Impacts Of Hillslope And Floodplain Characteristics On Groundwater Dynamics: Implications For Riparian Denitrification

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EXTENDED ABSTRACT

One of the beneficial roles of riparian buffers is the capacity to attenuate groundwater nitrate before it can discharge to streams. Denitrification is one of the most important processes that permanently removes nitrate from groundwater; it requires anoxic conditions, a carbon source, and a suitable residence time as the reaction is microbially mediated. As denitrification rates are highly dependent on carbon availability, there is a higher potential towards the soil surface where carbon sources are more abundant. These facts highlight the importance of hillslope-floodplain hydrology as to determine how much nitrate can be removed from the landscape. There are three crucial hydrological factors that impact denitrification. Firstly, proximity of the water table to the root zone; this determines the extent of the anoxic root zone as well as the level of activity as shallower water tables mean that the groundwater is interacting with surface soils that are richer in carbon. Secondly, residence time determines how much nitrate is transformed while it resides within the riparian buffer. Thirdly, base flow discharge determines the total nitrate mass interacting with the riparian buffer. It is postulated that the soil type (and hence hydraulic parameters) of both the hillslope and floodplain play a crucial role in determining whether or not the hydrology is favourable for denitrification processes.

HYDRUS-2D is used to model a typical hillslope-floodplain scenario; the floodplain hydraulic conductivity was assigned different values such that the ratio K_1:K_2 varies from 1:1 to 1:1000 (where K_1 and K_2 are the hydraulic conductivities of the floodplain and the hillslope, respectively; isotropic conditions were assumed). Nitrate transformation via denitrification was modelled with 1st order decay kinetics; the decay rate was assumed to decrease with depth following an exponential decay function. Nitrate mass balance was monitored at the top four meters of the floodplain area.

It is shown that the ratio K_1:K_2 is the key parameter that determines how favourable the floodplain hydrology is to maximise nitrate removal through denitrification. As the hydraulic conductivity of the floodplain soil decreases, the water table in the floodplain rises; the water table rises significantly as the conductivity ratio decreases to 1:100; lower ratios down to 1:1000 result only in a further marginal rise. However, the fluxes through the floodplain follow a different trend; as the floodplain hydraulic conductivity decreases, water fluxes through the floodplain continue to decrease and eventually water starts to ex-filtrate at the break of slope. The optimal range of K_1:K_2 of about 1:15 is shown to sustain a shallow water table and allows high water fluxes through the floodplain. Reactive transport modelling has confirmed that maximal denitrification occurs when K_1:K_2 is equal to 1:15; this optimal trend becomes more notable as the distribution of denitrification rates becomes more non-linear with depth (i.e., when there is a much higher activity toward the soil surface); for a typical sandy aquifer having a hydraulic conductivity of 5 m/day, the optimum hydraulic conductivity of the floodplain sediments would be in the order of about 0.33 m/day. For the head gradients, geometry, and decay rates used in this work, the most active denitrification region (at optimal K-ratio) was between 1-3 m below the floodplain surface; the nitrate removal capacity in this zone was 29% but accounted for 62% of the transformed nitrate mass in the floodplain. The most active layer in the floodplain (0-1 m zone) had a maximal removal capacity of 81%, however, it accounted for only 24% of the transformed nitrate mass in the floodplain due to a low nitrate influx into this zone.

