

Linking hydrology and biogeochemistry in complex landscapes: implications for diffuse nitrate pollution

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Elements of hydrological landscape structure and function

In summarising the different way in which hydrological systems are conceptualised, Falkenmark and Chapman (1989) distinguish between vertical hydrological processes (e.g. rainfall, evaporation) and the horizontal processes of flow generation. Similarly in ecology, Reynolds and Wu (1999) note that, whereas the study of patch dynamics emphasises a vertical standpoint, landscape studies have a horizontal perspective. Landscape-scale ecology involves the search for links between landscape structure and function (Tenhunen and Kabat, 1999). In the same way, biogeochemists have identified 'hot spots' where hydrological flow paths converge with substrates or other flow paths containing complementary or missing reactants. These hot spots exhibit disproportionately high reaction rates relative to the surrounding matrix (McClain *et al.*, 2003). In all these cases, the horizontal approach tends to encourage a pattern-oriented or geographical approach, emphasising the spatial organisation of ecological entities, with hydrological flow paths providing the functional linkage. In this sense, landscapes cannot be viewed simply as overlying mosaics of landforms, biological communities and land uses, since it is the interactions between ecological entities that are important. Put another way, the landscape system is more than just the sum of the individual parts (Burt and Pinay, 2005).

Cantwell and Forman (1993) introduced the concept of landscape graphs as a means of analysing flows of energy and matter at the landscape scale. They found that the 'necklace' was a very common topological landscape structure in which the same landscape elements (or patches) are linked together in a linear fashion (e.g. fields, hedgerows, riparian corridors). In the 'variegated necklace' pattern, different elements are joined together along a flow line (e.g. interfluvium → hillslope → floodplain). Some sites are particularly sensitive, for example hillslope hollows, because downslope drainage is concentrated there; this is Cantwell and Forman's 'candelabra' with several upslope elements focusing on one downslope node. Of course, any flow line can constitute either a conduit or a barrier, depending on the process mechanisms operating at a particular location along the flow line. In this regard, the near-stream or riparian portion of a flow path assumes particular importance in that it can function either as a conduit or as a barrier for energy and material moving downslope (Brinson *et al.*, 1984; Mulholland 1992; Pinay *et al.*, 1999). As discussed further below, processes

operating in near-stream areas often control stream chemistry so that there is no similarity between 'hillslope' water and 'stream' water. Moreover, because certain processes like denitrification operate effectively there, the riparian zone can function as an effective buffer between farmland and the river (Burt and Haycock, 1996; Burt *et al.*, 1999).

Hydrological conditions within the riparian zone

The riparian landscape is unique among environments because it is a terrestrial habitat strongly affecting and affected by aquatic environments (Malanson, 1993). Two particular features of riparian zones may be noted: their spatial structure and their interaction with surrounding ecosystems. Naiman and Decamps (1990) emphasised their role as terrestrial-aquatic ecotones, whereas Forman and Godron (1986) preferred to view them as corridors. In either case, the important processes operating involve flows of energy, matter and species, with the riparian zone potentially acting as both a conduit and a barrier. Pinay *et al.* (1990) identified the salient elements of riparian function, water and nutrient fluxes, in relation to the longitudinal and transverse structure of the riparian zone. They concluded that riparian zones are primarily transverse ecotones between terrestrial and aquatic ecosystems, while longitudinal ecotones occur in-stream, echoing the nutrient spiralling concept of Newbold *et al.* (1981).

