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Regional Patterns of Erosion and Sediment Transport in the Burdekin River Catchment

I.P. Prosser, C.J. Moran, H.Lu, A. Scott, P. Rustomji, J. Stevenson,
G. Priestly, C.H. Roth and D. Post

CSIRO Land and Water
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This study was part of a larger Meat and Livestock Australia (MLA) funded collaboration with CSIRO/DPI investigating the effects of grazing on sediment and nutrient exports from the Burdekin Catchment. At the same time we were able to draw on some of the innovative methodologies developed as a part of the National Land and Water Resources Audit (NLWRA) to determine sediment and nutrient export from Australia’s coastal catchments.

We gratefully acknowledge the funding support provided by MLA and NLWRA that made this study possible.

ABSTRACT

This project was carried out to identify the major processes involved in the delivery of sediment and nutrients to rivers within the Burdekin River catchment. It has identified critical areas of erosion potential, the physical processes that dominate in these areas and which areas are the major contributors of sediment and nutrients to the coast. The project outcomes will be of benefit to the grazing industry and other natural resource management agencies, enabling them to target these critical areas and thus to effectively use the resources directed at minimizing sediment and nutrient export from grazed land.

EXECUTIVE SUMMARY

The loss of sediment and nutrients from the land can have impacts downstream on the river and the marine environments that receive this material. In low input farming systems such as the northern beef industry, the bulk of nutrients, phosphorus and nitrogen, are transported with sediment. An essential part of minimizing the impact of sediment is to reduce losses from the landscape. In large regional catchments, such as the Burdekin River, there are a wide range of environments only some of which will contribute significant amounts of sediment to streams. There are also many opportunities for deposition of sediment in the catchment so that not all areas of erosion result in export of sediment from the catchment.

The aim of this report is to identify sediment sources in the Burdekin River catchment by identifying the dominant processes and the sub-catchments that have high erosion potential. The project also looks at patterns of sediment transport through the river network, identifying which reaches may be impacted by deposition of sand on river beds, and which sub-catchments contribute the most to suspended sediment loads and export from the river basin. We address these issues by constructing a sediment budget for the catchment. A sediment budget is an account of the major sources, stores and fluxes of sediment in the catchment.

Spatial modeling is the only practical method to assess the patterns of sediment transport in a large complex catchment as there are only limited measurements of sediment transport rates. Modelling can be used to interpolate these measurements and combine them with a basic understanding of transport processes and geographical information on controlling factors. This includes mapping of soils, vegetation cover, geology, terrain, climate and measurements of river discharge. We produce maps and summary statistics of predicted surface wash erosion, gully erosion, riverbank erosion and bedload and suspended load transport across the catchment.

The model results suggest that surface erosion varies by three orders of magnitude across the catchment. Only 25 % of the catchment has high surface wash erosion potential. Much of this is in the Bowen River sub-catchment, the area below the Burdekin Falls Dam and parts of the Upper Burdekin catchment. The Suttor and Belyando River catchments have low surface wash erosion potential.

Gully erosion is also a significant process contributing approximately 30% of the total predicted sediment load carried by streams. We predict it to be most pronounced in granitic and ancient sedimentary landscapes in the central part of the catchment. Gully and streambank erosion are the dominant sediment sources in the drier parts of the catchment where delivery of sediment to streams from surface wash erosion is low.

The sediment budget predicts that only 16% of suspended sediment and 4% of bedload delivered to the river network in any year is exported from the river mouth. The rest is stored within floodplains, as sand and gravel deposits on the bed of streams, and in reservoirs. This is typical of large river systems and much of the sediment remains stored for hundreds to thousands of years. We predict that the mean annual export of suspended sediment to the coast is 2.4 Mt/y. This conforms with monitoring of sediment loads in the lower river. Rapid accumulation of sand and gravel on the bed of rivers can degrade aquatic habitat, but we find that this is not a major concern in the Burdekin River catchment. Most river reaches are capable of transporting increases in supply of bedload from gully and riverbank erosion. Only in the area around the Burdekin Falls Dam and parts of the Bowen River catchment do we predict significant accumulation of sand and gravel.

Much of the suspended sediment load of the Burdekin River basin is generated from the Upper Burdekin catchment and the Bowen River catchment because of both high erosion rates and low amounts of deposition on floodplains in those areas. The Suttor and Belyando Rivers contribute relatively little suspended sediment because of extensive lowland floodplains and lower sediment supply to streams. Much of the catchment contributes very little to sediment export to the coast because of the long travel distances with many opportunities for deposition along the way, or because of low rates of sediment supply to the stream. We predict that 90% of the sediment delivered to the Burdekin Falls Dam is trapped by the dam. This results in approximately 95% of the sediment export to the coast being generated from just 13% of the catchment area. Overall the dominant sources are the sub-catchments downstream of the Burdekin Falls Dam, the Bowen River, and parts of the Upper Burdekin catchment. Grazing lands contribute 85% of this load simply because of the vast areas of grazing land within the catchment, occupying 90% of land in the catchment. The majority of grazing land, particularly in the drier parts of the catchment contributes little sediment to the coast.

The results from this project demonstrate that an assessment tool for constructing sediment budgets across a complex catchment, such as the one applied here, has strong potential for guiding further investigation, identifying areas for improved management and for setting targets of catchment restoration. Significantly, the results predict that erosion processes are highly focused, with much of the sediment being generated from relatively small areas. If future efforts at minimising soil loss are targeted towards these hotspots, using refined grazing management guidelines, a comparatively large benefit in reduced sediment loads downstream can be achieved with less effort. The targeted restoration (to be developed through further work in the project) need to be specially adapted to the particular soil and pasture communities prevalent in those sub-catchments or landscapes identified as hotspots. They also need to be differentiated to specifically address hillslope or gully erosion, whichever is the more important form of erosion in a particular area. The project results predict that each erosion process (surface wash, gully erosion, riverbank erosion) is significant in particular locations. Outputs from this research component should therefore assist the grazing industry, extension providers, and natural resource management agencies to appropriately target critical areas and as a consequence maximise resources directed at minimising sediment and nutrient export from grazed land. The project has also resulted in methods that can now be applied more readily to resource management issues in other catchments.

MAIN RESEARCH REPORT

Background

A significant aspect of achieving an ecologically sustainable beef industry is to ensure that the downstream impacts of grazing on streams are minimised. An essential part of minimising impact is to reduce the delivery of sediments and nutrients from land to streams. For low input farming systems such as extensive beef grazing, the bulk of the nutrient load is transported attached to sediment so that sediment and nutrient transport are intimately linked.

To put pastoral land use in the context of the regional catchments in which it occurs requires us to conceptualise the critical sources, transport pathways and sinks of sediment and nutrient in a catchment. We need to identify where sediment and nutrient is derived from, where it is stored within the catchment, and how much is delivered downstream to rivers and the sea. To quantify sources, stores and delivery is to construct a sediment budget for a catchment or any part of a catchment. This is a critical step to conceptualise the context of land use in a large regional catchment and to focus more detailed studies on the areas of greatest potential impact. Few studies of regional sediment and nutrient budgets have been conducted, and none to date pertain to the north Australian beef industry.

Grazed catchments such as the Burdekin are complex systems, often with considerable variation in grazing pressure, and diverse topography, soils, rainfall and vegetation cover. Thus before changing grazing management or even undertaking remediation measures we need to determine its significance and the spatial pattern of grazing impact for sediment and nutrient transport. We also need to put the more detailed investigations of other parts of this project in a broader regional environmental context for the results to be applicable across wider areas.

Some parts of the landscape are inherently more at risk of increased erosion and sediment and nutrient transport than others. It is important to identify these areas for these will be the sites that require the most careful management to ensure a sustainable future. For example, some landscapes have inherently poor soils where grass cover is susceptible to dramatic and long-lasting decline when subjected to grazing pressure or drought. Other factors that contribute to inherent risk of sediment and nutrient delivery to streams include steep slopes, high channel density, and high rainfall erosivity.

Sediment and nutrients are derived chiefly from three types of processes:

- runoff on the land, termed surface wash and rill erosion or alternatively hillslope erosion;
- erosion of gullies formed as a result of land clearing or grazing; and
- erosion of the banks of streams and rivers.

Photo 1: *Low ground cover and the head of an erosion gully in the Fanning River sub catchment of the Burdekin River.*

In many cases one process far dominates the other in terms of delivering sediments and nutrients to streams, and the predominant process can vary from one part of a large catchment to another. Management aimed at reducing sediment and nutrient transport will target each process quite differently. For example, stream bank and gully erosion is best targeted by managing stock access to streams, protecting vegetation cover in areas prone to future gully erosion, revegetating bare banks and reducing sub-surface seepage in areas with erodible sub-soils. Surface wash erosion is best managed by promoting consistent groundcover, maintaining soil structure, promoting nutrient uptake and promoting deposition of eroded sediment before it reaches the stream. Consequently it is quite important to identify the predominant sediment and nutrient delivery process before undertaking catchment remediation or making recommendations for changed grazing practice.

Sediment delivered to streams has several potential downstream impacts. High loads of suspended sediment, the silts and clays that are carried in the flow, degrade water quality in streams, reservoirs and estuaries. This is a result of both the sediment itself and the nutrients that the sediment carries. High concentrations of suspended sediment reduce stream clarity; inhibit respiration and feeding of stream biota; diminish light needed for plant photosynthesis; make water unsuitable for irrigation and require treatment of water for human use. The suspended sediment is also deposited in low energy environments. The main depositional environment for suspended sediment along the north Queensland coast is the in-shore marine environment of shallow waters, in-shore reefs, and tidal flats. Accelerated deposition in these areas can smother aquatic habitats and can increase turbidity through resuspension of the sediment. Not all suspended sediment delivered to streams is exported to the coast. Much of it is deposited along the way on floodplains, providing fertile alluvial soils, or it is deposited in reservoirs. The extent of this deposition is highly variable from one river reach to another. Deposition potential must be considered when trying to relate catchment land use to downstream loads of sediment.

Photo 2: *The Burdekin River at the Flinders Highway showing suspended load carried in the water and bedload deposits of sand and gravel.*

The formation of gullies and accelerated erosion of stream banks can supply large amounts of sand and gravel to streams. These are transported as bedload, being rolled, and bounced along the bed of streams. Where streams are unable to transmit the load of sand and gravel downstream, it is deposited, burying the bed, and in extreme examples forming sheets of sand referred to as sand slugs (Rutherfurd, 2000). Sand slugs are poor habitat. They can prevent fish passage, they fill pools and other refugia, and are unstable substrate for benthic organisms (Jeffers, 1998). Many semi-arid streams have natural beds of sand, however, so the presence of extensive sand deposits on the bed of these streams should not be taken as an indicator of degradation. In this project we assess whether changes to the supply of sand and gravel to streams are likely to have changed the composition of the bed of streams in the Burdekin catchment.

A reconnaissance level sediment budget for the Burdekin River catchment will provide an understanding of the critical processes of sediment and nutrient transport that can lead to downstream impact. It will place the beef industry in an appropriate regional context of broader land use issues. The budget will also identify sub-catchments with the greatest potential for downstream impact on aquatic ecosystems. These are the first steps toward better targeting of remedial and land conservation measures. The sediment budget demonstrates how relatively simple reconnaissance techniques can be used in regional policy development in relation to the beef industry. It provides producers with broad guidelines to identify the conditions under which there could be significant downstream impact of sediment and nutrient.

Photo 3: *A tributary of the Burdekin River at low flow showing extensive bed deposits of sand. These can be a natural feature of semi-arid rivers.*

Project Objectives

This report constitutes the final report for one of four research components (R1) of the MLA/CSIRO/QDPI project "Reducing Sediment and Nutrient Export From Grazed Land in the Burdekin Catchment for Sustainable Beef Production". The specific objectives of the component are:

- To survey the Burdekin catchment at a reconnaissance scale to identify crucial sub-catchments appropriate for more detailed investigation;
- to assess the most significant processes of soil erosion as they relate to grazing management; and
- to provide a framework for reviewing and integrating information currently available in the catchment.

Methods

The only practical framework to assess the patterns of sediment and nutrient transport across a large complex area such as the Burdekin River catchment is a spatial modelling framework. There are few direct measurements of sediment transport in regional catchments, and it is unrealistic to initiate sampling programs of the processes now and expect results within a decade. Furthermore, collation and integration of existing data has to be put within an overall assessment framework, and a large-scale spatial model of sediment transport is the most effective use of that data.

The assessment of sediment transport is divided into three aspects: hillslope erosion as a source of sediment; gully erosion as a source of sediment; and river links as a further source, receiver and propagator of the sediment. The methods used in each aspect of the spatial model are outlined below in brief. They were developed concurrently with a National Land and Water Resources Audit project on sediment budgets and reference is made to supporting technical documentation which contains details of the approach.

Hillslope Erosion Hazard

The controls on hillslope erosion by surface wash and rill erosion are well understood and there are several models which incorporate these factors. The best known model and the only one that can be applied across large regions is the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978) and its derivatives such as the Revised USLE (RUSLE; Renard *et al.*, 1997), Soiloss (USLE factors for NSW; Rosewell, 1993) and PERFECT (Littleboy *et al.*, 1992). Research on the processes of hillslope erosion has resulted in more detailed models of the mechanics of sediment detachment and transport but these cannot be used at regional scales because they require parameters which are unavailable beyond limited experimental conditions. Support for the USLE is given by studies which show that its empirical form is consistent with the mechanics of sediment detachment and transport included in the more detailed models (Moore and Burch, 1986; McCool *et al.*, 1989).

The RUSLE calculates mean annual soil loss (Y, tonnes/ha/y) as a product of six factors: rainfall erosivity factor (R), soil erodibility factor (K), hillslope length factor (L), hillslope gradient factor (S), ground cover factor (C) and land use practice factor (P):

$$Y = RKLSCP \tag{1}$$

The factors included in the RUSLE vary strongly across a diverse catchment such as the Burdekin, providing a method for estimating the spatial patterns of erosion using available spatial information for each factor.

The precise form of each factor is based on soil loss measurements on hillslope plots, mainly in the USA. Plot scale measurements of erosion have been undertaken in the Burdekin area (McIvor *et al.,* 1995; Scanlan *et al.,* 1996) allowing limited local calibration of the RUSLE factors, particularly the C factor.

The RUSLE is directly applicable for hillslopes up to 300 m in length. For longer hillslopes we can extrapolate the relationship based on expected runoff patterns on longer hillslopes. The L factor represents the increase in storm runoff volume with increasing hillslope length, and the increased propensity for rill erosion with increasing runoff. In native grasslands, woodlands and forests there is evidence that runoff volume grows only weakly or not at all with hillslope length (Bonell and Williams, 1987; Prosser and Williams, 1998). In these landscapes there are patches of runoff generation and patches of runoff adsorption and longer hillslopes do not necessarily yield more sediment than short ones. Thus the L factor was removed from the analysis in these areas and only applied to areas with cropping or improved pastures. Similarly, there are few land use practises such as tillage and construction of contour banks in extensive savannah grazing lands so the P factor was also removed from the spatial analysis.

Mean annual values for rainfall erosivity and the cover factor are often used in direct application of Equation (1) to calculate mean annual hillslope erosion. This neglects often important seasonal patterns of rainfall erosivity and cover. High intensity rains for example may be associated with seasons of low ground cover. To incorporate these effects we used the product of mean monthly cover (C_m) and the proportion of annual rainfall erosivity for each month (R_m/R). The monthly values of C_mR_m/R were then summed to give mean annual soil loss. It can be shown that incorporation of seasonal effects reduces predicted mean annual soil loss in Australia's tropics by a factor of 1.5. The modifications of Equation (1) discussed above yield

$$Y = KLS \sum_{m=1}^{m=12} C_m \frac{R_m}{R} \,. \tag{2}$$

Twenty years (1980-1999) of daily rainfall data mapped across Australia and 13 years (1981-1994) of satellite vegetation data were used to apply Equation (2). Details of the use of this data are given in Lu *et al.* (2001). The soil erodibility factor (K) was derived from the Australian Soil Resources Information System (as detailed in Lu *et al.*, 2001). The length and slope factors (L, S) were derived from the national 9" digital elevation model (DEM; approximately 250 m grid resolution) and scaling rules were determined from comparison with higher resolution DEMs (see Gallant, 2001 for details). This transformation was needed because the raw values in the 9" DEM do not accurately reflect the topographic details of hillslopes and valleys which are at a similar or finer scale than the resolution of the DEM.

The predictions of surface wash erosion under present land use need to be put in context of erosion under natural vegetation cover, for many areas have naturally high surface wash erosion. We predicted natural erosion using the same procedure as above, using a cover factor for native vegetation and keeping the other factors of soil erodibility, rainfall erosivity and topography as for the present day.

