Buffer zones and water quality protection: general principles

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Abstract

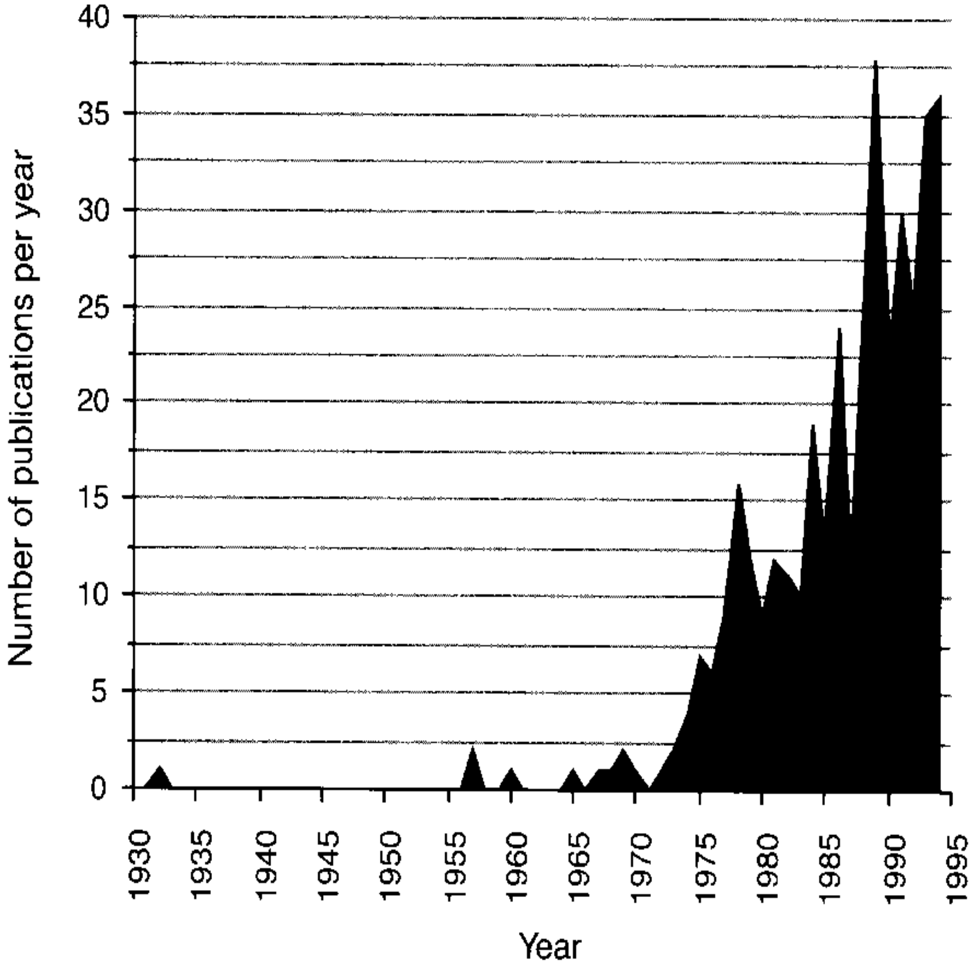
Riparian buffer zones (RBZ) improve water quality in different ways depending upon the pathway of delivery of water to the RBZ. Groundwater passing through the RBZ may be cleansed of nitrate and acidity due to a combination of denitrification, biostorage and changes in soil composition. Overland storm flows entering laterally from the uplands may be cleansed of suspended particulates, with adhering nutrients, inorganic toxins, and pesticides, as well as some dissolved nutrients and toxins. Sometimes these overland flows will also infiltrate within the RBZ and become a part of the groundwater, thus also obtaining the benefits associated with groundwaters in the RBZ. During stream flooding events, waters flooding out into the RBZ may also be cleansed of sediments, nutrients and toxic materials as a result of particulate trapping and the binding of materials on the leaf litter and soils within the RBZ. The RBZ is also an important source to the stream of high quality dissolved and particulate organic matter which is delivered both vertically and laterally. Forested RBZs also provide shade and evaporative cooling to streams, maintaining lower summertime temperatures critical to some biota. Factors which limit the effectiveness of the functions can be divided into internal and external. Factors external to the RBZ include watershed area and gradient, stream channel morphology, soil mineralogy and texture, bedrock type and depth, and climate. Factors internal to the RBZ include width and type of vegetation, waterlogging and organic content of soils, hydraulic conductivity, soil nutrient content and geochemistry. These water quality functions of RBZs and the factors which limit their effectiveness in various settings are reviewed from the world literature.

INTRODUCTION

Only a few papers which explicitly reported the results of studies of the water quality buffering effects of vegetated riparian zones were published prior to the early 1970s (Fig. 1). Although it is very difficult to draw sharp boundaries around this subject, there are now over 400 such papers and the rate of publication is about 30 to 35 papers per year. Despite this increasing rate of publication, our knowledge base concerning the water quality buffering effects of riparian zones is far from adequate. For descriptive aspects such as the removal of nitrate and particulate matter from the waters traversing the riparian zone or the release of organic matter to these waters we have considerable data but lack knowledge for how these functions change with climate or watershed management; species composition and age of the plant community; or how and when these functions will be saturated or exceeded. More fundamentally, we usually do not have an adequate understanding of the basic mechanisms involved in these processes or the controls over the rates of these processes. Lacking this understanding of mechanisms, we are in danger of being overconfident of our ability to predict system behaviour and response to major changes in inputs, invasions by exotic biota, or altered climate. With this situation in mind I will endeavour to review the world literature on riparian buffer zones, with my emphasis on streams and water quality.

