Determining the extent and condition of riparian zones in drinking water supply catchments in Sarawak, Malaysia

Emma Ligtermoet, Jane M. Chambers, Halina T. Kobryn and Jenny Davis

ABSTRACT

Land cover within eight drinking water catchments in Sarawak was classified into six categories using satellite imagery and GIS. The categories represented varying levels of vegetation modification from largely undisturbed or mature secondary vegetation (Category 1) through to bare, non-vegetated areas (Category 6). Rivers less than ~10 m in width were usually 'invisible' on satellite images because of dense canopy cover. More than 70% of headwaters in all catchments, except one (Buri Bakong), were not visible, indicating the presence of dense riparian vegetation. For the river sections that were visible on satellite images, 5%–22% of the riparian buffer was highly degraded (completely lacking vegetation). The highest degree of riparian modification occurred in the lowlands, the midland catchment of Tingkas and the highland catchment of Trusan. Although Sarawak government policy requires buffer widths of 5–50 m of natural vegetation to be retained along all streams and rivers in drinking water supply catchments these guidelines were not met at nine of the eleven field sites surveyed. These results suggest that compliance with buffer guidelines is important to water quality in rivers, particularly in logging areas, oil palm plantations and near settlements.

Key words | drinking water supply catchments, remote sensing, Riparian zones, tropical rivers, water quality geographical information systems (GIS)

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INTRODUCTION

The provision of clean water for drinking is vital to human health. In Sarawak, a state of Malaysia, rivers fulfil many important roles, not only culturally and economically, but also as the primary source of drinking water. Sarawak is experiencing rapid changes in land use and cover, especially in areas close to rivers (Douglas 1996). Changes in land use have followed national trends in Malaysia, occurring in three main phases: large-scale commercial logging during the 1960s; the introduction of oil palms in the mid-1970s; and a dramatic increase in the area under oil palms in the 1990s (Svan Hansen 2005). These changes, combined with an increasing population, mean that the provision of good quality water for drinking is a major environmental issue for the state.

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Many studies have shown that the maintenance of good water quality is linked to the condition of the riparian zone (Osborne & Kovacic 1993; Lin *et al.* 2002) which is defined as the transitional zone between terrestrial and aquatic systems adjacent to a stream or river (Holland 1988 cited in Risser 1990). Riparian zones provide connectivity within the landscape and benefit water quality by maintaining an intact buffer along the longitudinal length of the river (Tabacchi *et al.* 1998). Stream size, catchment characteristics and hydrological regime all contribute to determining the role and influence of the riparian zone on river systems (Naiman & Decamps 1997). Primary riparian processes influencing water quality are those of sediment trapping, nutrient buffering, the provision of allochthonous inputs, bank stability and temperature amelioration. The effect of the first two of these are most easily quantifiable through turbidity measurements and nutrient analyses. A meaningful assessment of nutrient status requires ongoing spatial and temporal sampling programs combined with equipment and facilities which were unlikely to be available in remote tropical regions. In contrast, turbidity is more reliably measured and so was chosen as the most feasible surrogate of water quality in this study.

Much of the knowledge of riparian zone function is drawn from the northern hemisphere and temperate climates (Downing *et al.* 1999; Ometo *et al.* 2000; Dudgeon 2003). There is little information on tropical systems and in existing tropical watershed studies, including those in Malaysia, there is an emphasis on sediment and soil erosion (Rose 1984; Staub *et al.* 2000; Douglas & Guyot 2005). More recently, the importance of land use change in the tropics and its effect on water quality has been recognised (Douglas 1999; Yusoff *et al.* 1999; Ometo *et al.* 2000).

Remote sensing provides a useful tool for examining catchment and riparian vegetation cover, particularly in remote tropical regions. However, delineation of riparian zones in the tropics remains difficult given the lack of strong moisture gradients and the resulting denseness of vegetation in both riparian and upland areas (Malanson 1993). This and the resolution of available imagery are challenges reflected in the literature of remotely sensing riparian ecotones (Fortin *et al.* 2000; Apan *et al.* 2002; Griffith 2002; Mertes 2002).

This study sought to determine the extent and condition of riparian zones on selected water supply rivers in Sarawak and their relationship to water quality and land use within catchments, primarily through the use of remote sensing. The primary questions driving this research were:

- How much of a river network is covered by riparian vegetation?
- What is the condition of the riparian vegetation?
- How are modified areas distributed throughout the river network?
- Is there any relationship between land cover patterns in the catchment and those of the riparian buffer zone?
- Can water quality be linked to riparian condition?

METHODS

Study area

Sarawak is the largest state in Malaysia, occupying an area of 124,450 km^2 and with a population of 2,473,554 (2007). The population includes a diverse mix of 27 ethnic groups. The climate is tropical, wet equatorial, with a milder southwest (June–October) and northeast monsoons (November–February) bringing heavy rains annually. Uniform temperatures prevail throughout the year with an average minimum of 23.3°C in January and average maximum of 30.9°C in July. Precipitation is high throughout the year, varying from 330 cm/month to 460 cm/month with minor and major rainy seasons (April to June and October to January respectively) (Svan Hansen 2005).

Sarawak can be divided into three broad physiographic regions: (1) coastal lowlands; (2) central midlands and; (3) interior highlands. The criteria for catchment classification based on altitude are given in Table 1. The landforms, soils and agricultural suitability of these regions were described by Teng (1994). The dominant landforms in the lowlands are: (a) coastal and inland organic (peat) swamps; and (b) coastal sand plain and clay plain (riverine floodplains). The midlands comprise primarily low inland hills. The interior highlands are located on the mountainous northeast-west divide between Malaysian and Indonesian Borneo.

This study sought to include representative catchments in each of these elevation classes. Necessary parameters for inclusion of a catchment were: the availability of recent,

Table 1 | Criteria for catchment classification based on altitude

Catchment type	Percentage area (km^2), within contour height boundaries of classification
Lowland (peat swamp)	100% of catchment less than 100 m
Lowland (other)	More than 80% of the catchment < 100 m
Midland (lower)	More than 30% of the catchment > 100 m and more than 40% of the catchment < 100 m
Midland (upper)	More than 50% of the catchment > 100 m and less than 25% of the catchment > 500 m
Highland	More than 50% of the catchment > 500 m

good quality satellite images; river visibility; provision of a representative range of land uses; landform types and elevation; the availability of water quality data; and the possibility of field access. Characteristics of the study catchments are summarised in Table 2 and their locations are given in Figure 1.