The cover factor for native vegetation was obtained by assessing areas of reserve where native vegetation cover is retained in each of Australia's native vegetation zones. In the reserves, the RUSLE C factor was determined from remote sensing data as part of the assessment of current soil loss. The native vegetation cover of these reserve areas was extrapolated across other areas using an empirical decision tree model based on climatic, topographic, and geological factors. The acceleration of current mean annual soil loss above natural rates was predicted as the ratio of the current to pre-European mean annual soil loss predictions. Further details are given in Lu *et al.* (2001).

Gully Erosion Hazard

As it is an expensive and time consuming effort to measure all the gullies within the Burdekin catchment, the extent of gullies was estimated by aerial photograph interpretation of a number of sampled areas. These were used to generate an empirical model of gully density based on various environmental attributes for which there is catchment-wide coverage.

Sample sites were selected in each of the major geology types, slopes and rainfall zones. To ensure satisfactory representation of the different terrains, each major land system is represented by a number of photographs, and the photographs covered all geographical areas of the catchment. There is however, a bias towards the central part of the catchment since suitable air photos were more readily available for this region. A total of 63 pairs of photos were used. Eroded gullies were mapped from the aerial photographs using a stereoscope and then scanned and digitised into a geographical information system (GIS). Each image was then geo-referenced using 5 to 6 control points, which were obtained from 1:100,000 topographic maps. For each air photo, the mapped gullies were grouped into areas (or polygons) of similar geology, land-use and slope. Each aerial photograph was then divided into blocks of similar terrain based upon land use, geology and relief. Each region, thus delineated, is allocated the gully density (km of eroded gully per km^2 of area) measured across that whole region. The gully density is then calculated by dividing the total length of gully by the area of the polygon, to give a value in km of eroded gully per km^2 of area.

For building a spatial model of gully density a grid resolution of 1.25 km was selected. We consider this to be the smallest scale at which gully prediction is feasible using the variables available. It is also the approximate scale at which the original aerial photograph interpretation was done. The gully erosion model was built using 75% of pixels for which there was aerial photograph interpreted gully density. The predictor environmental variables were also sampled over the same locations. These included climatic parameters such as mean annual rainfall; various soil attributes derived from the Atlas of Australian Soils and McKenzie *et al.* (2000); geology; land use; and terrain attributes derived from the 9" DEM. A number of training sets were used by varying the random sampling of pixel locations, and by varying the predictor variables. This ensured that the model was not sensitive to the precise choice of measured sites, and used the best combination of predictor variables.

Sets of gully density rules were determined using the CUBIST decision tree software. This is a data mining tool for generating rule-based predictive models for large volumes of data. The basic model building methods of CUBIST can be found in Quinlan (1993). CUBIST builds a model of gully erosion based on piece-wise linear multiple regression of the predictor variables. The remaining 25% of measured gully pixels were used to test the quality of the model. The best model was selected on the basis of the highest correlation coefficient, smallest absolute and relative error, and consistent statistical figures between training set and testing set. Finally, a gully density map was produced by applying the rules generated by the decision tree to the predictor variables mapped over the entire catchment. Hughes *et al.* (2001) contains further details of the method.

Sediment Delivery Through the River Network

Hillslope and gully erosion, together with erosion of streambanks, supply sediment to the stream network (the network of creeks and rivers in a catchment). The sediment supplied to a reach of river is then either deposited within the river, and its surrounding floodplain, or is transmitted to the next reach downstream. There is also substantial deposition in reservoirs.

To calculate the supply of sediment, its deposition and its delivery downstream is to construct a river sediment budget. We calculated budgets for two types of sediment: suspended sediment and bedload. A suit of ArcInfo^{TM} programs were used to define river networks and their sub-catchments; import required data; implement the model; and compile the results. The programs are referred to collectively as the SedNet model: the Sediment River Network model. Details of the model and its application to regional catchments in Australia is given in Prosser *et al.* (2001). That document describes all the equations and input data used. Here we give a brief descriptive summary of the approach.

The SedNet model calculates, among other things:

- the mean annual suspended sediment output from each river link;
- the depth of sediment accumulated on the river bed in historical times;
- the relative supply of sediment from surface wash, gully and bank erosion processes;
- the mean annual rate of sediment accumulation in reservoirs;
- the mean annual export of sediment to the coast; and
- the contribution of each sub-catchment to that export.

For this project, suspended sediment is characterised as fine textured sediment carried at relatively uniform concentration through the water column during large flows. The main process for net deposition of suspended sediment is overbank deposition on floodplains (e.g. Walling *et al.*, 1992). The amount of deposition depends upon the residence time of water on the floodplain and the sediment concentration of flood flows. The residence time of suspended sediment in streams is low, so there is negligible transient deposition of suspended sediment. Suspended sediment is sourced from surface wash erosion of hillslopes, gully erosion and riverbank erosion. The sediment budget is reported as mean annual values for either the current land use or for pre-European native vegetation cover.

Bedload is sediment transported in greatest proportions near the bed of a river. It may be transported by rolling, saltation, or for short periods of time, by suspension. Transport occurs during periods of high flow, over distances of hundreds to thousands of metres (Nicholas *et al.*, 1995). Residence times of coarse sediment in river networks are relatively long so there is transient deposition on the bed as the sediment works its way through the river network. In addition to that deposition, an increase in sediment supply from accelerated post-European erosion can cause the total supply of sediment in historical times to exceed the capacity of a river reach to transport sediment downstream. The excess sediment will be stored on the bed and the river will have aggraded over historical times (Trimble, 1981; Meade 1982). There has been a significant increase in supply of sand and fine gravel to rivers in historical times and deposition of this bedload has formed sand slugs: extensive, flat sheets of sand deposited over previously diverse benthic habitat (Nicholas *et al.*, 1995; Rutherfurd, 1996). The bedload budget aims to predict the formation of these sand slugs.

The basic unit of calculation for constructing the sediment budgets is a link in a river network. A link is the stretch of river between any two stream junctions (or nodes; Figure 1). Each link has an internal sub-catchment, from which sediment is delivered to the river network by hillslope and gully erosion processes. The internal catchment area is the catchment area added to the link between its upper and lower nodes (Figure 1). For the purpose of the model, the internal catchment area of first order streams is the entire catchment area of the river link. Additional sediment is supplied from bank erosion along the link and from any tributaries to the link

A branching network of river links joined by nodes was defined from the AUSLIG 9" digital elevation model (DEM) of Australia. The river network was defined as beginning at a catchment area of 50 km^2. This was an arbitrary choice used to limit the number of links across the assessment area, while still representing all large streams. The physical stream network extends well upstream of the limit in most areas and these areas are treated as part of the internal catchment area contributing material to the river link. Short links, where the catchment area had reached less than 75 km^2 by the downstream node, were removed. Links were further separated by nodes at the entry to and exit from reservoirs and lakes. Internal catchment areas for each link were also determined from the 9" DEM.

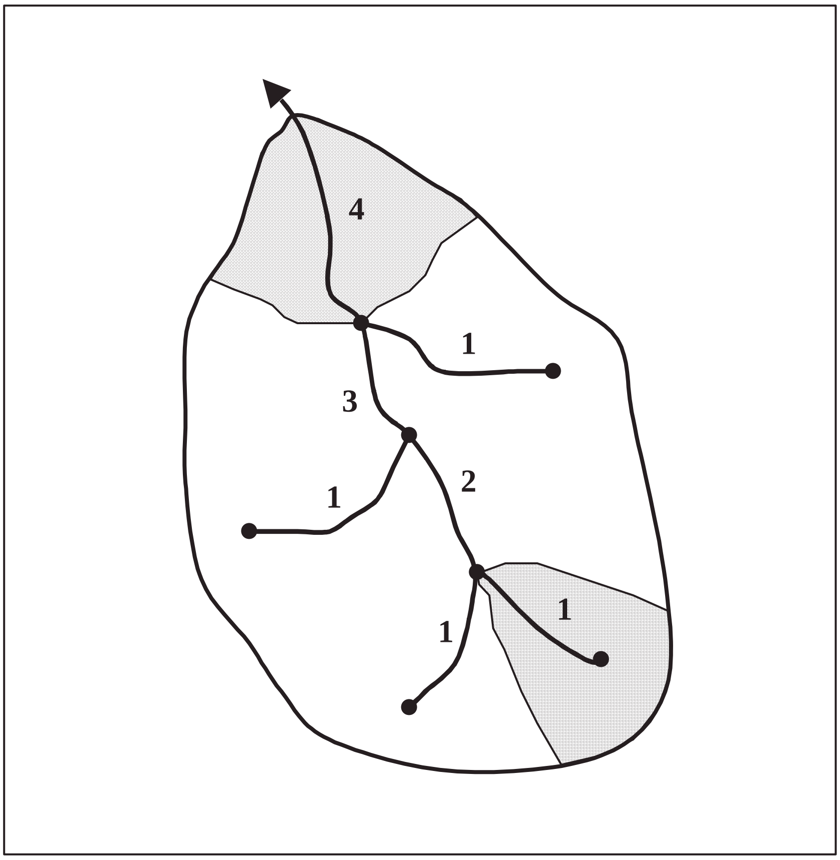


Figure 1: *A river network showing links, nodes, Shreve magnitude of each link (Shreve, 1966) and internal catchment area of a magnitude one and a magnitude four link.*

A sediment budget for bedload was calculated for each river link (*x*) in the network, working from the top of the basin to the sea (Figure 2). The aim was to define those links subject to net deposition because the historical supply of bedload has exceeded sediment transport capacity. The total mean annual load supplied to the outlet of the link at any time is compared with the mean annual sediment transport capacity at that point. If the load is in excess of capacity, the excess is deposited and the yield to the link immediately downstream equals the sediment transport capacity. If the loading to the outlet is less than the sediment transport capacity there is no net deposition and the yield downstream equals the loading to the outlet.

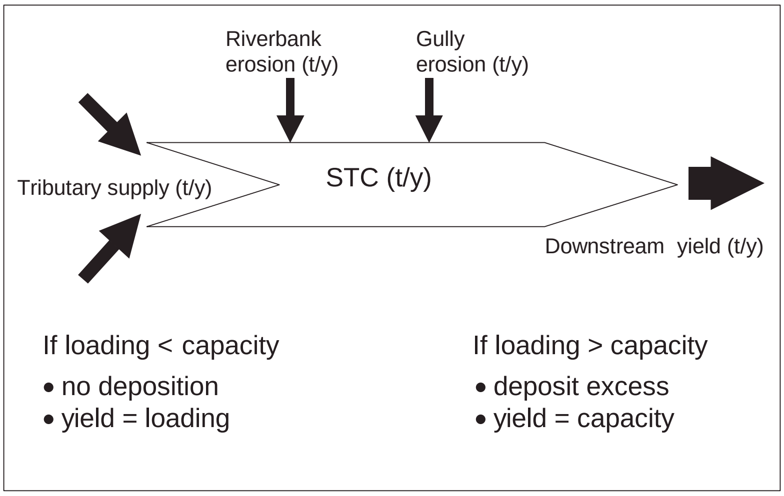


Figure 2: *Conceptual diagram of the bedload sediment budget for a river link. STC is the sediment transport capacity of the river link, determined by equation 3.*

Bedload is supplied to a river link from tributary links and from gully and riverbank erosion in the internal catchment area of the link. Half the sediment derived from riverbank and gully erosion contributed to the bedload budget and the other half contributed to the suspended load budget. This reflects observed sediment budgets (eg. Dietrich and Dunne, 1978) and particle size of the bank materials.

Mapping of gully erosion extent was described above. Gully density was converted to a mean annual mass of sediment derived from gully erosion by assuming development of gullies over 100 y and a mean gully cross-sectional area of 10 m^2.

The supply of sediment from riverbank erosion was calculated from the results of a global review of river bank migration data (Rutherfurd, 2000). The best predictor of bank erosion rate was found to be bankfull discharge. This was modified in the project to account for the condition of riparian vegetation. It was assumed that the bank erosion rate was negligible on rivers with intact native riparian vegetation. The presence and absence of native riparian vegetation was determined from the Australian Land Cover Change project which mapped vegetation present in 1995 at a resolution of 100 m (BRS, 2000). This is the best available data but is still a crude measure of riparian condition. The 100 m resolution fails to identify narrow bands of remnant riparian vegetation in cleared areas but it also fails to identify narrow valleys of cleared land penetrating otherwise uncleared land.

Once calculated, the total supply of bedload to a river link is compared to sediment transport capacity (STC_x). Sediment transport capacity is a function of the river width (w_x), slope (S_x), discharge (Q_x), particle size of sediment and hydraulic roughness of the channel. Yang (1973) found strong relationships between unit stream power and *STC*. Using Yang's (1973) equation, and average value for Mannings roughness coefficient of 0.025, we predicted sediment transport capacity in a river link (t/y) from:

$$STC_x = \frac{86 S_x^{1.3} \sum Q_x^{1.4}}{\omega w_x^{0.4}} \qquad (3)$$

where ω is the settling velocity of the bedload particles (m/s), and $\Sigma Q_x^{1.4}$ represents mean annual sum of daily flows raised to a power of 1.4 (Ml$^{1.4}$/y). This represents the disproportionate increase in sediment transport capacity with increasing discharge.

The suspended sediment loads of Australian rivers, and rivers in general, are supply limited (Olive and Walker, 1982; Williams, 1989). That is, rivers have a very high capacity to transport suspended sediment and sediment yields are limited by the amount of sediment delivered to the streams, not discharge of the river itself. Consequently, if sediment delivery increases, sediment yields increase proportionally.

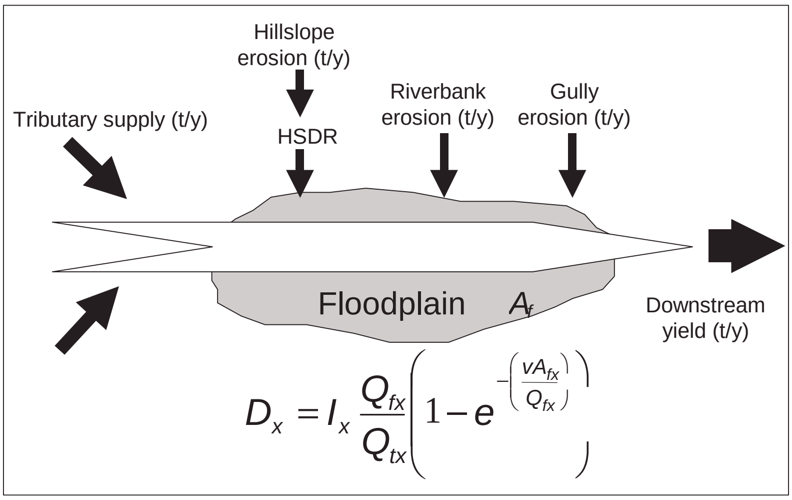
Deposition is still a significant process, however, and previous work has shown that only a small proportion of supplied sediment leaves a river network (Wasson, 1994).

Suspended sediment is supplied to a river link from four sources: river bank erosion, gully erosion, hillslope erosion and tributary suspended sediment yield (Figure 3). Prediction of surface wash and rill erosion was described above but only a small proportion of sediment moving on hillslopes is delivered to streams. The difference occurs for two reasons. First the RUSLE is calibrated against hillslope plots considerably smaller than the scale of hillslopes. Much of the sediment recorded in the trough of the plots may only travel a short distance (less than the plot length and much less than the hillslope length) so that plot results cannot be easily scaled up to hillslope predictions. Second, there are features of hillslopes, not represented by erosion plots, which may trap a large proportion of sediment. These include farm dams, contour banks, depressions, fences, and riparian zones. The most common way of representing the difference between plot and hillslope sediment yields is to apply a hillslope sediment delivery ratio to the RUSLE results (e.g. Williams, 1977; Van Dijk and Kwaad, 1998). This ratio represents the proportion of sediment moving on hillslopes that reaches the stream.

The main location for deposition of suspended sediment is on floodplains A relatively simple conceptualisation of floodplain deposition is to consider that the proportion of suspended sediment load that is available for deposition is equal to the fraction of total discharge that goes overbank. This assumes uniform concentration of suspended sediment with depth.

The actual deposition of material that goes overbank can be predicted as a function of the residence time of water on the floodplain. The longer that water sits on the floodplain the greater the proportion of the suspended load that is deposited. The residence time of water on floodplains increases with floodplain area and decreases with floodplain discharge. Floodplain area was mapped from the DEM using a flood routing model as described in Pickup and Marks (2001).

