Section 1

The River Environment

1.1
Floodplains in River Ecosystems

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1.1.1 FLOODPLAINS AS OPEN SYSTEMS

Strictly speaking, the riparian zone includes only vegetation along the bed and banks of the river channel (Tansley, 1911). However, the definition has been extended in recent years to include a wider strip alongside the channel; very often, the floodplain is taken to be consistent with this more broadly defined area. The riparian landscape is unique among environments because it is a terrestrial habitat strongly affecting and affected by aquatic environments (Malanson, 1993). Pinay *et al.* (1990) identify the salient process elements – water, nutrient and sediment fluxes – in relation to transverse and longitudinal structure of the riparian zone. They, like Naiman and Décamps (1990) highlight the role of the riparian zone as a terrestrial-aquatic ecotone between the terrestrial and the aquatic ecosystems, whereas Forman and Godron (1986) prefer to view the riparian zone as a corridor, thus emphasizing longitudinal rather than transverse fluxes.

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Schumm (1977) divided the channel network into three zones, as follows. Headwater streams, first- to third-order links within the channel network, which are the source regions for water, sediment and dissolved load (Figure 1.1.1). In Schumm's terminology, this is the *production* zone. Here, streams are closely coupled to hillslopes. There may be narrow floodplains between slope and channel, but often steep slopes connect directly to the channel. Given the inherent nature of the channel network, most of the channel length – and hence most of the basin area – is to be found in the headwater tributaries, and hence the emphasis on slope–channel coupling. The middle or *transfer* zone, channel links of fourth to sixth order, represents a transition. The floodplain becomes wider and transfers from water to land become relatively much more important when compared to fluxes in the other direction. By implication, longitudinal fluxes increase in importance given the dependence of (downstream) floodplains on fluxes from (upstream) headwater regions. In its lower regions, the floodplain is a *storage* zone, or sink, in which channel-to-floodplain transfers dominate.

The nature of the riparian zone will vary, depending on its location within the channel network and on regional climatic conditions (Décamps *et al.*, 2004). In the headwater tributaries, the delivery of water, sediment and solutes from slope to channel is most important. In the middle section, transfers from slope to channel can remain important but the channel also becomes a significant input source to the floodplain. Wide, lowland floodplains tend to be isolated from the surrounding hillslopes; they receive significant inputs from the channel and themselves become important source areas, especially during the flood recession and periods of low flow.

Given their location and topography, floodplains are likely to form wetlands, temporarily if not permanently. Even where the floodplain sediments are permeable, the combination of width and low gradient helps to maintain a high water table, with this control being accentuated as the floodplain width increases or where the alluvium is more fine-grained. Even above the water table, the soil is likely to remain close to saturation because of the capillary fringe effect (Gillham, 1984). Accepting the transverse nature of fluxes, as defined by Pinay *et al.* (1990), the floodplain water balance may be defined as follows.

Inputs: (a) overland flow from upslope (UOF); (b) subsurface flow from upslope (USSQ); (c) precipitation directly onto the floodplain (RF); (d) groundwater discharge from local aquifers into the floodplain (GW); (e) seepage from the river though the channel bank (BS); (f) overbank flooding from the channel to inundate the floodplain surface (OBI).

Outputs: (a) overland flow from floodplain to channel (FOF); (b) subsurface flow from the floodplain sediments to the river (FSSQ); (c) evaporation from the floodplain surface (ET); (d) percolation from the floodplain into local aquifers (PERC).

An imbalance between inputs and outputs must, by definition, involve a change of water storage within the floodplain (ΔS). The floodplain water balance may therefore be expressed as follows:

$$\mathrm{UOF} + \mathrm{USSQ} + \mathrm{RF} + \mathrm{GW} + \mathrm{BS} + \mathrm{OBI} - \mathrm{FOF} - \mathrm{FSSQ} - \mathrm{ET} - \mathrm{PERC} \pm \Delta \mathrm{S} = 0$$