Dominant land use types were derived from several sources including hardcopy agricultural maps (Regional Land Use (1:250,000) and Agriculture Capability Sarawak (1:1,000,000)) and digital vector files of land use and plantation profiles (both 1:50,000). Dominant soil groups were derived from both hardcopy soil maps (Great Soil Groups of Sarawak, Geological Map of Sarawak and Hydrogeological Map of Sarawak both 1:500,000) and soil profile vector files (Figure 2).

Description of spatial data

Following examination of 29 LANDSAT (TM) and 69 SPOT 5 files from 1996 to 2003, SPOT 5 images from 2001, 2002 and 2003 were chosen for analysis because they provided the best spatial resolution and river visibility (Table 3).

Image preparation

To speed up processing (using IDRISI Kilimanjaro v14), subsets of the images were created for each catchment. If a catchment was covered by more than one image file, a mosaic was created. Creating mosaics after, rather than before classification was necessary for two catchments (Trusan and Tingkas) due to differences in the original spectral labelling of the image files. Clouds and cloud shadows were masked.

Visible sections of rivers were digitised manually, in order to accurately classify the pixels bordering the river (in the riparian zone). River widths were measured at each bend and straight, or where the width noticeably changed. A river width classification code (R1–R5) was created based on existing Sarawak river buffer guidelines (DoE, undated) (Table 4). Given the difficulty in distinguishing natural riparian zones in the tropics (Malanson 1993; Apan *et al.* 2002; Mertes 2002; Griffith 2002) riparian 'buffers' representing the riparian zone were created, their widths based on the Sarawak guidelines (Table 4).

River lengths were measured by extracting and summing 'river' line features within the vector file attributes of each catchment. The average length of the digitised portion of river was calculated after the areas of each 'coded' reach were obtained. To determine the length of river network that was unclassifiable (invisible and/or headwater tributaries) the digitised portion was subtracted from the total length obtained from the vector file attributes.

Classification

Unsupervised classification was performed using a clustering algorithm. The 'CLUSTER' module in IDRISI implements a variant of a Histogram Peak cluster analysis technique (Richards 1993). The Cluster process searches for 'peaks' created by reflectance values in a spectral band, where the frequency is higher than that of its neighbours and can be carried out for numerous bands. Once the peaks are located each pixel in the image is assigned to its closest peak, creating a class labelled as a 'cluster' (Eastman 2003). The land cover class of each cluster is then determined by the analyst. A 'fine' generalisation level and maximum number of 10 clusters was used in the classification.

Image processing was executed using IDRISI's Macro model function, a graphical environment for building and executing a multistep model (Eastman 2003). This created a repeatable process that allowed new catchments and riparian buffer areas to be classified in the same way. The resulting classes of both the catchment and river buffer were then assigned into six primary categories from which the final summary statistics (area km^2) could be extracted. To maintain consistency across catchments and avoid inaccurately labelling the resulting classes, 'neutral' labels of 'Category 1–6' were assigned, representing a sliding scale of land cover/vegetation modification (Table 5). This system was used to avoid the assumptions that might be invoked by labels such as 'forest', 'shifting cultivation', 'grass land', which could not be verified with certainty.

Validation

Principal Component Analysis (PCA) and the use of Normalised Difference Vegetation Index (NDVI)* were explored to further distinguish the classes resulting from

Table 2 | Summary of characteristics of study catchments and satellite imagery used

Catchment and geographical location	Catch-ment type based on elevation	Satellite, year, resolu-tion (1 pixel = (m), number of spectral bands*	Catchment area (km^2)	Population of district (not catchment-unavailable)	Mean annual rainfall (mm) (1994–2004)	Dominant land uses in descending area (km^2) (extracted from digital land use files)	Soil group (dominant soil family)
Matu (Central) 2°40′ N, 111°33′ E	Lowland (peat)	SPOT (unknown), 2001, 20, 3	177	7.7	269.1	Swamp forest, sago, rubber, unsure, wet padi, swamp, grassland	Organic soils (Anderson) (deep peat) gley soils, organic soils (Mukah) (shallow peat)
Sebuyau (South west) 1°22′ N, 110°58′ E	Lowland (other)	SPOT 5, 2003, 10, 4	346	N/A	198.5	Primary forest, swamp forest, hill padi and minor crops, shifting cultivation, pepper, ruber, swamp, wet padi, nipah, hydro, grassland	Organic soils (Anderson) (deep peat), skeletal soils and oxisols, red-yellow podsolic soils, grey white podsolic soils, gley soils complex in south))
Buri Bakong (North) 3°55′ N, 114°10′ E	Lowland (other)	SPOT 5, 2003, 10, 4	1,023	N/A	287.4	Jungle, shifting cultivation, swamp, rubber	Red-yellow podsolic soils, organic (deep peat) gley soils, tiny amount skeletal soils (kapit) Catchment right next to large area of organic soils (Anderson)
Bau (South west) 1°19′ N, 110°03′ E	Midland (lower)	SPOT 5, 2002, 2.5, 3	259 (140 km^2 classified)	52.3	333.0	Shifting cultivation, jungle, rubber	Red-yellow podsolic soils, skeletal soils (kapit), podzols
Sarawak Kiri (South west) 1°22′ N, 110°18′ E	Midland (lower)	SPOT 5, 2002, 2.5, 3	607 (330 km^2 classified)	N/A	N/A	Shifting cultivation, jungle, rubber, primary forest, hydro, padi, unsure, pepper	Red-yellow podsolic soils, skeletal soils, podzols, skeletal soils, skeletal soils and oxisols (Quite complex)
Sri Aman (South west) 1°01′ N, 110°32′ E	Midland (upper)	SPOT 5, 2003, 10, 4	240	29.9	274.1	Hill padi and minor crops, unsure, rubber, primary forest, unsurveyed, jungle, shifting cultivation, wet padi, swamp, pepper, grassland, sundry (tree and non-tree) cultivation, hydro	Red-yellow podzolic soils, skeletal soils and red-yellow podsolic soils, gley, skeletal, and shallow peat soils
Tingkas (Central) 2°41′ N, 112°13′ E	Midland (upper)	SPOT (unknown) 2001, 20, 3	1,491	13.2	N/A	Primary forest, hill padi and minor crops, swamp forest, grassland, rubber, wet padi, hydro, pepper, coconut, sundry (tree) cultivation, lake pool and reservoir	Red-yellow podsolic and skeletal soils, red-yellow podsolic soils, organic soils (deep peat), gley soils, organic peat (shallow peat). Grey, white podzolic and shallow peat
Trusan (North east) 4°35′ N, 114°10′ E	Highland	SPOT 5, 2003, 10, 4	2,168	N/A	325.9	Jungle, primary forest, secondary jungle on hill padi, grassland, shifting cultivation, belukar jerami and hill padi, hydro, sundry (non-tree) cultivation	Skeletal soils and red-yellow podsolic soils, skeletal and gley soils, gley soils, recent alluvial soils, skeletal soils, red yellow podzolic and gley soils

