COOPERATIVE RESEARCH CENTRE FOR **CATCHMENT HYDROLOGY**

THE RIPARIAN NITROGEN MODEL (RNM) - BASIC THEORY AND CONCEPTUALISATION

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David Rassam / Daniel Pagendam / Heather Hunter

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The Riparian Nitrogen Model (RNM) - Basic Theory and Conceptualisation

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Preface

Across Australia there is great interest in riparian zone restoration as a means of improving waterway health. One of the features of riparian zones is their ability to significantly reduce nitrogen loads entering streams, by removing nitrate from groundwater passing through them. The Cooperative Research Centre (CRC) for Catchment Hydrology carried out research into the processes of nitrate transport and removal in riparian zones (1999-2005), in collaboration with the CRC for Coastal Zone, Estuary and Waterway Management.

The initial focus of the research was on field-based experimentation backed by detailed laboratory studies, to develop a sound conceptual understanding of the key processes involved. This included investigations of riparian zone hydrology and of denitrification, the microbial process whereby nitrate is converted to nitrogen gas and released to the atmosphere. From this information the Riparian Nitrogen Model (RNM) has been developed and incorporated into the CRC for Catchment Hydrology's modelling Toolkit. Used in conjunction with catchment water quality models, the RNM can estimate nitrate transport and loss in riparian zones and predict responses to changes in management.

This report provides a detailed description of the RNM, including the conceptual basis of the model and its formulation, the data requirements and the model outputs. It also outlines the features of a "riparian mapping tool" that helps users identify riparian areas where restoration activities are likely to be most effective in reducing stream nitrogen loads.

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Executive Summary

Riparian zones can provide a protective buffer between streams and adjacent land-based activities by removing nitrate from shallow groundwater flowing through them. Increased inputs of nitrate to natural waters contribute to problems including reduced water clarity and growth of weeds and algae. Catchment-scale, water quality models are useful tools for predicting catchment behaviour under various climatic conditions and land use scenarios. In this document, we present the Riparian Nitrogen Model (RNM); the development of the RNM is a major activity of project 2.22, "Modelling and managing nitrogen in riparian zones to improve water quality". The RNM may operate as a filter module within a catchment-scale model (such as E2), or as a stand-alone package that provides maps for targeted riparian restoration.

The RNM estimates the removal of nitrate as a result of denitrification, which is one of the major processes that lead to the permanent removal of nitrate from shallow groundwaters during interaction with riparian soils; this interaction occurs via two mechanisms, firstly, groundwater passes through the riparian buffer before discharging to the stream, and secondly, as surface water is temporarily stored within the riparian soils during flood event. Denitrification mainly occurs in the saturated part of the root zone, which implicitly means an anoxic, carbon-rich area. As the denitrification reaction is mediated by bacterial activity, it usually involves a significant time duration so the residence time of water in riparian buffers is of utmost importance. Therefore, the main factors that drive denitrification processes are: riparian vegetation (provide the carbon source), the proximity of the water table to the root zone (ensure anoxic conditions), and slow flow rates (result in a high residence time thus allowing denitrification to occur). 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 nitrate removal capacity of most soils is expected to be highest at the surface, where root density, organic matter, and microbial activity are highest; it declines rapidly with depth. In the RNM, the spatial decline in denitrification rates with depth is modelled using a 1st order decay function; the wetted root area is identified and an average denitrification rate is estimated. First-order decay kinetics are also used to model nitrate removal due to denitrification as the nitrate-rich groundwater resides in the riparian buffer; an average residence time is calculated, which depends on the floodplain geometry, the hydraulic conductivity of the soil, and the prevailing head gradients.

The RNM is most suitably applied in riparian buffers belonging to low- and middle-order streams; it estimates the mass of nitrate removed in riparian buffers mainly via three mechanism: firstly, as surface water perches in the floodplains of ephemeral streams; secondly, as groundwater (base flow) intercepts the root zone in perennial streams; and thirdly, as surface water is stored in the banks of perennial streams. The calculations are carried out on a sub-catchment scale (hydrologic, 'functional unit' in E2 terminology). The conceptual models adopted are as follows:

- In ephemeral low-order streams, a simple bucket model is used. Areas of potential groundwater perching are identified; i.e., areas where a conductive floodplain soil overlays a low-conductivity layer. During flood events, those areas fill like a bucket (surface water becomes groundwater), this water is then denitrified during the flood event, and subsequently drains back to the surface water system.
- In perennial middle-order streams, denitrification occurs as base flow intercepts the root zone. The hydrology of the floodplain plays an important role in deciding the extent of denitrification (a shallow water table and a high residence time promotes denitrification). Flat floodplains with medium-conductivity soils are most conducive to denitrification.
- In perennial middle-order streams, denitrification may also occur when stream water is temporarily stored in banks during flood events. The amount of water stored in banks will depend on the size of the flood event, the soil properties such as hydraulic conductivity and porosity, the geometry of the floodplain, and the residence time (which depends on the event duration).

The nitrate loads removed via each mechanism is estimated. The spatial distribution of catchment denitrification potential is used in conjunction with land use data to produce maps that inform managers where optimal benefits from riparian restoration should likely occur; those areas in the catchment that have the highest denitrification potential and the highest potential for contaminant generation (e.g., as a result of fertiliser application) must be the prime target for riparian restoration. The model also provides an option to carry out scenario ‘what if’ modelling that is a valuable tool for guiding managers on priorities for riparian restoration.

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A	Contributing area for a raster cell on the stream network
A_{ep}	Area of the saturated root zone; ephemeral model
b	Stream bank height
c_1	Channel depth coefficient
c_2	Exponent relating bank-full discharge to channel depth
c_3	Exponent relating channel slope to channel depth
c_4	Exponent relating meander wavelength to bank-full discharge
c_5	Bank-full discharge coefficient
c_6	Exponent relating contributing area to bank-full discharge
c_7	Exponent relating the ratio of PET and rainfall to bank-full discharge
C_i	Contamination index
C_o	Initial nitrate concentration
C_t	Nitrate concentration at any time t
d	Vertical depth below the ground surface
D	Denitrification index
$d(x,y)$	depth from soil surface in terms of (x, y) local coordinate system
D_{bf}	Denitrification index for base flow component
D_{bk}	Denitrification index for bank storage component
D_{ep}	Denitrification index for ephemeral streams
Dp_{bf}	Channel depth at bank-full discharge for a raster cell on the stream network
d_i	Distance between the riparian zone cell and the i^{th} stream network cell
d_p	Depth to the perching layer; ephemeral model
d_s	Depth to stream water level
$d_{sat}(x)$	Depth of saturated root zone at any distance x
d_u	Travel distance along the riparian buffer
e_i	Elevation of the ith closest stream network cell to the riparian zone cell
e_{rz}	Elevation of the phreatic surface at a cell in the riparian zone
$g(x)$	Function defining the riparian ground surface
K	Hydraulic conductivity of the riparian soil
k	Parameter describing the rate at which denitrification rate declines with depth (decay rate 1/L)
L	Width of the vegetated riparian zone
m	$\tan \phi$ (slope of riparian ground surface)
n	$\tan \theta$ (slope of water table in riparian buffer)
M	Meander wavelength for a raster cell on the stream network
N	Total number of raster cells contributing to a cell in the riparian zone
p	Ratio of PET to rainfall for a raster cell on the stream network
r	Depth of the root zone
$r(x)$	Function defining the root zone in the riparian buffer
R_d	is the nitrate decay rate at any depth
R_i	Restoration index for the i^{th} raster cell
R_{max}	Maximum nitrate decay rate at the soil surface (1/T)
R_u	Average denitrification rate across the entire active section of the riparian buffer
$R_u(x)$	Average denitrification rate at any distance x from stream

S	Slope of the stream for a raster cell on the stream network
S_l	Length of a pixel along the stream
t_u	Average groundwater residence time
U_i	UPNESS index
v	Volume of water interacting with the riparian buffer
V_{bf}	Total base flow volume
v_{bk}	Volume of stream water interacting with either side of the riparian buffer along a pixel on the stream network (bank storage model)
v_{ep}	Volume of stream water interacting with either side of the riparian buffer along a pixel on the ephemeral stream network having the potential for perching
v_{μ}	Average groundwater velocity through riparian buffers
w	Depth to groundwater (base flow model)
$w(x)$	Function defining the water table in the riparian buffers
x_i	Distance at which the water table insects the root zone
x_r	Minimum of x_i and L
r	depth of root zone
Δh	Rise in the height of the stream during a flood event
α	Decay constant for drainage from, or filling into banks
δ_i	Distance of the ith raster cell in the contributing area from the riparian zone (measured in cells)
η	Nitrate removal index
η_{per}	Nitrate removal index for middle order perennial streams
η_{ep}	Nitrate removal index for ephemeral streams
ϕ	Angle of riparian buffer ground surface
β	Angle of water table in riparian buffer
β_i	Base flow fraction
β_t	Total base flow volume
κ_i	Normalised hydraulic conductivity of the riparian soil
ω_i	Boolean variable taking the value of 1 where the ith raster cell in the contributing area has the potential for contaminant generation and 0 where it does not

1. Introduction

The floodplain riparian zone is the boundary that connects the terrestrial and aquatic ecosystems. The floodplain and the riparian zone are now often taken to be one and the same thing (Burt *et al.,* 2002). Riparian zones can provide a protective buffer between streams and adjacent land-based activities by removing nitrate from shallow groundwater flowing through them. The only removal mechanism that is considered in this document is denitrification, a process that results in the formation of gaseous nitrogen from the reduction of nitrate. There is agreement that denitrification is one of the major processes responsible for removal of nitrate in riparian buffers (Gilliam *et al.,* 1997).

1.1 Denitrification Processes: Theoretical Background

Nitrate, oxygen, organic carbon, and soil micro-organisms are key factors that influence denitrification. Organic carbon provides energy for microbial respiration and also serves as an electron donor for denitrifiers. Most studies of denitrification in riparian zones have found that under saturated conditions either nitrate or organic carbon limits the rate of denitrification. Localised supplies of particulate organic matter have been shown to be important in supporting high rates of denitrification, including discrete patches of soil organic matter (Groffman *et al.,* 1996, Gold *et al.,* 1998) as well as peat and buried river channel deposits (Devito *et al.,* 2000, Hill *et al.,* 2000). Oxygen availability reduces the rate of denitrification (Parkin and Tiedje, 1984). Low oxygen concentrations in riparian zones are favoured by water-saturation, which limits the diffusion of oxygen, and by microbial respiration, which consumes oxygen. Groundwater moving slowly along shallow subsurface paths in riparian buffers may interact with anaerobic soil zones, which are likely to have a high organic matter content as a result of accumulation and decomposition of plant residues. Those zones are favourable for denitrification processes.

1.2 Conditions Conducive to Denitrification

For maximal nitrate removal in riparian buffers, we require the following:

- <u>The very existence of the floodplain</u> is crucial. It is recommended that its width should be in the order of tens of metres such that it can provide a low hydraulic gradient. Buffer zones are most effective along the middle-order reaches of a river network and along low-order tributaries that have floodplains.
- <u>A well-vegetated buffer</u> provides a good carbon source, with deep and densely rooted vegetation advantageous. 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; it declines rapidly with depth.
- <u>The floodplain should have a suitable hydrology</u> that favours denitrification; specifically:
    - A shallow water table that intercepts the carbon-rich root zone, thus providing anoxic conditions.
    - Relatively slow flow rates that allow sufficient residence time for nitrate to be denitrified.

These conditions are achieved where a suitable soil occurs in the floodplain, with a hydraulic conductivity such that it promotes a shallow water table with flow rates that allow denitrification to occur. Burt *et al.,* (2002) have pointed out that soils of medium hydraulic conductivities are most conducive to denitrification, however, they have neither provided specific values nor have they supported their conclusion with any modelling. Rassam (2005) has shown that the conductivity ratio K_1:K_2 (where K_1 refers to the conductivity of the floodplain and K_2 refers to the conductivity of the upslope) is the key parameter that determines the suitability of the floodplain hydrology for denitrification processes; soils that are most conducive to denitrification are those having a medium hydraulic conductivity of about 0.1 to 1 m/day.