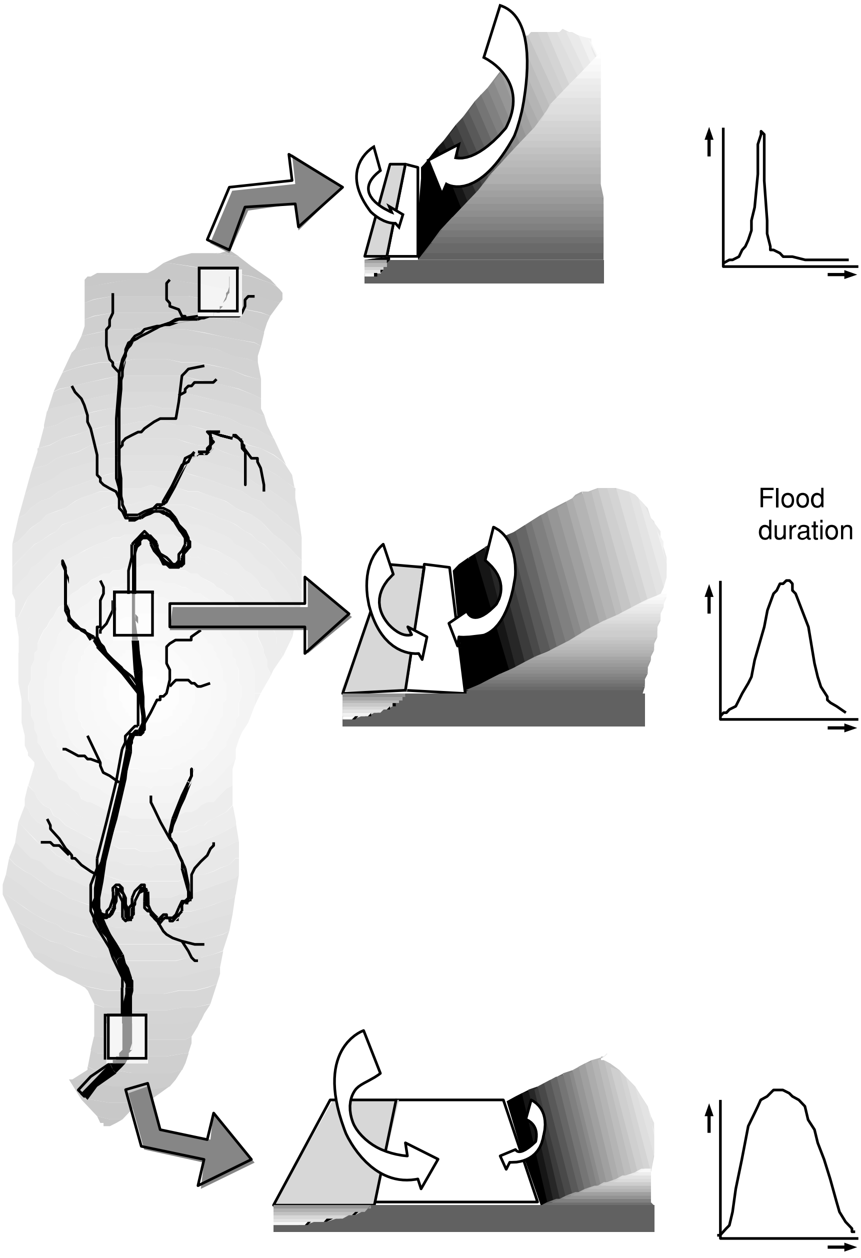

Figure 1.1.1 Preferential water and nutrient movements through the riparian zones as a function of their location within the drainage basin. Arrows symbolize the main water and associated suspended and dissolved matter transfer between upland and stream via the riparian zone. The riparian zones are shown in white, the rivers in light grey and the upland catchments in dark grey. Along small streams, most of the water and associated nutrients flow from the upland via the riparian zone whenever it exists, while along large streams the main flow direction is from the stream towards the floodplain (mainly during flood events) (adapted from Tabacchi *et al.*, 1998)