If we look at riparian vegetation and the soils in which they grow as a part of the landscape (Lowrance et al., 1985; Jordan et al., 1986; Correll et al., 1992), we can examine factors that control the health and functioning of these ecosystems and delimit them spatially. Some of these factors are internal or endogenous to the riparian ecosystems, while other factors are external or exogenous (associated with either the drainage basin or the stream channel) (Correll and Weller, 1989). Geomorphic factors may be internal (soil physics and chemistry, slope within the riparian zone) or external (watershed area and gradient, soil mineralogy and texture, bedrock type and depth, volume and composition of groundwater inputs, channel morphology). Watershed area and gradient are major determinants of the volume and kinetics of external inputs to riparian zones. Soil mineralogy is a very important determinant of the chemical composition of external inputs, whereas soil texture to a large extent determines the relative proportions of surface water and groundwater inputs. Lateral overland storm flows may be effectively cleaned by forested RBZs when these flows arrive as sheet flows from relatively small fields with slopes of 5% or less (Peterjohn and Correll, 1984), but when the fields are larger and storm flows become concentrated, they may erode channels through forested RBZs (Jordan *et al.*, 1993). Some success has been reported in treating these larger concentrated storm flows by the use of level spreaders and grassed filter strips prior to forested RBZs (Franklin *et al.*, 1992).

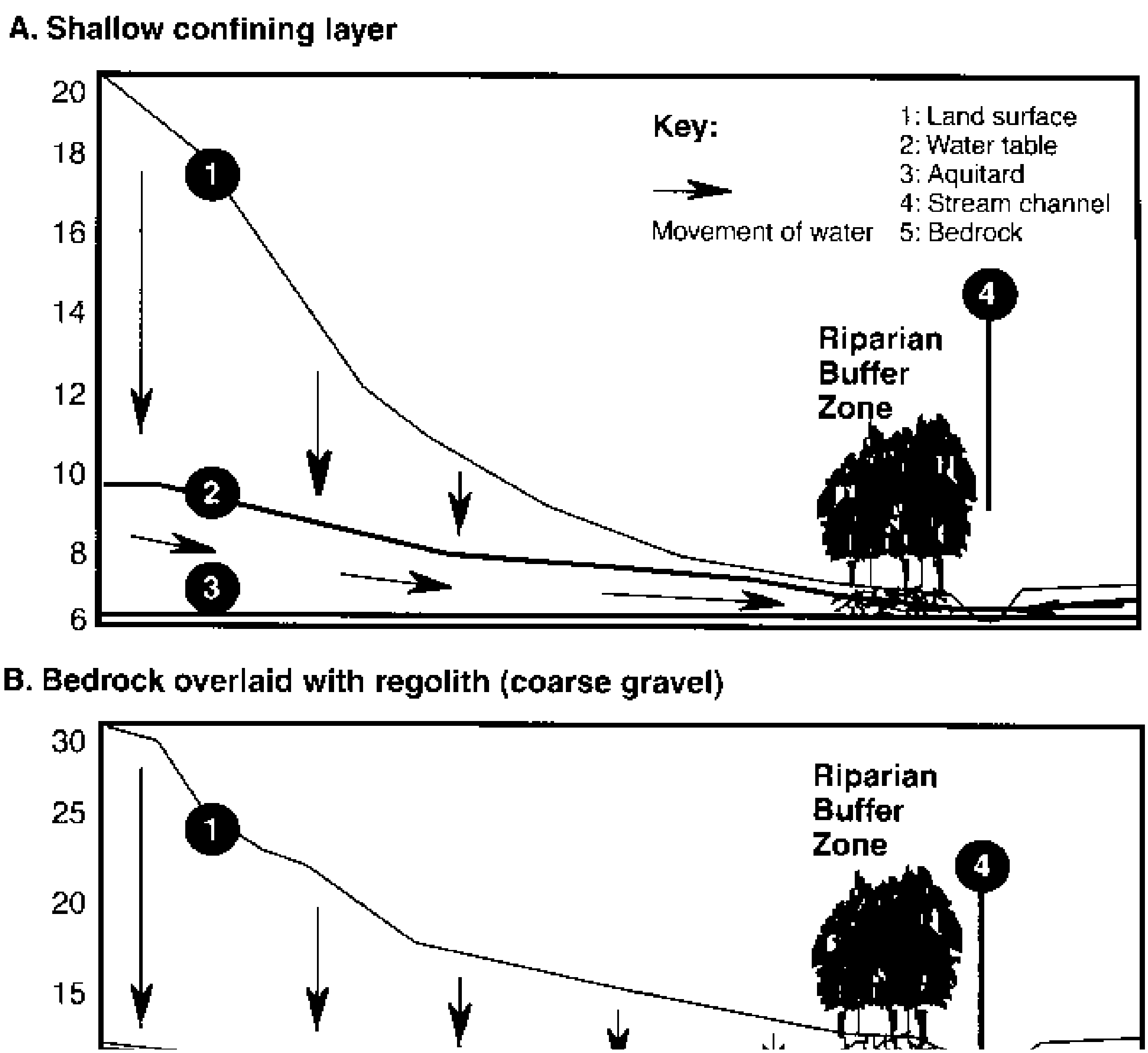
Figure 1. Number of publications related to riparian zones.