Source: Geographic Information System and Remote Sensing Unit (GIS/RS) technical Management Branch, JKR, Sarawak State Government.

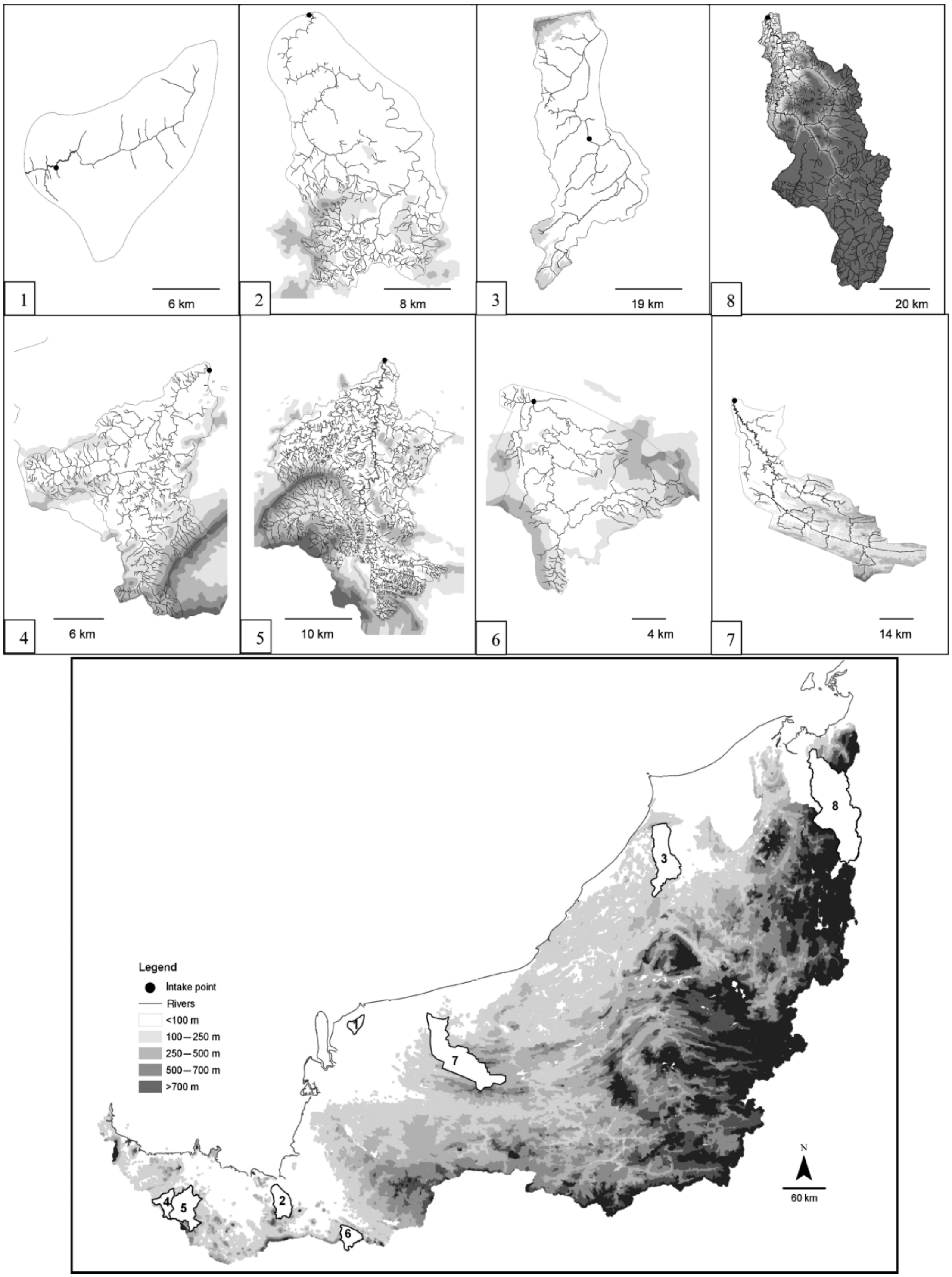

Figure 1 | The locations of the eight study catchments, within the State of Sarawak, shown with elevation. Lowland catchments: (1) Matu (peat), (2) Sebuyau, (3) Buri Bakong (mixed soils), midland catchments: (4) Bau, (5) Sarawak Kiri, (6) Sri Aman, (7) Tingkas and the highland catchment: (8) Trusan.

