Indices for Assessing the Spatial Distribution and Functions of Riparian Buffer Zones.

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Abstract: It is widely recognised that riparian zones can greatly reduce the movement of pollutants from hillslopes into streams. While several indices of stream condition exist, the spatial distribution of the pollutant and runoff trapping functions of the riparian zone remains poorly understood. This paper describes three indices, which quantify the spatial distribution of riparian zones that function as buffers. These indices have been developed based on a review of point-based riparian zone studies of sediment and pollutant trapping, and are designed with spatial extrapolation in mind. The indices describe the following pollutant trapping functions: 1. hillslope runoff interception, 2. hillslope sediment trapping, and 3. hillslope pollutant trapping. Each index and the spatial extrapolation techniques are described. These techniques include satellite-based remote sensing, geographical information systems, and terrain analysis. The spatial extrapolation techniques require four main products, a land use map, a riparian vegetation map, a map of soil depth and porosity, and a map of hillslope length and area. The indices are calculated using parameters from these four products. This suite of indices provides a measure of stream condition that explicitly considers buffering functions and permits a more process specific design procedure in planning catchment management.

Keywords: *riparian vegetation; pollutant; sediment; spatial distribution*

1. INTRODUCTION

Riparian zones act to buffer streams from sediment and pollutants travelling down adjacent hillslopes (Loch et al. 1999; McKergow et al. 2003; Vought et al. 1995). Grass strips in riparian zones increase surface roughness, which reduces the sediment transport capacity of shallow overland flow by reducing flow velocity (Prosser et al. 1995). This function is important because it reduces the sediment and sediment-sorbed pollutant loads entering the streams, thereby improving the downstream water quality and increasing stream health. This function is also important because it reduces sediment exports from coastal catchments into near shore waters, thereby protecting estuaries and near-shore habitats from excessive sedimentation rates. (Johnson et al. 1999). Riparian soils provide a site for water storage, reducing the amount of water delivered directly to the stream via overland flow, and reducing fluctuations in the height of the water table (Belsky et al. 1999; Tabacchi et al. 2000). This capacity of riparian zones to act as runoff, sediment and pollutant traps has been the focus of a number of studies (Loch et al. 1999; McKergow et al. 2003; Vought et al. 1995). However these studies are generally point based (i.e. the studies are based at the laboratory or hillslope scale). Moreover, a number of authors have identified the need for information about the spatial distribution of riparian filters relative to runoff/sediment/pollutant sources (Allan and Johnson, 1997; Narumalani et al. 1997).

Spatial information on the function of riparian buffers could be used to inform land management decisions about the amount and optimal location of land set aside for riparian buffer strips under different land uses, topography, soil types and climatic zones. This spatial information could also be used to identify the types of streams that are best suited to stream rehabilitation. Spatial data sources such as remote sensing, geographical information systems (GIS) and digital elevation models (DEMs) provide the necessary tools to generate such information. However, until recently a lack of high resolution multispectral satellite imagery has limited the application of remote sensing to mapping riparian buffers in large catchments. The advent of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor (15 metre pixel resolution for 3 visible bands) has enabled the more accurate identification of riparian buffer strips and vegetation.

This paper proposes three indices that quantify the following riparian functions: overland flow interception; sediment trapping and pollutant trapping. These indices have been derived from point-based studies, but can be calculated using spatial data sources. The indices are designed to compare the functioning of the existing riparian vegetation with the function of either a poor or ideal reference condition. In this study we take the reference conditions as being: 1. a riparian zone with no vegetation, or 2. a riparian zone capable of trapping all overland flow from the hillslope by a 1 in 5 year storm event.

The calculation of the riparian function indices described in this paper has not yet been carried out, however field data and spatial data have been collected for the Fitzroy catchment in Central Queensland and the indices presented in this paper will be calculated for this region in the near future.

The purpose of these indices is to quantify the existing filter and storage capacity provided by the current riparian zones throughout large catchments, moving beyond point-based surveys of riparian condition to a spatially explicit approach. This approach describes where existing riparian buffers are located in the catchment in terms of terrain, stream order and adjacent land use.

The indices will be most informative for lower order streams, as overland flow is the dominant form of sediment and pollutant transport in these streams. In higher order streams within-channel processes, floodplain processes and bank stability dominate sediment transport (Prosser et al. 2001). Indices for these riparian processes are also being developed but are not discussed here.

