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PREDICTING RIPARIAN ZONE FUNCTIONS USING REMOTE SENSING

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ABSTRACT: There is an increasing demand amongst resource managers for cost-effective watershed-scale inventories of riparian buffer condition and function. Recent developments in image processing software and decreasing satellite imagery costs enable a new methodology that can help meet this demand. ASTER satellite imagery, which has 15 metre pixel size, is processed with image segmentation software to identify riparian buffers and stands of riparian vegetation. Field data from a stratified sample of locations are used to identify the attributes of the riparian buffers (such as Manning's *n*) adjacent to different land uses. Field data are also used to identify the attributes of the riparian vegetation (such as average diameter at breast height and average tree height). These attributes are then spatially extrapolated across a large (16 000 km^2) watershed using a land use and vegetation classification derived from remote sensing. An independent set of field data is used to assess the classification accuracy and to assess the reliability of the attributes predicted by the classification. The spatially extrapolated attributes are used to calculate indices that describe some of the functions performed by riparian buffers and riparian vegetation at a whole-of-watershed scale. These function indices describe the hydrologic, geomorphic and ecological functions of the riparian zone. The hydrologic index describes runoff interception while the geomorphic indices describe sediment trapping, and bank reinforcement. The geochemical index describes pollutant trapping. The ecological indices describe stream shading and large wood recruitment. This paper contains a description and discussion of these indices, with some illustrative results for the large wood recruitment index. A more detailed description of the theory and results of the large wood recruitment index are contained in a companion paper.
KEY TERMS: vegetation mapping; watershed, riparian functions, prioritization

INTRODUCTION

The native trees and grasses that make up riparian vegetation provide a number of important functions at the watershed scale (Table 1). All of these functions assist in maintaining local biodiversity, water quality, and reducing the amount of sediment delivered to dams, reservoirs and sensitive estuarine environments.

Watershed management authorities are frequently required to make decisions about prioritizing areas for riparian zone protection and rehabilitation projects across large watersheds. The limited availability of resources for such projects make it especially important to identify high priority areas, and to identify which management strategies are likely to have the biggest effect in these areas. The prioritization of riparian rehabilitation and protection programs requires the capacity to quantify the various functions being performed by stands of riparian vegetation and riparian buffer strips throughout a large watershed.

The objective of this research is to quantify the spatial distribution of some of the hydrological, geochemical, geomorphic and ecological functions performed by woody vegetation and grasses in the riparian zones of a semi-arid watershed. This study aims to meet this objective by using spatial analysis techniques, including remote sensing, geographic information systems and terrain analysis, to assess the distribution of riparian zone functions in a semi-arid environment subject to cropping and grazing. Each riparian zone function is described in terms of an index: sediment trapping, pollutant trapping, overland flow interception, stream bank reinforcement, stream shading, and large wood recruitment. The approach described in this research could be applied to the riparian zones of other semi-arid watersheds that are subject to grazing and cropping. It could also be applied to riparian zones adjacent to other land uses and in other climatic regions, however a knowledge of the local hydrology, ecology and land use practices would be essential in interpreting the index results.

METHODS

Location

The research was conducted in the Nogoa sub-catchment (16,000 km^2) of the Fitzroy watershed in Queensland, Australia. The climate is hot and semi-arid, with domestic animal grazing, dry land cropping, and irrigated cropping the

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Table 1. The functions performed by riparian vegetation and buffer strips

Hydrological functions	rainfall interception, maintenance of the water table, hydraulic resistance to overland flow and floods
Geomorphic functions	sediment trapping, bank stabilization/reinforcement, altering the effect of sub-aerial processes
Geochemical functions	denitrification, trapping nutrients associated with fine particles
Terrestrial Ecological functions	habitat for various avian, mammalian, and herpetofauna, habitat corridors
Aquatic Ecological functions	providing shade for streams and waterholes, thereby buffering water temperature; providing a source of food via litter fall, and providing habitat via root mats and large woody debris

predominant land uses. The terrain typically has very low relief. Consequently the fluvial geomorphology is typical of a semi-arid lowland river, with very low channel slopes throughout the watershed. The region was extensively cleared in the 1960s and 1970s, but some portions of remnant riparian vegetation remain along the larger rivers. Vegetation and river channel surveys based on the techniques described in McDonald *et al*. (1990) were carried out at 38 sites within the study area. Riparian zones adjacent to all land uses and stream orders were included in the sampling regime.