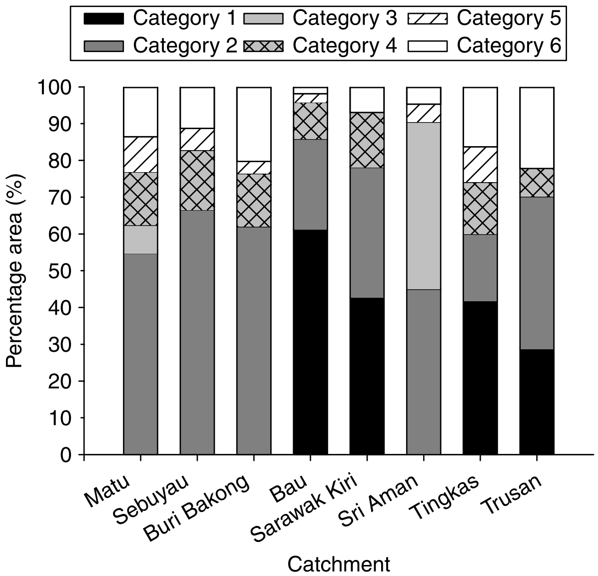

Figure 2 | Relative percentages of land cover assigned to each category within the riparian zone of each catchment. The categories indicate the levels of vegetation disturbance in each catchment from black (least disturbed) to white (completely cleared/built area). Catchments are ordered from lowland (left) to highland (right).

cluster analysis.

$$^{*}\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{RED})}{(\mathrm{NIR} + \mathrm{RED})}$$

where NIR = near infrared band and RED = red band.

PCA was useful in highlighting cleared features such as unsealed roads more clearly; however NDVI was most effective in separating out the various levels of disturbance/clearing found amongst the range of vegetation covers and was used, in particular to improve the classification of land cover in Sri Aman. Cluster categories could not be uniformly labelled across catchments due to the wide range of geomorphological and topographical features and the different resolutions and different times images were recorded at, creating variation in spectral reflectance. EXTRACT module in IDRISI was used to explore spectral responses contained within various cluster classes but was found to be useful only in clarifying similarity within a catchment (determining classes) but not for recognising like classes between the catchments.

Table 3 | SPOT satellite spectral bands

Band	Wavelength (μm)	Nominal spectral location
P	0.48–0.71	Panchromatic
B1	0.50–0.59	Green
B2	0.61–0.68	Red
B3	0.78–0.89	Near Infrared (NIR)
B4	1.58–1.75	Short wavelength infrared (SWIR)

Source: SPOT IMAGE technical data (2003).

Table 4 | Sarawak Government guidelines for buffer zone width (intact riparian vegetation), based on river width. These categories were assigned a River Code value (R1 being the narrowest to R5, the widest)

River/stream width (between banks (m))	Riparian Buffer reserve width (on each bank (m))	River Code (for vector files and classification)
>40 m	50	R5
20–40	40	R4
10–20	20	R3
5–20	10	R2
<5	5	R1

Example: Reach of river 30 m wide was assigned River Code R4 and had a riparian buffer 40 either side created.

Field validation of results

Riparian surveys were undertaken at one or two sites (depending on time and access) within each catchment during the dry season (June/July) in 2005. The field surveys provided a total riparian ranking score, which was derived from: 1) a functional attribute score (summarizing features directly influenced by the presence of riparian vegetation); 2) a condition score (reflecting the level of anthropogenic related riparian modification); and 3) a vegetation score (summarizing the ecological condition of the riparian vegetation in terms of structure and density) (Table 6). The land covers observed at these field survey sites were used as proxies to validate the GIS classification categories and to provide more detail on the characteristics of the categories. The logistics of more detailed field validation for remote sensing, in such highly inaccessible terrain was beyond the means of this study.

Water turbidity

The results of the riparian and catchment land cover analyses were compared with long term (1994–2005)

Table 5 | Land cover categories refined from unsupervised classification, representing an increasing scale of vegetation modification. The predominant visual feature used to recognise the class in the imagery is described, followed by a description of the vegetation

Category number	Category description from satellite imagery	Vegetation description (relating to structure density and complexity of vegetation cover)
1	Darkest cover	Continuous canopy cover
		Densest vegetation cover; possibly primary forest
		Assumed complex structure
2	Vegetation cover slightly lighter than Category 1	Canopy cover still relatively intact; possibly secondary forest
		Slightly less dense
		Relatively complex
3	Light, 'mosaic' vegetation	More open canopy than 1 and 2; mix of modified structural layers representing a combination of agricultural and secondary growth. Average complexity?
4	Bright, modified vegetation	Sparse canopy cover
		Poor structure; a mix of modified understorey and middlestorey
		Limited complexity
5	Very bright; highly modified vegetation	No canopy cover, only understorey and groundcover; e.g. grasses
		Very sparse density
		Limited complexity
6	Bare ground/roads/buildings	No vegetation present; bare soil or built environment
7	Water, or shadow from terrain representing vegetation cover	Where shadow, usually in unmodified mountainous terrain (Category 1 or 2 vegetation)

Table 6 | Riparian attributes from field assessment that contributed to the riparian ranking score

Riparian attribute score	Parameters included in score
Functional attribute (total score/8)	Bank stability
Good score: >6	Erosion
Poor score: <4	Slumping
	Sedimentation
	Percentage cover humus layer i.e. leaf litter
	Percentage % canopy cover i.e. shading
Condition (total score/8)	
Good score: >7	Longitudinal continuity: quantifies the number of breaks in visible riparian reach
Poor score: <4	Integrity of vegetation: measurement of anthropogenic disturbance
Vegetation (total score/8)	
Good score: >5	Vegetation density: sum of the density score for each dominant species recorder (between all structural layers)
Poor score: <3	Structure modification score: quantifies the vegetation structure

A total riparian ranking score of 0–24, was derived from: 1) a functional attribute score 0–8 (summarizing features directly influenced by the presence of riparian vegetation); 2) a condition score of 0–8 (reflecting the level of anthropogenic related riparian modification); and 3) a vegetation score of 0–8 (summarizing the ecological condition of the riparian vegetation in terms of structure and density).