2. Model Objectives

The Riparian Nitrogen Model (RNM) is being developed as a major activity of project 2.22, "Modelling and managing nitrogen in riparian zones to improve water quality". It is designed to operate at two different levels:

1. As a module within the catchment scale model E2, the RNM will deliver the following:
    - Estimate volumes of surface water that interact with riparian buffers in low order ephemeral streams and hence calculate the mass of nitrate removed. This interaction occurs as a result of water perching in floodplains belonging to low-order streams during flood events.
    - Estimate volumes of surface water that interact with riparian buffers in middle order perennial streams and hence calculate nitrate removal masses. This interaction occurs as a result of bank storage during flood events.
    - Use the base flow component of flow (calculated by the hydrologic engine, e.g. SIMHYD) and calculate the mass of nitrate removed. This interaction occurs as the base flow passes through the saturated portion of the root zone in the riparian buffers.
    * Provide scenario-modelling capability to test the positive impacts of riparian restoration.
2. As a stand-alone package, it will provide maps for targeted riparian restoration in catchments.

3. Model Conceptualisation

The Riparian Nitrogen Model calculates nitrate removal from groundwater and surface waters as a result of denitrification as these waters interact with riparian buffers. The model operates at two conceptual levels based on stream order; ephemeral low order streams and perennial middle order streams. Ephemeral streams are conceptualised as being streams that do not receive any kind of permanent base flow/interflow component, but rather, are channels for quick flow during events. Perennial streams are conceptualised as being those streams that do receive a permanent base flow/interflow component. These distinctions are of primary concern with regard to the mode of denitrification that is believed to take place. Table 1 shows the various processes considered in the RNM and the scales at which they are modelled. The conceptual models presented in this document are based on the experimental study conducted in South East Queensland reported by Rassam *et al.,* (2005).

3.1 Stream Ordering and Model Applicability

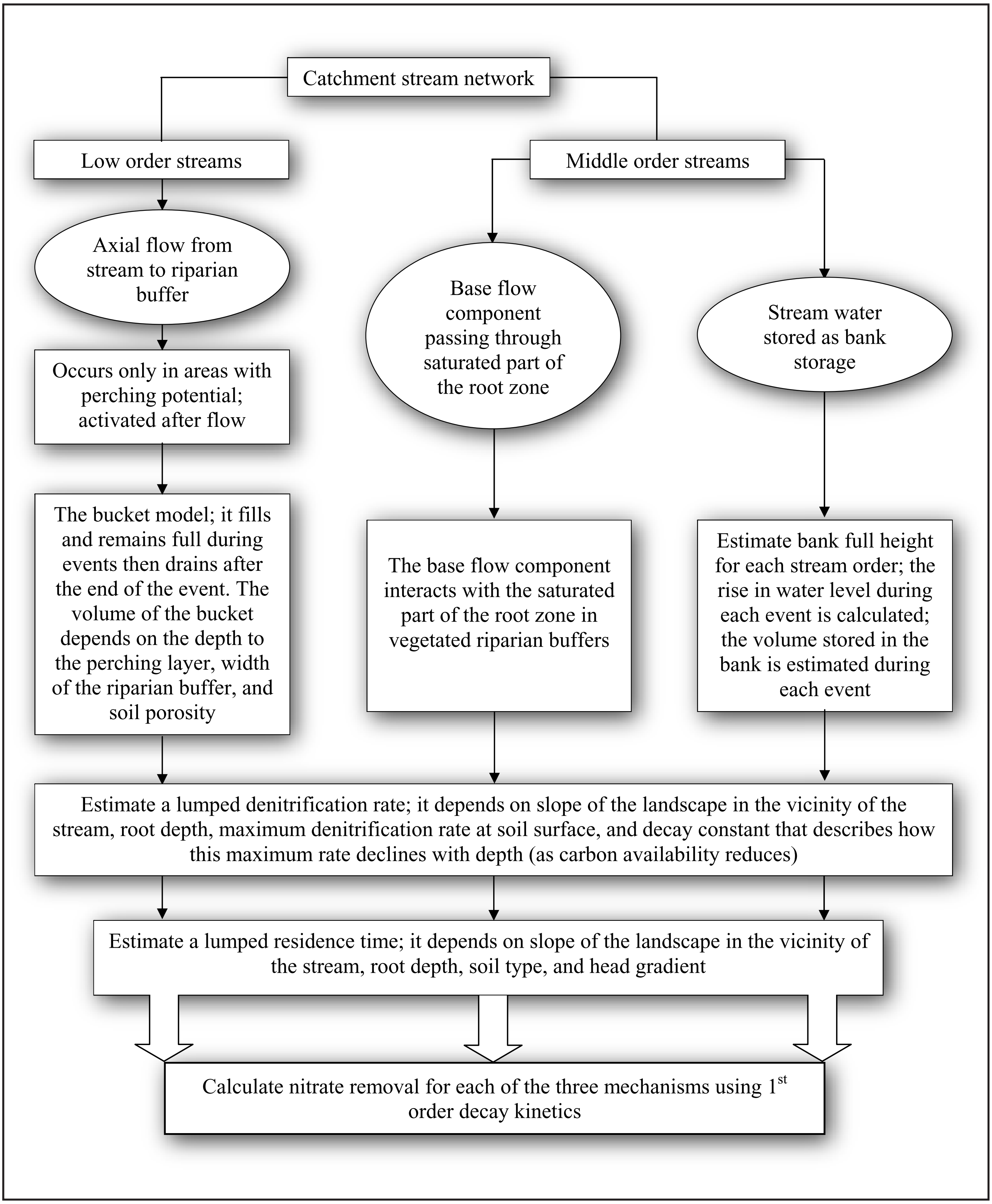
The RNM is most appropriately used in riparian buffers belonging to low- and middle-order streams. On high-order sections of large rivers, the upland areas may be too remote from the channel for buffer zones to have much effect (Burt *et al.,* 2002); the methodology is not suitable for large rivers floodplains where the dynamics of infiltration and drainage are very important.

The Riparian Nitrogen Model conceptualises a stream network as being comprised of three types of streams: (i) low order, ephemeral streams; (ii) middle order, perennial streams; and (iii) high order, perennial streams with large floodplains. The mechanisms of denitrification that are modelled in each of these three types of streams vary and it is therefore necessary to classify different sections of the stream network according to type. The method employed within the Riparian N Model for classifying a stream is based upon the idea of flow accumulation thresholds. A user must specify a flow accumulation threshold, which specifies the point at which the ephemeral stream network is initiated within a catchment. A second flow accumulation threshold must also be specified which identifies at what point streams cease to be ephemeral and can be considered to be perennial streams. The third type of stream (high order and perennial) are identified in one of two ways: (i) a third flow accumulation threshold is specified which identifies the initiation point of these streams; or (ii) a raster identifying large floodplains is input, which identifies those streams that intersect the floodplain area.

Figure 1 provides an example of how the three types of stream can be defined using three flow accumulation thresholds. The catchment is the Brisbane River Catchment, with green (low order), blue (middle order) and red (high order) streams defined using thresholds of 2 km^2, 50 km^2 and 1000 km^2 respectively.

Hill-slopes and valley bottoms have been identified as having distinctly different hydrological processes operating within them, with hill-slope flow paths primarily driven by topography and valley bottoms being far less predictable (Gallant and Dowling, 2003). The MRVBF (Multi-resolution Valley Bottom Flatness) algorithm (Gallant and Dowling, 2003) was developed in order to distinguish between these two hydrological/geomorphic features of landscapes; i.e., it can provide a raster identifying large floodplains that can be used to delineate high order perennial streams. The MRVBF algorithm produces a grid of a catchment, where cell values correspond to the relative lowness and flatness of the landscape in the context of the surrounding topography. The calculation of the index values is an iterative process, examining the attributes of flatness and lowness at a number of spatial resolutions, assigning the highest scores to those areas which can be considered to be low and flat at both fine and coarse spatial resolutions. MRVBF has been proposed as a useful tool in identifying alluvial floodplain areas for models such as SedNet (Wilkinson *et al.,* 2004). The identification of these alluvial areas is important for the RNM because it is not concerned with the processes operating within these alluvial systems, and must therefore be masked out of the spatial analyses.

Table 1. Flow Chart Showing Various Processes in the RNM.



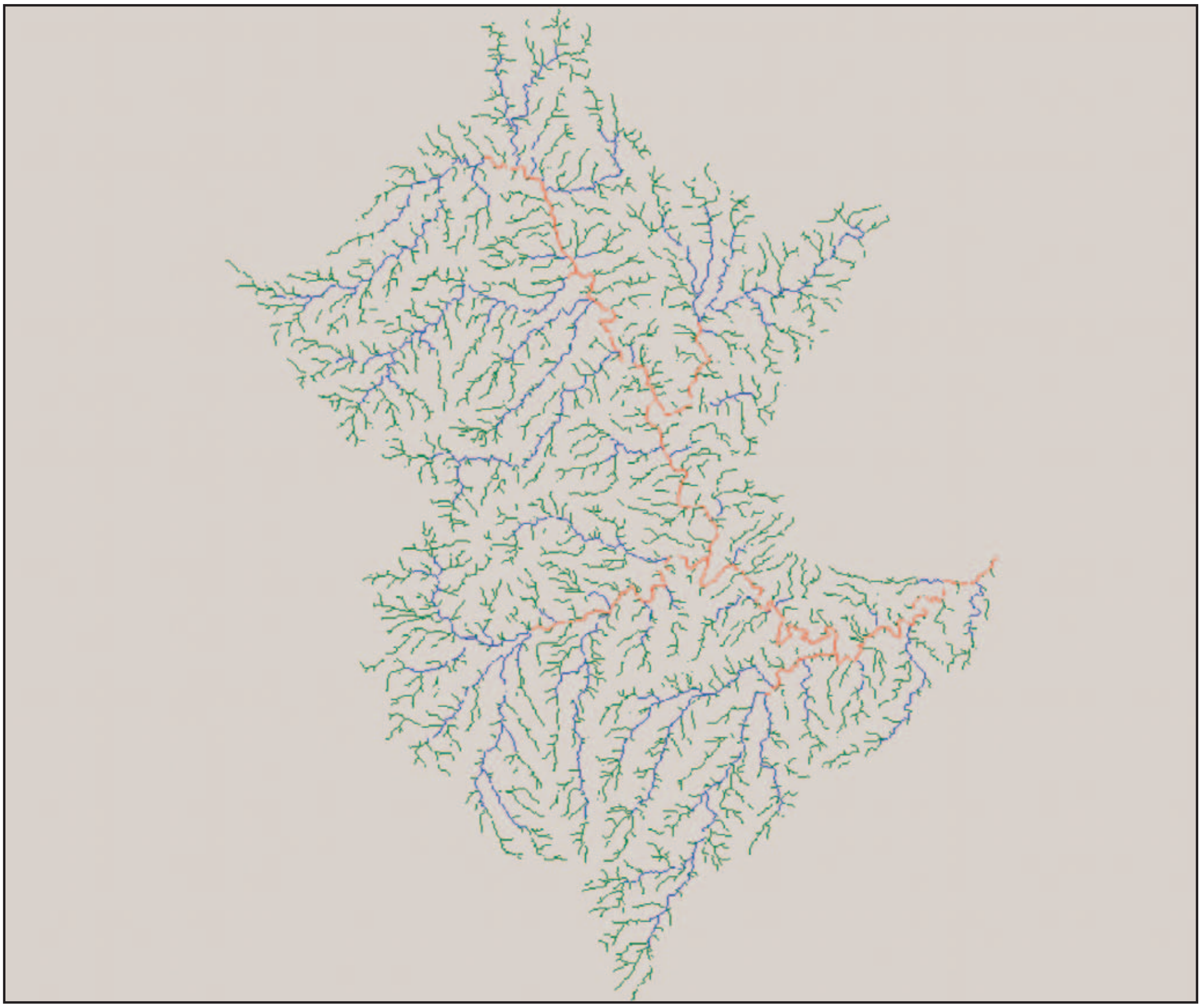


Figure 1. An Example of How the Three Types of Streams (Low, Middle and High Order) can be Generated Using Flow Accumulation Thresholds.