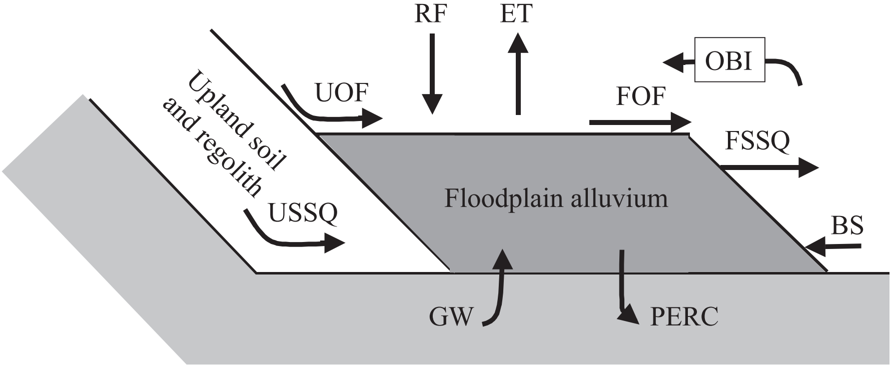

Figure 1.1.2 Water balance in the floodplain: UOF, overland flow from upslope; USSQ, subsurface flow from upslope; RF, precipitation directly onto the floodplain; GW, groundwater discharge from local aquifers into the floodplain; OBI, overbank flooding from the channel to inundate the floodplain surface; BS, see page from the river through the channel bank; FOF, overland flow from floodplain to channel; FSSQ, subsurface flow from the floodplain sediments to the river; ET, evaporation from the floodplain surface; PERC, percolation from the floodplain into the local aquifers. Reproduced by permission of Haycock Associates Limited from Burt, T. P., 1997, 'The hydrological role of floodplain within the drainage basin system', in *Buffer Zones*: *Their Processes and Potential in Water Protection*, Haycock, N. E., Burt, T. P., Goulding, K. W. T. and Pinay, G. (Eds), Quest Environmental Publications, Harpenden, UK, pp. 21–32

The floodplain water balance equation highlights the point that inputs to the floodplain can originate from both the adjacent hillslopes and from the river channel (Figure 1.1.2). As noted above, the relative importance of these runoff sources alters along the channel network. In headwater tributaries, riparian zone hydrology is closely controlled by topography. Assuming that there is no floodplain present and that steep slopes abut the channel, the river has only very limited influence on the water table within the riparian zone. High water tables may develop but these depend on drainage from upslope and will be temporary. If a floodplain is present, high water tables will be a much more regular occurrence, and both river and hillslope can influence water table height within the floodplain (Burt *et al*., 2002b). As one moves down the channel network, and floodplain width tends to increase, so the river becomes a relatively more important source of water to the floodplain. During winter floods, the floodplain can remain inundated for long periods of time; only during the flood recession is the dominance of hillslope sources re-established (Burt *et al*., 2002a).

River systems are open systems, dynamically linked in three dimensions by hydrological and geomorphologic processes which largely control their existence and maintenance via the timing and duration of floods and low-flow events. Process rates vary spatially in relation to the floodplain's location within the channel network.

Floodplains tend to widen downstream; this tends to be associated with higher water tables and a greater relative importance of river inputs when compared to hillslope sources. The operation of any particular process can therefore be expected to vary in relation to location within the river basin; further downstream, longitudinal fluxes will tend to become more important when compared to transverse fluxes.

Fluxes of solutes and sediments into and out of the floodplain are, of course, very largely dependent on the water fluxes. Floodplains may act as either a conduit or a barrier for all of these fluxes (Burt and Pinay, 2005). Where the floodplain acts as a barrier, or buffer zone, the internal storage and process mechanisms operating within the floodplain assume great importance. For example, the micromorphology and sediment stratigraphy of floodplains depends on a combination of channel and overbank deposition. These, in turn, influence flow paths and soil wetness across the floodplain, important controls on a process like denitrification, for instance, where process rates depend on a combination of nitrate input, soil carbon content and the development of anaerobic conditions.

In this hydrogeomorphic context, we define three fundamental principles driving the nitrogen cycle in river systems (Pinay *et al.*, 2002). In general, these principles should apply to other nutrients (Hedin *et al.*, 1998). The three fundamental principles that regulate the cycling and transfer of nitrogen in rivers are as follows: the mode of nitrogen delivery affects ecosystem functioning; the degree of contact between water and soil or sediment increases nitrogen retention and processing; the role of floods and periods of low flow in influencing pathways of nitrogen cycling.

