# Implementing the Riparian Nitrogen Model to assess the role of riparian buffers in the Maroochy Catchment

[1]D. Rassam, [2]D. Pagendam, and [2]H. Hunter

[1]CSIRO Land and Water, [2]Department of Natural Resources and Mines, E-mail: david.rassam@csiro.au

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**EXTENDED ABSTRACT**

Riparian zones can provide a protective buffer between streams and adjacent land-based activities by removing nitrate from shallow groundwater flowing through them. Catchment-scale water-quality models are useful tools for predicting catchment behaviour under various climatic conditions and land-use scenarios. In this paper, we use the Riparian Nitrate Model (RNM) to investigate the potential role for riparian zones in the Maroochy catchment to reduce nitrate loads to streams. The RNM operates as a filter (plug-in) module within E2; the latter is a node-link catchment-scale model capable of predicting the hydrologic behaviour of catchments.

We model sub-catchment processes in E2 by a combination of three types of processes: runoff generation, constituent generation, and filtering. Firstly, rainfall-runoff is modelled using SIMHYD, which has already been successfully applied in Australian catchments. Secondly, we use a simple constituent (or contaminant; nitrate in this case) generation model; this model uses two generation-processes, namely, the event mean concentration applied to surface flow, and the dry weather concentration applied to base flow. Thirdly, the RNM is used to estimate the removal of nitrate via denitrification as shallow groundwater interacts with riparian soils. The RNM is most suitably applied in riparian buffers belonging to low- and middle-order streams; we consider the removal of nitrate in perennial middle-order streams via two mechanisms: firstly, as base flow intercepts the root zone before discharging into a stream, and secondly, as stream water is temporarily stored in the bank during flood events. The nitrate load removed via each mechanism is estimated using $1^{st}$ order decay kinetics. The kinetics vary with the depth to groundwater, flood event size and duration, slope and width of the riparian zone, vegetation type, denitrification potential, and soil hydraulic parameters. In this paper we investigate the sensitivity of nitrate loads in streams to various model parameters and then demonstrate the impacts of re-vegetation and/or land clearing in the catchment.

Sensitivity analysis for the base flow component has shown that as the distribution of denitrification potential (which correlates with availability of dissolved carbon) down the soil profile becomes more non-linear, it becomes more sensitive to rooting depth. Denitrification during bank storage is reduced dramatically as the floodplain slopes up to $3^{o}$; the sensitivity increases during larger flood events. The modelling results for the Maroochy catchments have shown that the optimum rooting depth is 2-3 m and that increasing the riparian buffer width beyond 10 m results in minimal benefits. For the current denitrification rates used in this paper, the riparian buffers have the capacity to remove up to 20% of the nitrate load in the Maroochy sub-catchments. Normalising the potential nitrate removal capacity in a sub-catchment with respect to total length of the stream network enables us to quantify the capacity of a unit length of riparian buffer to remove nitrate; this attribute can then be used to prioritise riparian restoration, i.e., maximise the benefits per dollar spent. The modelling exercise also resulted in maps that identify Maroochy sub-catchments that will most likely benefit from re-vegetation and others that will be most adversely affected by land clearing activities.

# 1. INTRODUCTION

The dependency of agriculture on the use of nitrogen as a fertiliser to boost productivity has led to nitrate becoming the most widespread and common chemical contaminant of freshwater in the world (Brolger and Stevens, 1999). It is currently considered a major potential threat to the quality of coastal waters (Gold, *et al*. 2001) especially within Australia (Brolger and Stevens, 1999). An important function of riparian buffer zones is their ability to capture nitrate from catchment runoff and groundwater thus preventing degradation of the aquatic system. Riparian zones have been generally identified as the band of land, including wetlands and floodplains, between the terrestrial and aquatic ecosystems of headwaters, streams and rivers (Hill et al., 2000). 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). The main factors that drive the microbial denitrification process are: riparian vegetation (provide the carbon source to the bacteria), 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 deciding 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, and to decline rapidly with depth (Gold et al., 2001).

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 flood plain is controlled by (1) the distribution and magnitude of hydraulic conductivities both within the channel and the associated flood plain sediments; (2) the relation of stream stage to the adjacent groundwater gradients; and (3) the geometry and position of the stream channel within the flood plain. Burt et al. (2002) stated that: 'A flat riparian zone combined with soils of medium hydraulic conductivity provide optimal conditions for denitrification'. Rassam (2005) adopted a numerical modelling approach to confirm the conclusion of Burt et al. (2002), and identify an optimum hydraulic conductivity ratio (for hill slope and floodplain) that is most conducive for denitrification. Dahm et al. (1998) highlighted the importance of understanding nutrient dynamics at the surface water-groundwater interface of streams and rivers.

