IDENTIFYING PRIORITY AREAS FOR RIPARIAN REHABILITATION TO MINIMISE NITRATE DELIVERY TO STREAMS

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Abstract: Surface water and groundwater systems are connected with the head gradient between the river and the nearby aquifer controlling the magnitude and direction of the exchange flux between the two systems. The direction of the flux dictates whether the river gains water from the nearby aquifer, or loses water to it. The exchange between groundwater and rivers is a key component influencing not only river discharge/recharge (from a quantitative perspective), but also affects water quality, geomorphic evolution, riparian zone character and composition, and ecosystem structure. A number of processes contribute to the exchange flux between surface and groundwater, most importantly they include: aquifer recharge (including diffuse recharge, recharge from irrigation return, and recharge from overbank flow), bank storage, groundwater extraction, and evapotranspiration. Riparian zones can provide a protective buffer between streams and adjacent land-based activities by removing nitrate from shallow groundwater flowing through them. The flow of shallow groundwater through the biologically active root zone of riparian vegetation, which is inherently rich in organic carbon, facilitates the denitrification process. Hydrological factors are an important influence on the effectiveness of riparian buffer zones in reducing pollutant loads delivered to streams. Nitrate-bearing water can interact with sediments in many forms. The classical conceptual model for nitrate attenuation during base flow conditions in gaining streams suggests that groundwater travels laterally and interacts with the riparian soil before discharging to the stream. In this work, conceptual models for surface water-groundwater interactions are presented along with analytical mathematical functions that describe nitrate removal in riparian zones. These concepts were incorporated within a GIS modelling framework to develop the Riparian Mapping Tool (RMT), which assesses the potential of riparian zones to reduce nitrate delivery to streams. The RMT was adopted to prioritise riparian rehabilitation in the Tully catchment (QLD, Australia) with high-priority areas defined as those having a high potential for riparian denitrification and nearby land uses that generate high nitrogen loads.

1.0 Introduction

Aquatic organisms require nutrients for their metabolism, growth and reproduction, but when present in excess, nutrients are considered to be pollutants that can have adverse impacts on ecosystem health. Recent studies in several parts of Australia have shown nitrogen to be a key nutrient likely to trigger algal blooms and related problems in both coastal waters (e.g., Dennison and Abal, 1999; Murray and Parslow, 1999) and freshwater bodies (e.g., Mosisch *et al.*, 1999, 2001). Sources of nitrogen associated with land use include fertilizer application, soil erosion, inputs from human and animal wastes, and in some cases, precipitation (e.g., from vehicle emissions in large cities) (Hunter *et al.*, 2006).

Riparian zones can trap sediment and associated nutrients from surface runoff, thus reducing downstream loadings (Prosser *et al.*, 1999). In addition, riparian zones are host to a variety of sub-surface processes that have the potential to transform and remove nitrogen, including via the microbial process of denitrification (Cirmo and McDonnell, 1997). Many studies have demonstrated substantial reductions in nitrate as sub-surface water passes through riparian buffer zones (e.g., Hill, 1996; Dosskey, 2001) and the role of riparian zones in facilitating denitrification has received particular attention (e.g., Hill, 1979; Peterjohn and Correll, 1984; Haycock and Pinay, 1993; Hill, 1996; Vidon and Hill, 2004). Denitrification is of specific interest because it results in the conversion of nitrate to gaseous forms of nitrogen and is therefore a pathway for permanent removal of nitrogen from the land/water system.

Nitrate, oxygen, organic carbon, and soil micro-organisms are key factors that influence denitrification. Organic carbon provides energy for microbial respiration and typically 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 sub-surface paths in riparian zones may interact with anaerobic soil zones, which are likely to have high organic matter content as a result of accumulation and decomposition of plant and other biotic residues. These zones are thus favourable for denitrification processes. The factors that affect the extent of denitrification include: groundwater dynamics, the geometry of the riparian zone and how it links to the stream, and the nature of riparian vegetation. Maximal nitrate removal in riparian zones requires the following: (1) the existence of a floodplain; (2) a well-vegetated riparian zone that provides a plentiful source of organic carbon through the soil profile; (3) a suitable floodplain hydrology conducive to denitrification.