Riparian Function Indices

The Sediment Trapping Index

Riparian zones provide one of the last terrestrial sinks of sediment prior to it entering the river network (Johnson *et al*., 1999). Consequently, information about the spatial distribution of the sediment trapping capability of existing riparian vegetation is of great value. The sediment trapping index (*STI*), has been adapted from Hairsine and Rose (1992) as

$$STI = 1 - \left[\frac{n(noRZV)}{n(current)} \right]^{\frac{1}{m}}, \tag{1}$$

where *n(noRZV) i*s the Manning's roughness coefficient *n* of a riparian zone with no riparian vegetation, and *n(current)* is the Manning's n of the current riparian zone vegetation and *m* is approximately 2 (Hairsine and Rose, 1992). The formulation of the index assumes that sediment transport is occurring in transport limited circumstances both for the current and no riparian vegetation case. The *STI* approaches 1 when the Manning's *n* of the existing riparian vegetation is much higher than the Manning's n of a riparian zone with no riparian vegetation, and approaches 0 if the current Manning's n is similar to the value for a riparian zone with no vegetation.

The Pollutant Trapping Index

The pollutant trapping index (*PTI*) refers to the capacity for riparian zones to trap pollutants carried in shallow overland flow from the adjacent hillslope. The pollutant trapping index is described by

$$PTI = 1 - \frac{n(current) \;\; N(current)}{n(noRZV) \;\; N(noRZV)}, \tag{2}$$

where , *N(current)* is the current concentration of sediment adsorbed nutrients per unit mass of sediment leaving the riparian zone (enrichment ratio) and *N(noRZV)* is the concentration of sediment adsorbed nutrients per unit mass of sediment that would leave the riparian zone if there was no riparian vegetation. This index follows the approach developed by Hairsine and Rose (1992) with modification based on Palis *et al*. (1990) for sediment-bound nutrient transport. This index could be used to calculate pollutant loads for a range of different pollutants provided that specific enrichment ratio data was available for that pollutant on that soil type.

The Overland Flow Interception Index

Overland flow entering a riparian zone from an adjacent hillslope can potentially be stored in riparian soil. The volume of overland flow that can be stored in the riparian zone is determined by the available soil water storage, which in turn is determined by the width of the riparian zone and the depth and porosity of the riparian soils (Herron and Hairsine, 1998). This index uses the model of Herron and Hairsine (1998) which defines the riparian ratio Ψ as the ratio of riparian zone width to hill-slope length (expressed as a proportion of the total hill-slope length) required to capture the runoff generated by a 1 in 5 year rainfall event of 30 minutes duration, under soil storage limiting conditions. The model of Herron and Hairsine (1998) has been modified slightly to enable calculation using spatial data. The new model uses hillslope and riparian areas rather than lengths. On this basis the $\Psi_{5\,year}$ is defined as

$$\Psi_{5year} = \left[1 + \left(\frac{\left(pD - PT \right)}{T\left(P - I_c \right)} \right) \right]^{-1}, \tag{3}$$

where p is the available porosity, D is the depth to the water table or an impermeable layer, P is the precipitation rate of a 1 in 5 year storm event, T is the duration of the rainfall event for a 1 in 5 year storm event and I_c is the infiltration rate of the hillslope for a particular land use and soil type. This index is used as a reference point for comparison with current riparian ratio $\Psi_{current}$ values as measured using remote sensing and a digital elevation model (DEM).