An increase in supply of suspended sediment from upstream results in a concomitant increase in mean sediment concentration and mean annual suspended sediment yield. Thus increases to suspended sediment supply have relatively strong downstream influences on suspended sediment loads. Sediment deposition in reservoirs is incorporated in the model as a function of the mean annual inflow into the reservoir and its total storage capacity (Heinemann, 1981).



$$D_x = I_x \frac{Q_{fx}}{Q_{tx}}\left(1 - e^{-\left(\frac{vA_{fx}}{Q_{fx}}\right)}\right)$$

Figure 3: *Conceptual diagram for the suspended sediment budget of a river link. HSDR is hillslope sediment delivery ratio. The equation is for the amount of sediment deposited on the floodplain (t/y), where* I_x *is the sediment load input to the link,* Q_{fx}/Q_{tx} *is the proportion of flow that goes overbank,* A_{fx}/Q_{fx} *is the ratio of floodplain area to floodplain discharge and* v *is the sediment settling velocity.*

The procedures above were applied in sequence to each river link from the top of the basin to the sea, adding suspended load and predicting its loss through deposition along the way. The final calculation is of mean annual suspended sediment export to the sea.

Contribution of Sediment to the Coast

One of the strongest interests in suspended sediment transport at present is the potential river export to estuaries and the coast. Because of the extensive opportunities for floodplain deposition along the way, not all suspended sediment delivered to rivers is exported to the coast. There will be strong spatial patterns in sediment delivery to the coast because some tributaries are confined in narrow valleys with little opportunity for deposition, while others may have extensive open floodplains. There will also be strong, but different patterns in sediment delivery to streams. Differentiation of sub-catchments which contribute strongly to coastal sediment loads is important because of the very large catchments involved in Australia; the Burdekin River drains an area of 130,000 km^2 for example. It is not possible, or sensible, to implement erosion control works effectively across such large areas.

The contribution of each sub-catchment to the mean annual suspended sediment export from the river basin was calculated. The sub-catchments are the link internal areas described in Figure 1. The calculations were made once the mean annual suspended sediment export was calculated. The method tracks back upstream calculating from where the sediment load in each link is derived. The calculation takes a probabilistic approach to sediment delivery through each river link encountered on the route from source to sea.

Each internal link catchment area delivers a mean annual load of suspended sediment (LF_x) to the river network. This is the sum of gully, hillslope and riverbank erosion delivered from that sub-catchment. The sub-catchment delivery and tributary loads constitute the load of suspended sediment (TIF_x) received by each river link. Each link yields some fraction of that load (YF_x). The rest is deposited. The ratio of YF_x/TIF_x is the proportion of suspended sediment that passes through each link. It can also be viewed as the probability of any individual grain of suspended sediment passing through the link. The suspended load delivered from each sub-catchment will pass through a number of links on route to the catchment mouth. The amount delivered to the mouth is the product of the loading LF_x from the sub-catchment and the probability of passing through each river link on the way:

$$CO_x = LF_x \, x \, \frac{YF_x}{TIF_x} \, x \, \frac{YF_{x+1}}{TIF_{x+1}} \, x ...... x \, \frac{YF_n}{TIF_n} \qquad (4)$$

where n is the number of links on the route to the outlet. Dividing this by the internal catchment area expresses contribution to outlet export (CO_x) as an erosion rate (t/ha/y). The proportion of suspended sediment passing through each river link is ≤ 1. A consequence of Equation (4) is that all other factors being equal, the further a sub-catchment is from the mouth, the lower the probability of sediment reaching the mouth. This behaviour is modified though by differences in source erosion rate and deposition intensity between links.

Suspended Sediment Budget Under Natural Conditions

There are naturally strong differences in suspended sediment load across diverse environments. To assess the extent to which the current sediment loads reflect the natural circumstances, and to what extent they reflect accelerated sediment supply, requires prediction of natural sediment loads. This is necessarily a fairly speculative process as there is limited knowledge of natural conditions, and no sediment load data other than for a few small catchments which remain relatively undisturbed. Methods to estimate the natural rate of hillslope erosion were described above. The delivery of this sediment to streams was determined using the same hillslope sediment delivery ratio as for present conditions. The natural rates of gully and riverbank erosion are negligible compared to current rates and were not included in the analysis, thus all sediment is supplied from hillslopes. Deposition of suspended sediment was modeled as described above assuming no changes to flood flow. Reservoir deposition was, of course, omitted.

Hydrology

Several hydrological parameters are used in the river sediment budget methods. These need to be predicted for each river link across the river basin. The variables needed are:

- the mean annual flow
- the mean annual sum of $Q^{1.4}$ for calculating mean annual sediment transport capacity;
- the bankfull discharge; and
- a representative flood discharge for floodplain deposition.

Values for mean annual flow were derived from available gauging records and a simple empirical rule based upon rainfall and catchment area was used to predict values in ungauged river links. The same approach was used for the mean annual sum of $Q^{1.4}$. The other two hydrological parameters were also derived from gauging records by regression against mean annual flow.

Results and Discussion

Figure 4 shows the major localities and roads in the Burdekin River catchment. This is presented to help locate areas on the following maps of erosion and sediment transport where localities are not shown to improve clarity. Major rivers and sub-catchments are referred to in the results and these are shown in Figure 5, together with average annual rainfall. This shows a strong rainfall gradient away from parts of the catchment that are close to the coast. Thus the Bowen River and lower Burdekin River have higher rainfall than the rest of the catchment and this feature is carried through into patterns of erosion hazard, vegetation cover, and river discharge.

Hillslope Erosion Hazard

Figure 6 shows the patterns of hillslope erosion for the catchment based on each 9" pixel. Most areas of the catchment have soil loss rates of <20 t/ha/y but there are occasional areas with rates as high as 100 t/ha/y. A few pixels are predicted to have erosion of 100 - 276 t/ha/y but they are so small in extent to not be visible on Figure 6. Such values are unrealistic and probably result from minor artefacts in the DEM or remote sensing data. The values of hillslope erosion represent local movement of soil on hillslopes. It is important to realise that hillslope erosion values overestimate sediment delivery to streams as much of the sediment that is moving may be deposited before reaching the stream. For instance, material eroded on a ridge slope might end up being deposited in colluvial fans on flatter valley bottoms or on river frontage areas before reaching streams.

As expected, Figure 6 shows that the north Burdekin catchment has considerably more erosion than the southern part of the catchment. Most of the north-eastern part of the catchment (including Douglas, Running, Star, Keelbottom and Fanning Rivers) experiences high soil erosion except for the rain forest at Paluma High Range. The worst areas affected are located on the eastern side of a ridge of the Leichhardt Range, north of the Burdekin River, downstream of the Burdekin Falls Dam and part of the south side of the river on the end of the Leichhardt Range. The sub-catchments to the north of the Bowen River are predicted to have high erosion as well, except for the National Parks close to Mt. Dalrymple. Sub-catchments surrounding Clarke River and the areas around Cape River near the junction with Burdekin River face medium hillslope erosion. Low to medium erosion rates are found in the rest of the sub-catchments. The high erosion rate in the Bowen River catchment is a new result and needs field verification. It arises from the combination of high rainfall erosivity on sloping land with at times low ground cover. The seasonal ground cover is modelled at a 5 km resolution, and separated from perennial cover, assumed to be tree cover. It is possible that the method used underestimates ground cover in areas of pasture adjacent to or intermingled with forest. Significant stone and rock cover may reduce actual rates of surface wash erosion in some areas of high surface wash erosion potential. Rock often dominates the surface in areas where soil formation cannot naturally keep pace with soil erosion.

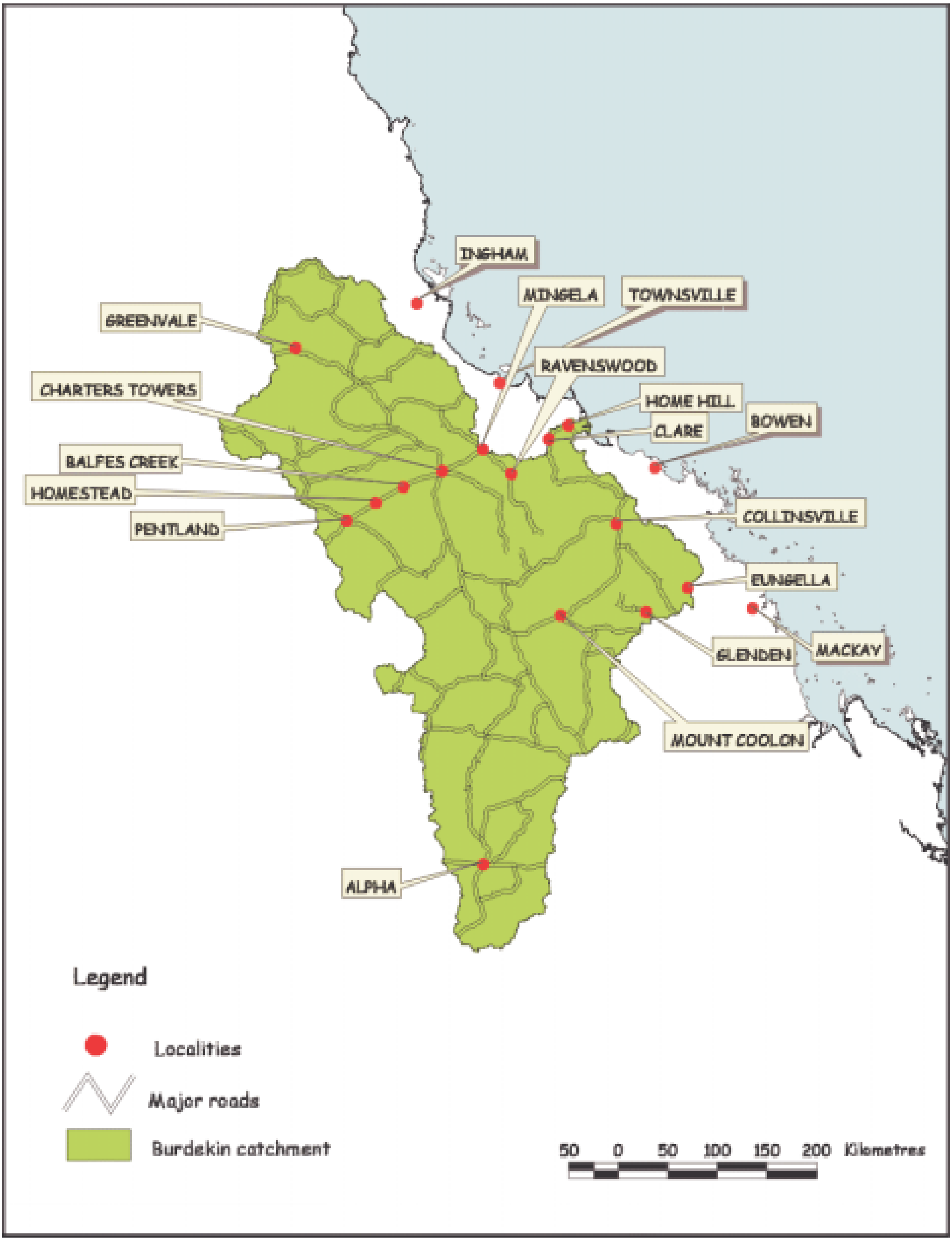


Figure 4: *Location map for the Burdekin River catchment.*

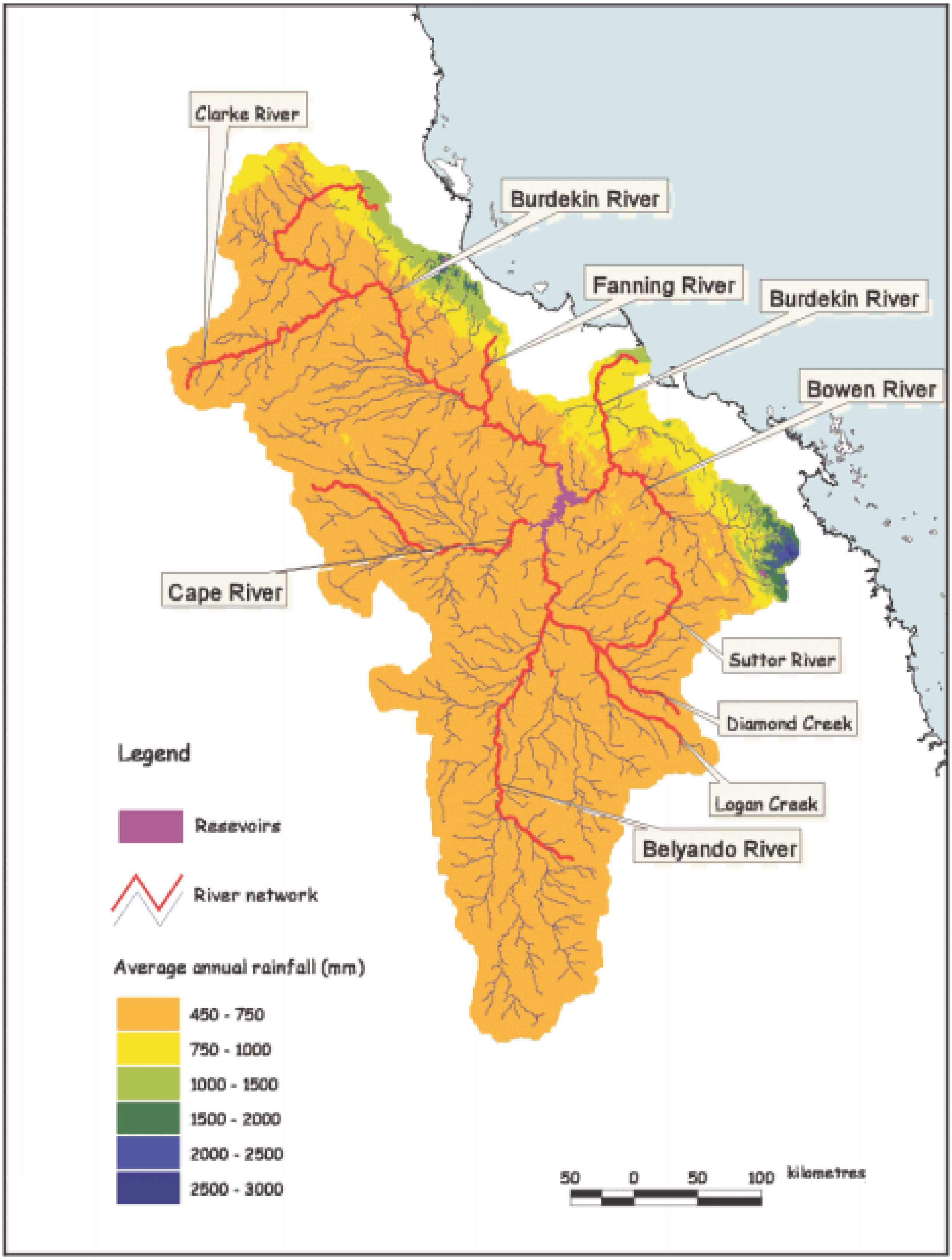


Figure 5: *Map showing mean annual rainfall for the Burdekin River catchment and river names referred to in text.*

