MEAT & LIVESTOCK AUSTRALIA

On farm

Reducing sediment export from the Burdekin Catchment

Volume I Main Research Report

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Abstract

There is concern that high grazing pressures and inappropriate grazing land management have resulted in increased sediment and nutrient export from grazed catchments. In order to address some of these issues, Meat and Livestock Australia initiated a major project in 1999 in the Burdekin catchment to improve the understanding of grazing impacts on catchment response as the basis for refining guidelines and recommendations for improved grazing management to minimise soil degradation. The project has seen the successful development and implementation of innovative methodologies and tools suited to studying the interaction between cattle grazing and landscape response, as a result of which a risk assessment framework to manage sediment export at the property scale was developed and from which two sets of grazing management guidelines were derived, one targeting the management of sediment export from degraded headwater areas, the second providing a set of recommendations to manage degraded river frontages. These and other outcomes achieved by this project have assisted the beef industry to maintain a more positive public image and to be seen as responding to community concerns in relation to impacts of grazing on the Great Barrier Reef World Heritage Area.

Executive Summary

The loss of sediment and nutrients from grazing lands can have impacts downstream on the riverine and marine environments that receive this material. In low input grazing systems such as those typical of the northern beef industry, the bulk of nutrients, including phosphorus and nitrogen, are transported with suspended sediment. There is growing concern that high grazing pressures and poor grazing land management have resulted in increased flows of sediments and nutrients through and out of grazed catchments. Apart from the detrimental and often permanent effects of nutrient and water loss on pasture productivity, there is concern that the off-site effects may impact negatively on water quality in rivers, health of in-stream ecosystems, productivity of estuarine breeding grounds of commercial fisheries and in the case of north-east Queensland Australia, the ecology of near-shore reefs and seagrass beds.

In order to address some of these issues, Meat and Livestock Australia (MLA) initiated a major project in 1999 in the Burdekin catchment to provide a better process understanding of grazing impacts on catchment response as the basis for refining guidelines and recommendations for improved grazing management. To meet this goal, the project was structured into the following four components:

A. A reconnaissance scale survey of the Burdekin catchment 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 modelling framework for reviewing and integrating information currently available in the catchment;
B. Development of a detailed sediment budget for a sub-catchment identified as having significant actual erosion hazards in order to assess sediment and nutrient transport and storage mechanisms in relation to grazing pressure at sub-catchment scale;
C. Studies to improve our understanding of animal dynamics in relation to spatial variation of grass species and fodder biomass over larger areas, the interactions with surface condition and the resultant changes in sediment export, for varying landscapes;
D. Quantification of the principal determinants of sediment and nutrient generation, redistribution and export from hillslopes with varying levels of grazing-induced impacts on soil surface condition.

Results from component A indicate that hillslope and gully erosion is very variable across the catchment, with major hotspots identified in the Bowen sub-catchment and the granodiorite landscapes to the east and south of Charters Towers. However, only about 16% of the total eroded sediment is delivered to the mouth of the Burdekin. Sediment export to the coast is estimated to have increased by as much as 5 times the natural rate. It is predicted that 85% of this sediment comes from just 10% of the land. The highly specific source of the sediment provides clear guidance for further assessment and targeting the control of sediment export. Finally, this project component has developed a set of GIS analysis tools that can be applied relatively routinely to other catchments in Australia. These tools attempt to combine the best available regional data with an understanding of the processes of erosion and sediment transport at the regional scale. They produce a unique set of mapping capabilities not produced by other erosion mapping or water quality assessment tools.

In component B, the monitoring of hillslope and gully erosion and modelling of sediment export at sub-catchment scale in one of the hotspot landscapes (granodiorite areas around Charters Towers) allowed us to determine a more detailed sediment budget, distinguishing between hillslope, gully and streambank erosion. This work has shown that although most of the gullies have existed in granodiorite landscapes for a long period of time, gully erosion is still an important component of the sediment budget, accounting for the vast majority of the bedload deposited in the streams, and around half of the suspended sediment delivery from the sub-catchment. It can be shown that improving ground cover will produce a substantial decrease in the export of fine sediment from the sub-catchment. This reduction will be even more pronounced in sub-catchments where hillslope erosion is a more dominant process.

Results from component C emphasise the importance of managing grazing pressure at the paddock level. The study paddocks varied with respect to the composition of vegetation, productivity (forage yield), and with regard to the degree and extent of erosion. There are several lessons from our data. Under virtually all conditions, areas near water will be heavily used and there will be minimal cover. Watering points should therefore be located on flat areas with a low risk of erosion. Greater risk is associated with low cover combined with a large area that contributes runoff (e.g., lower hillslope positions), and with highly dispersible soil types. Smaller-scale measurements confirmed the continuous use of grazed patches, once they are established. If grazing pressure is high, native perennials are unlikely to persist in these preferentially grazed areas. In granodiorite landscapes, Indian Couch grass produced far less biomass than the “3P” native perennials. Perennial grasses were associated with sites that exhibited lower rates of erosion. Low utilization rates and early wet season spelling will contribute to higher production and maintenance of native perennial grasses. Burning resulted in short-term shifts in cattle distribution, and burning can be used to effectively remove patches established by repeated grazing.

The main findings from component D indicate that soil surface condition, as expressed by amount and quality of ground cover, and soil structural features at the surface (crusts) and near the surface (compaction), is clearly related to grazing impact. When soil surface condition is poor, i.e. low levels of cover, presence of crusts and generally compact A-horizons, runoff can be expected to be high because of low infiltration. Conversely, with enduring high levels of soil cover (>75%), soil macro-fauna will reverse some of the adverse soil conditions, leading to a recovery of soil hydrological function. Exclosure sites in the Burdekin have indicated that such recovery can occur within 10-15 years. A simple soil surface condition assessment framework for crusting/hard setting rangeland soils suitable for use by graziers and that encompasses a wide range of surface conditions was developed as a tool to assist in the assessment of soil surface condition.

Five guiding principles to manage sediment export from grazed landscapes were derived from the findings of the four project components:

1. Target catchment rehabilitation efforts at the hotspot areas. The first principle is that efforts directed at rehabilitating landscapes to minimise sediment and nutrient export from grazing lands of the Burdekin River catchment should be aimed at those areas identified as a significant source and where intervention is likely to have a large impact on achieving reduced end-of-valley sediment export targets.
2. Design effective grazing management strategies based on an understanding of dominant erosional processes. A thorough understanding of which erosional processes are the dominant source (i.e hillslope delivery vs. gully erosion vs. channel erosion) is a prerequisite for effective design of the most appropriate grazing management responses. In some instances such measures may include engineering solutions to the remediation of the more extensive gully networks located on river frontage.
3. Match the scale of grazing management to the scale of dominant erosional processes for management to be effective. Two steps are required. First, it is necessary to clarify which erosion process dominates where, in a particular situation. Then it is necessary to match the erosion processes and their spatial distribution against the spatial distribution of cattle. Where high cattle pressure coincides with high erosion risk this constitutes the area most in need of intervention.
4. Develop and prioritise the guidelines for managing sediment export within a property management planning context. In order to assist producers in their decision making in relation to where to prioritise management intervention to reduce sediment export, it is necessary to place the principles enunciated above into a risk management framework that can underpin property scale trade-off and planning decisions.
5. Focus grazing management needs on soil health rather than simply on ground cover. This principle formulates the need for grazing management to shift from purely managing pasture cover and species composition to managing soil health as the main determinant of runoff and sediment generation.

A risk assessment framework to manage sediment export at the property scale was developed for granodiorite landscapes. It is based on an assessment of landscape condition for three different stream type categories. Two sets of grazing management guidelines have been developed, one targeting the management of sediment export from degraded headwater and first order creek areas of granodiorite landscapes, the second providing a set of recommendations to manage degraded river frontages. A suite of pasture biomass and cover thresholds is proposed to assist the differentiation between degraded and non-degraded landscape conditions. The risk framework and the recommendations derived from it will now be tested through exposure to graziers and further refined as part of the current project.

Several significant outcomes were achieved by the project. It has seen the successful development and implementation of innovative methodologies suited to studying the interaction between cattle grazing and landscape response. Applying these new techniques allowed us to obtain baseline data hitherto lacking and to significantly advance our understanding of landscape processes. The tools developed in component A have had a major impact on the prioritisation of investment of NAPSWQ funds in the Burdekin catchment and it is likely that project outputs will continue to inform catchment management in the Burdekin. Partly as a result of the project outcomes, the beef industry has maintained a more positive image in the media and is seen to respond to community concerns in relation to impacts on the GBRWHA.

Main Research Report

1. Background to project and the industry context

Pronounced variability of seasons with extended droughts in the past two decades, combined with changed cattle production systems have placed increased pressure on native pastures across Northern Australia (NA). The resultant increase in grazing pressure has coincided with a growing awareness that activities in one part of a catchment not only affect land condition and processes where they occur, but that the changed processes on land can also lead to changes in waterways and downstream waterbodies. Apart from the detrimental and often permanent effects of nutrient and water loss on pasture productivity, there is particular concern that the off-site effects may impact negatively on water quality in rivers, health of in-stream ecosystems, productivity of estuarine breeding grounds of commercial fisheries and the ecology of off-shore reefs.

Large areas of the catchments discharging into the Great Barrier Reef Lagoon (GBRL) along Australia's north-east Queensland coast are used for beef production. There is evidence that excessive grazing pressure in the past decades has led to widespread land degradation in some of these catchments (Tothill and Gillies, 1992; Ash et al., 1997). De Corte et al (1994), and Rogers et al. (1999) have shown that soil erosion has affected significant areas of the Burdekin catchment, a major catchment draining into the GBRL. Apart from loss of soil productivity, enhanced erosion rates in grazing lands are believed to have significantly increased delivery of sediments and nutrients to the GBRL, potentially threatening the health of near-shore reef and seagrass systems in the GBRL.

The increased delivery of sediments and nutrients to the GBRL has received widespread attention and has been vigorously debated over the past years. There is now little doubt that post-European settlement has significantly increased the delivery of sediments and nutrients to rivers, and hence to the GBRL. Several independent studies using different methodologies have come to the conclusion that there has been approximately a four to five-fold increase in sediment delivery (Brodie et al., 2001; Neil et al., 2002, McCulloch et al., 2003) and similar increases in nutrient delivery (Furnas, 2003). In the case of the Burdekin, the majority of the increase in sediment and nutrient delivery is assumed to be from grazing lands, mainly because grazing as a land use covers about 95% of the catchment (Roth et al., 1999). Recent evidence obtained from the analysis of coral cores, points to the introduction of initially sheep and later cattle to the catchment in the late 1860s as the trigger of increased sediment delivery (McCulloch et al., 2003).

The harder question to answer is whether the increased delivery of sediments and nutrients is harming the GBRL. This remains a contentious issue. On the one hand, there is clear evidence that turbidity of near-shore sea water brought about by wave re-suspension as a result of the frequent south-easterly trade-winds is likely to be greater than any sediment delivery-induced increase to turbidity, so that some argue that any increase in sediment delivery is not likely to have a detrimental effect (Larcombe and Woolfe, 1999). More recently, the emphasis has shifted to the increased delivery of nutrients, and in particular the synergistic effects between nutrients and suspended sediments forming so-called 'marine snow', which has been shown to have detrimental impact on the recruitment of corals (Fabricius and Wolanski, 2000). In summary, there is now widespread consensus amongst leading scientists in the region that if unchecked, further increases in the rate of sediment and nutrient delivery to the GBRL will adversely impact near-shore reefs and seagrass beds (Williams et al., 2001; Reef Science Panel, 2003). This is borne out by evidence from overseas (Hawaii and Florida), where decline in reef systems has been clearly associated with nutrients originating from terrestrial runoff. Increased levels of sediments and nutrients are not likely to have direct impacts, but there is evidence that increased levels of nutrients (in particular dissolved nitrogen) in combination with a change in the composition of suspended sediments will reduce the ability of corals to recover from damage caused by natural events such as bleaching and cyclones (Wolanski, 2001). As a more in depth discussion of this highly complex topic is beyond the scope of this chapter, the reader is referred to some of the more detailed reviews on this issue (Reef Science Panel, 2003; Furnas, 2003).

Against this backdrop of major national debate, the beef industry has been under pressure to demonstrate that it is taking measures to minimise its potential impact on the GBRL. At the same time, there is also increasing awareness of the need for Australian rural industries to be productive, but not at the expense of degrading our natural resources so as to impair their capacity for use, including use by future generations. This need has been enunciated in the principles of ecologically sustainable development and the production of “clean and green” agricultural products. So, the issue of soil erosion and sediment and nutrient export is not just a question about impacts on the GBRL, but needs to be seen within the broader context of sustainable beef production, which includes retaining the integrity of the land resource as the main basis for pasture and beef production. Hence, minimisation of soil erosion is as much about maintaining future productivity as it is about limiting off-site impacts.

In response to this, MLA through its North Australia Program commissioned a review in 1997 to assess information on the effects of grazing management in grazed lands of Northern Australia, on water and nutrient cycles and the downstream fluxes and impacts of water, sediment and nutrients (Hook, 1997). This was followed by a scoping study (Roth et al., 1999), also commissioned by MLA, with the specific objective of identifying the key research issues that a multi-disciplinary research program needed to address in relation to grazing management and sediment and nutrient export, as well as nominating suitable focus catchments for the above research.

Based on the recommendations made by the scoping team, MLA selected the Burdekin catchment as focus catchment and commissioned a team lead by CSIRO Land and Water to develop and carry out a research project to address the issue of sediment and nutrient export from grazed catchments in Northern Australia. Initially, this was to be a 2 ½-year project from January 1999 to June 2001, but it was subsequently extended until June 2002. This report is the final report on the 3 ½-year project duration.

2. Project objectives

The overall goal of this project was to provide a better process understanding of grazing impacts on catchment response as the basis for refining guidelines and recommendations for improved grazing management to:

- Ensure the beef industry’s long-term economic sustainability by retaining or improving the productive capacity of the soil resource base by reducing on-site water and nutrient loss;
- Meet national and international standards of sustainable beef production by reducing detrimental off-site impacts due to sediment and nutrient delivery; and
- Enhance the beef industry’s capability of modelling grazing management impacts on the soil and water resource base across a range of scales to respond to broader community concerns.

To achieve these goals, we identified four main project objectives:

1. 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;
2. To construct a detailed sediment and nutrient budget for a sub-catchment identified as having significant actual erosion hazards in order to assess sediment and nutrient transport and storage mechanisms in relation to grazing pressure at sub-catchment scale;
3. To improve our understanding of animal dynamics in relation to spatial variation of grass species and fodder biomass over larger areas, the interactions with surface condition and the resultant changes in surface hydrology and sediment transport, for varying soil types and landforms;
4. To quantify the principal determinants of sediment and nutrient generation, redistribution and export from hillslopes with varying configurations of grazing management induced variations of soil surface condition.

The project was structured into four research components, each dealing with one of these objectives. Chapter 4 of this report addresses objective 1, Chapter 5 addresses objective 2, Chapter 6 addresses objective 3 and Chapter 7 addresses objective 4, respectively.

3. Research framework

Based on the recommendations provided by Hook (1997) and the assessment undertaken by Roth et al. (1999), the key research issues in relation to sediment and nutrient export from grazed catchments can be grouped into the following two critical sets:

1. *Impacts of grazing management on sediment generation and nutrient loss at scales ranging from hillslope to catchment*
2. *Quantification of key determinants of sediment, nutrient and overland flow processes at various scales and their modelling to enable extrapolation to other catchments in Northern Australia*

In order to address these issues, a research framework was drawn up by Roth et al. (1999) to provide the basis for this research project. An adaptation of that framework, as utilised by the project team as the conceptual basis for the project, is presented in Figure 3.1 and discussed below.

After the identification and acquisition of the key data sets, the first step is the construction of a reconnaissance level sediment budget for the whole focus catchment to delineate the actual erosion “hotspots” or vulnerable sub-catchments suitable for further detailed studies (component 2 in Figure 3.1). This higher level sediment budget needs to be coupled to an assessment of the risk of sediment delivery and export from various regions within the focus catchment, also enabling an estimate of grazing impacts on sediment export to estuarine or marine systems at larger scale. As such it represents a framework to conceptualise the key erosion and sediment delivery processes across the catchment, as well as provide a useful framework to integrate existing and new data.

Following the selection of a suitable sub-catchment with a high level of current or potential erosional activity, a more detailed sediment and nutrient budget is established for the selected hotspot region by quantifying sources, internal deposition and export and by breaking down sediment into size classes and relating it to nutrient loss (component 2 in Figure 3.1). This is done using a similar approach, but with new data acquired during the project life. This spatially referenced budget needs to be closely linked to a spatial analysis of grazing management impacts ranging from hillslope to sub-catchment scale (component 3 in Figure 3.1). Linking these two components is the key step to assessing the impact of cattle behaviour and grazing management on sediment and nutrient loss for different land types at a range of scales.

Ideally, the sediment and nutrient budgets and the spatial analysis of grazing impact need to be closely linked to the assessment of the on-site effects of erosion, i.e. the impact of nutrient and water loss on pasture productivity and, ultimately, economic indicators such as animal production (component 4, Figure 3.1). Successful assessment of the on-site impacts will also need to account for the role of different land types on the severity of soil and water loss impacts, which might be carried out through producer led monitoring, which could be part of this component. Unfortunately, due to resource limitations, this component was not pursued in the study reported here.

Whilst the above research components are designed to address the first set of issues as defined above, the ensuing research components are directed more towards tackling subset 2 and enhancing our process understanding to enable the development of modelling tools and extrapolation techniques. At the hillslope scale, entrainment, transport and deposition of sediment and nutrients depends on the amount and characteristics of overland flow and entrained sediment and their relationship to topography and surface condition as affected by grazing management (component 5, Figure 3.1). Ultimately, this requires information on the size distribution of sediments transported at varying scales. Coarse material will be rapidly deposited as soon as transport power decreases, while finer material is transported through the system and removed by major channels. As nutrients are closely linked to the fine fractions, it is likely that nutrient delivery is tightly related to delivery of fine sediments. At larger scales, there is a need to improve our understanding of how surface hydrology affects gully and channel processes (component 6, Figure 3.1). Consequently, these two separate components are critical steps in formulating robust conceptual models that in turn lend themselves to the development of numerical simulation models (component 7, Figure 3.1).

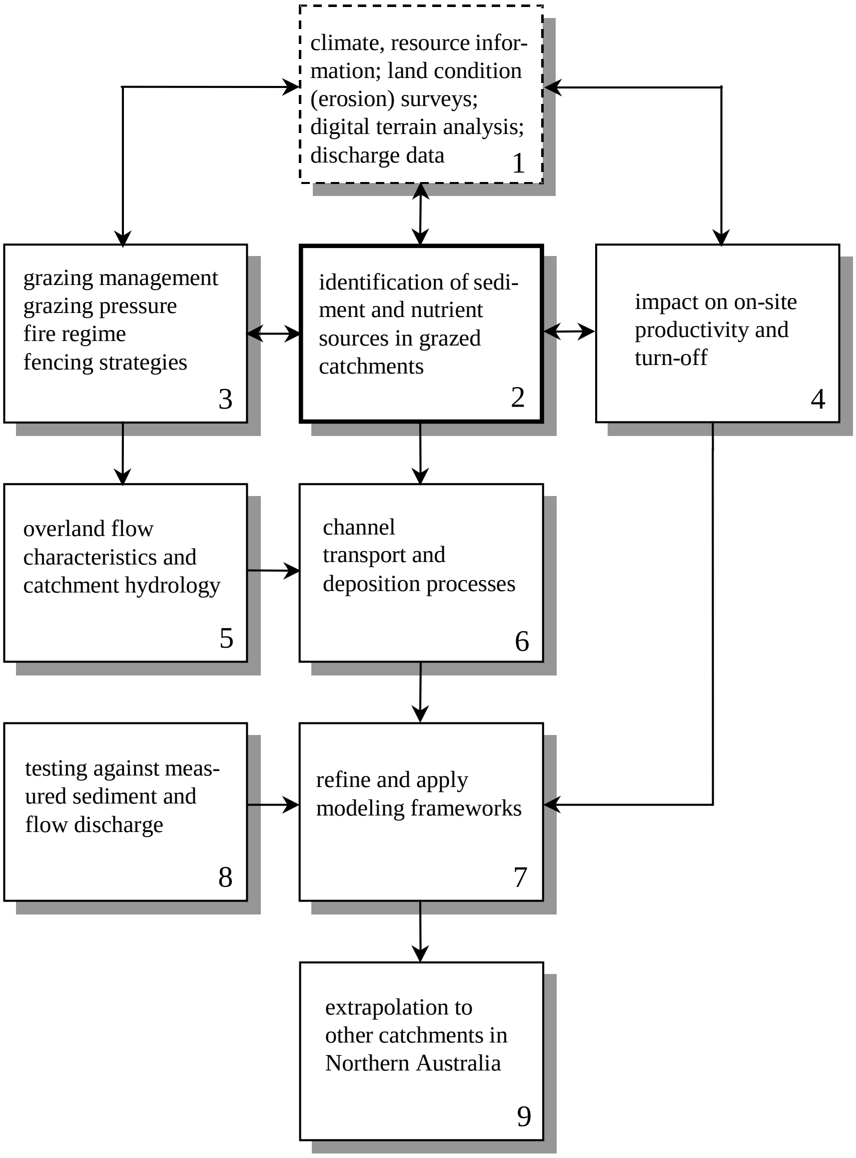

Figure 3.1: Overview of the project's research framework (adapted from Roth et al., 1999)

An important requirement of the modelling work is the need to identify key determinants of sediment and nutrient loss that can be characterised by surrogate measures more readily available in some of the data sparse environments across northern Australia. This entails a need to "strip down" some of the existing, more complex models to simpler approaches and represents a major part of the modelling component 7. Whilst the quantification of detailed sediment and nutrient budgets at sub-catchment scale (component 2) and the determination of overland flow and sediment and nutrient transport (component 5 and 6) would provide the basic dataset for the simplification of these models, testing against independent measures such as water, sediment and nutrient discharge at various points in the studied sub-catchments is a prerequisite for model validation (component 8, Figure 3.1).

Given the extent of the beef industry and the general paucity of key land resource and hydrological data across northern Australia (NA), the development of robust models is essential if the work carried out in a particular focus catchment is to be used for extrapolation to other catchments across NA (component 9, Figure 3.1).

Due to the resource and time constraints of the project, the project team in discussion with MLA decided to place a greater emphasis on combining targeted field measurements during the three wet seasons of the project (1999/2000 to 2001/2002) with the development or refinement of various models to perform longer-term extrapolations using sensitivity and scenario analysis techniques. The main focus therefore was on components 2, 3, 5, 6 and 7, with some activities in component 8. Component 9 was addressed through other initiatives such as the National Land and Water Resources Audit.

4. Reconnaissance sediment budget across the Burdekin River catchment

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4.1 Introduction and objectives

This chapter reports on the whole-of-catchment sediment export modelling component of the project. The aims of this component were to survey the Burdekin catchment at a reconnaissance scale to:

- assess the most significant processes of soil erosion as they relate to grazing management;
- provide a framework for reviewing and integrating information currently available in the catchment; and
- identify sub-catchments of concern for more detailed investigation.

The project met these aims by modelling the pattern of erosion and sediment transport in the catchment using a geographical information system (GIS). The GIS was used to build a model of sediment budgets in the catchment: *SedNet* (Prosser et al. 2001) and to integrate all existing information and provide layers of new information. The Burdekin catchment was the first place where the SedNet model was applied but it has since been applied across the Australian continent as part of the National Land and Water Resources Audit (NLWRA 2001). The model is now being used extensively in Queensland and elsewhere to underpin policies such as the National Action Plan for Salinity and Water Quality and the Great Barrier Reef Protection Plan.

The results of the catchment-wide sediment budgeting have been presented before both as a final report to MLA (Roth et al. 2000) and as a published technical report (Prosser et al. 2002). Since presenting those reports, further refinements have been made to the GIS techniques used in *SedNet* so here we outline the changes that have been made, and present and discuss the final results.

4.2 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 sediment from land use to streams. 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 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 material budget for a catchment or any part of a catchment.

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 the spatial pattern of grazing impact for sediment transport. 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 can be derived from two types of processes, runoff from hillslope paddocks and erosion of channels and gullies. In many cases one process far dominates the other in terms of delivering sediments and nutrients to streams, and the dominant process can vary from one part of a large catchment to another. Furthermore, management aimed at reducing sediment and nutrient transport will target each process quite differently. Consequently it is quite important to identify the predominant sediment and nutrient delivery process before undertaking catchment remediation or making recommendations for changed grazing practise.

One of the current concerns over sediment transport in rivers is the threat that it may pose to waterbodies downstream, including rivers, estuaries and ultimately the inshore marine environment including inshore coral reefs and sea grass beds (Williams, 2001). In a large catchment such as the Burdekin, these waterbodies can be up to several hundreds of kilometres downstream of the eroding sediment sources. The waterbodies receive only a fraction of the total amount of eroded sediment; the rest is deposited along the way on footslopes, river beds, floodplains and in reservoirs. Consequently, not all sediment sources will contribute to downstream sediment loads. By constructing sediment budgets that map the deposition we have for the first time predicted the sediment sources that deliver to the coast separating that from mapping of total erosion in the catchment.

4.3 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 processes 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 in the catchment is divided into six aspects:

- sheetwash and rill erosion;
- gully erosion;
- riverbank erosion;
- floodplain deposition;
- river bed deposition;
- reservoir deposition; and
- resultant river sediment loads.

Each component is mapped across the catchment as mean annual rates of erosion, deposition or transport. A summary of each component is given below, including recent changes to the GIS techniques. Readers are referred to published technical reports for further details.

4.3.1 Sheetwash and rill erosion

This is the erosion of soil on land by surface runoff and rainfall during intense storms. It is also referred to as hillslope erosion and soil erosion. Erosion from sheetwash and rill erosion processes was estimated using the Revised Universal Soil Loss Equation (RUSLE; Renard *et al.*, 1997) as applied in the NLWRA project (Lu *et al.,* 2001). The RUSLE calculates mean annual soil loss (*Y,* tonnes ha^{-1} y^{-1}) 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*):

$$Y = RKLSCP \qquad (1)$$

The land use practice factor includes the use of engineering works and other practices not associated with cover management to reduce soil erosion. Such practices are not widely used in the Burdekin catchment and there is no mapping of their use so the P factor was removed from the analysis.

Revisions have been made to the calculation of the C factor since the NLWRA and Burdekin results were originally published. These are detailed in Lu et al. (submitted) and include improved removal of artefacts from clouds in the ground cover estimation and incorporation of typical cover retention practice on sugar cane lands. The original results used annual tillage practices for cane lands.

The delivery of sediment to streams from sheet and rill erosion on hillslopes is modified by the hillslope sediment delivery ratio (HSDR). There are no direst measurements of HSDR so it was determined by calibration of the sediment budgets against a set of catchment observations (Prosser et al. 2001). A value of 10% was found to produce the best results.

4.3.2 Gully erosion hazard

Gullies are small streams which have incised into soil in historical times (i.e. in the last 150 years) and which have eroded headwards to form deep incisions in small valleys, which normally would not contain stream channels. The bare and steep banks of these channels are a significant source of sediment. Only gullies with bare eroded banks large enough to be visible on aerial photographs were mapped. As it is an expensive and time consuming effort to measure all the gullies within 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. Details of the methods used are given in Prosser et al. (2002) and Hughes et al. (2001). The NLWRA work incorporated the Burdekin samples with other regions to build a broader prediction of gully erosion across Queensland coastal catchments. Here we revert to using the Burdekin samples alone to predict gully erosion just for the Burdekin catchment. There are only minor differences in the results for the two regions.

Sample sites were selected in each of the major geology types, slopes and rainfall zones. A total of 63 pairs of photos were used. 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 data on 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; terrain attributes derived from the 9" DEM, and remote sensing data of MSS bands. 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.

To determine supply of sediment to streams from gully erosion the gully density (km of gully per km^2 of land) is converted to a sediment supply ($t\ y^{-1}$) by multiplying it by a typical cross-sectional area of gullies ($10\ m^2$), average dry bulk density of eroding materials ($1.5\ t\ m^{-3}$), and then dividing by the average time over which gullies have developed (100 y).

The above approach does not fully account for extensive gully networks along certain reaches of the Upper Burdekin. These systems are probably a result of past mining (tin dredging) activities. A separate assessment of these gully systems in alluvial plains is provided in Appendix 1 (Volume II).

4.3.3 Riverbank erosion

Riverbank erosion is modelled as there are generally few direct measurements of bank erosion over the length of individual river reaches. A global review of river bank migration data (Rutherfurd, 2000) suggested the best predictor of bank erosion rate (*BE*) was bankfull discharge equivalent to a 1.58 year recurrence interval flow. We modified Rutherfurd's rule to account for the observation that bank erosion rates are negligible where native riparian vegetation is undisturbed compared to that where the vegetation has been cleared.

We have since made further modifications to the predictions. In Australia, many rivers have very low gradients with consequent low energy flows that are not capable of erosion. This can be represented through calculation of stream power. Rutherfurd found a significant relationship between bank erosion and stream power ($\rho g Q_x S_x$) where *p* is the density of water, *g* is the acceleration due to gravity, Q_x is the mean annual flow ($ML\ y^{-1}$) and S_x is the energy slope normally approximated to channel gradient. There are less data to support this relationship but it does fit the observed patterns of river erosion across Australia.

In some places riverbanks are not composed of erodible alluvial sands and clays but have rocky banks which do not erode. We have incorporated this into the model by reducing the bank erosion in narrow alluvial valleys to the limit of predicting negligible sediment from rocky gorges.

The new equation used to predict bank erosion in each river link *x* is:

$$BE_x = 0.00002 \rho g Q_x S_x (1 - PR_x)(1 - e^{-0.008 F_x}) \qquad (2)$$

where BE_x is the bank erosion rate in m/y, PR_x is the proportion of riparian vegetation, and F_x is the width of alluvial floodplain in m. Derivation of the input parameters for each river link is described in Prosser et al. (2001). The predicted bank erosion rate is converted into sediment supply (t y^{-1}) by multiplying *BE* by channel length (m), bank height (m), and average particle density of bank materials (1.5 t m^{-3}).

4.3.4 Sediment delivery through the river network

Soil, riverbank and gully erosion supply sediment to the river network, which is then either deposited within river links or is transmitted downstream. These budget or mass balance calculations are made for each link of the river network in the catchment. A link is the stretch of river between tributary junctions (Figure 4.1). All river links with a catchment area of >75 km^2 were mapped. The catchment area contributing directly to each river link (internal catchment area) was also defined. Across the Burdekin catchment this produced 1020 river links and associated sub-catchments.

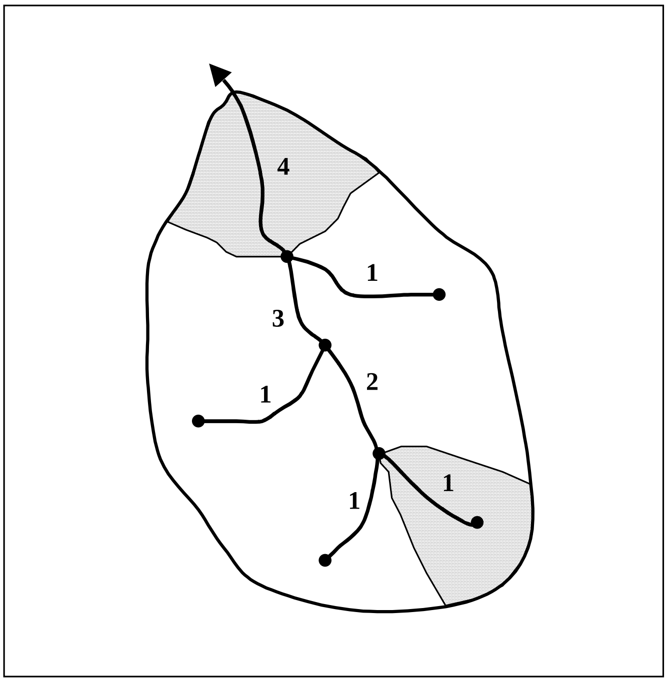

Figure 4.1: A river network showing links, nodes, stream type of each link, and internal catchment area of an order one and order four link.

Details of the methods used in the river budgets are given in Prosser et al. (2001, 2002). The budgets model the transport of bedload and suspended load independently. Suspended sediment is supplied from all three sediment sources. Bedload supply from soil erosion is negligible and so is ignored. Half the sediment from riverbank and gully erosion is input into the bedload budget while the other half contributes to the suspended load budget. This reflects observed particle size distributions and field-based sediment budgets.

There is net accumulation of bedload on river beds when the supply of sediment from upstream exceeds the capacity of the flow to transport the sediment (Figure 4.2). The amount in excess of transport capacity is deposited on the bed. If the transport capacity is greater than the supply of bedload then it is transported downstream to the next river link. Sediment transport capacity is a function of slope, flow volumes, and width of the river link.

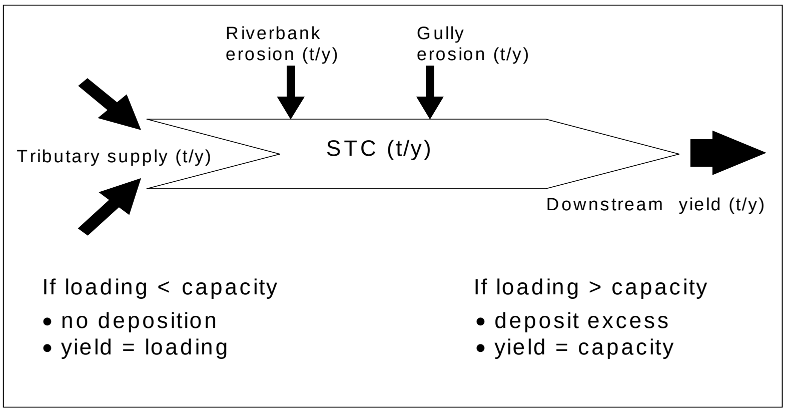

Figure 4.2: Conceptual diagram of the bedload sediment budget for a river link. STC is the sediment transport capacity of the river link.

Suspended sediment loads of rivers are generally supply limited. 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. Deposition on floodplains and reservoirs is still a significant process, however, and previous work has shown that only a fraction of supplied sediment leaves a river network (Wasson, 1994). There is negligible net accumulation of suspended sediment within most river channels.

The suspended sediment budget for a river link is illustrated in Figure 4.3. We model floodplain deposition through a simple conceptualisation of the principle driving effects. First, only the fraction of total discharge that goes overbank carries sediment that can be deposited. We assume that the sediment concentration in the flood flows is approximately the same as that carried in the channel. The actual deposition of material that goes overbank is 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 extent was derived from the NLWRA database (Pickup and Marks, 2001). Discharge modelling for this and other aspects of the sediment budgets is described in Young et al. (2001). 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). Because nearly all flow in the Burdekin River occurs in summer the value of mean annual flow input into reservoir deposition calculations was doubled. This incorporates the seasonality of flow and reduces the trap efficiency of the Burdekin Falls dam.

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.

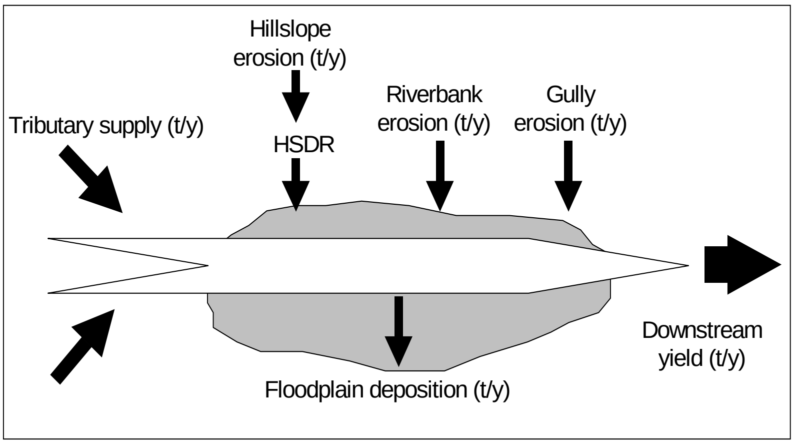

Figure 4.3: Conceptual diagram for the suspended sediment budget of a river link. HSDR is hillslope sediment delivery ratio.