3.2 Conceptual Model for Denitrification in Ephemeral Streams

The conceptual model for denitrification in low order ephemeral streams is shown in Figure 2; the surface (stream) water is likely to interact with the carbon-rich root zone of the riparian buffer in areas where a localised perched shallow groundwater table forms; this happens when a low-conductivity confining layer underlies the permeable soil of the floodplain.

Denitrification in riparian zones of ephemeral streams takes place during flow events, after surface water flows laterally from the stream and into the riparian zone to form a shallow perched water table. Rassam *et al*. (2005) have shown that this storage mechanism is significant and should be taken into consideration in catchment water quality models. Where conditions are appropriate, this results in the denitrification of water derived from surface runoff, which later drain from the riparian zone and return to streams at lower areas in the catchment.

A simple bucket model similar to that presented by Rassam *et al*. (2003) is adopted to model the denitrification process. The bucket is assumed to fill during flow events; its size depends upon the width of the riparian buffer, the depth to the perching layer, and the soil porosity. The total volume stored in the functional unit depends on the total length of ephemeral streams that occur in areas of perching potential. The bucket has an increasing denitrification rate towards the surface. The residence time is directly related to the duration of the event. The model keeps track of the volumes stored in the riparian buffers during flow events; the water volume that is likely to be denitrified is that portion that interacts with the carbon-rich root zone. It is mentioning that the volumes that get temporarily stored in the riparian zone do not affect the stream hydrograph in any way.

3.3 Conceptual Model for Denitrification in Perennial Streams

Denitrification in riparian zones of perennial streams primarily occurs via two mechanisms; firstly, while base flow passes though the riparian zone; and secondly, as stream water gets stored in banks when a flood wave passes. Denitrification is assumed to occur only in the saturated part of the root zone across the width of vegetated riparian buffers.

The first mechanism (shown in Figure 3) involves the entire base flow component of flow obtained from the catchment rainfall-runoff model (e.g. SIMHYD). The extent of interaction between base flow and the saturated part of the root zone plays a crucial role in deciding the amount of denitrification that takes place; it is a function of root zone depth and depth to water table. Rassam (2005) has shown that medium conductivity soils result in optimum hydrological conditions regarding denitrification processes.

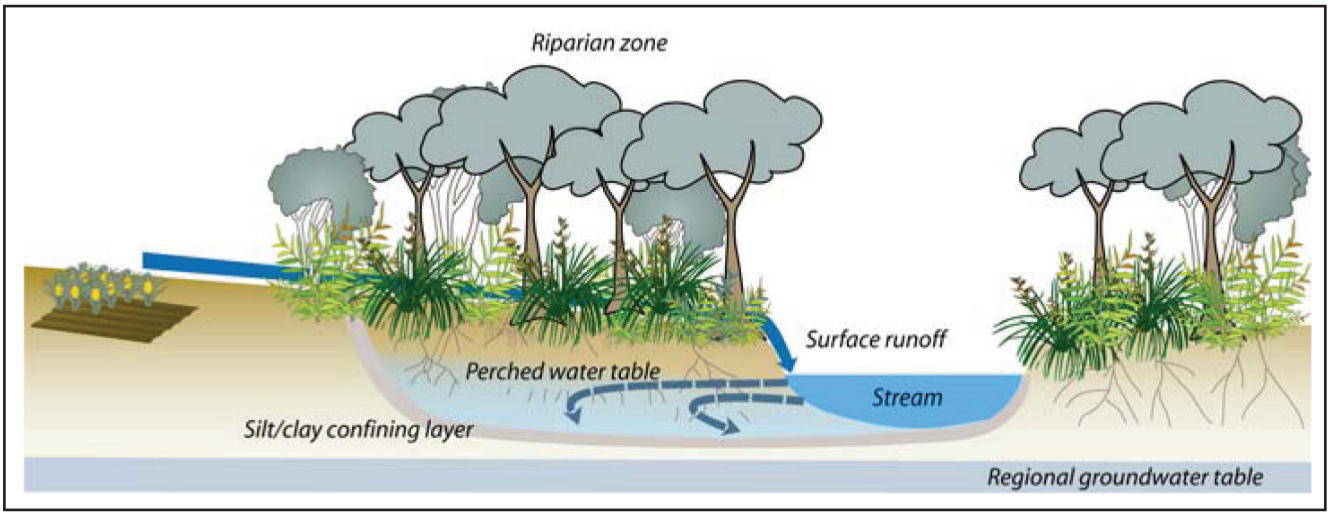


Figure 2. Surface Water Interaction with Riparian Buffers in Ephemeral Streams.

The second mechanism involves that part of the stream flow that is stored in stream banks as a flood wave passes (bank storage); this is similar to the concept of lateral flow described previously for ephemeral streams, i.e., surface water temporarily becoming groundwater, denitrifying, then draining back to the surface water system. The volume of water stored depends on the width of the floodplain and its slope, the soil's specific yield, and the volume of the flood event. Referring to Figure 4, during each flow event an approximate rise in stream level (Δh) is estimated and the associated volume stored across an area ΔA is then calculated. The model keeps track of the volumes stored in the bank during flow events; however, these volumes do not affect the stream hydrograph. Stream water is assumed to instantaneously saturate the riparian zone soil up to flood height, which is a justifiable assumption for permeable upland soils.

For both mechanisms, an average denitrification rate is estimated depending on floodplain slope, root depth, and the inherent denitrification rate of the floodplain soil and how it declines with depth. The average residence time generally depends on the hydraulic conductivity of the floodplain soil; for the base flow component it also depends on head gradients, and in the bank storage component it depends on the event duration.

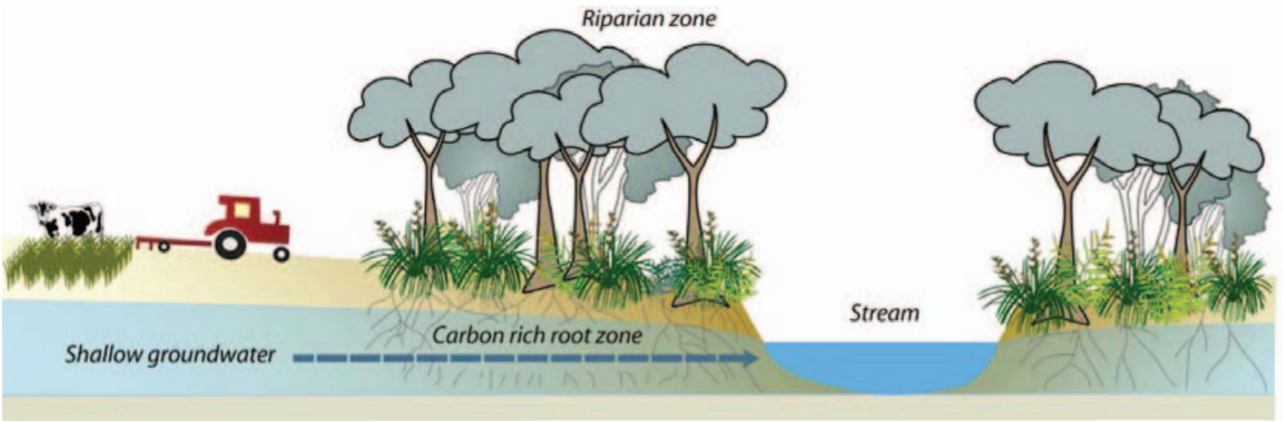


Figure 3. Ground Water Interaction with Riparian Buffers in Perennial Streams; Base Flow Component.

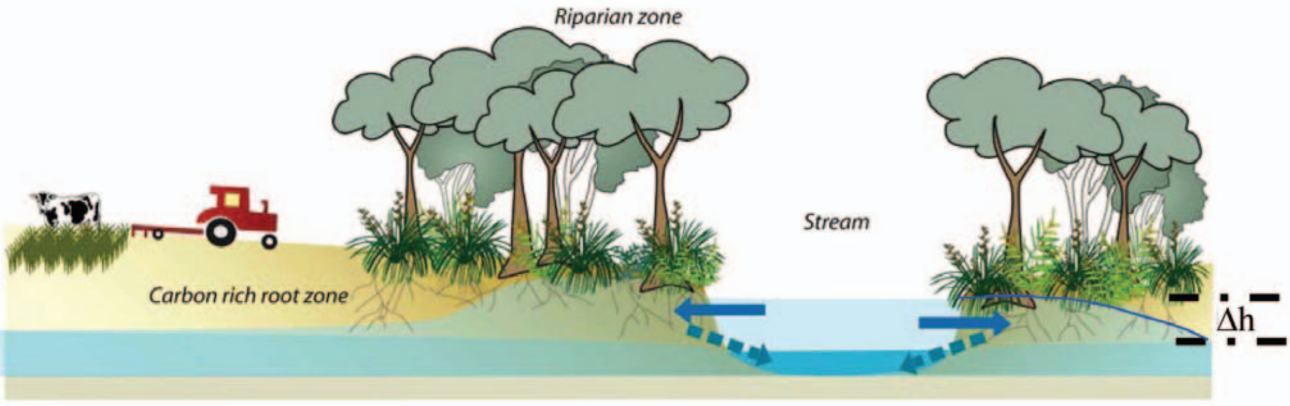


Figure 4. Surface Water Interaction with Riparian Buffers in Perennial Streams; Conceptualisation of Bank Storage During Flood Events.

4. The Riparian Nitrogen Model Input

The input to the Riparian Nitrogen Model (RNM) comprises two components: firstly, data sets obtained from the parent model (e.g., E2), and secondly, user input. It is recognised that data availability is a crucial element to any successful catchment-scale modelling activity; this rule also applies very well to the RNM. Flexibility is incorporated into the RNM by providing simpler alternative options when the required data sets are lacking. For example, the user can provide a spatial grid of vegetation, or a simple estimate of the percentage of the stream network that is vegetated. This will determine the fraction of riparian zone plan area that supports denitrification.

4.1 Input from Parent Model E2

- Time series of flow rates (and base flow separation) for each functional unit.
- Nitrogen loads for surface and base flow components obtained from time series for nitrate concentration and flow rate. Ideally, the user should define the proportion of total nitrogen that is considered as nitrate in the pollutant load for surface flow and base flow. However, default values for partitioning the nitrogen loads will be provided based on available data and expert opinion.

4.2 User Input

User input is as shown in Table 2 below, categorised into three classes: M (mandatory, meaning the model does not run without this data, which must be provided by the user); MD (mandatory, meaning the model does not run without this data; but if the user cannot provide this input, default values are provided or alternative data sets are required); and O (optional, meaning the model can run without this data).

Table 2. Data Requirements for the RNM.

Input Option*	Description	Type	Comments
M	DEM and stream network	Raster	Should be available for the parent model
M	Accumulation thresholds	Values	Individual thresholds for ephemeral low-order, middle order perennial, and high-order perennial streams; the latter is not needed if maps of large floodplains are provided
M	Fraction of stream reaches that are vegetated	Raster or value	-
M	Riparian buffer width	Raster or value	-
MD	Soil hydraulic conductivity	Raster, value, or range	Default values available for the ‘range’ option, defined as low, medium, or high
MD	Soil porosity	Raster, value, or range	Default values available for the ‘range’ option defined as sand, silt, or clay soils
MD	Rooting depth	Raster, value, or range	Default values available for the ‘range’ option defined as shallow or deeply rooted vegetation
MD	Maximum denitrification rate at soil surface	Value	High and low default values available for well-vegetated and poorly vegetated riparian buffers
MD	Decay of denitrification rate with depth	Value	-
MD	Perching potential (presence of perching layers and their depth	Raster or value	Raster may be created based on expert opinion of geomorphology, bore log data or combinations of these in a fuzzy membership context[#]
MD	Average bank-full height for each stream order	Value	-
MD	Proportion of total nitrogen that is nitrate	Value	-
MD	FLAG UPNESS index	Raster	Alternative MRI-Darcy model available
O	Floodplain maps	Raster	This becomes mandatory if an accumulation threshold is not provided for high order perennial streams
O	Areas of potential base flow based on groundwater flow systems	Raster	This option may enhance the management layers by informing where base flow is likely to occur

* M is Mandatory; MD is Mandatory but default values are provided; O is Optional.