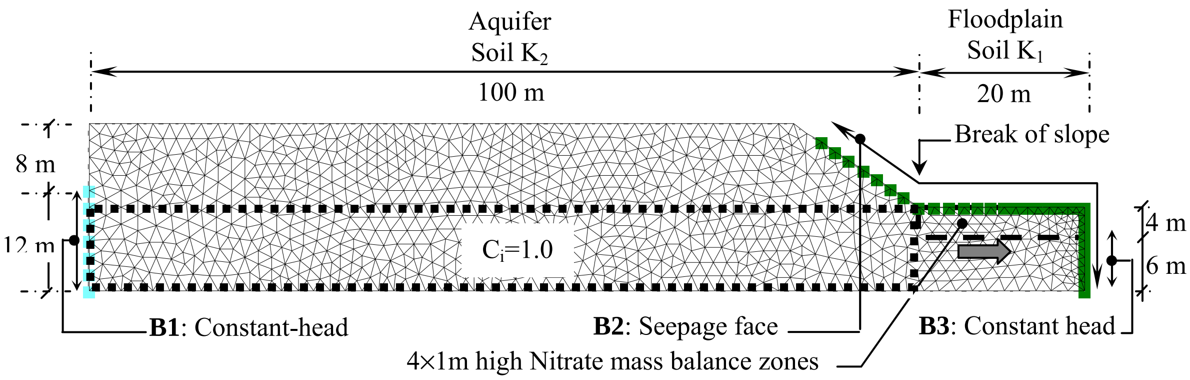

Figure 1: Flow domain and boundary conditions; C_i is initial unit concentration in dotted region

1. INTRODUCTION

An important function of riparian buffer zones is their ability to attenuate nitrate from catchment runoff and groundwater thus limiting degradation of the aquatic system. Denitrification is one of the main processes responsible for nitrate removal in riparian buffer zones; it is of particular importance because it is a pathway for permanent removal of nitrogen from the system. Many researchers have observed substantial reductions in nitrate as water passes through riparian buffer zones (Haycock and Pinay, 1993; Lowrance et al., 1984). Denitrification processes mainly occur in the saturated part of the root zone, which implicitly means an anoxic, carbon-rich area. As the reaction is mediated by bacterial activity, it usually involves a significant duration so the residence time of water in riparian buffers is of utmost importance. The main factors that drive denitrification processes are: riparian vegetation (as a source of carbon), the proximity of the water table to the root zone (to promote anoxic conditions), and slow flow rates (for longer residence times in the root zone). The geometry of the riparian buffer and how it links to the stream also plays a crucial role in determining the extent of denitrification. The extent of groundwater nitrate removal within riparian buffers is directly related to the flow path and travel time through the buffer in addition to the denitrification rates along the flow path. The nitrate removal capacity of most soils is expected to be highest at the surface, where root density, organic matter, and microbial activity are highest, and to decline rapidly with depth (Gold et al., 2001). It is apparent that the efficiency of riparian buffers to remove nitrate is highly dependent on their hydrology.

Peak denitrification rates are expected to occur in shallow aquifers where the watertable is high and intercepts the carbon-rich soils in the riparian root zone. The hydraulic conductivity of the floodplain sediment controls both the depth to the water table as well as flow rate; the latter affects both residence time and the volume of water that may pass through the riparian buffer. High permeability floodplain soils cannot maintain a shallow water table thus missing the opportunity of interacting with the carbon-rich surface soils; in addition, they result in a shorter residence time, which means a shorter interaction time with the floodplain sediments and a lower likelihood to develop anoxic conditions. On the other hand, low-conductivity soils have the ability to maintain a shallow water table but do not allow a large volume to pass through the riparian zone; they also promote seepage at the break of slope hence bypassing the floodplain. Woessner (2000) pointed out that management of near-channel groundwater and surface water to maintain stream health and floodplain biological function requires hydrogeologists to refocus their conceptual models of water exchange between the aquifer and the stream. He added that the flow, transport, and exchange of groundwater, nutrients, carbon, and oxygen in the floodplain is controlled by (1) the distribution and magnitude of hydraulic conductivities both within the channel and the associated floodplain sediments; (2) the relation of stream stage to the adjacent groundwater gradients; and (3) the geometry and position of the stream channel within the floodplain. Burt et al. (2002) supported the conclusions made by Woessner (2000) by stating that: ‘A flat riparian zone combined with soils of medium hydraulic conductivity provide optimal conditions for denitrification’.