The importance of riparian zone hydrology in influencing the extent of denitrification has been emphasised by many studies (e.g., Martí, 2000; Burt *et al.*, 2002; Butturini *et al.*, 2002; Rassam *et al.*, 2006). The classical conceptual model for denitrification suggests that groundwater travels laterally and interacts with riparian sediments before discharging to the stream. The mechanism is typical of base flow conditions. This conceptual model for denitrification implies that a shallow water table intercepts the carbon-rich root zone, thus providing anoxic conditions, and that flow rates are relatively slow such that they allow sufficient residence time for the denitrification reactions to occur. These conditions are achieved where soil in the floodplain has a hydraulic conductivity that 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. Furthermore, Rassam (2005) has subsequently shown that the conductivity ratio K_1:K_2 (where K_1 refers to the conductivity of the floodplain and K_2 the conductivity of the upslope soil) is the key parameter that determines the suitability of the floodplain hydrology for denitrification processes; soils that are most conducive to denitrification are those with a medium hydraulic conductivity of about 0.1 to 1 m/day. Topography has been found to play a substantial role in determining the hydrological functioning of riparian zones (Devito *et al.*, 2000). Topographic slope influences the hydraulic gradient and therefore the volume and velocity of water entering the riparian zone, whilst concavity of the riparian profile enhances the interaction between sub-surface water and superficial soil horizons. Stream channel geometry is also important; where stream channels are incised, water tables tend to be lowered, limiting the ability of the riparian vegetation to aid denitrification or take up nitrate. For example, Micheli and Kirchner (2002) found that channel incision lowered water tables and dried out stream banks in Montane Meadows of the Western United States so much that a change in the type of vegetation took place.

Within the last decade, there has been increased interest in applying catchment hydrological models to determine the likely impacts on water quality from changes in land use or land management practices. Progress in scientific understanding of hydrological processes at the catchment scale relies on making the best possible use of advanced simulation models as large amounts of data increasingly become accessible (Troch *et al.*, 2003). An extensive range of hydrological models has been developed with different applications in relation to the riparian zone (e.g., Fernandez *et al.*, 2002; Silva and Williams, 2001; and Cosandey *et al.*, 2003).

The use of a DEM for predicting catchment behaviour via what is commonly referred to as "terrain analysis," has been in use for well over two decades. Moore *et al.* (1991) provide a good review of the topic, stating that the topography of a catchment has a major impact on the hydrological, geomorphological and biological processes active in the landscape. These authors provide a plethora of examples of how a DEM can be used to examine primary topographic attributes, analytically derived compound topographic indices, solar radiation processes, erosion processes and soil properties. One of the earliest breakthroughs in this area was TOPMODEL, which introduced the wetness index of Beven and Kirkby (1979) and can be used to identify the parts of catchments that might be surface saturated. Within TOPMODEL, the topographic index is used to estimate the depth to the water table. Troch *et al.* (1993) showed that for two basins in Pensylvania, the assumption of a linear relationship between water table depth and the Wetness index was reasonable. This type of research has encouraged the use of simple spatial indices for the prediction of more complex phenomena. In recent years, a number of GIS tools have been developed for the purpose of making rapid, broad-scale assessments of catchments. McGlynn and Seibert (2003) assessed the "buffer capacity" (the ability to buffer hillslope runoff) of riparian zones using a novel form of terrain analysis. This study highlighted that DEMs house a very large amount of information regarding catchment functionality. Other terrain analysis tools such as MRVBF (Multi-resolution Valley Bottom Flatness) (Gallant and Dowling, 2003) have been used for generating indices of valley slope and scale. The index has potential utility in the identification of groundwater constrictions and in the delineation of geomorphic units such as depositional parts of landscapes. Baker *et al.* (2001) outline the MRI-DARCY model, which attempts to predict sub-surface discharge to rivers, lakes and wetlands at a scale useful to environmental managers. MRI-DARCY is described as being "topographic", highlighting that the model assumes a strong relationship between groundwater movement and aspects of the DEM. Whilst Baker *et al.* (2001) recognise that aspects of their modelling could be regarded as a "gross over-simplification", we argue that this type of approach is required to make rapid, broad-scale assessments in very large study areas. There is a need for tools that can attain enough predictive accuracy at the catchment scale to aid in management decisions, whilst only requiring a limited amount of easily available data.