A fuzzy surface of perching potential may be constructed by using an inverse distance weighted method with bore stratigraphy data that show locations of shallow low-conductivity layers.

5. The Riparian Nitrogen Model Engine

5.1 Modelling a Variable Denitrification Rate with Depth

Denitrification rates are highly correlated with the level of organic carbon in the soil, which is largely associated with grass growth, litter fall, and the roots of riparian vegetation. It is assumed that organic carbon levels are maximal at the soil surface and decline with depth. In the RNM, the distribution of denitrification rate with depth is modelled using a 1st order decay function as follows:

$$R_d = R_{max} \frac{e^{-kd} - e^{-kr}}{1 - e^{-kr}} \qquad (1)$$

where: (refer to Figure 5A)

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

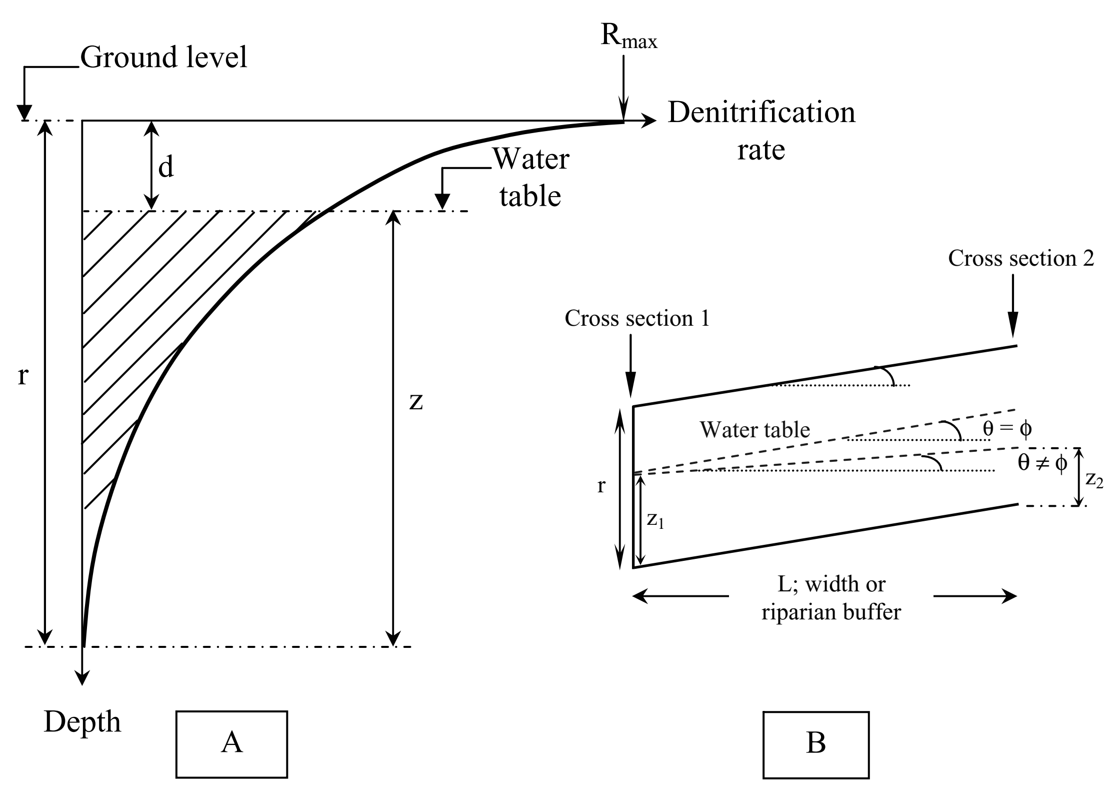


Figure 5. Distribution of Denitrification Rate Along the Riparian Buffer.

Denitrification in soils under anaerobic conditions is controlled largely by the supply of readily decomposable organic matter for microbial reduction of nitrate. Burford and Bremmer (1975) showed that the denitrification capacities of 17 soils were very highly correlated (r=0.99) with water-soluble organic carbon. Figure 6 shows that Equation 1 is capable of modelling a measured dissolved organic carbon profile; therefore, since dissolved organic carbon and denitrification potential are highly correlated (Burford and Bremmer, 1975), we expect that Equation 1 is suitable for modelling the decay of denitrification rate with depth. The current formulation ignores temperature effects on denitrification rates.

Since the upper horizons of riparian soils are invariably unsaturated for most of the time, the maximum denitrification rate at the soil surface is unlikely to be operable. On the other hand, denitrification processes are negligible below the rooting depth as insufficient carbon is available; the formulation of Equation 1 ensures zero denitrification below the rooting depth (R_u=0 at d=r). Denitrification processes are assumed to be active only in the saturated (anoxic) part of the root zone below the water table (throughout interval z between d_1 and d_2, Figure 5A). We can define an average denitrification rate Ru throughout the interval z as follows:

$$R_u = \frac{1}{r-d}\int_d^r R_d dy \qquad (2)$$

Referring to Figure 5A, this means that the product (zR_u) is equal to the hatched area, which represents the overall denitrification potential across the saturated portion of the root zone. Note that if the water table is not parallel to the ground level ($\theta \neq \phi$; Figure 5B), the hatched area or the length ‘z’ (see Figure 5A) will vary across the floodplain length (i.e., $z_2<z_1$; see Figure 5B); in that case we need to mathematically define the water table then conduct a second integration across the floodplain width L to obtain the overall average R_u for the entire riparian zone.

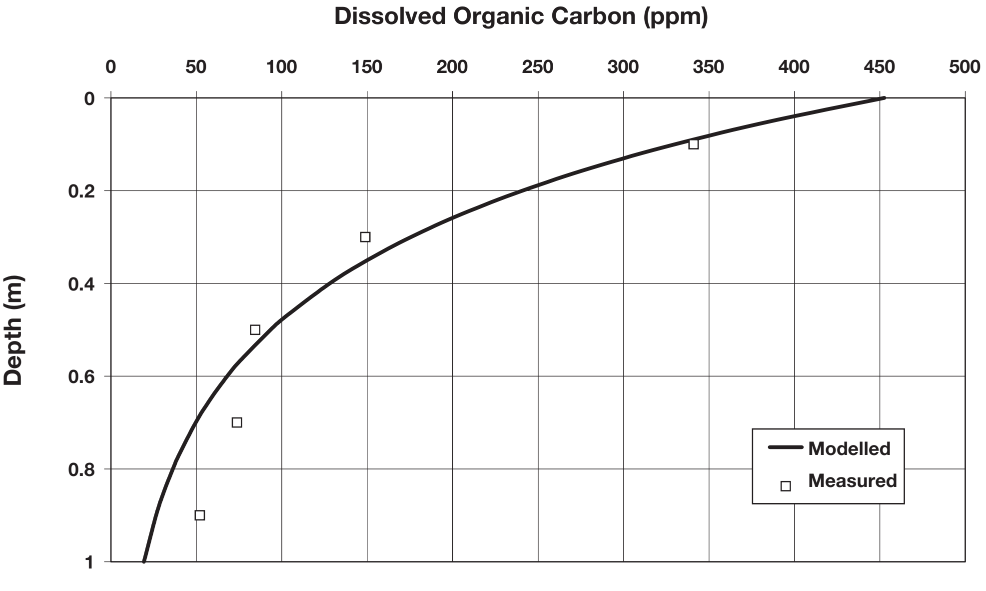


Figure 6. Suitability of Equation 1 to Model Soil Carbon Profiles.

5.2 Modelling Catchment Denitrification Processes

5.2.1 Denitrification in Ephemeral Low Order Streams: the Bucket Model

Stream water is likely to interact with riparian buffers adjacent to low order ephemeral streams during flow events in areas where a perched water table is likely to form; i.e., areas where a conductive floodplain soil overlies a low-conductivity confining soil layer. During a flow event, stream water flows laterally into the floodplain thus forming a perched water table (refer to Figure 7); the water resides and denitrifies during the event and then drains back to a stream at some lower area in the catchment, complete mixing is assumed to occur in the perched aquifer.

The amount of nitrate removed will depend on the volume stored during an event, the residence time, and the mean denitrification rate:

- Volume of perched water: The areas in a functional unit of vegetated riparian buffers on ephemeral streams with the potential to form a perched water table are identified. The volume of perched water that interacts with the carbon-rich rooting zone depends on the depth to the perching layer, the width of the riparian buffer, the porosity of the soil, the slopes of the ground surface and the water table, and the depth of the rooting zone. The volume of perched water that interacts with the root zone per unit length on either side of an ephemeral stream with a fine confining soil layer located at a depth d_d is calculated as follows:

The length of the saturated root zone at any distance x is defined as:

$$d_{sat}(x) = w(x) - r(x) \tag{3}$$

where w(x) defines the water table as follows:

$$w(x) = d_p - nx \tag{4}$$

where d_p is the depth to the perching layer, and r(x) is a function that defines the root zone:

$$r(x) = (d_p - r) + mx \tag{5}$$

Therefore, the saturated root zone is:

$$d_{sat}(x) = r - x(m + n) \tag{6}$$

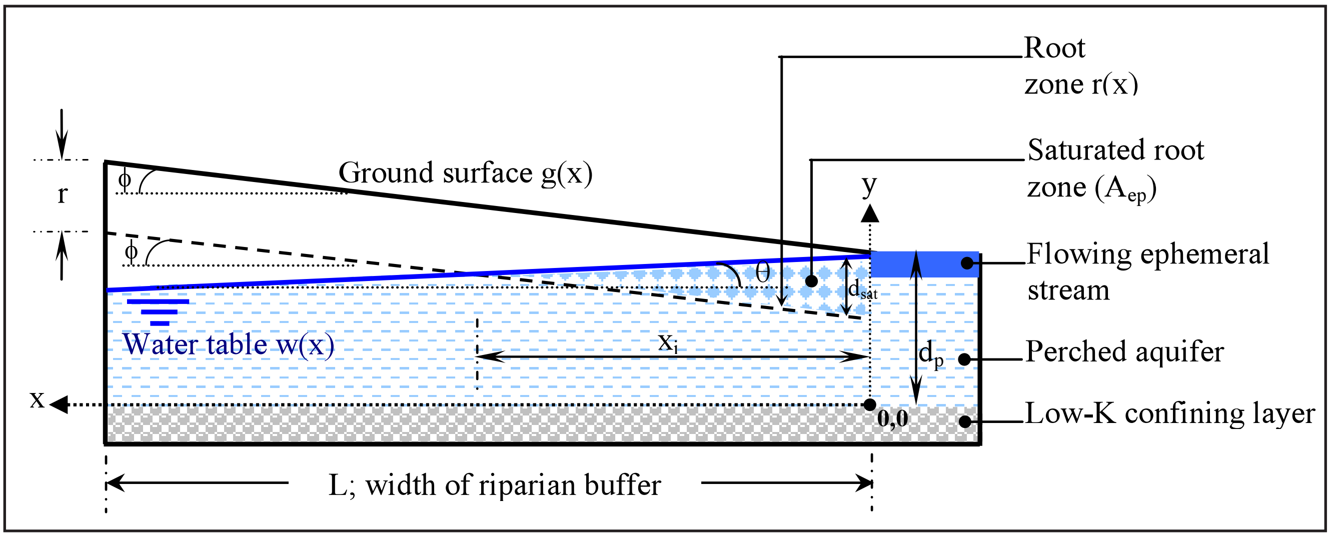


Figure 7. Conceptual Model for Denitrification in Ephemeral Streams.

where:

$$m = \tan(\phi) \tag{7}$$

and

$$n = \tan(\theta) \tag{8}$$

We define x_r, is the active width of the riparian zone as:

$$x_r = \min(x_i, L) \tag{9}$$

where L is the width of the vegetated riparian zone, and x_i is the distance at which the water table insects the root zone and is obtained by equating w(x) and r(x):

$$x_i = \frac{r}{m+n} \tag{10}$$

The area of the saturated root zone (see Figure 7) is defined as follows:

$$A_{ep} = \int_0^{x_r} d_{sat}(x)dx \tag{11}$$

Integrating Equation 11 yields:

$$A_{ep} = rx_i - \frac{1}{2}x_r^2(m+n) \tag{12a}$$

$$v_{ep} = A_{ep}S_l \tag{12b}$$

where:

S_l is the length of a pixel along the stream and v_{ep} is the volume of stream water interacting with either side of the riparian buffer along a pixel on the ephemeral stream network having the potential for perching.