It is postulated that the hillslope and floodplain hydraulic properties play a crucial role in determining whether or not the hydrology is favourable for denitrification. In this paper, a numerical modelling approach is adopted to support this hypothesis and identify the optimal range of hydraulic conductivities (of both the floodplain and upslope) that are most conducive to denitrification processes. Reactive transport modelling is used to evaluate the potential denitrification efficiencies for the range of hydraulic conductivities investigated. An idealised hillslope-floodplain scenario is modelled; it is relevant to middle order streams that have a base flow groundwater component discharging into them. This hypothetical study is closely related to the experimental study conducted by Rassam et al. (2005b) at Coochin Creek, South East Qeensland, Australia.

2. MODELLING EXPERIMENT:

HYDRUS-2D (Šimůnek et al., 1999) is used to simulate variably saturated water flow and reactive solute transport for a typical hillslope-floodplain situation; the problem is conceptualised as shown in Figure 1, which shows the finite element grid and imposed boundary conditions. The left-hand side of the flow domain B1 was assigned a constant head=12 m resulting in a 10% gradient towards the stream; the right-hand side (the stream bank and the floodplain surface) was modelled in two stages. During the first stage of the modelling, the entire stream bank and floodplain surface was assumed to be a seepage face (B2, Figure 1); the simulation was continued until a steady state condition was achieved to determine the height of the active seepage face (representing the potential stream height). During the second stage of the modelling the height of the active seepage face was used to assign a constant head boundary of the same magnitude that represents the stream (B3, Figure 1); the steady-state pressure head distribution obtained from the 1st stage simulation was used as the initial condition for the 10-day second stage simulation. Note that upstream flow from the catchment and its effect on stream height was ignored. The aquifer was represented by a sandy soil having a constant isotropic hydraulic conductivity K_2=10 m/day; the floodplain was represented by a variety of soils having different hydraulic conductivities K_1 such that the ratios K_1:K_2 vary from 1:1 down to 1:1000.

Reactive transport simulations were conducted to investigate the extent of nitrate influx and its transformation in the floodplain for a variety of conductivity ratios. HYDRUS-2D includes 1st order decay kinetics, which is suitable to model denitrification processes (Rassam et al., 2005a). Denitrification rates are highly correlated with the level of soluble organic carbon in the soil (Burford and Bremmer, 1975), which is largely associated with grass growth, litter fall, and the roots of riparian vegetation; carbon levels are approximated to be maximal at the soil surface and decline rapidly with depth. The distribution of denitrification rate with depth can be modelled using an exponential decay function as follows:

$$R_d = R_{max} e^{-kd} \tag{1}$$

where R_d is the decay rate (indicating denitrification) at any depth d (1/T; where T refers to time units), R_{max} is the maximum decay rate at the soil surface (1/T), d is the vertical depth below the ground surface (L; where L refers to length units), and k is a parameter describing the rate at which denitrification rate declines with depth (decay rate 1/L).

An initial unit nitrate concentration (relative concentration) was assumed in part of the flow domain area outside the floodplain (dotted rectangular area in Figure 1; C_i=1.0); this introduces a continuous flux of a unit nitrate concentration into the floodplain area during the simulation. Three different decay constants were examined, k=0, 0.5, and 1.0 m^{-1} (see k in Equation 1); the maximum denitrification rate at the soil surface was kept constant at R_{max}=0.5 day^{-1}; this value was based on field and laboratory denitrification experiments (CRC Catchment Hydrology Project 2D, unpublished data). In HYDRUS-2D, the decay rate is a material property; therefore we need to introduce a number of material types (soil types associated with the finite element nodes) to describe a soil profile having a variable denitrification potential (as described by Equation 1). Five material types were used to represent the floodplain area, (e.g., for k=0.5 m^{-1}, implementing Equation 1, decay rates were as follows: Material 1, nodes at floodplain surface R_o=R_{max}=0.5 day^{-1}; Material 2, nodes at 1 m depth R_1=0.303 day^{-1}; Material 3, nodes at 2 m depth R_2=0.184 day^{-1}, and so forth). A sixth soil type (with R=0) was used to represent the aquifer soil. Denitrification was assumed to be non-carbon limited, which indicates a healthy vegetated riparian buffer (i.e., abundant carbon). To monitor the denitrification activity at various floodplain levels, the upper portion of the floodplain was discretised into four, 1-m mass balance zones (top 4-m zone of the floodplain, see Figure 1); nitrate mass balance was calculated for those four floodplain zones for various k-values.