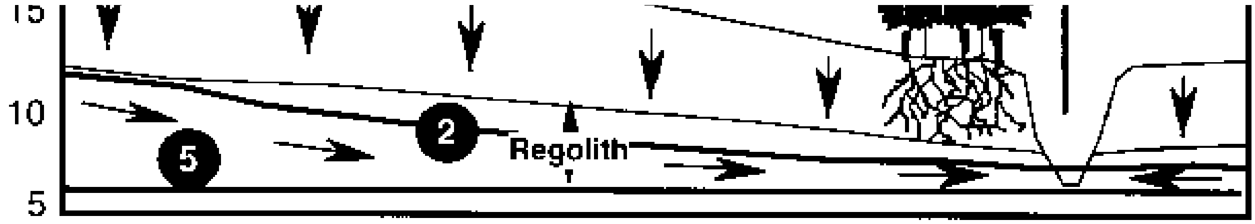


HYDROLOGY OF THE RIPARIAN BUFFER ZONE

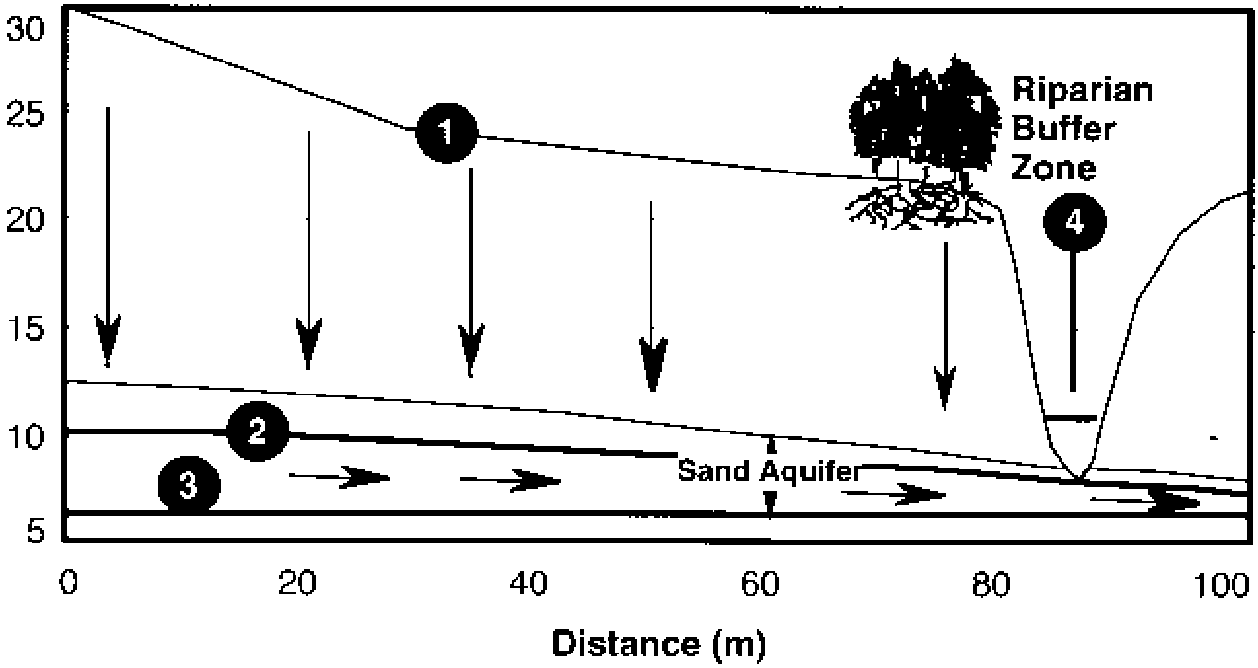
Since the water quality effects of the Riparian Buffer Zone (RBZ) are highly dependent upon the volume and pathway of water movement through this zone, it is obvious that an understanding of hydrology is important (Fig. 2; Mitsch *et al.*, 1977; LaBaugh, 1986; Chescheir *et al.*, 1988; Correll and Weller, 1989; Dosskey and Bertsch, 1994). The major climatic control factors are the components of the hydrological cycle: precipitation, runoff, and evapotranspiration (ET) (Correll and Weller, 1989). ET is, in turn, governed primarily by such factors as vegetation, humidity, temperature, wind and sunlight. Thus, to some extent the riparian vegetation has a feedback to the hydrological cycle. The output of the external watershed equals precipitation minus ET minus infiltration to noncommunicating deep aquifers. Depending upon the situation, some of this watershed output will be directly into the riparian zone from upslope areas and some of the output will be to the adjacent stream channel. Channel waters will have various amounts of inputs to the riparian zone via groundwater or surface flooding, depending upon stream discharge rate. The output of the riparian zone equals precipitation plus surface and groundwater inputs minus ET minus infiltration to deeper layers. If the local groundwater passes beneath the RBZ or the whole stream system at too great a depth, the riparian zone cannot interact (Fig. 2C; Denver, 1991; Staver and Brinsfield, 1991). In some cases overland storm flows entering the RBZ infiltrate the soils and become groundwater (Cooper *et al.*, 1995; Correll *et al.*, 1996). If this infiltration is not detected, data are easily misinterpreted. Stable isotope studies have shown that the source of water for ET of stream bank trees is sometimes lateral shallow groundwater flows rather than water from the channel (Dawson and Ehleringer, 1991). In a number of studies hydrological tracers such as bromide have been injected into the groundwater in order to demonstrate that sampling points downgradient were actually along the path of groundwater flow (Hill, 1990, 1991; Jordan *et al.*, 1993; Hubbard and Lowrance, 1994; Lockaby *et al.*, 1994). These tracer methods are usually qualitative rather than quantitative. In some cases (Triska *et al.*, 1989, 1990a ; Simmons *et al.*, 1992; Nelson *et al.*, 1995) the tracer was mixed with a nutrient such as nitrate or ammonium and was added to the system continuously for an extended time. Then ratios of nutrient to tracer were measured down gradient to detect nutrient transformations and to correct for the inevitable effects of dilution. An inadequate understanding of the hydrology of RBZ study sites usually limits the quantitative interpretation of study results.