4.4 Results and discussion

4.4.1 Sheetwash and rill erosion

Figure 4.4 shows the patterns of soil erosion for the catchment. Only 10% of the catchment has a soil loss rates of >20 t/ha/y, showing the value in targeting erosion control to problem areas. The mean soil erosion rate is 7 t/ha/y and the median is 5 t/ha/y. The total amount of soil erosion predicted across the catchment is approximately 90 Mt/y. This about ¾ of the original estimate of 120 Mt/y. The reduction is because of an increase in ground cover detected by more sophisticated processing of the remote sensing data. The predictions match well observations of soil erosion across Australia (Lu et al., submitted).

Figure 4.4 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 Running River, Star River, Keelbottom Creek, and Fanning River) experiences high soil erosion except for the rain forest at High Range. The worst areas effected 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 the Clarke River and the areas around the Cape River near the junction with the Burdekin River face medium hillslope erosion. Low to medium erosion rates are found in the rest of sub-catchments.

In some areas, soil erosion occurs irrespective of ground cover as a result of high intensity rainfall and steep slope. Much of the pattern shown in Figure 4.4 could occur from natural variation in the susceptibility to erosion. To examine this question we interpolated the vegetation cover in reserves across the whole catchment to produce a prediction of erosion under natural conditions. The other four factors were left as they are. The resulting prediction of pre-European erosion is shown in Figure 4.5. Also shown is the difference between erosion under current land use and natural erosion. This shows that the current pattern of erosion largely mimics the natural pattern except where land is cleared in the most erodible parts of the catchment. The difference map shows that erosion in the southern and western part of the catchment has increased by < 3 t/ha/y but in the wetter and steeper areas of the north and east there are increases of 3 – 10 t/ha/y and in 10% of the area there are increases of > 15 t/ha/y predicted.

Table 4.1 divides hillslope erosion into land use classes. The total soil loss is dominated by native pastures in semiarid woodlands simply because the vast majority of the catchment has that land use. This land use is also predicted to have the highest erosion rate with the exception of crops other than sugar cane. These crops occupy only a small area and their mapping from the original land use map is uncertain, so little can be interpreted by the rates. Differences in soil erosion rates between land uses are partly a result of associations with other factors. Sugar cane in the Burdekin River catchment for example is grown on flat areas with a naturally low erosion potential. As expected, forested lands have the lowest erosion rate, despite often being located on the steepest and wettest parts of the catchment. This shows the significance of maintaining good vegetation cover in areas naturally prone to erosion.

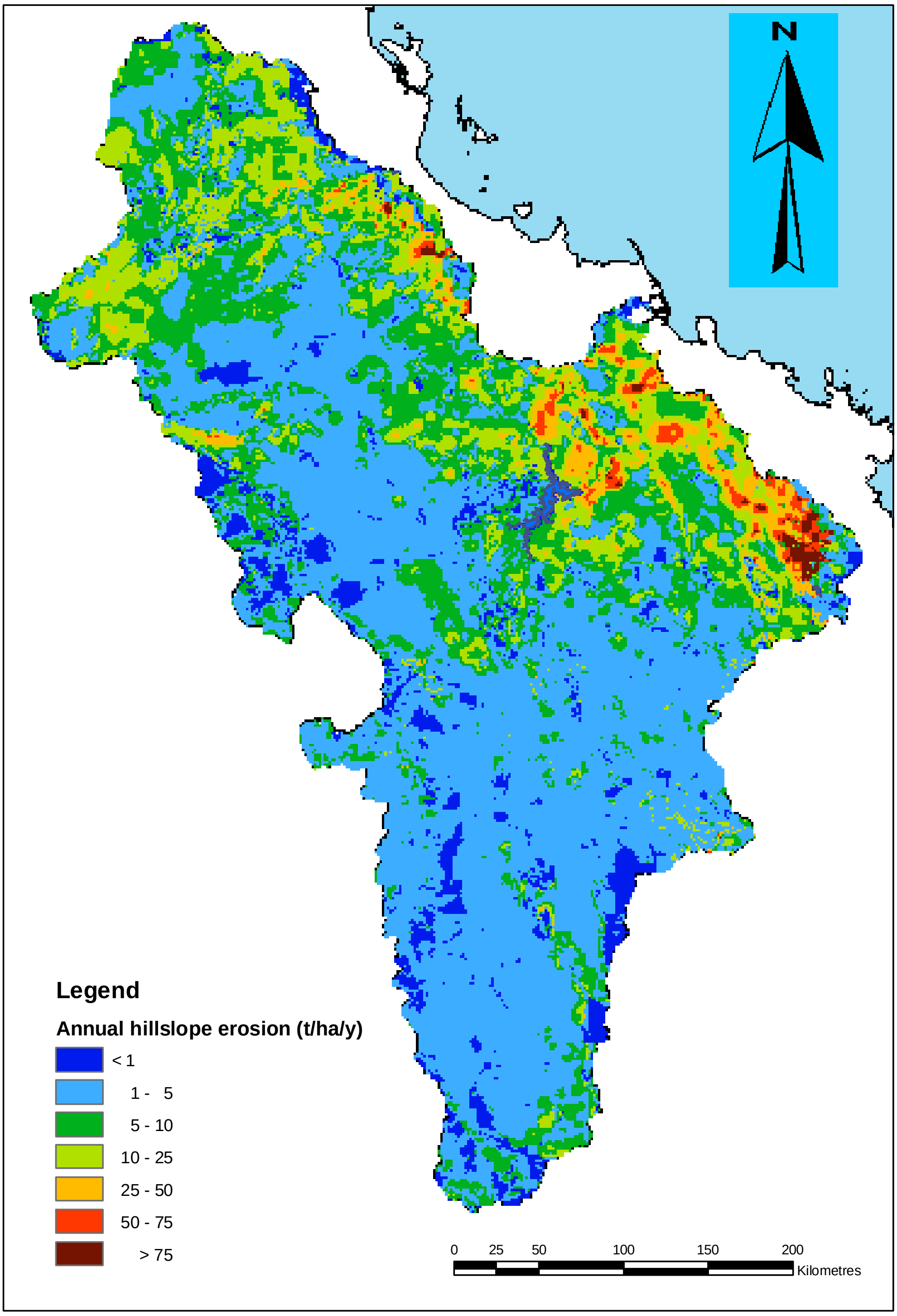

Figure 4.4: Predicted mean annual soil erosion rate in the Burdekin River catchment.

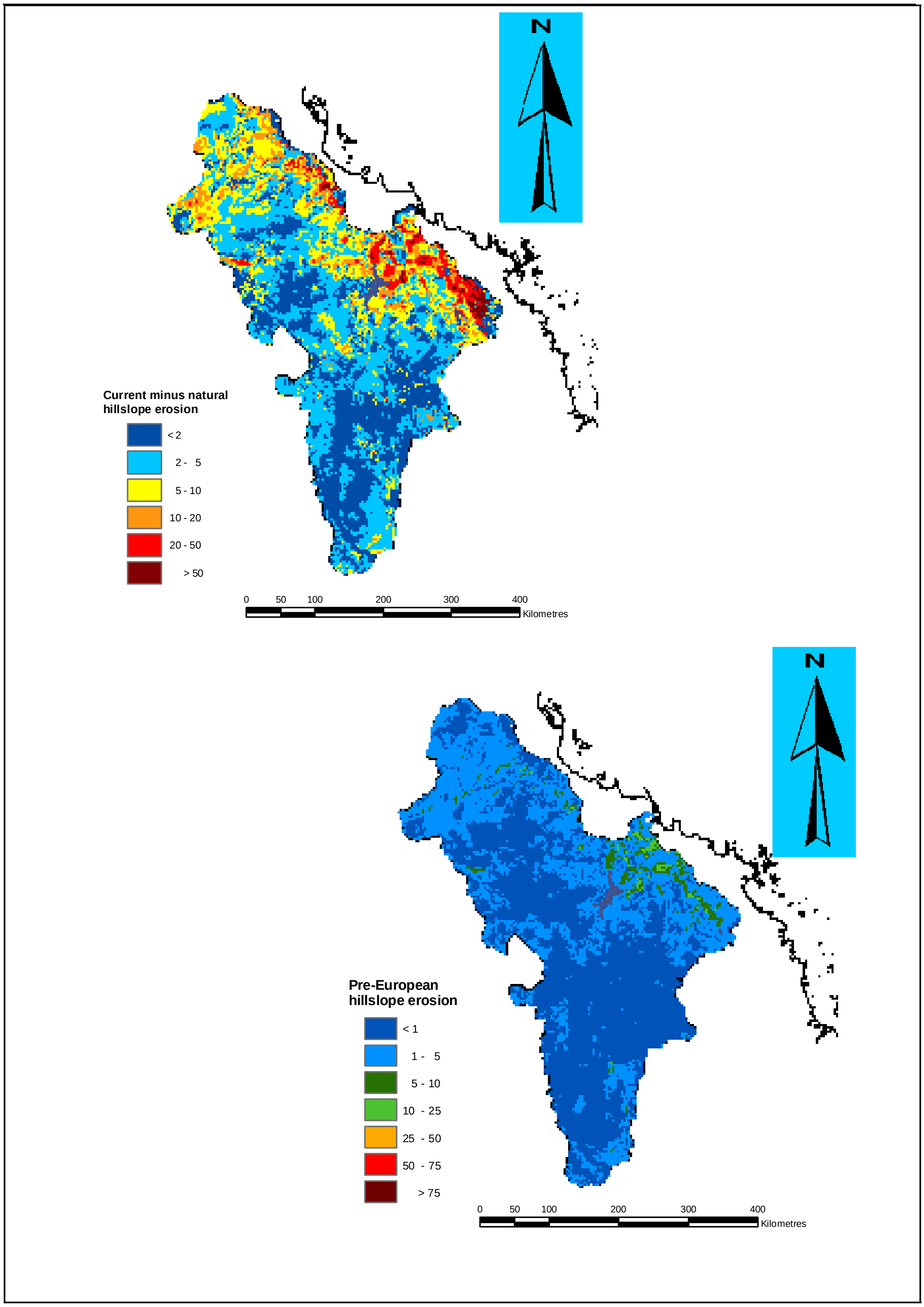

Figure 4.5: Predicted pre-European soil erosion rate, and difference between current and pre-European soil erosion rate.

The results predict that most erosion occurs in grazed areas of medium slope gradient and where ground cover is below 40%, which is supported by field assessment of erosion (McIvor *et al*., 1995).

Table 4.1: Soil Loss from land use categories in the Burdekin River Catchment.

Land Use Category	Area (km^2)	Proportion of total area (%)	Total soil loss (t/year)	Prop. of total catchment erosion (%)	Average soil loss rate (t/ha/year)
Native pastures	117,000	90	88,700,000	95	7.6
Improved pastures	2,600	2	1,000,000	1.1	3.8
Sugar cane	150	0.1	53,000	0.06	3.5
Other crops	730	0.5	1,100,000	1.2	15
Forest and other reserves	9,500	7	2,500,000	2.7	2.6

4.4.2 Gully erosion

It was found that the most robust predictors for discriminating gully density within the Burdekin catchment were: mean annual rainfall; geology; Landsat MSS bands 1 to 4; relief; elevation; and soil attributes including, A horizon clay content, B horizon clay content, A horizon texture, B horizon texture, and solum depth. Among these predictors, elevation, geology, and mean annual rainfall were the most important predictors. Details of the model accuracy are given in Roth et al. (2001).

Figure 4.6 shows that the majority of gullies are formed in the central part of the catchment in the areas with moderately steep slope and on granitic lithologies and on some of the metamorphosed sedimentary rocks. The highest gully densities are in the area between Belyando River and Sellheim River and the areas from Charters Towers to Burdekin Falls Dam on the both sides of Burdekin River. 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.

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 area 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 suggests a more balanced approach targeting both processes is needed for the northern beef industry.

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 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 needs to be carried by the river network.

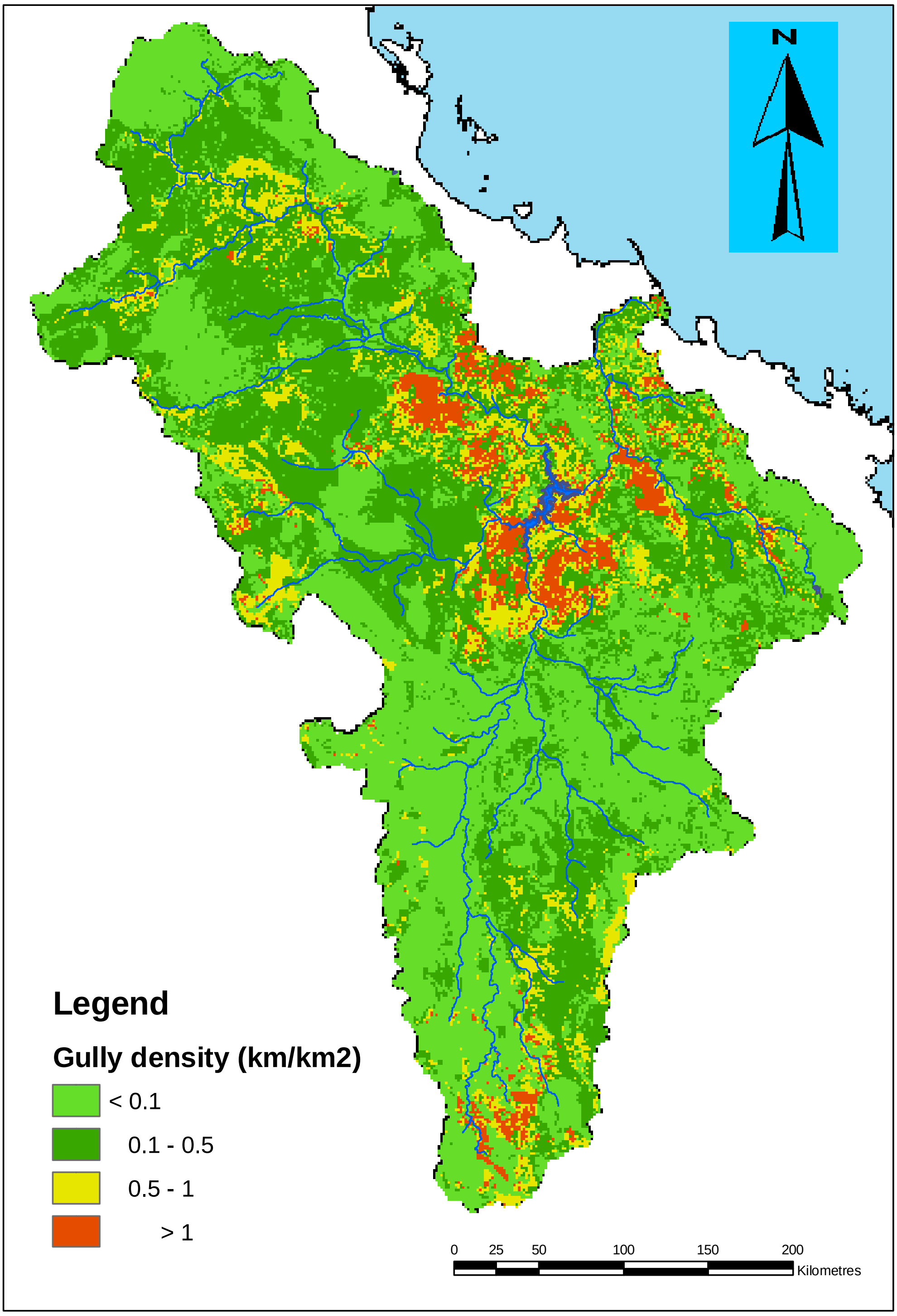

Figure 4.6: Predicted density of gully erosion across the Burdekin River catchment.

4.4.3 Riverbank erosion

Rivers carry sediment generated from erosion of the river and stream banks themselves, as well as from other sources. Figure 4.7 shows the predicted pattern of bank erosion in the catchment. The Burdekin River itself and some of the tributaries such as the Cape and Bowen Rivers have the highest bank erosion because they have very high stream power and have degraded riparian vegetation to some extent. Other areas have low bank erosion as a result of low gradients or largely intact riparian vegetation.

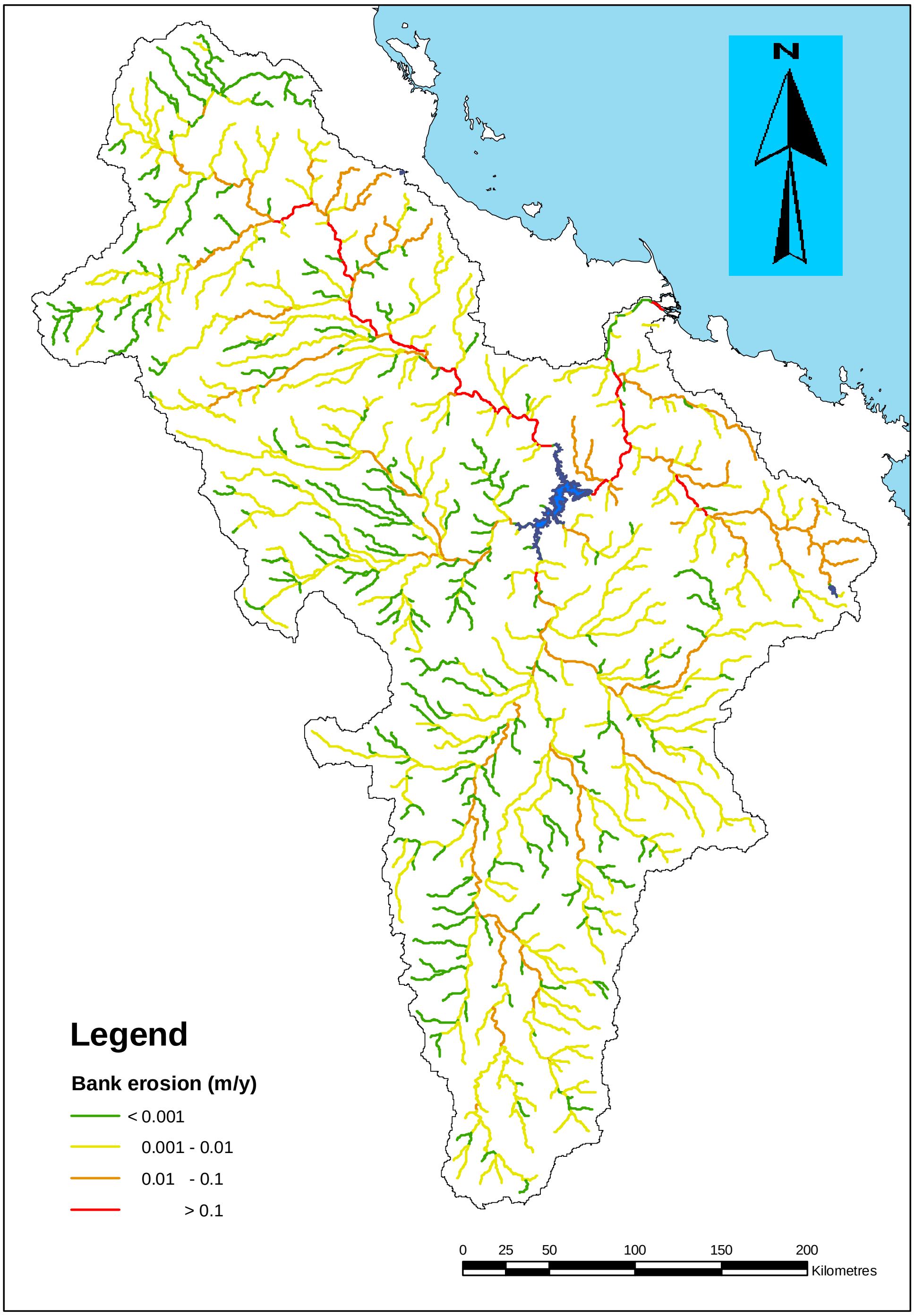

Figure 4.7: Predicted patterns of riverbank erosion across the Burdekin River catchment.

The bank erosion mapping is the most uncertain aspect of the sediment budgets and requires field verification. More importantly, the controls on bank erosion are less well understood than the other erosion processes and much work is needed at the catchment-scale to better understand the factors that determine the pattern of bank erosion in any catchment.

4.4.4 Sediment delivery through the river network

Table 4.2 shows the predicted mean annual amount of sediment supplied to streams from the three erosion processes and shows the summary results from the river sediment budgets. Hillslope or sheet erosion is the dominant process because of the often low vegetation cover and tropical rainfall in the catchment. Gully erosion is also a very significant source of sediment, and while riverbank erosion is the predicted to be the smallest source it cannot be neglected. 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 riverbank 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 4.2: Components of the sediment budget for the Burdekin River Basin.

Sediment budget item	Predicted mean annual rate (Mt/yr)
Hillslope erosion	9.2
Gully erosion rate	5.1
Riverbank erosion rate	1.1
Total inputs	15.4
Floodplain deposition	7.4
Reservoir deposition	3.0
River bed sediment deposition	2.6
Sediment delivery to coast	2.4
Total losses	15.4

The modelled sediment budgets predict that, overall, only 16 % 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. There is relatively little of the river network affected by bedload deposition and the issue of current concern in the catchment is suspended sediment, so we present only suspended sediment results here. Full discussion of bedload is given in Prosser et al. (2002).

4.4.5 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. The resultant mean annual sediment loads for each river link are shown in Figure 4.8. 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.). It is the Burdekin and Bowen Rivers that have the highest sediment loads both because of significant sediment sources in the catchment and low deposition potential in relatively narrow valleys. The Suttor and Belyando Rivers have lower sediment loads because of lower erosion rates and more significant deposition of sediment in extensive downstream floodplains.

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 5 times the natural rate. This is probably a maximum increase given the harsh assumptions about no gully or riverbank erosion.

4.4.5 Contribution of suspended sediment to the coast

One of the strongest interests in suspended sediment transport at present is the source of sediment exports to estuaries and the coast. Because of the extensive opportunities for floodplain deposition along the way, not all eroded sediment is exported to the coast. A map of erosion in a catchment may be very different to a map of contribution of erosion to export at the coast. This is because there are some places that deliver very effectively to the coast and others where much of the sediment is stored along the way. Overall, only 16% of the erosion in the Burdekin catchment reaches the coast.

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.

Fortunately our mapping of patterns of erosion, deposition and sediment transport enable us to predict for the first time in detail the sources of sediment delivered to the coast. We have done this for the internal catchment area of each river link in the catchment. 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 *x* 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:

$$CO_x = LF_x x \frac{YF_x}{TIF_x} x \frac{YF_{x+1}}{TIF_{x+1}} x......x \frac{YF_n}{TIF_n} \qquad (3)$$

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 (3) is that, with 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.

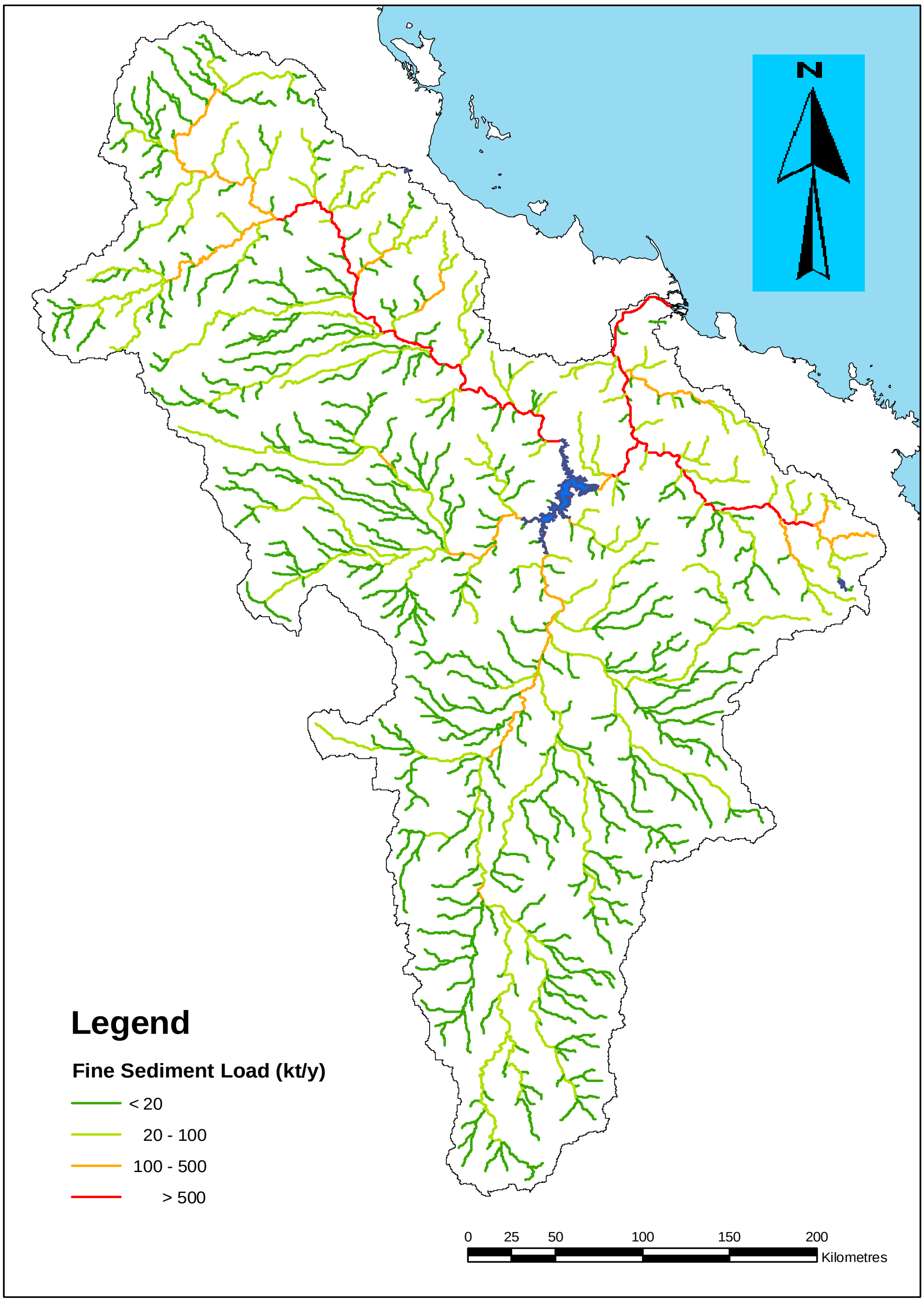

Figure 4.8: Predicted mean annual suspended sediment load in the Burdekin River catchment.

Areas close to the coast with high erosion rate and effective sediment delivery are the most significant contributors to export. Upstream, it is the Burdekin and Bowen Rivers that contribute much of the suspended sediment load (Figure 4.9). The Suttor, Belyando and Clarke Rivers make much lower contributions because of both lower sediment supply and extensive lowland floodplains. A result of the very different erosion rates and sediment delivery efficiency is that 85% of sediment exported to the coast is predicted to come from just 10% of the assessment area. The Bowen River catchment contains much of this land.

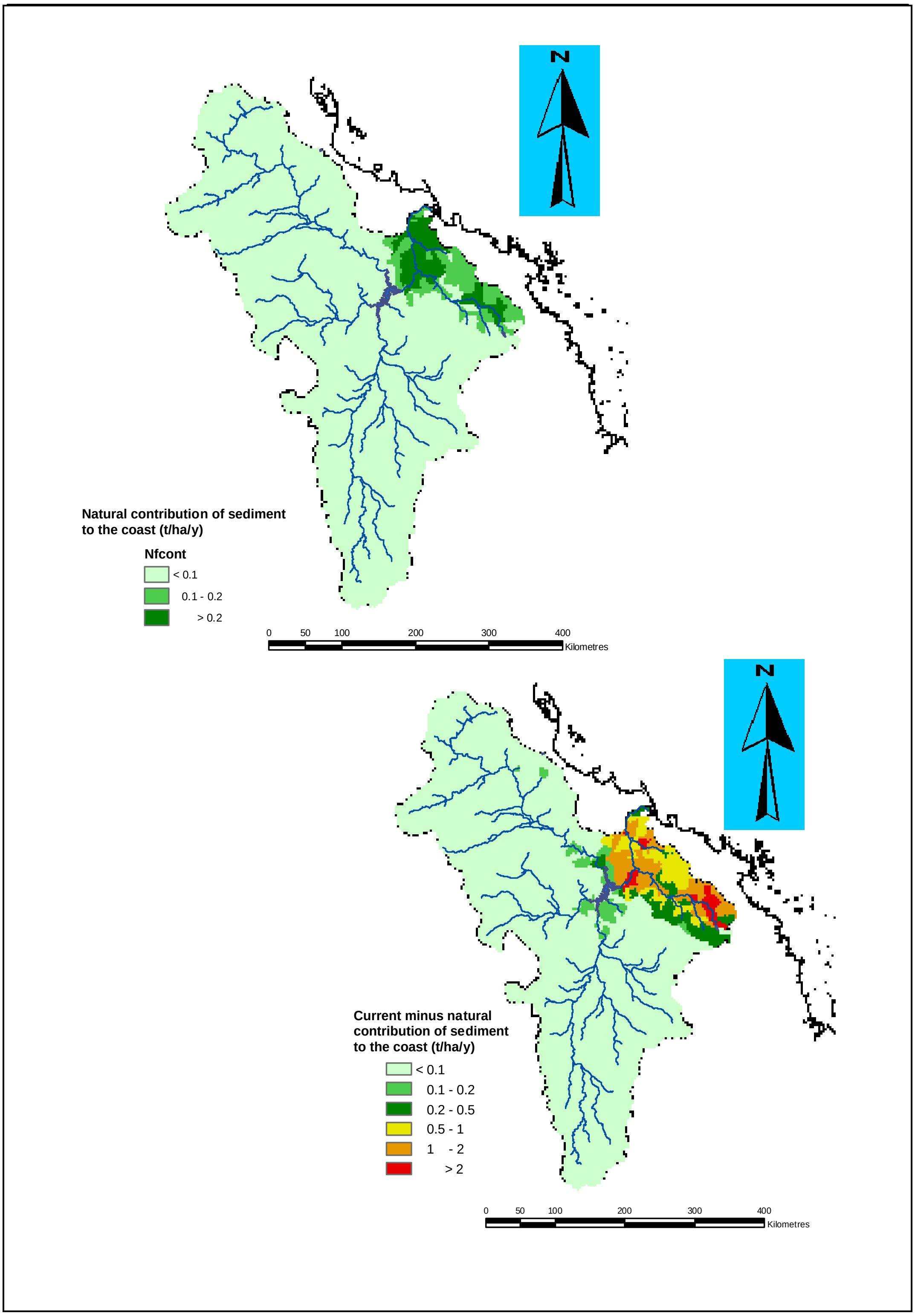

Figure 4.9: Predicted natural contribution of suspended sediment to export at the coast, and the difference between the current and natural contribution.

Rivers naturally export sediment so much of the area contributing to export might naturally do so. Consequently, in Figure 4.9 we also produce a prediction of the natural contribution to export, based upon natural soil erosion rates, and excluding the effect of the Burdekin Falls dam. Also shown here is the difference between current and natural contribution to export. This shows the areas where there is greatest potential to reduce sediment loads in future through improved land management. Note that even without a large reservoir the Bowen River and lower Burdekin areas are the most significant contributors of sediment.

Whilst soil erosion is a widespread issue across the Burdekin River basin, our results show that focused management can be used to effectively 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. The results are produced from a reconnaissance survey and further investigation is needed before investing considerable funds in sediment control. The results do, however, provide guidance on where to start those investigations, they show what the crucial knowledge gaps are, 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.

4.5 Conclusions

Hillslope soil erosion 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 soil 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 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.

Sediment export to the coast has increased by as much as 5 times the natural rate. It is predicted that 85% of this sediment comes from just 10% 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, the project has developed a set of GIS analysis tools that can be applied relatively routinely to other catchments in Australia. These tools attempt to combine the best available regional data with an understanding of the processes of erosion and sediment transport at the regional scale. They produce a unique set of mapping capabilities not produced by other erosion mapping or water quality assessment tools.

5. Sub-catchment scale erosion studies and sediment budget

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5.1 Introduction and objectives

By necessity the reconnaissance sediment budget of the whole catchment, presented in Chapter 4, is only a crude assessment of the extent of sediment and nutrient problems in any given regional catchment or sub-catchment. This chapter aims at assessing the processes in more detail for a sub-catchment where beef production is the main land use, where there is land-holder interest in reducing downstream impacts, and that has been identified as a hotspot sub-catchment in the preceding chapter. The reconnaissance sediment budget gives an overall assessment of the importance of channel and gully erosion in relation to the contribution of sediments and nutrients from hillslopes, but it is not be able to assess these in detail, or how the relationship changes between these processes as catchment size increases. Thus the aim of the sub-catchment scale work reported in this chapter is to take a hotspot sub-catchment and investigate sediment and nutrient sources, forms, and stores in more detail. Working at the smaller scale, but one that is still significant for catchment groups, will allow more detailed field surveying, monitoring and modelling work, enabling us to derive management guidelines commensurate with the scale (paddock) at which producers typically make their grazing management decisions.

The sub-catchment chosen for the detailed sediment budget will also be used for hillslope sediment and nutrient loss measurements discussed in Chapters 6 and 7. We supplemented these hillslope measurements with measurements of sediment and nutrient generation from streams and gullies. We also surveyed in-stream sediment stores in more detail to build predictive relationships on where the different sediment fractions are having an impact and what can be done to reduce that impact.

The more detailed measurements of sediment and nutrient loads at various scales enables us to refine the understanding of controls on sediment and nutrient transport in grazed catchments that we have derived in Chapter 4. It also enables us to develop more advanced versions of our DEM based models of sediment and nutrient transport. By constructing finer resolution DEMs and by using more detailed cover information we were able to investigate terrain and cover based patterns of erosion and deposition on hillslopes and how they change with hillslope topography and grazing pattern. This enabled us to identify and provide guidelines on the combinations of topography and grazing pattern that lead to problems of sediment and nutrient delivery to streams. The modelling in the sub-catchment component is intermediate in scale between the whole catchment hazard assessment in Chapter 4 and the detailed inclusion of patch models described in Chapters 6 and 7.

Therefore, the overall objective is to construct detailed sediment and nutrient budgets of small sub-catchments (approx. 20 km^2) within the Burdekin River that have significant potential for soil erosion and downstream delivery of sediments and nutrients, are of significance to the beef industry and have active community interest in minimising impacts of grazing. Specific objectives for the sub-catchments are to:

- Quantify hillslope, gully and bank erosion sources and relate these to stock management practices (see Chapter 6);
- Assess where sediment is stored within the sub-catchments, both on farm and in-stream to assess potential ecological impacts.
- Use the results to refine the broader regional assessment of sediment transport (feedback into the SedNet model, Chapter 4).
- Provide simple guidelines for identifying the conditions under which gully and hillslope transport processes are significant, and the critical sites that need protection or remediation.

5.2 General methodological approach taken

Deriving a sediment budget at the sub-catchment scale required us to monitor erosion, and the fluxes of water and sediment across a range of scales from the plot, through the hillslope, to the sub-catchment. A variety of techniques were used including microplots, runoff troughs, and stream gauging stations, coupled with intensive field monitoring of landscape conditions (using Tongway landscape function analysis, LFA) and gully location and growth (using erosion pins and GPS techniques). These measurements and analyses were combined into a sediment transport model (SubNet) in order to develop a sediment budget and provide a tool for analysing the impact of changes in management on sediment loss. The methods and scales utilised and outcomes obtained in this project component are summarised in Table 5.1.