The current riparian ratio is given by

$$\Psi_{current} = \left[\frac{A_{RZ}}{A_{RZ} + A_{CZ}} \right], \tag{4}$$

where A_{RZ} is the area of the riparian zone, and A_{CZ} is the area of the contributing hillslope. Consequently the Overland Flow Index (*OFI*) is defined as

$$OFI = \left(\frac{\Psi_{current}}{\Psi_{5year}} \right). \tag{5}$$

The *OFI* describes the current riparian zone as a proportion of a hypothetical riparian zone that would trap all the runoff generated by a 1 in 5 year storm event. Where the area of the current riparian zone exceeds the amount required to trap all of the runoff, the index will have a value greater than 1; where there is no riparian vegetation the index will approach 0.

Bank Reinforcement Index

Riparian vegetation reinforces stream banks by altering the hydrology and mechanical strength of the stream bank. The index is adapted from the research described in Abernethy and Rutherfurd (2001) as

$$BRI = \left(1 + \left(\frac{RD - BH}{RD + BH} \right) \right), \tag{6}$$

where RD is rooting depth (a function of bank exposure and vegetation type grass, shrubs, trees) and BH is bank height (a function of channel metrics generated from the DEM). This index scales between 0 and 1, where 0 represents large bank heights and small rooting depths (associated with unstable banks) and 1 represents rooting depths that are equivalent to the bank height (associated with stable banks).

Stream Shading

Vegetation that overhangs, or is immediately adjacent to a stream channel or waterbody provides shade for that waterbody. The shading function of riparian vegetation is important for two reasons: 1. it reduces fluctuations in water temperature, which in turn reduces fluctuation in dissolved oxygen and pH levels within the stream; and 2. it reduces the amount of light reaching the stream, thereby maintaining the existing trophic state of the stream (Poole and Berman, 2001). The stream shading index presented here is a highly simplified version of the model described in Chen *et al*. (1998). If the terrain and radiative transfer terms are considered constant, then a stream shading index (*SSI*) can be calculated as

$$SSI = \left[\left(\frac{H \times D}{W_C} \right) \times \left(1 + \left| \cos \Theta_S \right| \right) \right], \tag{7}$$

where H is the mean height of the riparian vegetation, D is the projected foliage cover, W_C is the width of the channel as calculated by hydraulic geometry from the channel network, Θ_S is the channel heading in degrees.

Large Woody Debris Volume

The hydraulic and ecological importance of large woody debris has been the focus of a number of previous studies, which are summarized in the companion paper (Lymburner *et al*., 2004). The vegetation classification techniques described in (Walker *et al*., 1986) are linked via fieldwork to the large woody debris recruitment model as described in Marsh *et al*. (2001) as

$$LWV = 0.2 \times VEG_d - 0.054 \tag{8}$$

where VEG_d is the density (m^3 ha^{-1}) of woody riparian vegetation in the pixel immediately adjacent to the waterbody.

Table 2. The parameters required to calculate the indices and the spatial coverages used to extrapolate each parameter

Parameter	**Spatial Coverage**	**Riparian Function Index**
Manning's n for Shallow Overland Flow	Vegetation and Land Use Map	STI, PTI
Percentage Foliage Cover	Vegetation and Land Use Map	SSI
Vegetation Height	Vegetation and Land Use Map	SSI, LWV
Volume of Wood	Vegetation and Land Use Map	LWV
Rooting Depth	Vegetation and Land Use Map	BRI
Channel Depth	Channel Geometry Map	BRI, SSI
Channel Width	Channel Geometry Map	BRI, SSI
Soil Porosity	Soil GIS	OFI
Soil Depth	Soil GIS	OFI
Enrichment Ratio	Soil GIS	PTI
Hillslope Infiltration Rate	Soil GIS	OFI
Rainfall Intensity	Climate GIS	OFI
Storm Duration	Climate GIS	OFI

Parameter Extrapolation

To calculate the riparian function indices across large watersheds it is necessary to spatially extrapolate each parameter required by Equations (1) to (9). A list of parameters, the spatial coverage, and the indices that use the parameter is contained in Table 2. Pre-existing soil GIS (1:500 000) (Woodward, 1977)and climate GIS (1 km^2 grid) (Bureau of Resource Sciences, 2001) layers were used to provide the soil and climate parameters. New vegetation, land use and channel geometry maps were generated for the study area using satellite imagery and a digital elevation model. The details of how these maps were generated are given below.