Figure 2. Watershed cross-sections.





C. Deeply incised channel and a sand aquifer



OXIDATION / REDUCTION POTENTIAL OF THE SOILS

Many of the characteristics of riparian zones, such as the species composition of the vegetation and rates of processes such as denitrification, require that the soils be anaerobic or of low oxidation/ reduction potential (Eh) at least part of the year. The vegetation of the riparian zone is of fundamental importance in maintaining this low Eh. The below-ground processes which result in this low Eh are composed of a series of biogeochemical reactions that occur in a defined order (Billen, 1976). These reactions transfer electrons from organic matter, released from the plants, to various terminal electron acceptors. The availability of terminal electron acceptors determines which level in the series will dominate below-ground processes at any one time and place in the riparian zone. Some of the more commonly important reactions are manganate ion reduction, denitrification, ferric iron reduction, sulphate reduction, and methanogenesis. They occur in this order as a result of thermodynamic considerations. None of these reactions can proceed in the presence of molecular oxygen. Once oxygen has been consumed by processes such as respiration, and sulphide and ammonium ion oxidation, then manganate reduction may proceed. Once all manganate is reduced or if none occurs at the site, then denitrification can proceed, and so on. The reversibility of many of the reactions is limited by the production of volatile end products or changing pH. These factors and others produce a series of negative feedback mechanisms which tend to limit the further progress of a given belowground process (Correll and Weller, 1989). For example, in the case of sulphate reduction, as the ratio of electron acceptor to product decreases (e.g. $S0_4^{=}/S^{=}$), the equilibrium Eh required for the reaction to proceed declines. As the absolute concentration of sulphate declines, Eh must also decline for the reaction to proceed. As the pH rises, due to consumption of hydronium ions in the reaction, the Eh must decline for the reaction to proceed. At the same time the rates of entry of oxygen and other more easily reduced electron acceptors, such as nitrate, continue at previous rates, which will raise the Eh if sulphate reduction rates begin to slow down. Another example is denitrification. As the reaction proceeds, pH rises due to hydronium ion consumption in the reaction, and nitrate is converted to dinitrogen and nitrous oxide gases which evolve from the system, and the rate of denitrification slows while the rates of other processes such as nitrification may increase. For the riparian zone to maintain a low Eh it is therefore essential in the long run that the plants have a high primary productivity and that enough of the resulting photosynthate be released below-ground to provide enough electrons to drive these reactions at high rates. Despite the relative ease of measuring soil Eh, few studies have reported this critical parameter. Exceptions include Jacobs and Gilliam (1983, 1985), Davidson and Swank (1986), Pinay *et al.* (1989), Jordan *et al.* (1993) and Correll *et al.* (1996).

RIPARIAN EFFECTS ON THE GROUNDWATER ENTERING THE STREAM

Most of the water flowing down the channel of most streams reached the channel at some point as groundwater moving from a recharge area to the stream. This groundwater may move as shallow lateral flows (Fig. 2A) or as deeper flows that surface in the channel from strata below the channel (Fig. 2B). Of course a little of the rain water is deposited directly in the channel (channel interception) and some arrives as overland storm flows. The overland storm flows are of short duration following intense rain events and are usually less than 30% of the annual stream discharge, with the exception of systems with very heavy clay soils where infiltration is very limited. Thus, the quality of the water in the channel during baseflow periods between major storms is highly dependent upon processes within the RBZ. As used here the RBZ includes much of what is sometimes referred to as the hyporheic zone.