The concept behind this approach is to measure the fluxes of water and sediment across a range of scales. This allows us to not only determine the relative importance of hillslope, gully and streambank erosion, but also to determine total sediment loss at the sub-catchment scale. This is necessary as not all of the sediment that is eroded at the point or hillslope scale ends up leaving the catchment – in fact, much of this eroded sediment is re-deposited before it leaves the catchment. Determining how much sediment is eroded, and how much is redeposited, is therefore vital if we are to examine the impact of changes in land management on sediment loss. Monitoring across a range of scales also allows us to compare the rates of erosion from grazing land to other land use types.

Table 5.1: Scales of monitoring in the sub-catchment component.

Method	Scale	Erosion type	Monitoring
Microplots	0.24 m^2	Hillslope	Sediment loss under different cover levels
LFA transects	~ 10 m	Hillslope	Changes in surface condition
Runoff troughs	0.07 – 0.26 ha	Hillslope	Sediment loss from an entire hillslope
Profiler transects	~ 2 m	Gully/hillslope	Erosion on hillslopes above gullies
Erosion pins	~ 1 m^2	Gully	Rate of gully slumping
GPS monitoring	~ 10 m^2	Gully	Rate of gully extension
Air photo interpretation	10.5 – 13.5 km^2	Gully/hillslope	Total gully extent, surface vegetation cover
Stream gauging	10.5 – 148 km^2	All	Sediment loss from an entire sub-catchment

Having determined the approach to be taken, the next task was the selection of appropriate sub-catchments in which to carry out this monitoring. Results from Chapter 4 indicated that the ‘Goldfields’ country around Charters Towers was at risk of high levels of both gully and hillslope erosion (Figures 4.4 and 4.6). Because of this (and because of accessibility from Townsville and co-operation from the graziers and Landcare groups in this area) two sub-catchments near Mingela were selected for intensive study (see Figure 5.1). These catchments were the Weany Creek and Wheel Creek sub-catchments, draining parts of Virginia Park Station and Meadowvale Station, respectively.

Instrumentation of these catchments with the methods shown in Table 5.1 took place in mid to late 1999. The instrumentation described in Table 5.1 was in place in time to monitor the 1999/2000 wet season.

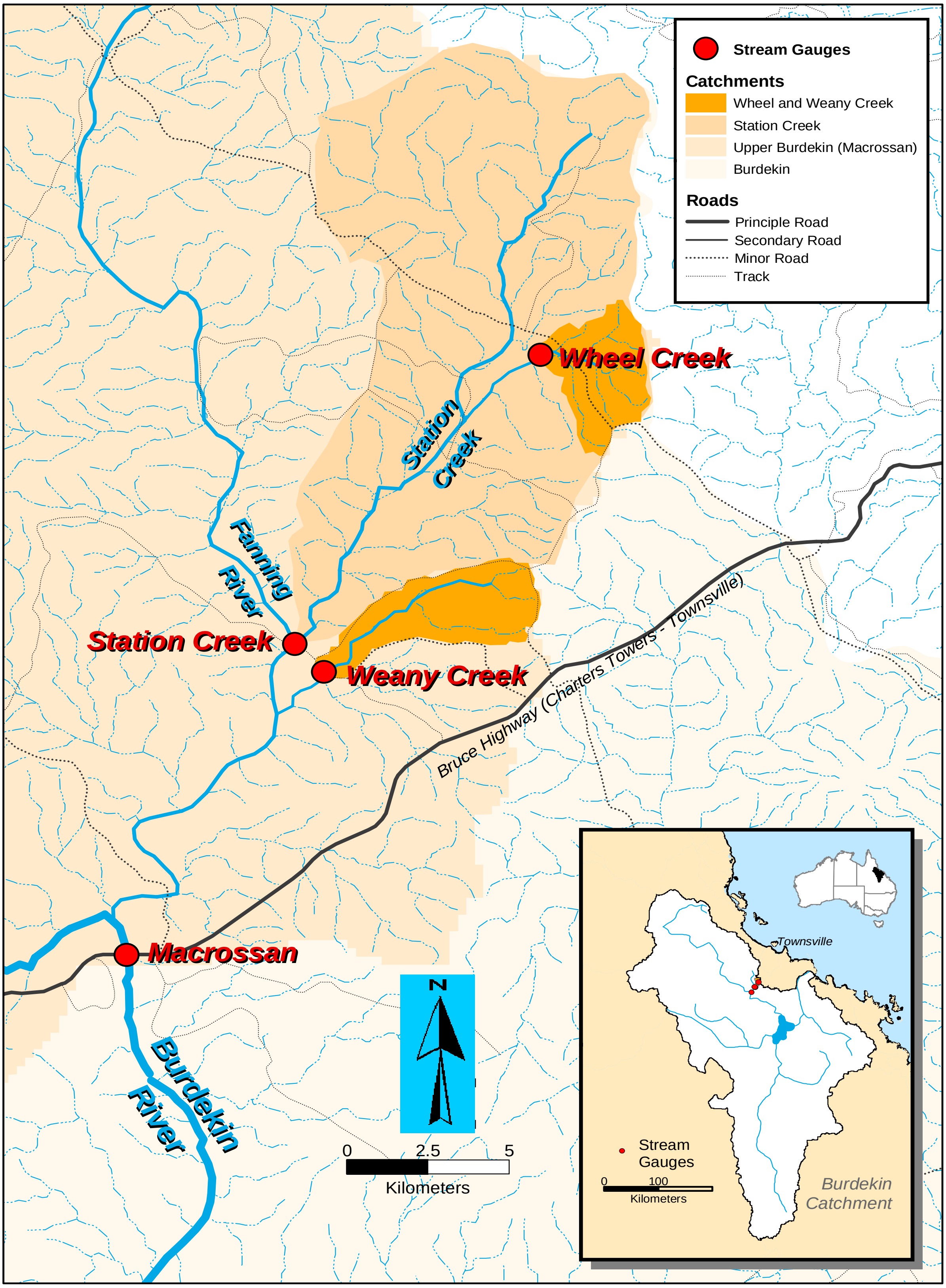

Figure 5.1: Location of the MLA Project 3.224 gauging stations.

5.3 Methods

As the monitoring occurred across a range of scales as shown in Table 5.1, this section will describe the monitoring methods across these scales, moving from the small scale to the larger scale. That is, in the same order that they are listed in Table 5.1.

Figures 5.2 and 5.3 show the location of the erosion pins, transects, microplots, GPS gully monitoring, and associated small-scale monitoring on Virginia Park (Weany Creek) and Meadowvale Station (Wheel Creek) respectively.

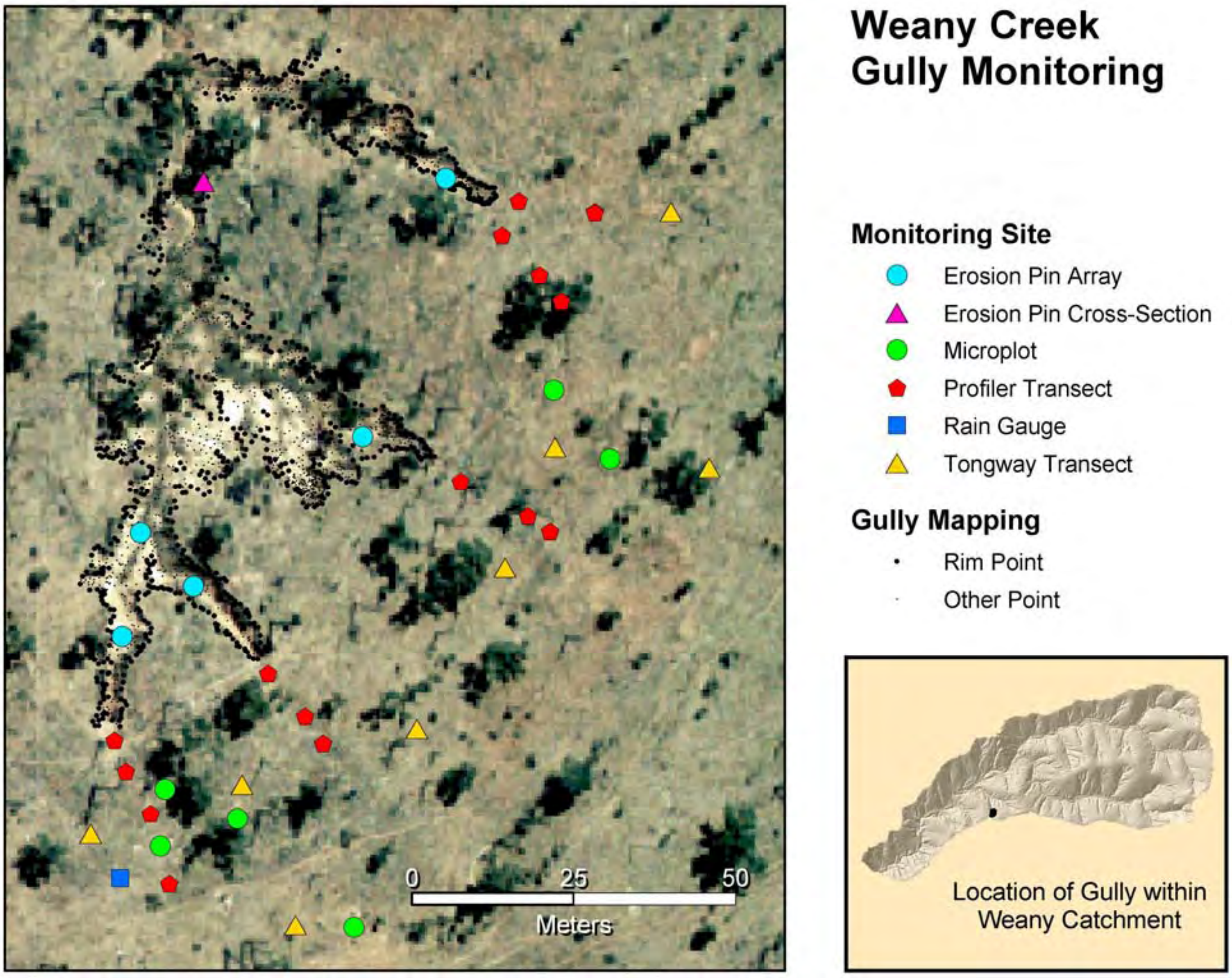

Figure 5.2: Gully and hillslope erosion monitoring in Weany Creek (Virginia Park Station).

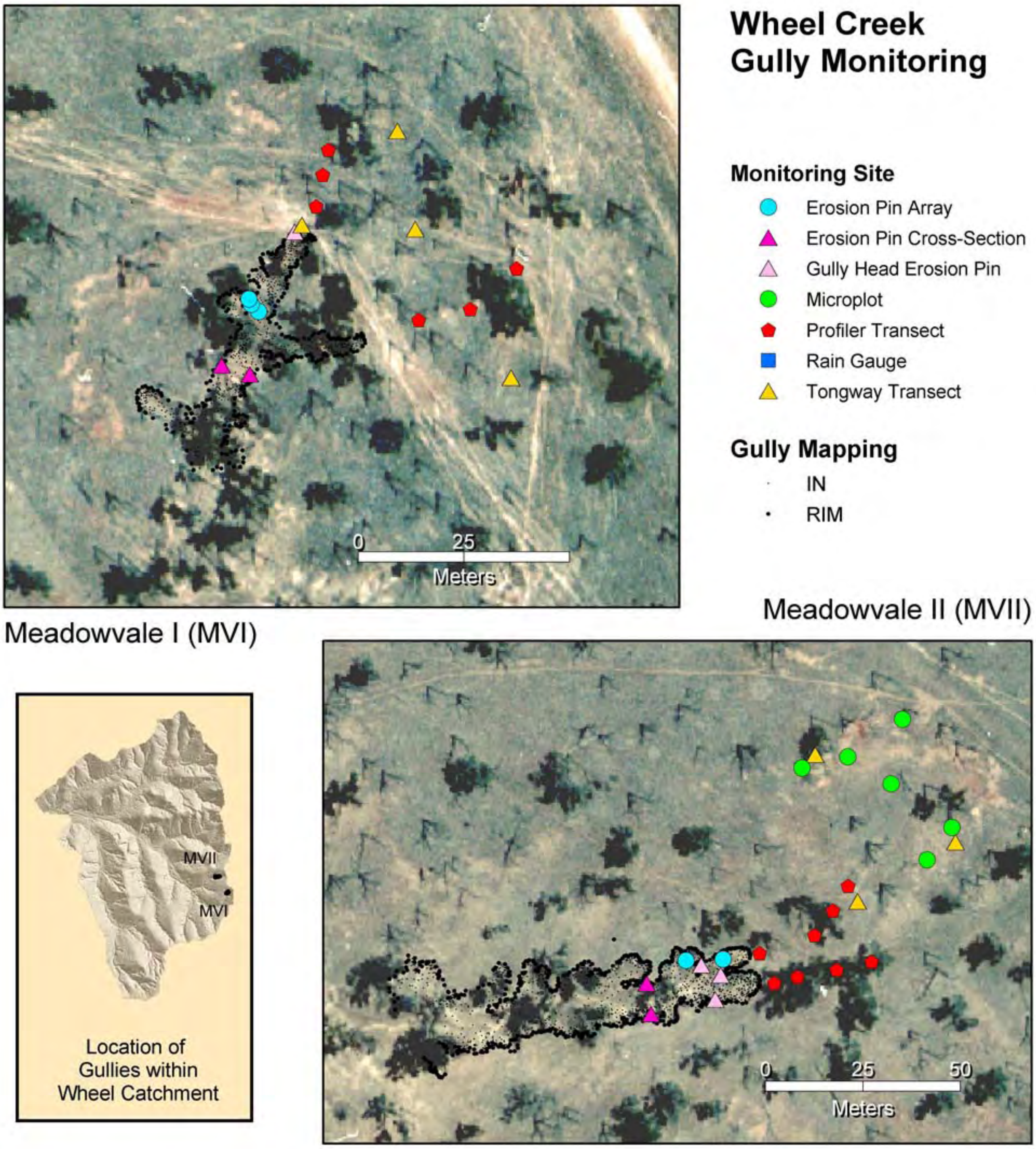

Figure 5.3: Gully and hillslope erosion monitoring in Wheel Creek (Meadowvale Station)

5.3.1 Hillslope monitoring

Microplots

At the point scale, the first problem is to estimate the fine sediment dislodged from hillslopes through rainsplash and overland flow. This was achieved through the use of 'microplots', 0.24 m^2 plots that monitor the suspended sediment concentration and total volume of runoff during a rainfall event. Size of the microplots was selected to match the size of the runoff plots used in the rainfall simulation experiments discussed in Chapter 7. Rain falling on the microplot (seen in the foreground in Figure 5.4) runs into the trough at the bottom of the plot, carrying suspended sediment with it, and is captured in the storage drum seen in the background. Appendix 2 (Volume II) gives a full description of the microplot methodology. A total of 12 microplots were set up (Figures 5.2 and 5.3), 6 on Virginia Park and 6 on Meadowvale Station. These microplots covered a range of cover types as can be seen from the very low cover and very high cover plots in Figure 5.4. Samples were collected from these microplots after major rainfall events, and analysed for volume, turbidity, pH, electrical conductivity, and total suspended solids.

Figure 5.4: Microplots on Virginia Park Station.

Landscape Function Analysis (LFA) transects

These 10 m long transects were taken on representative areas of the Weany and Wheel Creek monitoring areas, generally above the runoff troughs (see below), or immediately above gullies (see Figures 5.2 and 5.3). Within each transect, we measured soil surface condition and the size and connectivity of covered and bare patches in order to provide information about the quality of the soil cover. These data have only been used qualitatively at this point in time. However, it is anticipated that future analysis and refinement of these techniques (in conjunction with their developer, Dr David Tongway of CSIRO Sustainable Ecosystems) will lead to improved ways of deriving soil health and erosion potential.

Runoff troughs

At the hillslope scale, we monitored the discharge of water and fine sediment from four micro-catchments ranging in area from 0.07 to 0.26 hectares. By comparing these results with those obtained at the microplot scale (above), we are able to estimate what proportion of eroded sediment is transported not just 30 cm, but hundreds of metres, and is therefore capable of being exported from the catchment. This proportion varies with cover and slope.

Originally we attempted to do this by re-instrumenting a series of runoff troughs on Cardigan station. However, after the 1999-2000 wet season, we discovered that the runoff in these troughs could not be related to the cover characteristics of the catchments being drained by the troughs. This was because the troughs drained areas that had been used for pasture manipulation by CSIRO Tropical Agriculture, and thus the areas contained a number of different cover types. Nevertheless, this work at Cardigan Station proved to be a useful pilot study.

In 2000, a number of runoff troughs on Meadowvale Station were re-activated. These runoff troughs are located just out of the eastern edge of Wheel Creek catchment, immediately to the right of MVI in Figure 5.3. Queensland Department of Primary Industries (QDPI) built them in the mid-1980's and details are reported in Scanlan et al. (1996). At the Meadowvale site, they required little work to be re-activated. An example of one of these troughs is shown in Figure 5.4. Water flowing over the surface is intercepted by this runoff trough and channelled into the pit seen at the far end of the trough. Here a proportional sample is taken for water quality analysis, and a tipping bucket records the total volume and timing of the discharge. Samples were collected from these runoff troughs after major rainfall events, and analysed for turbidity, pH, electrical conductivity, and total suspended solids. Additionally, the coarse sediment collected in the troughs was removed after two years in order to provide an estimate of bedload movement.

Figure 5.5: Runoff trough on Meadowvale Station.

Profiler transects

Above each monitored gully shown in Figures 5.2 and 5.3, a series of 'profiler transects' were set up. These transects measure change in surface elevation by measuring the distance from the instrument to the ground (Figure 5.6). These measurements are highly accurate and can determine changes in surface elevation of just a few millimetres. At the beginning and end of each wet season, the profile meter was used to measure the change in surface elevation, and therefore rates of erosion and deposition. These profiles allow us to measure hillslope erosion immediately above the gully, where concentration of surface flow can lead to rates of erosion much higher than found elsewhere on the hillslope.

Figure 5.6: Profile meter in operation on Meadowvale Station, set up in a drainage line upstream of a gully head.

5.3.2 Gully monitoring

After water flows across the hillslope, if it is to be lost from the catchment, it must enter the drainage system at some point. Normally this occurs when water flows into a gully. However, in addition to concentrating flow, gully systems can also act as significant sources of sediment, with erosion of gully heads, slumping of gully sidewalls and gully slope erosion. This erosion was monitored through using a combination of erosion pins and global positioning system (GPS) techniques.

Erosion pins

Erosion pins were used to measure the advance of a gully head (edge pins), and gully slumping (arrays and cross section pins) - Figures 5.2 and 5.3 show the location of erosion pin arrays. Erosion pins are 30 cm long and were hammered perpendicularly into the ground, either to a depth of 20 cm (edge and array pins) or flush with the surface of the ground (cross-section pins).

Gully advance

Erosion pins were spaced 50 cm apart around the edge of the gully head, at a distance depending on the anticipated advance of the gully. Pins around the gully head were placed further from the gully than those along the gully sides to allow for more rapid rates of erosion. Figure 5.7 shows an example of pins located along a gully side on Meadowvale Station. At the beginning and end of each wet season, the distance from the erosion pin to the edge of the gully was measured. Differences between one measurement and another gave the rate of gully advance.

Gully slumping

Generally 25-30 pins were placed on a 500 x 500 mm grid at various locations in and around the gully. Gully banks, floors, and scalds were targeted with this form of monitoring. Similarly, cross-sectional arrays of gully pins were set up, spanning the gully width at 500 mm intervals, perpendicular to flow. At the beginning and end of each wet season, the length of the exposed pin was measured using an electronic digital calliper. Here, differences between one measurement and the next gave the rate of erosion or deposition.

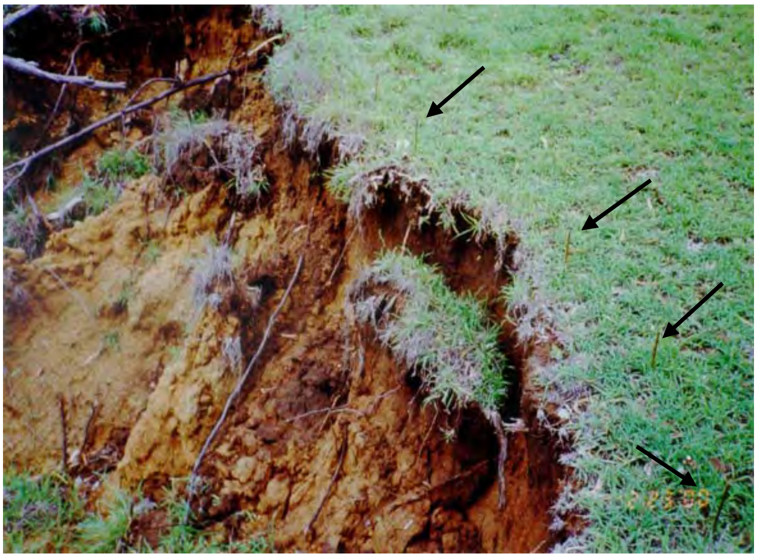

Figure 5.7: Erosion pins for monitoring gully advance on Meadowvale Station. Arrows indicate position of pins. Gully head advance is measured perpendicularly from the pin to the gully edge.

GPS techniques

To determine the change in volume of each gully over the wet season, a kinematic global positioning system (GPS) was used. This instrument is highly accurate and can determine movements of 2.5 cm. An example of the GPS gully data can be seen in Figures 5.2 and 5.3. A GPS survey was conducted at the beginning of each wet season. Changes between seasons allowed us to determine the change in gully volume from year to year. This technique also provided a valuable back-up to the edge pin monitoring above, as when erosion exceeded expectations, and the edge pins disappeared into the gully, the GPS data could be used to determine the rate of gully advance.

Air photo interpretation

Air photo interpretation was used in three ways – to determine the total extent of gullies; to determine the growth of gullies through time (gully chronosequence); and to determine surface cover conditions to calculate hillslope erosion.

Gully extent

To determine the total extent of gullies in Weany and Wheel creeks, air photos were flown in the year 2000 at a (high) resolution of 1:8,000. Observation of these photos under a stereoscope allowed gullies to be identified. These photos were then scanned and ortho-rectified so that the gullies could then be mapped and converted into GIS layers.

Gully chronosequence

To determine the growth in gullies through time, a series of air photos were examined, and the gullies on them identified and mapped. This was done for air photos purchased from Department of Natural Resources and Mines (DNR&M) for the years 1945, 1961, 1975, 1981, 1990, and our photos, taken in 2000.

Surface cover

Cover was classified by creating a vegetation index from the 25 cm pixel scanned colour air photos (captured September, 2000) for the Weany and Wheel Creek catchments. A cover factor term was then assigned to each index class. To obtain the vegetation index, the PD54 (Pickup *et. al.,* 1993) method was employed on a 2 m pixel re-sampled photo mosaic. PD54 differentiates between vegetation cover and bare soil by comparing reflectance of red and green visible light. This index was used in the SubNet model to calculate the hillslope erosion component.

5.3.3 Stream gauging

The final measurement of the loss of water and sediment from a catchment can be taken at the mouth of the catchment. As shown in Table 5.2, we instrumented three creeks in order to determine the total discharge of water and sediment from them. Water depth, velocity, turbidity, and suspended sediment concentration were monitored at these sites.

Depth of water is monitored using a *Dataflow* pressure transducer, velocity is measured using a *Starflow* doppler velocity meter, turbidity is measured using a *Greenspan* turbidimeter, and suspended sediment concentration is measured by taking a sample in an *ISCO* sampler, sieving and drying it in order to determine the weight of suspended solids in the sample.

Two types of gauging station were constructed as part of this study. These are shown in Figures 5.8 and 5.9. The original design, shown in Figure 5.8 incorporated a series of bottles which were designed to fill as the level of water in the stream rose, and then close as the water level went higher. A system of floats and magnets ensured that the sample was not contaminated after collection. While this system worked well during the 1999/2000 wet season, it was augmented in 2000 through the addition of an automated ISCO sampler. Later designs (as represented in Figure 5.9) lacked the bottles and were thus more streamlined. A comparison of results from these two sampling systems may be found in Section 5.5. In the foreground of Figure 5.9 can be seen the velocity meter, turbidity sensor, depth sensor and ISCO pump inlet, while in the background can be seen the tower containing the electronics and pump for the ISCO sampler.

Figure 5.8: In-stream monitoring gear in Weany Creek (Virginia Park Station). Downstream end of mechanical sampler opened to expose the rising stage sampling bottles. Turbidity probe mounted on the left base of the mechanical sampler. Flow velocity meter can be seen protruding from creek bed a few meters upstream of the sampler.

Appendix 3 (Volume II) gives a detailed description of the work required to install gauging stations in Weany and Wheel creeks. Data have been collected in these two sub-catchments from the 1999/2000 wet season onwards. Appendix 4 (Volume II) contains all of the processed data from Weany and Wheel Creeks, that is, discharge and suspended sediment load. The steps taken to transform the raw depth, velocity, turbidity and sediment data collected in Weany Creek into discharge and suspended sediment load are described in Section 5.5.1.

Figure 5.9: In-stream monitoring gear in Station Creek (Virginia Park Station). Flow velocity meter on left, turbidity sensor and auto-sampler intake on the right hand side. Auto-sampler and rain gauge on the platform in background.

In 2001, a decision was made to also gauge Station Creek, a much larger catchment (see Table 5.2). This decision was made in order to determine how much of the sediment leaving the smaller creeks was transported through Station Creek (i.e. to derive scaling principles). Similarly, during the extension phase of the project, a turbidity sensor was placed on the Burdekin River at Macrossan Bridge in order to determine the fluxes of suspended sediment from the upper Burdekin catchment. Data have been collected from these two sites from the 2001/2 wet season onwards. It is hoped that these data will provide information on scaling, determine whether the Weany Creek and Wheel Creek sub-catchments are representative of the Upper Burdekin, and provide estimates of the total export of suspended sediment from grazing lands into the Burdekin Falls Dam. Currently, however, with just one wet season worth of data, little can be made from the data at these two sites.

Table 5.2: Stream gauges operated in the Burdekin River catchment by CSIRO Land and Water (Davies Laboratory). Catchments funded by this study are shown in red.

Catchment	Funding	Dominant land use	Area (km^2)
Wheel Creek	MLA	Grazing	11
Main Creek	TFTA	Military	13
Weany Creek	MLA	Grazing	14
Thornton Creek	TFTA	Military	84
Fanning River West Branch	TFTA	Military	146
Station Creek	MLA	Grazing	148
Keelbottom Creek	TFTA	Military/National Park	1,170
Burdekin River	MLA	Grazing	36,390

An associated CSIRO project, funded by the Department of Defence, has allowed us to instrument a further four sub-catchments in the Townsville Field Training Area (TFTA). While data collection has only just begun at these four sites, they will provide useful baseline data from catchments without grazing activities. This will allow us to more accurately assess the impact of cattle grazing on hydrologic response and sediment export at the sub-catchment scale. The stream gauges operated by CSIRO Davies Laboratory are shown in Table 5.2. These stream gauges cover a wide range of catchment sizes, from 11 km^2 to 36,390 km^2. It is worth noting that the Main Creek sub-catchment is also located within a granodiorite landscape and corresponds to Weany and Wheel Creek. However, it is in better condition than the latter two (predominantly covered by perennials and little to no Indian couch), and since 1999, cattle have been removed from TFTA, so that we expect over time to be able to compare grazing vs. non-grazing by comparing the two MLA sub-catchments with Main Creek.

5.4 The SubNet model

While much of the monitoring described above was needed in order to measure the rates of erosion and transport of sediments at the sub-catchment scale, it was also required to provide inputs for a sub-catchment scale sediment transport model.

The SubNet model is an offshoot and modification of the SedNet model described in Chapter 4. It allows us to take advantage of the more detailed data we have collected at the sub-catchment scale. Where SedNet had to use broad generalisations to determine gully erosion, for example, SubNet makes use of the detailed gully mapping that has been carried out in the Weany Creek catchment. It is also calibrated, in that the outputs from the model have been compared with and calibrated to the outputs of water and suspended sediment from the catchment.

Analogous to SedNet, SubNet is an integrative tool. It provides a way of determining a sediment budget at the sub-catchment scale. It also allows us to carry out property management scenarios, for example, "what happens to sediment loads if cover is increased to 70% in one particular paddock draining into a catchment?" and more importantly, is seen as a potential tool for use in future target setting exercises as part of the National Action Plan for Salinity and Water Quality.

The model has been calibrated in the Weany Creek catchment, and we plan to extend its application to Wheel Creek, and a new sedimentary-country catchment in the next 4 years (during the new MLA project).

5.4.1 Stream network

As described in Section 5.3.2 above, a set of low altitude air photos were flown for the Weany Creek catchment. Using these air photos, a 5 metre resolution digital elevation model (DEM) and colour digital orthophotos at 25 cm resolution were generated. This DEM was used to generate a stream network divided into reaches (called links). The resulting stream network can be seen in Section 5.5.3 (Figure 5.29). Connectivity, channel gradients, and stream type information were attached to each link at this time. Channel widths for each stream link section were measured from the air photos and input directly into the SubNet database. Channel width, in combination with the stream slope derived from the DEM and discharge determined from the stream gauging (Section 5.3.3 above) was used to assign a stream power to each stream link.

Unlike SedNet, the scale of SubNet means that there are no large reservoirs or lakes, nor are there significant floodplains. Because these depositional areas do not exist in SubNet, essentially all fine sediment in the SubNet stream channels (except the course bedload) will be transported out of the catchment.

The main improvement of SubNet over SedNet is in the modelling of hillslope, gully, and bank erosion at higher resolution at the sub-catchment scale. These improvements are discussed in the following sections.

5.4.2 Hillslope erosion

Hillslope erosion was determined using the Universal Soil Loss Equation (USLE), in which:

Soil Loss (t/ha/yr) = R * K * L * S * C * P

These factors are defined below. Each factor was determined across a regular 5 metre grid within the catchment, maintaining a spatial context for soil loss determination.

R = Rainfall Erosivity

We used an average value based on the erosivity grid created for the National Land and Water Resources Audit (NLWRA) – see Lu *et al.* (2001). For Weany Creek the average value of R was 2722 $MJmmha^{-1}hr^{-1}yr^{-1}$.

K = Soil Erodibility

The Weany Creek catchment is mapped as Dalrymple Soil Association according to the Dalrymple Land Resource Survey (1:250,000). A K factor of 0.03 was estimated for this soil association and applied as a constant K factor for the entire catchment. This value was the same one used in the NRIC grid used in the MLA scoping study by Roth et al., 1999.

LS = Slope and Length factors

As discussed in Chapter 4, for grasslands and woodlands the hill-length term (L), relating runoff volume (and thus eroding power) to increasing hill-length, was considered unnecessary and was removed from the analysis.

The slope term S considers angle of slope. This is because soil erosion increases with increasing slope. The angle of slope for each DEM grid cell in Weany Creek was determined using an ARCINFO Grid function called Slope (http://www.esri.com/) applied to a 5x5 metre pixel smoothed DEM. Slope angle for a cell is measured using a 3x3 matrix of grid cells. Slopes in Weany Creek catchment are gentle and, although ranging from 0% – 66%, the average slope was 4% with a standard deviation of 2.5 (see Figure 5.16).

C = Cover factor

Vegetation cover was classified by creating a vegetation index from the 25 cm pixel scanned colour air photos as described in Section 5.3.2. Derived ground cover for the Weany Creek catchment is shown in Figure 5.10.

P = Land use practice factor

This accounts for the effects of contours, strip cropping or terracing. As these are not practiced in the Weany Creek catchment, this factor was not used.

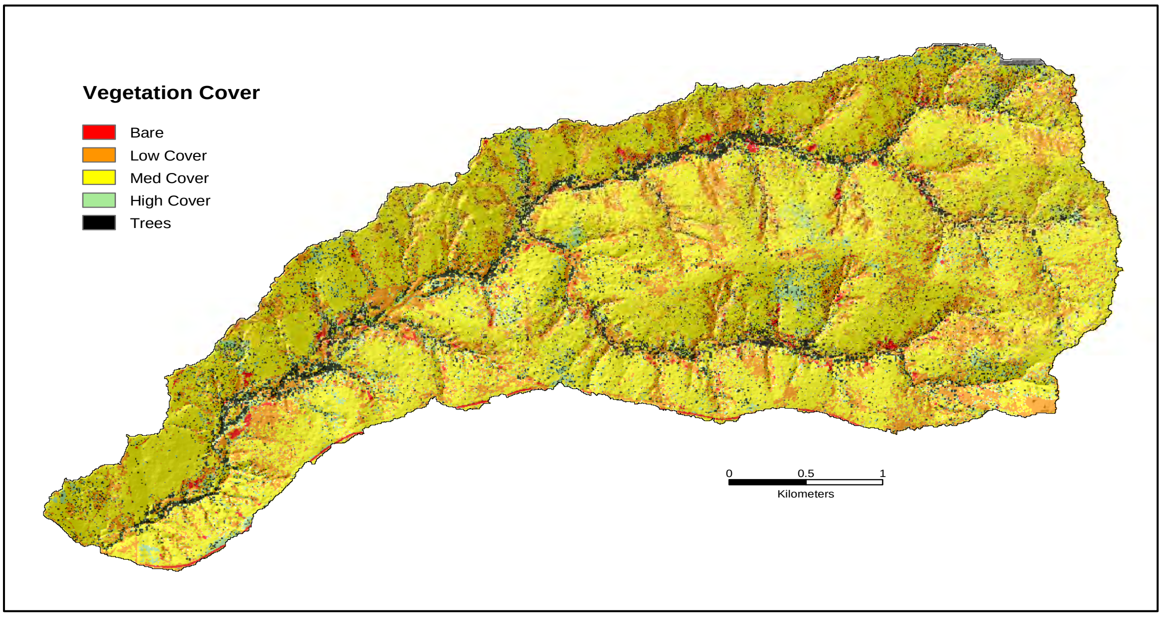

Figure 5.10: Ground cover in Weany Creek as derived from aerial photography classification.

An attempt was made to correlate vegetation cover index values with field site data (over 600 measurements taken in November 2000 from 13 transects; see Chapter 6 for details). Cover for each site had been measured visually from above as a percentage cover over a $1m^2$ BOTANAL plot area. However, as discussed in Chapter 6, correlation was poor and could provide no assistance in providing calibration data for the vegetation index. The reason for this poor correlation needs further investigation, planned as part of the ongoing project. The two datasets are at a different scale, yet the poor correlation persisted even when the air photos were re-sampled at a coarser scale.

Despite the current imperfect match with field data, the vegetation index appeared to show expected patterns. That is, areas of known scald showed up as low cover, while areas of rubbervine infestation near the stream showed up as high cover. Because of this, as a first approximation, we were sufficiently confident in classifying ground cover into 5 categories. We then assigned what we considered “typical” cover factors in the USLE (where higher values mean more erosion) for each cover class to create a grid of C values:

Cover Class	Proportion of area	Cover factor
Trees	16%	0.01
High cover	16%	0.01
Medium cover	41%	0.1
Low cover	24%	0.4
Bare ground	3%	0.5

5.4.3 Hillslope delivery ratio (HSDR)

HSDR, the hillslope delivery ratio is a measure of how much of the sediment mobilized from a site is actually delivered into the drainage system across the intervening hillslope. In SedNet, HSDR was set to a constant value (10%, see section 4.3.1).

For the Weany Creek SubNet model, we chose to make the HSDR spatially variable. This allows us to better define the sources of hillslope erosion at the paddock scale.

A spatially variable HSDR was estimated by examining the distance from each point in the catchment to a drainage channel and then assigning a ratio to each grid cell based on an inferred relationship between distance and HSDR. Euclidean distance (the straight line distance between the creek and a selected point on the slope) was related to HSDR via the following relationship:

$$HSDR = 0.1366 \times e^{(-0.0091 \times EucDist)}$$

The HSDR resulting from application of this relationship is shown in Figure 5.11. This relationship provides agreement with the following observations:

- HSDR has an inverse exponential relationship to distance from drainage (Lu, pers. comm.);
- HSDR has reduced to 5% by around 100m from the stream;
- HSDR is negligible (1% or less) after about 300m from the stream;
- The average HSDR for the catchment is approximately 5%.