Remote Sensing

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite was used to generate a vegetation and land use classification. The spatial resolution varies with wavelength: 15 meter pixel size for visible and near-infrared and 30 meter for short wave infrared. For more details on the ASTER satellite see the ASTER Users Handbook available on the internet at http://asterweb.jpl.nasa.gov/documents/aster_user_guide_v2.pdf.

The image processing and classification in this study was undertaken using eCognition ™ software, as it classifies image objects (like strips of riparian vegetation) rather than individual pixels. One of the important features of this approach is that the scale and the criteria used to generate image objects are defined by the user rather than the satellite. This was particularly important in this project because it enabled the definition of image objects at a scale that corresponded to the narrow strips of riparian vegetation. The 15 meter pixel size of the satellite imagery combined with eCognition ™ enabled identification strips of riparian vegetation that were 15 meters or more wide.

The satellite imagery was classified into four vegetation classes (closed forest, open forest, woodland and open woodland) and four land use classes (grazing, heavy grazing, cropping and bare soil). Twenty three field sites were used to train the classification and an independent set of fifteen sites were used to evaluate the accuracy of the classification. An overall classification accuracy of 96% was achieved. There was some confusion between woodland and open woodland, but there was no confusion between the other classes. The classification was used to generate two maps, a vegetation structural map and a land use map. It is important to note that for the purposes of calculating the STI and PTI the vegetation, irrespective of structure, was reclassified based on the land use adjacent to it. For example, if a stand of riparian vegetation was adjacent to a grazing paddock then it would be classified as grazing. This is because the land use map in this project was used to extrapolate the Manning's n of the ground cover, and the Manning's n of the ground cover was significantly (p values < 0.0017 based on a Wilcoxon rank sum test) related to land use, but was not related to vegetation structure. The lack of spatial information about the distribution of fences makes it necessary to assume that the ground cover levels under the riparian vegetation are the same as those observed in the paddock adjacent to the riparian vegetation.

Terrain Analysis

A channel network was calculated from a 25 meter digital elevation model (DEM) (Queensland Department of Natural Resources Mines and Energy, 2001)using a D-infinity algorithm (Tarboton, 1997). A 5 km^2 watershed area threshold was used to initiate the stream channel network, and all stream links were assigned a Strahler stream order. Due to the presence of large floodplains within the study area the channel network predicted by the DEM was incorrect in some areas. The stream channels were manually digitised for these areas by comparing the DEM derived channel network with the satellite imagery, and identifying the channel location in the imagery. This step was essential to avoid underestimating the amount of riparian vegetation in the watershed. Hydraulic geometry relationships were established for each stream order. These relationships were used to assign channel width and bank heights to each link in the stream network according to stream order.

RESULTS AND DISCUSSION

A sample of the results generated by the LWV index (Equation 9) is shown in Figure 1. For more detailed results and further details about the calculation of LWV see companion paper (Lymburner *et al*., 2004).

The results of each riparian zone function index need to be interpreted with an awareness of the local hydrological conditions. For example, LWD volumes along first order streams (location A in Figure 1) is not important within the Nogoa watershed because the highly ephemeral flow means that 1st order streams do not support an aquatic ecosystem. Consequently location A would be of low priority for a management strategy aimed at maintaining levels of LWD. On the other hand, LWD volumes along 5th and 6th order streams are of great importance because the waterholes that form in these streams during a dry period require LWD to protect fish in these waterholes from aerial predation (Crook and Robertson, 1999). Consequently locations B and C are of high priority for the aforementioned management strategy. The LWV index could be used to inform what sort of management options would be appropriate at each location. The potential for LWD recruitment at location B is relatively low, making this location a candidate for manual placement of LWD and riparian tree planting to ensure supplies of LWD in the future. On the other hand there is high potential for LWD recruitment at Location C, making this location a candidate for conservation/protection. The LWV index would yield the same results for both the semi arid and the humid watershed, however the aquatic ecology of the two watersheds will differ dramatically, so watershed managers need to interpret the results of the LWV and other indices with the local ecology and hydrology in mind.