turbidity data available for the riverine water intake points located just upstream of water treatment plants. Because the intake points were located at the lower end of each catchment the water quality data were well suited for comparison with overall riparian network condition and catchment condition. Monthly rainfall data (mm) from 1994 to 2004 for each catchment was supplied by the Department of Irrigation and Drainage of Sarawak. River water quality data (monthly values; 1994–2005) was supplied by the Public Works Department of Sarawak (Jabatan Kerja Raya, JKR). This study focused on turbidity as the proxy for water quality condition, as excess sediment loading (causing high turbidity) is recognised in Sarawak as one of the primary threats to water quality (NREB 2007; Douglas 1999) and nutrients are often bound to sediment particles. High turbidity has also been linked to land use change and clearing (Douglas 1996, 1999; Douglas & Guyot 2005); processes that result not only increased sediment load but also nutrient input into rivers (Boulton & Brock 1999). Turbidity is also a more robust measurement to be conducted in remote locations with minimal sample processing facilities, unlike the requirements for nutrient analysis. There was insufficient long term data available for other parameters such as total nitrogen, aluminium and BOD to be used in quantitative analysis. Mean annual turbidities for each river were categorized according to the National Water Quality Standards for Malaysia (NWQSM) and compared to the riparian zone attributes (percentage cover, percentage riparian and catchment modification). Turbidity data were not available for the Trusan or Tingkas catchments. SPSS Statistics package was used to conduct regression and correlation tests (Pearson) between the long term turbidity data and catchment and riparian condition results.

RESULTS

Riparian condition

Rivers less than ~10 m in width were usually 'invisible' on the satellite images because of dense canopy cover. Accordingly it was inferred that these reaches were protected by intact and relatively undisturbed vegetation and the percentage of non-visible tributaries indicated the proportion of a river network that was covered by dense riparian vegetation. It was the condition of the remaining river sections that were visible on remotely sensed images, and which could be classified using GIS, that were assessed in more detail. As a consequence, the following results reflect changes in the mid to lower parts of the catchment where human use was greatest.

River networks in all catchments except one (Buri Bakong) comprised ~70% or more canopy-covered headwater reaches, (Table 7). The latter midland catchment had the smallest relative network of invisible tributaries (56%)

Table 7 | Lengths (km) of river networks in each catchment, the proportion of river lengths visible on images (where digitising and unsupervised classification of the riparian buffer was possible) and the remaining lengths of non-visible tributaries (not included in classification). Classifiable riparian area (both km^2 and as a proportion of the classifiable catchment area) is also given

Catchment	Total river length (km)	Portion of river length available for analysis (km)	Average length of visible, digitised rivers (km)	Percentage of river digitised (whole image/or portion) (%)	Length of non-visible tributaries (km)	Percentage of non-visible tributaries (%)	Riparian area (classifiable) (km^2)	Riparian area (% of catchment)
Matu	56.70	56.70	11.40	20.10	45.30	79.90	0.77	0.44
Sebuyau	434.29	434.29	43.90	10.00	390.10	90.00	2.95	0.89
Buri Bakong	281.70	281.70	124.90	44.30	148.80	55.70	3.88	0.42
Bau	463.60	251.50	31.40	6.77/or 12.48	220.10	93.2/87.3	2.07	1.58
Sarawak Kiri	1,410.70	712.10	210.70	14.9/or 29.59	5,011.40	85.1/	2.93	0.95
Sri Aman	259.93	259.93	45.30	17.43	214.60	82.60	2.20	0.92
Tingkas	715.93	715.93	180.40	25.20	535.50	74.80	18.31	1.23
Trusan	2,152.50	2,152.50	229.50	10.66	1,923.00	89.34	17.30	0.92

Notes: For drinking water catchments Bau and Sarawak Kiri, the respective lengths of classifiable river and the non-visible headwaters are given both as percentages of the complete river network and of the area of catchment covered by the satellite image (due to the partial satellite image coverage of these catchments).