A 5 m wide buffer alongside the streams and gullies was set to zero. This is because based on field observations all of the erosion occurring within 5 m of the stream or gully in Weany Creek is mainly gully or streambank erosion.

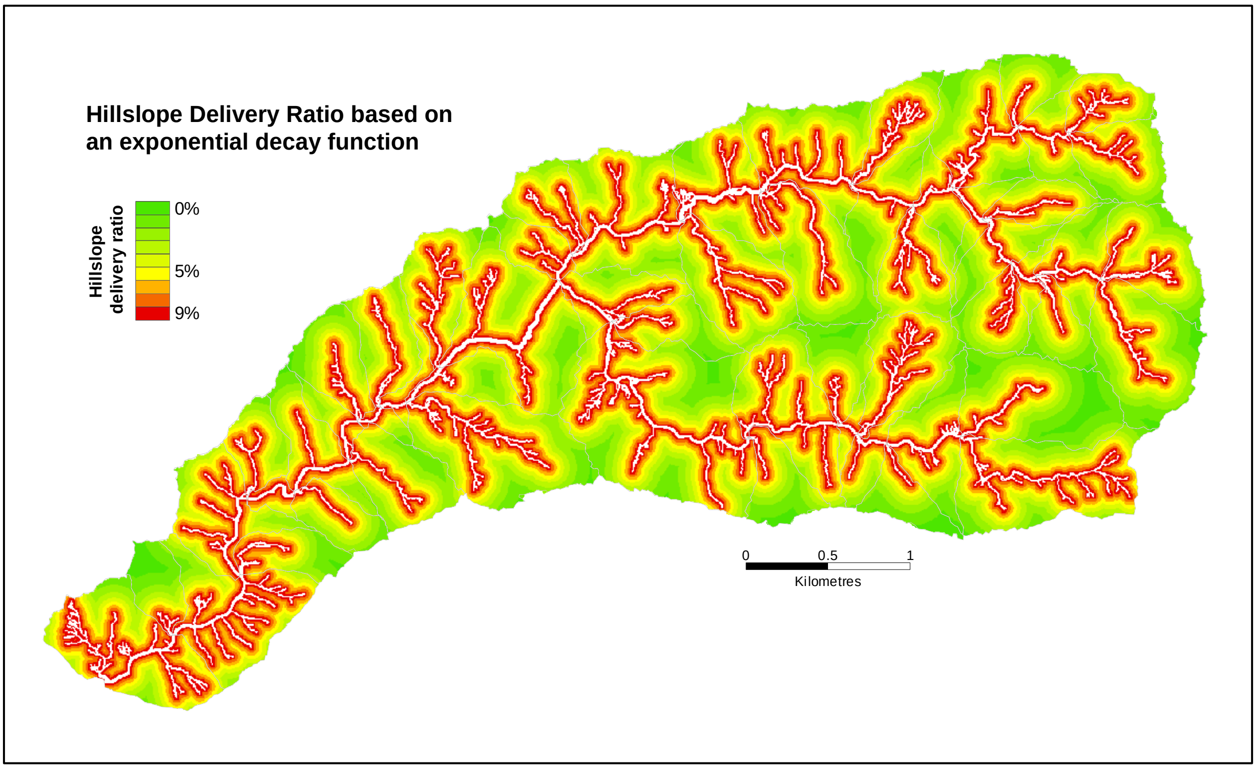

Figure 5.11: Spatially variable hillslope delivery ratio in relation to the stream network in the Weany Creek catchment.

5.4.4 Gully and bank erosion

Because of the relatively small size of the Weany Creek catchment, we were able to map individual gullies and divide them into head, middle and valley sections, where each represented a different erosional regime. Three main processes are responsible for the addition of sediment through gully erosion – gully head advance, gully sidewall slumping and sidewall sheet erosion when the sidewall has started to flatten in older sections of the gully. In the following, for convenience the latter two are lumped, defined as all inputs of sediment through sidewall retreat and flattening of the gully profile and termed 'gully slumping'. As a result of this overall approach, rather than estimating total gully length per catchment based on a gully density estimate as is done with SedNet, we were able to include measured gully characteristics directly into SubNet, greatly refining the gully erosion estimates when compared to SedNet. The gully sections that we identified are:

Gully heads – top 23% of the gully – these are the most active part of the gully, where the most slumping occurs, and where all of the gully head advance takes place, walls are vertical or nearly so;

Gully middles – middle 38% of the gully – these still have a significant amount of slumping, although the walls tend to slope at a lower angle;

Gully valleys – bottom 39% of the gully – these behave more like a stream, and in general have less slumping than either of the categories above;

Streams – derived from the 1:250 000 map sheet – rates of stream bank erosion are assumed to be the same as in gully valleys.

The sub-division of the stream network into these gully types may be seen in section 5.5.3 (Figure 5.29).

Measurements of gully head migration and gully slumping (described in Section 5.5.3) were then used to provide the inputs of sediment from gully erosion into the SubNet model.

5.5 Results and discussion

5.5.1 Sub-catchment water and sediment yields

Depth and velocity of water, turbidity and suspended sediment concentration was collected for all events in Weany and Wheel Creek for three wet seasons, and for Station Creek and Burdekin @ Macrossan for one wet season. An example of these data are shown in Figure 5.12.

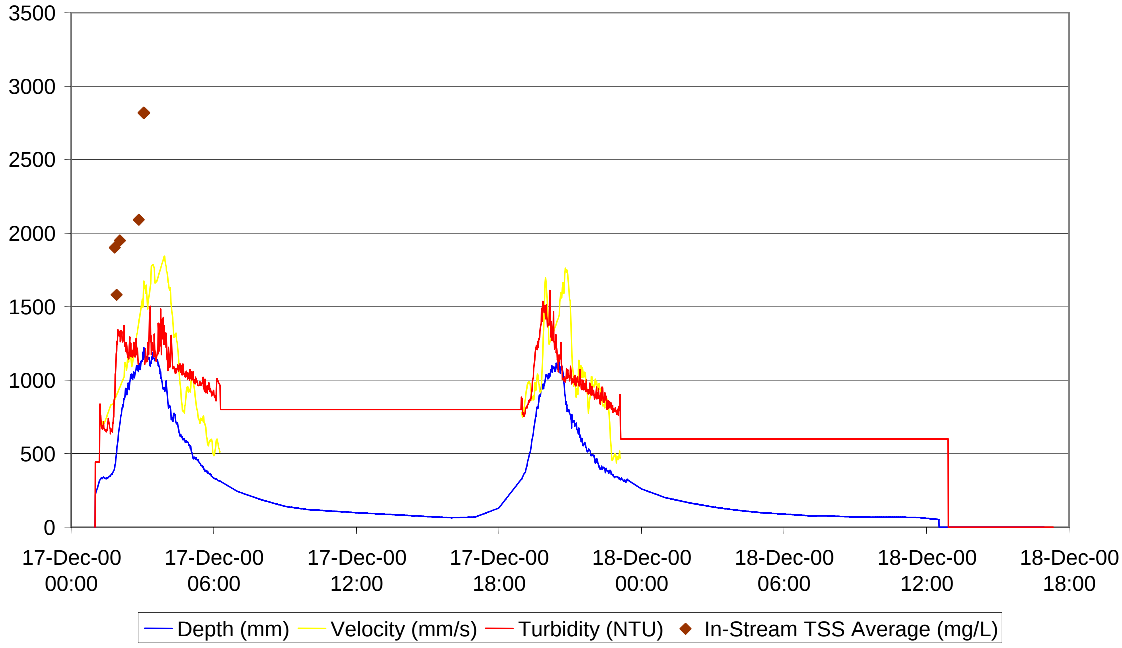

Figure 5.12: Raw data collected in Weany Creek gauging site on 17 – 18 December 2000.

To calculate the discharge of water from a catchment, the depth of water was multiplied by the velocity of water by the cross-sectional area of the stream at each time step (one minute in this study). The depth and velocity data were first smoothed over a 5 minute period in order to remove sharp, unrealistic rises and falls caused by errors in the measuring instrument. Errors may arise in this calculation due to errors in the following:

- the measurement of depth (very small – less than 10 mm);
- the measurement of velocity (moderate – perhaps as high as 100 mm/s);
- changes in, and errors in the measurement of the cross-sectional profile (very small – less than 10 mm per point, and likely to average out across the profile;
- rating curve, used when the depth of water is less than 300 mm (small, less than 2% total error);
- converting the velocity in the middle of the stream to a velocity across the rest of the profile. This is where most of the errors will be introduced, and could be significant.

Overall, the error in discharge is probably less than 20% of the total discharge. This is around twice the error found at gauging stations operated by the Department of Natural Resources and Mines, and is mostly due to the conversion of velocity in the middle of the stream to a continuous profile across the stream. Measurements of the cross-sectional velocity profile were made in Weany Creek during an event on 15 February 2002 (see Appendix 4, Volume II), which has reduced these errors significantly. However, because of the intermittent nature of flow in these creeks (flowing for less than 6 hours at a time, a few times per year), similar measurements have not yet been made in Wheel Creek. This 20% is therefore an upper estimate. Overall, we would expect the error in discharge to be no more than 10% of the total discharge, especially in Weany Creek.

The measurement of turbidity shown in Figure 5.12 was then converted into a suspended sediment concentration. It will be seen that turbidity (and velocity) is only measured when there is more than 300 mm of water in the stream. Thus, when there is less than 300 mm of water in the stream, the turbidity needs to be estimated as shown in Figure 5.12. While this does introduce another source of error into the determination of suspended sediment discharge, it is only a minor one, as (for example) in Weany Creek over the period 1999-2002, only 11.5% of the water and 7.6% of the sediment was discharged when the water level was lower than 300 mm. By far the vast majority of the water and sediment is discharged during the peak of the event.

Comparing turbidity with suspended sediment concentration in Weany Creek for the 2000-2001 wet season (Figure 5.13), we see that there are two distinct relationships – one for the sediment samples taken from the in-stream bottles (blue diamonds), and another for the sediment samples taken from the ISCO sampler (red squares). We believe that the in-stream samples show a greater variability because a significant standing wave is set up behind the sampler during large flow events. This would be expected to pick up sediment from the bed of the stream and deposit it in the bottles (remembering that the bottles are always filled up at the top of the water column (see Figure 5.8). As the ISCO samples are all taken from 300 mm above the bed of the stream, this standing wave would have much less effect on them (Figures 5.8 and 5.9). It would also ensure greater consistency between ISCO samples and therefore less variability.

As the ISCO samples are taken from lower in the water column, it may be thought that they would have higher suspended sediment concentrations than samples taken from the surface of the water, however, Figure 5.13 shows the reverse to be true – the suspended sediment concentration of the ISCO samples are actually lower than that of the in-stream samples. We believe the reason for this may lie in the ISCO sampling mechanism. The sample collected by the ISCO pump requires the water sample to travel up a 5-10 m vertical tube before sampling. This forces the heavier suspended sediment to drop out of the sample before it is collected. This may also explain the greater variability seen in the in-stream samples, as this heavier component may show greater variability than the lighter fraction.

While there is still some discussion as to which sample is more representative, in the current analysis, it is the relationship created using the ISCO samples, which has been used. This is because the ISCO sampler is a widely used hydrological tool and use of this relationship ensures greater consistency with other studies undertaken in Australia and around the world.

It is interesting to note in Figure 5.14 that the same difference is not seen in Wheel Creek. Here, the in-stream samples show greater scatter than the ISCO samples, but approximately the same relationship. Also, the relationship derived between turbidity and SSC from the ISCO samples is almost identical in Wheel and Weany Creeks (the red lines and equations in Figure 5.13 and 5.14). This lends support to the use of the ISCO samples, and suggests that the relationship we have used is the correct one. It may be some characteristic of the sampling design at Weany Creek that has led to the unusual behaviour of the in-stream samples.

Data are being collected in 2002/3 to compare the in-stream and ISCO samples to attempt to determine the underlying cause of this discrepancy and to determine which relationship is more valid. It is possible though unlikely that the ISCO sampler is slightly under-estimating the total suspended sediment concentration of the water.

Having chosen a relationship between turbidity and SSC, we then used the continuous turbidity time series to calculate a continuous SSC time series. Multiplying this time series by the time series of discharge allowed us to determine the continuous discharge of suspended sediment. An example is shown in Figure 5.15. Hydrographs for all events on Weany and Wheel Creek are compiled in Appendix 4 (Volume II).

The gauging sites on Weany, Wheel and Station Creeks, as well as the Burdekin River at Macrossan Bridge, have allowed us to determine the discharges of water and sediment from each of these catchments. These discharges are summarised in Table 5.3, along with data from Thornton Creek, an ungrazed catchment in the Townsville Field Training Area (TFTA). The implications of the results in Table 5.3 will be examined in the following two sub-sections dealing with water yield and sediment yield.

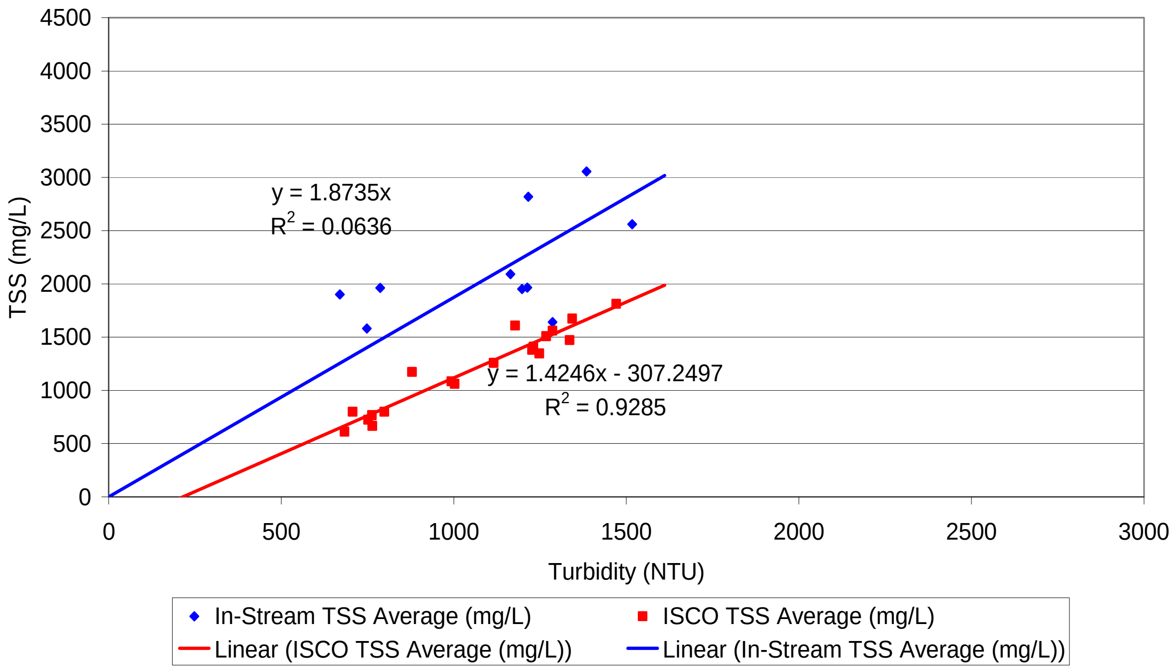

Figure 5.13: Turbidity versus suspended sediment concentration for Weany Creek 2000-2001.

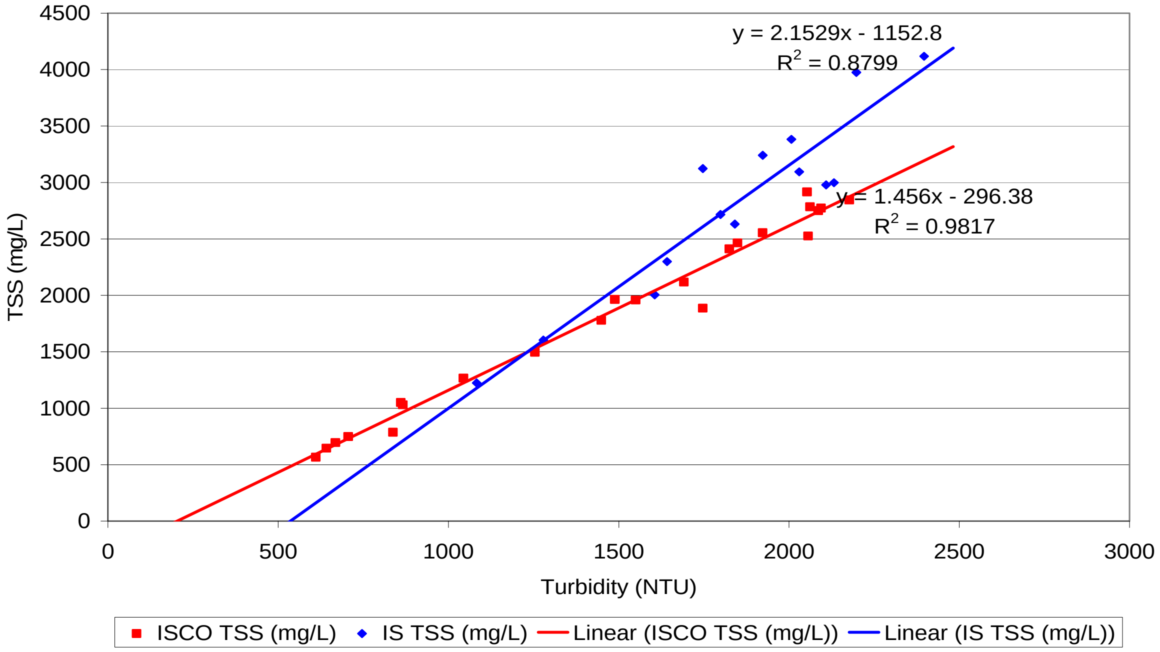

Figure 5.14: Turbidity versus suspended sediment concentration for Wheel Creek 2000-2001.

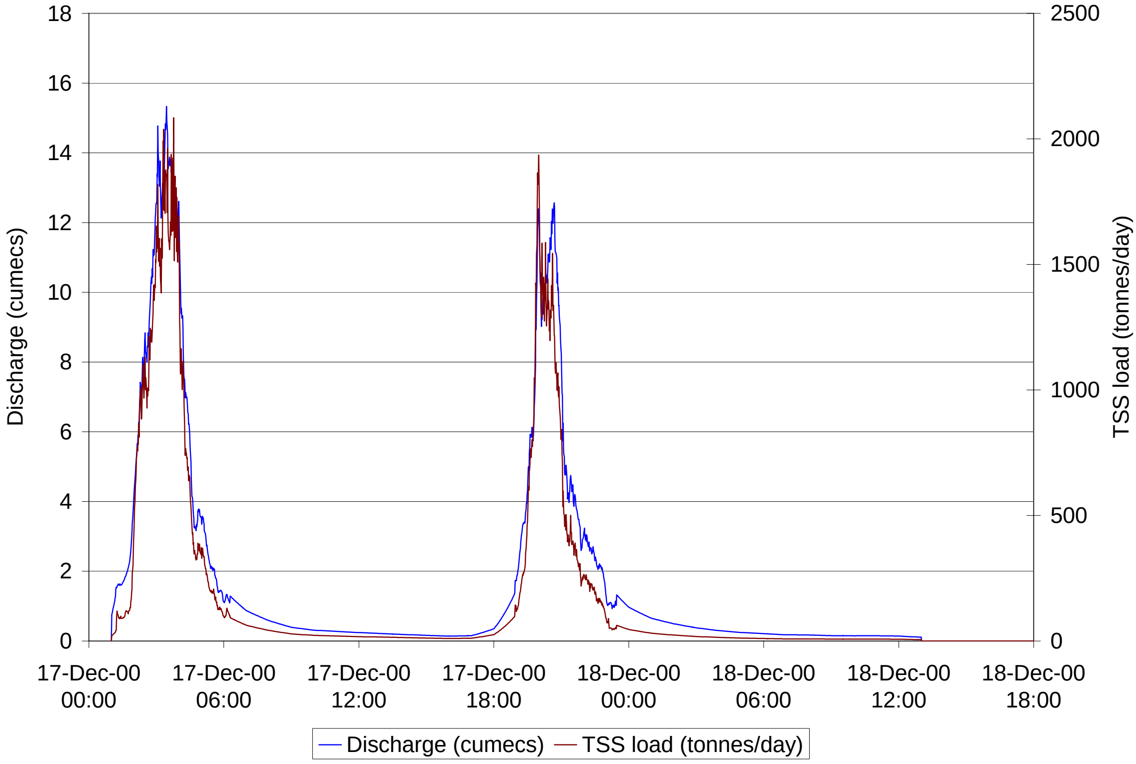

Figure 5.15: Discharge of water and suspended sediment from Weany Creek 17-18 December 2000.

Water yield

The 1999/2000 wet season was wetter than average, with precipitation at the sites being slightly above the long-term average of 648 mm at Charters Towers. By comparison, precipitation in 2000/2001 and 2001/2002 was well below average. Although rainfall was lowest in the 2000/2001 wet season, it was very uniformly distributed, allowing for continued good pasture growth in that year to carry though from 1999/2000. Despite having the lowest total rainfall in 2000/2001, both catchments had higher percent yields in 2000/2001 than in 2001/2002. This is mainly a reflection of different rainfall patterns, with more frequent, higher intensity rainfall occurring in 2000/2001. As the trends in ground cover essentially remain constant over the entire three-year monitoring period (see Chapter 6, Figure 6.6), the variations in runoff coefficients observed in Table 5.3 must be assumed to be primarily a function of rainfall characteristics. This illustrates the variability of runoff and catchment water yield for any one year, and also indicates why long-term monitoring records are required to enable more reliable separation between grazing impacts and rainfall impacts on runoff and sediment delivery.

The range of percent yield seen across these catchments (2-16%) is comparable with the yields of rangelands catchments in Northern Australia monitored by Natural Resources and Mines (DNR&M). The large variability in percent yield from year to year however implies that any change in yield due to the impact of improved management techniques may be very difficult to detect.

Comparison of these sub-catchment water yields with measurements made at the microplot and hillslope runoff scale will be carried out in Section 5.5.2.

Sediment yield

In general, Wheel Creek yielded slightly less suspended sediment (tonnes/ha) than Weany Creek over the 3 years of the study. This occurred despite Wheel Creek having a higher average suspended sediment concentration in 2000/2001. The lower sediment discharge is because Wheel Creek had a much lower water yield than Weany Creek in 2000/2001 (3% compared to 7%).

This lower yield of suspended sediment from Wheel Creek is curious, as analysis of the cover characteristics of the two catchments shows that despite Wheel Creek having slightly more tree and high cover, it has far less medium cover, and far more low cover and bare ground (see Table 5.4). Wheel Creek also has generally steeper slopes than Weany Creek. These two factors imply that Wheel Creek should yield more suspended sediment that Weany Creek. However, as discussed in section 5.5.1, given the 20% uncertainty associated with the discharge determinations at this point in time, the two differences may not actually to be significant. Also, differences in peak rainfall intensity are a key driver of runoff, and we noted fairly pronounced spatial variability between rainfall events even on short distances of several km between the rain gauges at Virginia Park and Meadowvale, so the assumption of uniform rainfall within each of the two sub-catchments may not necessarily hold, possibly explaining some of the difference observed.

Table 5.3: Discharges of water and sediment from the gauged catchments

Catchment	Rainfall	Discharge	Yield	Suspended sediment concentration (mg/L)			Load
	(mm)	(mm)	(%)	25th *	Median	75th *	(tonnes/ha)
Wheel 99/00	658	105	16	67	68	100	0.21
Weany 99/00	789	100	13	405	405	535	0.59
Wheel 00/01	387	12	3	716	1183	2166	0.15
Weany 00/01	367	24	7	548	548	832	0.29
Wheel 01/02	456	9	2	432	583	1323	0.11
Weany 01/02	576	25	4	832	1001	1689	0.42
Station 01/02	536	39	7	578	690	866	0.38
Burdekin 01/02	789	87	11	99	159	412	0.51
Thornton 01/02	134	7	5	94	144	244	0.04

* 25th and 75th percentiles

Other factors leading to differences in sediment yield could be subtle differences in catchment topography. Wheel Creek has a different ratio of headwater stream length to second order stream length within the monitored section, as opposed to Weany Creek (Figure 5.16). Also, Wheel Creek has a flatter mouth with wider riparian areas than Weany Creek, which is quite narrow and more steeply sloped at its mouth. However, the relatively low number of monitored events at this stage (a total of 10 flow events in Weany Creek, and 9 in Wheel Creek over the 3 wet seasons monitored) does not permit a final resolution of the differences noted between the two catchments, and the separation of grazing (cover), rainfall and topographic factors determining sediment yield between the two sub-catchments will be one of the unresolved issues receiving greater emphasis in the current project as more data becomes available.

The sediment yields of the larger catchments were similar to those from the smaller catchments (Table 5.3). Only Thornton Creek (the ungrazed catchment) had a significantly lower sediment yield than the others. As Thornton Creek received considerably less rainfall in 2001/2002, it is impossible to state whether this difference was due to the effects of grazing or precipitation. Subsequent monitoring over the coming years will allow us to determine if this effect is maintained, and if so, what is causing it.

Comparison of these sub-catchment suspended sediment yields with measurements made at the microplot and runoff trough scale will be carried out in Section 5.5.2.

Table 5.4: Comparison of cover and slope between Wheel and Weany Creeks.

	Cover characteristics					Mean slope (%)
Catchment	%Trees	%High	%Medium	%Low	%Bare	
Wheel	17	17	32	27	7	4.4
Weany	16	16	41	24	3	3.9

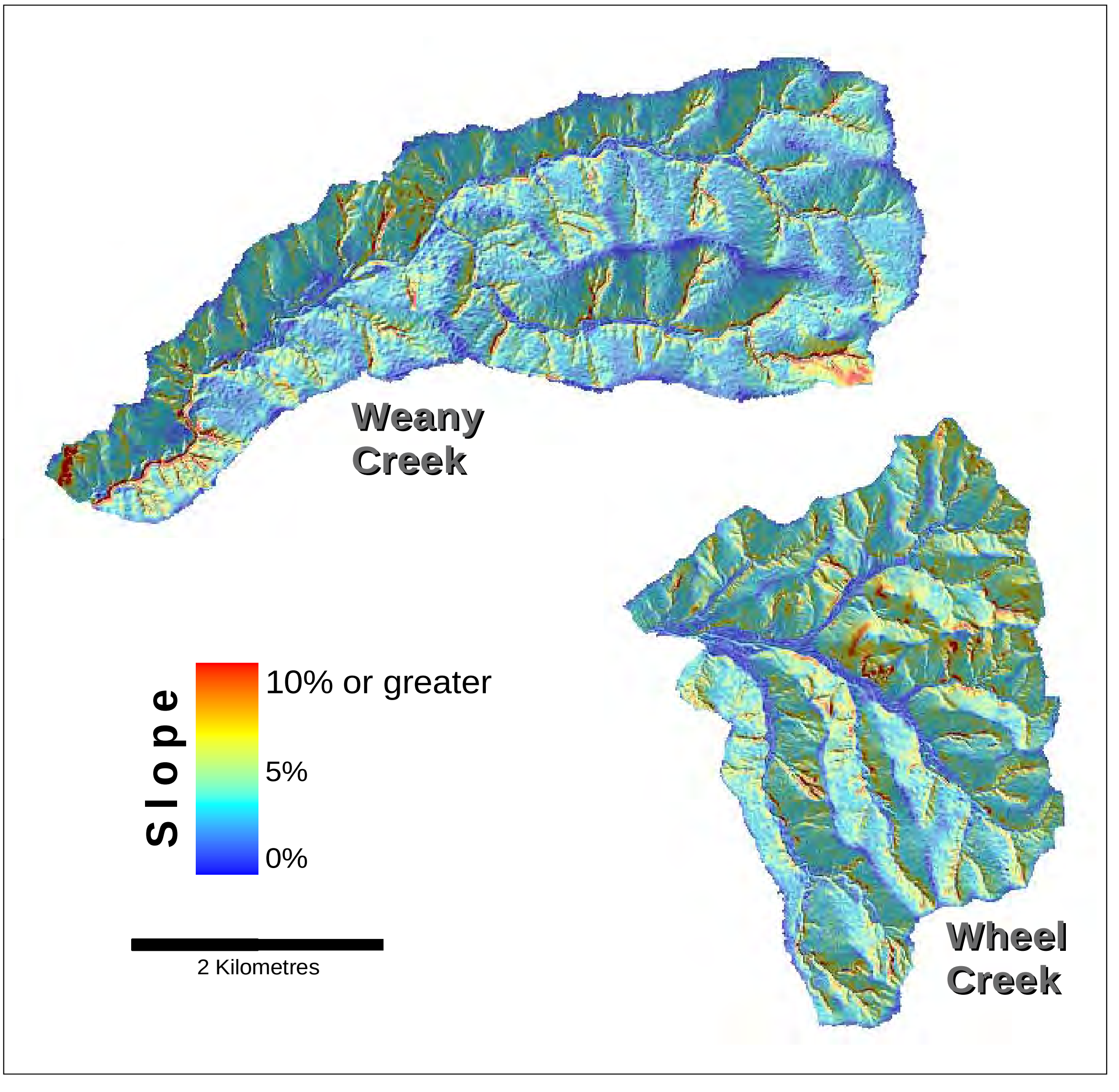

Figure 5.16: Comparison of slope for Wheel and Weany Creek. Note the flatter topography at the mouth of Wheel Creek, offering more possibility of sediment storage than the narrow, more steeply sloped mouth of Weany Creek.

5.5.2 Estimates of hillslope erosion rates

Estimates of fine sediment loss by hillslope erosion in the Weany Creek catchment have been made in two ways – firstly, by direct measurement using the microplots and runoff troughs described in Section 5.3.1, and secondly through the use of the 'Universal Soil Loss Equation' (USLE) in the SubNet model. These different approaches will be discussed and compared in the following three sub-sections.

Microplots

Water

The relationship between percent cover and percent yield for runoff coming off the microplots is not straightforward. As can be seen from Figure 5.17, an exponential decay type function only can be observed in instances with low rainfall intensity. At higher intensity, the relationship breaks down. Whilst it is possible that at high rainfall intensities, measurement errors caused some erroneous runoff sampling (see Appendix 2, Volume II), it is more likely that high rainfall amounts associated with high intensity rainfall led to saturation excess controlled runoff rather than Hortonian overland flow. This would be in line with observations made by McIvor et al. (1995), who found that a relationship between ground cover and runoff only holds for intensities <25 mm/h or rainfall amounts <50mm. This is also corroborated by the rainfall simulation results presented in Chapter 7 (Figure 7.3). So, at this stage, what we can interpret from these results is that low intensity, small rainfall (<15mm/h) events are likely to produce little runoff from well-covered patches, whereas at high intensity (>45mm/h), cover does not control runoff, and yield is more a function of rainfall properties, irrespective of cover. In addition, other factors such antecedent soil moisture is also known to be important (Scanlan et al., 1996). Insufficient data at this stage does not yet allow for a complete stratification of the data by rainfall classes, antecedent moisture and cover classes, but it is expected that this will be possible during the course of the current project.

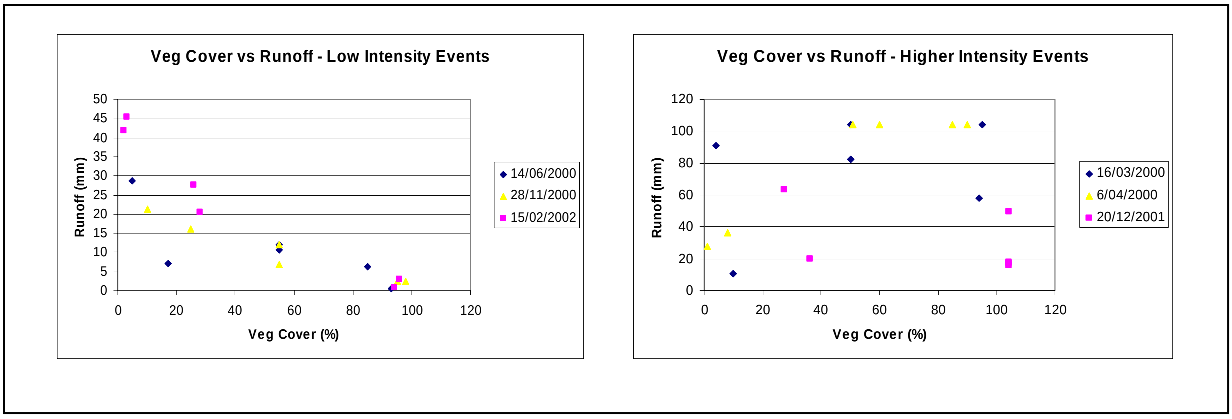

Figure 5.17: Relationship between ground cover and runoff as measured in the microplots, for events with low rainfall intensity (left side) and high rainfall intensity (right side).

Sediment

The microplot data allowed us to derive a relationship between percent cover and suspended sediment concentration under natural rainfall conditions (Figure 5.18). However, there is considerable scatter associated with this relationship, given that we have not separated out other important factors like antecedent moisture, rainfall intensity, rainfall duration and soil surface condition features other than cover (see Chapter 7). Overall, whilst the function is an exponential decay function as to be expected based on results from other workers (e.g. McIvor et al., 1995; Scanlan et al., 1996), concentrations of suspended sediments in the microplots are low, even in the low to bare cover range. This is particularly the case when Figure 5.18 is compared with Figure 7.3B. In the latter case, we used high intensity rainfall for a 30-minute duration, resulting in a rainfall intensity x rainfall amount envelope that we did not encounter under natural conditions. Hence the function in Figure 5.18 can be considered to represent the lower boundary and the function in Figure 7.3B the upper boundary of the cover – sediment concentration envelope. Interestingly, both functions tend to show considerably less scatter at cover levels <40-60%, and minimum sediment concentrations seem to be in the order of 0.15 g/l. Reasons for this are discussed in Chapter 7.

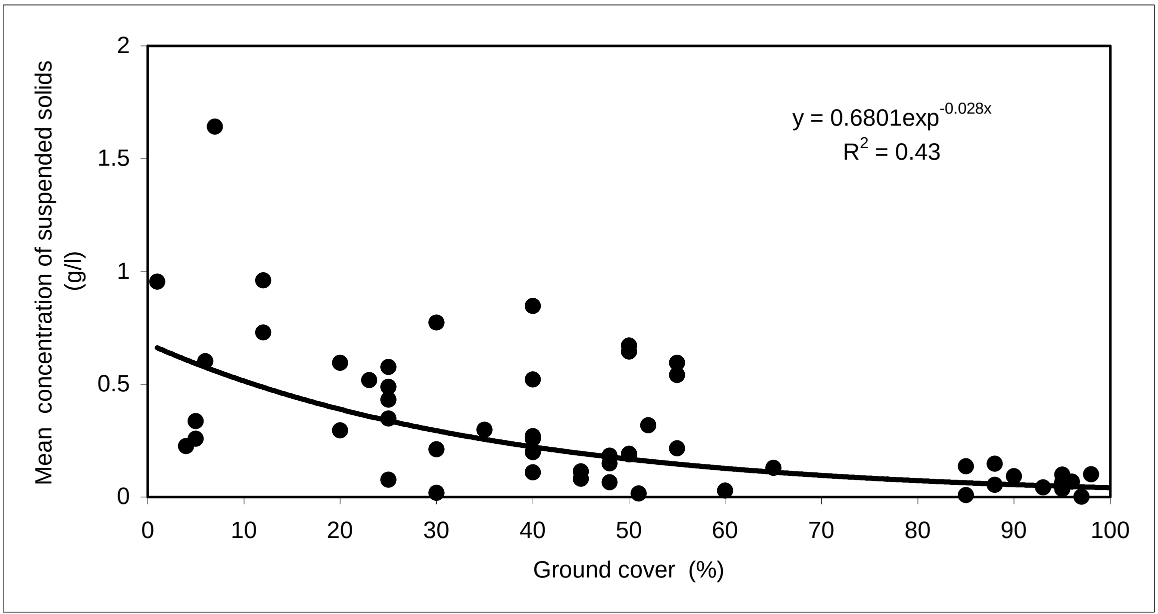

Figure 5.18: Relationship between ground cover and the mean concentration of suspended sediments in runoff obtained from the microplots.