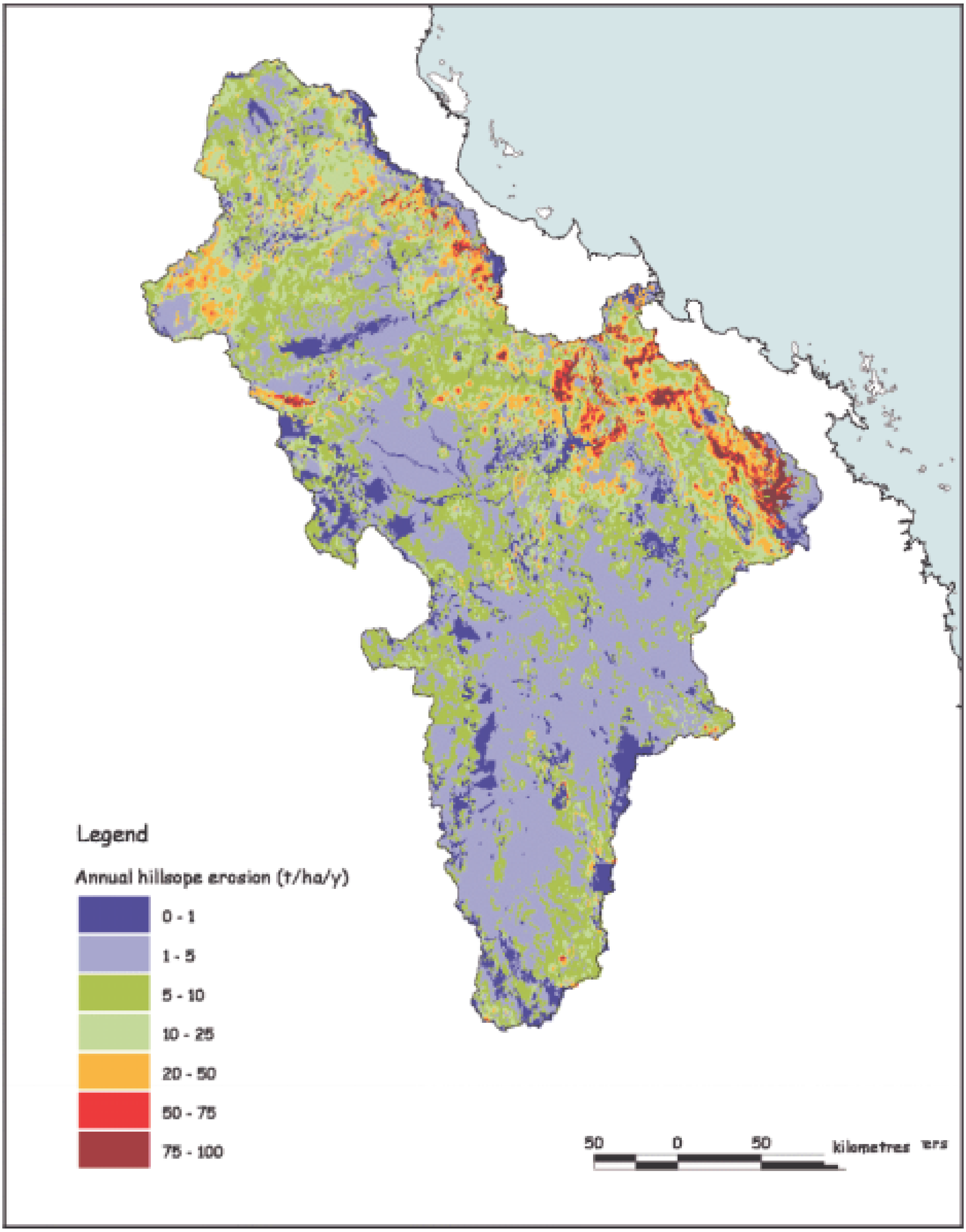


Figure 6: *Predicted hillslope erosion hazard in the Burdekin River catchment for each 9" cell.*

It was found that about 1.2 x 10^8 tonnes of soil is moved annually on hillslopes in the catchment. We have applied the same method of assessing hillslope erosion to the Australian continent (as part of a National Land and Water Resources Audit project) and found that the Burdekin catchment contributes over 19 % of the continental total soil erosion. The average soil erosion in the Burdekin catchment is 9.5 t/ha/y, which is just over twice the national average (4 t/ha/y). This is a result of the tropical savannah climate, which brings high intensity rains in summer, and which can fall on low cover land at the start of the season (this is in strong contrast to southern Australia). All northern regions experience high soil erosion potential.

Soil erosion potential varies by three orders of magnitude in the catchment. If we classify pixels with a soil loss rate below 0.5 t/ha/y as having low erosion potential, larger than 10 t/ha/y as high erosion potential, and in between as medium erosion potential, then about 5% of the catchment area is within the low erosion potential class, 25% in high erosion potential, and 70% is in the medium hillslope erosion class. Overall, 27% of the area is predicted to erode at a rate greater than the catchment average rate of 9.5 t/ha/y. This shows the highly skewed distribution of soil erosion and the considerable value in targeting erosion control to problem areas, rather than uniform soil erosion control or that purely responsive to local perception.

Table 1 divides hillslope erosion into land use classes. There is relatively little difference in the predicted erosion rate between land use categories, although forested lands are lower than agricultural and pastoral areas. The lack of difference in erosion rate is because of the association of land use with other factors that influence erosion. The forested areas of the catchment tend to be the steepest and wettest parts and thus have an inherently high erosion risk. The total soil loss is dominated by native pastures in semiarid woodlands simply because the vast majority of the catchment has that land use.

The results predict that most erosion occurs in grazed areas of medium slope gradient and where ground cover is below 40%. Furthermore, the predicted patterns are sensitive to these factors, which is supported by field assessment of erosion (McIvor *et al.*, 1995). Thus it is important to have accurate information on cover and terrain for reliable assessment of erosion patterns. We found that using the seasonal greenness method produced quite different patterns to just uniform assignment of a cover factor to all grazed woodlands and to SLATS project derived cover information. Our results suggest that further work on remote sensing of grazing pressure on grasslands would be beneficial. The details of terrain shape strongly affect erosion and sediment delivery and these details are not well represented on the 9'' DEM. We used high resolution DEM's to modify the values on the 9" DEM where available but, there is a need for higher resolution DEM data for more accurate assessment of erosion patterns.

Table 1: *Hillslope soil loss from land use categories in the Burdekin River catchment.*

Land use category	Area (km^2)	Proportion of total area (%)	Predicted total soil loss (t/y)	Proportion of total catchment erosion (%)	Average predicted soil loss rate (t/ha/y)
Native pastures	117139	90.00	117,571,237	95.12	10.04
Improved pastures	2625	2.02	2,016,700	1.63	7.68
Sugar cane	154	0.12	424,568	0.34	27.63
Other crops	729	0.56	786,372	0.64	10.79
Forest and other reserves	9501	7.30	2,798,635	2.26	2.95

Figure 7 shows the average monthly distribution of predicted total soil loss within the whole catchment. Not surprisingly we found that 91% of the soil loss happens in summer period (November to April) with 66% occurring during December to February. There is little predicted erosion activity during winter due to the lack of erosive rainfall.

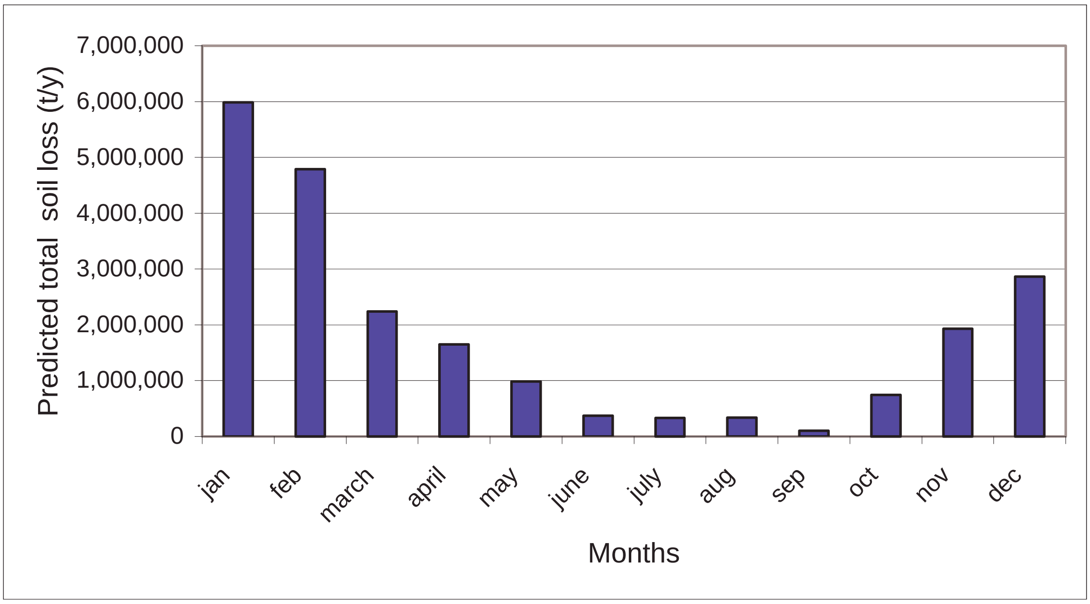


Figure 7: *Monthly distribution of predicted total soil loss within the Burdekin River catchment*

The contribution of each of the RUSLE factors to the overall pattern of erosion is shown in Figure 8. The strong influence of hillslope gradient and rainfall erosivity is shown by these maps, with much of the high erosion hazard occurring on sloping land with high rainfall erosivity. The northern part of the catchment has higher rainfall erosivity because of high annual rainfall but also because of greater penetration of intense summer storms from the coast. The cover factor is usually one of the strongest controls on erosion pattern but in the Burdekin catchment there is relatively little variation because of the relatively uniform land use across the catchment. Cover in particular years will have strong variation across the catchment as a result of strong variations in rainfall for that year across the catchment, but over time these tend to even out to similar mean cover values. Expected differences in cover as a result of differences in inherent soil fertility are not born out by the results and are worthy of further investigation. The precise pattern of erosion hazard within the areas of high slope and rainfall erosivity is influenced by soil erodibility which varies strongly within individual sub-catchments.

Much of the pattern of surface wash erosion across the catchment could result from natural variation in the susceptibility to erosion, particularly as the pattern is dominated by slope and rainfall erosivity which are inherent features of the landscape. Figure 9 compares the natural surface wash erosion potential to the current potential by incorporating natural vegetation cover, determined from reserve areas in the catchment. This shows that the overall pattern of erosion predicted for today is broadly similar to that under natural conditions. The vast majority of the catchment has a current erosion rate <5 times higher than the natural rate. There are, however, areas of greatly accelerated erosion hazard in the Upper Burdekin River and Bowen River sub-catchments. In the Upper Burdekin River, these are areas with low absolutes rates of erosion so the increase poses little problem but in the Bowen River sub-catchment they are areas where clearing has increased erosion in areas of high inherent hazard.

Gully Erosion Hazard

It was found that the most robust predictors for discriminating gully density within the Burdekin catchment were: landuse, geology, soil texture, rainfall, indices of seasonal climate extremes and terrain-based attributes such as slope and hill slope length.

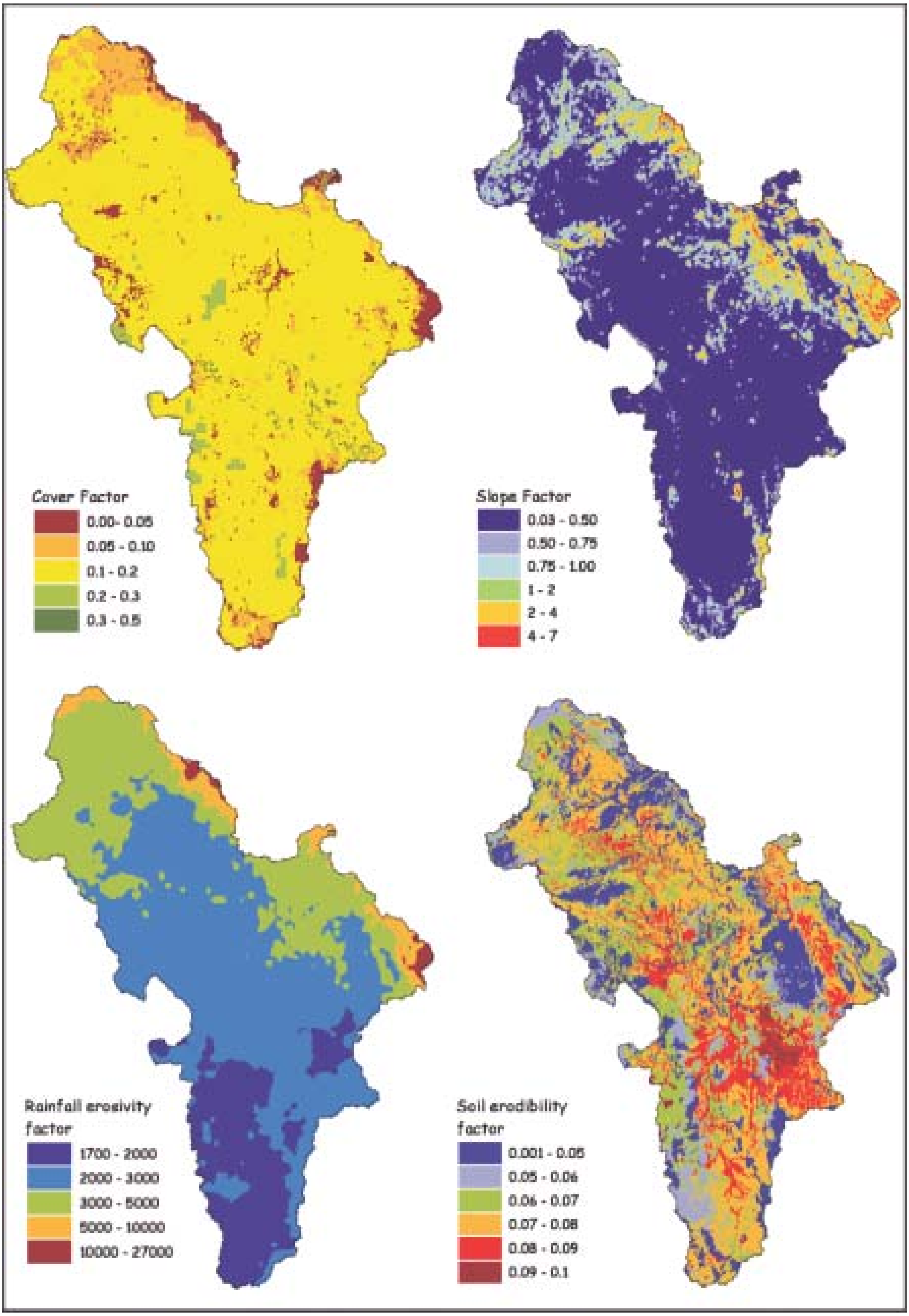


Figure 8: *Maps of RUSLE factors that contribute to Figure 6.*

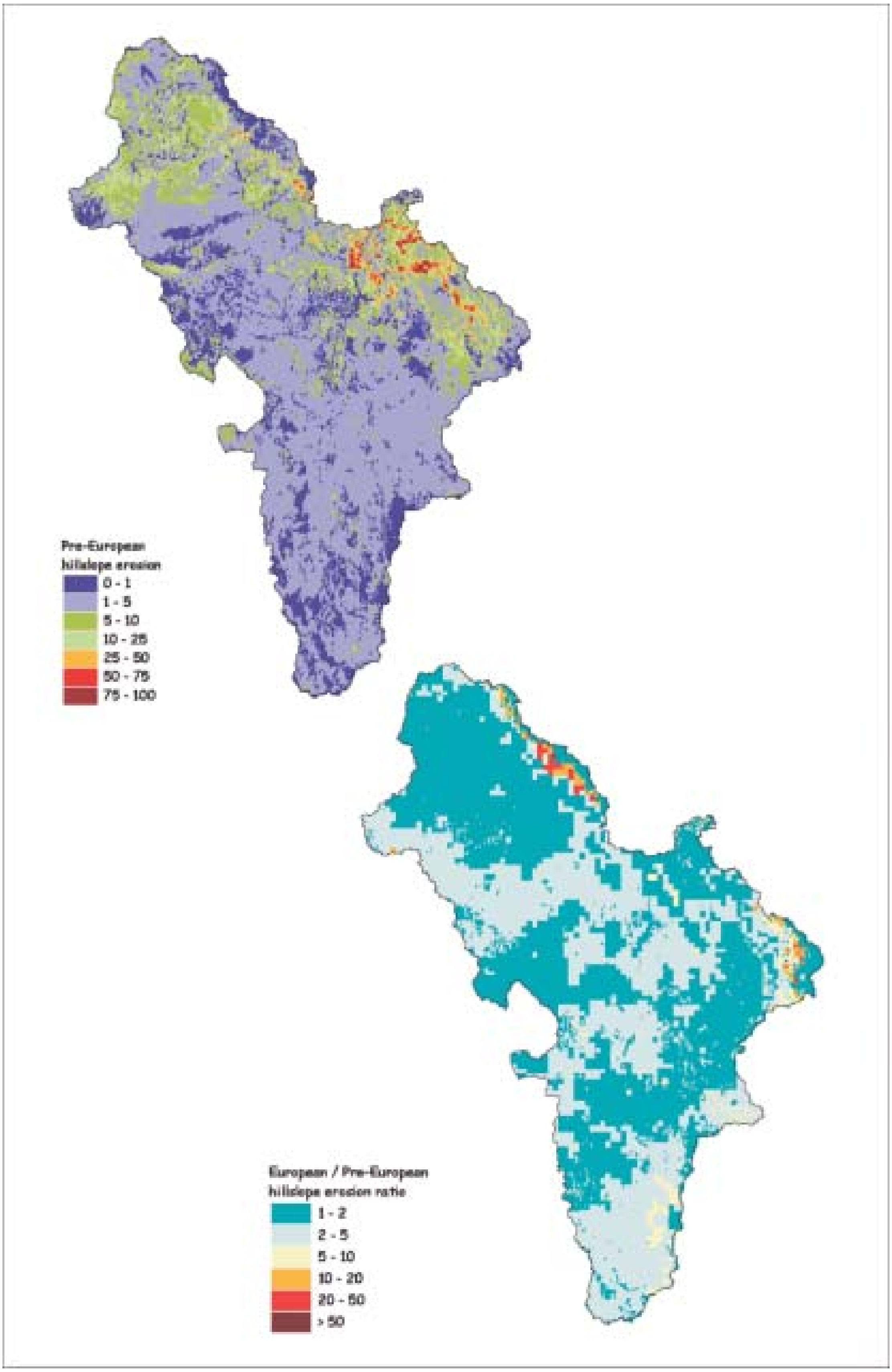


Figure 9: *Pre-European hillslope erosion rate as predicted by the RUSLE, and ratio of current to Pre-European results.*

Among these predictors, elevation, geology, and mean annual rainfall were found to be the most important, producing a correlation coefficient of 0.86 and a relative error of 0.30. The figures were improved to 0.96 and 0.14, respectively, when the four MSS bands and relief were added to the model. Further improvements are mainly due to soil attributes. The best overall regression figures are given in Table 2.