1.1.2 THE MODE OF NITROGEN DELIVERY AFFECTS RIVER ECOSYSTEM FUNCTIONING

The first principle is related to the delivery patterns of nitrogen inputs along river corridors. River systems and their riparian zones can be viewed as open ecosystems, dynamically linked longitudinally, laterally and vertically by hydrologic and geomorphic processes (Ward, 1989). In small, forested headwater streams, particulate organic nitrogen is the main form of nitrogen transferred to the aquatic system, primarily as litter fall from the adjacent riparian vegetation (Cummins *et al.*, 1983; Minshall *et al.*, 1983). Nitrogen-fixing plants such as alder (*Alnus* spp.) are often found in riparian forests. They contribute large amounts of nitrogen rich organic matter, which can reach several kg of dry matter per m^2 (Chauvet, 1987). Eventually, these particulate inputs contribute to the export of dissolved organic nitrogen via surface and subsurface pathways after degradation and recycling processes have occurred (Newbold *et al.*, 1981; Elwood *et al.*, 1983; McClain *et al.*, 1997; Clark *et al.*, 2000; Stepanauskas *et al.*, 2000). Due to their location along the edge of rivers, riparian forests also receive, recycle and transfer large amounts of sediments and nutrients to streams (for nitrogen, it is mainly as nitrate by subsurface flow) from upslope ecosystems (Peterjohn and Correll, 1984; Lowrance *et al.*, 1995). Fortunately, riparian zones can efficiently utilize and retain nitrate inputs from upslope as long as the subsurface water flow intercepts roots and microorganisms. Therefore, riparian zones deliver nitrogen to streams mainly as particulate organic matter.

In the floodplains of most large rivers, the main inputs of nutrients, sediment and organic matter are mainly via surface flow from upstream (Figure 1.1.1). Indeed, significant amounts of these materials are deposited during floods (Brinson *et al.*, 1983; Schlosser and Karr, 1981; Lowrance *et al.*, 1986; Grubaugh and Anderson, 1989; Brunet *et al.*, 1994). River floodplains are recognized as important storage sites for sediments and associated nutrients mobilized from upstream catchments during floods (He and Walling, 1997). The transfer and storage of materials in floodplains are largely under the control of flood duration, frequency and magnitude that, collectively, create a mosaic of geomorphic surfaces influencing the spatial pattern and successional development of riparian vegetation (Salo *et al.*, 1986; Roberts and Ludwig, 1991). The fluxes of matter via flood deposits are responsible for the high nutrient-cycling capacity of floodplain soils, as compared to upland ecosystems (Brinson *et al.*, 1984). The significantly higher fertility of floodplain soils is illustrated in an agricultural example from Bangladesh. Historically, flood-mediated sediment and nutrient deposits on the Ganges and Bramaputhra river floodplains supported up to three crops of rice per year without fertilizer addition, while upland soils only sustained one crop a year (Mathab and Karim, 1992; Haque and Zaman 1993).

1.1.3 INCREASING CONTACT BETWEEN WATER AND SOIL OR SEDIMENT INCREASES NITROGEN RETENTION AND PROCESSING

The second basic principle is that the area of water–substrate interface (i.e. water–sediment or wetland–upland length of contact) is positively correlated with the efficiency of nitrogen retention and use in river ecosystems. This occurs both instream and in the riparian and floodplain zones. The nitrogen cycle is driven by processes that occur on or at the interface of particulate material such as stones, soils, sediments or algal mats (Ponnamperuma, 1972; Hill, 1979; Jones and Holmes, 1996; Valett *et al.*, 1996). Hence, increased length of contact between water and these substrates increase the biological use and thereby the total amount of nitrogen processed.