Within the last decade the literature on hydrological modelling and the implications for catchment water quality modelling has rapidly expanded. This interest is due to the critical importance of catchment modelling in determining the impact of human development on water quality for the catchment and receiving environments for future management and the elusive quest for sustainability. Continued progress in scientific understanding of hydrological processes at the catchment scale relies on making the best possible use of advanced simulation models and large amounts of data, which are becoming increasingly accessible (Troch, *et al.* 2003). An extensive range of hydrological models has been developed with different applications in relation to the riparian zone. Silva and Williams (2001) studied the impact of buffer zones on river water quality. Fernandez et al. (2002) developed a GIS-based, lumped parameter water quality model to estimate the spatial and temporal nitrogen-loading patterns of watersheds in East Carolina. Band et al. (2001) presented a hierarchical distributed model to evaluate and predict the distribution of water, carbon and nitrogen cycling within a forested watershed, as well as the export of nitrate. Cosandey, *et al.* (2003) was able to successfully model denitrification within a riparian zone based on three dimensional soil horizon cartography and soil process functional units. At the catchment scale the application of the Soil Water Assessment Tool (SWAT), a continuous spatially explicit simulation model designed to quantify effects of landuse and management change on water quality within agricultural basins, achieved insightful results related to the long-term sustainability of current management techniques (Vache, *et al.* 2002).

The Cooperative Research Centre for Catchment Hydrology (CRC CH) has developed a modelling capacity to undertake whole-of-catchment analyses, covering a wide range of water and land management; it was delivered via the software product E2, which allows modellers to construct models by selecting and linking component models from a range of available options. In this paper, we use E2 in conjunction with the Riparian Nitrogen Model of Rassam et al. (2005) to assess the role of riparian zones on nitrate loads in streams; we implement the model in the Maroochy catchment. The aims of this paper are: firstly, to investigate the sensitivity of nitrate loads in streams to riparian buffer width, rooting depth, and denitrification potential; and secondly, to demonstrate the impacts of re-vegetation and/or land clearing in the catchment.

## 2. STUDY CATCHMENT

The Maroochy catchment covers an area of over 60,000 ha and is located in South East Queensland, Australia, 100 km north of Brisbane. The Maroochy has been one of the focus catchments for the development projects of the CRC CH; Searle (2005) carried out an extensive modelling study to predict the pollutant loads from the Maroochy catchment; he concluded that diffuse sources are the most significant contributors to pollutant export from the catchment. It is close to the experimental site of project 2.22 of CRC CH; it was hence chosen as a pilot catchment for testing the Riparian Nitrogen Model (RNM). Details of the landscapes and soils are found in Searle (2005). The Maroochy catchment has a coastal sub-tropical climate; average rainfall is about 1,700 mm/yr (two thirds of rainfall is in summer) and actual evaporation is about 1,430 mm/yr.

## 3. MODELLING EXPERIMENT

Models created in E2 are able to predict the hydrologic behaviour of catchments. The main model structure is 'node-link', where sub-catchments feed water and material fluxes into nodes, from where they are routed along links. Sub-catchment processes are modelled by a combination of up to three types of processes: runoff generation, constituent (or contaminant) generation, and filtering (Argent et al., 2005). The former two components produce daily time-series for discharge and contaminant load (nitrate in this case) in the catchment. The latter filtering component is of special interest in this paper; we use the Riparian Nitrogen Model of Rassam et al. (2005) as a "Plug-In" filter option for E2 to assess the role of riparian zones on nitrate loads in streams. The three basic model components and their corresponding input parameters for the Maroochy catchment are detailed below.

### 3.1. Rainfall-Runoff Model

Among the variety of rainfall-runoff models available within E2, we use the SIMHYD model (Peel et al., 2000; Chiew et al., 2002) because it is simple and has been successfully used in Australia. It is a daily conceptual model that estimates stream flow from daily rainfall and areal evapotranspiration data. The model has three stores for interception loss, soil moisture, and groundwater; it has 7 parameters, which do not have a direct physical meaning since SIMHYD merely mimics hydrological processes.