In this work, we use the Riparian Mapping Tool (RMT) of Rassam and Pagendam (2006) to identify high priority riparian restoration areas in the Tully catchment. This novel GIS technique can help land managers identify riparian areas of middle order streams where rehabilitation is likely to be most effective in enhancing denitrification and reducing nitrogen loads to streams. The RMT had been successfully implemented in the Maroochy catchment

(Rassam et al., 2005b). To optimise the benefits of riparian rehabilitation, we envisage that information from the RMT can be evaluated alongside priorities for achieving other objectives such as stabilising stream banks. The RMT stems from the Riparian Nitrogen Model of Rassam *et al.* (2005a, 2007). This mapping tool encompasses the hydrological and chemical processes that underpin denitrification in a spatially explicit and simple manner, with relatively low data requirements. It relies on a number of terrain analysis methods to identify potential denitrification "hotspots", but also requires the user to conduct a number of statistical analyses involving spatial and temporal datasets to identify predictive models for: (i) groundwater depth in riparian buffers; and (ii) baseflow delivery to streams. This document outlines the steps taken to use the RMT in the Tully-Murray system in North Queensland and presents detailed maps of potential priority restoration areas in the catchment.

2 Methods

This section outlines the denitrification model and spatial analyses employed by the Riparian Mapping Tool (RMT). The RMT makes use of two indices: (i) a denitrification and nitrate removal index; and (ii) a contaminant interception index. The first of these indices uses a model of first order denitrification kinetics to quantify the proportion of nitrate removed from groundwater passing through the riparian zone. This denitrification index is based on the model of Rassam *et al* (2005a, 2007), which first appeared as the Riparian Nitrogen Model. The second index attempts to assess the amount of nitrate that cells in the riparian zone intercept and therefore have the ability to denitrify. This contaminant interception index is based on an analysis of a neighbourhood of cells in close proximity to the riparian zone and their land uses and an estimation of baseflow delivery.

2.1 Denitrification and Nitrate Removal Potential

Denitrification occurs while nitrate-rich groundwater interacts with the carbon-rich riparian sediments, which may be conceptualized as shown in Figure 1. 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. Rassam et al. (2005a, 2007) have adopted a 1st order decay function to describe the distribution of denitrification rate with depth:

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

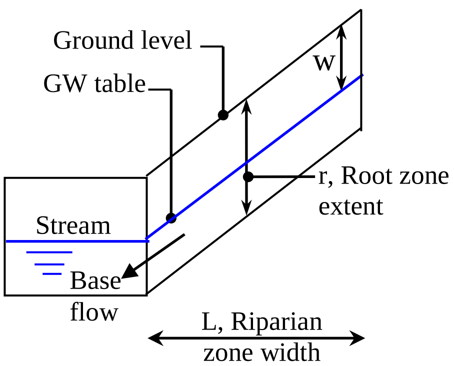

Figure 1: Conceptual model for hydrology

where R_d is the denitrification rate at any depth d (hours^{-1}), R_{max} is the maximum rate at the soil surface, *d* is the vertical depth below the ground surface (m), *r* is the depth of the root zone (m), and *k* is a parameter describing the rate at which denitrification rate declines with depth (m^{-1}). The average denitrification rate across the riparian zone is given by (Rassam *et al*., 2005a, 2007):

$$R_{\mu} = \frac{R_{\max}}{(r-w)(1-e^{-kr})}\left(\frac{e^{-kw}-e^{-kr}}{k}+(w-r)e^{-kr}\right) \tag{2}$$

where w is depth to the water table and r is the extent of the root zone (see Figure 1). The average residence time (in hours) of groundwater traveling across the riparian zone to the stream is calculated as:

$$t_{\mu} = \frac{L}{K\sin(\theta)} \tag{3}$$

Where K is the hydraulic conductivity (m/h), L is the riparian buffer width (m) and θ is the topographic slope of the riparian buffer towards the stream channel (radians).