3. RESULTS:

3.1. Water Flow Modelling

Figure 2 shows the water table profiles in the floodplain for all the modelled hydraulic conductivity ratios. The general shape of the water table depends on the hydraulic conductivity ratio K_1:K_2. As the hydraulic conductivity of the floodplain's soil decreases, the water table in the floodplain rises. It is notable that the water table

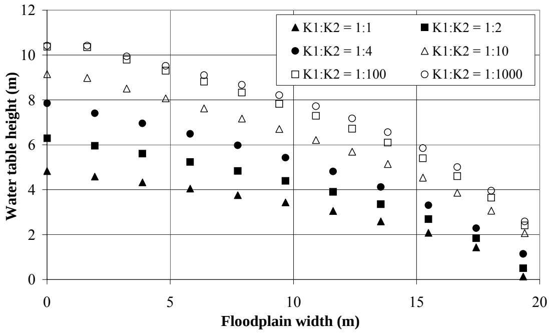

Figure 2: Phreatic surface in floodplain

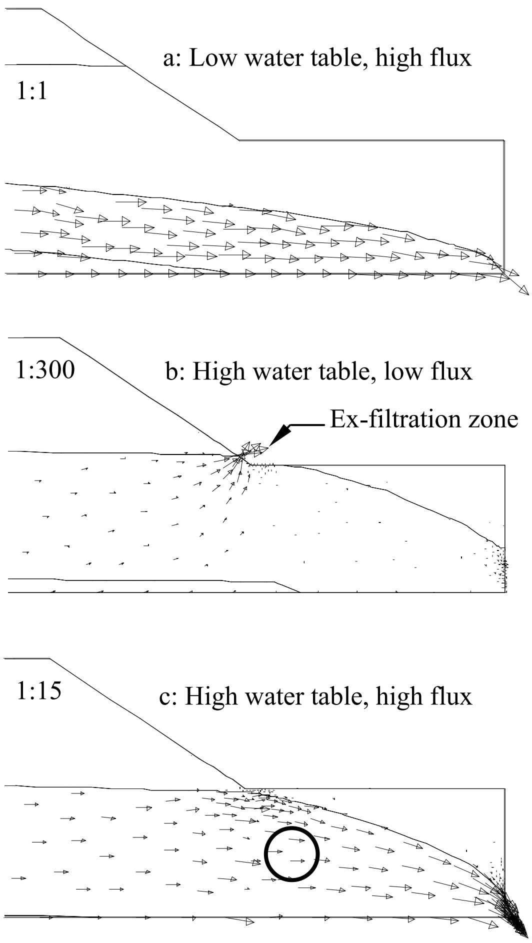

Figure 3: Velocity vectors and water table in floodplain for various K-ratios

rises steadily as K_1:K_2 ratios decrease down to 1:100; lower ratios down to 1:1000 result only in a marginal rise in the water table. The overall rise in the water table (measured at a cross section passing through the break of slope) is very significant and amounts to 5.6 m as K_1:K_2 drops from 1:1 to 1:100. Figures 3b and 3c show that the water tables for K_1:K_2=1:300 and 1:15 are almost identical whereas it is much lower for K_1:K_2=1:1