Table 1: SIMHYD parameters (from Searle, 2005)

| | Param. Name | Forested | Non-forested |
|---|---|---|---|
| Rainfall intercept. storage capacity | INSC | 5 | 4.8mm |
| Infiltration coeff. | COEFF | 200 | 200mm |
| Infiltration shape | SQ | 1.5 | 1.5 |
| Soil moisture storage capacity | SMSC | 240 | 220mm |
| Interflow coeff. | SUB | 0 | 0.8 |
| Recharge coeff. | CRAK | 0 | 0.9 |
| Baseflow coeff. | RK | 0.3 | 0.09 |

Rainfall data were obtained from the NRM SILO data drill database (SILO, 2004); evapotranspiration data was obtained from the Bureau of Meteorology. The model was run for 21 years during the period 1980-2000. The optimum model parameters for the Maroochy catchment are listed in Table 1. Discharge data from four gauging stations in the Maroochy catchment were used for the calibration process; good agreement ($R^2$ = 0.88 to 0.94) was obtained between the predicted and observed discharge values (Searle, 2005).

### 3.2. Constituent Generation Model

We use a simple constituent (or contaminant; nitrate in this case) generation model; this model uses two generation-processes where the rates vary with land-use: the event mean concentration (EMC) and the dry weather concentration (DWC). The former is applied to surface (quick) flow during flood events (i.e., discharge > base flow), and the latter is applied to slow (base) flow (i.e., discharge ≤ base flow).

Land uses and associated contaminant concentrations (in mg/L) used were as follows: National Parks, Managed Forests, Plantation, Native Bush (EMC=0.32; DWC=0.16); Grazing (EMC=0.64; DWC=0.28); Broad-acre Agriculture, Intensive Agriculture (EMC=0.84; DWC=0.28), Suburban, Dense Urban (EMC=0.64; DWC=0.6); Rural Residential (EMC=0.64; DWC=0.28). These values are nitrate-N concentrations, which were obtained by multiplying the total-N values obtained from Searle (2005) by 0.4 (this fraction was obtained from the Queensland NRM surface water database).

### 3.3. The Riparian Nitrogen Model

The RNM estimates the removal of nitrate as a result of denitrification that occurs when shallow groundwater interacts with riparian soils; this interaction occurs via two mechanisms, firstly, as the 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 events.

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, which ensures that denitrification occurs only in the root zone (maximal at soil surface, declines exponentially with depth, and attains a zero value below the root zone, refer to Eq. 1 in Rassam et al., 2005); 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 analysis presented in this paper is restricted to middle order perennial streams, i.e., considers the latter two mechanisms. The calculations are carried out on a functional unit/sub-catchment scale (where functional units here represent various land uses within a sub-catchment). The conceptual models for groundwater and surface water interactions, mathematical expressions for denitrification, and other model details are found in Rassam et al. (2005).

For the current study, we used a digital elevation model (DEM) with a 25-m cell size. The flow accumulation threshold for perennial streams was set at 5 $km^2$. High order streams masked out from the analyses (Rassam et al., 2005) were identified as regions with a multi-resolution valley bottom flatness (MRVBF) index>4.5 (Gallant and Dowling, 2003). The rasters for soil porosity and hydraulic conductivity were obtained from the Soil Hydrological Properties of Australia dataset (Western and McKenzie, 2004). The maximum denitrification rate at the soil surface was 0.58/day; k=1.16/m, where k is an exponential decay

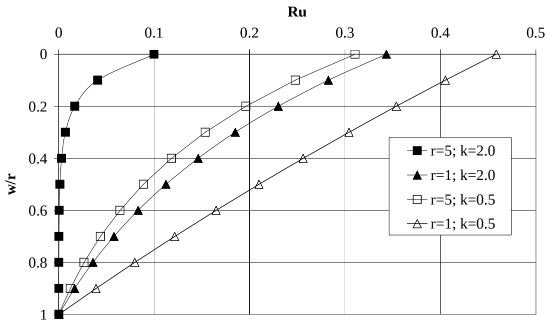


Figure 1: Average denitrification rate $R_u$ ($day^{-1}$), depth to water table w (normalised with respect to rooting depth r); base flow

constant that describes how denitrification potential decreases with depth.

The amount of water stored in stream banks during flood events was evaluated using the model presented by Rassam et al. (2005). Channel metrics parameters for the Maroochy catchment were not available thus they were obtained from Stewardson et al. (2005). Parameters for calculating bank-full discharge were as follows: discharge coefficient=0.38; area exponent=0.554; meander exponent= 0.444; PET exponent=-0.08. Parameters for calculating channel depth were as follows: depth coefficient=0.403; bank-full discharge exponent=0.379; slope exponent=-0.087; meander exponent=-0.08.