2. RIPARIAN FUNCTION INDICES

2.1. Overland Flow Interception

Overland flow entering a riparian zone from an adjacent hillslope can 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). By reducing the amount of overland flow entering a stream channel riparian soil storage also reduces the amount of flow-transported sediment reaching the stream channel.

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 $\Psi_{5\text{ year}}$ is defined as

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

where: p is the available porosity; D is the depth to the water table or an impermeable layer; and pD is the product of p and D, P is the precipitation rate of a 1 in 5 year storm event (mm/hr); T is the duration of the rainfall event for a 1 in 5 year storm event (hr) and I_c is the infiltration rate of the hillslope (mm/hr) for a particular land use and soil type. The spatial data inputs for this model are described in section 3 of this paper.

This index is used as a reference point for comparison with current riparian ratio $\Psi_{current}$ values as measured using remote sensing and a DEM. The current riparian ratio is given by

$$\Psi_{current} = \left[\frac{A_{RZ}}{A_{RZ} + A_{CZ}}\right], \tag{2}$$

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

$$OFI = \left(\frac{\Psi_{current}}{\Psi_{5year}}\right), \tag{3}$$

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 zone (identifiable via riparian vegetation) the index will approach 0.

2.2. Trapping Sediment From Overland Flow

The sediment trapping index (STI) is particularly important because it represents a vital riparian process. Sediment exports from coastal catchments in Queensland present a major environmental threat to the Great Barrier Reef, and 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. This information is also of great importance because of the need to prioritise riparian zone rehabilitation across large catchments.

The STI, has been adapted from (Hairsine and Rose, 1992) as

$$STI = 1 - \left[\frac{n(noRZV)}{n(current)}\right]^{\frac{1}{m}}, \qquad (4)$$

where *n*(*noRZV*) is 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 actual and reference case, and would be of particular importance in areas where the OFI is less than 1. 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.

2.3. Trapping Pollutants From Overland Flow

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 PTI describes one of the important functions served by riparian zones in maintaining water quality for both consumptive and ecological purposes. The pollutant trapping index is described by

$$PTI = 1 - \frac{Mannings'\,n(current)\;N(current)}{Mannings'\,n(noRZV)\;N(noRZV)}, \qquad (5)$$

where, *Manning's n*(*current*) is the sediment trapping capacity of the current riparian zone, *N*(*current*) is the current concentration of sediment adsorbed nutrients per unit mass of sediment leaving the riparian zone (enrichment ratio), *Manning's n*(*noRZV*) is the sediment trapping capacity of the riparian zone without any vegetation, 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. Such information would be of particular interest for areas where the OFI is less than 1.

3. SPATIAL DATA PARAMETERS

Spatial parameters are required to calculate the indices listed above, and these parameters are derived from different sources as described in Table 1. The riparian vegetation map and land use map are generated from ASTER satellite (see http://asterweb.jpl.nasa.gov/) imagery using eCognition ™ software. Both of these maps are based on supervised classifications of the ASTER imagery, and the classifications are subject to established accuracy assessment routines. The nature of optical remote sensing makes it impossible to directly measure the amount of ground cover (and the associated amount of surface roughness) underneath a tree canopy (Walker et al. 1986). Consequently ground cover levels beneath tree canopies must be inferred using a combination of canopy density and land use. Fieldwork has been carried out to establish the links between canopy cover, land use and ground cover levels for the study area. Whilst a stable relationship may exist for all of the field sites, areas that were not sampled in study may vary from this relationship as a result of grazing pressure. This variance can be constrained using multi-temporal satellite data to estimate grazing pressure(Pickup and Bastin, 1997).

Table 1. Parameters required for the calculation of indices

Parameter	Source
p (porosity at depth 1m)	Soil G.I.S.
D (depth to the impervious layer (m))	Soil G.I.S.
Ic (infiltration rate of hillslope) mm/hr	Soil G.I.S. and Land Use Map
P rainfall rate (mm/hr)[1]	Climate G.I.S
T (time period of rainfall event)[1]	Climate G.I.S
Manning's n(noRZV) Manning's n of a riparian zone with no riparian vegetation	Literature Value (Loch et al. 1999)
NnoRZV (enrichment ratio)	Literature Value (Palis et al. 1997)
Ncurrent (enrichment ratio)	Literature Value (Palis et al. 1997)
Manning's n(current) Manning's n of current RZV	Riparian Vegetation Map, Land use map and literature value (Loch et al. 1999)
A_{RZ} (area of the riparian zone)	Riparian Vegetation Map
A_{CZ} (area of the contributing zone)	Digital Elevation Model