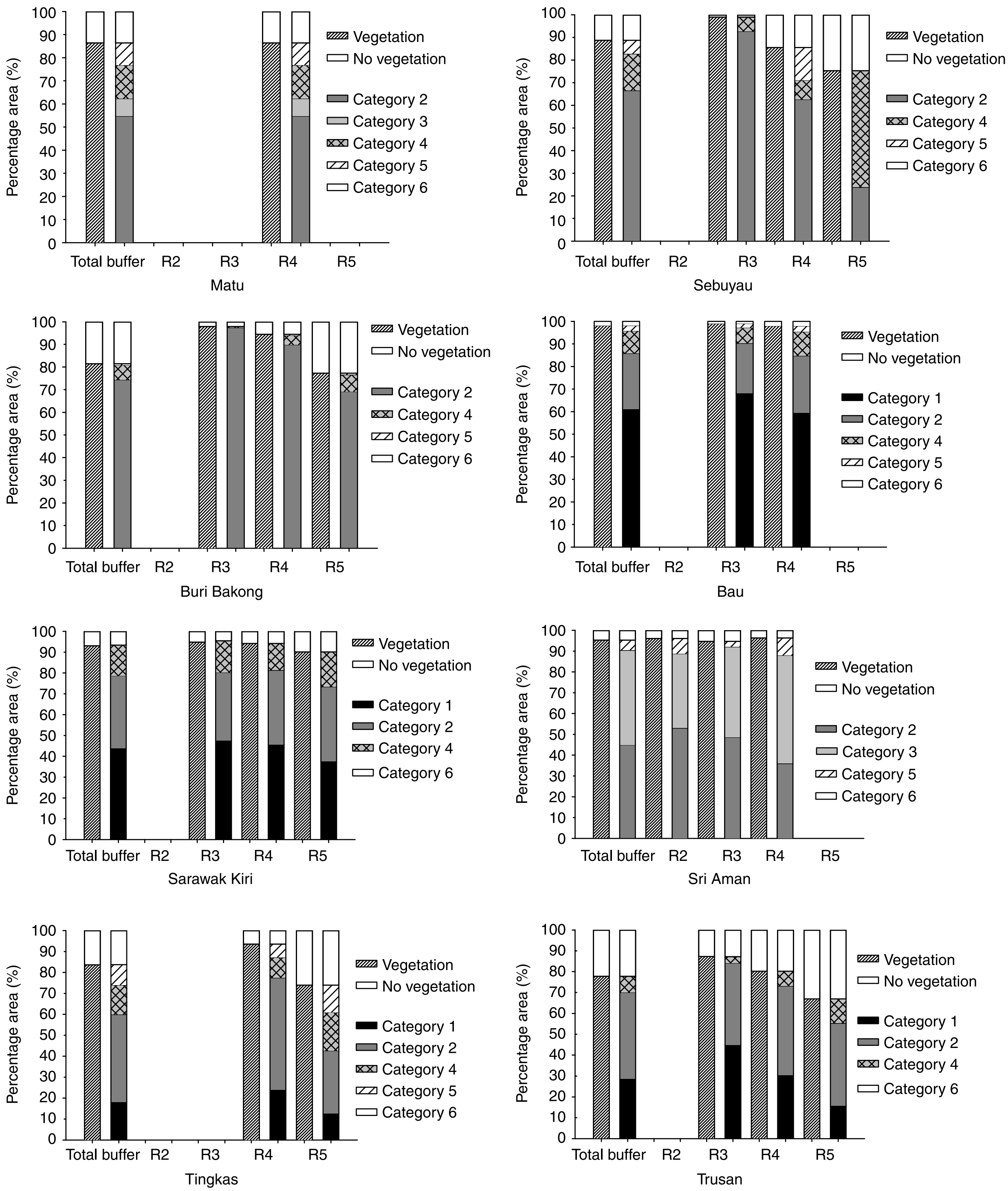

Figure 3 | Relative percentages of land cover assigned to each category over the entire visible river network (first two bars) and separately in each coded section of classified riparian buffer zone (not including the invisible headwater streams). River codes R2, R3, R4 and R5 represent a river width of 5–10, 10–20, 20–40 and >40 m respectively with buffer widths of 10 m, 20 m, 40 m, 50 m respectively. Two bars are present for the total visible river network (far left) and each coded river section. The first represents vegetation presence vs absence (presence = Categories 1–5, absence = Category 6). The second bar shows the relative percentage areas of each Category (an increasing scale of modification from the *x* axis).

while Sebuyau, Bau and Trusan, representing low, middle and highland catchments respectively, had the greatest proportions of unclassifiable headwater riparian reaches (90%, 89% and 93% respectively).

Modification of riparian buffers was broadly related to the change in geomorphic features associated with the low/mid and highland catchments. The highest degree of riparian modification occurred in the lowlands, the midland catchment Tingkas and the highland catchment of Trusan (~30% or more highly modified Categories (4–6)). The remaining midland catchments had ~10–20% of Categories 4–6 (Figure 3).

Distribution of modified riparian zones along the river networks

The lowland catchments of Sebuyau, Buri Bakong and the highland catchment Trusan showed the greatest relationship between increasing river width and increasing riparian vegetation modification (Figure 3). Although the entire classifiable river length of Matu was R4, the distribution of modification reflected a gradient from least disturbance upstream, to substantial modification downstream (towards and past the intake point). Tingkas also displayed a continuum of modification with river width, from the high altitude headwaters to the lowland outlet. The other midland catchments were comparatively uniform in the level of disturbance in each of the coded river width reaches, with Bau and Sarawak Kiri only showing very slight decreases in riparian quality with wider river and buffer widths (Figure 3). In Sri Aman, high modification (Category 6) occurred throughout all river codes while proportion of Category 2 (little disturbance) decreased with river width.

Land use within catchments

Land cover within the study catchments was classified into six categories representing various levels of vegetation modification from largely undisturbed or mature secondary vegetation (Category 1) through to bare, non-vegetated areas including roads and dwellings (Category 6) (Table 4). All catchments, except one (Sri Aman), comprised 60% Category 1 and 2 (combined) cover. The midland

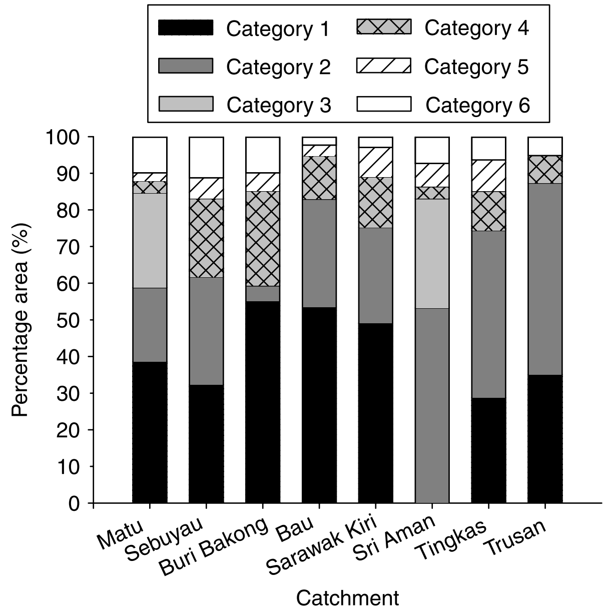

Figure 4 | Relative percentages of land cover assigned to each category over the entire catchment. The categories indicate the levels of vegetation disturbance in each catchment from black (least disturbed) to white (completely cleared/built area). Catchments are ordered from lowland (left) to highland (right).

catchment of Sri Aman was significantly modified with no Category 1 (continuous, dense, canopy cover) and a large percentage of Category 3 vegetation (agriculture/secondary growth). Bau (midland) and Trusan (highland) displayed the best vegetation quality with the smallest combined percentage values of highly modified land covers (Category 5 and 6) and greatest combined Category 1 and 2 values (Figure 4).

Comparison of land use/cover in catchments and riparian zones

Although comparison of catchment and riparian zone categories was complicated by the different levels of resolution in the images used for each, some evidence that activities occurring within a catchment were influencing the riparian zone was detected. The differences between the percentage areas of each land cover category in the riparian buffer zone and catchment area are shown in Figure 5.

Modification of land cover was found to be greater in the riparian buffer zone than in the wider catchment for the classified river networks of lowland Matu, Sebuyau, Buri Bakong, midland Tingkas and highland Trusan.