Nitrogen transformations

The first studies which directly measured nitrate concentration decreases in groundwater as it moved through riparian zones along streams were in the Coastal Plain of North Carolina (Gilliam *et al.*, 1974; Gambrell *et al.*, 1975). High concentrations of nitrate in shallow groundwater percolating out of row crop fields declined rapidly before reaching the stream channels and streams in these areas did not have the high nitrate concentrations one would expect from the watershed land use. In the early 1980s these results were repeated and more directly related to the presence of deciduous hardwood forests in the RBZs at three Atlantic Coastal Plain sites: Little River watershed near Tifton, Georgia (Lowrance *et al.*, 1983; Lowrance *et al.* 1984a, 1984b, 1984c), two sites in North Carolina (Jacobs and Gilliam, 1983, 1985), and the Rhode River watershed in Maryland (Correll, 1983; Correll *et al.*, 1984; Peterjohn and

Correll, 1984). All of these sites were in regions of the Coastal Plain where most of the discharge from agricultural fields moves as shallow lateral groundwater flows to stream channels. Thus, it moves through the rooting zone of riparian forests in soils that are often waterlogged and maintain a low oxidation/ reduction potential. These studies led to mass balances for total nitrogen retention of 74 kg N/ ha yr or 89% of inputs at the Rhode River site and 26 kg N/ha yr or 67% of inputs at the Little River site. At the Beaverdam Creek site in North Carolina nitrate retention was 30 kg N/ha or 85% of nitrate inputs.

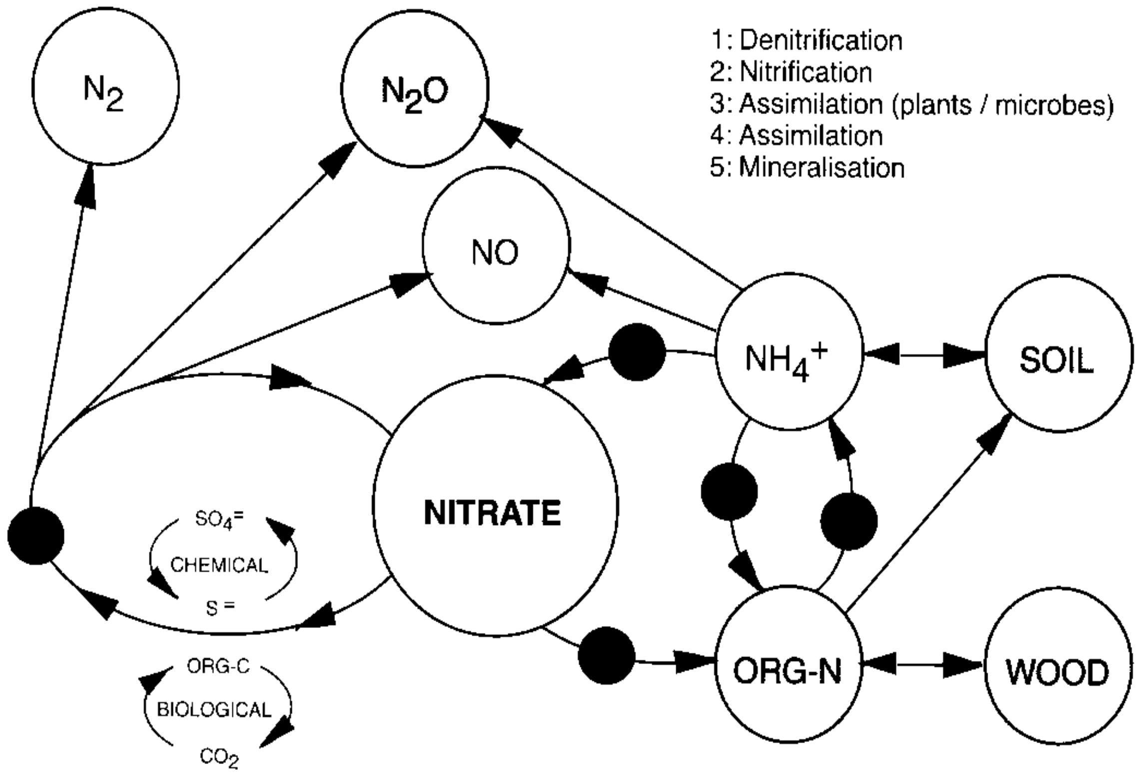
These early studies were of great interest to both environmental scientists and land managers. Within a few years similar studies were publishing results from a series of new and different sites. These include the Garonne River and its tributaries in France (Pinay and Decamps, 1988; Pinay *et al.* 1989); intensively managed sheep pastures in New Zealand with grassed RBZs (Cooke and Cooper, 1988; Cooper, 1990; Schipper *et al.*, 1994a, 1994b); grassed and forested RBZs in England (Haycock and Burt, 1993a, 1993b; Haycock and Pinay, 1993); forested RBZs in Rhode Island (Groffman *et al.*, 1991, 1992; Hanson *et al.*, 1994); the Mahantango Creek watershed in the Ridge and Valley area of Pennsylvania (Schnabel, 1986; Schnabel and Stout, 1994); forested and grassed RBZs in Illinois (Osborne and Kovacic, 1993); Ontario, Canada (Warwick and Hill, 1988), and two additional sites in the Atlantic Coastal Plain on the eastern shore of Maryland (Jordan *et al.*, 1993; Correll *et al.*, 1996). At all of these sites lateral flows of groundwater had decreases in nitrate concentration as they moved through the RBZ. More limited studies were also reported from Germany (Knauer and Mander, 1989) and Estonia (Mander *et al.*, 1989).