Assuming the riparian zone to comprise a distinct hydrological unit, its water balance may be defined as follows:

Inputs

1. Overland flow from upslope (UOF)
2. Subsurface flow from upslope (USSQ)
3. Precipitation directly on to the riparian zone (RF)
4. Groundwater discharge from local aquifers into the riparian zone (GW)
5. Seepage from the river channel through the bank (BS)
6. Over-bank flooding from the channel to inundate the floodplain surface (OBI)

Outputs

1. Overland flow from the riparian zone to the river (FOF)

2. Subsurface discharge from the riparian zone to the river (FSSQ)
3. Evaporation from the riparian zone (ET)
4. Percolation from the riparian zone into aquifers below (PERC)

Any imbalance between inputs and outputs must, by definition, involve a change of water storage within the riparian zone (ΔS). The water balance in the riparian is therefore as follows:

$$\text{UOF} + \text{USSQ} + \text{RF} + \text{GW} + \text{BS} + \text{OBI} - \text{FOF} - \text{FSSQ} - \text{ET} - \text{PERC} \pm \text{DS} = 0$$

Of course, not all these processes may be involved at any given place or at any particular time. The water balance does, however, emphasise how inputs to the riparian zone can originate both from the adjacent slopes and from the river channel. This balance is likely to alter from headwater tributaries to lowland reaches. In headwater valleys, slopes are intimately coupled to streams. There may or may not be a narrow riparian zone with the potential to provide some buffering function between terrestrial and aquatic ecosystems (Burt *et al.*, 2002a). In the middle reaches of a river basin, floodplains are wider and there is a balance between inputs to the riparian zone from hillslopes and from the channel (e.g. Burt *et al.*, 2002b; Jung *et al.*, 2004). Bank storage is an important process during flood events, both in-channel and out-of-bank. Hillslope discharge to the riparian zone is held up during flood events but dominates the recession. Focused inputs from hillslope hollows can be very important in maintaining the water table locally. In large river basins, the floodplain becomes an important source of runoff in its own right and there may be little or no influence from surrounding hillslopes. Drainage of the riparian zone to allow intensification of agricultural activity encourages subsurface flow and, in contrast to buffering processes, may increase nutrient leaching as a result. Slope drainage can then by-pass the riparian zone via ditches and drains, limiting the opportunity for buffer zone functions to operate.

For headwater catchments, studies conducted within the NICOLAS programme (Nitrogen Control by Landscape Structures in Agricultural Catchments; Burt *et al.*, 2002a) indicated two contrasting modes of soil saturation depending on whether or not there is an area of flat ground adjacent to the river. Where the riparian zone is flat, the water level in the river acts as a datum around which the riparian water table fluctuates. However, where the land slopes right down to the river, the river does not significantly influence water tables in the riparian zone. Figure 1a shows average water table elevation by row (10-metre spacing between rows) for a woodland site in the U.K. The pattern is essentially one of parallel response, with all rows showing much the same response to seasonal variations in inflow to the riparian zone. In contrast, where the riparian water table is constrained by the river level, a 'hinged' pattern of response is seen. Figure 1b shows the seasonal pattern of response for a site in the Netherlands. There is a wide range of water table variation on the slope but minimal variation nearer the stream. Even in summer, there is sufficient hydraulic gradient from slope to channel to sustain soil saturation within the riparian zone.

In some situations, when discharge from the slope falls to a very low level or ceases altogether, the hydraulic gradient reverses in summer, with the water table in the riparian zone being sustained by seepage from the stream through the bed and banks of the channel. This is the case for a site in France, shown in Figure 2. Because there is very little flow in the stream itself during the summer, the water table in the floodplain falls well below the surface. It is clear that early autumn recharge of the riparian zone is also generated from the channel rather than from upslope. It is only at the end of October, after rainfall has recharged soils on adjacent hillslopes, that the hydraulic gradient reverses once more, and a flow direction from slope to channel is restored. Haycock and Burt (1993) described a similar pattern of seasonal reversal in the hydraulic gradient for a floodplain in southern England. Only when flow is from slope to stream can the buffer zone functions of the riparian zone be active.