Table 2: *Best achieved statistical figures of gully density model generated by CUBIST software using selected climatic and environmental predicting attributes.*

	Training Set	Testing Set
Average error (km km^{-2})	0.1992	0.3727
Relative Error	0.64	1.15
Correlation coefficient (r)	0.81	0.43

Figure 10 predicts that the majority of gullies form in the central part of the catchment in the areas with moderately steep slopes on granitic lithologies and on some of the metamorphosed sedimentary rocks. The worst areas are between the Suttor River and Bowen River and in the upper catchments of the Clarke and Cape Rivers. Much of the north western and southern parts of the catchment are relatively unaffected by gully erosion. Very little gully erosion is found on the young mafic volcanics (basalts) as a result of their stable permeable soils and generally low relief. Similarly the unconsolidated sedimentary materials have little erosion because of low gradients and permeable soils. The difference in mapped gully density between geological classes is shown in Figure 11. In addition, the gully mapping done from aerial photographs revealed that cleared land had much higher gully densities than uncleared land. The mean gully density on cleared land is around 0.68 km/km^2, but in areas where the savannah woodland has been left uncleared it is around 0.19km/km^2. There was good visibility on the aerial photographs for both land cover cases, so we do not believe this result is due to a measurement bias toward cleared land. The possibility of systematic differences in geology, slope and other factors between cleared and uncleared land were not investigated.

The range of gully densities in the Burdekin river catchment are similar to that found in the more intensively studied areas of SE Australia. Using that broader context we define a gully density lower than 0.1 km/km^2 as areas of low gully erosion severity, 0.1 to 1 km/km^2 as medium severity, and greater than 1 km/km^2 as high severity. We found that 2.5% of the catchment (326,000 km^2) has high gully erosion, about 70 % faces medium gully erosion and the remaining 27.5 % has no or low gully erosion. Thus, even more so than for hillslope erosion, the problems of gully erosion are highly localised and land management that targets these areas would be more successful than uniform management across the catchment.

Reconnaissance level analysis of sequential aerial photographs in an area of granodiorite (part of the granitic complex) suggests that the gullies are still actively eroding headward in contrast to those of southern Australia. We might thus expect annual sediment yields from gullies to be higher than the measured rates in southern Australia, however there are no such data for northern Australia yet. This gap is being filled by work in component R2 of the project. If we assume a typical sediment yield of 50 tonnes per kilometre of gully per year then a gully density of 1 km/km^2 would result in an areal based sediment yield of 0.5 t/ha/y, of the same order or lower than might be expected from the hillslopes, although much of the hillslope material may not be delivered to the stream. In gullied landscapes of humid areas, the yield from gullies far outweighs the hillslope sediment yield because of denser ground cover and denser gully networks. In those areas sediment control is now focussing largely on gully erosion control. Our data for the Burdekin catchment suggest a more balanced approach, targetting both processes, is needed for the northern beef industry.

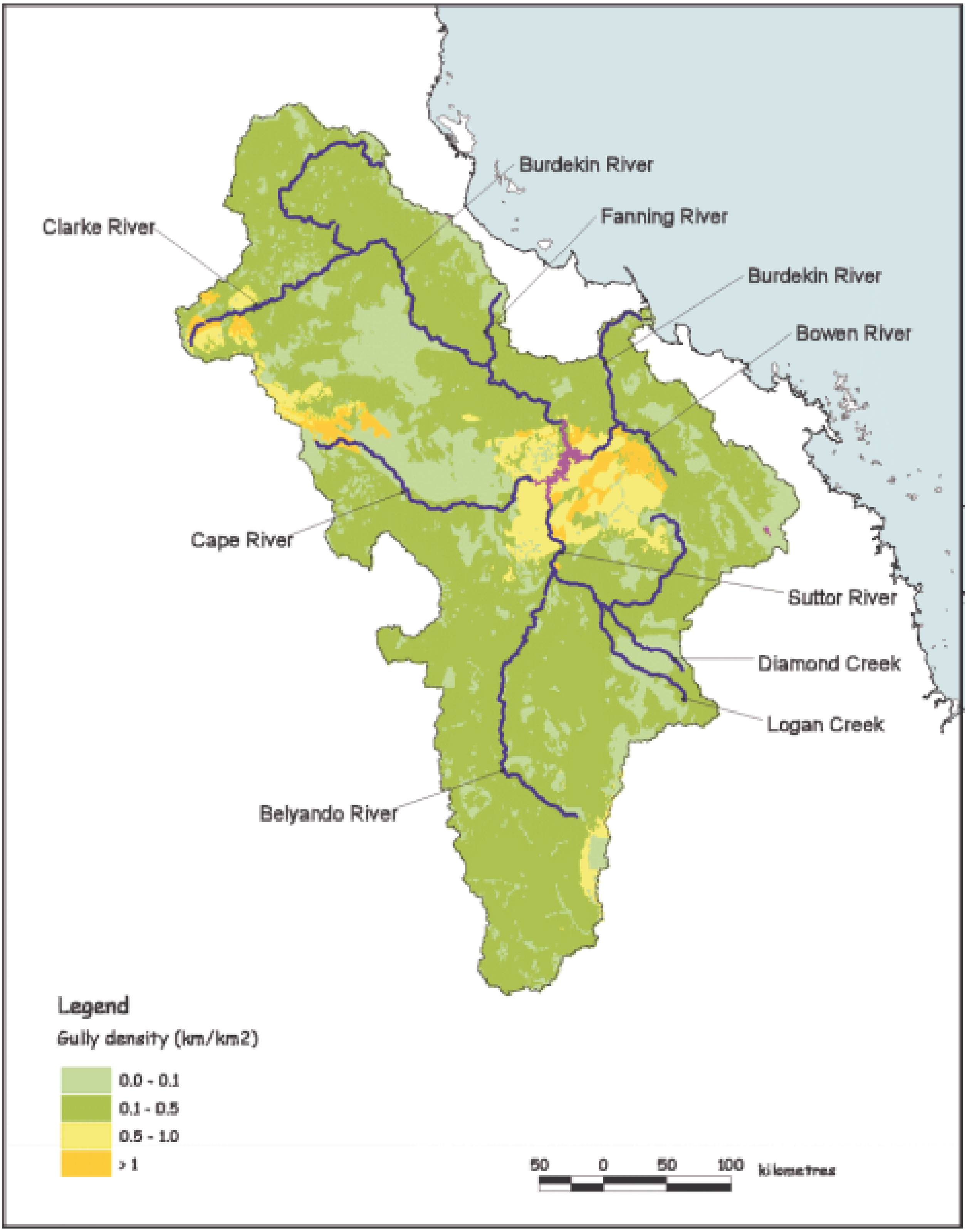


Figure 10: *Predicted density of gully erosion based on 1.25 km pixels.*

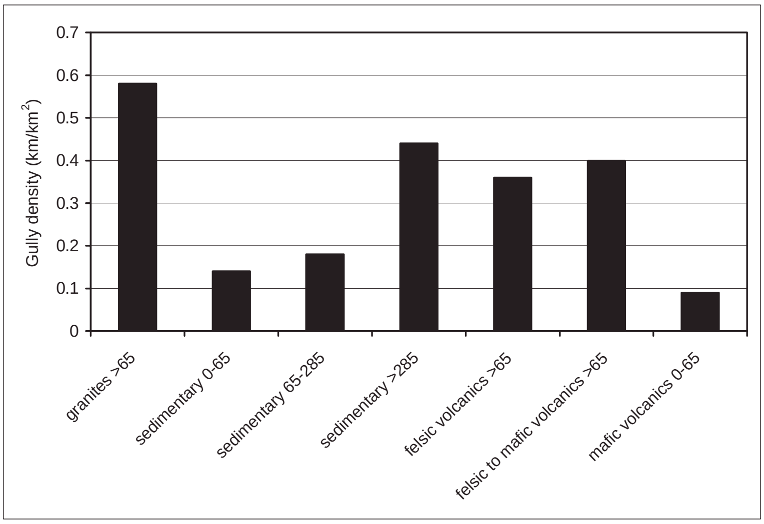


Figure 11: *Mean gully density classified by major geology class (lithology and age in My). Granites >65 include granodiorites.*

A typical gully would have an eroded depth of 2 m and a width of 5 m giving a total sediment yield of 10,000 m^3 per kilometre of channel. In the granite/granodirorite areas this would have resulted in a total sediment yield of approximately 80 t/ha using a sediment density of 1.5 g/cm^3 and a gully density of 0.57 km/km^2. This is the total volume of sediment that is carried by the river network.

Streambank Erosion

Rivers also carry sediment generated from erosion of the river and stream banks themselves, and this needs to be considered before examining river sediment loads. One of the two main factors controlling riverbank erosion in the model is the extent of native riparian vegetation, shown in Figure 12. This is only a crude measure of riparian vegetation because of the 100 m resolution of the vegetation cover data used. This is, however, the best available data at present. The alternative is to not include bank erosion as a sediment source. This was rejected because reconnaissance level observations suggest that it is a non-trivial contribution to the total catchment sediment budget. To remove riparian vegetation from the prediction of bank erosion results in erroneous results because it predicts that the highest rates of erosion are in National Parks and other reserve areas where there are high energy rivers. Studies of historical riverbank erosion show that these reserves have not experienced major bank erosion, unlike many cleared streams (Rutherfurd, 2000). The potential for erosion in these areas is prevented by the relatively undisturbed vegetation. Our mapping of riparian vegetation provides only a first-order overview of controls on bank erosion rate. Higher resolution mapping is required to show the detail within the more heavily used parts of the catchment.

Figure 12 shows coherent patterns in the proportion of each river link that contains intact native riparian vegetation. The Belyando and Cape Rivers and many of the tributaries of the Burdekin River above the Burdekin Falls Dam have a high proportion of native vegetation cover. Areas of low cover include the Burdekin River below Burdekin Falls Dam, the lower Bowen River, the Suttor River and Diamond and Logan Creek *sub catchment*s.

River discharge is the other factor controlling bank erosion rate in the model. When combined with riparian vegetation the results predict that much of the bank erosion occurs in the lower Burdekin River and the lower reaches of the Bowen River where high discharge is combined with a low proportion of native riparian vegetation. This matches casual observation where bank erosion of up to 100 m in historical times has been reported. The Burdekin River above the Burdekin falls Dam is also predicted to be an area of significant bank erosion, but the potential is not realised in some places because of significant rock outcrop in narrow gorge sections of the river.

Sediment Sources to the Stream Network

Each of the sediment sources described deliver sediment to the network of streams and rivers in the Burdekin River basin. The delivery of sediment to streams from surface wash erosion on hillslopes is modified by the hillslope sediment delivery ratio. There are very few data from which to define the hillslope sediment delivery ratio. Edwards (1993) observed that hillslope plot erosion measurements generally record about ten times the soil loss as from mini-catchment studies, suggesting a hillslope sediment delivery ratio of around 0.1. In the absence of better information we calibrated the hillslope sediment delivery ratio to produce sediment yields observed near the mouth of the Burdekin Basin. This process is described below. We found the best results were obtained using a hillslope sediment delivery ratio of 10 %. It was assumed, within the errors of the broad catchment sediment budget, that all sediment derived from gully erosion was delivered to the stream network. Streambank erosion, by definition, delivers sediment to the stream network.

Table 3 shows the predicted mean annual amount of sediment supplied to streams from the three processes. Surface wash erosion is the dominant process because of the often low cover and tropical rainfall in the catchment. Gully and riverbank erosion are also significant sources of sediment. Figure 13 shows the spatial pattern of hillslope sediment sources compared to the sum of gully and stream bank sources for each sub-catchment. Strong patterns emerge in this map. While hillslope sediment sources dominate overall, this is restricted to the near coastal areas where there is the greatest potential for surface wash erosion. Much of the catchment is predicted to have only a weak dominance of surface wash erosion, possibly not significant given the uncertainties in the model, or is dominated by gully and streambank erosion because of the low rates of hillslope erosion. This suggests that all erosion processes need to be managed to reduce sediment loads in the catchment. It should be noted that surface wash erosion is believed to only contribute to suspended sediment loads, while gully and riverbank erosion contribute relatively equally to bedload and suspended load. When this is taken into account surface wash erosion is the most significant contributor to suspended loads in the basin.

Table 3: *Components of the sediment budget for the Burdekin River Basin.*

Sediment budget item	Predicted mean annual rate
Hillslope delivery	12.3 Mt/y
Gully erosion rate	5 Mt/y
Riverbank erosion rate	1.1 Mt/y
Total sediment supply	18.4 Mt/y
Total suspended sediment stored	13 Mt/y
Total bed sediment stored	3 Mt/y
Sediment delivery from rivers to estuaries	2.4 Mt/y
Total losses	18.4 Mt/y