Mechanisms of nitrate removal or transformation in the RBZ

The mechanisms responsible for these widely documented retentions of nitrate have proven rather elusive. Candidate mechanisms include denitrification, assimilation and retention by the vegetation, and transformation to ammonium and organic nitrogen followed by retention in the soils of the RBZ (Fig. 3). It is quite clear in a number of studies that the nitrate is not simply converted to other soluble forms of nitrogen and discharged in the stream channel (e.g. Lowrance *et al.* 1983, 1984a, 1984b, 1984c ; Peterjohn and Correll, 1984; Correll and Weller, 1989; Jordan *et al.*, 1993; Correll *et al.*, 1996). Few studies have accurately measured the amount of nitrate removed by any one of these mechanisms at a given site and no study has measured the removal rate by all three mechanisms.

Denitrification is most often invoked as the primary mechanism of nitrate retention; however the extreme spatial and temporal variability of denitrification rates in RBZs make it very difficult to determine accurate fluxes (Correll, 1991; Weller *et al.*, 1994). Laboratory incubations of soil samples demonstrate the potential for denitrification, but these measurements are hard to extrapolate to the field. The products of denitrification include dinitrogen, nitrous oxide and nitric oxide and the proportions of these products are highly variable. Most studies do not measure all of these products. Instead they use chemical inhibitors to stop the production of dinitrogen. These inhibitors may cause more artefacts.

Figure 3. Mechanisms of nitrate removal in riparian buffer zones.



Field studies of nitrate mass balance show that nitrate is effectively removed: a) at all times of the year in temperate climates; and b) from groundwaters moving in subsoils at depths of several metres. Studies of potential denitrification in riparian soils find that most of this potential is in the top few centimetres of soil (Ambus and Lowrance, 1991; Ambus, 1993; Pinay *et al.*, 1993). Conditions in the deeper subsoil include low temperature, low pH and low concentrations of dissolved organic matter. These facts lead some to scientists to conclude that assimilation by the vegetation is the primary mechanism of nitrate removal (e.g. Fail *et al.*, 1986). While the vegetation may be very important in explaining the nitrate removal, nitrate is removed in the winter at sites where the vegetation is hardwood deciduous forest that is dormant in the winter. Further, measurements of nitrogen accumulation in the annual accretion of woody biomass was only 12 to 20 kg N/ha yr (Peterjohn and Correll, 1984; Correll and Weller, 1989). Thus, even if all of the nitrogen for this biomass came from nitrate in the groundwater it would only account for about 30% of the nitrate removal. It is highly likely that some of the nitrogen assimilation occurred from other sources. Jacobs and Gilliam (1983) also found that accumulation of nitrogen in riparian vegetation explained a relatively minor portion of the nitrate that was removed at their sites. These facts make it likely that assimilation and storage in woody biomass is a significant mechanism, but not the primary mechanism. However, it is possible that assimilation by the vegetation and recycling to the forest floor as litter is important in unravelling the overall primary mechanism. The rate of assimilation at the Rhode River site was 77 kg N/ha yr and litter fall plus throughfall was 66 kg N/ha yr (Peterjohn and Correll, 1984). Thus, assimilation by the forest could be the primary mechanism of nitrate removal from groundwater during the growing season and the flux of organic nitrogen delivered to the forest floor as litter could be gradually mineralised and denitrified at the soil surface. Such a mechanism would, however, not explain nitrate removal during the winter. Studies in New Zealand have shown high rates of dissimilative nitrate reduction to ammonium, which is then bound to the soils of the RBZ (Schipper *et al.*,1994a). Some scientists believe that nitrate removal from the groundwater traversing RBZ subsoils is accomplished by chemical rather than biological denitrification (Mariotti *et al.*, 1988). Strong reducing agents such as iron sulphides may react with nitrate to produce dinitrogen and sulphate. Certainly some RBZs at times reduce sulphate to sulphide (Correll and Weller, 1989; Jordan *et al.*, 1993), and at times sulphide is oxidised back to sulphate and released (Correll and Weller, 1989). If chemical denitrification does take place, it still would depend, in the long-term, upon adequate supplies of organic matter in the subsoils of the RBZ to maintain a low enough Eh. Understanding the primary mechanism of nitrate removal is very important. If this is the primary mechanism at such sites, the system's soils will eventually become nitrogen saturated. Some evidence of potential nitrogen saturation has been demonstrated at sites in Rhode Island (Hanson *et al.*,1994). If RBZs do become nitrogen saturated and cease to carry out their nitrate removal function the result would be very serious declines in receiving water quality.

In some RBZs soil Eh is not low enough some of the time to allow denitrification at significant rates. This may be short-term, as associated with periods between rainfall events, or longer-term due to extended drought, or it may be a seasonal phenomenon. It may also be spatially very patchy (e.g. Weller *et al.*, 1994). In such situations an alternation of denitrification and nitrification are observed (e.g. Duff and Triska, 1990; Triska *et al.*, 1990b, 1993; Jones *et al.*, 1994). In both processes significant nitrogen losses as nitrous oxide and nitric oxide occur in addition to the production of dinitrogen by denitrification. Some researchers believe that this alternation of nitrification and denitrification help to explain the large nitrate removals observed in RBZs.