Hydrological pathways, flow path chemistry and coupling between the riparian zone and the river

Bishop *et al.* (2004) argue that, since the chemistry of water moving downslope is determined at any given point by soil chemistry, the particular role of the riparian soil is to set the stream water chemistry, since this is the last soil in contact with the soil water before it becomes stream water. Cirimo and McDonnell (1997) also emphasise the importance of saturated near-stream zones, which they describe as the "focal point in non-point source loading of N to stream channels". They felt that there must be a link between the dominant flow path and solute transport but, given the dominance of pre-event water in storm runoff, they concluded that biogeochemical response was decoupled from hydrology in the near-stream zone. They repeated the findings of Robson *et al.* (1992) that the chemical concentrations of all flow lines may be 'reset' in the riparian zone of the stream. Thus, there is a need to understand how hillslope water is routed into and through the near-stream zone, and how biogeochemical and hydrological processes interact there.

In the absence of direct measurements of hillslope processes, there has been a great temptation to infer solute delivery mechanisms from observations of stream water chemistry. Mixing models have often been used to calculate the contributions of different flow components to the storm hydrograph (e.g. Pilgrim *et al.*, 1979; Anderson and Burt, 1982; Burns *et al.*, 2001). Buttle (1994) notes that the large majority of hydrograph separations derived from mixing models indicate that pre-event water supplies at least half of streamflow at peak discharge in small and medium-sized catchments. Given such consistent results, apparently at odds with the rapid runoff response, the need to identify links between hillslope flow paths and solute removal is obvious (Kirchner, 2003).

The capacity of near-stream areas to act as nitrate buffer zones has been recognised for over two decades (Peterjohn and Correll, 1984). Research has sought to establish conditions under which such buffer zones can function effectively (See Haycock *et al.*, 1997 for a review). In relation to diffuse nitrate pollution, the process of denitrification has attracted considerable attention. In