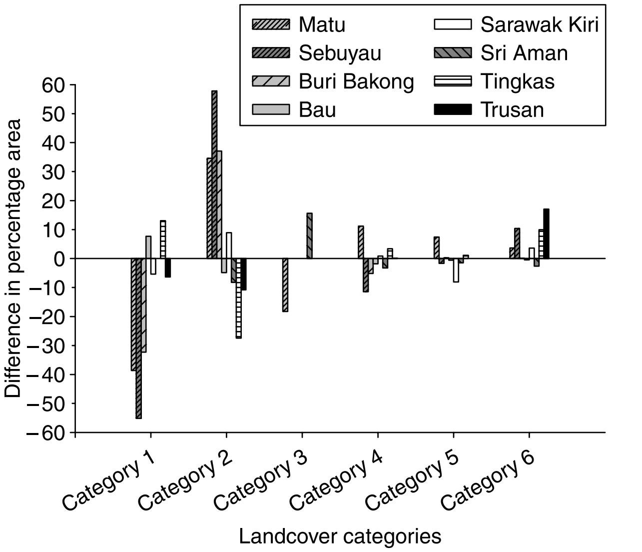

Figure 5 | Difference in percentage areas between land cover categories (1–6) occurring in the riparian buffer zone vs the entire catchment. Positive values indicate riparian percentage area is greater for that land cover category than that of the catchment. Negative values indicate that category occupies a larger percentage area in the catchment compared with the riparian buffer.

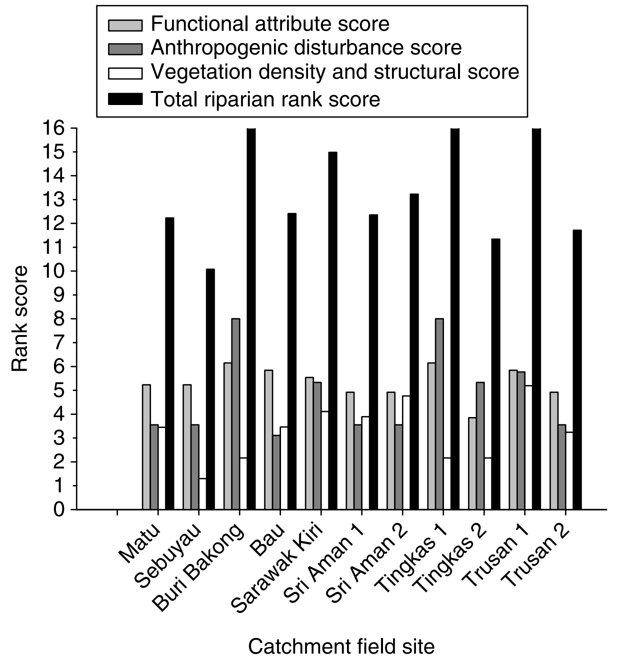

Figure 6 | A total riparian ranking score of 0–24 (black bars: higher values indicate better condition), derived from: (1) a functional attribute score 0–8 (influenced by the presence of riparian vegetation); (2) a condition score of 0–8 (reflecting the level of anthropogenic disturbance); and (3) a vegetation score of 0–8 (summarizing the ecological condition of the riparian vegetation in terms of structure and density).

Midland catchment Bau's riparian area was slightly less modified than that of its catchment, while Sarawak Kiri and Sri Aman were similar. Tingkas showed an increase in the percentage of modified vegetation (Category 4, 5 and 6) in the riparian zone, while Category 2 decreased.

The catchments with the greatest difference between riparian buffer and catchment land cover modification, indicating that their riparian zone had been disproportionally influenced by anthropogenic modification, were those that showed increased disturbance with increased river width (Trusan, Tingkas, Buri, Matu and to a lesser extent, Sebuyau). Those midland catchments with similar catchment and riparian zone land cover areas (Sri Aman, Bau and Sarawak Kiri) were those where the riparian zone was consistently modified from headwaters to intake points.

Field validation

The sites with the highest riparian scores in the field validation exercise (Tingkas 1, Trusan 1 and Buri Bakong; Figure 6) comprised predominantly Category 1 (or 2 at Buri Bakong), reflecting good agreement between riparian scores and the GIS classification. Trusan Site 1 had a poorer condition score relative to Buri and Tingkas 1 (reflecting the Category 4 and 6 recorded for this catchment) but a higher vegetation score, suggesting that disturbance rather than vegetation type may have a greater influence on the GIS land cover categories. This also indicated that while disturbance might modify the land cover allocation, the remaining vegetation could still be in good condition. The catchments with the lowest riparian scores (Sebuyau, Tingkas 2 and Trusan 2) contained higher proportions of Category 4.

Although Sarawak government policy requires buffer widths of 5–50 m of natural vegetation to be retained along all streams and rivers in drinking water supply catchments these guidelines were not met at nine of the eleven field sites surveyed. Of the two sites where the guidelines were met, one was found in the lower reaches of Buri Bakong and the other in an 'unclassifiable' stretch of a canopy-covered headwater stream on a ~10 m wide tributary of Tingkas (Site 1).

Water quality: turbidity

Catchments were ranked in order of the highest proportion of canopy-covered streams and compared with mean

Table 8 | A comparison of the riparian condition and water quality (mean annual turbidity data 1994–2005) for each of the eight catchments studied. In each column the catchments are ranked from best to worst catchment for that attribute, the following values in each column represent the value on which the ranking was based

	Ranking of catchment by	Highest invisible tributary cover (%) where 1 = highest coverage	Riparian modification (% land cover category) where 1 = least modified	Catchment modification (% land cover category) where 1 = least modified	Long-term turbidity (mean annual NTU, 1994–2005) where 1 = lowest (best) value
Lowland	Matu	5 (79.9%)	7	4	1 (7.12 ± 1.15)
	Sebuyau	1 (90.0%)	6	7	4 (22.57 ± 3.05)
	Buri Bakong	8 (55.7%)	8	5	6 (60.50 ± 2.90)*
Midland	Bau	3 (87.3%)	1	1	5 (34.36 ± 4.80)
	Sarawak Kiri	7 (70.4%)	2	3	2 (19.89 ± 2.61)
	Sri Aman	4 (82.6%)	4	8	3 (22.04 ± 3.47)
	Tingkas	6 (74.8%)	5	6	N/A
Highland	Trusan	2 (89.3%)	3	2	N/A

*Exceeded Class IIB NWQSM.

annual turbidity values. The only evidence of a possible relationship was displayed by Buri Bakong which had the lowest percentage of canopy covered tributaries (ranked 8th, 55.7%) and the highest long term (1994–2005) mean turbidity value of 60.5 NTU (Table 8), which exceeded the NWQSM Class IIB guidelines. There were no significant relationships between long term turbidity and vegetation change in the catchment or classifiable riparian areas. The closest (but not significant) correlation of -0.635 ($P = 0.088$; Pearson) was found, between long term turbidity and the percentage of 'invisible' tributary cover. Achieving statistically significant results were impaired by the small dataset.