For the clearing and re-vegetation scenarios, we used a rooting depth of 5m and a width of 25m. Nitrate loads for fully vegetated and totally cleared riparian zones were calculated using hypothetical rasters for vegetation cover (using rasters with full no vegetation cover, respectively). The effect of re-vegetation was calculated as follows: nitrate load under full vegetation – nitrate load under current conditions. The effect of clearing was calculated as follows: nitrate load under current conditions - nitrate load under no vegetation. For the sensitivity analyses, we used the current vegetation conditions and ran multiple scenarios for various riparian zone widths and rooting depths.

## 4. RESULTS AND DISCUSSION

### 4.1. Sensitivity Analysis

The sensitivity analysis for the base flow component has shown that as the distribution of denitrification rates $R_u$ down the soil profile becomes more non-linear (k increases), it becomes more sensitive to rooting depth (Figure 1). When w/r becomes zero, this means that that water table

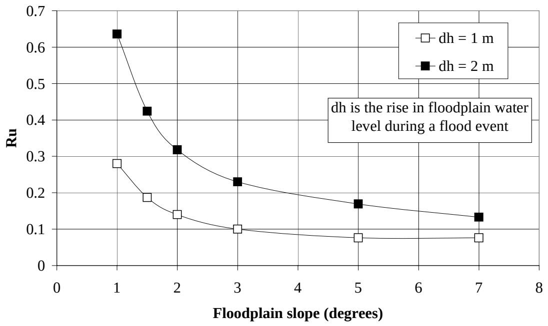


Figure 2: Average denitrification rate $R_u$ (day$^{-1}$) versus floodplain slope; bank storage

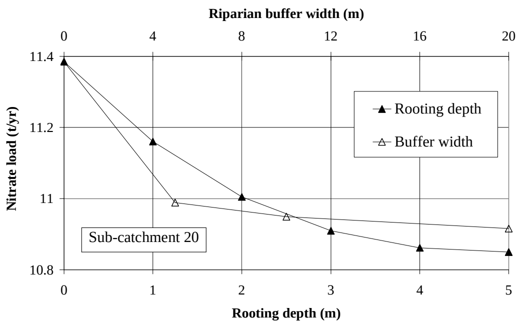


Figure 3: Nitrate load versus rooting depth and buffer width

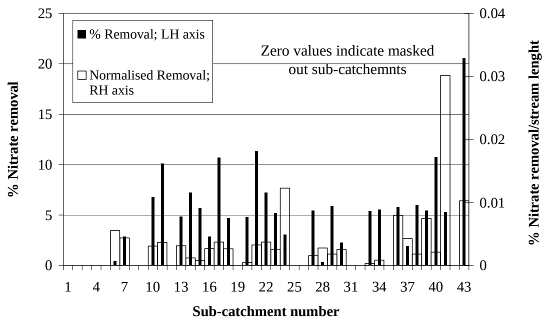


Figure 4: Nitrate removal for Maroochy sub-catchments

is located at the soil surface, which results in maximal denitrification rate. When w/r becomes unity, this means that the entire root zone is unsaturated; i.e., it does not support denitrification.

The advantages of flat floodplains have been highlighted by Burt et al. (2002) as they provide a higher residence time and increase the likelihood of interaction with the more active surface sediments; there is also the added advantage of larger stream volumes interacting with riparian sediments during events. For the bank storage component, the denitrification rate $R_u$ is reduced dramatically as the floodplain slopes up to 3$^o$; the sensitivity increases during larger flood events, i.e., for higher dh values (see Figure 2). This is mainly due to the fact that the water table is intercepting the more active sediments located closer to the floodplain surface (refers to Eq. 1, Rassam et al., 2005). A flat riparian buffer means that larger volumes of stream water are interacting with the riparian sediments during flood events.

The modelling results for the Maroochy catchments have shown that the optimum rooting depth is 2-3 m; sample results for sub-catchment 20 are shown in Figure 3. According to the model conceptualisation (Rassam et al., 2005), increasing rooting depth (i.e., having trees compared to shrubs) results in stretching the active zone where denitrification can occur; in addition, it also implies that a deep water table is more likely to intercept it thus providing conditions conducive to denitrification.

A riparian buffer width of about 5-10 m results in optimal nitrate removal (see Figure 3). A wide riparian buffer provides a higher residence time thus increasing the overall denitrification potential (for the base flow component); it also means that there is a larger volume of stream water interacting with riparian sediment during flood events (for the bank storage component).