- **Residence time:** The duration of the flood event mainly controls residence time. We assume that the filling and drainage processes are analogous, therefore, residence time is assumed to be the duration between the beginning of the flood event and the start of recession period.
- **Average denitrification rate:** This is mainly influenced by the rooting depth and the decay rate k. The calculation is carried out on a pixel basis in vegetated riparian buffers of low order streams. They are averaged to obtain a mean denitrification rate, which is calculated as follows.

Since the dependent variable in Equation 1, d, is measured from the ground surface, we need to transform it in terms of the current coordinate system (see location of origin 0,0 in Figure 7):

$$d(x,y) = g(x) - y \tag{13}$$

where y is the vertical coordinate of any point under consideration and g(x) defines the ground surface as follows:

$$g(x) = d_p + mx \tag{14}$$

The average denitrification rate at any distance x is:

$$R_u(x) = \frac{1}{d_{sat}(x)} \int_{r(x)}^{w(x)} \frac{e^{-kd(x,y)} - e^{-kr}}{1 - e^{-kr}} dy \tag{15}$$

which, upon integration, yields:

$$R_u(x) = \frac{1}{d_{sat}(x)} \frac{R_{max}}{k(1 - e^{-kr})} \Big[e^{-kx(m+n)} - e^{-kr}(1 - k(nx + mx - r)) \Big] \tag{16}$$

The average denitrification rate across the entire active section of the riparian buffer is:

$$R_u = \frac{1}{x_r} \int_0^{x_r} R_u(x)dx \tag{17}$$

Integrating Equation 17, we obtain:

$$R_u = \frac{1}{A_{ep}} \frac{e^{-kr} R_{max}}{k\left(1 - e^{-kr}\right)} \tag{18}$$

$$\left[\frac{1}{e^{-kr}(m+n)} \left(1 - e^{-kx_r(m+n)}\right) - x_r\left(1 + kr\right) + \frac{kx_r^2}{2}(m+n) \right]$$

The results of Equation 18 are shown in Figure 8.

The perched water that interacts with root zone (having a volume $V = A_{sat}$(stream length) has an initial nitrate concentration C_o; it denitrifies at the mean denitrification rate and resides for a period equal to the mean residence time. A new nitrate concentration C_t is calculated; nitrate removal is calculated during every flood event in the functional unit and is equal to $V \times (C_o - C_t)$.

5.2.2 Denitrification in Perennial Middle Order Streams

Denitrification in base flow component

Denitrification in the base flow component occurs as water passes through the saturated part of the root zone. The factors that influence denitrification are:

- **Rooting depth:** The root zone is the carbon-rich area where denitrification is most likely to occur. The activity is highest at the surface and declines with depth. Therefore, deeply rooted vegetation offers a larger active (reaction) area.
- **Depth to water table:** Denitrification reactions only occur under anoxic (i.e., saturated) conditions. The shallower the water table the larger the saturation root zone area; a shallow water table has a very favourable effect as the denitrification

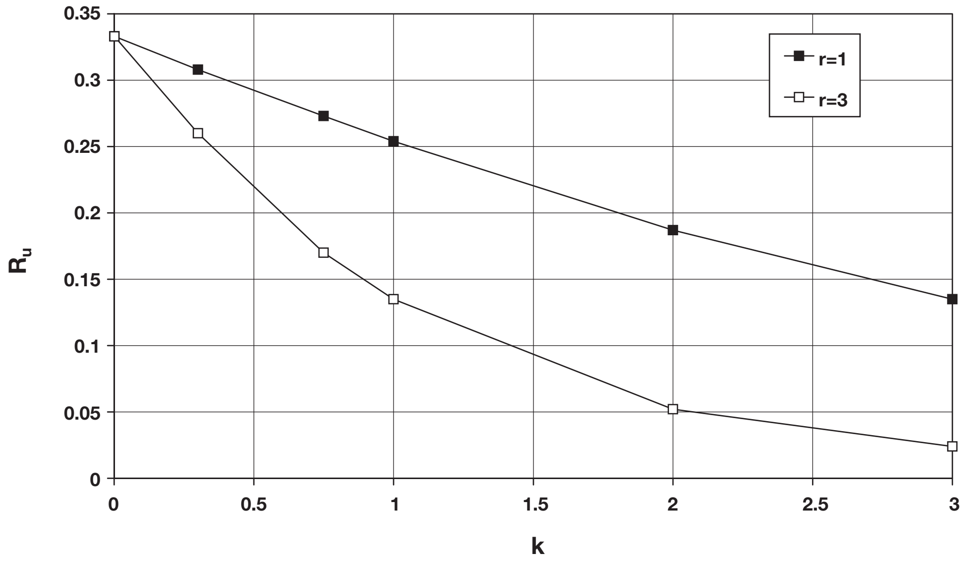


Figure 8. Effect of k on Mean Denitrification Rate for Two Values of Rooting Depth.

rate increases exponentially towards the soil surface. The spatial distribution of the 'depth to groundwater' is identified using FLAG UPNESS index (Roberts *et al.,* 1997); in the absence of the UPNESS index, an alternative model is available.

- **Flow rates and residence time:** Denitrification reactions are mediated by bacteria and require some time to reach peak activity; thus there should be an appreciable residence time for nitrate removal to take place. If flow is too fast then only a small proportion of the nitrate will be transformed. Conversely, if flow is too slow, the residence time will be high but the volume of water passing through the riparian buffer will be very low. Therefore, there exists an optimal flow rate that allows a high residence time and at the same time maximises transport through the riparian buffer. Residence time is directly proportional to the width of the riparian buffer.

The factors listed above are incorporated into the conceptual model for denitrification. It is worthwhile mentioning that the model is not dynamic, i.e. it does not model a variable water table depth during events; rather, it assumes a constant (non-event) depth to the water table that is spatially variable depending on landscape attributes (namely UPNESS index). The 'optimal hydrology' means a high water table level and maximal flow through the floodplain; it is associated with soils of medium-conductivity ranging from 0.1 to 1 m/day (Rassam, 2005). Residence time is a function of travel distance and flow rate; the latter is in turn a function of hydraulic conductivity and head gradient.

The hydrology of the floodplain is conceptualised as shown in Figure 9; the water table is considered to be a linear function with a slope equal to that of the ground surface (and therefore also the root zone). The variable w describes the depth to the water table. The saturated part of the root zone (area A, Figure 9) extends across the entire width of the riparian zone.

The cross-sectional denitrifying area A is easily calculated for the entire width of the riparian zone. It should be noted that denitrification only occurs when the depth to the water table is less than the depth to the bottom of the root zone (i.e. denitrification occurs when w > r).

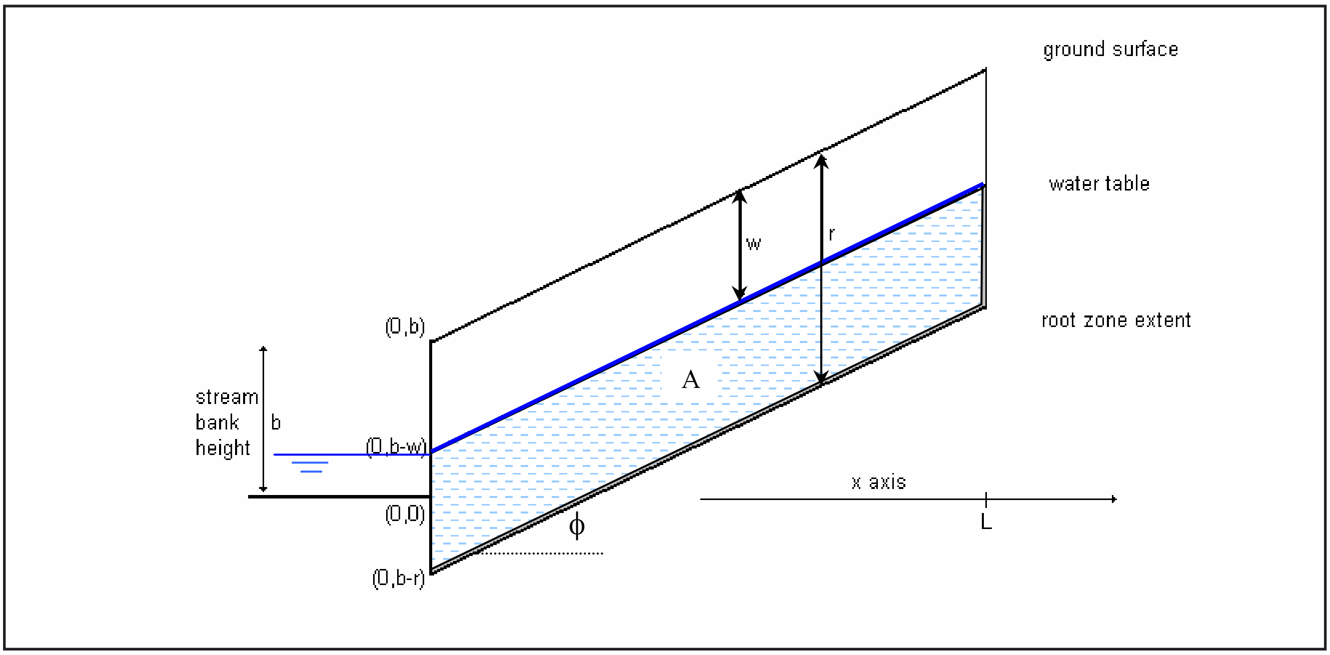


Figure 9. Conceptual Model for Denitrification; Base Flow Component in Perennial Streams.

$$A_{bf} = L(r - w) \qquad \text{for } w < r \qquad (19)$$

where:

w is the depth to groundwater. The average denitrification rate operating within the cross-sectional denitrifying area can be easily calculated. We use a 1st order decay function to describe the change of denitrification rate with depth as in Equation 1:

The average denitrification rate is calculated as follows:

$$R_{\mu} = \frac{R_{max}}{(r - w)} \int_{w}^{r} \frac{\left(e^{-ky} - e^{-kr}\right)}{\left(1 - e^{-kr}\right)} dy \qquad (20)$$

$$R_{\mu} = \frac{R_{max}}{(r - w)\left(1 - e^{-kr}\right)} \left(\frac{e^{-kw} - e^{-kr}}{k} + (w - r)e^{-kr} \right) \qquad (21)$$

$$R_{\mu} = 0 \qquad \text{for } w \geq r \qquad (22)$$

where:

y	is the vertical depth below the ground surface (L)
k	is the rate at which denitrification declines with depth (1/L)
R_{max}	is the maximum rate of denitrification at the soils surface (1/T)
R_u	is the average denitrification rate across the saturated root zone

Figures 10 and 11 show the results of Equation 21; as k increases, the distribution of Ru down the soil profile becomes more non-linear. When k attains very low values the distribution becomes linear and independent of rooting depth (when k=0, R_u becomes equal to 0.5).

The travel distance is simply defined as:

$$d_u = \frac{L}{\cos(\phi)} \qquad (23)$$

where ϕ is the floodplain slope.

Using Darcy's equation, we can determine the expected velocity of the groundwater for the given gradient:

$$v_{\mu} = K \tan \phi \qquad (24)$$

where:

v_{μ} is the average groundwater velocity

K is the hydraulic conductivity of the riparian soil.