DISCUSSION

Influence of riparian condition (categories) on function

The six categories of land cover detected by the unsupervised classification theoretically represented a ranking of riparian function. Thus, those catchments (Buri Bakong, Trusan, Matu, Sebuyau and Tingkas) with the highest proportion of Category 6 land cover (no vegetation) could be considered to have the poorest buffers. However, the importance of having fewer highly disturbed areas (Category 5 and 6) needs to be compared with presence of good quality vegetation (Categories 1 and 2). Several studies have emphasized the negative impact of breaks in the riparian buffer, or the presence of completely cleared areas (such as Category 6) on water quality. Sponseller *et al.* (2001) in a study on relationships between land use, spatial scale, stream macroinvertebrates, and water quality had originally seven cover classes of land use categories from GIS classification but reduced these to forest and non-forest cover for analysis. This suggests that the presence of Category 6 vs Categories 1–5 is probably the most influential difference affecting water quality. The 'quality' of the existing vegetation (proportions of Categories 1–5) impacts riparian function with increasing disturbance reducing the resilience and effectiveness of the buffer.

Interaction of environmental and anthropogenic activities influencing the distribution of modified areas along the river network and wider catchment

The majority of land use and land cover changes are driven by humans, rather than by natural processes (Lambin *et al.* 2005; Svan Hansen 2005) and this appeared to be the case in the Sarawak drinking water catchments. The distribution and extent of anthropogenic activities were, to a large degree, determined by soil type and the terrain. Land use was more concentrated along rivers in highland areas because in regions of steep terrain rivers are the primary transport routes. In the lowland areas land use was concentrated along rivers because these areas contained the most favourable soil types for cultivation. Land use in both the riparian zone and the wider catchment tended be similar in the midland catchments because the soil types and terrain tended to be more homogenous within these regions. Shifting agriculture or other local scale cultivation was still concentrated along the river networks in all these catchments, reflecting the traditional social importance of Sarawak's rivers for transport and settlement.

Field assessment vs. unsupervised classification

Remotely sensed classes do not necessarily correspond to typical classes derived from ground surveys and achieving an exact match between remotely sensed categories of landscape classification and data from field surveys remains a challenge for remote sensing applications (Wright *et al.* 2000; Mertes 2002). It can be difficult to link remotely sensed data with more traditional ecological and geomorphic parameters. For example, the ecologically distinct plantation and forest communities and resulting variation in riparian function they provide, were indistinguishable on spectral signature alone. Nevertheless the unsupervised classification results displayed a correspondence to the surveyed vegetation of field sites, as illustrated by the examples of Buri and Tingkas.

Factors affecting the riparian ranking score included environmental characteristics such as slope and soil and the position of the site within the river network, both of which in turn influence human land use and riparian modification. An increase in the number of sites surveyed would allow statistical comparisons to be made.

Differences between the representation of categories on the catchment and riparian scale were found. For example, in some catchments, Categories 1 or 3 or 5, while present in the overall catchment classification, could often not be distinguished in the riparian buffer. These differences may be real, or the product of differences in the satellite imagery used and scale of analysis. Inaccessible terrain and time constraints made more thorough ground truthing unachievable, which highlights the challenges of undertaking studies in remote tropical catchments and the reliance on remote sensing imagery.

Relationship between riparian condition and water turbidity

Buri Bakong was the only catchment with a significantly reduced percentage of canopy-covered headwaters. Its classified riparian network also displayed the greatest riparian vegetation modification. These riparian features were probably responsible for the high turbidities recorded in Buri Bakong (exceeding the guidelines in the long term dataset). Given the comparatively less disturbance in the catchment area, the poor water quality of the catchment appears to be more a result of vegetation disturbance in the riparian zone (particularly in its headwaters) than of the broader catchment. The high turbidity was likely to be a result of logging activities evident in the upper catchment and around the headwaters. Logging dramatically increases sediment input into streams (Greer *et al.* 1995; Douglas 1996; Iwata *et al.* 2003). While both catchment and classifiable riparian vegetation showed poor correlations with long term turbidity, the correlation (-0.67) between the percentage of canopy covered tributaries and long term turbidity, while not returning a significant P value, suggests perhaps there may be a non-linear, 'threshold' relationship (given $<50\%$ tributary coverage resulted in such a leap in the long term turbidity value). The headwaters of a catchment are where the greatest interaction with the riparian zone occurs and hence where the most effective water quality control by riparian vegetation is achieved, as several studies have emphasized (Allan 1995; Osbourne & Wiley 1998; Pinay *et al.* 2002). These results suggest that compliance with buffer guidelines is important, particularly in the headwaters and areas of high disturbance such as logging activity and oil palm plantations (Department of Environment, no date).

CONCLUSIONS

This study produced the first comprehensive datasets on land cover and riparian zone condition for drinking water supply catchments in Sarawak. This information provides a baseline against which future changes in land use and land cover change can be assessed. Although more than 70% of the headwaters in all catchments (except Buri Bakong) contained dense riparian vegetation, the 5%–22% of the riparian zones on visible rivers that lacked vegetation are cause for concern. Greater compliance with current guidelines that require buffer widths of 5–50 m of natural vegetation to be retained along all streams and rivers in drinking water supply catchments is recommended, particularly in logging areas, oil palm plantations and areas of settlement.

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