Other effects on groundwater quality

Although RBZ effects on nitrogen, especially nitrate, are often emphasised in studies of riparian buffering, there are other significant water quality effects. The pH of groundwater is often significantly altered. Below-ground processes often consume or release hydronium ions (Correll and Weller, 1989). In non-calcareous, poorly buffered soils, such as are found on parts of the Atlantic Coastal Plain, groundwater draining from row crops is quite acidic, due to the effects of nitrification in the fields and acid deposition (Correll *et al.* 1987). As it moves through RBZs both plant assimilation of nitrate and denitrification consume hydronium ions and the pH increases to values less toxic to aquatic animals (Peterjohn and Correll, 1986; Jordan *et al.*, 1993). These pH changes, when coupled to other data, can be used to calculate metabolic rates (e.g. Jones Jr. *et al.*, 1994). Dissolved phosphorus and organic carbon concentrations usually increase as groundwater moves through RBZs (Correll and Weller, 1989; Jordan *et al.*, 1993). This is the result of the low Eh in these riparian soils.

SEDIMENT, NUTRIENT AND PESTICIDE TRAPPING ON THE SURFACE

The role of riparian vegetation in trapping sediments and adhering phosphorus was reported in widely cited articles by Karr and Schlosser (1978) and Schlosser and Karr (1981a, b). Riparian vegetation facilitates the removal of suspended sediments, along with their nutrient contents, from two types of surface water: a) overland storm water entering laterally (Mitsch *et al.*, 1979; Peterjohn and Correll, 1984; Lowrance *et al.,* 1988; Klarer and Millie, 1989; Chescheir *et al.,* 1991; Parsons *et al.,* 1994); and b) flood waters entering from the stream channel (Kitchens *et al.,* 1975; Hart *et al.,* 1987; Kleiss et al., 1989; Hupp and Morris 1990; Hupp *et al.*, 1993; Johnston, 1993; Brunet *et al.,* 1994). In both cases riparian vegetation plays an important role in removing and retaining particulates. Increased friction with soil surfaces can cause reduced velocity and consequent sedimentation of particulates, but riparian vegetation and the layer of litter it deposits on the soil surface are much more effective at slowing the velocity of the surface waters. The fine roots of the plants, which are concentrated on or near the surface, and the microbial communities on the surfaces of the soil, litter, and above-ground plant organs also are able to assimilate dissolved nutrients from the surface waters (Peterjohn and Correll, 1984). Relatively few studies have examined the effectiveness of RBZs in trapping pesticides and other toxic materials from overland storm flows. Early work by Correll *et al.* (1978); Rhode *et al.* (1980), and Asmussen *et al.* (1977) found that most of the herbicides atrazine, alachlor, trifluralin, and 2,4-D were removed from cropland discharges. More recently Schultz *et al.* (1994) found that a reconstructed three-tiered riparian buffer in Iowa was effective in removing atrazine from cropland discharges.

IS THE VEGETATION IMPORTANT OR NECESSARY?

Questions are often asked about the efficacy or necessity for vegetation in the RBZ. Does it matter whether vegetation is present? Is woody vegetation more effective than grass or herbaceous vegetation? Are broadleaved hardwoods better than coniferous trees? How wide a zone of vegetation is needed? These are all good questions for which we have few good answers. Although there was general agreement among studies of riparian forest buffers in the Atlantic Coastal Plain that nitrate was efficiently removed from shallow groundwater (Jacobs and Gilliam, 1983; Lowrance *et al.* 1983; Peterjohn and Correll, 1984), this in itself did not prove that the forest was necessary for this process. Studies on the North Carolina Coastal Plain found that fields could be cropped right up to the stream channel and nitrate removal would still occur efficiently, if controlled drainage structures were used to prevent the drying of the riparian soils (Gilliam *et al.*, 1979, 1986). Groffman *et al.* (1991) reported that denitrification potentials in surface soils of grassed RBZs in Rhode Island were somewhat higher than in forested RBZs. Further, Haycock and Burt (1993a, 1993b) found that grass riparian zones in England were very effective in nitrate removal from groundwater. Haycock and Pinay (1993) found that poplar forested RBZs were somewhat more effective at nitrate removal than grass, especially in the winter. Osborne and Kovacic (1993) found that forested RBZs in Illinois were more effective than grass for nitrate removal, but less effective for removal of phosphate and dissolved organic phosphorus from groundwater. Finally, Correll *et al.* (1996), in a comparison of two adjacent RBZ sites in Maryland, one grassed and one forested, found that they had similar nitrate removal efficiencies.

While there is considerable uncertainty on the exact role of riparian vegetation and the relative efficacy of various types of vegetation, it seems clear that grass or dense herbaceous vegetation is more effective at trapping particulates from overland storm flows (Osborne and Kovacic, 1993; Parsons *et al.*, 1994), but that woody vegetation may be more effective at removing nitrate from groundwater. In the long term it is clear that riparian vegetation is necessary to maintain the organic matter in riparian soils, which is needed for maintaining low Eh and processes such as denitrification. Woody vegetation, especially forest, is also more effective at providing organic matter in the deeper subsoils, where it is needed for effective denitrification in groundwater. However, changes in soil chemistry are slow and therefore the effects of present land management may not be apparent for decades.