The proportion of nitrate removed in the riparian zone by denitrification can be calculated using 1[st] order decay kinetics as follows:

$$D = 1 - e^{-R_{\mu}t_{\mu}} \tag{3}$$

where D is the denitrification potential (0 to 1) representing the proportion of nitrate that is removed via denitrification, and t_{μ} is the mean residence time. The latter is calculated based on Darcy's Law using the prevailing head gradients and hydraulic conductivity at any pixel in the landscape; note that according to the conceptualization shown in Figure 1, the head gradient is equivalent to the riparian zone slope. The total nitrate mass that can potentially be removed at riparian zones is proportional to D and the volume of water that interacts with the buffer (assuming constant nitrate concentration); we can define the Nitrate Removal Index as follows:

$$\eta = D\,v \tag{4}$$

where η is the Nitrate Removal Index, and v is the volume of water interacting with the riparian buffer. In this paper, we use a linear model relating average precipitation and evapotranspiration to baseflow delivery, which was used as a proxy for v.

2.2 Contaminant Interception and Rehabilitation Potentials

We use a simple nitrate generation model where concentrations vary with land-use; land uses and associated nitrate concentrations are derived from normalized DWC (Dry Weather Concentration) values provided by Chiew *et al* (2002). We note that whilst the contaminant generation potential of land uses is derived from DWC values, the actual magnitude is unimportant within the RMT: it is the relative magnitudes of the DWCs in a catchment that affects the output of the RMT. The RMT generates a map of nitrate interception potential in riparian buffers, calculated by examining the neighbourhood disc of each of the i cells in the riparian zone within a prescribed search radius (z_{max}). For each of the n_i cells within this search radius we allocate the pairs (DWC_j, z_j) to the set S_i, where the elevation for a neighbouring cell is equal to or greater than that of the riparian cell in question. This ensures that lower cells cannot contribute groundwater to higher cells. We therefore define the set $S_i=\{(DWC_1, z_1), (DWC_2, z_2), .., (DWC_n, z_n)\}$ where DWC_j is the dry weather concentration of the j^{th} cell in the neighbourhood disc and z_j is the distance from the focal riparian cell to the j^{th} cell within the neighbourhood disc.

The member pairs of the set are used to determine the contaminant interception potential (CIP) of the i^{th} riparian zone cell as follows:

$$CIP_i = \sum_{j=1}^{n_i} \frac{DWC_j}{z_j^{\ 2}} \quad (5)$$

2.3 The Restoration Index

The spatial datasets corresponding to η and CIP_i have values between 0 and 1. These two indices are combined into a restoration index:

$$R_i = \eta_i CIP_i \quad (6)$$

where R_i is the 'Rehabilitation Potential' for the i^{th} raster cell, which provides a useful measure of a riparian buffer's ability to intercept contaminants as well as successfully removing them via denitrification. As a final step to aid the restoration of riparian buffers, the index *R* is reclassified into 10 categories according to the deciles of the distribution of the values comprising *R*. As an example, a riparian zone with a score of 4 falls between the 30^{th} and 40^{th} percentiles of *R*.

2.4 Contaminant Generation Potential

Draft QLUMP (Queensland Land Use Mapping) 2004 shape files were obtained through the Queensland Department of Natural Resources and Water. The DBF (DBase) file associated with the shape file was imported into Microsoft Access and the various land uses attributed to each polygon were re-grouped into a simpler structure containing 5 broad land use categories: (i) water; (ii) urban; (iii) vegetated; (iv) grazing; and (v) agriculture. Once the reclassification was complete, the shape file was projected to Albers equal area projection and then converted to a raster. Raster pixels were assigned values that reflected the contribution of the particular land use to groundwater nitrate contaminationThe normalization was undertaken such that the land use with the greatest pollution potential (agriculture) had a value of 1.0 and all other land use DWCs were scaled relative to agriculture.

2.5 Statistical Model for Predicting Baseflow Index

Gauging station data was collated for the Tully-Murray as well as neighbouring coastal catchments (i.e. the Johnstone and Herbert River catchments). For each geographical location where data had been collected, the entire time-series (daily) was passed through a Lyne-Hollick digital filter (Lyne and Hollick, 1979) for the purpose of Baseflow separation (with filtering parameter α set to the default of 0.925). As noted by a number of previous authors (e.g. Lacey and Grayson, 1998; Mazvimavi *et al*., 2004), baseflow delivery to streams can be a function of a variety of biophysical characteristics. We therefore set about to identify significant environmental predictors of baseflow contribution. Each time-series was used to calculate baseflow index (BFI) which was used as the response variable in a linear model, with a number of potential predictors, including: elevation, average long-term rainfall, flow type (unregulated or regulated), average long-term potential evapotranspiration (PET), Contributing Area, Soil hydraulic conductivity and porosity, MRVBF and wetness Index. Of these potential predictors, We identified a reasonable (R^2 = 0.68), and highly significant relationship between BFI and rainfall ($p = 8.55E-6$) and PET ($p = 0.024$). All statistical analyses were performed in the R statistical environment. Figure 3.3.1 shows the observed and predicted levels of BFI for the 24 sites used in this analysis, with the 1:1 line superimposed.