One of the main advantages of this approach is that it informs multiple criteria decisions on where to restore and protect riparian vegetation. For example, if a catchment manager simultaneously wishes to maintain levels of stream shade and bank stability, the results of SSI and BRI indicies could be compared to identify stands of riparian vegetation that were simultaneously providing stream shade and reinforcing stream banks.

The accuracy of the parameters predicted by the spatial extrapolation techniques has been assessed using independent training and evaluation sites. Parameter reliability has also been assessed at the polygon level by considering overall parameter accuracy and classification reliability at that particular polygon (eCognition ™ provides information about classification stability on a per polygon basis). The uncertainty of individual indices has also been assessed from standard error propagation of the index equations and the uncertainty of index input parameters. Index reliability has been assessed at the polygon level too. The index reliability at the individual polygon level is relatively poor on account of the cumulative uncertainties. However, it is not the intention of this approach to quantify the riparian functions at an individual polygon level. Rather it is the aim of this approach to estimate the functions provided by riparian vegetation along stream reaches throughout a watershed.

This approach to riparian vegetation assessment can be applied to any large watershed (> 100,000km^2) at very low cost, if a DEM and appropriate satellite imagery are available. However, fieldwork must be undertaken to establish three relationships: 1. The relationship between vegetation structural classes and vegetation parameters; 2. The vegetation structural classes at a number of sites in the watershed to train and evaluate the classification; and 3. The hydraulic geometry parameters for each stream order. The use of ASTER data would be ineffective if the majority of riparian zones were less than 15 metres wide, however the indices developed in this study could easily be applied to higher resolution imagery. A disadvantage is that it doesn't provide high accuracy assessments of conditions at a particular point in the river network. Consequently this approach should be seen as complimentary to (rather than a replacement for) traditional stream survey techniques such as the index of biotic integrity (Karr *et al*., 1986). However, the approach described in this study would be useful for identifying areas of interest for these more detailed stream survey techniques.

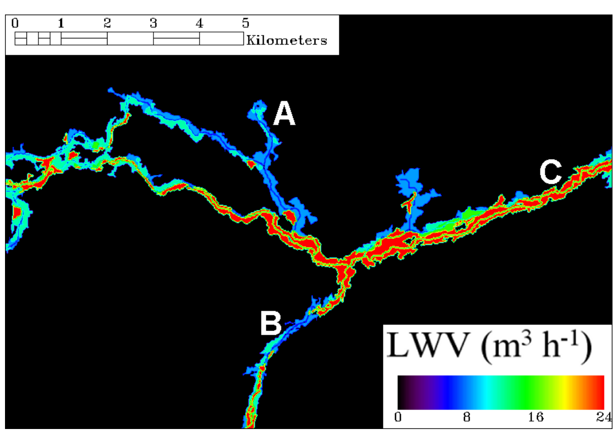

Figure 1. Large woody debris volumes for riparian zones in a section of the Nogoa watershed. The stream entering from the bottom of the figure is a 6th order stream, and the streams entering from the left are anabranches of a 5th order stream.

CONCLUSIONS

A method for assessing riparian zone functions across large catchments has been developed, and demonstrated for the large woody debris volume index in a section of the Nogoa watershed. This provides a decision support tool for watershed managers who need to prioritize projects aimed at protecting and restoring riparian zones. The spatial information generated by this approach is particularly useful because it allows watershed managers to assess the efficiency of the multiple functions being performed by riparian vegetation within the watershed.

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