The relationship between percent cover and suspended sediment concentration shown in Figure 5.18 was used in conjunction with the percent cover of the catchment shown in Figure 5.10 to predict the suspended sediment concentration of water running off a 0.24 m^2 plot anywhere in the catchment. As the relationship between percent cover and percent yield shown in Figure 5.17 is too poorly defined to use in a predictive sense, it was assumed that 50% of the rain falling on a 0.24 m^2 plot will run off it. This was done in order that the microplot results could be compared to the USLE results used in the SubNet model.

There is some disparity between these estimates, with the USLE estimates being around 4 times higher than the microplot estimates (Figure 5.23 shows the USLE estimates). There are two reasons for this – firstly, the data collected from the microplots only reflects that sediment which is generated on a 0.24 m^2 plot – any increase in sediment concentration due to entrainment by runoff is not considered at this scale. Secondly, there is a large variability associated with the relationship seen in Figure 5.18 and 7.3B. As discussed, this is because the impacts of rainfall intensity, rainfall amount, and antecedent rainfall are not accounted for in this relationship. The impact of these variables will also affect the estimates of sediment generated.

Until we have refined our direct measures of sediment delivered from hillslopes as part of the ongoing project, we opted to rely only on the USLE estimates for the purposes of developing the sediment budget and to carry out scenario analysis using SubNet. Further work is planned in order to determine a better estimate of scaling factors in this catchment. For the moment however, making use of the USLE estimates has allowed us to predict the impact of various scenarios on sediment yield (see Section 5.7).

Runoff troughs (hillslope scale)

Water

Two of the runoff troughs on Meadowvale Station (MVTB1 and MVTB2) are located in an old QDPI cattle exclosure, and the other two are located on an adjacent hillside, outside the exclosure (Scanlan et al., 1996). The exclosure fence was opened up some years ago, and cattle now have access to the exclosure, although they do tend to graze it at a lower intensity, presumably because their access is restricted by the remainder of the fence. This relatively lower intensity of grazing appears to have an impact on the movement of water inside the exclosure, with water yields inside the exclosure averaging 1.0% compared to 3.1% outside (see Table 5.5). Also, although the suspended sediment concentrations are about the same inside and outside the exclosure, the annual sediment yield is much lower inside, averaging 0.004 tonnes/year, compared to 0.014 tonnes/year outside. The volume of coarse sediment being moved across the landscape appears to be much higher outside the exclosure than inside, with between 5 and 10 times as much bedload collected in the trough outside the exclosure (see Table 5.5).

Table 5.5: Water and sediment yields of the four runoff troughs (2000-2002) at the Meadowvale exclosure site.

Runoff trough	Area (hectares)	Slope (%)	Grazing treatment	Annual water yield (%)	Suspended sediment concentration (mg/L)	Suspended sediment yield (tonnes/ha/year)	Coarse sediment collected (tonnes/ha/year)
MVTB1	0.21	4.0	Moderate	1.0	99	0.004	0.002
MVTB2	0.26	4.0	Moderate	1.0	99	0.004	0.001
MVTB3	0.07	3.5	Heavy	2.0	109	0.011	0.020
MVTB4	0.13	3.5	Heavy	3.7	109	0.017	0.005

The discharge of water from the runoff troughs under high grazing pressure (outside the exclosure) is compared with those under low grazing pressure (inside the exclosure) in Figure 5.19. The regression coefficient in Figure 5.19 can be interpreted as a scaling factor – in other words, the runoff troughs under low grazing pressure tend to discharge on average approximately 37% of the volume of water of those under high grazing pressure. However, this can only be regarded as a very preliminary result given the small number of observations and their uneven spread.

While this result indicates that increasing grazing density increases runoff, it is not certain what happens to this increased runoff with increasing scale. That is, how much of this additional water finds its way out of the catchment? Examining the data on an event-by-event basis and plotting the catchment discharge against the grazed hillslope plot data in a similar manner to above, we have determined that the yield of water from the Wheel Creek catchment is approximately 83% of that at the hillslope scale (see regression coefficient in Figure 5.20). That is, on average approximately 83% of the water that is generated at the hillslope scale actually reaches the stream network and exits the catchment. This is not strictly true as some of the water exiting the catchment may be travelling via a subsurface route and may therefore not be collected at the hillslope scale. Also, the variability of rainfall across the catchment may mean that while 60 mm may have fallen on the runoff troughs, the amount falling across the catchment on average may have been considerably more (or considerably less) than this. However, this 83% is a reasonable first approximation, and again, we require more observations to populate the regression in Figure 5.20 to obtain a more robust scaling factor.

The analysis can be taken one step further. Making the very coarse assumption that the runoff generation and infiltration processes vary with scale in the same ways under high and low grazing pressure, based on the above two scaling factors we can estimate that reducing grazing pressure everywhere would hypothetically lead to a reduction in runoff at the sub-catchment scale of 70%. However, significantly more data is required to confirm this projection.

Given the small number of observations, it is clearly premature to make firm conclusions on scaling factors. However, what we have demonstrated here is a robust approach to deriving scaling factors between different scales of observation that might enable us to differentiate the impact of different levels of grazing intensity on catchment hydrological response. We anticipate that as the current project continues to monitor runoff and erosion at the hillslope and catchment scale, we will be able to consolidate the results presented here. As we have now also established a range of new micro-catchment runoff flumes at Virginia Park within Weany Creek sub-catchment, we should be able to test the approach for a second catchment.

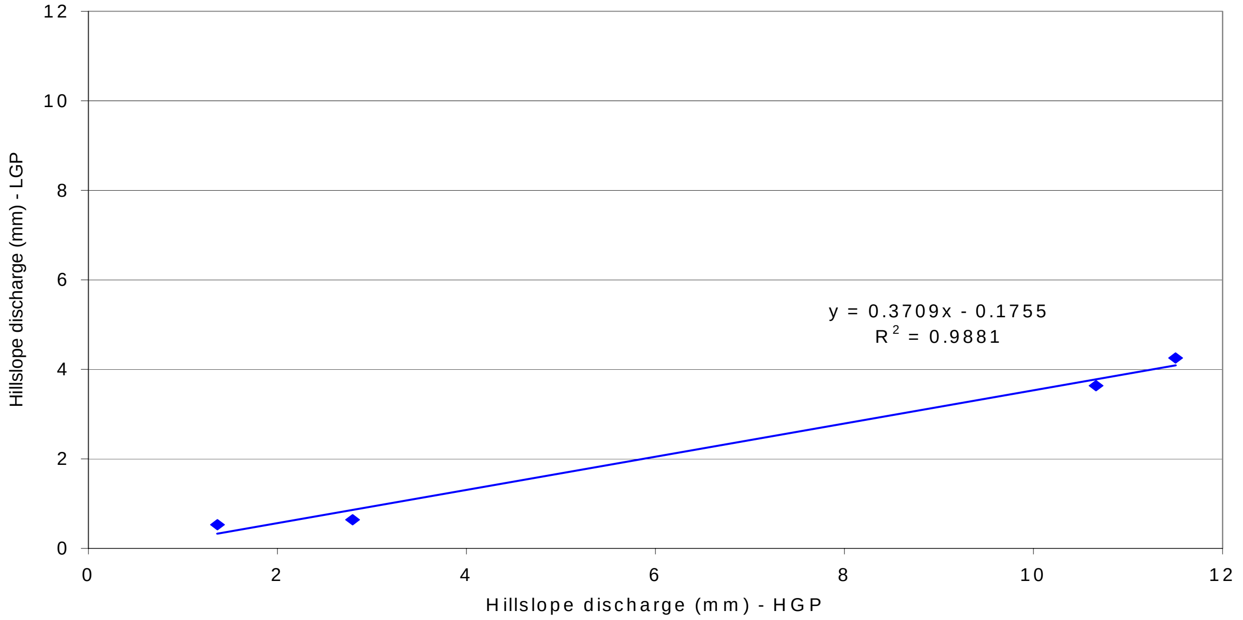

Figure 5.19: Discharge from the runoff troughs under high grazing pressure (HGP) versus those under low grazing pressure (LGP; 2000-2002).

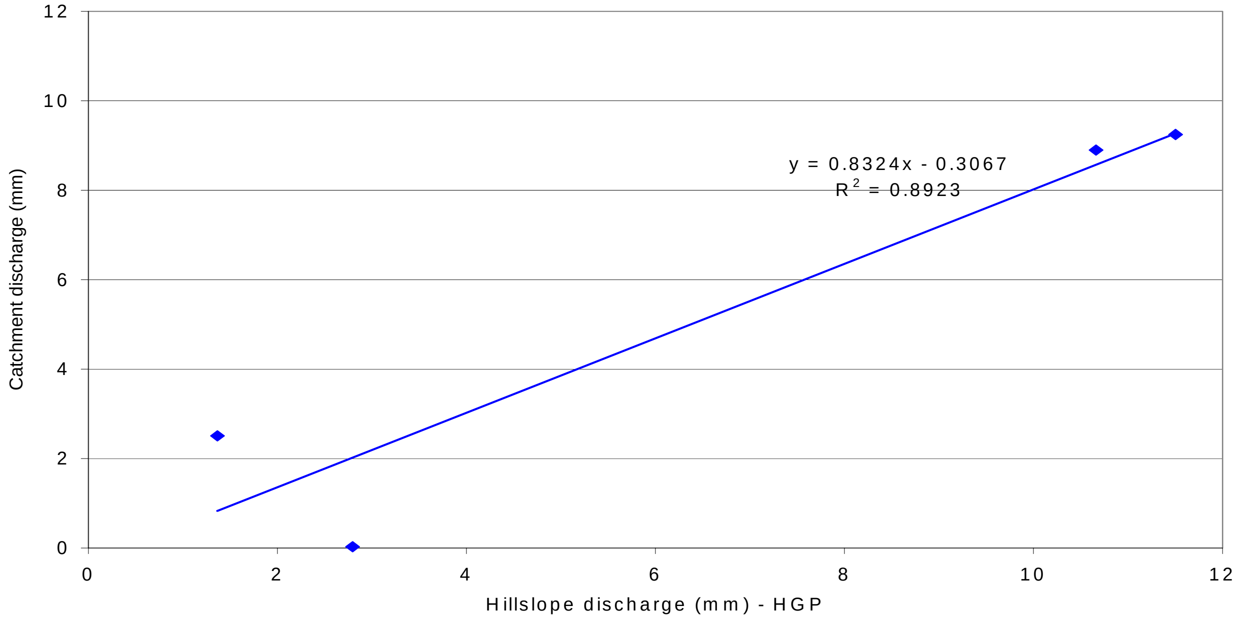

Figure 5.20: Runoff trough discharge (high grazing pressure - HGP) versus Wheel Creek discharge (catchment discharge; 2000-2002).

Sediment

At the scale of the runoff troughs, the situation with regards to suspended sediment is similar to that for water. However, as the suspended sediment concentration of the runoff troughs under high levels of grazing is slightly greater than that of the runoff troughs under low levels of grazing (Table 5.5), the relationship described above for water is strengthened somewhat. Whereas the runoff plot under lower grazing pressure yielded just 37% of the water, it yields only 34% of the suspended sediment (Figure 5.21).

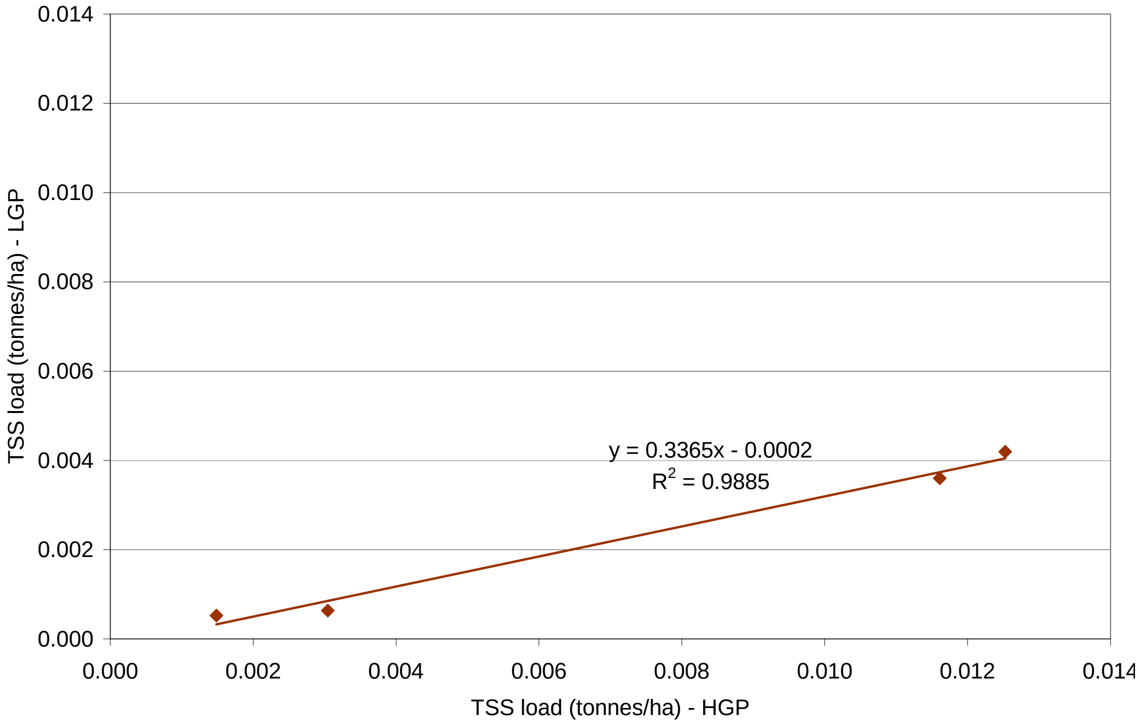

Figure 5.21: Discharge of suspended sediment from the runoff troughs under high grazing pressure (HGP) versus those under low grazing pressure (LGP; 2000-2002).

Note however that even accounting for the fact that cover levels are high on all runoff plots, the total sediment loss is very low, indicating that we may have overestimated the actual contributing area. As the plots are unbounded, we used a high precision GPS system to determine a high resolution DEM of the hillslope, in order to derive the flow lines. Recent results from the USA (Howes, 1999) suggest that we have to increase the density of points by at least one order of magnitude to be confident in the actual flow lines and contributing areas. This will be undertaken as part of the ongoing project, and we will be able to retrospectively correct the data in Table 5.5 and Figures 5.19 to 5.21 if required.

Comparing the discharge of sediment from the hillslope with the discharge of sediment from the catchment analogous to runoff discharge however tells a very different story. Whereas for water, only around 83% of the discharge at the hillslope scale exited the catchment, for suspended sediment on a unit area basis, approximately nine times as much suspended sediment is discharged from the catchment than is discharged from the hillslope (see regression coefficient in Figure 5.22). Clearly, this is physically impossible if hillslopes were the only source of sediments. Even if we have grossly underestimated hillslope soil loss at this point, the error could not be so large. Hence, we can infer that there must be other sources of sediment entering the stream network. These other sources would include gully erosion, streambank erosion, and hillslope erosion on steeper and more denuded slopes close to the stream. These possibilities will be explored in Section 5.5.3.

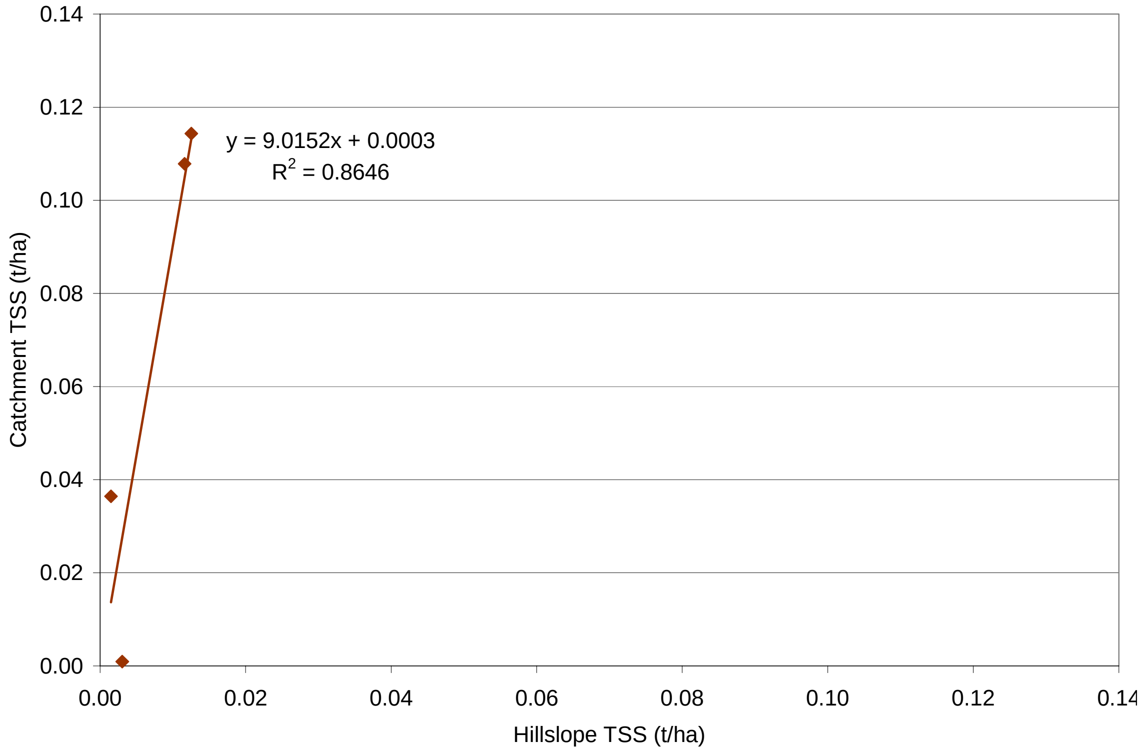

Figure 5.22: Discharge of suspended sediment from the runoff troughs (high grazing pressure) versus that from Wheel Creek 2000-2002.

Again, the small amount of observations underlying the relationships in Figures 5.21 to 5.22 at this stage does not allow for any more conclusive interpretations, and the regressions at this stage only serve the purpose of illustrating an approach to scaling the hillslope data against the catchment sediment discharge. The additional flumes established at Virginia Park have been located in order to better differentiate between sources of runoff and sediments originating from different sections of the hillslopes.

SubNet results (sub-catchment scale)

The spatial distribution of hillslope erosion in the Weany Creek catchment, as determined by the USLE is shown in Figure 5.23. The factors that vary across the catchment to give this pattern are cover and slope. Rainfall erosivity, soil erodibility, and hillslope length are also used to derive these predictions of hillslope erosion, but these are assumed to be constant across the catchment. It can be seen that the rate of hillslope erosion in the streamlines is quite low. In Figure 5.23 this is because of tree, bush and vine cover in the streams. However, these areas are in any case set to zero hillslope erosion using the following procedure : the width of the ‘streams’ was measured and a buffer zone created across the stream width. Alongside the ‘gully valleys’, ‘gully middles’ and ‘gully heads’, the buffer was set to 5m on either side. All of the erosion that occurs within this narrow strip is therefore gully erosion. The width of this strip can be seen in Figure 5.24. However, just outside this protected area, rates of hillslope erosion can be quite high. The other area of high hillslope erosion can be seen in the south-eastern part of the catchment. This is caused by the steep slopes in this part of the catchment (see Figure 5.16).

It is important to note that Figure 5.23 represents the total amount of soil eroded. Not all of this finds its way out of the catchment. In fact, around 95% of it is redeposited before getting into a drainage line. The closer to a drainage line the erosion occurs, the more likely it is to be exported from the catchment. This is represented in the model by the hillslope delivery ratio (HSDR) shown in Figure 5.11. Multiplying these two factors together (Figures 5.11 and 5.23) yields the total amount of suspended sediment delivered to

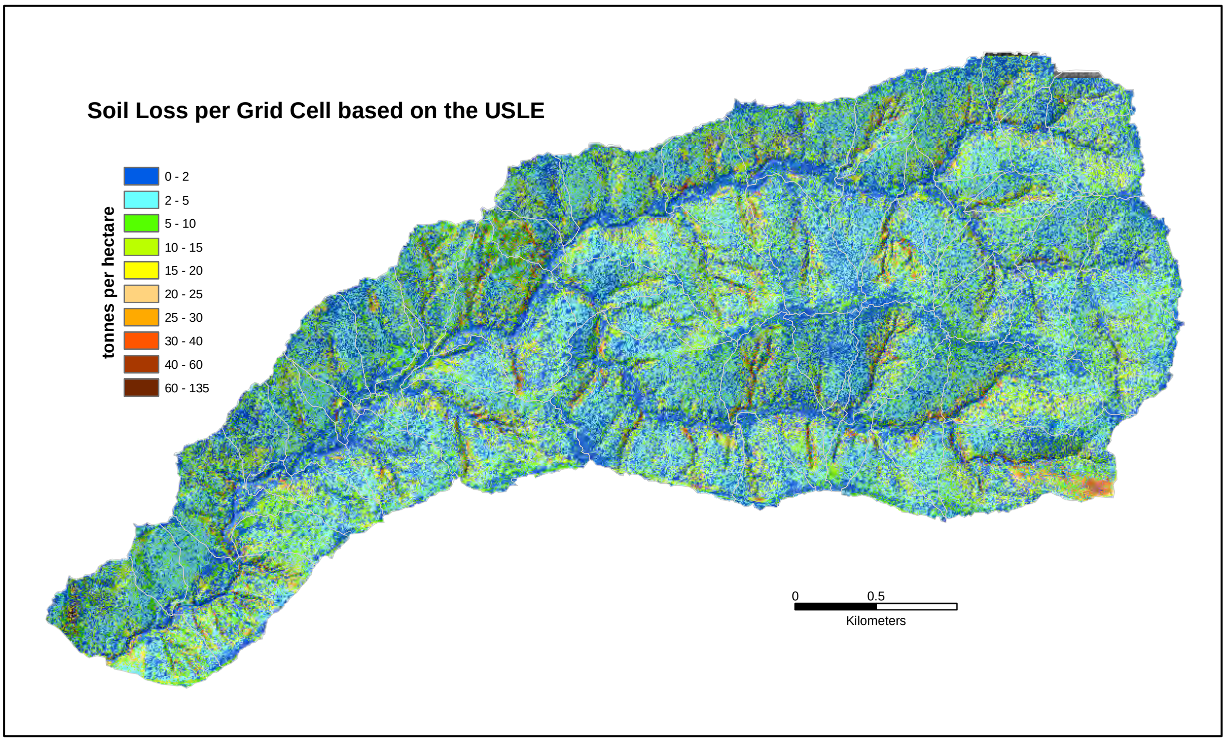

Figure 5.23: Hillslope erosion in the Weany Creek sub-catchment as predicted by the SubNet model.

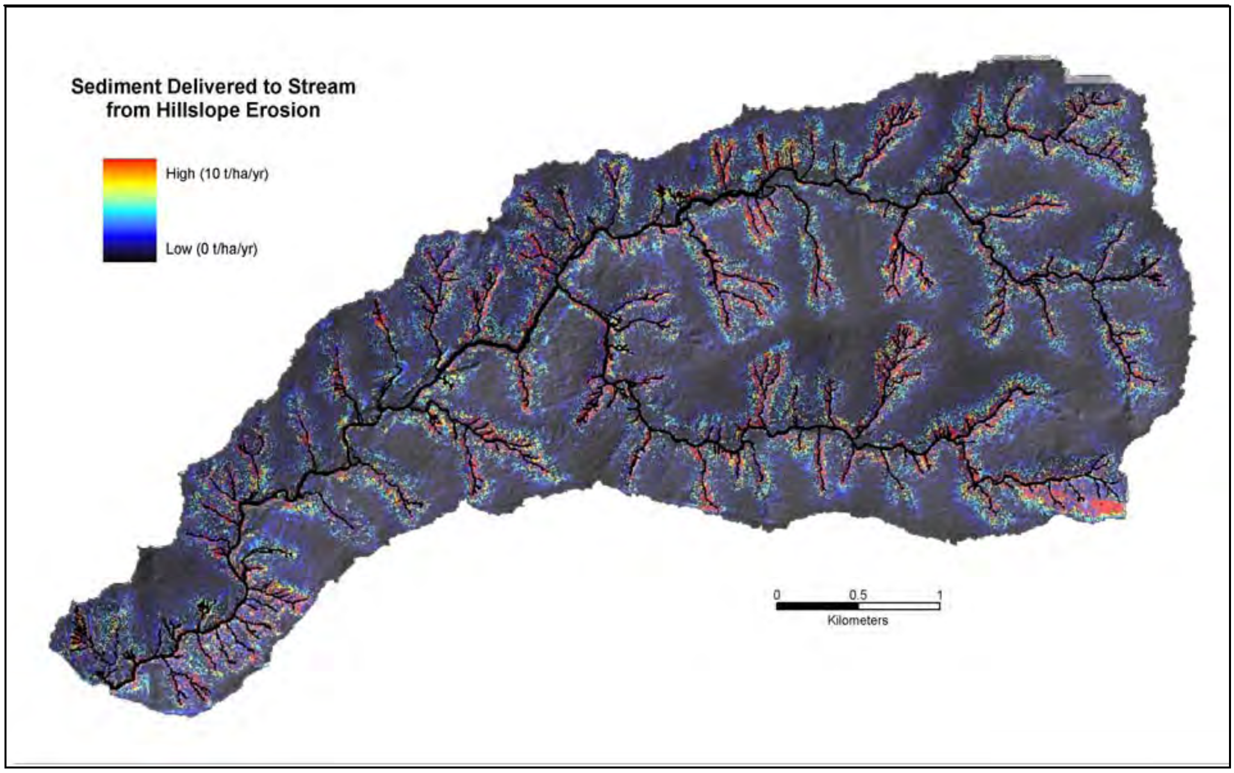

Figure 5.24: Predicted sediment delivery from hillslope erosion in Weany Creek sub-catchment.

the stream (Figure 5.24). The stream power of Weany Creek is sufficient to transport all of this suspended sediment out of the catchment, and therefore Figure 5.24 also represents the total amount of suspended sediment lost from the catchment due to hillslope erosion. It can be seen that most of the hillslope slope sediment being lost from the catchment is sourced from areas very close to the streamlines. Most of the hillslope erosion that occurs on the ridges is not lost from the catchment, but rather is re-deposited further down the hillslope. Eventually of course, this sediment may be lost from the catchment if it is re-suspended during a subsequent runoff event.

Notwithstanding the small number of observations and the possible underestimation of hillslope soil loss discussed in the preceding section, the modelling results presented here at least qualitatively match the sediment discharge results shown in Table 5.5. What we can conclude from both sets of data is that the following sediment delivery processes are acting:

- A direct, but low level of delivery of sediments from hillslopes further upslope from the drainage lines (mainly suspended sediments);
- A direct delivery of larger amounts of sediments from gullies and badlands directly adjacent to streams; and
- An additional, indirect contribution of hillslope runoff to enhanced sediment delivery from gullies and badlands through the delivery of high amounts of runoff into gullies or onto badlands as run-on.

In this way, we can at least qualitatively reconcile the contrasting preliminary scaling factors derived in Figures 5.19 to 5.22 and the discharge measured at the mouth of the catchment. This conceptualisation is further borne out by the infiltration data in conjunction with results of hillslope runoff modelling presented in Chapter 7.

5.5.3 Estimates of gully erosion rates

Gully head migration

Gully head migration was determined using two techniques : air photo interpretation and gully monitoring.

Air photo interpretation (gully chronosequence)

As described in Section 5.3.2, mapping of gullies from air photos was carried out for Wheel and Weany Creeks for the years 1945, 1961, 1975, 1981, 1990, and 2000. The results of this gully mapping are shown in Figures 5.25 and 5.26.

Unfortunately, the air photos available for the various years were taken at different scales, with 1945 and 1975 being at 1:34,000 scale, 1961, 1981, and 1990 being at 1:25,000 scale, and 2000 being at 1:10,000 scale. This makes inter-comparison between years difficult, as it is easier to see gullies at smaller scales. Secondly, not all areas of the two sub-catchments were visible in the air photos for each year. The extents of the air photos can be seen as straight lines on Figures 5.25 and 5.26. As none of the photos covered the entire catchment (with the exception of the photos that were flown as part of this project in 2000), a quantitative comparison could not be made between years for the full extent of each sub-catchment.

Despite these difficulties however, the gully chronosequences do provide valuable insights into the history of the gullies in Wheel and Weany Creek catchments. It can be seen for example that much of the gully network was already established in 1945, and since that time, it seems to have been extending quite slowly. It is especially difficult however to compare the 2000 air photos with the remainder as they were flown at a much lower elevation, precisely so that we could map the gullies in the catchments. Even ignoring the extent of the red lines on Figures 5.25 and 5.26 however, it is clear that gully extension is proceeding relatively slowly. The results of the gully monitoring program described in the next section give a more accurate estimate of the growth of gullies over the last 3 years.

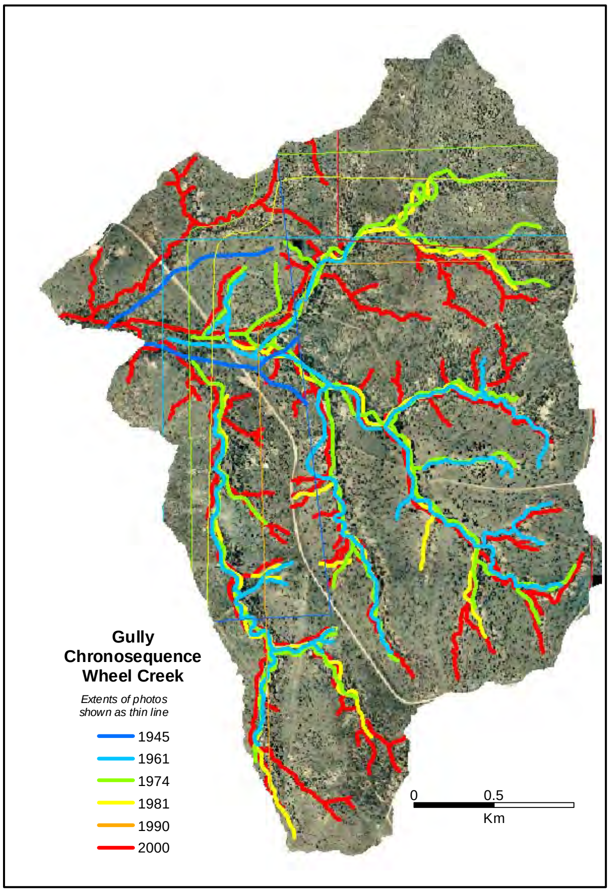

Figure 5.25: Gully chronosequence in Wheel Creek catchment.

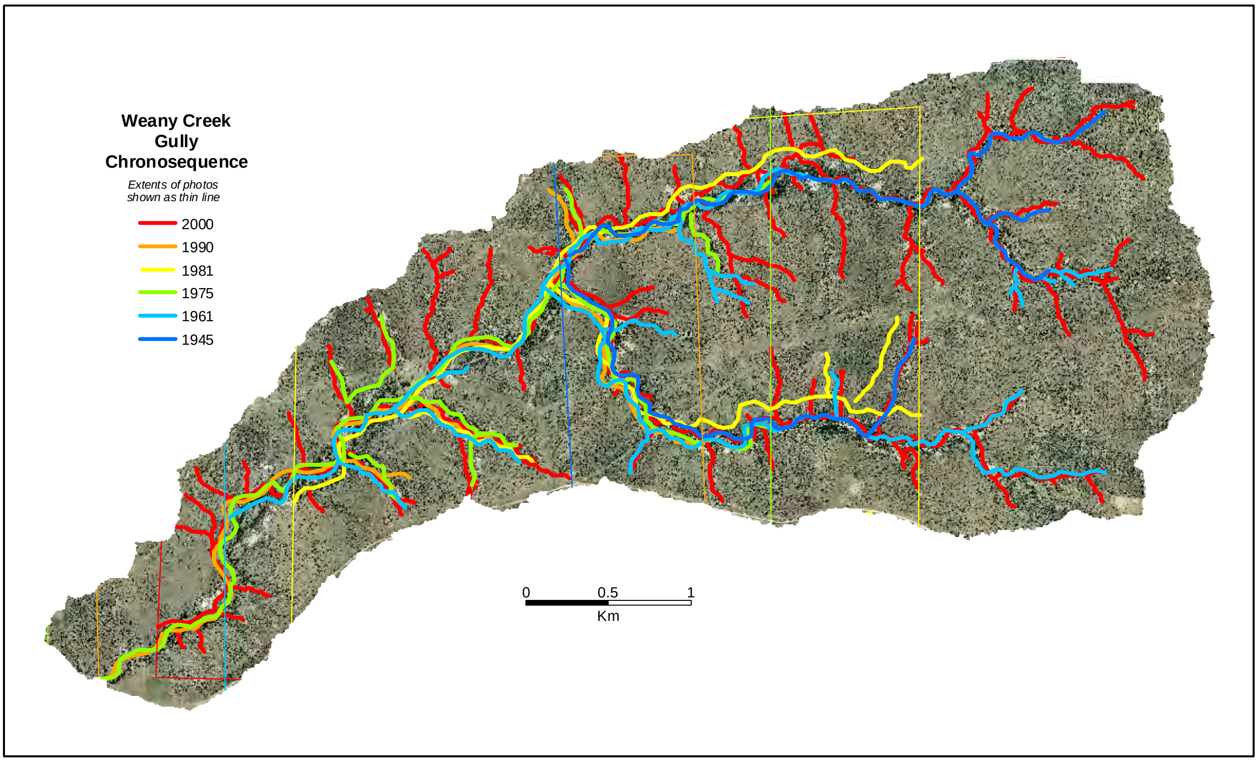

Figure 5.26: Gully chronosequence in Weany Creek catchment.

Gully monitoring

Based on the gully monitoring described in Section 5.3.2, we were able to directly measure gully head migration for four gully heads in Weany Creek catchment and two in Wheel Creek catchment. Figure 5.27 shows an example of this analysis.

Combining the data obtained for the six gully heads in Wheel and Weany Creek for the years 1999-2001, we determined that gully head migration was in the order of 0.05 metres/year (for an averaged size/depth gully this equates to about 0.17 tonnes/year per gully head).

This rate of gully advance was applied to all of the gullies in Weany Creek. This is believed to be an adequate first estimate of gully advance in this catchment. Current research is concentrating on varying this rate of gully advance based on the contributing area and slope upslope of the gully. As the advance of a number of gully heads is continued to be monitored and once sufficient data from more seasons becomes available, it will be possible to derive a predictive relationship and apply this to the remainder of the catchment using a digital elevation model to derive upslope contributing area and slope.