The statistical model used to infer baseflow contribution throughout the catchment had the form:

$$\mathrm{BFI} = \alpha + \beta_1(\mathrm{Rainfall}) + \beta_2(\mathrm{PET}) \tag{7}$$

2.6 Statistical Model for Predicting Depth to Groundwater

Groundwater data for the Tully-Murray system as well as neighbouring coastal catchments (i.e. Johnstone and Herbert) were obtained from the Groundwater database managed by the Queensland Department of Natural Resources and Water. At each bore location, spatial attributes of three topographic indices were obtained: (i) Compound Topographic Index (CTI) or “Wetness” Index (Beven *et al*., 1979); (ii) Multi-resolution Valley Bottom Flatness (MRVBF; Gallant and Dowling, 2003); and (iii) MRI Darcy Index (Baker *et al*., 2001). Each of these three indices was obtained from analysis of 250m digital elevation models (DEM). Bores that were within a 250m buffer of a drainage network derived from the 250m DEM, were retained for the statistical analysis, whilst those that lay outside of this buffer zone, were considered to not be representative of the riparian zone. In total, 23 groundwater bores were used to formulate the statistical model.

All three topographic indices were calculated using TIME (The Invisible Modelling Environment) of Rahman et al., (2003), with the MRVBF and CTI being implemented in the Terrain Analysis Library. The MRI Darcy Index was custom coded in C#. Default parameter sets were used for MRVBF and CTI, with the MRI Darcy Index using a 10km^2 threshold for the initiation point of perennial streams. Data for the three topographic indices were appended to groundwater sites using the GridSpot plug-in for ArcGIS. The linear model identified was used to create a raster of predicted groundwater depth. Where the model predicted groundwater depth to be positive (i.e. above ground level), raster values were truncated to equal zero.

The statistical model identified for the prediction of groundwater depth was:

$$\begin{aligned}\mathrm{Depth} = \alpha + \beta_1(\mathrm{CTI}) + \beta_2(\mathrm{MRVBF}) + \beta_3(\mathrm{MRI\,Darcy}) + \beta_4(\mathrm{CTI} \times \mathrm{MRVBF}) \\ + \beta_5(\mathrm{CT}I \times \mathrm{MRI\,Darcy})\end{aligned} \tag{8}$$

2.7 Denitrification Potential

Denitrification potential of riparian zones was predicted using a digital elevation model (25m cell resolution) and subsoil hydraulic conductivity (obtained from the Soil Hydrological Properties of Australia (SHPA) dataset, 1km cell resolution). A riparian zone of 50m width either side of the stream network was considered in the analysis performed by the RMT. For each raster cell within the riparian zone, estimates were made of groundwater velocity and residence time, based on the topographic slope and the subsoil hydraulic conductivity.

For each raster cell in the riparian zone, the RMT also estimates an average denitrification rate, based on the predicted depth to groundwater and three parameters governing the decline in denitrification rates with soil depth (R_{max}, k and r). We implemented the RMT using the parameter based on experimental estimates of denitrification rates outlined in Rassam *et al* (2005b).

3.0 Results and discussion

The statistical model for predicting depth to groundwater table used in this study was based on a number of topographic indices one of which was the MRI-Darcy Index that required the specification of a flow accumulation threshold that represents the initiation points of groundwater fed (perennial) streams. In our analysis, this was set to 10km^2, since this was in good agreement with the uppermost position of groundwater sites in close proximity to streams. The choice of this threshold may result in a bias towards riparian zones belonging to streams with a flow accumulation greater than or equal to $10km^2$; the model would likely ignore riparian zones in very low order streams. Such streams that have a low flow accumulation threshold (low order) are likely to be ephemeral losing streams and where the hydrological conceptualization of the model is not applicable. The statistical model comprised of highly significant predictors and therefore provided us with strong evidence that the predictors used have a very real relationship with groundwater depth.