The depth to the impermeable layer parameter D used in this study is based on soil depth as defined in a soil GIS. The depth and soil porosity parameters are based on a limited number of pits dug at various points in the catchment as part of the soil mapping exercise as described in Speck et al. (1968). As a result of this there are likely to be localized inaccuracies in terms of soil depth. Soil depth is used as the D parameter in this case because the impermeable layer in the riparian zone of a low order stream in a tropical semi-arid area is likely to be bedrock, and the OFI assumes that the soil profile is dry at the beginning of the 1 in 5 year storm event. This is a reasonable assumption for the study area, but would need to be re-examined if the index were to be applied to humid-temperate, or tropical streams, where the existing water table may limit the available soil water storage. The DEM (Adsett et al., 2002) and soil GIS (Speck et al., 1968) are provided by the Queensland Department of Natural Resources and Mines. The Climate GIS was calculated using the AUSIFD computer program (Jenkins 1997).

4. DISCUSSION

The indices will identify low order streams channels that are adjacent to areas with high erosion rates and will provide information about the adequacy of the riparian buffer strips in these areas. This information would be useful for a catchment management strategy aimed at reducing sediment loads in the stream network, allowing for prioritisation of available resources.

The indices will also identify areas where low order streams are adjacent to areas with high pollutant loading rates. In such areas sediment trapping may be adequate, but pollutant trapping inadequate. Identifying such areas is of great interest for two reasons: 1. These areas would be a high priority for a catchment management strategy aimed at reducing pollutant loads, and 2. These may be areas where buffer strips are ineffective due to the nature of pollutant transport mechanisms or low soil water storage potential. If the indices indicate that buffer strips are ineffective in a specific area or environment, the information is still useful because it indicates that other pollutant management options need to be explored (Nash and Murdoch, 1997).

There are some limitations to this approach that relate to the accuracy of the spatial datasets from which the indices are derived, and the assumptions made in extrapolating some parameters. These limitations are addressed briefly in Section 3. These limitations will reduce accuracy of predicting conditions at any specific location, however by quantifying the accuracy of the remote sensing classification, soil GIS and DEM and describing the relationship between the field data and the remote sensing classification it is anticipated that users of the indices will be aware of these limitations. It is also recommended that the assumptions made in calculating these indices be re-assessed prior to applying these indices to other climatic regions.

The fifteen metre pixel size of the satellite imagery will limit the capacity to identify small grass buffer strips in this study. This is not a major limitation for the study area because infrequent but intense rainfall events that occur in the semi-arid tropics necessitate broader buffer strips to effectively trap the sediment and pollutants carried in overland flow. In other environments or studies where more accurate estimates of buffer widths are required the indices

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[1] Rainfall event parameters relate to a 1 in 5 year storm event.

described in this paper could be applied to high resolution satellite or airborne scanner imagery.

The nature of the indices is flexible and allows for adaptation to different environments if the appropriate parameters are available. This is advantageous, because it allows for customisation of riparian buffer widths that suit local soil, terrain and climatic conditions, rather than an arbitrary approach to riparian buffer widths. If the appropriate pollutant loads and enrichment ratios were available, then the pollutant trapping index could be used for spatially distributed source-sink pollutant modelling.

The indices would be useful for informing catchment management strategies aimed at sediment and pollutant load reductions. This is possible because the indices address the different behaviour of overland flow, sediment, and sediment-sorbed pollutants in riparian zones. This is an important development because it allows for the differentiation of riparian filter behaviour adjacent to different land uses, and allows identification of riparian areas that are adequate for some purposes but not for others.

When combined with other spatial indices (that were assessed but are not discussed here) that describe the ecological and hydraulic functions of the riparian zone, we begin to see a complex spatial pattern of the role and adequacy of the existing riparian zone in performing a range of functions. This information should be useful in guiding the spatial prioritisation and the selection of management measures for riparian zones across large catchments.

5. CONCLUSIONS

Indices have been presented that describe the spatial distribution of three functions of the riparian zone. These indices are based on point-based research, and have been adapted to enable calculation using spatial data sets. The accuracy of these indices is limited to the accuracy of the spatial data from which they are calculated, however they provide a level of information about the spatial distribution and effectiveness of riparian filter strips throughout the catchment that has been unavailable up to now.

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