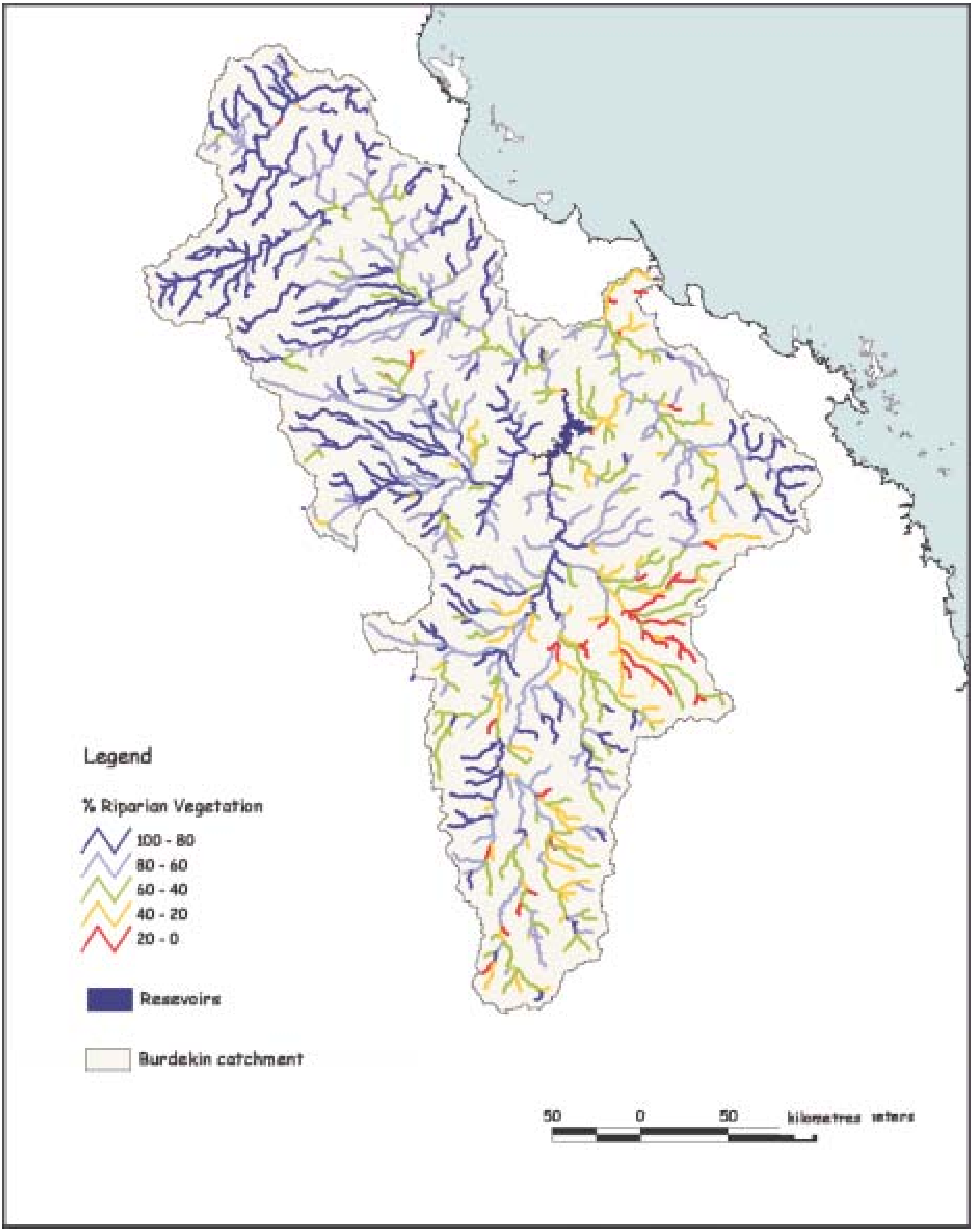


Figure 12: *Mapped amount of intact riparian vegetation.*

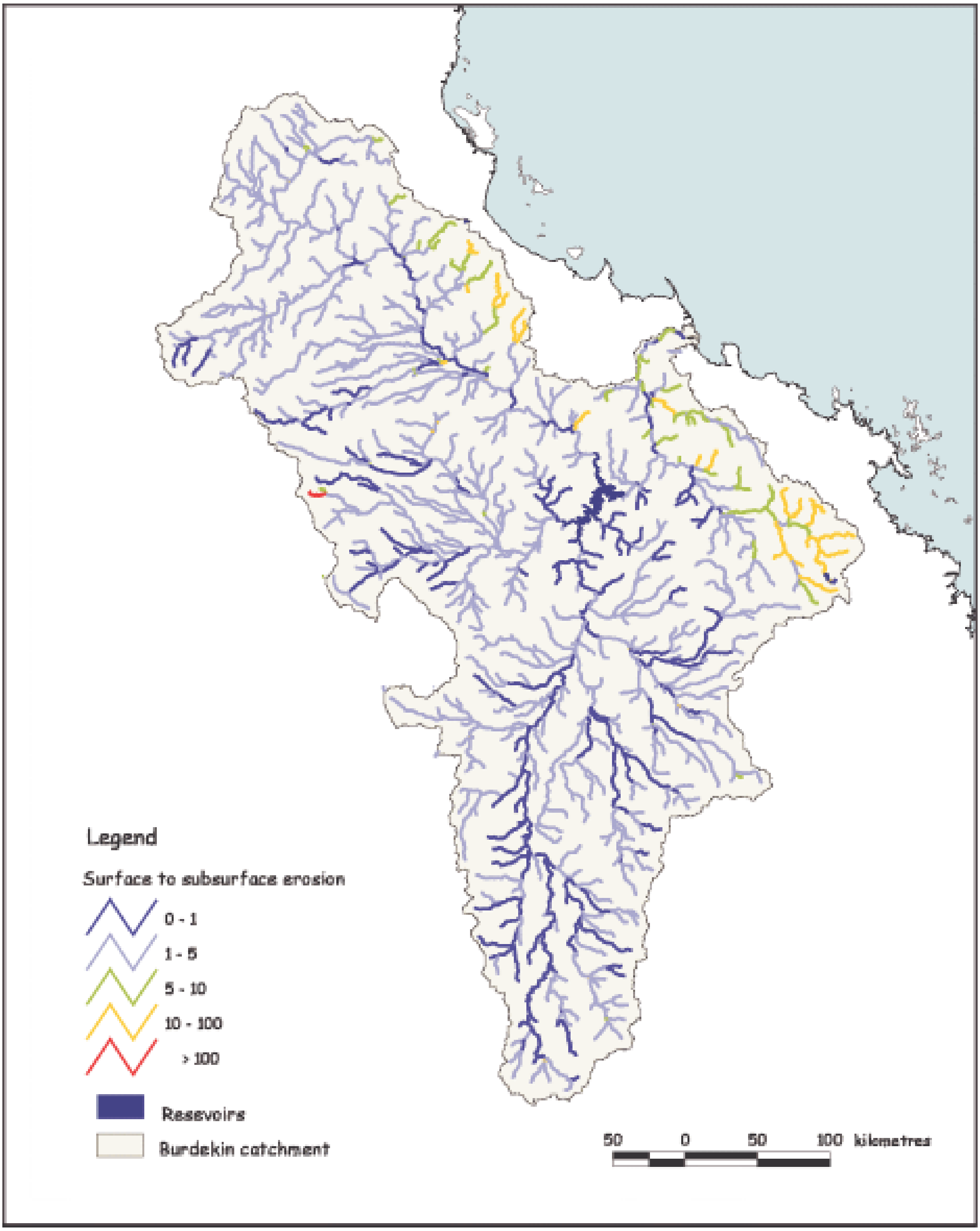


Figure 13: *Predicted ratio of surface (hill) to subsurface (gully and bank) erosion.*

Sediment Delivery Through the River Network

On-site erosion hazard is of concern for continued productivity of the land but can only be translated to downstream impacts if the eroded sediment is transported along the river network. The modelled sediment budget for the basin predicts that, overall, only 13 % of sediment delivered to streams is exported at the coast. The rest is stored in floodplains or on the bed of streams, with some storage in the basin also occurring in reservoirs.

To illustrate the degree of variability of sediment transport within a large basin we first examine some of the input data into the predictions before describing the results. This also serves to illustrate the extent of data synthesis that has gone into the analysis.

Analysis of the discharge data for the Burdekin river basin showed a good relationship between the discharge term of sediment transport capacity ($\Sigma Q^{1.4}$) and catchment area for each of the gauging stations but only if the western and southern areas of low relief and low rainfall were treated separately from the NE part of the catchment. The relationships are shown in Figure 14. The NE part of the catchment produces seven times the $\Sigma Q^{1.4}$ term for a catchment area of 1000 km^2 compared to the SW part of the catchment. Thus, the NE part will have the greater sediment transport capacity for bedload, all other factors being equal. We examined whether the higher discharge per unit area in the NE was a function of higher rainfall. A regression for the whole basin that also includes mean annual rainfall largely explains the difference in behaviour between the two areas. The final method used to predict flow, combined data for the Burdekin river basin with those available for other regions to produce a more comprehensive model, still based on rainfall and catchment area.

River width increases downstream as the greater discharge carves a wider channel. The rate of increase influences the sediment transport capacity of each reach, as wider channels have slightly lower sediment transport capacity. Air photograph analysis showed considerable scatter in width (w in metres) between measured reaches, but a significant relationship with catchment area (A_x in km^2) emerged (Figure 15). A better model was produced by including floodplain width (F_x, m) and river slope (S_x) into a multiple regression ($r^2 = 0.55$):

$$w_x = 0.092 A_x^{\ 0.34} F_x^{\ 0.5} S_x^{\ 0.29} . \qquad (5)$$

There is still considerable uncertainty in this relationship but the sediment budget results are relatively insensitive to river width so this uncertainty has little effect on the predictions. The effect of river width is overwhelmed by that of discharge and river slope as outlined below.

The discharge and river width predictions, together with measured river slope, are combined to determine the sediment transport capacity of each river link. This is the prime control on whether bedload is likely to accumulate as a result of increased supply of sand and gravel.

Predicted patterns of sediment transport capacity within the basin are shown in Figure 16. These show a three order of magnitude variation from one part of the basin to another. There are very high sediment transport capacities in the Burdekin and Bowen Rivers and some of their tributaries. Low sediment transport capacities are predicted in the Suttor and Belyando Rivers, considering their catchment area, as a result of both low slope and low discharge. Slope can vary by an order of magnitude from one reach to another.

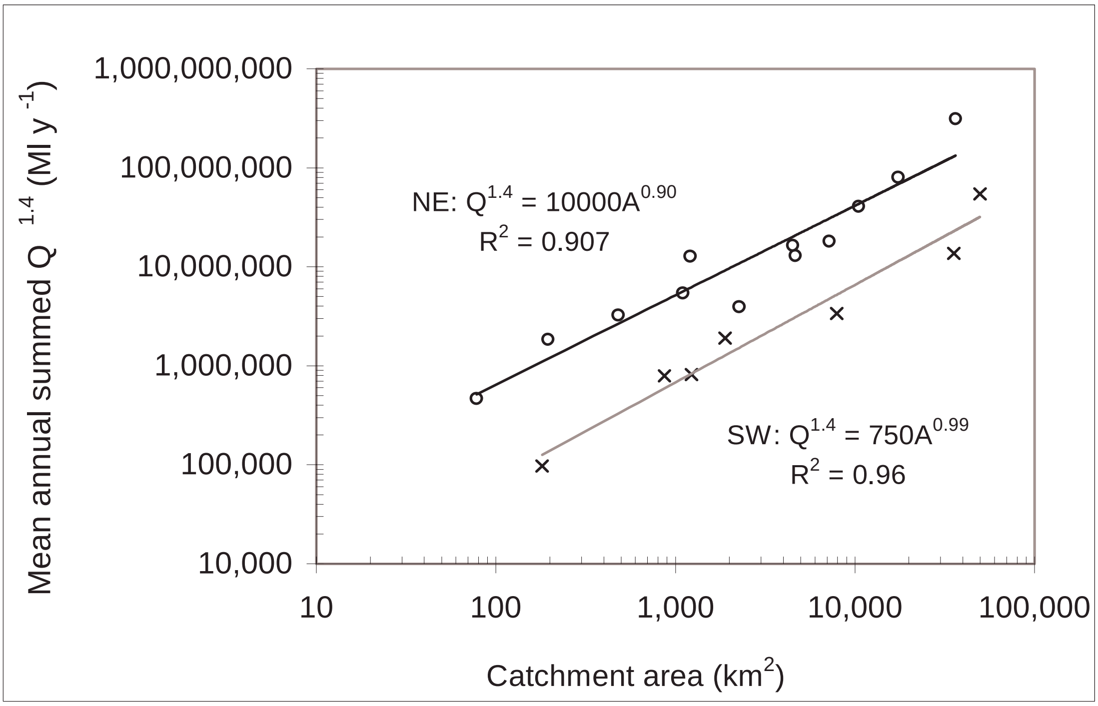


Figure 14: *Regionalisation of the discharge term of streampower ($\Sigma Q^{1.4}$) with catchment area for the NE and SW parts of the Burdekin catchment.*

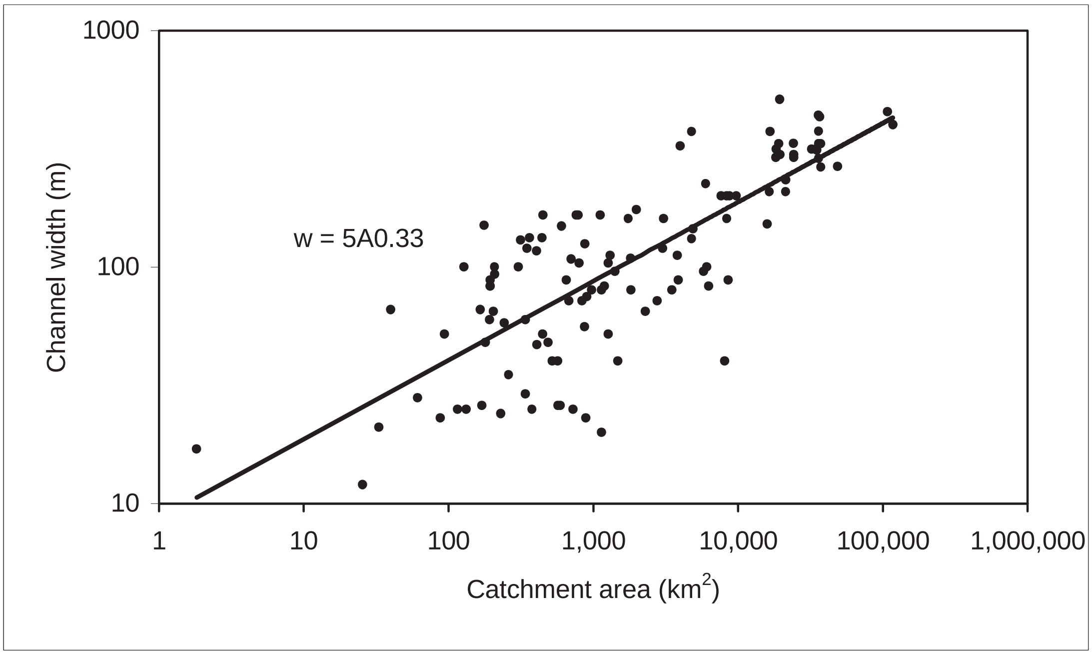


Figure 15: *Relationship of river channel width with catchment area for 120 measurements of channel cross section from aerial photographs of the Burdekin River catchment.*

Bedload Deposition

The bedload sediment budget predicts the accumulation of sand and gravel on the bed of rivers as a result of increased rates of gully and bank erosion. We consider that where historical bed deposition is in excess of 30 cm, there is likely to be some impact on bed habitats. This might be through filling of pools, smothering of cobble beds with finer grained sediment or reduced diversity of bed forms. Our results suggest that only 11 % of the river network length in the basin has bed deposition in excess of 30 cm. This is slightly higher than the national median value of 7 % found by applying the same techniques as part of the National Land and Water Resources Audit (NLWRA, 2001). The incidence is less though than much of south eastern and south western Australia. The most significant area impacted is that to the east of the Burdekin Falls Dam, which includes part of the Bowen River catchment (Figure 17). This is an area of predicted high bedload supply from gully and bank erosion processes and only moderate sediment transport capacity. Most areas of the catchment have either a low supply of bedload (the Suttor and Belyando Rivers) or high sediment transport capacity due to the seasonally high discharge (Burdekin River and its tributaries). Many rivers in the basin have natural stream beds of sand. This is a common feature of semi-arid streams and our results confirm that this is not a feature of river degradation, as might be suggested from studies of coastal streams in southern Australia.

River Suspended Loads

The river budget for suspended load predicts mean annual suspended loads through the river network allowing for deposition on floodplains and in reservoirs. Floodplain extent is expected to grow as one travels downstream and the river becomes larger, and as elevation becomes lower. This pattern can be seen in Figure 18, but there are significant variations which influence the effectiveness of sediment delivery. The Cape, Suttor and Belyando Rivers have more extensive lowland floodplains than the Burdekin River and its tributaries or the Bowen River Thus we can expect that there is more efficient sediment delivery through the Burdekin and Bowen Rivers than the others.

The resultant mean annual sediment loads for each river link are shown in Figure 19. The predicted mean annual export to the sea is 2.4 Mt/y. This value is broadly comparable to the results of suspended sediment monitoring in the lower reaches of the Burdekin River where a mean annual load of 2.8 Mt/y is recorded (Furnas pers. comm.). Earlier measurements by Belperio (1979) reported a mean annual load of 3 Mt/y. Sediment loads in tropical rivers are highly variable from one year to another so variation between monitoring periods and predicted averages are to be expected.

Our predictions of the natural export to the sea, based on removing gully and bank erosion and using the pre-European rate of hillslope erosion, suggest that the current export is approximately 6 times the natural rate. This is probably a maximum increase given the harsh assumptions about no gully or riverbank erosion. Unfortunately it is impossible to assess pre-European rates of these processes.

It is the Burdekin and Bowen Rivers that are predicted to contribute much of the suspended sediment load (Figure 19). The Suttor, Belyando and Clarke Rivers have much lower loads because of both lower sediment supply and extensive lowland floodplains. The other clear feature in Figure 19 is the sharp decrease in load below the Burdekin falls Dam. The Brune Rule (Brune, 1953) used in the model predicts that the dam traps 90 % of sediment supplied to it. This is typical for large dams. At such a rate of deposition the dam is predicted to be losing 0.1 % of capacity per year. The high trapping efficiency is not necessarily in conflict with the constant turbidity of the reservoir waters for turbidity can be maintained by suspension of a low concentration of very fine particles. The bulk of the deposition in the reservoir will be of the coarser clays, silts and sands. Nevertheless the strongly seasonal flow regime may result in an overestimation of deposition in the reservoir, as it is calculated using mean annual inflow. A series of high flows in summer, carrying substantial loads will reduce the trap efficiency. The actual amount of sediment stored in the reservoir can be measured to check the results.