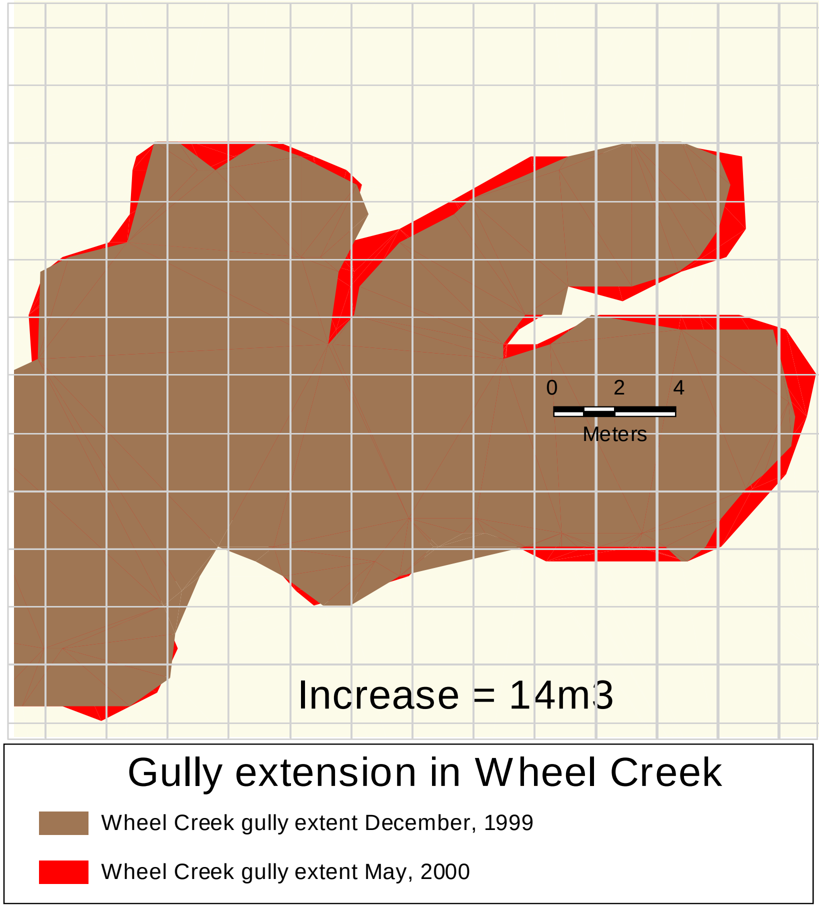

Figure 5.27: Example of data on gully head advance obtained during the 1999/2000 wet season in Wheel Creek sub-catchment.

Gully slumping

The gully monitoring program described in Section 5.3.2 also provided detailed profiles from which we could estimate annual change in cross-section per unit length for 'gully head' sections. Change in cross-section for a representative gully is shown in Figure 5.28. The three lines in Figure 5.28 represent the depth of the gully in 2000, 2001, and 2002. Note that deposition occurs in some parts of the profile, and erosion in others.

Overall, summarising the data gathered from the three cross-sections in Weany Creek and three in Wheel Creek, we determined the rate of gully slumping to be approximately $0.016m^2/m$ at gully heads (equating to 0.024 tonnes/year per meter length).

Gully slumping was not measured in gully middles and valleys. Based on field observations and some erosion pin and cross-section data, we have assumed that slumping in middle sections occurred at 50% of the rate monitored at gully heads, while slumping in gully valleys occurred at 25% of the rate monitored at gully heads. Similarly, stream channel erosion was assumed to occur at 25% of the rate seen at gully heads. Work is currently underway to refine these figures based on additional monitoring sites.

Gully slumping and streambank erosion was then proportionally reduced by the percent of riparian vegetation. Thus, 50% riparian cover reduced gully erosion by 50%. The percent of riparian vegetation was determined by estimating (from aerial photos) the area covered by trees within a 5 m buffer on each side of each gully/stream. Thus, based on the total length of each gully section (including stream channels) plus a count of the number of gully heads in each stream link watershed, and using the estimates of erosion discussed above, we were able to calculate the total gully erosion from each SubNet watershed.

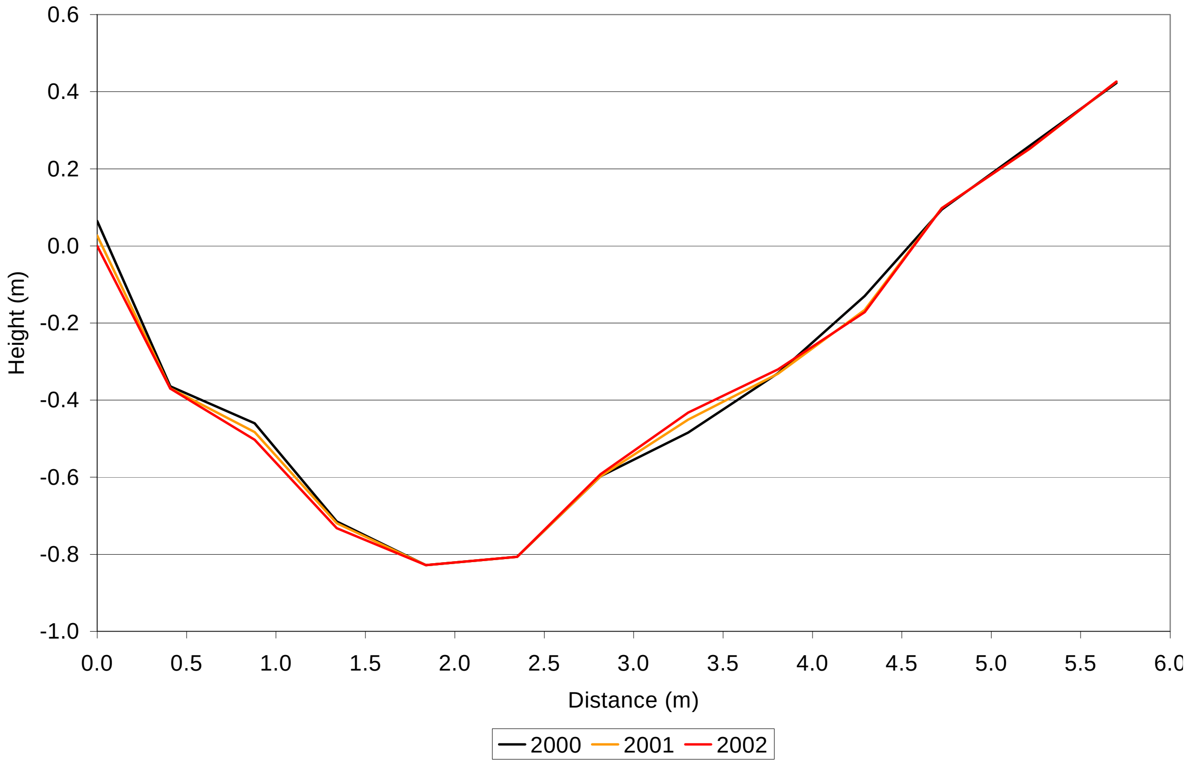

Figure 5.28: Change in cross-section 2000-2002 for a representative gully in Weany Creek. Note that zones of deposition (e.g. section 3.3 – 4.2 m) can alternate with zones of erosion (e.g. section 0 – 1.2 m) within the same cross-section.

SubNet results

The measurements of gully head advance and gully slumping described above were used as inputs into the SubNet model. This allowed us to determine gully erosion throughout the Weany Creek catchment, and derive a sediment budget, comparing the rates of gully erosion with the rates of hillslope erosion.

The different types of drainage lines can be seen in Figure 5.29, where the gully heads are red, gully middles are orange, gully valleys are green, and streams are blue.

The rates of gully and streambank erosion in the various parts of Weany Creek are also shown in Figure 5.29 (the SubNet model breaks a sub-catchment up into smaller sub-catchments for analysis).

Unlike hillslope erosion, all of the sediment being eroded from gullies is added directly into the stream. However, it is assumed that hillslope erosion only transports fine sediment overland, whereas gully erosion adds both fine and coarse sediment to the stream. Based on an examination of the soil type in this region, we have assumed a 50:50 split between fine and coarse sediment being added from gully erosion (based on the fact that typical clay:sand ratios in the B-horizons of Red Duplex soils on granodiorite are 51:49; Rogers et al., 1999).

It can be seen from Figure 5.29 that gully erosion is at its highest in sub-catchments with a more dense network of gullies, and sub-catchments which have a higher proportion of gully heads and gully middles to gully valleys and streams.

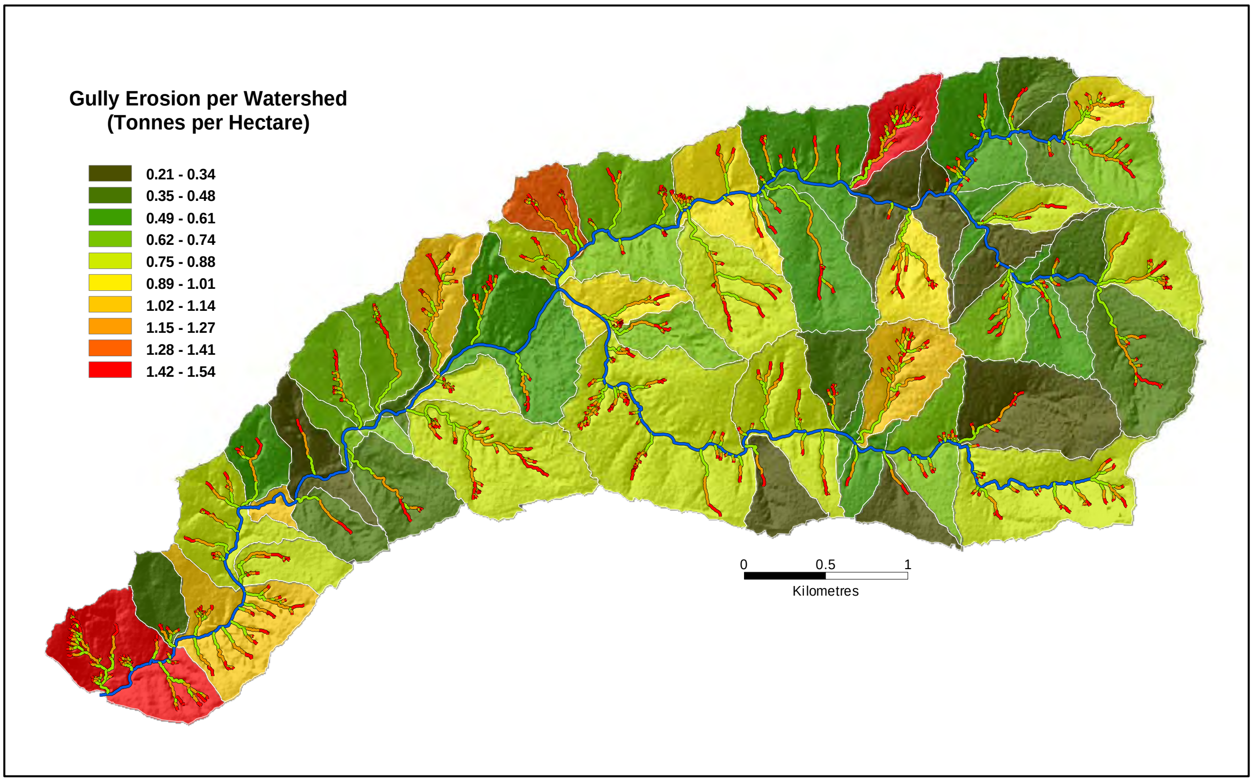

Figure 5.29: Drainage types and gully erosion in the Weany Creek sub-catchment, as predicted by SubNet.

5.6 Sub-catchment sediment budget

Having derived estimates of both hillslope and gully erosion, and routed them through the stream network using the SubNet model and the measured discharge from Weany Creek, we are now in a position to derive a sediment budget for the Weany Creek catchment. Table 5.6 shows the sediment budget for the Weany Creek catchment. The average predicted export of sediments from Weany Creek is predicted to be 874 tonnes per year, corresponding to a unit area sediment discharge of 0.65 t/ha per year. This can be considered to be a low value, and reflects the below average rainfall experienced in two of the three monitoring years. The ratio of sediment export to sediment delivery is 71%, very much greater than the corresponding value of 16% for the whole of the Burdekin River catchment (Table 4.2). It is well known that headwater streams have a far greater sediment export ratio than catchments in the lowlands, and it is also well known that the sediment export ratio decreases with increasing catchment size (Wasson, 1994).

The other noteworthy difference between the whole-of-catchment budget in Table 4.2 and the budget for Weany Creek in Table 5.6 is the higher proportion of sediments being delivered from gully erosion in Weany Creek. Whilst across the Burdekin catchment hillslope erosion was predicted to be the main source of sediments and accounted for about 61% of sediments delivered to the stream network, in the

Table 5.6: Sediment budget for Weany Creek catchment.

Budget Component	Bedload (tonnes/year)	Suspended sediments (tonnes/year)	Total sediments (tonnes/year)
Hillslope delivery	0	432	432
Gully erosion :			
- *Head advance*	*(66)*	*(66)*	
- *Slumping and slope erosion - heads*	*(153)*	*(153)*	
- *Slope erosion - middles*	*(104)*	*(104)*	
- *Slope erosion - valleys*	*(47)*	*(47)*	
Total gully erosion	370	370	740
Streambank erosion	28	28	56
Total sediment delivery	398	830	1228
Sediment stored in streambed	354	0	354
Total sediment export	44	830	874

case of Weany Creek hillslope delivery accounts for only 35% of sediment delivery. Conversely, gully erosion on a whole-of-catchment basis supplies only about 33% of the sediment load; in Weany Creek the corresponding proportion is 60%. Most of this material originates from a small band along the creek and drainage lines, so that the 85/10 rule evident at broader catchment scale seems to hold on the smaller sub-catchment scale, i.e. 85% of the sediment comes from just 10% of the area, providing a strong indication of where to focus remediation efforts. The implications of these findings for grazing management will be discussed in detail in Chapter 9.

Note that the stream power in Weany Creek is not sufficient to export all of the coarse sediment from the catchment. As a result 89% is stored within the catchment, and the other 11% is exported. This corresponds to storing 354 tonnes of coarse sediment in the streambed of the catchment each year. This represents an accumulation of less than 1 cm of sand per year in the 21 km of streams in the catchment, and is thus entirely plausible.

For fine sediment, there appears to be an approximately equal amount derived from gully erosion as from hillslope erosion. However this estimate is based on our current level of monitoring data, which is far from perfect. We are able to assess the reliability of the model prediction of fine sediment export in Table 5.6 by comparing this prediction with our estimate of fine sediment export from the Weany Creek catchment, derived from the stream gauging station. From the data in Table 5.3, we can calculate the total volume of suspended sediment export for the 3 years of record. These are as follows:

1999/2000 – 803 tonnes;

2000/2001 – 399 tonnes;

2001/2002 – 435 tonnes;

Average – 546 tonnes

In view of all the measurement uncertainties discussed in the previous sections, and given that the 2000/2001 and 2001/2002 wet seasons were characterised by below average rainfall compared to the rainfall pattern used in the modelling, the average measured discharge of suspended sediment compares reasonably well to the 830 tonnes per year predicted by the SubNet model. A systematic analysis of uncertainty for the various sediment budget components is yet to be done. However, considering the results of our experience with the SubNet model to date and an assessment of possible measurement error associated with the various monitoring techniques, and considering the critical gaps in our monitoring strategy, the following can be listed as some areas of improvement which we intend addressing in the current project.

A better differentiation of hillslope erosion rates and sediment delivery ratios in relation to different hillslope positions and cover conditions – this will be addressed in the current project by a greatly enhanced hillslope monitoring program using a series of flumes and micro-catchments characterising different hillslope sections. Most likely we will confirm high erosion rates on the scalds and badlands adjacent to the gullies and creek lines.

Table 5.6 indicates that only 5% of sediments delivered to Weany Creek come from streambank erosion, but to date we have no measures to confirm this – several bank erosion monitoring sites have now been established on Weany Creek to fill this gap.

Catchment discharge is still relatively uncertain, given that we assume a distribution of flow velocity from point measures in the middle of the creek: - velocity distribution profiles will be determined as part of the current project to derive more realistic flow velocity – flow depth relationships. Improving on the flow velocity term will have a great effect on total sediment discharge. Uncertainty in sediment discharge is also present due to the as yet unresolved discrepancy between the ISCO turbidity samplers and the mechanical samplers, and we plan on carrying out specific experiments to clarify which sampling protocol to use as the basis for constructing the turbidity – sediment concentration relationships.

Whilst we believe we have fairly robust methods of determining spatial distribution of ground cover distribution across the sub-catchment, the discrepancies in absolute relative values between the remotely sensed data presented in this chapter and the actual ground sampled data presented in the next chapter need to be resolved. An underestimation of cover will strongly affect hillslope erosion rates in the model, and may be one of the causes explaining the higher sediment export in the budget when compared to the actual measured sediment discharge.

5.7 Scenario modelling using SubNet

Whilst we recognise that the SubNet model needs to be further refined to deal with some of the uncertainties discussed above, we have sufficient confidence in the model for it to be used in scenario analysis to predict the impact on sediment delivery of a number of grazing management scenarios. In order to illustrate the potential of SubNet to be used as a tool to assist in deriving grazing management guidelines and, possibly, to support target setting processes as envisaged under the National Action Plan or the Reef Protection Plan, we defined a number of different grazing management scenarios aimed at minimising hillslope sediment export in Weany Creek. The results of this exemplary application in scenario analysis are presented below.

In the first case, we take the case where a grazier decides to rehabilitate the entire catchment, so that ground cover levels exceed 60% over the entire catchment.

In the second case, we assume that there are only enough resources to rehabilitate around 110 hectares of the catchment. Assuming that the grazier chooses to target specific areas for rehabilitation, i.e. presumably those areas that have the lowest levels of cover, where will that grazier get the best value for money in terms of reducing sediment export? On the valleys/footslopes, midslopes, or ridges?

Grazing scenarios :

Case 1: Increase cover to >60% over the entire catchment (1,350 ha);

Case 2a: Increase cover to >60% on 118 ha of footslopes adjacent to drainage lines (404 ha);

Case 2b: Increase cover to >60% on 107 ha of midslopes (431 ha);

Case 2c Increase cover to >60% on 103 ha of ridges (422 ha).

The effects of these scenarios on the export of fine sediment from the catchment are shown in Table 5.7. Note that because these actions are only affecting hillslope erosion, they will have no impact on the erosion of coarse sediments. Even if they did, as most of the coarse sediment is trapped in the catchment (Table 5.6), any impact on the export of coarse sediment would be minimal.

Table 5.7: Predicted effect of various grazing scenarios on export of fine sediment (tonnes/year) from Weany Creek.

Current condition	Increase to > 60% cover over the			
	Whole catchment	Valleys	Midslopes	Ridges
830	425	634	747	800

As expected, increasing cover across the whole catchment leads to a significant decrease in the export of fine sediment from the catchment, from 830 tonnes/year to 425 tonnes/year, by virtually eliminating all hillslope erosion. The remaining export is predominantly due to gully erosion.

If the grazier can only rehabilitate 110 hectares of his property, the best place to do it would appear to be along the stream valleys. Money spent rehabilitating midslopes or ridges would not yield as much of a decrease in suspended sediment export. This occurs for two reasons – firstly, the valleys are closer to the streamlines and therefore deliver more suspended sediment into the streams, and secondly, slopes in the valleys in Weany Creek can be quite large (see Figure 5.16), so that rehabilitation of areas adjacent to streams might offer a significant buffering capacity for sediments derived from higher upslope. In contrast, in Wheel Creek, slopes close to the streamlines are quite low, and one could therefore hypothesise that as a result, the optimum strategy for Wheel Creek may well be different to Weany Creek.

The implications of the above results for choosing the best grazing management strategies will be discussed further in Chapter 9.

5.8 Conclusions

In this chapter we have shown how detailed monitoring and modelling of a sub-catchment in the ‘Goldfields’ country of the Burdekin Catchment can allow us to produce a sub-catchment sediment budget, distinguishing between hillslope, gully and streambank erosion. This work has shown that although most of the gullies have existed in this catchment for a long period of time, gully erosion is still an important component of the sediment budget, accounting for the vast majority of the bedload deposited in the streams, and around half of the suspended sediment delivery from the sub-catchment. Despite this, we have shown that improving ground cover will produce a substantial decrease in the export of fines from the sub-catchment. This reduction will be even more pronounced in catchments where hillslope erosion is a more dominant process.

6. Spatial analysis of grazing impacts on vegetation at hillslope and sub-catchment scale

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6.1 Objectives

For producers, the paddock is the effective unit of management and it is at the paddock level that decisions are made on stocking rates, location of watering points, and on other improvements that influence grazing patterns. Paddocks in the extensive grazing lands of northern Australia are typically large and they usually include a range of plant communities and topographic features that influence the distribution of livestock. Grazing pressure by livestock is usually greater near watering points, along fence lines, at salt licks, and in areas with preferred forages and the result of an uneven pattern of grazing is that some areas sustain greater impacts than others. Even with a low average stocking rate, most paddocks will have areas that are “overgrazed” and other areas that are rarely used. Sustained high grazing pressure can lead to long-term changes in botanical composition to less productive species, lower water use efficiency, reduced ground cover, and reduced productivity of forage species and livestock. These changes are often accompanied by deterioration in soil condition (scalding in extreme situations), which can lead to increased rates of water runoff and a higher susceptibility to erosion (Trimble and Mendel 1995; see also Chapter 7).

Impacts of grazing occur at scales from the individual plant to the full paddock and an understanding at all levels is important to developing robust management guidelines. At the paddock level, the landscape-scale distribution of grazing impacts is important because it describes the extent of impacts that occur in high-risk or high-impact areas. High-risk/high-impact areas include locations where there is a sufficient contributing area for runoff to lead to formation or advance of gullies, hillslopes adjacent to drainages where runoff is directed into a channel, or in landscapes with soil types and slopes that are highly susceptible to erosion. At the intermediate (hillslope) scale, the size and distribution of grazed patches is important, because the effects of numerous small patches are likely to be less than the effects of a few very large patches. At the smallest scale, it is necessary to know the fine-scale pattern of covered and bare ground and fine-scale characteristics such as soil surface condition in order to evaluate trends in condition (e.g., Tongway and Hindley 1995). These small-scale factors account for detachment and entrapment of particles and they are strongly related to runoff at the microplot scale, and are discussed in greater detail in Chapter 7.

Based on these principles, our objectives for this component were to:

- Describe patterns of ground cover and grazing impacts for selected focal paddocks and sub-catchments;
- Based on the above information, develop the capacity to predict grazing patterns in typical paddocks within the Burdekin catchment and link these grazing patterns to soil and vegetation responses;
- Link this understanding of spatial grazing behaviour and its impacts to landscape models of sediment and nutrient movement;
- Use this information to develop management recommendations on how to minimise sediment and nutrient flows into streams and rivers (i.e. stocking rates, spelling regimes, paddock design and fencing, fire regime, location of water and supplement points).

6.2 General methodology

We conducted measurements of vegetation and cover attributes at scales of the full paddock, at the hillslope scale, and at a scale that resolves plant and inter-plant patches. We conducted aerial surveys to quantify the location of cattle, and we examined correlations between cattle locations and vegetation attributes associated with increased rates of runoff of water and nutrients. We interviewed graziers and reviewed existing data, both published and unpublished, on the distribution of grazing impacts. Information from graziers, published and unpublished sources, and this study were used to develop a model for predicting the spatial distribution of grazing impacts. This section of the report provides a general overview of methods used. Detailed descriptions of the methods and procedures are provided in Appendix 5, and metadata from the study is in Appendix 6, both in Volume II of this report.

6.2.1 Selection of sites and characterisation of focal paddocks

Measurements of vegetation and aerial surveys for cattle locations were conducted on properties to the north and northeast of Charters Towers. Study paddocks varied in size from 240 to 2900 ha (Figure 6.1**)**, and the condition of areas of the paddocks ranged from poor to very good (see Appendix 5, Volume II for a detailed description of the paddocks). Two of the primary study paddocks (Virginia Park and Fanning River) are on granodiorite soils of the moderately fertile Goldfields association. These paddocks included some exposed granite and stony areas. The third primary study paddock was Fletchervale, a paddock north of Charters Towers on fertile basaltic red (kraznozem) soils and associated basaltic black soils (heavy grey-brown cracking clays). This paddock included red basalt plateau areas to the west, and the paddock is divided by Allingham Creek, which contained water throughout the study. Study paddocks varied considerably with respect to soils, topography, plant communities, and grazing history, and they are briefly described below.

Fletchervale paddock: This paddock has a history of light grazing and remains in very good condition, with a predominance of native perennial grass communities. Water is well distributed throughout the 2411 ha paddock via access to Allingham Creek, and from 2 additional water points.

Fanning River paddock: This paddock is in a recovery phase from some heavy grazing in the past and the prolonged drought of the 1990s. Throughout the period of our study the 2882 ha study paddock at Fanning River was moderately stocked and most of the paddock is covered by perennial grasses, although overall basal area of perennial tussock grasses is still < 2%. There are 6 water points in the paddock and grazing is well distributed throughout the paddock.

Virginia Park Stud Paddock: The focal study paddock at Virginia Park was selected to coincide with hydrological measurements and it was the smallest paddock studied (240 ha). Vegetation in the paddock reflects heavy grazing in the past and the effects of the drought during the 1990s. The grassy layer is dominated by Indian couch (*Bothriocloa pertusa*), and exotic species characteristic of heavily grazed areas, and some of the paddock is in a degraded condition with active gullies and scalds. There are small areas of the paddock, especially in the northwest sector, that still support native perennial tussock species. The paddock at Virginia Park contains 1 improved water point (windmill) and the paddock is bisected by Weany Creek. Animals can obtain water in pools that remain after rains.

Fletcherview: Data from previous studies at sandalwood paddock, Fletcherview station were also analysed and used in this study. The 467 ha paddock at Fletcherview was smaller than average and the soils are a mixture comprised of fertile basaltic rocky red (euchrozems) associated with basaltic black soils (similar to Fletchervale), along with basaltic sediments and some areas where the underlying granodiorite and sedimentary soils are exposed. This paddock has been moderately grazed over many years and it is generally in good condition. Some areas of the paddock exhibited localized degradation, including scalding. During the drought, the period of study for this paddock, biomass production was about 1300 kg/ha, and preferential grazing of some areas on cracking clay soils resulted in conversion of the dominant grass species from native tussock grasses to introduced annuals.

A summary of the vegetation characteristics of each paddock studied is provided in Table 6.1. Soil types within the two paddocks representative of Goldfields country were fairly uniform, with Narrow-Leafed Ironbark/Bloodwood being the main vegetation unit. The two sites on basalt (Fletchervale and Fletcherview) were more varied. Dominant grass species varied across all paddocks. Fletchervale and Fanning River were dominated by native perennial species, while 78% of quadrats from Virginia Park recorded Indian couch (*B. pertusa*) as the dominant species (4% and 31% of quadrats from Fletchervale and Fanning River, respectively, were dominated by Indian couch). Black speargrass (*Heteropogon contortus*) was the most frequently recorded dominant species at Fanning River (41% of quadrats), while both desert bluegrass (*Bothriocloa ewartiania*; 25%) and curly bluegrass (*Dicanthium sericeum;* 17%) were important native perennial species at Fletchervale.

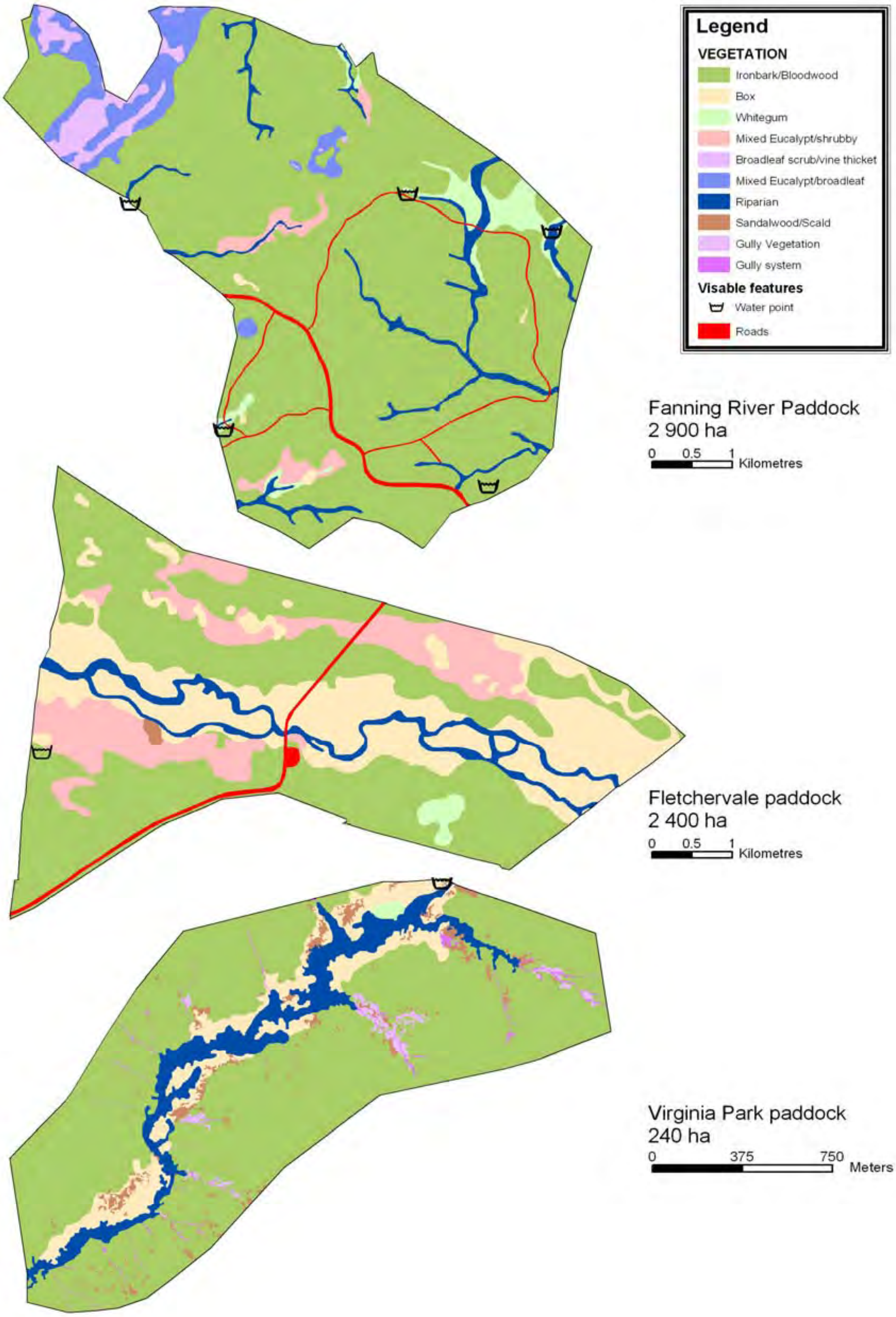

Figure 6.1: Vegetation maps of the three primary study paddocks, with scales of their relative size.

Table 6.1: Composition of studied paddocks by vegetation type.

	Fanning River		Fletchervale		Virginia Park		Fletcherview	
	Ha	%	Ha	%	Ha	%	Ha	%
Box	7.0	0.2	677.4	28.1	22.7	9.4	95.4	20.3
Broadleaf scrub/vine thicket	78.5	2.7						
Ironbark/Bloodwood	2349.3	81.4	1200.2	49.8	183.1	75.6	290.5	61.5
Mixed Eucalypt/broadleaf	144.3	5.0					2.1	0.4
Mixed Eucalypt/shrubby	56.2	1.9	359.4	14.9	2.9	1.2	50.6	10.7
Riparian	124.3	4.3	113.6	4.7	23.5	9.7		
Roads	47.0	1.6	32.9	1.4				
Whitegum	80.5	2.8	22.0	0.9	0.8	0.3	26.3	5.5
Sandalwood			5.7	0.2	7.0	2.9	7.4	1.6
Gully system					2.2	0.9		

6.2.2 Observations of cattle distribution

Cattle locations in focal study paddocks were recorded from aerial surveys conducted early in the morning or in the late afternoon. For all surveys, cattle locations were recorded by two observers in a small aircraft, flying slowly and at low elevation over the study paddocks (Figure 6.2). The aircraft flew linear transects that permitted clear views of all areas of the paddock. As necessary, the aircraft circled some areas to ensure that all animals were observed or to provide a longer period to count large mobs. Morning flights began as soon as light permitted; evening flights were scheduled to occur during period when animals were active.

Data from prior studies at Fletcherview were also used to evaluate spatial distribution of cattle at the full paddock scale. At Fletcherview, observers on a 4-wheel bike recorded observations of cattle grazing at roughly monthly intervals throughout the year (while paddocks were stocked) during the period of 1995-1997. The observation period was 24 hours, divided into an AM and PM observation sections which extended from dawn to mid-day or when all cattle camped around middle of day (AM), and midday to around 10.00 pm, or when all cattle camped for night (PM). Scan sampling (Altmann 1974) was used at 15-30 minute intervals, and for each mob the location (Figure 6.3), dominant activity, and number of animals in each class (calf, cow, steer) was recorded.

Figure 6.2: Aerial photograph of cattle gathering near a watering point. Note close proximity of watering point to a drainage, and scalded area in upper left corner of picture. Although this paddock is in excellent condition, some areas are much more heavily used than others. Vegetation near the watering point is different than that of surrounding areas.

6.2.3 Vegetation measurements

Vegetation was measured at the full paddock, hillslope, and small plot scales. This allowed us to link the results obtained in the component with the sub-catchment and patch scales of observation underlying the results discussed in Chapter 5 and Chapter 7, respectively. We developed and evaluated new protocols for measuring vegetation, and thus there was an evolution in techniques during the period of the study. At the full-paddock scale, we settled on the use of linear, non-aligned transects 1-2 km long, located to intersect both areas of low and high grazing pressure, most significant vegetation communities and landscape features throughout each paddock. Ten 4-m^2 sampling quadrats were located in a stratified random manner along each 200 m section of these transects. One quadrat was placed at a random location within each 20-m subsection of each 200 m section (i.e., a non-aligned transect design). Variables recorded included herbage biomass, total projected cover and dominant species, using BOTANAL techniques (Tothill et al. 1992). Overall quadrat defoliation scores (Andrew, 1988) were also recorded, along with ratings for perennial tussock grass basal area, dominant erosion type and severity (after Tongway and Hindley 1995) and descriptors for dominant vegetation community and soil type or landscape feature within a 10m radius of quadrat. Where seasonal burning occurred, burning status was also recorded.

Hillslope scale measurements were recorded from permanent 100 m sections of existing paddock transects at Mt Success paddock, Fanning River, in areas that included low, medium, and high grazing pressure intersecting ridge tops, riparian areas or grazing gradients out from water points. On each transect, a 100 m survey tape was used to accurately record the location of identifiable “patch” types, within which variables such as herbage biomass, dominant species composition, pasture height, total projected cover and overall defoliation were recorded, using techniques outlined above for paddock scale transects. These transects were re-scored at approximately 2 month intervals between June 2001 and September 2002 to examine trends in patch dynamics in response to seasonal grazing patterns.

6.2.4 Use of existing data

Previous studies of cattle grazing patterns, vegetation, and defoliation conducted at Fletcherview from 1995 to 1997 were used to develop and test the cattle grazing distribution model. These data were used to quantify use of vegetation types, topographical area, and to evaluate movements of cattle. In addition, we gathered information on the spatial distribution of grazing impacts, grazing behaviour, and movement patterns of cattle from a wide variety of sources, including Hodder and Low (1978), Low et al. (1981), Senft et al. (1983, 1987), Andrew and Lange (1986a, 1986b), Andrew (1988), Senft (1989), Pickup (1994, 1996), Laca and Demment (1996), Bailey et al. (1996), Friedel (1997), Moen et al. (1997), Stafford-Smith (1988), Farnsworth and Beecham (1999), Wallis de Vries et al. (1999) and Johnson et al. (2001, 2002).

6.2.5 Predicting cattle distribution and cattle impacts

Two contrasting approaches were used to develop a model for predicting the distribution of cattle grazing and subsequent impacts on vegetation. The first approach was based on a quantitative statistical procedure and emphasized use of data from BOTANAL samples. The second approach used data from this study as well as published and unpublished information on grazing by cattle and sheep and expert knowledge obtained from producers in the region to construct rule-based models.