Therefore the average groundwater residence time t_u is:

$$t_u = \frac{d_{\mu}}{v_{\mu}} = \frac{L}{K \sin \phi} \qquad (25)$$

Spatial distribution of depth to water table 'w'

The FLAG (Fuzzy Logic Analysis GIS; Roberts *et al.,* 1997) model is a simple tool for predicting groundwater discharge within large catchments. The FLAG model is unique in that models for predicting groundwater discharge are generally complex and data intensive (Laffan, 1996). One of the indices within the FLAG model is the UPNESS index, which provides a quantification of the proportion of the landscape that is connected to each cell in a catchment via a monotonically uphill path (Dowling, 2000). UPNESS has been shown to be a reasonable predictor of the depth to a water table in the Wagga Wagga and Kyeamba Creek Catchments of New South Wales (Summerell *et al.,* 2004) and can be thought of as an index of subsurface water accumulation. Linear relationships between the depth of a water table and UPNESS were determined to be strong for bores where subsurface hydrology was governed by hill-slope processes rather than by the processes operating within alluvial areas. The Riparian N Model is not concerned with modelling the process of denitrification within alluvial systems and the UPNESS index was therefore deemed suitable for estimating depth to groundwater in riparian zones.

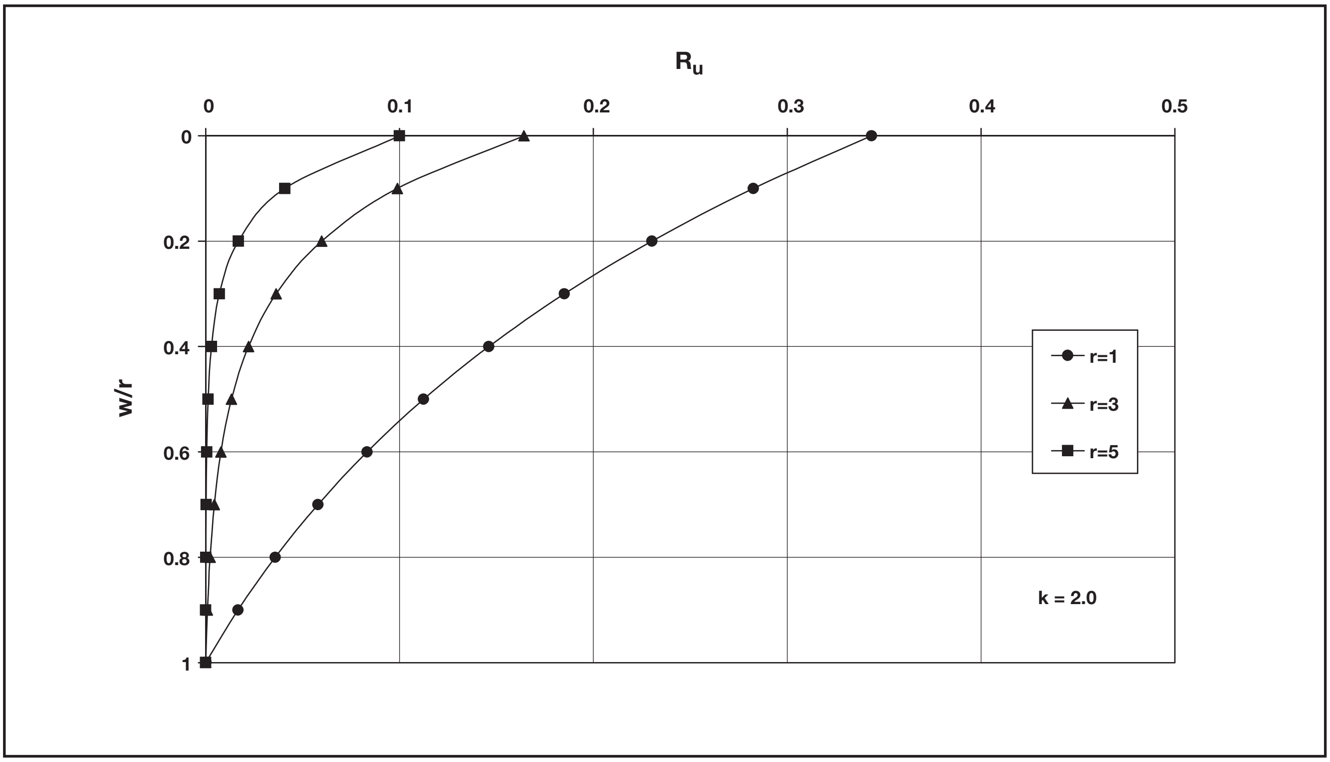


Figure 10. Average Denitrification Rate for Various w/r Ratios; High k.

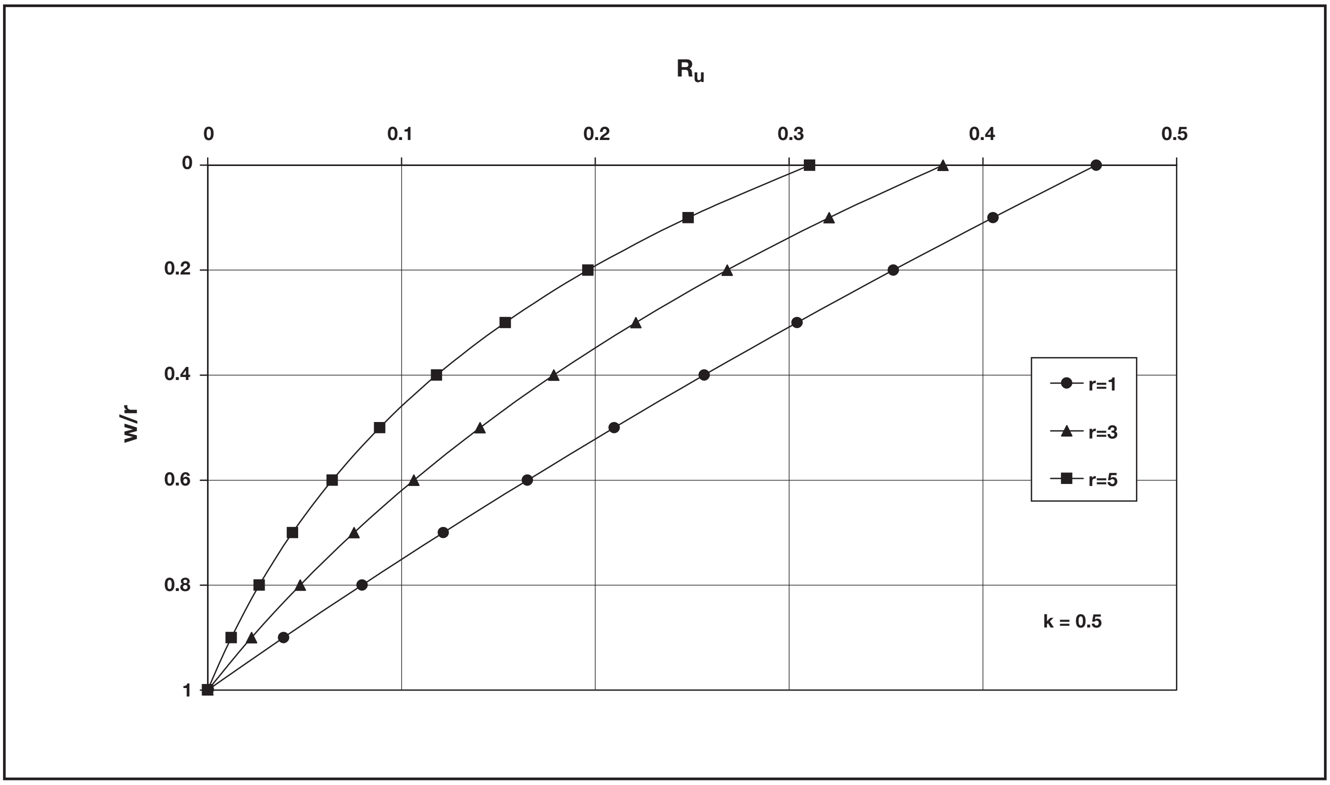


Figure 11. Average Denitrification Rate for Various w/r Ratios; Low k.

In order to estimate depth to groundwater using the UPNESS index in the Riparian N Model, a user must provide the model with: (i) a raster of the UPNESS index (output from the FLAG model); and (ii) an ESRI shape file of bores where groundwater depth has been measured. The Riparian N Model pre-processor uses this information to fit the best possible linear regression model between UPNESS and depth to groundwater. The automated regression procedure used by the pre-processor creates a number of regression models, using the raw data (i.e. no transformations), log-log, semi-log, square root and inverse transformations. The regression model which results in the largest value of the R^2 statistic is deemed to be the best model and is then used to then estimate depth to groundwater on a cell by cell basis for the entire riparian zone.

In the absence of an UPNESS raster for determining depth to groundwater, an alternative method is included in the Riparian N Model, which is based on the MRI-DARCY model (Baker *et al.,* 2001). The MRI-DARCY model estimates a phreatic surface within the riparian zone by using an inverse distance weighted method to interpolate groundwater elevations between streams. The model assumes that perennial streams are essentially sets of points where the phreatic surface intersects the topographic surface. The phreatic surface for cells in the riparian zone is determined by finding the closest 10 stream network raster cells and using their elevations in an inverse distance weighted estimate of the elevation of the water table in the riparian zone. The inverse distance estimator is:

$$e_{rz} = \frac{\sum_{i=1}^{10} \frac{e_i}{d_i^{\,2}}}{\sum_{i=1}^{n} \frac{1}{d_i^{\,2}}} \tag{26}$$

where:

e_{rz}	is the elevation of the phreatic surface at a cell in the riparian zone;
e_i	is the elevation of the i^{th} closest stream network cell to the riparian zone cell;
d_i	is the distance between the riparian zone cell and the ith stream network cell.

The depth to groundwater at each cell in the riparian zone can then be determined by calculating the difference between the topographic elevation and the phreatic surface elevation.

<u>Apportioning of base flow across a functional unit in the catchment:</u>

In the absence of ground water flow system maps that show likely areas of base flow, it is postulated that base flow volumes are directly proportional to the hydraulic conductivity of the soil and the driving head; a proxy indicator for the latter in the FLAG UPNESS index. We can define the base flow fraction as follows:

$$\beta_i = U_i \kappa_i \tag{27}$$

where the subscript i indicates the pixel number at any cell on the stream network, β_i is the base flow fraction, U_i is the UPNESS index, and (i is the normalised hydraulic conductivity of the riparian soil neighbouring the stream (ranges from 0 to 1). The summation of base flow fractions across a functional unit is given by:

$$\beta_t = \sum_{0}^{n} \beta_i \tag{28}$$

where n is the total number of pixels representing perennial streams in a functional unit. We can now apportion the base flow at any pixel as follows:

$$v_{bf} = \frac{\beta_i}{\beta_t} V_{bf} \tag{29}$$

where v_{bf} is the base flow volume at pixel i, and V_{bf} is the total base flow volume for the functional unit under consideration obtained from a rainfall-runoff model (e.g. SIMHYD).

Denitrification in Bank Storage Component

This is a mechanism whereby surface water interacts with riparian buffers during flood events (Rassam *et al.,* 2005). As a flood wave passes, the water level in the stream increases and inundates a previously dry part of the root zone. The amount of nitrate removed via this mechanism will depend on the amount of water stored during events, the residence time, and the mean denitrification rate at the level of inundation:

- **Volume of bank storage:** An approximate bank-full height needs to be defined for each stream order (or stream order classes, where a class is a cluster of stream orders). Bank full discharge is defined for the entire functional unit and each flood event is then scaled with respect to the bank-full discharge to yield a rise in stream level Δh (see Figure 4). The wetted area associated with every flood event is then calculated based on floodplain geometry; the volume is estimated from knowledge of the specific yield
- **Residence time:** The flood event duration mainly controls residence time. We assume that the filling and drainage processes are analogous, therefore, residence time is assumed to be the duration between the beginning of the flood event and the start of the recession period.
- **Average denitrification rate:** It is mainly influenced by rooting depth and floodplain geometry.