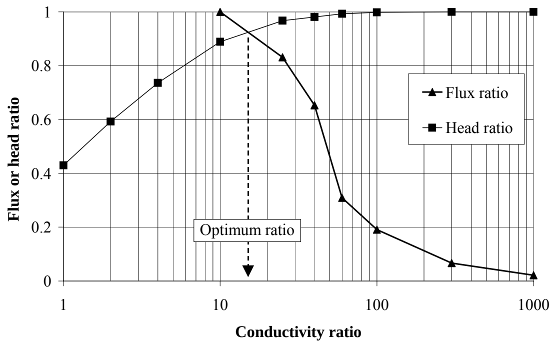

Figure 4: Flux and head ratios as a function of conductivity ratio

(Figure 3a). The velocity vectors in Figure 3b show that the fluxes for K_1:K_2=1:300 are very low meaning that the floodplain's low hydraulic conductivity is hindering flow; for the current geometry and pressure heads, this is causing the flow to be diverted to seepage at the break of slope (also termed ex-filtration; see Figure 3b). Note that when K_1:K_2 =1:15, no seepage component is present and the entire flow occurs within the floodplain. A quantitative study of the fluxes through the floodplain shows how the floodplain's hydraulic conductivity affects the volume of base flow discharging to the stream. In order to demonstrate how K_1:K_2 affects the pressure heads and fluxes in the floodplain, both were normalised with respect to the maximum value (maximum flux when K_1:K_2= 1:1, and maximum head when K_1:K_2= 1:1000), respectively. The flux ratio was obtained by dividing the flux to the stream by the total influx through the constant-head boundary B1 (see Figure 1); the pressure heads were monitored at a cross section passing through the break of slope.

The results in Figure 4 show that the optimum hydraulic conductivity ratio is 1:15. The term 'optimum' here describes a condition where a high water table (and hence a larger volume of saturated root zone) is coupled with a conductive soil that allows high flux to occur in the floodplain. A low hydraulic conductivity does result in a high water table but may hinder flow altogether thus deeming the floodplain ineffective in transporting any nitrate-rich water that could potentially lead to high denitrification.

For the optimal case shown in Figure 3c (K_1:K_2 =1:15) the magnitude of the velocity vector in the floodplain close to the break of slope is about 0.3 m/day (see encircled area in Figure 3c); this is based on K_2=10 and K_1=0.67 m/day (the former is typical for sands and the latter is typical for loams to sandy loams). This allows a suitable residence time for denitrification to occur; a parcel of water takes about 6 days to pass through a 20 m wide floodplain. The width of the riparian buffer varies across a catchment. Rassam et al. (2005c) conducted a study in the Maroochy Catchment and found that the optimal benefits of riparian buffers are realised for widths of up to 10m.

3.2. Reactive Transport Modelling

Figure 5 shows the transformed nitrate masses for the three k values used; k=0 is a hypothetical case where the denitrification potential is assumed to be uniform with depth whereas k=0.5 and 1 m^{-1} are more realistic values representing reality where denitrification potential is high at the surface and declines rapidly with depth as soluble organic carbon becomes scarce. When k=0, the transformed nitrate mass simply decreases as less water fluxes (and less nitrate mass) pass through the floodplain. When k≠0 (there is more activity near the floodplain surface), an optimal conductivity ratio that maximises the transformed nitrate mass is noted. Results obtained from the reactive transport modelling confirm earlier trends observed in Figure 4 relating to the optimum conductivity ratio. Figure 5 shows that maximal transformed nitrate mass also occurred when K_1:K_2 =1:15. The overall transformed nitrate mass decreases when k increases; as R_{max} is equal for all cases, increasing k results in reducing the denitrification potential (area under the rate versus depth curve becomes smaller). As k increases (denitrification potential becomes more non-linear, i.e. activity becomes more restricted to the soil surface), the increase in transformed nitrate mass becomes more significant as the conductivity ratio approaches the optimum; referring to Figure 5, note that m_5/m_{15}=6 and 20 for k=0.5 and 1.0 m^{-1}, respectively (where m_5 and m_{15} are the transformed nitrate masses for K-ratios=5 and 15, respectively).