The modeling exercise suggested that riparian zone restoration for the purpose of denitrification of groundwater delivered to streams should firstly target streams in the central catchment (shown in red in Figure 2). Lower order streams found in the upper parts of the Tully-Murray (shown in blue in Figure 2) have a much lower restoration potential. Figure 3 classifies the catchment into different restoration areas where the high number (red areas approaching a score of 10) indicating high priority areas.

Riparian rehabilitation should target low areas in the landscape (that have shallow water tables), flat areas (that allow a high residence time for denitrification to occur), regions of medium hydraulic conductivity soils (that allow a high flux and result in a relatively high water table as demonstrated by Rassam, 2005), and areas where current land use results in maximal nitrate delivery to streams. The advantages of flat floodplains have been highlighted by many researchers 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.

There is a recognised lack of reliable information available to land managers to support their decision making on nitrogen management issues, which compromises the effectiveness of rehabilitation. The spatial variability of the factors that control denitrification in riparian zones deems the task of identifying areas of optimal benefits a difficult one. Implementing the Riparian Mapping Tool in the Tully-Murray System has demonstrated its ability to identify areas where optimal benefits of riparian rehabilitation are likely to occur. Field data has verified the suitability of the proposed component indices to describe the underlying physical processes associated with nitrate generation and its potential removal via denitrification in riparian zones. The study results can be used to make informed decisions regarding riparian rehabilitation, which would optimise the investments made and lead to better management of the nitrogen problem and improve stream water quality.

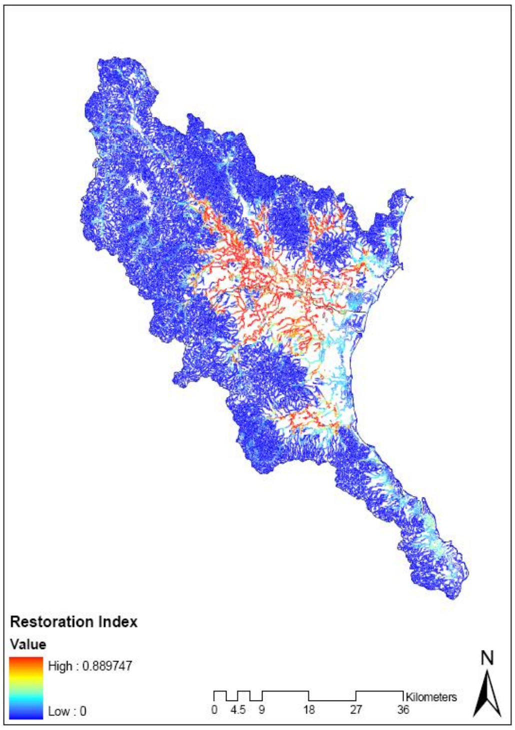

Figure 2. Map of the RMT restoration index for riparian zones in the Tully

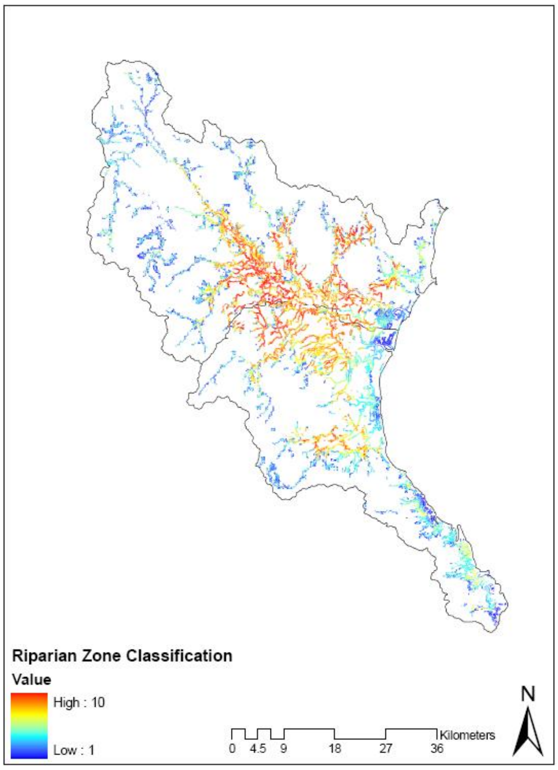

Figure 3. Map of riparian zones, classified for prioritization of restoration in the Tully

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