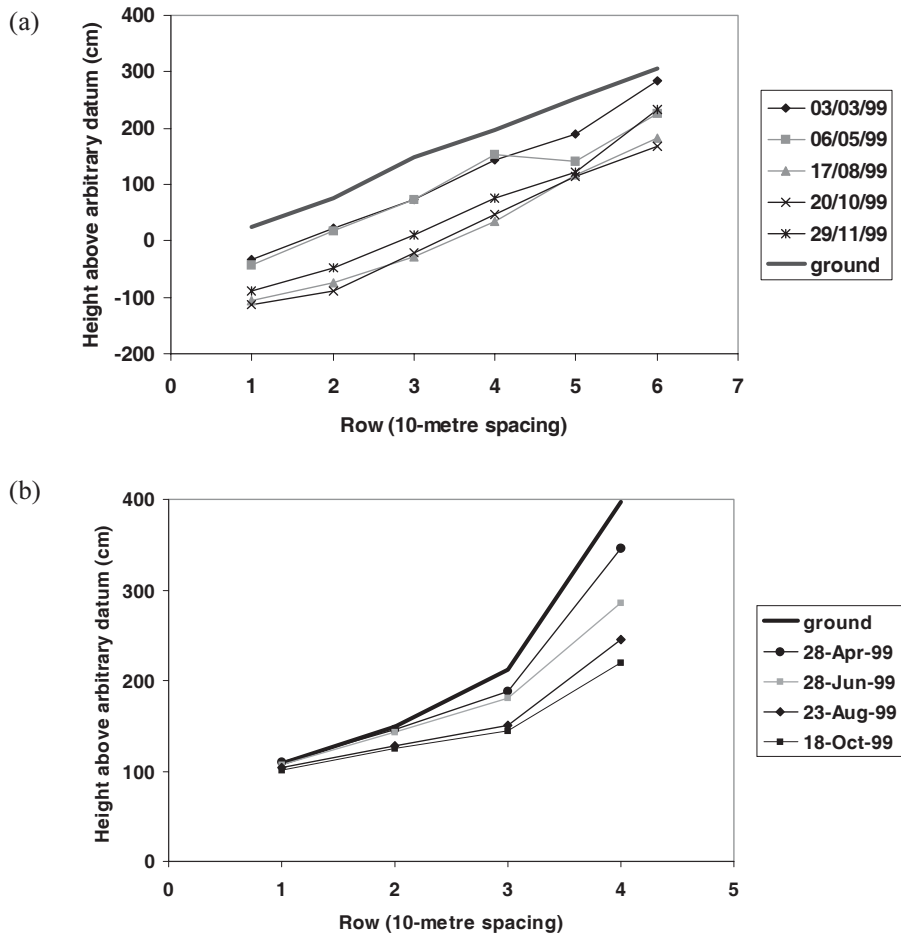


Figure 1 Average water table elevation by row at NICOLAS sites: (a) UK wood; (b) Netherlands grass.

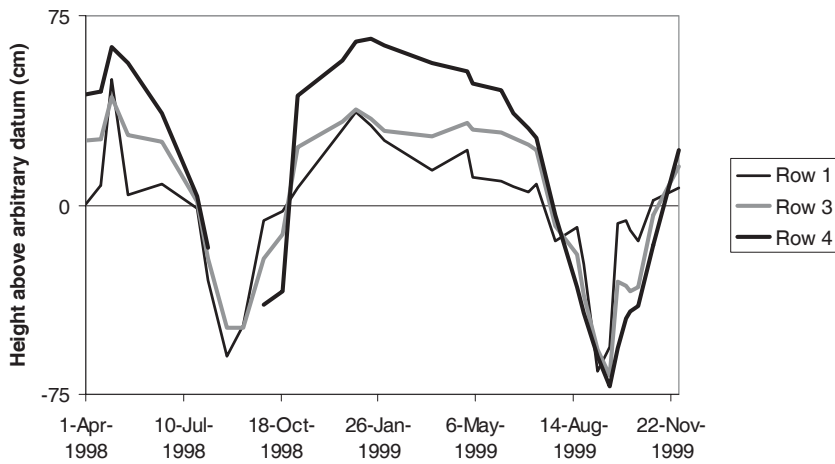


Figure 2 Water table elevations for a floodplain in Brittany (See Burt *et al.*, 2002 for details of the site). Row 1 is nearest the stream channel. Results for Row 2 mirror those for Row 1 and consequently are not shown here.

addition to anaerobic conditions, denitrification requires a carbon substrate (electron donor), and a ready supply of nitrate in soil water. Sabater *et al.* (2003) show that reduction in nitrate loads can take place under a wide range of conditions. Neither climate nor vegetation cover in the riparian zone seem critical, as long as the near-stream hydrology is conducive to denitrification. However, as seen above, the very existence of a floodplain is crucial

in providing a low hydraulic gradient, so encouraging a high water table. Soil hydraulic conductivity is also important in providing optimal soil water residence times within the riparian zone (Burt *et al.*, 2002b). Some alluvium may be too permeable to sustain high water tables for long periods (Burt and Arkell, 1987; Welsch *et al.*, 2001). On the other hand, if riparian sediments are too impermeable, too little water may flow through to optimise