Nitrate mass balance is investigated in order to understand the dynamics of nitrate transport and transformation in various parts of the floodplain. This is important because one needs to know which part of the floodplain contributes most to denitrification. The upper layer of the floodplain near the surface that has the highest denitrification potential is mostly unsaturated; on the other hand, most of the nitrate present in groundwater interacts with the deep riparian soil that has the lowest denitrification potential. The results are listed in Table 1.

Figure 6 shows the influx nitrate mass into the top 4-m (the four mass balance zones referred to in Section 2 and shown in Figure 1) of the floodplain and how it is affected by the conductivity ratios. As expected, more nitrate passes through the deeper floodplain zones. The nitrate influx into the surface layer of the floodplain (top 1 m) rises sharply as the conductivity ratio approaches 1:15, then it continues to rise marginally as the ratio further decreases. In the intermediate zones (1-3 m), the optimal conductivity ratio (K_1:K_2 =1:15) results in the highest influx of nitrate.

Figure 7 shows the proportion of the influx nitrate that has decayed (denitrified) in the floodplain. In the upper layer (0-1 m), 76% of the incoming nitrate was transformed due to a high denitrification potential (for K-ratio=15); in contrast, only 10% of the nitrate passing through the deeper zone (3-4 m) was denitrified. The maximum denitrification capacity at optimal conductivity ratio in zones 1-2 m and 2-3 m was