The bank storage process is conceptualised as shown in Figure 12; we consider a stream having a bank height 'b' and a neighbouring floodplain sloping at an angle ϕ. As a flood wave passes, the water level in the stream increases by an amount (h thus inundating an area of the floodplain ΔA. A mean residence time is calculated based on the event duration (based on a spell-type analysis of the hydrograph). An average denitrification rate is calculated using concepts similar to those used for the base flow component. During an event, water that has been stored in the area (ΔA) denitrifies, and as the event recedes it drains back to the stream with a lower nitrate level. This process is dynamically linked to the stream hydrograph. The filling and drainage processes may simplistically assumed to be instantaneous or may alternatively be modelled as follows:

$$h(t) = \Delta h e^{-\alpha K t} \tag{30}$$

where Δh is the maximum rise in water level during an event, K is the hydraulic conductivity, t is the time variable, and α is a decay constant (e.g., day^{-1}).

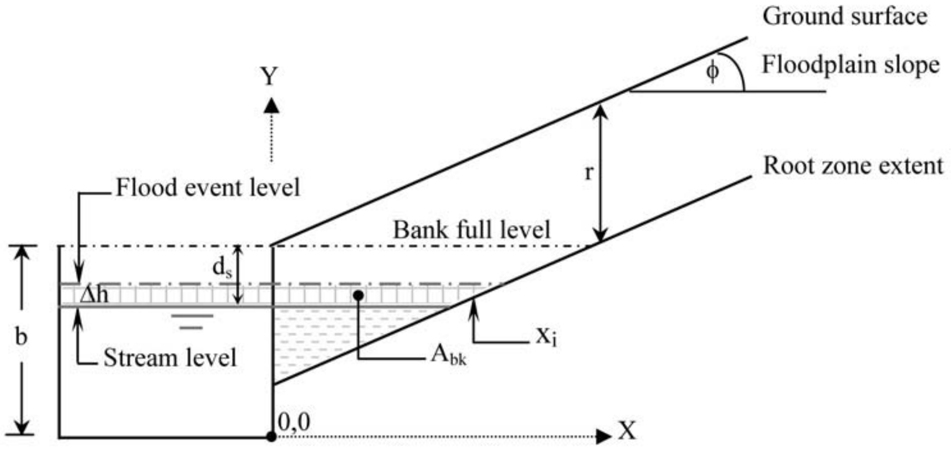


Figure 12. Conceptual Model for Denitrification; Bank Storage Component in Perennial Streams.

An approximate bank-full height (b) needs to be defined for each stream order (or stream order classes, where a class being a cluster of stream orders). Bank full discharge is defined for the entire functional unit; e.g., the 90th percentile discharge; each flood event is then scaled with respect to the bank-full discharge. Therefore, (h is calculated for each stream order (or class) during every event based on knowledge of (b). The inundated area A_{bk} on one side of the stream is calculated as follows:

$$A_{bk} = \frac{\Delta h}{2}\left(\min\left(\max\left(\frac{r-d_s}{\tan(\phi)},0\right),L\right) + \min\left(\max\left(\frac{r-d_s+\Delta h}{\tan(\phi)},0\right),L\right)\right) \quad (31a)$$

$$v_{bk} = A_{bk} S_l \quad (31b)$$

where:

Δh	is the change in the height of the stream during a flood event
d_s	is the depth to stream water level
L	is the width of the riparian zone
r	is the depth of the root zone
ϕ	is the slope of the floodplain.
S_l	is the length of a pixel along the stream
v_{bk}	is the volume of stream water interacting with either side of the riparian buffer along a pixel on the stream network

Since 'd' in Equation 1 is defined from the soil surface, we need to transform it in terms of the current coordinate system (see location of origin 0,0 in Figure 12).

$$d(x,y) = \tan\phi x + b - y \quad (32)$$

where b is the stream bank height. We integrate the denitrification rate along Δh to obtain an average rate then integrate this average rate across the width of the floodplain to obtain an overall average denitrification rate. The average denitrification rate R_u is obtained as follows:

$$R_\mu = \frac{R_{max}}{A_{bk}} \int_{b-d_s}^{b-d_s+\Delta h} \int_0^{x_i} \frac{\left(e^{-k\tan\phi x - kb + ky} - e^{-kr}\right)}{1-e^{-kr}} dxdy \quad (33)$$

$$R_\mu = \frac{R_{max}}{A_{bk}\left(1-e^{-kr}\right)} \left(\frac{(1-e^{k\Delta h})(e^{-kd_s}(e^{-x_i k\tan\phi}-1))}{k^2\tan\phi} - \Delta h x_i e^{-kr}\right) \quad (34)$$

where:

R_{max}	is the maximum denitrification rate present at the ground surface
k	is the rate at which denitrification declines with depth (1/L)
b	is the bank height
x_i	is the point where the water table intersects the root zone extent, it is defined by:

$$x_i = \frac{r-d_s+\Delta h/2}{\tan(\phi)} \quad (35)$$

Figure 13 shows the effect of floodplain slope on the average denitrification rate for bank storage for two values of Δh.

Nitrate removal is calculated during every flood event in a functional unit. The nitrate resides in the stream bank for a period equal to the mean residence time and denitrifies at a mean denitrification rate as defined by Equation 34.

Channel Metrics:

In order to perform the calculations relating to Equations 31-35, estimates of stream channel depth at any discharge are needed (b and d in Figure 12); they are determined for each cell in the stream network. The approximate channel depth at bank-full discharge is given by Stewardson *et al.,* (2005) as follows:

$$Dp_{bf} = c_1 Q_{bf}{}^{c_2} S^{c_3} M^{c_4} \qquad (36)$$

where:

Dp_{bf}	is channel depth at bank-full discharge for a raster cell on the stream network;
Q_{bf}	is the bank-full discharge for a raster cell on the stream network (calculated using the relationship above);
S	is the slope of the stream for a raster cell on the stream network; and
M	is the meander wavelength for a raster cell on the stream network
c_1	is the channel depth coefficient;
c_2	is the exponent relating bank-full discharge to channel depth;
c_3	is the exponent relating channel slope to channel depth.
c_4	is the exponent relating meander wavelength to bank-full discharge

The bank-full discharge is defined as follows (Stewardson *et al.,* 2005):

$$Q_{bf} = c_5 A^{c_6} e^{pc_7} M^{c_4} \qquad (37)$$

where:

Q_{bf}	is the bank-full discharge for a raster cell on the stream network;
A	is the contributing area for a raster cell on the stream network;
p	is the ratio of PET to rainfall for a raster cell on the stream network;
c_5	is the bank-full discharge coefficient;
c_6	is the exponent relating contributing area to bank-full discharge;
c_7	is the exponent relating the ratio of PET and rainfall to bank-full discharge;

In the absence of estimates for meander wavelength, M^d may simply be assumed to be equal to unity (Stewardson *et al.,* 2005).

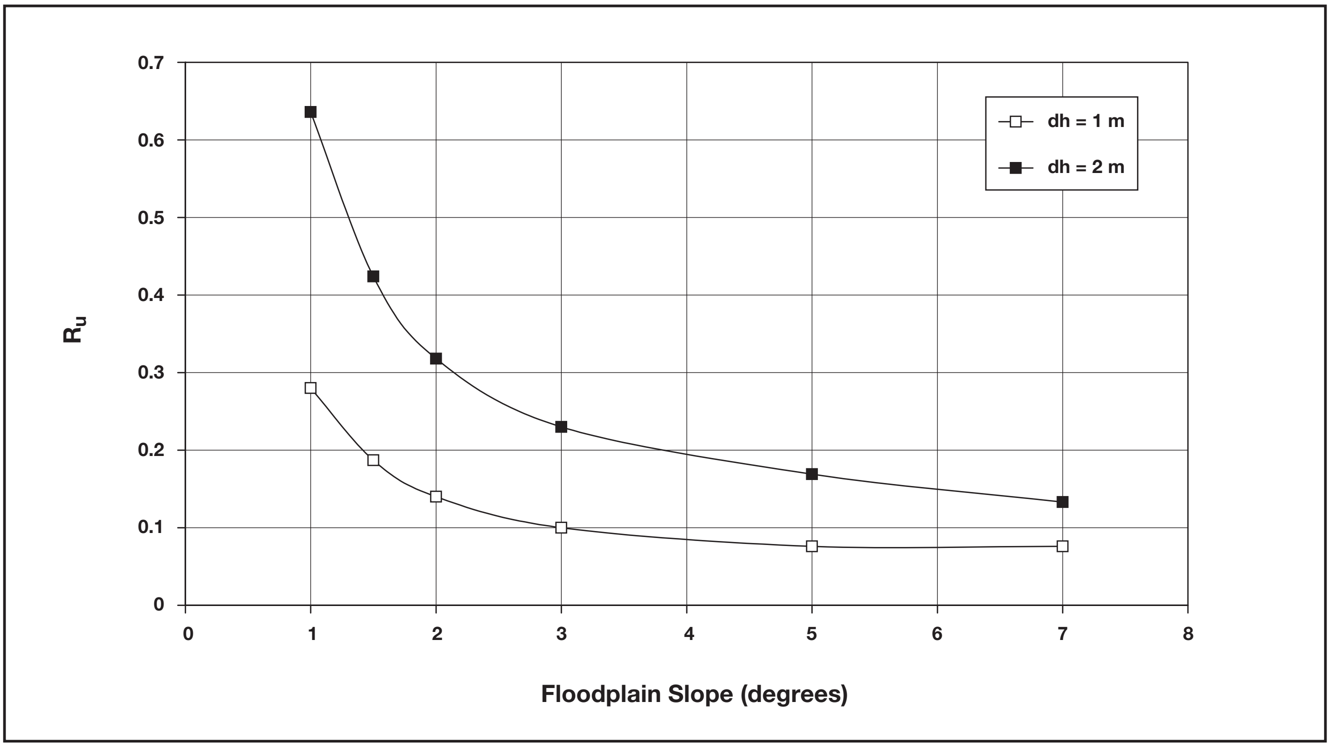


Figure 13. Effect of Floodplain Slope on Mean Denitrification Rate for Bank Storage.

5.3 Modified Nitrate Loads in Catchments

A simple 1st order decay function is used to calculate nitrate removal with time as a result of denitrification; it is given by:

$$C_t = C_0 e^{-R_u t_u} \qquad (38)$$

where:

C_t is nitrate concentration at any time t (M/L3; where M refers to mass units)

C_o is the initial nitrate concentration (M/L3)

R_u is the average denitrification rate through the saturated rooting zone defined by either of Equations 18, 21, or 34 (1/T)

t_u is the residence time (T)

Figure 14 demonstrates the suitability of Equation 38 to model observed field nitrate concentrations; Equation 38 is used in conjunction with the daily nitrate loads (from E2) to yield reduced loads after accounting for denitrification processes.

