank destabilization due to the thawing of ground ice. Bank collapse features are particularly common along larger rivers (Figure 9.4). Once initiated, these features rapidly develop, with stream banks often eroding at rates of metres per year. Formation of thermokarst (hummocky ground formed by thawing of ice-rich permafrost) has dramatic consequences for riparian hydrology and biogeochemistry by removing vegetation from the riparian zone, exposing mineral soil, and enhancing export of sediment and nutrients.

Figure 9.4: *Thaw slumps in permafrost regions can cause extensive and rapid downcutting of stream channels, removing riparian vegetation and exporting riparian soils and sediments downstream*

9.4. Human drivers of change in riparian zones

Although riparian areas are extremely important from the point of view of the biodiversity they host, as well as of the services they offer, they are also among the most threatened areas of the world (Tockner and Stanford 2002). In Europe and North America up to 90% of floodplains are severely modified for agriculture, intensive forestry or urban uses, and riparian habitats are among the most threatened by expansion of human activities. Here we discuss briefly some of the human pressures driving changes in riparian zones.

9.4.1. Hydrological regime

Human activities in any location within a catchment will affect ecological functions and their translation to ecosystem services. In the uplands, groundwater extraction can cause streams and riparian zones to dry out by reducing streamflow and drawing down the water table. When hydrological inputs from the surrounding uplands are lost, the subsurface connection between streams and riparian zones can be reduced and riparian vegetation may no longer have access to a perennial source of water. Dewatering of stream-riparian corridors has occurred extensively in arid regions, and has consequences for plant species richness. Plant species richness declines as flow permanence declines in desert riparian zones; loss of obligate wetland species contributes to the decline (Stromberg et al. 2007). Extensive piped drainage of catchments via tile drains or open ditches in agricultural lands and storm drains in urban areas may bypass the riparian zone entirely (Figure 9.5). For example, urbanization often results in deepening of the water table in riparian zones, due to diversion of flows (Groffman et al. 2003). Impervious surfaces in the uplands, including pavement, rooftops, and compacted soil amplify peak flows to streams or riparian zones, creating flash floods. High peak flows during storms can cause channel down-cutting and erosion of stream-bank sediments, leading to hydrologic disconnection of the riparian sub-surface from the stream channel (Paul and Meyer 2001).

Hydrological disconnection also occurs due to direct modification of stream channels and riparian zones. Levees built to protect settlements and farms from floodwater may separate a substantial fraction of the riparian area from the action of fluvial processes. This has consequences of eliminating sediment accrual within riparian zones, and reduces flood mitigation and groundwater recharge, because water is flushed more rapidly through the stream channel. Bank stabilization, rip-rapping, and lining of channels have similar consequences and, importantly, result in lowered water tables, restricting water availability in shallow riparian soils (Groffman et al. 2003). Finally, dams alter the hydrologic regime

Figure 9.5:
A buffer strip (grass plus a narrow woodland strip) in Switzerland, near Lausanne. The buffer protects the stream from surface runoff but, unless tile drains are blocked, subsurface runoff will continue to enter the stream unimpeded

of riparian zones by decreasing peak discharge, and significantly extending the inter-flood interval, or time period between floods.

9.4.2. Biogeochemistry

Changes in the hydrological regime alone alter the biogeochemical functions of riparian zones, because of the multiple roles of water in biogeochemical processes. Vegetation subject to drought stress has reduced capacity for uptake of nutrients, and retention and removal of nutrients by soil micro-organisms slows due to water limitation. Rapid runoff or bypassing of the riparian zone during floods decreases water residence time in the riparian zone, and this decreased contact time of solutes and biota restricts the capacity for nutrient retention. Thus, the timing of nutrient delivery to stream-riparian corridors can shift from baseflow to peak flows with increasing hydrologic modification to the catchment (Table 9.2).

Humans directly manipulate the biogeochemical functions of riparian zones through application of fertilisers and pesticides. Although riparian zones may foster high rates of nutrient retention, this capacity for retention can be exceeded when runoff from fertilised fields and residential stock yards results in high loading of nutrients. In addition to increased downstream transport of nutrients, increased nutrient availability in riparian zones can support

Land use	Percentage nitrate exported in baseflow	Percentage nitrate exported in high flow
Agricultural, forested buffer	94	6
Urban	86	14
Mixed (forest, farmland, urban)	78	22
Mixed (forest, farmland)	58	42
Mixed (forest, farmland)	47	53
Forest/residential	21	79
Urban/suburban	10	90
Farmland, tile-drained	3	97

Table 9.2: *The proportion of total nitrate flux exported by baseflow and high flow for a range of streams draining a variety of land uses. Data assembled by Craig et al (2008). Increasing agriculture and urbanisation in catchments results in a shift in the timing of nutrient delivery from baseflow in forested catchments to high-flow events in extensively modified catchments*

growth of invasive plans. Similarly, although riparian zones may promote retention and breakdown of pesticides, this capacity can be overwhelmed by excessive inputs, especially when the spatial extent of riparian zones has been reduced in favour of other land uses. Finally, novel compounds introduced in agricultural and wastewater runoff may cause increased mortality of biota, with potential consequences for riparian food webs. Wastewater from urban areas that is discharged into rivers after treatment may contain high levels of currently unregulated compounds, such as personal care products, caffeine and antibiotics (Chapter 5). These persistent pollutants often have unknown impacts, but are likely to influence riverine and riparian biota for some distance downstream.