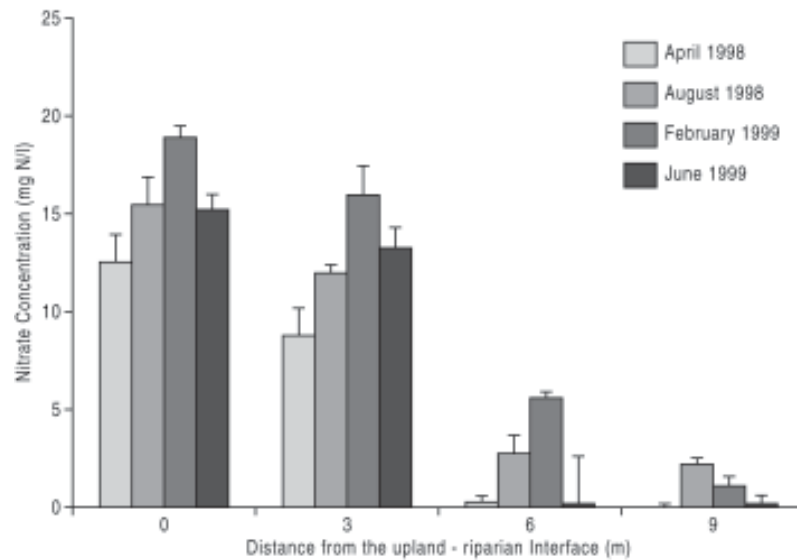


Figure 3 Nitrate concentrations across a floodplain in Brittany (Details of nitrate dynamics at the field site are described in Clément *et al.*, 2003).

the impact of denitrification (Burt *et al.*, 1999). Soils of medium hydraulic conductivity in combination with appropriate geomorphology are most likely to provide the most favourable conditions for denitrification therefore. Figure 3 shows the pattern of nitrate loss at the French NICOLAS site, the hydrology of which has already been described (Figure 2). The effect of denitrification is clearly very rapid once hillslope water enters the floodplain. Measurements of potential denitrification show that further along the flow line nitrate is a limiting factor (Clément *et al.*, 2002, 2003). Thus, the active buffer zone is at the hillslope-floodplain boundary, whilst further into the floodplain, there is potential for buffering *if* any nitrate travels that far.

Nitrate buffer zones and catchment management

It may seem paradoxical that the particular role of the riparian soil is to set the stream water chemistry, since this is the last soil in contact with the water before it becomes runoff (Bishop *et al.*, 2004), and yet to be functional, a riparian buffer zone must effectively decouple the hillslope from the stream. The degree of biogeochemical decoupling between hillslope and channel depends on what opportunity there is for different source waters to mix within the near-stream zone, and on the residence times of the different source waters as they flow through the zone (Haycock *et al.*, 1997). The size and extent of the saturated area will be of some importance in this respect therefore. Of course, channel flow remains a mixture of different source waters, and if significant amounts of water bypass the saturated riparian soils, either by flowing across the surface (Waddington *et al.*, 1993) or through permeable strata below the floodplain alluvium (Burt *et al.*, 1999), the buffer zone will be ineffective. The optimal condition would seem to be one of intermediate permeability where residence times are sufficient to allow significant amounts of both throughflow and denitrification. To operate

effectively, the riparian ‘buffer zone’ therefore requires a balance between the functions of conduit and barrier; this is not just a question of interaction with different soils conditions but depends on flow path length and residence time within a distinctive biogeochemical environment (Burt, 2005).

Within the catchment system, three broad zones may be defined in relation to nitrate buffer zones:

- (1) In the headwater zone, discharge through the saturated riparian zone is high compared to storage volume; in other words the average residence time is low. This may prevent anaerobic conditions from developing and so limit denitrification. Therefore, active buffer zones may well be limited in time and space in headwater valleys, but given the total length of the low-order tributaries (over 50% of perennial stream length are composed of first-order streams: Brinson 1993), their cumulative effect may still be significant.
- (2) Further downstream, where slope angles are lower and water stays longer in the riparian zone, soil conditions may well favour denitrification. However, the hydrological integrity of the whole riparian/floodplain zone is vital, and if the water table is lowered for any reason, usually because of land drainage, the buffer zone functions will almost certainly be lost, at least as far as nitrate is concerned.
- (3) Large rivers are not well connected to their adjacent catchment areas. There may be connectivity at some points in place and time (see Burt *et al.*, 2002a), but there can be many reasons why water tables are too low on the floodplain to sustain optimal conditions for denitrification (Pinay *et al.*, 1998). On the other hand, channel-floodplain linkage (the ‘bank storage’ effect) will be more important, so that some buffering still takes place and makes some contribution to reducing river nitrogen loads (Marmonier *et al.*, 1995).

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