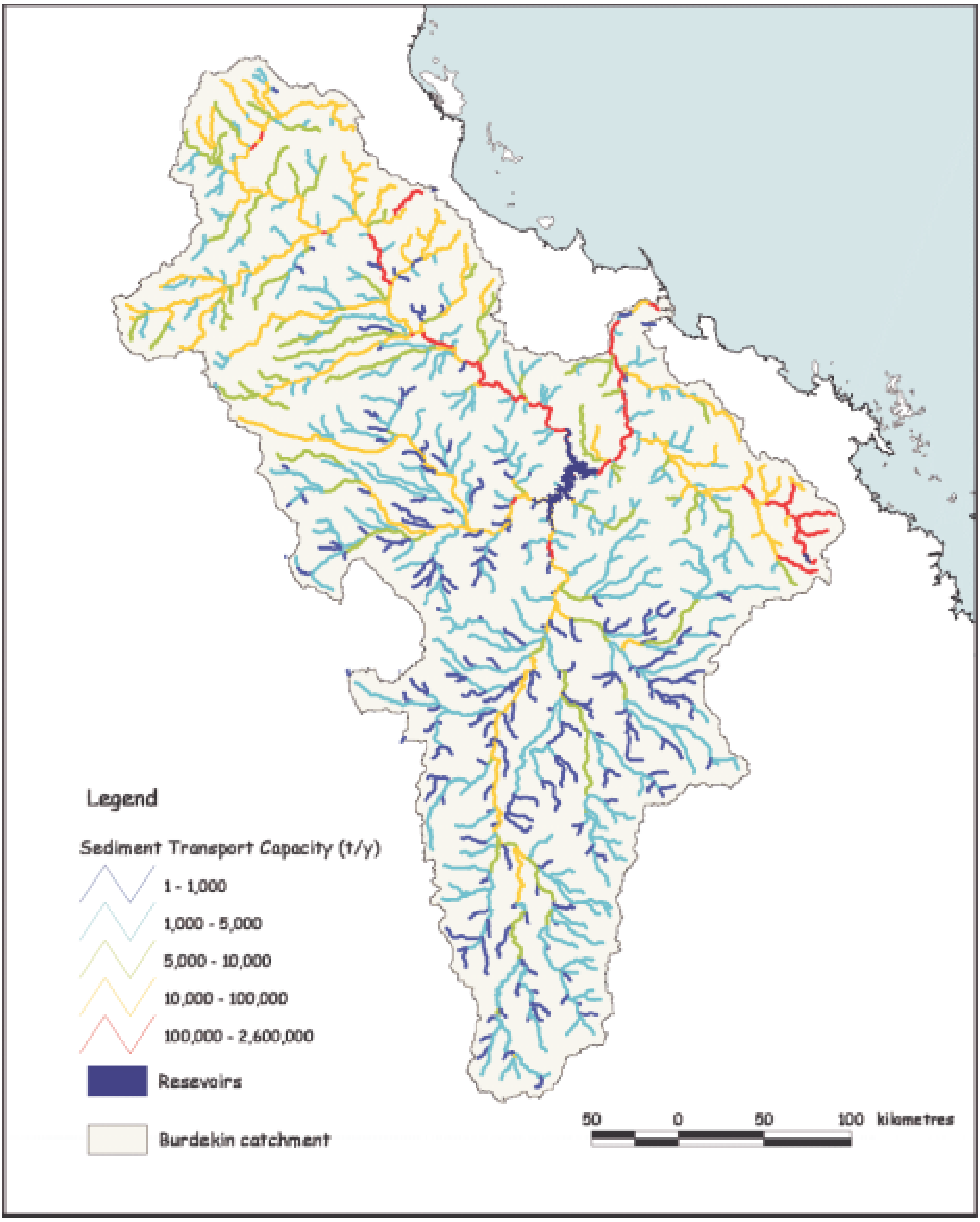


Figure 16: *Predicted sediment transport capacity.*

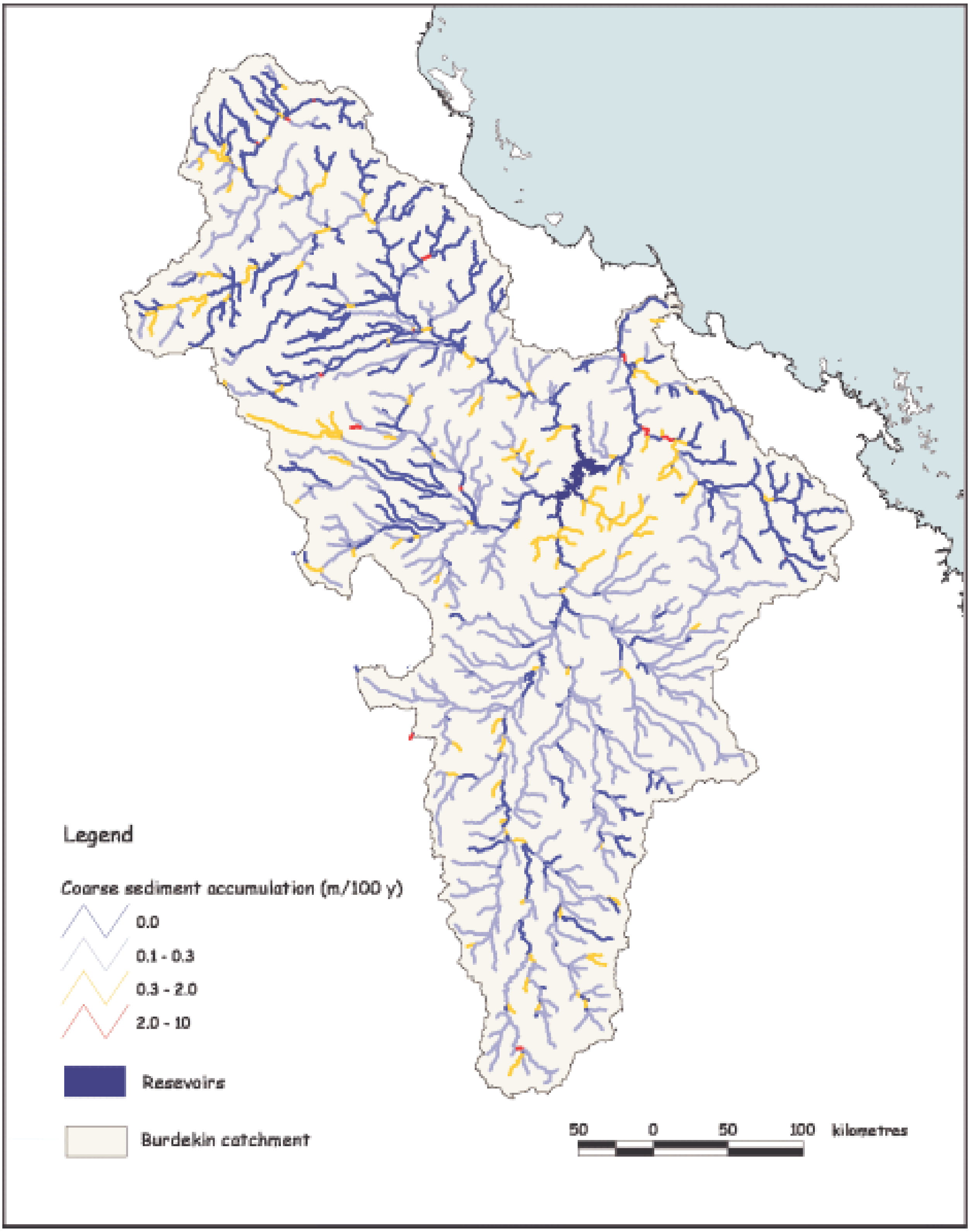


Figure 17: *Predicted bedload deposition.*

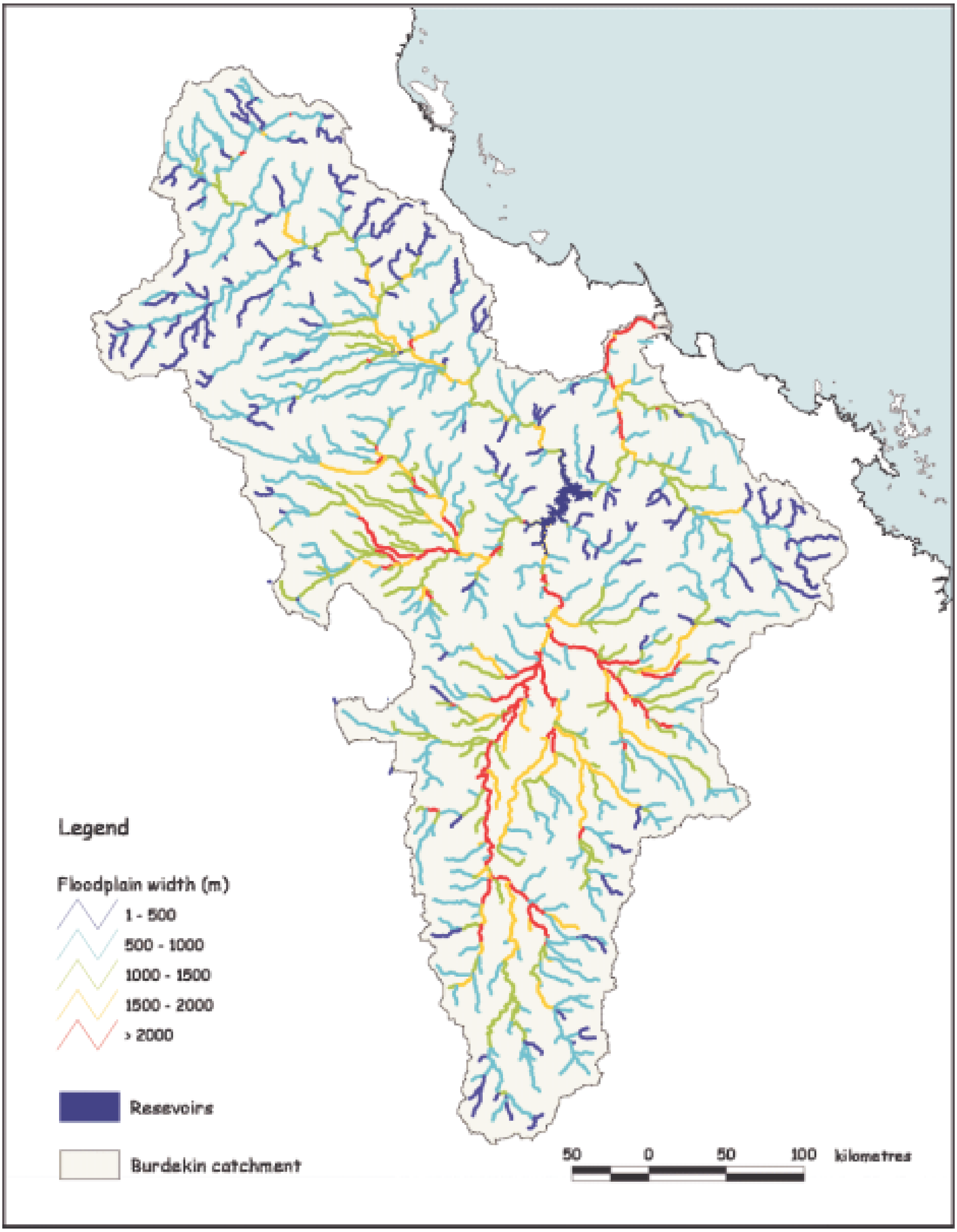


Figure 18: *Predicted floodplain width.*

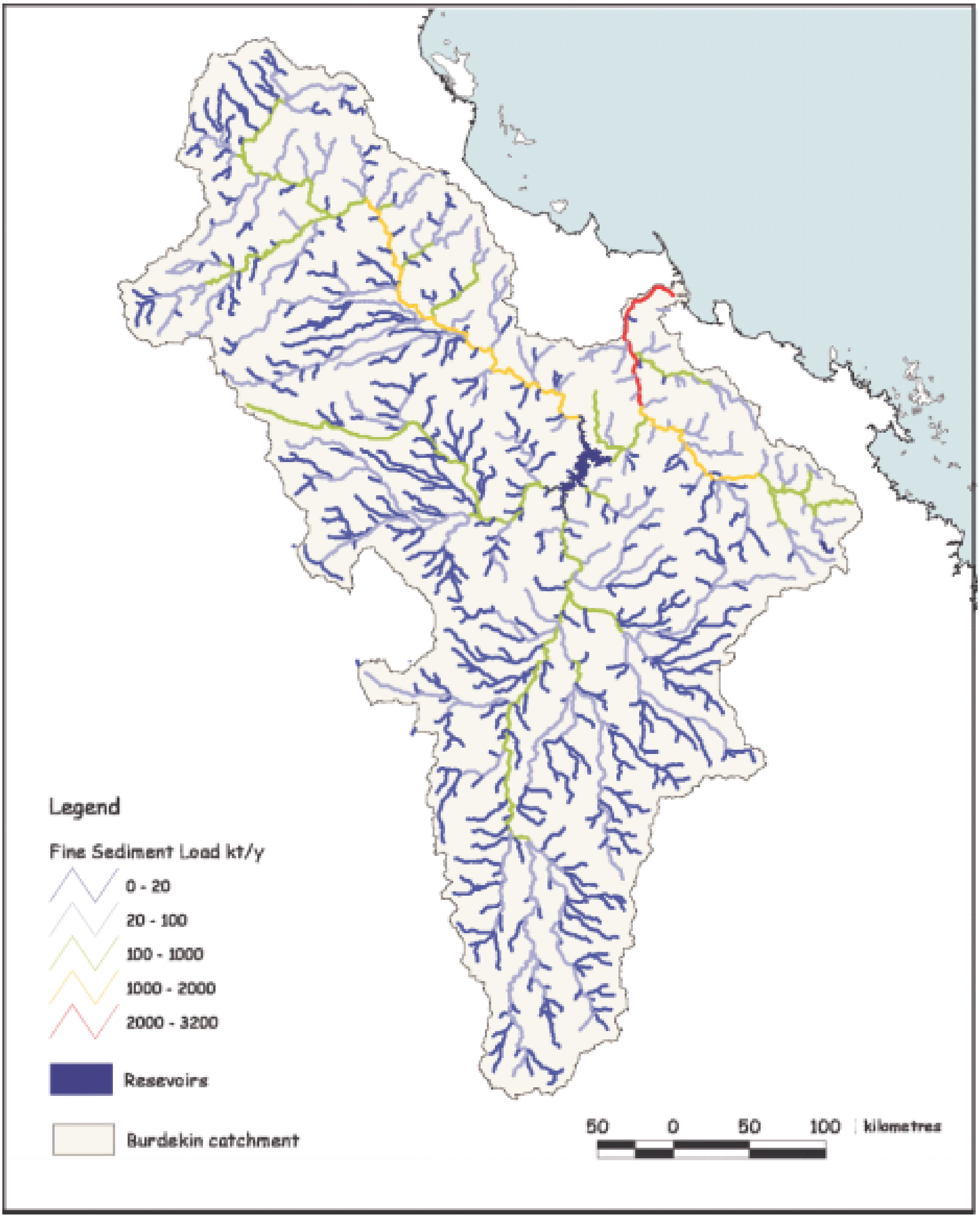


Figure 19: *Predicted suspended sediment load.*

Contribution to Sediment Export at the Coast

Estuaries and coastal waters are of particular concern for suspended sediment as they are the ultimate areas of sediment deposition. Along the tropical coast of Queensland estuaries have strong tidal currents and open mouths. They flush most sediment out to the coastal waters. There, increased rates of deposition can smother significant habitats such as sea grass beds and inshore reef communities. The sediment can also be a supply of nutrient, and change the food web structure. Resuspension of sediment by waves and currents increases the turbidity of water and decreases light penetration, which can inhibit growth of organisms.

Given that only 13 % of sediment delivered to streams within the Burdekin River basin is actually exported from the mouth, it cannot be concluded that increased erosion upstream in a sub-catchment results in a significant increase to export at the coast. For erosion upstream to link to the coast there must be efficient delivery of the sediment through the river network. In many of the bigger catchments there are source areas of sediment hundreds of kilometres from the coast and many opportunities for the sediment to be deposited in floodplains or reservoirs as it travels through the river network, as discussed above.

To further examine sediment export at the coast we have taken the results of our link by link sediment budget and worked back up the river network to trace where the sediment comes from. Each river link carries sediment contributed from its internal sub-catchment and from tributaries to the link. Each river link also deposits a proportion of the mean annual load that it carries. We have worked back up each tributary to find the contribution from each internal sub-catchment to export from the Burdekin River basin. The result is expressed as a mean annual sediment contribution in t/ha/y from each *sub catchment* that reaches the coast.

Sub-catchments which make a substantial contribution to the export at the coast are those with high erosion and limited floodplain extent between the source and sea. Sub-catchments close to the coast are more likely to contribute to the coastal export because of limited possibilities for that sediment to be deposited along the way. This is the overall pattern shown by the results (Figure 20). Inland sub-catchments will contribute significant amounts of sediment to the coast if the erosion rate is high and the river delivers sediment efficiently. Parts of the Burdekin River meet these conditions. The Burdekin Falls Dam, however, plays a significant role in reducing sediment delivery from upstream sub-catchments. Much of the Suttor and Belyando catchments export little sediment to the coast, while the Bowen River sub-catchment is predicted to be a strong contributor.