9.4.3. Biota

Introduction of invasive species can significantly reduce the portfolio of ecosystem services provided by riparian ecosystems. Non-native plants in particular are often successful invaders of riparian zones, and can affect biotic interactions directly, as well as alter abiotic conditions. For example, the invasive shrub Tamarix thrives in dryland riparian zones of the South West US, especially those subject to flood suppression (Stromberg et al. 2007). Tamarix is associated with drawdown of the water table and increasing groundwater salinity, conditions that are detrimental to native plants. High densities of Tamarix reduce the structural and species diversity of riparian vegetation, degrading habitat quality for some bird species. Non-native plant species that fix nitrogen increase nutrient availability in riparian ecosystems, even at low plant densities, and have consequences for the capacity of riparian zones to perform the service of nutrient retention.

Humans directly alter the biotic composition of riparian zones through vegetation removal, agriculture, and livestock grazing. Riparian zones are cleared of vegetation during forestry, or in preparation for agriculture. Clear-cuts near streams result in significant increases in nutrient loading to streams; increased stream temperatures, which in turn have consequences for stream biota; and decreased inputs of woody debris, which in intact riparian zones contributes structural habitat and organic matter to the stream. In some regions, crops are planted right to the margins of streams, which eliminates riparian habitat entirely. In urban or suburban areas, riparian flora may be intentionally replaced by non-native species (turf grass, non-native trees and shrubs), creating novel communities of plants. Human use of these parklands may be intense. Finally, introduction of livestock grazing to riparian zones has unintended effects of compacting soil, trampling or consumption of vegetation, and destabilization of stream banks; these can often be an important source of sediment input to the channel and require careful management to exclude stock access if in-stream habitats e.g. fish spawning gravels, are to be protected (Figure 9.6).

9.4.4. Interactive effects

By changing individual hydrological, biogeochemical, or biotic attributes of riparian zones, human activities may have consequences for whole riparian ecosystems.

Figure 9.6: *River bank restoration on the Eden River in NW England. The simple expedient of fencing protects the river bank from erosion as livestock no longer have access. It is, however, necessary to provide drinking troughs as part of the scheme*

For example, hydrological disconnection of streams from riparian zones may limit growth of native plant species, which can result in bank destabilization, a decrease in the nutrient-retention capacity of the riparian zone due to decreased plant abundance or resource limitation of micro-organisms, and a change in the quality of food supporting food webs. Such cascading effects are characteristic of all ecosystems, but riparian zones are particularly subject to feedbacks involving disparate spatial locations, owing to connectedness via hydrological flow paths (Burt and Pinay 2005; Chapter 10). As integrators of all activities on the land, streams are sensitive to a host of pressures including impacts from urbanisation, agriculture, deforestation, invasive species, flow regulation, water extractions and mining. The impacts of these individually or in combination typically lead to a decrease in biodiversity because of reduced water quality, biologically unsuitable flow regimes, dispersal barriers, altered inputs of organic matter or sunlight, degraded habitat and so on. Despite the complexity of these interactions, a large number of stream restoration projects focus primarily on physical channel characteristics. Palmer et al (2010) argue that this is not a wise investment if ecological recovery is the goal. Managers should critically diagnose the factors impacting an impaired stream and prioritise those problems most likely to limit restoration (Chapter 11).

9.5. Riparian zone destruction and restoration

In intensively managed areas like city centres and suburbs, streams, rivers and riparian zones may bear little resemblance to their natural character. Small streams are buried, larger ones are channelized and all riparian vegetation may be removed. Extractive activities take place in the floodplain or channel, often removing vast quantities of material as aggregate for construction and leaving great pits that fill with water. Here, the centuries of work of the alluvial system is exploited for useful materials, but the ecosystem has been transformed and a return to its prior state is extremely unlikely, even with intervention. Highly channelized and hardened river banks require continuous vigilance and repair in the face of flooding. On the other hand, recent decades have seen massive efforts at river restoration, many of which provide a cosmetic fix to a degraded system but do not restore underlying ecosystem functions and services (Bernhardt et al. 2005; Palmer et al. 2010; see also Chapter 6). For example, in arid Phoenix, Arizona, USA, riparian restoration projects are *de rigueur*, yet none of these projects relies on restoration of the natural flow regime of the river and all are instead dependent upon imported water to maintain planted riparian vegetation.

We must, however, end on a positive note. Modern legislation to manage river basins, such as the European Water Framework Directive (WFD: 2000/60/EC) tend to adopt a holistic approach focusing on the achievement of "good ecological status". The WFD is formulated to favour functional aquatic habitats as well as potable drinking water. As noted at the start of this chapter, there is an intuitive assumption that the condition of the stream and the condition of the riparian zone are intimately linked. Thus, protection of the riverine environment demands, almost by definition, that full attention is paid to the quality of the riparian zone. Rehabilitation of natural habitats, restoring wetlands and removing inappropriate land uses in the riparian zone can all contribute to a sustainable future for our rivers and their habitats. In the decades to come, climate change may become the main driver of long-term change in river ecology but in the short term, land use seems to be a more important factor. Restoration of riparian zones to their natural condition is a great challenge to scientists, regulators, politicians and land owners alike but may nevertheless provide the most cost-effective means of managing our river basins going forward. Probably, a traditional approach to nature conservation in riparian zones based on biodiversity and naturalness is insufficient in itself, but a wider perspective, considering all the benefits to the river system, provides justification for maintenance of riparian zones in good ecological status.

9.6. References

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