When sample sizes are adequate and data quality is high, the main advantages of the statistical approach are that it is more defensible and limitations of the techniques can be clearly identified. Balancing these advantages are difficulties in generalizing results from the actual areas studied, limitations of data from a few sites or seasons, and questionable assumptions of statistical methods used to evaluate habitat associations.

The second approach has the potential to be more robust and, in this case, it leverages a broad research base from a wide geographical area. Because growth seasons during the period of this study were well above average, the impacts of grazing were greatly reduced from those observed in dry years and the ability to use existing knowledge was a significant advantage.

We first evaluated distribution patterns by cattle by assigning landscape attributes to all locations where cattle were observed. Attributes included distance to a fence, distance from a water point, vegetation type, and distance to drainages (a gully or stream bed). When possible, locations on areas recently burned were recorded. Statistical procedures suitable for examining these types of relationships include logistic regression (usually as a Generalized Linear Model – GLM), neural networks, and classification and regression trees (CART). The use of CART for this study was considered the most appropriate because it will always find a model that accounts for observed patterns, although a fully explanatory model will be statistically unjustified and is likely to be too complex to lend insight to important processes (Breiman et al. 1984).

Consequently, in the first case, we opted for classification and regression tree analysis (CART; Breiman et al., 1984), as it is suitable for explaining the variation in a single response variable by one or more explanatory variables, and the response variable can be categorical (classification tree) or numerical (regression tree). Similarly, the explanatory variables can be either ordinal or categorical. One of the most important aspects of CART analysis is its ability to include records with missing values in the analysis. A comprehensive explanation of CART can be found in Breiman et al. (1984), while De'ath and Fabricus (2000) and De'ath (2002) provide an accessible application to ecological data.

The general procedure for constructing CART analyses is to repeatedly partition the data into mutually exclusive groups defined by the value of a single explanatory variable. At each split, the data are separated into two mutually exclusive groups, each of which is as homogeneous as possible. At the limit, the splitting procedure is repeated until all observations are accounted for. This of course yields an overly large tree, and the tree must be pruned back to a useful size. For numerical data, each group can be characterized by its mean value. Construction of models of grazing impacts followed Breiman et al. (1984) and used a 10-fold cross-validation procedure to evaluate models and to estimate standard errors (SE) for each model. The resulting (very complex) trees were pruned to a final size by selecting the smallest tree with an estimated error rate that was within 1 SE of the minimum for all trees evaluated. Initial trees were grown until additional splits accounted for less than 0.1% of variance (i.e., cp = 0.001). The S-Plus RPart library (Therneau and Atkinson 1997; Atkinson and Therneau 2000) was used for all CART analyses.

6.3 Results and discussion

6.3.1 Cattle distribution

Fletcherview data

Observations of the spatial distribution of cattle were obtained from Fletcherview Station from 24 day-long observation periods between July 1995 and May 1997. These data were analyzed to determine use of vegetation communities and soil types, movement rates, and to evaluate other variables for inclusion in the grazing model. The spatial dispersion and movement rate of mobs were determined from these records by digitizing the location of each mob using the ArcView GIS for spatial analyses (Figure 6.3).

A total of 1807 mobs were recorded (average 75/day) from the 24 day-long observation periods of Fletcherview. Of these, 18 days of observations were from the dry season and 8 days were from the wet season. The highly biased sampling occurred due to the prolonged drought during the mid-1990's when wet season rains failed to eventuate. It is important to note that plant production, and consequently cover and some other vegetation attributes, were consistently below average for this period.

Focal paddocks

Multiple flights were conducted over a combination of 12 season/paddock combinations, resulting in observations of 6358 cattle at 909 locations (Table 6.2). This corresponded to a total of 54 aerial surveys over the period of the study. Overall, cattle were well distributed within all paddocks (Figure 6.5) and mob sizes were roughly similar between paddocks. This distribution is consistent with the placement of watering points throughout study paddocks, which permitted cattle to access all areas of paddocks and remain within about 2 km of a source of water. Previous studies showed that cattle near Alice Springs routinely travelled up to 5 km from water when green forage was relatively available, and more then 10 km when forage was scarce (Hodder and Low 1978). In addition, highly favourable conditions for plant growth resulted in an abundance of forage throughout the paddocks during the period of study, and whilst biomass yield varied significantly between sites, cover tended to be high as a result of generally favourable conditions (Figure 6.4). During some periods of the study water was available from flowing streams or puddles. Fletchervale, in particular, has a permanent stream running through the middle of the paddock and a seasonal swamp at one end.

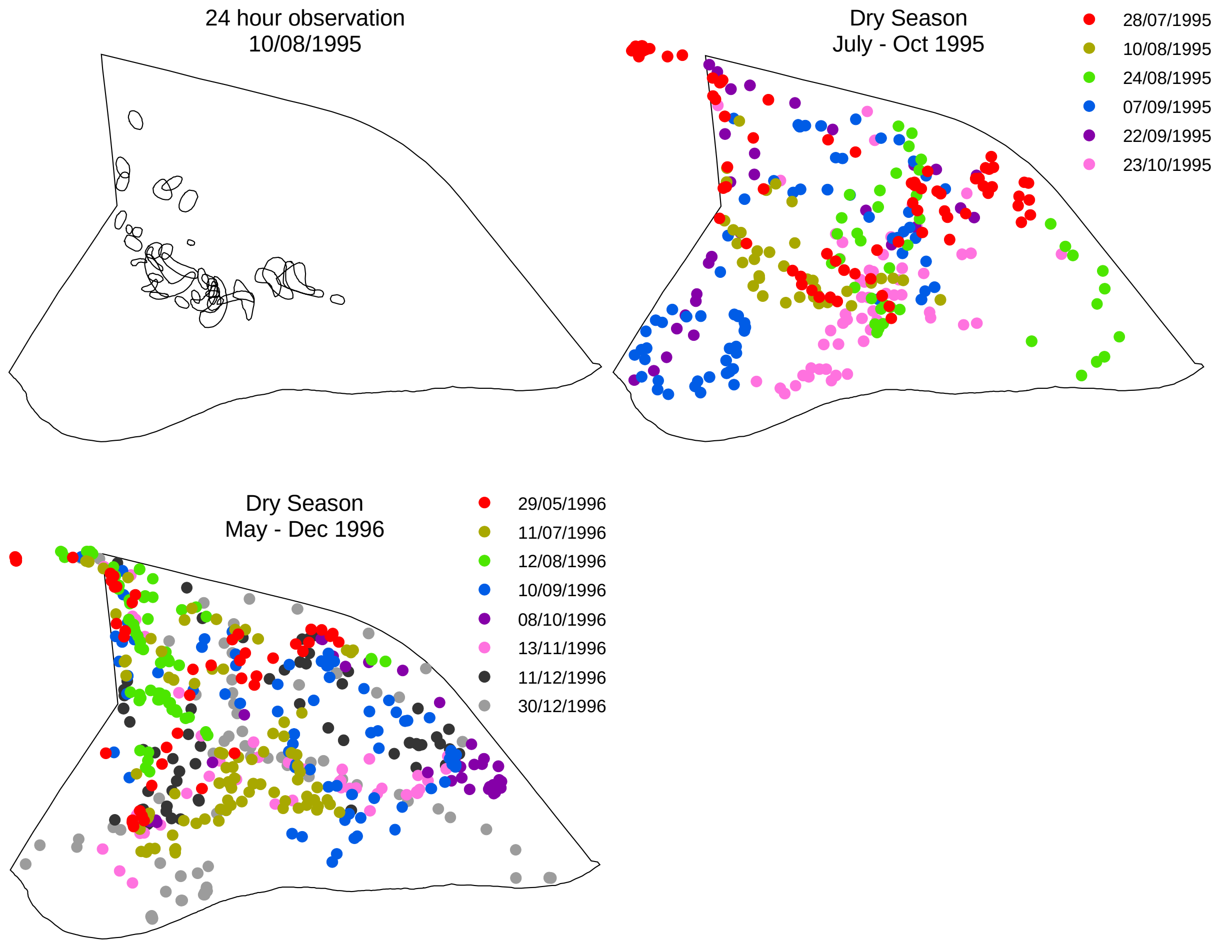

Figure 6.3: Centres of location polygons for cattle locations at Fletcher View paddock during the dry season. Points outside paddock at upper left are for cattle accessing a watering point that was sometimes open.

The average group size of mobs was 7.0, and mobs tended to be slightly smaller at Fanning River than other paddocks (Table 6.2). The size of mob is important in determining the likely impact of grazing at a local scale. Generally speaking, if mob sizes are consistently large but in a paddock with overall low stocking density, local impacts are likely to be much greater, with increased heterogeneity in the impacts of grazing. Small mob sizes generally indicate more dispersed grazing, resulting in a more uniform utilization of herbage. Equally, large mobs in situations of high stocking density are also likely to lead to a more uniform impact of grazing (at a higher overall rate of utilisation).

Table 6.2: Summary of cattle observations from aerial surveys

Paddock	Season	Year	Mobs	Total Beasts	Mob Size			
					Mean	Median	Min	Max
Fanning River	Dry	2001	200	938	4.7	4	1	32
	Dry	2000	180	956	5.3	4	1	30
	Wet	2000	73	794	10.9	7	1	75
	Wet	2001	157	746	4.8	4	1	42
Fletchervale	Dry	2000	81	714	8.8	8	1	25
	Dry	2001	82	743	9.1	8	1	26
	Wet	2000	35	536	15.3	12	3	60
	Wet	2001	51	344	6.7	4	1	39
Virginia Park	Dry	2000	11	88	8	6	4	17
	Dry	2001	20	262	13.1	9.5	1	60
	Wet	2000	15	218	14.5	11	6	40
	Wet	2001	4	19	4.8	5.5	1	7
All			909	6358	7	5	1	75

Figure 6.4: Examples of a paddock with good growth of native perennial grasses (photograph on left) and a grazed paddock dominated by introduced Indian couch grass (*Bothriocloa pertusa*; photograph on right). Note the dramatic differences in yield, but much smaller differences in total projected cover.

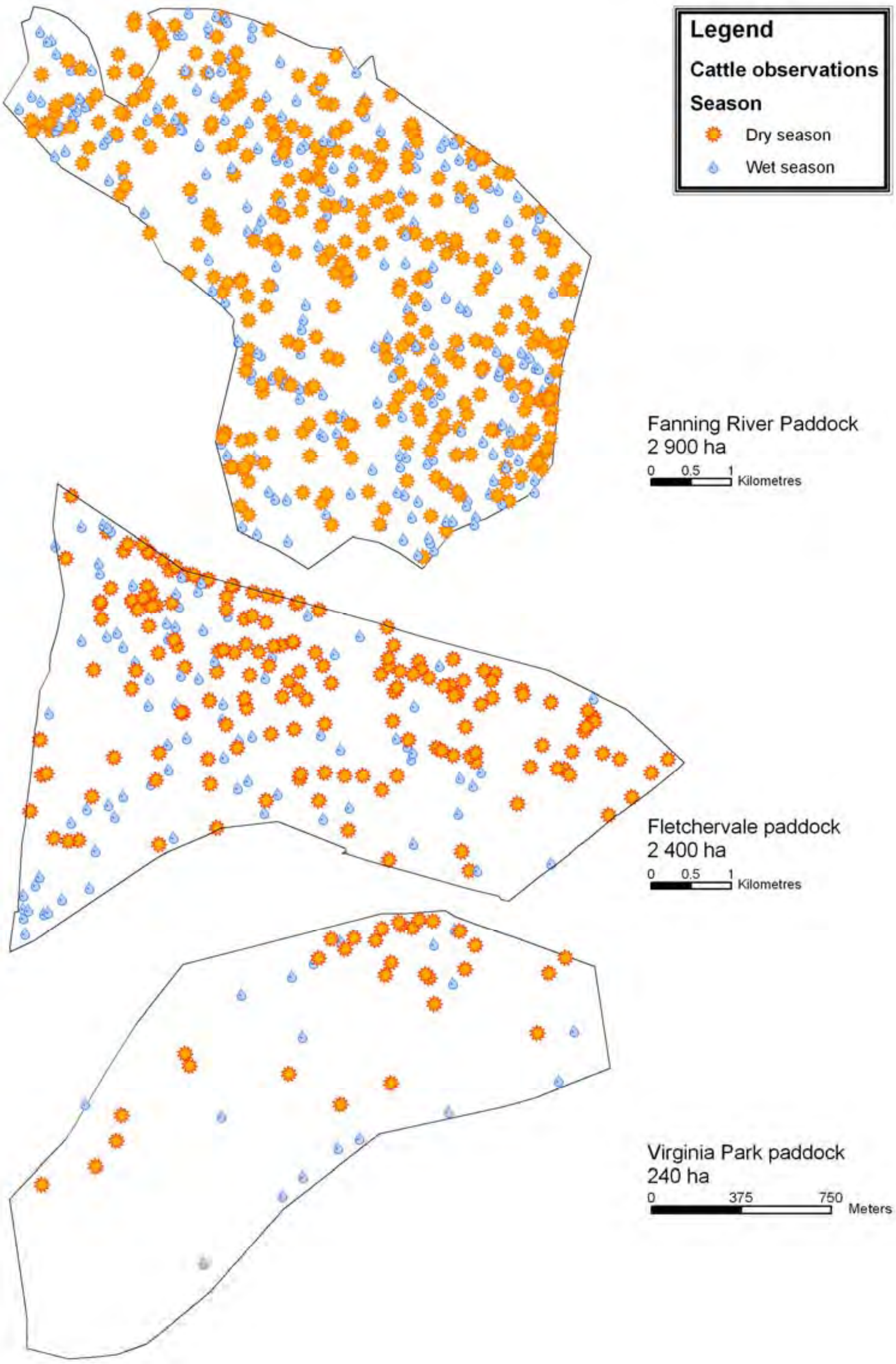

Figure 6.5: Observations of cattle mobs in the three primary study paddocks, during the wet and dry seasons.

6.3.2 Distribution and condition of ground cover

Full-paddock sampling of the three primary study paddocks consisted of more than 250 km of transects and a total of about 13,500 samples. Across all paddocks and sampling dates, cover averaged 85% and standing biomass averaged 2380 kg/ha. Estimates of both cover and yield remained consistently high throughout both wet and dry seasons, across all paddocks (Table 6.3, Figure 6.6, 6.7). These estimates were much higher than expected prior to the study, and they resulted from above average precipitation at some of the sites, or very evenly distributed rainfall where there was average to below average rainfall (Virginia Park). In both instances, this lead to very favourable growing seasons until near the end of the study in 2002. There was no dry season sampling of Virginia Park in 2001 because cattle had been removed from the paddock several months prior to sampling.

Trends in yield were more indicative of overall paddock condition and vegetation types than was cover. Yields remained relatively high in Fanning River and Fletchervale, reflecting the predominance of perennial tussock grasses in these paddocks, and the lower yields at Virginia Park were consistent with the high frequency of Indian couch (*Bothricloa pertusa*). These trends were especially apparent in 2000 and 2001, when greater precipitation permitted the vegetation to more fully express its potential for growth.

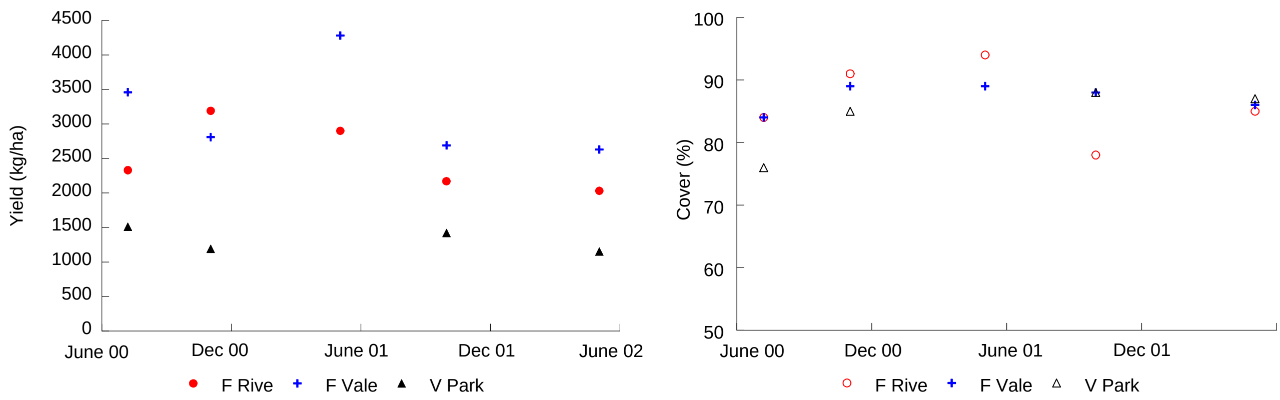

Figure 6.6: Average cover and yield for unburned quadrats in each paddock from July 2000 through May 2002. Note overall high cover levels, which averaged 85% over all paddocks during the period of the study.

Table 6.3: Sample size and mean cover (%) for wet and dry season samples across all years.

	Dry season		Wet season	
Paddock	N	Mean	N	Mean
Fanning River	1890	82	3001	87
Fletchervale	2037	87	2549	86
Virginia Park	1208	86	1182	82
All	5135	85	6732	85

Trends in cover and yield across vegetation types generally followed those of larger-scale paddock measurement. To obtain a finer-scale evaluation of trends and distribution of areas with cover level that may permit runoff of water and sediments, quadrats were assigned to cover level categories of high, moderate, and low which corresponded to cover levels of greater than 75%, 25-75%, and less than 25%, respectively. Across all paddocks, 80% of quadrats had high cover, and only 2% of quadrats fell into the low cover category. These results were reasonably consistent across paddocks, but they varied between years and seasons within paddocks (Figure 6.6). The proportion of quadrats in the low and moderate cover categories varied from 8% to 37% for unburned plots and 16% to 68% for burned plots. At Virginia Park, the proportion of quadrats categorized as high cover varied from 66% (June 2000) to 88% (May 2001). Eleven to 32% of quadrats were classified as moderate cover at Virginia Park.

Ground and aerial sampling of cover (Figure 5.10) yielded different estimates for the proportion of the Virginia Park paddock with a low cover. A significant source of discrepancy between the ground and aerial estimates of cover is related to differences in the time of sampling. The lowest cover estimates were obtained from quadrats measured in June 2000, some 3 months before the aerial photographs were acquired. Because the paddock was continuously stocked at a moderately heavy rate during this period (approximately 50% utilization on a yearly basis), we would expect cover to decline substantially between the time of ground sampling and acquisition of the aerial photographs. The first ground-based cover estimates subsequent to the aerial photographs were in November, but early rains in 2000 yielded a total of 86 mm of precipitation between the time of the aerial photographs and ground-based samples. The paddock at Virginia Park has a high dominance of Indian couch (78% of quadrats), and Indian couch responds very rapidly to rainfall. Thus actual cover levels in Virginia Park at the time aerial photographs were acquired were certainly lower than those represented in either June 2000 or November 2000.

After accounting for changes in cover due to different sampling times, cover estimates from aerial sampling still appear to be too low. As discussed in Chapter 5, cover estimates were obtained from aerial photos by assuming a linear relationship between cover class and the PD54 vegetation index. Results from ground-based BOTANAL sampling suggest this relationship is nonlinear, and the cover classes in Figure 5.10 might be skewed. A lumping of the cover classes 'high' and 'medium' in Figure 5.10 into 'high' as per ground observations, a shift of the cover class 'low' in Figure 5.10 to 'medium' as per ground observations, and the designation of the cover class 'bare' in Figure 5.10 as 'low' for the ground observations brings the two methods into close alignment. If this distribution of cover were assumed to be correct, then we have to assume that the SubNet modelling overestimates the hillslope erosion component in the sediment budget presented in Table 5.6, bringing it more into line with the measured sediment discharge.

Two factors are thus likely to account for most of the discrepancy between the ground and aerial-based estimates of cover. The first factor is the need to acquire aerial and ground samples at the same time for calibration purposes. The second factor is the algorithm used to correlate the PD54 index to actual soil surface cover, and complications imposed by red soils. The PD54 index may have been distorted because the growth form of Indian couch sometimes yields high cover levels even when yield (biomass) is very low (e.g., Figure 6.7). This characteristic can permit a disproportionately high red reflectance signal to originate from the soil surface, thereby increasing the ratio of red to green visible light over that observed from other vegetation types with a similar cover (but greater biomass). Work is underway in the new project to address these methodological problems. Once the methodological problems are resolved, it will be possible to retrospectively derive improved cover estimates and to more accurately estimate parameters necessary for the SubNet modelling.

Burning is commonly used to improve forage quality, but it also influences a number of characteristics important to evaluating risk of erosion. Burning modified yield to a much greater degree than cover, reducing average standing biomass at the time of sampling by about 50%. However, effects of burning were highly variable, depending on the interval between the burn and time of sampling, and on the initial biomass and burn conditions. At the extremes, burning reduced average standing yield to 120 kg/ha at Virginia Park in May 2002, while an average biomass of 2890 kg/ha was recorded from burned plots at Fletchervale in 2001.

The effect of burning was also reflected in scores that rated the type and severity of erosion. Burning resulted in a 50% increase in the frequency of quadrats with sheet erosion (26 vs 17% over all samples) and an increase in severity ranking. Again, there was large variation across paddocks and sampling dates. In the burned areas, only 11% of quadrats at Fletchervale exhibited any type of erosion, whereas 49% of quadrats at Virginia Park showed signs of erosion, primarily sheet erosion (46%). There were similar increases in erosion severity, although the largest increases in erosion severity were in the "low" category, suggesting that erosion due to burning was generally of short duration and was not detectable after vegetation greened up subsequent to precipitation.

Efforts to measure impacts of grazing have focused on ground cover, largely following results of runoff studies that clearly identified a runoff response to cover (Scanlan et al. 1996). However, data from runoff experiments conducted as part of this study showed that cover, by itself, explains only a small part of the variance in runoff (see discussion in Chapter 7 and Figure 7.3). We regularly measured cover, biomass, and other attributes along transects originating at a watering points. Data from one of these transects is shown in Figure 6.7, which demonstrates the rapid change in yield and much slower response in projected cover as standing biomass is consumed. Data in Figure 6.7 were recorded at sites near a watering point, and they reflect very heavy use of the area during the dry season and the rapid reduction in standing biomass (yield). Along with changing cover and biomass, heavy use by cattle compacts soil, destroys cryptogrammic soil crusts, and leads to reductions in soil biological activity (Trimble and Mendel 1995, see also Chapter 7). The overall consequence of these effects is a decrease in soil surface condition, and increases in soil compaction and bulk density, leading to a reduction in water infiltration rate and an increase in erosion risk.

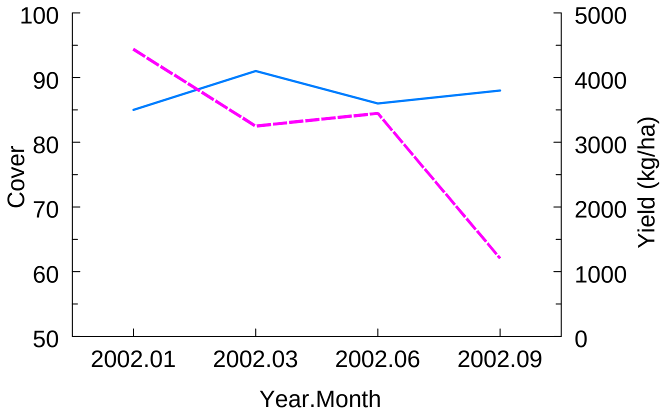

Figure 6.7: Area-weighted mean values for cover (solid blue line) and standing biomass (yield; dashed magenta line) during 2002 at Fanning River. Note relatively constant cover but strongly decreasing biomass.

Overall, cover levels remained high throughout the study and we observed few indications that current levels of grazing were adversely impacting study paddocks through effects on reducing levels of projected cover. However, these results need to be interpreted in the broader context of historic climate records. The pattern of precipitation during most of the period of the study (1999-2002) was unusually favourable for plant growth. In addition, there were clear indications that previous land use had resulted in degradation, including formation of scalds, gullies, and very substantial changes in species composition of paddock vegetation. Thus the analyses reflected both current and past conditions.

6.3.3 Statistical modelling of grazing impacts from BOTANAL sampling

Predicting grazing impacts on cover

Data from aerial surveys of cattle distribution and from BOTANAL sampling at the full paddock scale were used to derive statistical models of the impacts of cattle grazing. The fundamental statistical approach was to examine relationships between predictor variables and responses (Table 6.4).

The analyses in Table 6.4 resulted in final CART models that consistently included variables for distance to water and distance to a fence, and they rarely included variables for dominant species, topography, or distance to a drainage line (gully or other similar area). For paddocks that were burned prior to vegetation sampling, the burn status (burned or not burned) always entered the model at a high level.

Results from the CART modelling thus supported previous observations of factors that influence the distribution of grazing impacts and they clearly identified factors associated with the spatial distribution of grazing at the full-paddock scale. A strength of the analyses was the use of paddocks that had different structure. CART analyses of Virginia Park, for example, reflected greater use of relatively flat areas on the plateau adjacent to the road. Although far from water, these areas were heavily used by cattle and the importance of water as a determinant of grazing impact was therefore de-emphasized. In contrast, overall grazing impacts in the Fanning River paddock were very low and small heavily-used areas near water showed up in the CART analysis as an important determinant of cover (Figure 6.8).

Analysis using CART provided a firm statistical basis for including factors in a model for predicting the spatial distribution of grazing impacts on cover, but it did not identify a single model suitable for widespread application across the soil, topographical, and vegetation types examined in this study. A major limitation of the study was the very small amount of variation in cover and defoliation due to the exceptionally favourable growing seasons, and thus the absence of strong patterns in variation that could be detected by the analyses. A consequence of these conditions was that patterns were subdued, and thus all of the pruned trees from the CART analysis accounted for less than 30% of the variation in cover or defoliation at the full paddock scale. In other words, most of the variation was attributed to random patterns and it could not be associated with any independent predictor or combination of predictors that we examined.

Table 6.4: Models and data used for the CART analysis of grazing impacts distribution.

Response Variables	Predictor Variables	Data Sets/Subsets
cover	dominant species group	all V Park and F River
defoliation	distance to water	V Park (all seasons)
erosion severity	distance to fence	V Park wet season
	distance to drainage	V Park dry season
	burn status	F River all seasons
	topography	F River wet season
	vegetation community	F River dry season

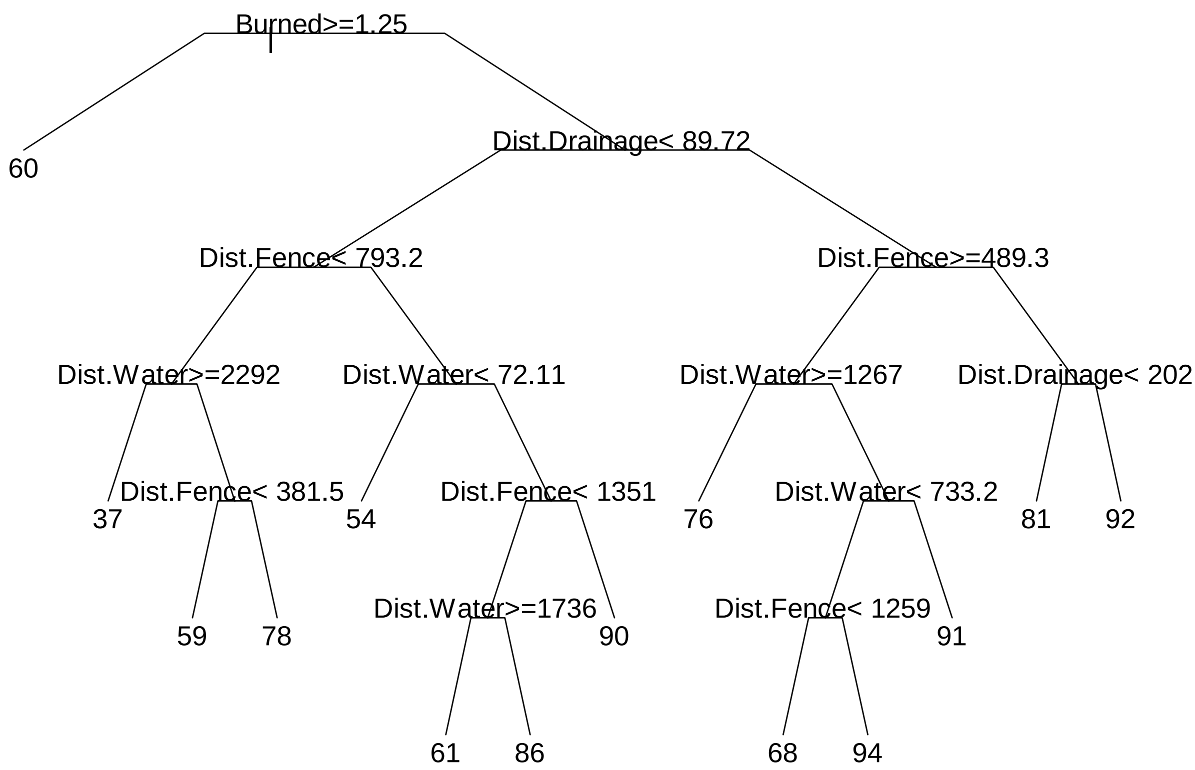

Figure 6.8: Regression tree for total projected cover during the dry season at Fanning River. A regression tree is similar to a binomial key. Data for each quadrat are compared to the decision rule at each node of the tree. If the data are consistent (e.g., the rule is true), the data are then compared to the next rule on the left side of the node. If not true, the data fall to the right, until they reach an end. Numbers at the end are the average cover for quadrats that meet all criteria at prior nodes. E.g., the first criterion in this tree is whether a site was recently burned. The average cover for all burned quadrats was 60% (i.e., Burned >= 1.25; cases categorized to the left side of the first node). Variables represented in the final tree were burned (1=No, 2=Yes), distance to a drainage, fence, and water (m).

Predicting grazing impacts on sheet erosion severity

At the full paddock scale, we evaluated data collected as part of the BOTANAL process to detect correlations between erosion severity and other variables thought to relate to risk of erosion. We constructed statistical models with erosion severity as the dependent, categorical variable (0=no erosion to 3=severe), and examined relationships with total projected cover (percent), yield (kg/ha), distance to a drainage (m), and whether the site was recently burned (1=no, 2=yes). We evaluated relationships between these variables using classification and regression trees (CART; Breiman et al. 1984).

The regression tree for erosion severity at Virginia Park is shown in Figure 6.9. The CART analysis shows that cover accounts for more variance in erosion severity than any other variable, and that a cover level of 60-70% partitions out most of the quadrats (a total of 418) that show significant signs of erosion. So, the first split for cases with cover < 80% is to the right, at the top of the diagram. The second split – quadrats with cover less than 58% - separates 217 records, with an average erosion severity of 1.92. For cases with < 80% cover (but > 58%), the next node separates cases with more or less than 72% cover. For cases with < 72% cover (211 quadrats), the average erosion severity was 1.48. In addition, a small number of sites (n=8) close to or in riparian areas (i.e., location near the bottom of hillslopes) were much more likely to exhibit erosion, even when cover was > 70%. Results of the CART analysis are consistent with our prior beliefs about factors contributing to erosion, but again the CART model accounted for less than 30% of the overall variance in erosion severity at Virginia Park or Fanning River.

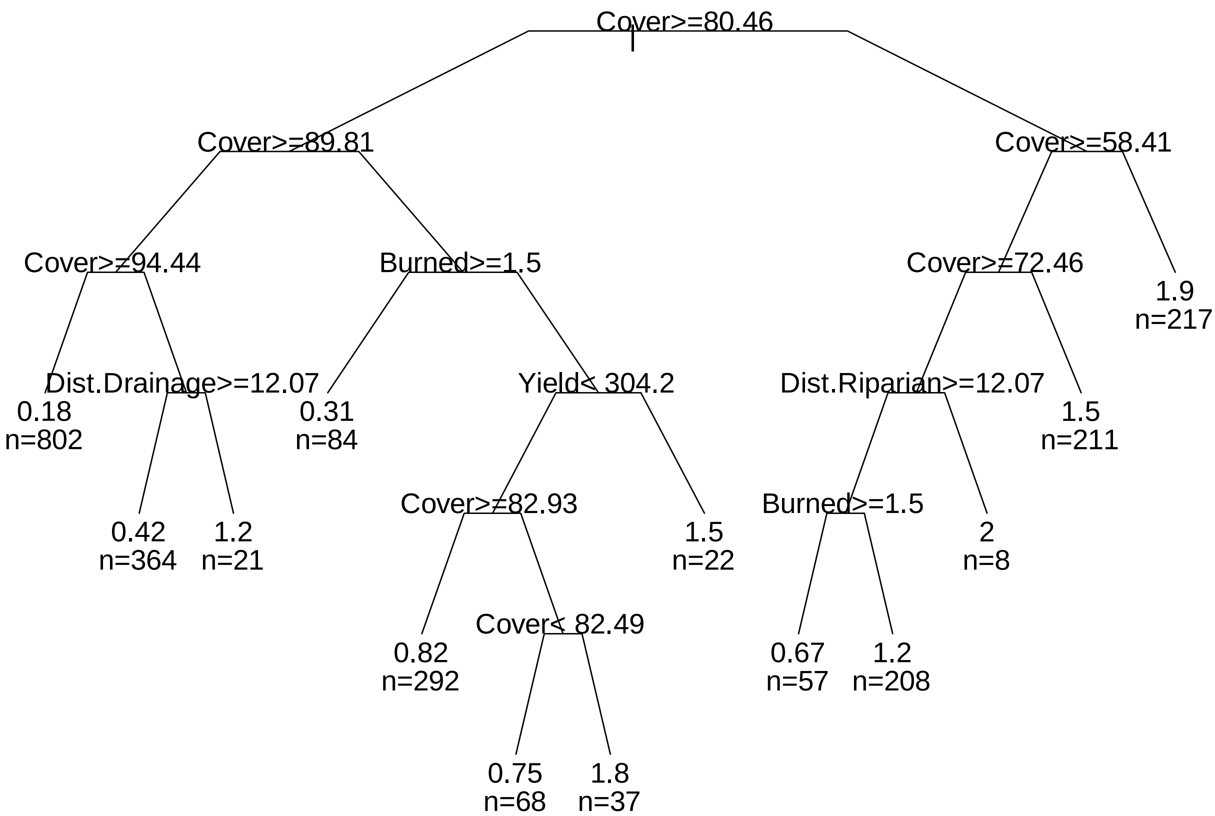

Figure 6.9: Regression tree accounting for erosion severity at Virginia Park. Data for each quadrat are compared to the decision rule at each node of the tree. If the data are consistent (e.g., the rule is true), the data are then compared to the next rule on the left side of the node. If not true, the data fall to the right, until they reach an end. Numbers at the end are the average for all cases that meet all criteria above the end. Numbers at the ends in this figure are mean values for erosion severity (0 = no sign of erosion to 3=severe erosion). The first node in this tree separates quadrats with more or less than 80.46% cover. Quadrats with < 80% cover are then separated into groups with greater or less than 89.81% cover, etc. See text for a detailed explanation of this tree.

6.3.4 Rule-based modelling of grazing impacts

Most studies of foraging by herbivores have focused on determining rules used to select areas or plant communities, and on evaluating the consequent effects on vegetation (Senft 1989; Stafford-Smith 1988; Bailey et al. 1996; Moen et al. 1997). Previous studies have explored a wide variety of approaches, from highly detailed mechanistic simulation models, to more conceptual and theoretical constructs. In general, models that focus on dynamics over large spatial scales (100's of km^2) and longer time frames (seasons to years) have a reasonably high degree of success. Models that operate over smaller scales and shorter time frames have been less successful in explaining variation in herbivore locations and patterns of impact. To some degree, scale-related differences in success of models is a reflection of the total amount of variation present in the system, and in the precision necessary to distinguish a (sometimes trivial) predicted result from a random variation. Using a simple rule based on snow depth, it's relatively simple to predict that winter ranges of herbivores will be at lower elevations where there's minimal snow depth. Similarly, in the arid rangelands of Australia, sheep and cattle distributions are overwhelmingly determined by water distribution and thus livestock distribution patterns are relatively easy to predict when compared to the more complex and smaller systems typical of NE Queensland (Hodder and Low 1978; Stafford-Smith 1988; Pickup 1994).