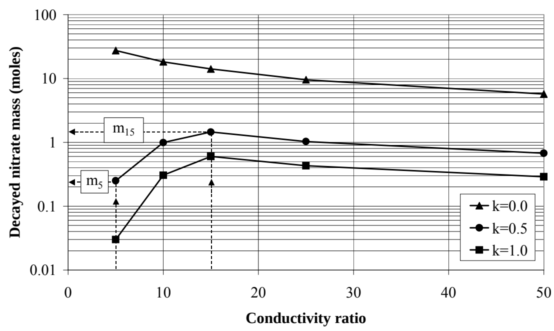

Figure 5: Decayed nitrate mass versus conductivity ratio

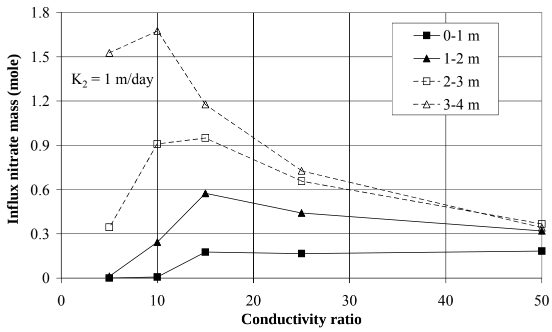

Figure 6: Nitrate load in various depth intervals of floodplain

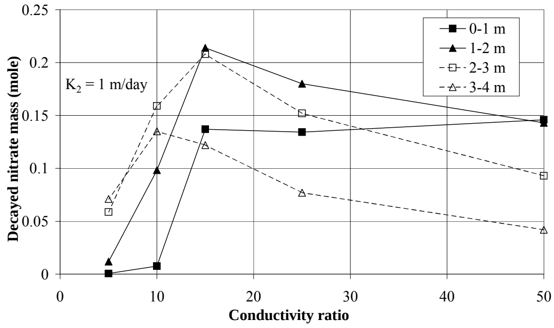

Figure 7: Decayed nitrate mass in various depth intervals of floodplain

Table 1: Nitrate mass balance data

K ratio	#	4×1-m Mass balance zones			
		0-1 m	1-2 m	2-3 m	3-4 m
50	I	0.18	0.32	0.36	0.34
	D	0.14	0.14	0.09	0.04
	F	0.77	0.44	0.25	0.12
25	I	0.16	0.44	0.65	0.77
	D	0.13	0.18	0.15	0.08
	F	0.81	0.41	0.23	0.10
15	I	0.17	0.57	0.95	1.17
	D	0.13	0.21	0.20	0.12
	F	0.76	0.37	0.21	0.10
10	I	0.007	0.24	0.91	1.67
	D	0.007	0.01	0.16	0.13
	F	1.0	0.4	0.17	0.08
5	I	0.0006	0.01	0.34	1.52
	D	0.0006	0.01	0.06	0.07
	F	1.0	1.0	0.17	0.04

#: I & D refer to nitrate mass (mole) where I=Input into zone and D=Decayed; and fraction F=D/I

37% and 21%, respectively; despite those low percentages, these two zones resulted in the highest nitrate transformation and accounted for 62% of total denitrification (refer to Table 1).

4. DISCUSSION AND CONCLUSIONS:

The efficiency of riparian buffers to remove nitrate varies with hydrological conditions, extent of riparian vegetation, and landscape attributes.

The key hydrological conditions that affect denitrification in riparian buffers are the proximity of the water table to the carbon-rich root zone, the flow rate within the floodplain (which determines residence time), and the flow volume (which determines the mass of nitrate that could potentially interact with the floodplain sediments). As K_1:K_2 decreases (where K_1 and K_2 are the hydraulic conductivities of the floodplain and the hillslope, respectively), the water table in the floodplain rises whereas the water and nitrate fluxes decrease; the optimal ratio K_1:K_2=1:15 maintained the highest groundwater table and allowed maximal water and nitrate fluxes into the floodplain.

Riparian vegetation is an important source of organic carbon, a crucial element for denitrification; organic carbon is more abundant at the soil surface and declines rapidly with depth. Therefore, the denitrification potential is maximal at the surface and declines with depth; this decline is closely related to the distribution of roots and their depth. From a modelling perspective, the maximum denitrification rate at the surface (R_{max}) and the decay parameter k (of Equation 1) both describe the denitrification potential of the riparian buffer. The decay parameter k has a great impact on the activity of the buffer. As k increases (while R_{max} remains constant), the overall denitrification potential is reduced because it becomes more restricted to the floodplain surface; this also means that a high water table becomes more advantageous and largely enhances denitrification thus having the suitable floodplain hydrology becomes more critical. Reactive transport modelling has shown that for k values between 0.5 and 1.0 m^{-1}, denitrification potential was maximised when K_1:K_2=1:15; for a typical sandy aquifer having a hydraulic conductivity of 5 m/day, the optimum hydraulic conductivity of the floodplain sediments would be in the order of about 0.33 m/day.

The landscape attributes have an important impact on denitrification processes; the relative levels of the groundwater table, the floodplain, and the stream are all critical. It was shown that as the conductivity of the floodplain decreased, water was diverted from flowing through the floodplain and was flowing preferentially as seepage through the break of slope. The slope of the floodplain greatly impacts the potential for denitrification; steep floodplains offer a lower chance for groundwater to interact with their sediments (Rassam et al., 2005c). For the flat floodplain considered in this study, it was shown that the uppermost layer that had a maximal removal capacity of 81% but only contributed to 21% of the total removed nitrate. However, depths ranging from 1-3 m that had a removal capacity of only 29% accounted for 62% of the total removed nitrate.

The current study highlights the important role of floodplain hydrology and its effects on potential denitrification, which has significant implications on riparian management. The optimal hydraulic conductivity concept discussed in this paper is one of many attributes indicating that a riparian buffer is conducive to denitrification. Rassam et al. (2005a) incorporated the concepts presented in this paper into the Riparian Nitrogen Model (RNM), a GIS-based, catchment-scale model that estimates nitrate removal due to denitrification. The RNM guides land managers to optimise riparian restoration by providing maps for targeted restoration.

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