### 4.2. Nitrate Removal

Figure 4 shows the potential for nitrate removal in the Maroochy sub-catchments; these values are the difference between the pass-through scenario (no riparian buffer) and the fully vegetated scenario. For the denitrification rates used in this paper, the riparian buffers have the capacity to remove up to

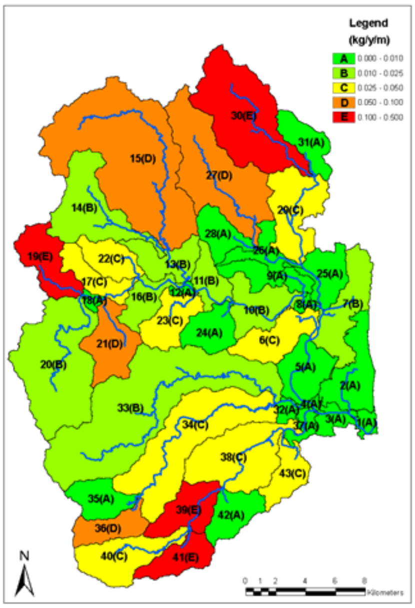


Figure 5: Effect of clearing riparian vegetation in the Maroochy (kg $NO_3$/yr/m stream length)

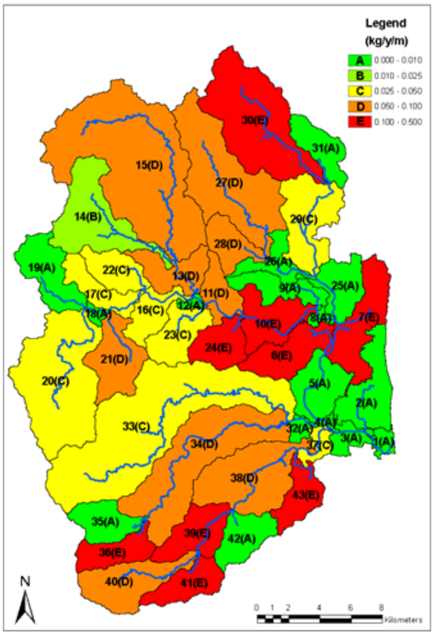


Figure 6: Effect of riparian re-vegetation in the Maroochy (kg $NO_3$/yr/m stream length)

20% of the nitrate load (in sub-catchment 43, see solid bar in Figure 4). There are four sub-catchments that have a 10% removal capacity, and the remainder averaged at 5%. The potential for a particular sub-catchment to remove nitrate is directly related to its total stream network length as more streams mean more riparian buffers. We normalise the nitrate removal potential of a sub-catchment to length of streams to obtain the capacity of a unit length of riparian buffer along the stream network to reduce nitrate (see open bar symbols in Figure 4). This provides us with a direct measure for the capacity of riparian buffers, which can be used for targeted restoration. That is, land managers should pursue the restoration process by first targeting areas having the maximum nitrate removal capacity per unit length of stream. Targeted restoration can also be explicitly linked to the proximity of a particular land use; Rassam et al., 2005 defined a 'Contamination Index' and aggregated it with denitrification potential to produce a 'Restoration Index' that identifies 'Hot Spots' where riparian restoration is likely to result in maximal benefits.

Figure 5 shows the potential adverse effects of clearing riparian vegetation in the Maroochy catchment quantified as increased nitrate load per unit length of the stream network; red areas having the highest impact are those that are currently heavily vegetated and thus would have the highest adverse impact when cleared. Figure 6 shows the potential benefits of riparian re-vegetation in various Maroochy sub-catchments.

## 5. CONCLUSIONS

Implementing the Riparian Nitrogen Model (RNM) in the Maroochy catchment has highlighted the importance of hydrology in influencing the extent of nitrate removal from groundwater via denitrification. A shallow groundwater table combined with a flat floodplain maximises denitrification potential. Deeply rooted vegetation enhances carbon availability thus increasing denitrification potential. A wide riparian buffer increases residence time in addition to providing a larger buffer for stream water to interact with riparian sediments during flood events. It was shown that a rooting depth of about 2-3 m when combined with a riparian buffer width of 5-10 results in optimal nitrate removal capacity. The maximum nitrate removal capacity in the Maroochy was found to be about 20%. Normalising the nitrate removal capacity with respect to the length of the stream network provide a direct measure for the capacity of a unit length of riparian buffer to remove nitrate via denitrification. The RNM was also used to provide maps that show the adverse impacts of land clearing and potential benefits of re-vegetation in the Maroochy catchment.

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