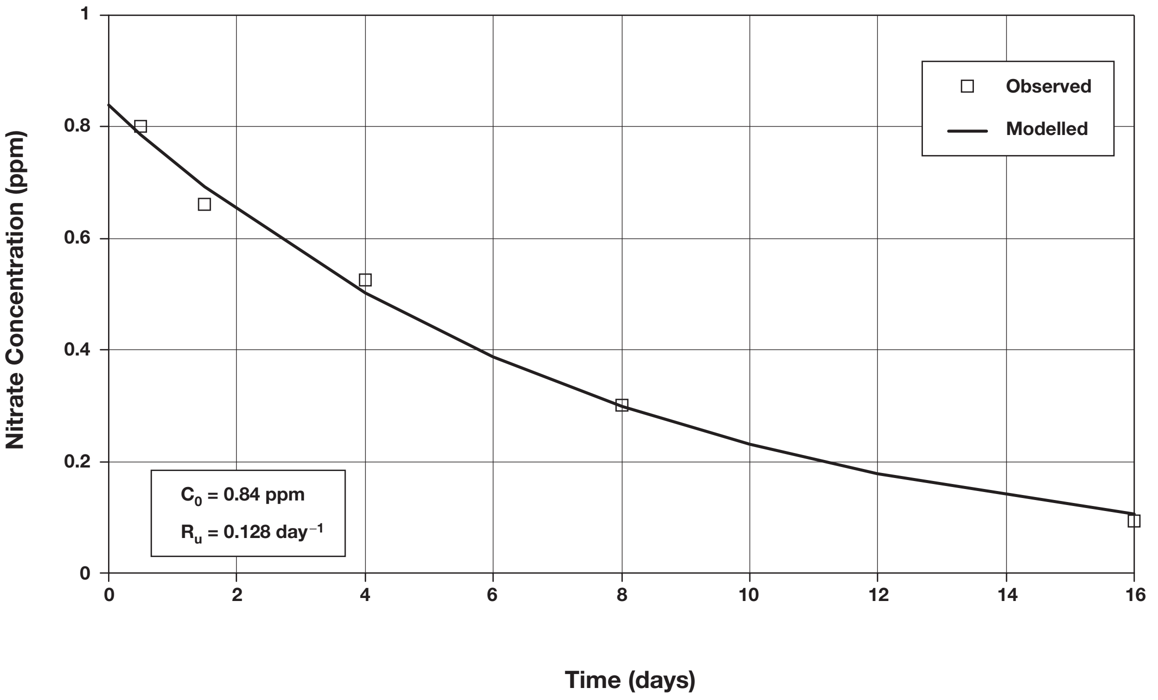


Figure 14. Suitability of 1st Order Decay Kinetics to Model Denitrification.

6. Riparian Management Layers

Calculations of nitrate removal in the RNM are not spatially explicit; i.e., the RNM does not estimate how much nitrate is removed at every stream reach (as represented by a pixel in the model). This is because the parent E2 calculates flow at a functional unit scale. However, given all of the uncertainty associated with denitrification calculations and the scarcity of any associated datasets, it is not appropriate to present results at any finer scale.

Nevertheless, finer spatial explicitness is required, especially when management options for riparian restoration are being considered. Data scarcity may be a problem, but where data are available, we are able to provide guidance on where management may be carried out. For example, assuming we have completely barren riparian zones throughout a catchment, where do we target the restoration process to maximise nitrate removal and improve water quality?

We can achieve this by knowing the key factors that contribute to the enhancement of denitrification in riparian buffers most of which were discussed in the previous sections:

1. Healthy riparian buffers with a variety of vegetation (including deeply rooted).
2. Flat floodplains tens of metres wide having a suitable hydrology; i.e., having a relatively shallow water table.
3. Riparian buffers with very shallow, low-conductivity soil layers 1 to 5 m deep, to promote perched water tables in the vicinity of low-order ephemeral streams.
4. Areas with a relatively shallow, low-conductivity soil layer 10 to 20 m deep that promotes local groundwater flow in middle-order perennial streams; i.e., a middle order stream located relatively high in the catchment that has a base flow component. Maps of groundwater flow systems (Coram *et al.,* 2001) could also inform where areas of potential base flow are likely to be.
5. Floodplains with medium conductivity soils (in the order of 0.1 to 1 m/day); i.e., to allow sufficient residence time and a relatively shallow water table.

The RNM is able to quantify the potential of riparian buffers to remove nitrates via denitrification. We also need to identify areas where nitrate contamination is likely to occur; riparian restoration is then targeted at areas that have both the highest contamination potential and the highest denitrification potential.

6.1 Nitrate Removal Potential

The proportion of nitrate removed in the riparian zone by denitrification can be calculated using a 1st order decay function where the rate constant is the average denitrification rate and the time variable is the average residence time:

$$D = 1 - e^{-R_\mu t_\mu} \qquad (39)$$

where:

D	is the 'denitrification index' representing the proportion of nitrate that is removed via denitrification defined by either of three conceptual models presented in Section 5.2
R_u	is the mean rate of denitrification defined by either of three conceptual models presented in Section 5.2
t_u	is the mean residence time defined by either of three conceptual models presented in Section 5.2

The total nitrate mass that can potentially be removed at riparian buffers is proportional to the denitrification index and the volume of water that interacts with the buffer (assuming the incoming nitrate concentration is constant); we can define the nitrate removal index as follows:

$$\eta = D\,v \qquad (40)$$

where η is the nitrate removal index, and v represents the volume of water interacting with the riparian buffer. For low-order ephemeral streams, η is defined as:

$$\eta_{ep} = D_{ep}v_{ep} \tag{41}$$

where: η_{ep} is nitrate removal index for ephemeral streams, D_{ep} is the denitrification index for ephemeral streams (defined in Equation 39 using R_u from Equation 18, and t_u based on mean flood event duration), and v_{ep} is the volume of water interacting with riparian buffers belonging to ephemeral streams defined by Equation 12b. Similarly, η for middle order perennial streams is obtained by combining base flow and bank storage processes and is given by:

$$h_{per} = D_{bf}v_{bf} + D_{bk}v_{bk} \tag{42}$$

where: the first term of the right hand side of the equation represents nitrate removal in base flow and the second term represents nitrate removal in bank storage; η_{per} is nitrate removal index for middle order perennial streams; D_{bf} is the denitrification index for base flow component (defined by Equation 39 using R_u from Equation 21 and t_u from Equation 25), and v_{bf} is the base flow volume passing through the riparian buffer defined by Equation 29; D_{bk} is the denitrification index for bank storage component (defined in Equation 39 using R_u from Equation 34 and t_u is based on mean flood event duration), and v_{bk} is the volume of water stored in stream banks defined by Equation 31b.

6.2 Contamination Potential

An index of contaminant generation potential for each raster cell in the riparian zone is determined by examining the quantity and proximity of agricultural land use within that cell's contributing area. Examining the contributing areas of individual cells in the riparian buffer for the purpose of constructing an index drew upon ideas presented in Burkart *et. al.,* (2004). Scores were attributed to cells in the riparian zone as follows:

$$C_i = \sum_{i=0}^{N} \frac{\omega_i}{\delta_i} \tag{43}$$

where:

C_i	is the 'contamination index' for a riparian cell;
δ_i	is the distance of the i^{th} raster cell in the contributing area from the riparian zone (measured in cells);
ω_i	is a Boolean variable taking the value of 1 where the ith raster cell in the contributing area has the potential for contaminant generation and 0 where it does not; and
N	is the total number of raster cells contributing to a cell in the riparian zone.

The contributing area to a riparian cell is identified; the regions within this contributing area where agriculture is present are given a score depending on the proximity to the riparian cell and the type of land use (as different crops require different fertiliser amounts). The scores generated for each cell in the riparian zone are normalised such that they vary between 0 and 1.

6.3 Restoration Potential

The spatial datasets corresponding to the contamination generation index and the denitrification index are both calculated such that values fell between 0 and 1 (inclusive). These two indices are combined into an aggregated index, which reflects the importance of a riparian zone in terms of its ability to intercept nitrogenous contaminants and remove them via denitrification.

$$R_i = \eta_i C_i \tag{44}$$

where:

R_i	is the 'restoration index' for the ith raster cell;
η_i	is the nitrate removal index for the i^{th} raster cell defined by either Equation 41 or Equation 42; and
C_i	is the normalized contaminant generation index for the i^{th} raster cell.

It is obvious that the restoration index would achieve the highest values when both the nitrate removal and contaminant indices are maximal. Therefore, this aggregated index provides a useful measure of a riparian buffer's ability to intercept contaminants as well as successfully removing them.

In order to prioritize the restoration process, we need to lump areas based on a certain range of R_i values; we create five categories where 1 represents the lowest priority area and 5 represents the highest priority area; for example, the area designated 1 represents R_i=0 to 0.2; and the area designated 5 represents R_i=0.8 to 1.

7. The Riparian Nitrogen Model Output

The output of the model is as follows:

- Modified nitrate loads at a functional unit scale. The model keeps track of the removed nitrate masses at each conceptual level (in ephemeral streams as a result of perching, in perennial streams as a result of base flow input and bank storage).
- Modified nitrate concentrations at a functional unit scale
- Water volumes that interacted with the riparian buffer at various conceptual levels.
- GIS Management layers for targeted riparian restoration.

8. Scenario Modelling

The RNM module may be used to carry out scenario or 'What if' modelling to test various scenarios that may help managers with their decision-making. A very positive aspect of scenario modelling is that the emphasis is on relative, rather than absolute, values in comparing results of different scenarios. The following are some possible scenario options:

- Suppose riparian zones in a catchment are completely degraded and we have a certain budget for restoration. Based on the guidance provided by the management GIS layers, we can trial hypothetical restoration options and gauge what the likely outcomes will be. Restoration options include varying: locations, buffer widths, and fraction of catchment restored.
- We can test how the rooting depth (i.e., vegetation type) affects the efficiency of denitrification in riparian buffers.
- We can test the sensitivity of various catchments to certain parameters such as rooting depth. We can also compare hypothetical restorations in various catchments to see which one responds better.

9. Conclusions

Until now, the effectiveness of riparian restoration efforts has been compromised by a lack of reliable information for landholders, to support their decision-making on nitrogen management issues. Development of the Riparian Nitrogen Model has helped fill this knowledge gap.

The RNM operates as a filter module within the catchment-scale model, E2; it estimates the removal of nitrate by denitrification, in situations where shallow groundwater interacts with the riparian soils. The RNM operates at three conceptual levels:

- Firstly, in ephemeral low-order streams, a simple bucket model is used. Areas of potential groundwater perching are identified, where a conductive floodplain soil overlays a low-conductivity soil layer. During flood events, these areas fill like a bucket (i.e., surface water becomes groundwater); this water then loses nitrate through denitrification and subsequently drains back to the surface water system as the flood event subsides.
- Secondly, in perennial middle-order streams, denitrification occurs as groundwater (base flow) intercepts the root zone. The hydrology of the floodplain is important in determining the extent of denitrification (a shallow water table and a high residence time promote denitrification). Flat floodplains with medium-conductivity soils are most conducive to denitrification.
- Thirdly, in perennial middle-order streams, denitrification may also occur when stream water is temporarily stored in banks during flood events. The amount of water stored will depend on the size of the flood event, the soil properties (e.g., hydraulic conductivity and porosity), the geometry of the floodplain, and the residence time.

The nitrate loads removed via each mechanism are estimated using 1st order decay kinetics. The decay rate constant (which represents the denitrification rate) varies with soluble organic carbon content and hence decreases with soil depth, as carbon levels decline. For each conceptual model, an average denitrification rate is calculated at each pixel along the stream network. This represents the denitrification potential of the adjacent floodplain and is dependent on the floodplain geometry and hydraulic parameters. The total mass of nitrate removed via each mechanism is calculated based on the denitrification potential, the residence time, and the volume of water that interacts with the floodplain.

The RNM allows users to evaluate the effects of improved riparian zone management on catchment nitrogen budgets and water quality. Furthermore, the spatial distribution of catchment denitrification potential may be used in conjunction with land use data, to indicate the relative potential for nitrogen removal in different parts of a catchment. This information can guide land managers in identifying where their riparian restoration activities may be of greatest benefit in terms of reducing stream nitrogen loads.

The RNM is thus a valuable tool that can help optimise the investments being made in riverine restoration to better manage the nitrogen problem and improve water quality.

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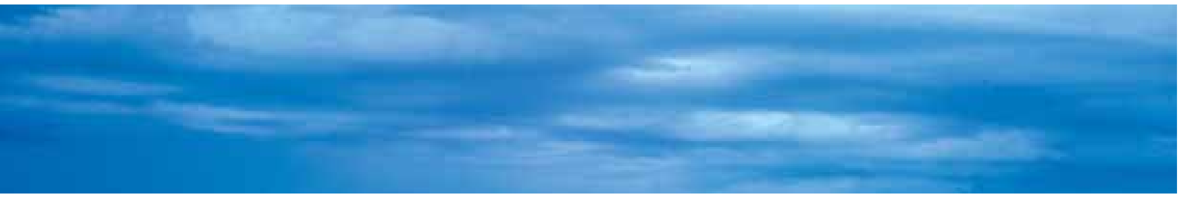

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