RIPARIAN VEGETATION AS A SOURCE OF ORGANIC MATTER TO THE CHANNEL

Most stream channels are partially heterotrophic ecosystems which rely on organic matter inputs from the riparian zone and watershed for much of the organic matter used as an energy source to drive their food webs (Fisher and Likens, 1973; Minshall, 1978; Triska *et al.*, 1982; Conners and Naiman, 1984; Cuffney, 1988; Kleiss *et al.*, 1989). Many studies have shown that most of the particulate organic matter and much of the dissolved organic matter inputs are derived from areas immediately adjacent to the stream channel (Sedell *et al.*, 1974; McDowell and Fisher, 1976; Winterbourn, 1976; Triska *et al.*, 1984; Sidle, 1986; King *et al.*, 1987; Chauvet and Jean-Louis, 1988; Cushing, 1988; Gurtz *et al.*, 1988; Benson and Pearson, 1993; Sweeney, 1993). Vegetation along the stream bank and overhanging the channel contributes vertical litter fall and vegetation near the bank contributes litter by downslope lateral movement. The relative proportion of these two types of input varies dependent upon the local situation.

Role of riparian vegetation in stream temperature control

Riparian forests reduce solar heating of stream water by shading, especially in low order streams (Brown and Krygier, 1970). Any riparian vegetation provides cooling by evapotranspiration of soil water and shallow groundwater (Beschta, 1984; Theuer *et* al., 1984; Sinokrot and Stefan, 1993). This cools waters flowing into the stream channel laterally and waters exchanging between the channel and the hyporheic zone. The evapotranspiration cooling is greatest when the vegetation is forest, since forest has the highest leaf area index and consequently the highest evapotranspiration rates. Hardwood deciduous riparian forest in temperate climates has evapotranspiration rates as high as 118 cm per year (Peterjohn and Correll, 1986).

Riparian vegetation as a source o f large woody debris

Stream channels benefit from a steady input of woody branches and tree trunks. This debris and the debris dams that result bring about complexity in channel morphology and more useful habitats for stream biota (Minshall, 1978). The necessary woody debris originates almost entirely in the riparian zone (Webster, 1977). This literature will not be reviewed here; for a comprehensive review see Harmon *et al.* (1986).

RIPARIAN BUFFERS AND FORESTRY

When forested watersheds are clear-cut the rates of erosion and nutrient leaching increase until the vegetation begins to recover. Studies of the effects of clear-cuts on stream water quality have been reviewed by Vitousek (1981) and Webster *et al.* (1992) and will not be discussed here. However, in a few studies paired forested watersheds were subjected to experimental logging. Typically, the streams draining all would be monitored for several years, then one or more would be clear-cut, some would be clear-cut but a forest buffer strip would be retained, and at least one would be maintained as a forested control. Following the logging the water quality of the streams would be monitored to document the speed of recovery. Examples of such studies include West Virginia (Aubertin and Patric, 1974), Pennsylvania (Lynch and Corbett, 1990); and western Australia (Borg *et al.*, 1988); the results were similar. If a forested buffer was maintained, only small increases in suspended sediments and nutrients were observed in the streams compared with controls and complete clear-cuts.

RESTORATION OF FORESTED RIPARIAN BUFFERS

Once land managers became aware of the benefits to be gained from RBZs, a movement began to restore these vegetated buffers in areas where they had been destroyed. Two research projects in the United States have been attempting to re-establish native hardwood forest in stream riparian zones while monitoring their effectiveness. Several projects are under way on the Little River watershed in Georgia and early results indicate some success both in establishing forest and intercepting agricultural pollution (Hubbard *et al.*, 1995; Lowrance *et al*., 1995). Another project on the White Clay Creek watershed in Pennsylvania encountered more difficulty in reestablishing hardwood forest, but is now making progress (Sweeney, 1993). In some cases the sapling trees need protection from browsing and girdling as well as intense competition from exotic plants before they can become reestablished.

SUMMARY

The efficacy of RBZs in removing pollutants from surface and groundwater is highly dependent upon hydrology. For effective removal of particulates and dissolved nutrients and toxic materials, surface flows must occur as sheet flow rather than highly focused flows. For effective removal of nitrate and acidity, groundwater must move through the RBZ at a slow speed and at a shallow enough depth to be within the rooting zone of riparian vegetation. The vegetation in the RBZ must provide enough friction to surface flows to improve the efficiency of particulate trapping and provide surface litter to facilitate the assimilation of dissolved nutrients and toxic materials. The vegetation must also release enough organic matter at the depth of the groundwater to maintain a low enough Eh to allow rapid rates of denitrification. Riparian vegetation also provides shading and evaporative cooling of the stream channel. Cooling is most effective if the vegetation has a high leaf area index which reaches a maximum in hardwood deciduous forest. Vegetation also provides the stream channel communities with litter and large woody debris.

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