A result of the very different erosion rates and sediment delivery efficiency is that 95% of sediment exported to the coast is predicted to come from only 13% of the assessment area. This is in part attributable to the trapping efficiency of the Burdekin Falls Dam, which was dealt with in the section on suspended sediment loads (p31). While soil erosion is a widespread issue across the Burdekin River basin, targetted management can be used to address specific problems. If the goal is to reduce sediment loads to the coast then remedial works can be focussed on particular sediment sources and the land uses and erosion processes found there. We predict 85 % of sediment is delivered to the coast from grazing lands in the Bowen River Basin and lower Burdekin. While cane lands only produce 0.8 % of the soil erosion, they are close to the coast and are in sub-catchments which deliver 9 % of the total export at the coast. These results are produced from a reconnaissance survey and further local investigations are needed before investing considerable funds in sediment control. The results do, however, provide guidance on where to start those investigations, and they provide testable hypotheses on the sources of sediment. Sediment delivery to the coast is not the only concern and the same principles can be applied if the target is to reduce sediment delivery to particular reservoirs, lakes or individual river reaches of high value.

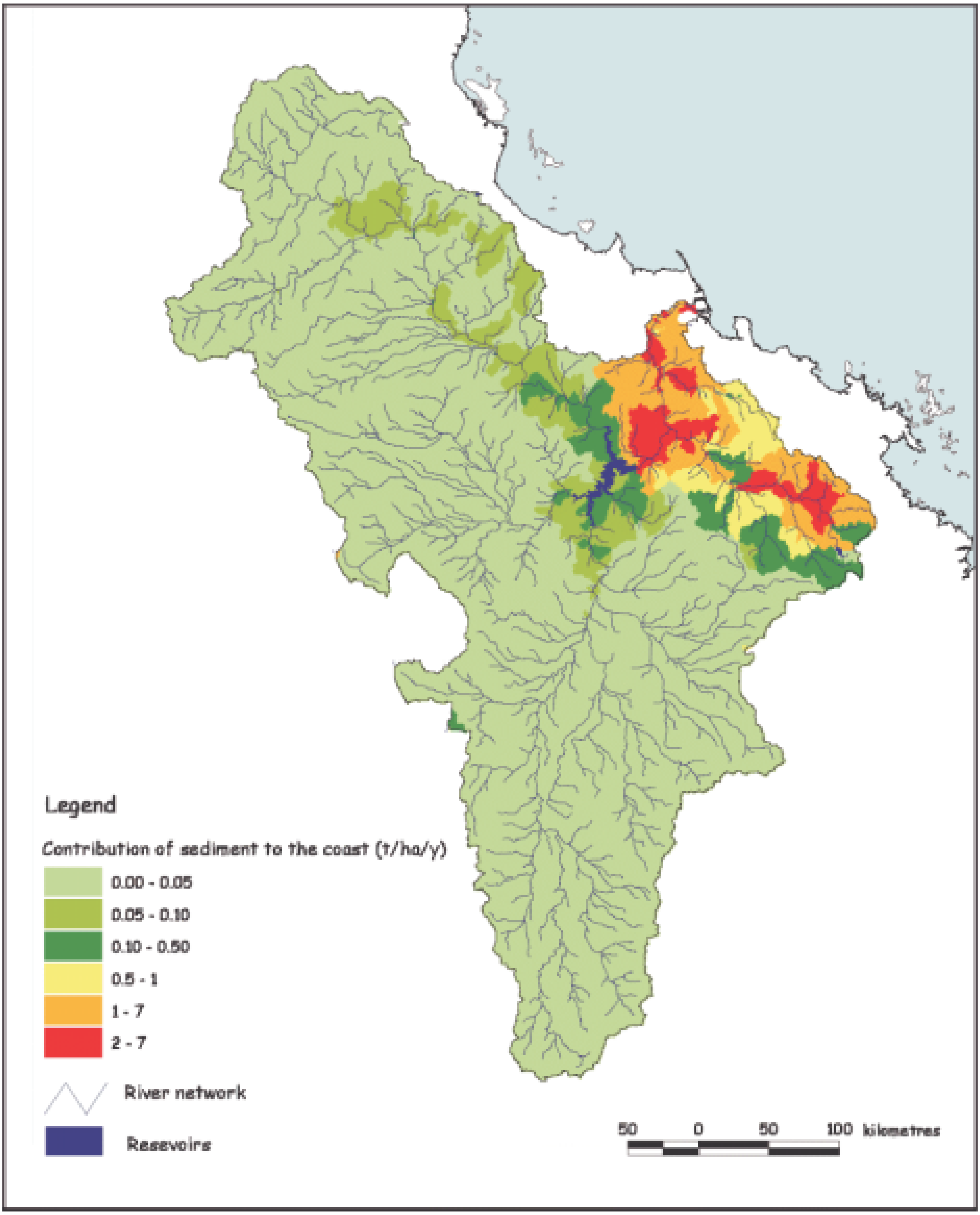


Figure 20: *Predicted contribution of suspended sediment to the coast for sub-catchments within the Burdekin River catchment.*

Summary Plots and Calibration of Suspended Sediment Load

The sections above have concentrated on predictions of the river sediment budgets and their implications with little discussion on tests of their accuracy. Figure 21 shows a plot of how suspended loads grow with catchment area from our results. Each point on the plot is the predicted value for a particular river link. This is a common way of summarizing catchment sediment yield data (Walling, 1983). For comparison, measured sediment yields across Australia are plotted on the same basis in Figure 22, as assembled by Wasson (1994). There are 278 observations in Figure 22, but only two of them with a catchment area > 1 km^2 are from central or north Queensland. More data have become available since 1994 but there is a still a paucity of measurement of sediment load patterns. Both graphs show a line fitted by linear regression on a logarithmic plot. The exponent on area in the equation for the line is less than one in both cases. This means that as catchment area increases there is a less than equal increase in sediment yield. Small catchments are directly nested within larger catchments, so the yield might be expected to grow equally with catchment area. That it does not, is usually taken as a measure of the intensity of deposition along the river length. The coefficient before area in the equation is the sediment yield at a catchment area of 1 km^2.

There is considerable scatter of suspended sediment yields about the line in Figure 21. This is to be expected because of the diverse environments and land use intensity of each sub-catchment. Points along the top of the graph are from the Burdekin and Bowen Rivers. Those along the bottom are from the Belyando and Suttor Rivers. There is a sharp decrease in predicted sediment yield below the Burdekin Falls Dam. This recovers as sediment is supplied from catchments downstream.

There are two poorly defined variables in the suspended sediment model that directly influence the equation of the line in Figure 21. The coefficient in the equation is determined by the average sediment supply to streams in the network. This is determined by the rate of bank, gully and hillslope erosion but also by the value used for hillslope sediment delivery ratio. The hillslope sediment delivery ratio is poorly defined by measurements in the Burdekin basin or anywhere else. Doubling the hillslope sediment delivery ratio significantly increases the supply of sediment to streams. This relative increase is then passed on to all river sediment yields downstream and is reflected in a proportional increase in the coefficient before A. The slope of the line in Figure 21 is determined by the value chosen for the settling velocity of suspended sediment on the floodplain. A faster settling velocity means that more sediment will settle out of the flow for a given residence time on the floodplain. This increases the rate of deposition, decreases the slope of the regression line, and reduces the sediment export from the basin.

We found the best results were produced by using a hillslope sediment delivery ratio of 10% and a sediment settling velocity of 1×10^{-6} m/s, equivalent to a silt sized particle. It is possible to set a high a value for hillslope sediment delivery ratio and compensate for this by simulating very strong deposition on floodplains, thereby still producing the correct basin sediment yield. There are two indicators which can be used to prevent this situation. The first is the ratio of sediment derived from hillslopes to that derived from gully and bank erosion. The fallout radionuclide concentrations of sediment can be used to separate hillslope sediment sources from bank and gully erosion (Wallbrink *et al.*, 1998). They indicate that gully and bank erosion are at least as significant as hillslope erosion in gullied catchments. Preliminary measurements in the Burdekin River basin confirm this observation (Olley, pers. comm.). Increasing hillslope sediment delivery ratio makes hillslope erosion dominate in all landscapes.

The second indicator of reasonable parameterisation is the rate of floodplain deposition. Floodplains accumulate slowly, at rates of the order of 1 m per 1000 y, or 1 mm/y on average. Our choice of floodplain settling velocity produces a rate at or below 1 mm/y over 72% of the basin. Only in the Bowen River catchment did rates get higher. This may be an indicator of overestimation of erosion rates in this area, as discussed earlier. A further overall indicator of reasonable patterns in the river sediment budgets is the ratio of bedload to suspended load. Gully and bank erosion contribute evenly to each budget but by the catchment mouth, bedload makes up only 0.1% of the total load, meeting common observations of suspended load dominance on large rivers (Richards, 1982).

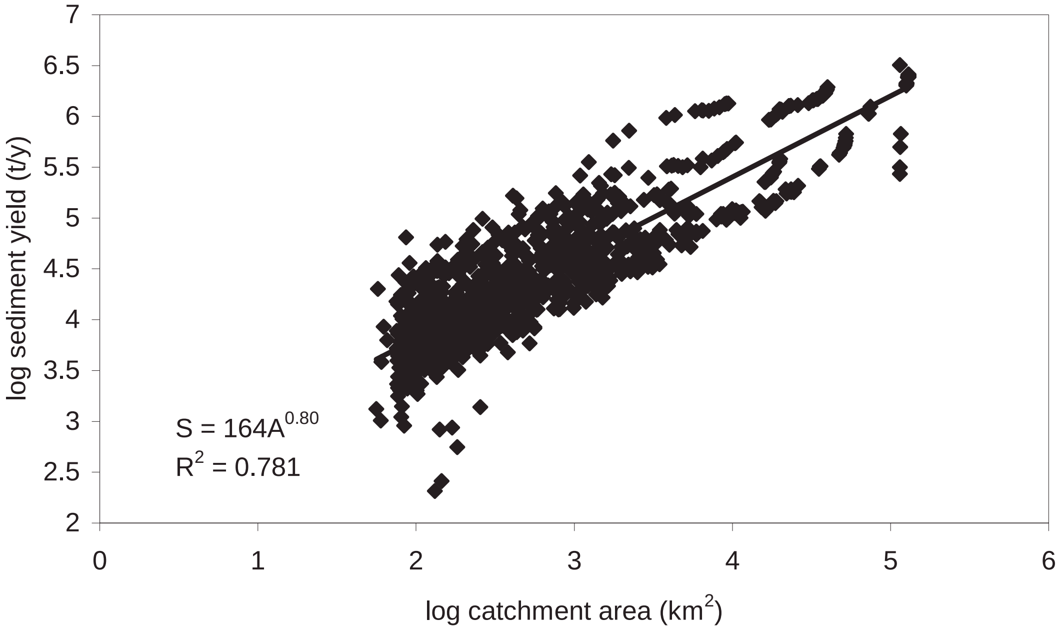


Figure 21: *Summary of predicted suspended sediment yield across the Burdekin catchment. Each point is a separate river link.*

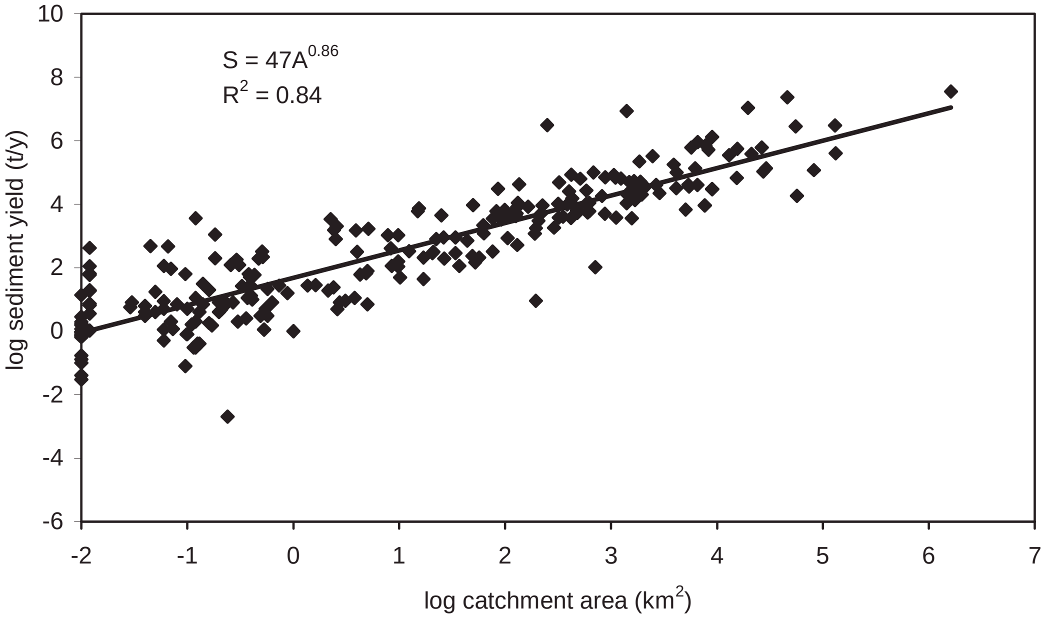


Figure 22: *Sediment yield data for Australian catchments compiled by Wasson (1994). Only data for areas >0.01 km^2 are shown.*

Improvements Required

This is the first study to attempt a comprehensive prediction of sediment sources and patterns of sediment transport within a large regional catchment. Every effort has been made to make the best use of available information and the methods incorporate the current knowledge of large-scale controls on sediment transport processes. As an initial study though there is much scope for improvement, and further investigation is warranted if major expenditure on reducing sediment loads is envisaged. Areas of weakness in understanding at the moment include:

- data on the rates of riverbank erosion;
- higher resolution mapping of riparian condition;
- more comprehensive mapping and prediction of gully erosion;
- the history of sediment supply, particularly from gully erosion;
- independent data on hillslope sediment delivery ratio;
- data on particle size composition of suspended sediment; and
- assessment of the variability of bankfull discharge from one river link to another, which exerts a strong control on deposition potential.

Conclusions

Hillslope erosion hazard is clearly very variable across the catchment, with potential erosion hotspots predominantly located in the NE of the catchment (Douglas, Star, Keelbottom, Fanning sub-catchments) and the Bowen sub-catchment. Equally, gully erosion varies significantly across the catchment being worst in the central parts of the catchment surrounding the Burdekin Falls Dam on granitic (mainly granodiorite) lithologies. The patterns of hillslope and gully erosion differ suggesting that each process is fairly independent and that in each location an assessment needs to be made of the dominant source of sediment. The Burdekin catchment has areas where each process dominates the other. In terms of national significance, the catchment has higher than average predicted rates of hillslope erosion, because of the tropical rainfall and seasonally poor cover.

The development of improved grazing management guidelines will need to be specially adapted to the particular soil-pasture communities prevalent in those sub-catchments or landscapes identified as hotspots. To achieve maximum impact on reduction of sediment loss, they also need to be differentiated to specifically address hillslope or gully erosion, whichever is the more important form of erosion in a particular area. The outputs from this research component should therefore assist the grazing industry, extension providers and natural resource management agencies to appropriately target the critical areas, so that a comparatively large benefit in reducing sediment loads delivered downstream can be achieved with less effort.

Despite the moderate gully erosion and bank erosion few of the streams appear to be impacted by increased bedload. This is because of the high energy of many of the effected streams. Many areas in Australia that have had dramatic changes to the morphology of river beds are where there has been catastrophic widening of the streams themselves or intense gully erosion and the Burdekin River catchment has not experienced this. The Bowen River and area surrounding the Burdekin Falls Dam, however, could be impacted by sediment deposition.

Suspended sediment loads in rivers are on average predicted to have increased by 15 times. The assumptions used in that analysis were fairly harsh, as that was all that was possible given the data. Even so, there are clearly substantial increases to suspended sediment loads and the possibility of predicted in-stream impacts as a result of those changes cannot be dismissed.

Sediment export to the coast has increased by as much as 6 times. It si predicted that 95% of this sediment comes from 13% of the land. Potential impacts on sea grass beds, in-shore reefs and other marine organisms cannot be dismissed. The highly specific source of the sediment provides a clear focal point for further assessment and targeting the control of sediment delivery to streams.

Finally, another important conclusion from the work to date is that we can derive some relatively simple, yet robust regionalisation rules for the assessment of sediment delivery hazard based on basic attributes such as rainfall, topography and catchment size. This will greatly facilitate the extrapolation of results obtained in the Burdekin to other catchments in Northern Australia, as these attributes are readily available. The accurate measurement of ground cover and its changes over time is critical to future assessment of soil erosion problems in the semi-arid tropics.

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