Riparian wetlands provide a large contact area between water and soils that promote nitrogen retention and processing, thereby regulating fluxes from uplands to streams. The wetland–upland contact zone can be envisioned, as a first approximation, as the contact zone between the riparian wetland and the uplands. This zone of contact varies both in depth and width as a function of the river's geomorphology and hydrologic regime. During high water periods, the extension of the saturated area increases away from the stream and extends further upslope while, during low-water periods, the saturated area shrinks in extent and decreases in length upslope (Beven and Kirkby, 1979).

There has been considerable interest in restoring or promoting the use of riparian wetlands to mitigate diffuse nutrient pollution (Peterjohn and Correll, 1984; Lowrance *et al.*, 1985; Pinay and Labroue, 1986, Haycock *et al.*, 1997). Surprisingly, several attempts to relate the percentage area of riparian wetlands with nutrient fluxes at the outlet of drainage basins have failed (Osborne and Wiley, 1988; Tufford *et al.*, 1998). One of the major reasons for the lack of correlation is that riparian efficiency is driven by hydraulic connection with upland inputs since nitrate is often a limiting nutrient (Groffman and Hanson, 1997; Lowrance *et al.*, 1997). Riparian zones represent a mosaic of physical and functional units whose patterns are shaped by long-term geomorphic development of the floodplain. These biophysical units can be connected or disconnected hydrologically from each other and from the upland catchment (Brinson, 1993). Therefore, the efficiency of a riparian zone in regulating nitrogen fluxes is not a function of the surface area of the riparian zone but rather a function of the hydrological length of contact between the riparian zone and the upland drainage basin (Haycock and Pinay, 1993; Matchett, 1998, Burt *et al.*, 1999).

This can be illustrated by comparing first-order streams (i.e., small perennial streams without any tributaries) to larger rivers. First-order streams represent more than 50 % of the entire length of the river network, while higher-order rivers represent only a few percentage of the total length in a given catchment (Naiman, 1983). As a consequence, riparian zones associated with small-order stream develop a more intimate wetland–upland interface than riparian zones along high order rivers (Brinson, 1993), and better contribute to mitigating diffuse pollution from the catchment (Peterson *et al.*, 2001). Moreover, for a given surface area of riparian zone in a catchment, small streams are more efficient in retaining upland nutrients than larger streams because of the close proximity of water to sediments or soils.

Throughout the world, many upland streams have been subjected to human modifications such as channelization, impoundment or removal of riparian vegetation. All anthropogenic impacts tend to reduce both the spatial extent of saturated areas and the duration of riparian soil saturation (Worrall and Burt, 1998). Moreover, straightening river channels, dredging riverbeds, or clogging of interstitial spaces by fine sediments, reduce the size of the hyporheic zone and its exchange rates with surface water, thereby affecting the nutrient recycling capacity of the stream. As a consequence, these human impacts reduce the efficiency of the river network to mitigate diffuse nutrient pollution.

1.1.4 FLOODS AND DROUGHTS ARE NATURAL EVENTS THAT STRONGLY INFLUENCE PATHWAYS OF NITROGEN CYCLING

The third principle is related to the role of floods in shaping the characteristics of nitrogen cycling. Changes to the water regime, either through alterations to the frequency, duration, period of occurrence and intensity of water levels, directly affect nitrogen cycling in alluvial soils by controlling the duration of oxic and anoxic phases (Ponnamperuma, 1972; Keeney, 1973; Patrick, 1982). Flooding duration is controlled by local topography; low areas are flooded more often and longer than higher ones, producing variations in biogeochemical patterns at the metre scale (Pinay *et al.*, 1989; Pinay and Naiman, 1991). Biogeochemical processes, especially for nitrogen, are sensitive to the redox status of the soil. For instance, ammonification of organic nitrogen can be realized both under aerobic and anaerobic conditions but the nitrification process, which requires oxygen, can only occur in aerated soils or sediments. For instance, Hefting *et al.* (2004) found in a pan-European study that water table elevation was the prime determinant of the nitrogen dynamics and its endproducts. Three consistent water table thresholds were identified. In sites where the water table is within −10 cm of the soil surface, ammonification is the main process and ammonia accumulates in the topsoils. Average water tables between −10 and −30 cm favour denitrification and therefore reduce the nitrogen availability in soils. In drier sites, where the water table is below −30 cm, nitrate accumulates as a result of high net nitrification.

Short-term periodicity of aerobic–anaerobic conditions through groundwater level movements allows all nitrogen cycling processes to occur simultaneously at the same location in accordance with the level of soil-water saturation. Several studies have demonstrated that alternating aerobic and anaerobic conditions enhance organic matter decomposition and nitrogen loss through denitrification (e.g. Reddy and Patrick, 1975; Groffman and Tiedje, 1988; Pinay *et al.*, 1993). Moreover, it has been shown in an experimental study that the rate of nitrogen mineralization is much greater during a flooded period than during a non-flooded one (Neill, 1995). Overall, natural water table fluctuations in floodplains are key drivers of soil fertility with changes to the natural flood regime often decreasing productivity. However, drier periods are also important since they allow mineralization of more complex organic matter structures (e.g. hemicellulose and lignin) and contribute to soil fertility by providing another inorganic nitrogen source (ammonia and nitrate) to plant and microbes which otherwise would be sequestered as organic residues.

The flood regime also indirectly affects nutrient cycling in floodplain soils by influencing soil structure and texture through the deposition of sediment. The alluvial soil grain size mosaic and the proportion of different grain size deposits varies spatially and temporally following extreme flooding (Petts and Maddock, 1996; Richter and Richter, 2000). At small scales, geomorphic and hydrologic processes influence the sorting of sediment deposits on a grain-size basis. This creates a mosaic of soils of different textures. It is the soil or sediment texture that influences denitrification rates, as well as other biogeochemical cycles (Pinay *et al.*, 2000). Fine structures such as clay develop large surface areas per unit of weight or volume, which provide greater chemical adsorption sites (Paul and Clark, 1996) and microbial habitats (Ranjard *et al.*, 2000). For instance, the fastest denitrification rates are measured in soils with fine texture. Below a threshold of ~ 65 % of silt and clay, floodplain soils do not show any significant denitrification. Above that threshold, denitrification increases linearly. In fine-textured floodplain soils, the denitrification rates are of the same order of magnitude as nitrogen mineralization, with annual denitrification representing up to 70 % of the nitrogen deposited during floods (Pinay *et al.*, 1995). Thus, floodplains contribute to the regulation of nitrogen fluxes by sorting sediments mobilized during floods and recycling nitrogen deposited during a flood.

1.1.5 NEW CHALLENGES

There are several new scientific challenges which need urgent attention. Quantifying the cumulative effects of water regime changes on the functioning of floodplains is an important scientific challenge. For instance, a reduction of the high-water period duration along low-order streams would lead to downstream movement of the dry–wet interface into the riparian zone, thereby favouring further intrusion of upland allochthonous nitrates within the riparian zone (Burt, 1997). Moreover, it is expected that this will also lead to further intrusion of pesticides in riparian soils since these xenobiotic molecules are often found together with nitrate. To what extent does this intrusion reduce bacterial denitrification of newly contaminated soils where pesticide decomposition would be less effective since the bacterial population was not adapted to repeated pesticide application (Abdelhafid *et al.*, 2000)? A second challenge concerns the scale of appraisal of water regime change effects on nutrient cycling. Depending on the spatial and temporal monitoring scale, the consequences of water regime changes on gaseous nitrogen end products varies (Bodelier *et al.*, 2000). Contrasting field and laboratory results on the respective importance of different processes on end products appears to result from the difference between space and time scale at which the studies are conducted. Another issue is related to the determination of the respective roles of human impacts and natural changes on river ecosystem functions (Vitousek *et al.*, 1997). In most cases, pristine ecosystems are in different ecoregions than human impacted ones, hence limiting the ability to extrapolate process rates and trends from natural to modified systems (Tol and Langen, 2000). However, in both cases, the main principles regulating the cycling and transfer of nitrogen in river ecosystems remain valid despite differences in process rates. Therefore, sustainable management practices should be assessed according to their impact on (1) the delivery mode of nitrogen to river ecosystems, (2) the length of contact between water, soil and sediment, and (3) the timing, rate and duration of floods and drought.

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