This study conducted an extensive program of field measurements of cattle distribution, vegetation, and soil condition over 3 paddocks. Few studies, and virtually no producers, could reasonably be expected to pursue a similarly intensive and expensive program. However, even with more than 10,000 records of vegetation and soil, we were unable to develop a statistically rigorous model that accounted for more than 30% of the variation in cover, defoliation, or erosion condition at the paddock scale.

Our inability to develop a robust statistical model even using tools like CART is clearly the result of the complex set of paddock attributes and management actions that strongly influence animal behaviour and, more importantly, the consequences of those behaviours on attributes that affect the likelihood of runoff of water and sediments. To estimate parameters for a rigorous statistical model that incorporates the most important parameters, data must be collected from "treatments" that vary with respect to these parameters in a design that permits independent assessment of the effect of each parameter and interactions between them. At the full-paddock scale, this is simply not possible from a single project.

Given the number of important factors and the scale of the response we wish to predict, there are two alternative approaches for more accurately predicting the spatial distribution of grazing and its effects on vegetation and soils. The first approach is to use a detailed simulation model, such as SAVANNA (Liedloff et al. 2001) or Moo (Fred Watson, personal communication) and explicitly represent the spatial distribution of animals. While detailed models are likely to provide the necessary accuracy, their implementation requires extensive data that is unavailable for most areas. In particular, erosion risk and animal movements at the sub-paddock scale are strongly influenced by topography (Ganskopp and Vavra 1987), local plant community attributes, and sward structure (i.e., patch grazing; Gammon and Roberts 1978). The location of patch formation, in particular, will be very difficult to predict without detailed information at the paddock level. In pastures in the Northern Territory that are burned almost every year and that are contained within uniform sort units, grazed patches can be removed by burning and can subsequently be re-established independently of their previous locations in the following wet season. In other areas, where burning is much less frequent, grazed patches persist from one year to the next, and their area is expanded over time. This pattern was confirmed by our data from hillslope-scale (100m) transects. Working in northern Australian tropical savannas, Mott (1987) found that patch formation was independent of stocking rate, and that the total area of a grazed patch was a function of the number of animals, and not paddock area when total paddock area was limited (4 – 6.7 ha; Mott 1987). Elevation models and other paddock characteristics (e.g., standing biomass, functional group composition, soil attributes) are currently not generally available at the necessary level of resolution to accurately estimate parameters for more detailed models.

The second approach is to develop a more general model based on a set of rules that incorporate existing knowledge of the system. This approach makes use of all relevant quantitative information, but it encapsulates important dynamics in a set of simple rules that can also be based on a qualitative understanding of system behaviour (Starfield 1990). This method would also allow the incorporation of producers knowledge but this was not attempted in our study. These models are much easier to explain than conventional models, the assumptions are more explicit, and connections between inputs and outputs are easier to trace. Rule-based models may be static or dynamic; frame-based models are a quantitative instantiation of conceptual state-and-transition models, such as those developed for NE Queensland rangelands (Ash et al. 1994). Models of these types have successfully been used to improve understanding and management of a variety of systems including rangelands (Hahn et al. 1999), population dynamics (Starfield et al. 1995), and arctic ecosystems (Rupp et al. 2000).

An objective of this project was to explain spatial variation in the impacts of grazing on traits important to runoff of water and sediments, rather than to account strictly for animal distributions. We thus developed a set of criteria that could be used as a basis for a rule-based model to account for spatial distribution of animal impacts, without needing to explicitly account for animal distributions under all conditions. Rules were developed from data collected by this study and from other sources, and they include characteristics at both paddock and site scales.

Model description

Variables and their incorporation into rules focused on a structure to account for paddock-scale variation in the distribution of grazing impacts that may lead to increased runoff of water, sediments, or nutrients. To be widely applicable, rules were based on data that are generally available, data that can be derived from generally available sources, and data that represents paddock specific characteristics essential to the analysis. Examples of the paddock-specific data are utilization rates and forage biomass. In theory, these data could be obtained from simulation modelling (e.g., GRASP) and producer interviews, but in most cases some variables will need to be measured in the field. Variables that cannot be easily measured in the field, that are not available from existing databases, and that cannot be derived from remotely sensed data were not included in the model. This excluded some factors that are well known to be associated with grazing patterns, including site-level (small-scale) variation in soil fertility and in vegetation composition.

This simple model was not designed to fully account for the distribution of cattle or of grazing activity, but instead focuses on identifying the (usually small) parts of paddocks that are most likely to be heavily grazed, and where disproportionate grazing is likely to lead to runoff and erosion. To evaluate risk to waterways, results from this model need to be combined with other features (e.g., hillslope position) to develop an overall risk factor. Hillslope position, for example, cannot be accurately determined from existing digital elevation models for Queensland and it was thus not included in this model. However, as it is likely that higher resolution DEMs will become available in the near future (e.g. 3” AUSLIG DEM), the inclusion of topographic attributes related to cattle movement in the landscape will need to be included

Table 6.5: Description of criteria, associated rules, and references included in the rule-based model for prediction of the spatial distribution of grazing impacts at the paddock scale.

Scale	Criterion	Unit	Levels and description	Reference
paddock	grass standing biomass	kg/ ha	0-1000, 1000-2500, > 2500; partly dependent on site	Ash et al. 2001; Owens et al. 1991
paddock	paddock burned	% of paddock	0, 1-25, 25-100	this study
paddock	utilisation rate	% utilization	low (< 25), moderate (25-50), high (> 50)	Ash et al. 2001; Senft 1989; this study
site	distance to fence	m	close (<30), other (> 30)	this study
site	distance to water point	m	close (0-150), moderate (150-300), far (> 300)	this study; Owens et al. 1991;
Site	site burned		yes, no	this study; Fletcherview data; expert opinion
Site	topograply		Rough (steep, gullies, etc); gentle	this study; Ganskopp and Vavra 1987
	water distribution		Even, too few, in corner, etc	Pickup 1994; Stafford-Smith 1988; Hodder and Low 1978
	soil stability		Slake test	Tongway and Hindley 1995
	species composition (3P)			
	slope			Tongway and Hindley 1995; Ganskopp and Vavra 1987

with the objective of improving on the predictions presented here. The paddock in Virginia Park will be further examined in the current project to evaluate the merits of including high resolution terrain attributes.

Model criteria were selected by examining relationships in data collected for this study, through interviews with local producers (including owners or managers from stations used for this study), and from published and unpublished literature. The final set of criteria and the rules that relate to each criteria are summarized in Table 6.5 and they are described below. Rules used to classify paddocks are summarized in Figure 6.10. Any area of a paddock can be assigned attributes evaluated in the model. Following from the top to bottom, each area can be classified as having a low, moderate, or high likelihood of damage from grazing.

The model uses both paddock-scale and site-scale attributes. A site is defined as a homogeneous area with respect to the variables, and an appropriate definition for a site is thus situation-specific. In general, the model could be evaluated on a grid with cells of 100-900 m^2. Cell size will be important where the environmental gradients are large (e.g., the edge of a gully or bottom of a hillslope), and cell size will be unimportant when gradients are shallow (e.g., the middle of a flat grassland, far from water).

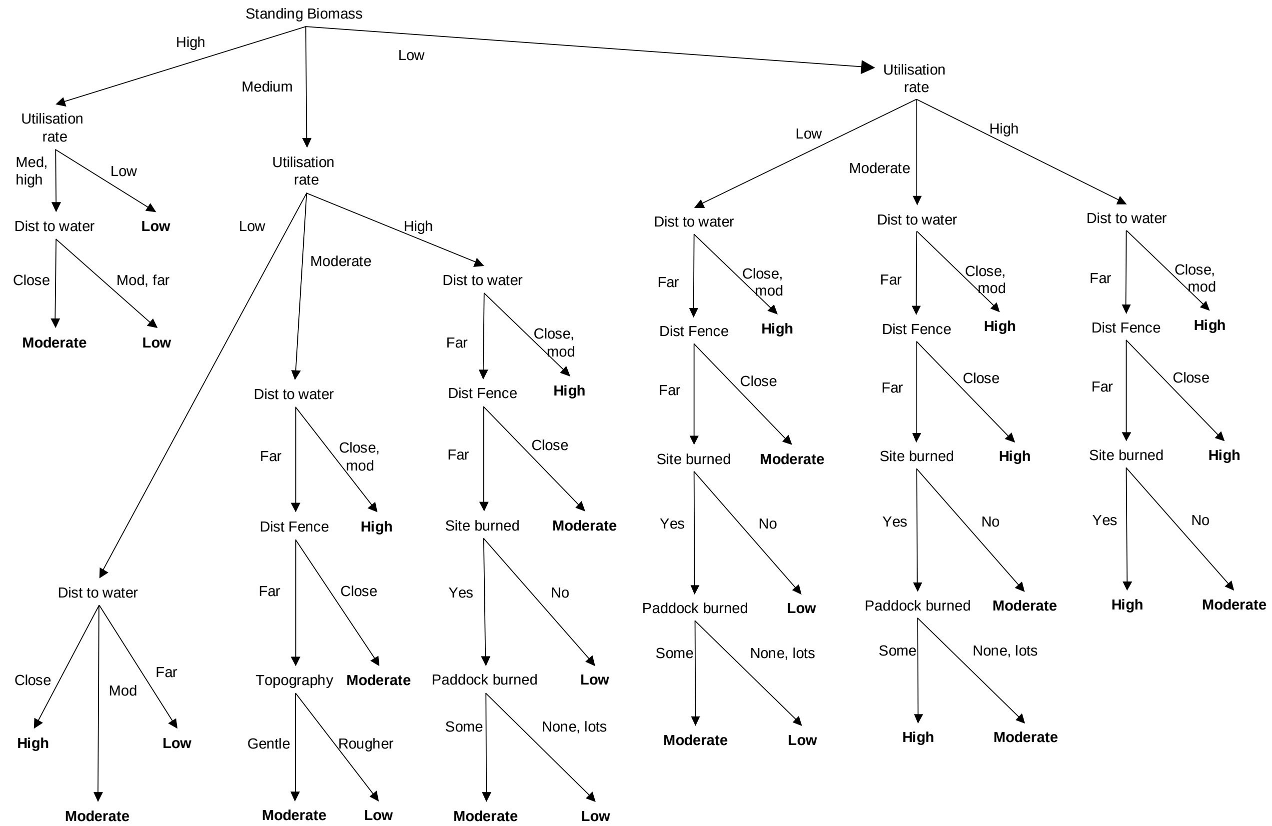

Figure 6.10: Structure of rules used to classify paddock sites into categories of low, moderate, or high likelihood of sustaining grazing impacts sufficient to induce runoff. Criteria are evaluated from left to right.

Assessment of model attributes

In the following section, we discuss in greater detail the attributes utilized in the proposed model, integrating existing data, producer knowledge, and results obtained from this study.

Biomass

At the full paddock level, the frequency of quadrats that exhibited signs of erosion and the severity of erosion was correlated with paddock-level forage biomass (Table 6.6). Relationships between biomass class and erosion severity were much stronger than the correlation between forage biomass and cover class (Figure 6.11). These data supported the use of standing biomass as a high-level variable useful for roughly partitioning the data into separate categories.

Table 6.6: Percent of quadrats recorded in each erosion category, in 3 biomass classes.

	Erosion severity			
Biomass	None	Low	Moderate	Severe
Low	66	19	10	4
Med	82	13	4	1
High	92	6	1	1

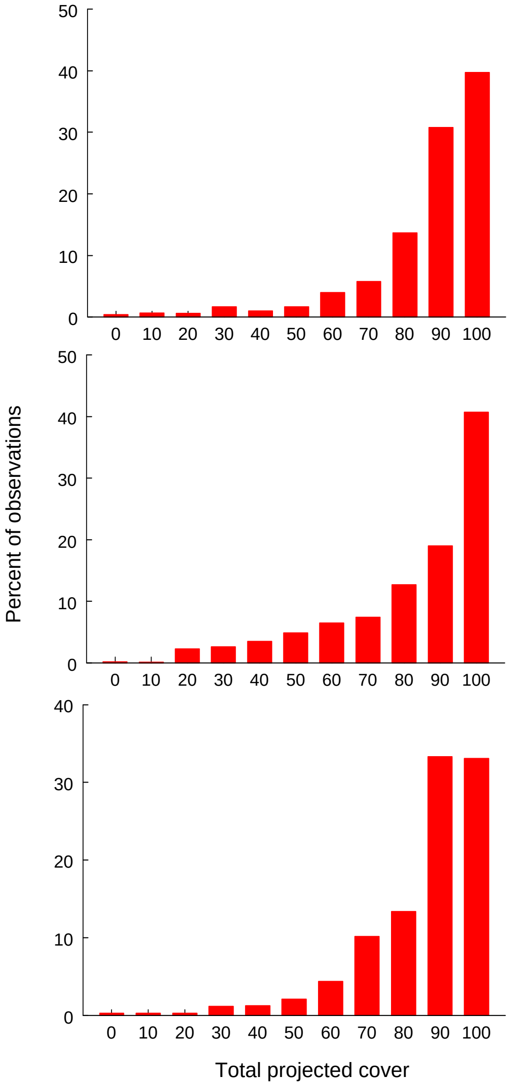

Figure 6.11: Frequency distribution of quadrats by cover class for paddocks categorized by yield (kg/ha). Yield classes were low (< 1500 kg/ha, top), moderate 1500-3000 kg/ha), or high (> 3000 kg/ha, bottom).

Utilisation rate

Data from this study revealed a very poor relationship between defoliation and cover across all paddocks, but a much stronger relationship when partitioned by biomass. As grazing pressure increases, patch grazing, heavy use of areas near water sources, and trampling will result in a greater likelihood of damage to soil and a consequent increase in erosion. The combination of standing biomass and utilization permits derivation of a grazing intensity, which is statistically related to infiltration (Gifford and Hawkins 1978) and clearly related to the rate and extent of degradation or recovery of paddocks (Ash et al. 2001).

Distance to water

Problems associated with heavy grazing near watering points are well known among producers, range managers, and the public (e.g., Andrew 1988). In this simple model, we used data from 100m transects at Fanning River to determine reasonable estimates for the “sacrifice” zone surrounding each watering point. Categorical distances are based on relatively few data and they will likely be refined with additional information. Based on relatively few data, it appears that impacts of grazing around water points are far more restricted in this area than at other locations (Owens et al. 1991; Pickup 1994)

Distance to fence

Aerial observations of cattle, especially from Virginia Park, support anecdotal observations that grazing is often greater near fences than at random locations with paddocks. Data from full-paddock sampling is consistent with this assertion, but sample sizes are small and this should be treated more as a hypothesis than a conclusion.

Burning

Producers readily identified burning as an effective management action that rapidly modifies animal distributions. Aerial observations of cattle suggested that the effects of burning, and the effects of grazing on burned communities, varies with pasture condition, the proportion of paddock burned, and stocking level. If a small proportion of the paddock is burned and forage is in short supply, cattle will quickly consume new growth on burned areas. If forages are abundant, burning has less of a concentrating effect. If most of the paddock is burned, then burning is less likely to influence animal distribution. Regardless of grazing intensity, burning reduces cover and thus predisposes soil to the erosive action of precipitation relative to unburned areas. Effects of burning on cover were previously reviewed (Section 6.3.2).

Application and assessment of the grazing impact model

The rule-based model and model parameters were evaluated by examining the ability of the model to account for observations of quadrats exhibiting signs of erosion. At the highest level, the model performed reasonably well on paddocks with moderate and high levels of standing biomass, but there were significant discrepancies at Virginia Park, where signs of erosion were much more widespread and the model did not include many areas where there were signs of erosion. At this point, it is unclear whether the occurrence of grazing impacts at locations not predicted by the model were an indication of model failure, or whether this resulted from historical impacts of grazing. Full-paddock sampling clearly showed that defoliation (a measure of utilization) was poorly correlated with erosion severity in many areas (Figure 6.12). A poor correlation between heavy defoliation and erosion severity may only indicate a resilient plant community, but an area with very low defoliation and severe erosion is likely an artefact of historical use. A model based on current conditions (e.g., yield, stocking rate, utilization) may not accurately account for historical circumstances. In the future, we expect to address this question by applying the model to a broader range of paddocks and, if necessary, by exploring additional factors to account for historical management practices.

Overall, the model performed reasonably well on the paddocks in better condition (e.g., higher biomass and lower utilisation), but it will likely need refinement for paddocks in the lower production categories. The only data available to test predictions under conditions of low biomass production was Virginia Park. Because of the small size of this paddock (less than 250 ha), results may not be applicable to the larger paddocks more typical of the region. The current model provides a significant prototype for a simple model that can be widely applied, but there is a need to evaluate and refine the model from paddocks that exhibit wider variation in utilization, soil type, topography, and water distribution. This study examined a single paddock in each combination of biomass and utilization, and the lack of replication prevented rigorous evaluation of model results. A goal of the current project is to refine the model and application and evaluation on a range of paddocks.

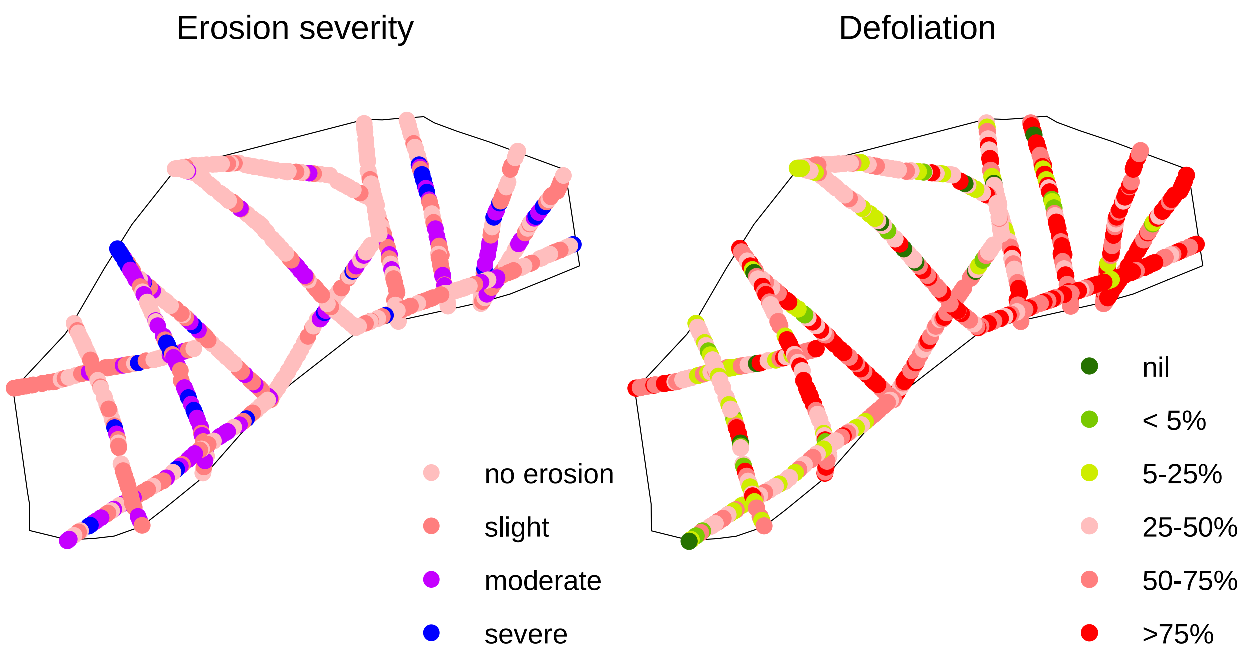

Figure 6.12: Map of recorded sheet erosion severity and defoliation at Virginia Park. Note areas where erosion severity is high, but defoliation is relatively low (< 50%). These areas may have a high risk of degradation, but lower utilization, or they may indicate historical patterns of use.

In addition to the comparison in Figure 6.12, we also compared the erosion severity ranking for each observation point with the hillslope erosion rate predicted from SubNet (as shown in Figure 5.23). We did this by matching each point in Figure 6.12 with the corresponding pixel containing results from the SubNet simulation. The result of this comparison is shown in Figure 6.13 in the form of box plots for each erosion severity class. Overall, scatter between the erosion severity ranking derived from the BOTANAL plots and the calculated hillslope erosion rates using SubNet is very large. However, it is encouraging to see that there was a general trend for higher erosion severity to correspond to higher hillslope erosion rates, both for the median values, as well as for the upper quartiles. To better understand these results, we reclassified SubNet outputs as low, moderate, or high based on predicted sediment rate (< 3.3 tons/ha, 3.3-6.6, and > 6.6, respectively). For the lowest observed erosion severity class, 81% of the predicted values were classified as low or moderate, while in the highest observed severity class (erosion severity= 3), 68% of values from SubNet were classified as moderate or high. We therefore have some confidence that the spatial impacts of grazing on cover relate to actual locations of soil erosion.

Further work is required to better understand the origin of the scatter. At this point, we can offer two possible explanations. One possibility is that the scatter between the two methods is related to the discrepancies between the cover estimates from the BOTANAL plots and the cover derived from the aerial photographs, which was discussed earlier in section 6.3.2. A second factor may be that much of the existing evidence of erosion is the result of past land use activities, and that we are still seeing evidence of these events. The persistence of historical patterns of land use complicates analyses based on current conditions (i.e., cover), and differing rates of recovery of heavily used areas contributes to variation between predictions and observations.

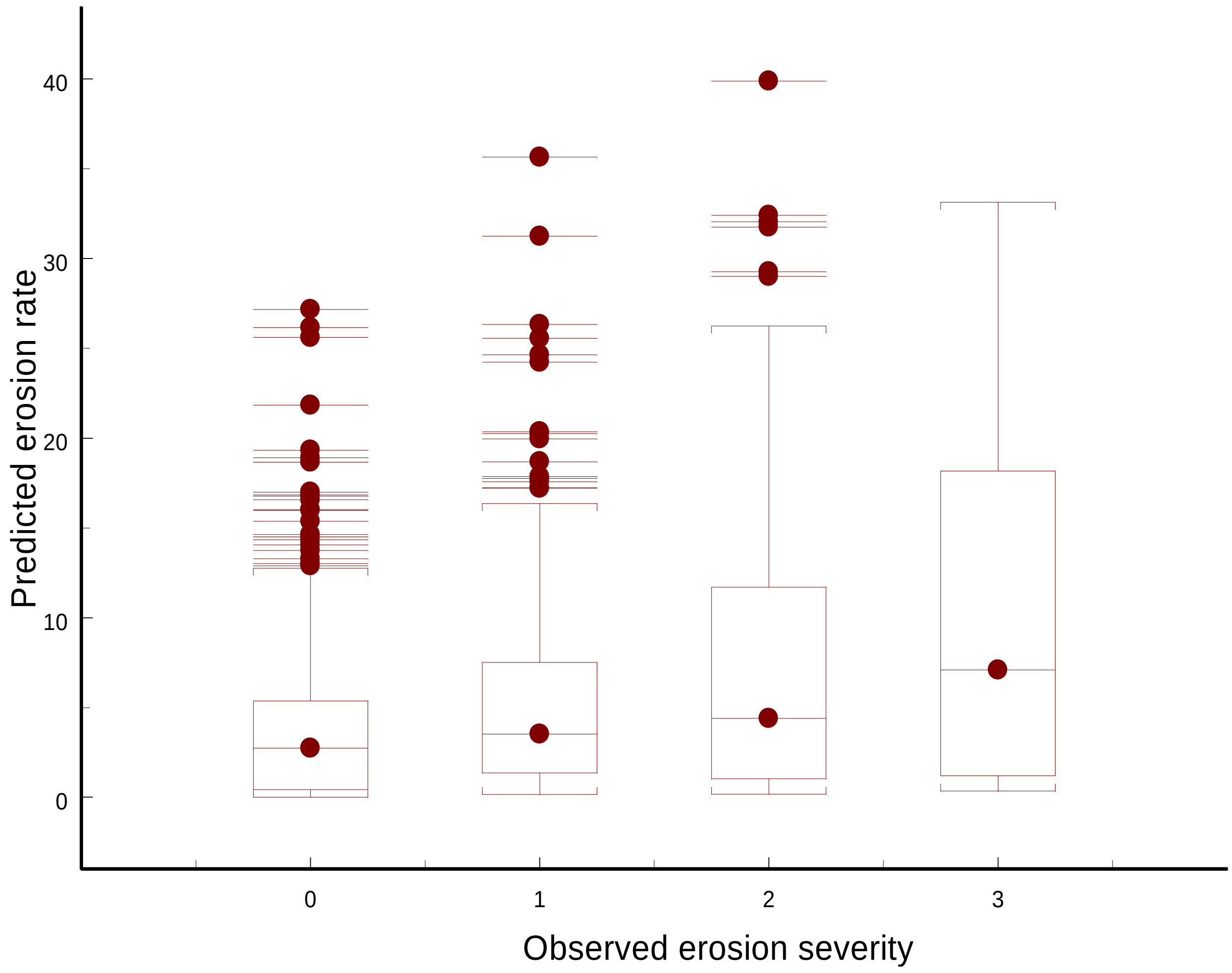

Figure 6.13: Comparison of erosion severity rankings (0=none to 3=severe) obtained from the BOTANAL sampling in November 2000 (Figure 6.12) with hillslope erosion estimates obtained from the corresponding pixels in the SubNet simulation (Figure 5.23). The upper and lower box boundaries correspond to the 25 and 75% quartiles, and the upper and lower bars correspond to the 5 and 95% percentiles, respectively. The dot in the box corresponds to the median, and outliers are shown as individual dots.

Factors not included in the rule-based model

The inability of the model to accurately account for much of the variance in grazing distribution could be the result of a genuinely random process, or it could indicate that important variables were not included in the model. It is well known that grazing animals generally prefer sites with high forage quality and quantity, and that selection of particular species can vary with location and with season (e.g., Andrew 1986). In our area, data from Fletcherview showed that cattle actively select sites on blacksoil and basaltic red soils and they avoid basalt ridges (Chi-square = 58.3, d.f. = 4, P < 0.001). Similarly, cattle selected box communities and avoided white gum communities (Chi-square = 50.8, d.f. = 5, P < 0.001), and used iron bark-bloodwood communities in proportion to their availability. Data from Wambiana (O'Reagain et al. 2002) showed that cattle grazed brigalow more heavily than other communities, but it was not apparent whether this observation reflected the availability of high-quality legume species or reflected the composition or quality of grasses and forbs.

The objective of the model was to provide a simple and general tool that could be widely applied, thus the spatial distribution of vegetation could not be included because this type of data is expensive to collect and it is available for only a few intensively studied paddocks. Our ability to apply a model including vegetation is extremely limited with existing technology.

6.4 Conclusions

Results from this component of the study emphasise the importance of managing grazing pressure at the whole-paddock level. The study paddocks varied with respect to the composition of vegetation, productivity (forage yield), and with regard to the degree and extent of erosion. There are several lessons from our data:

Under virtually all conditions, areas near water will be heavily used and there will be minimal cover. Watering points should therefore be located on flat areas with a low risk of erosion. Greater risk is associated with low cover combined with a large area that contributes runoff (e.g., lower hillslope positions), and with highly dispersible soil types.

Smaller-scale measurements confirmed the continuous use of grazed patches, once they are established. If grazing pressure is high, native perennials are unlikely to persist in these areas.

In this climate and on goldfields soils, couch grass produced far less biomass than the “3P” native perennials. Perennial grasses were associated with sites that exhibited lower rates of erosion. Low utilization rates and early wet season spelling will contribute to higher production and maintenance of native perennial grasses.

Burning resulted in short-term shifts in cattle distribution, and burning can be used to effectively remove patches established by repeated grazing.

In the future, model improvement may be possible by incorporating producers knowledge, for instance to capture local knowledge about selection for different soil types, coupled with more quantitative data on distance to water, slope angle and slope position.

7. Process studies on hillslope runoff, sediment and nutrient generation

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7.1 Introduction and objectives

Soil erosion can only occur when there is runoff or overland flow to entrain sediments. The incidence of runoff is governed by soil factors controlling infiltration. Under rangeland conditions, infiltration is predominantly affected by the extent to which the soil surface is crusted or soil structure has declined, in particular as grazing decreases the level of ground cover, exposing the soil surface to direct raindrop impact. Consequently, any attempts to understand the mechanisms of runoff generation need to start by analysing the effects of spatial variation of grazing-induced changes in pasture composition and levels of soil cover on infiltration. Whilst tools exist to study these mechanisms at patch and plot scale, we still have little understanding of how these relationships change as one moves from patch to hillslope or landscape scales.

Past studies in the Burdekin relating stocking rates to soil erosion at the hillslope scale have focused on *average* soil loss in relation to *average* ground cover and cover composition across a plot (McIvor et al., 1995; Scanlan et al., 1996). Less attention has been directed at understanding how cattle grazing affects soil surface condition in the various patches resulting from preferential grazing and how this relates not only to soil loss, but also to nutrient loss and, more generally, to soil hydrologic function. In this context, soil surface condition is understood to encompass not only the amount of ground cover but also a range of soil surface features related to near surface soil structure and soil hydrologic function, such as extent and type of surface crusts. Interactions between distribution and amount of cover and the different expression of surface crusts have been shown to be the key factor determining the partitioning of rainfall into infiltration and runoff in semi-arid savannas (Casenave and Valentin, 1992), but have not been extensively investigated in semi-arid savanna woodlands of Australia.

To more effectively manage sediment and nutrient export, graziers require adequate tools to monitor and assess the condition of the soil resource, not just based on assessments of cover and pasture species composition, but taking into account key soil attributes at the soil surface. Tongway and Hindley (1995) have developed a comprehensive monitoring approach to assess soil surface condition for use by State agency technical officers. However, it is a relatively complex and time consuming method, and not necessarily intended for use by graziers as a routine land management tool. To be useful to graziers, any soil surface condition assessment tool must rely on simple diagnostic features that are easily and rapidly recognised in the field, and the resultant assessment must relate back to runoff and sediment delivery processes on hillslopes in paddocks.

Consequently, this component aims at providing information on rates of runoff and sediment generation for the different grazing pressure/surface condition configurations identified within the study sites and is critical to improve our process understanding at hillslope scale. Therefore, the specific objectives of this component were:

- To quantify the relationships between grazing management induced variations in soil surface condition, runoff generation and sediment detachment for different representative soil types.
- To derive scaling factors to enable scaling up of runoff, sediment and nutrient delivery from patch to hillslope scale.
- To utilise the established relationships and scaling factors to test and refine a modelling framework to model runoff, sediment and nutrient redistribution along hillslopes and their delivery to drainage lines.
- To identify the key determinants of runoff, sediment and nutrient delivery at hillslope scale and derive management guidelines to minimise soil and water loss at paddock scale.

7.2 Methods

7.2.1 Site selection

Soils in the Upper Burdekin are varied but generally old and weathered with a large proportion of duplex and gradational soils (Rogers et al., 1999). With the exception of soils derived from basalt (vertosols or ferrosols), most soils are low in inherent fertility and, due to their surface textural properties, are particularly prone to crusting and hard-setting. Therefore, six study sites were selected on duplex or gradational soil types, as these are typical of large areas of the catchment. For logistical reasons, the sites selected were located within a range 80-180 km west of Townsville. Summary details of each site are presented in Table 7.1, and more site information is presented in Appendix 8 (Volume II). Three of the sites (sites 2, 3 and 4) had been previously studied as part of a joint Defence Dept. and LWRRDC sponsored project (Ash et al., 2000). At each site, the overall range of soil surface condition as affected by grazing pressure and as reflected in levels of ground cover and crust morphological features was assessed and grouped into three to six major categories. Individual plots reflecting the main classes identified were selected with two to four replicates per class, resulting in about ten to sixteen plots per site. Site conditions ranged from very heavily grazed and degraded to exclosure sites with no grazing for more than 15 years (Table 7.1). A total of 75 individual plots were investigated across the six sites.

7.2.2 Rainfall simulation

Rainfall simulation was chosen as the main tool to concurrently determine infiltration and runoff properties. The rainfall simulator consists of a 1m^2 drop-forming chamber mounted on a 4 m high aluminium tower. Drop formers consist of capillary tubes with an inner diameter of 0.5 mm placed at 2 cm intervals on the base of the chamber. The tower is attached to a trailer-mounted support equipped with a winch that allows the simulator to be lifted for assembly and relocation purposes. Rainfall intensity is controlled through the closed chamber by a precision peristaltic pump and can be varied between 30 – 75 mm/h. Target intensity and rainfall duration chosen for this study were 60 mm/h for 30 minutes, which represents a storm event having about a 1-year return period for north-eastern Queensland (Canterford, 1987).

Metal runoff plot frames 0.4 by 0.6 m in size were placed in the middle of the rainfall plot, thus allowing for a 0.2 – 0.3 m buffer zone around the plots. An angle grinder was used to cut slots into dry ground to enable insertion of the frame into the soil without disturbing surface features. Key soil surface features were recorded for each plot. These included estimates of ground cover (green material and litter), an assessment of microrelief and plot slope, a range of macroscopically visible crust and surface features following criteria suggested by Tongway and Hindley (1995) and included presence and type of crust, extent of cryptogams, extent and nature of surface lag and gravel cover, presence of pedestals, degree of litter incorporation, presence of macropores and extent of surface castings. Further details of the rainfall simulator, its set up and operation are provided in Appendix 8 (Volume II).

Table 7.1: Summary description of the six study sites and key soil surface attributes.

	Site 1 Thalanga	Site 2 Pinnacle transect	Site 3 Simpson's dam	Site 4 High range	Site 5 Meadowvale	Site 6 Wambiana
Date studied	July 1998	November 1998	April 1999	November 1999	June 2000; July 2001	May 2002
Longitude and latitude	S20°21'57.91"; E145°47'38.27";	S19°32'42.71" E146°19'40.66"	S19°27'22.47" E146°13'41.87"	S19°27'58.07"; E146°26'33.42"	S19°50'30.67" E146°35'19.81"	S 20 34'; E 146 07'
General description	NAP 3.218 (A Noble) Stylo monitoring site with native pasture (moderately to heavily grazed) and a Stylo dominant pasture; ground cover very patchy; general site condition moderate to poor	Heavily grazed site; ground cover patchy with large inter-spersed scalds; general site condi-tion poor	Moderately to heavily grazed site; ground cover patchy with large interspersed scalds; general site condition moderate to poor	Site on Dotswood military training area (TFTA sec-tion); site with no grazing over the past 20 years; general site condi-tion excellent, except for occa-sional permanent military vehicle tracks	Main NAP 3.224 erosion monitoring site (micro plots; hillslope runoff plots; stream gauging); history of heavy stocking but with a grazing exclosure; general site condition poor to very poor (with exception of exclo-sure with excellent condition)	Paddock 1 in DPI Wambiana grazing trial; fairly heavily stocked over the last 5 years; good cover of perennials; some patches with less desirable species; clumps of Carissa (~25% of area) ungrazed for many years; general site condition moderate
Vegetation – dominant trees	Silver-leafed Ironbark (Eucalyptus melanophloia)	Narrow-leafed Ironbark (Eucalyptus creba)	Reid River Box (Eucalyptus brownii)	Narrow-leafed Ironbark (Eucalyptus creba)	Narrow-leafed Ironbark (Eucalyptus creba); Bloodwood (Corymbia erythrophloia)	Reid River Box (Eucalyptus brownii); Current bush (Carissa ovata)
Vegetation – dominant grasses or legumes	Wiregrass (Aristida spp.); Stylo (Stylosanthes spp.)	Wiregrass (Aristida spp.); Desert Bluegrass (Bothriochloa ewartiana)	Desert Bluegrass (Bothriochloa ewartiana); Golden Beard Grass (Chrysopogon fallax); Hairy Panic (Panicum effusum)	Kangaroo grass (Themeda triandra); Black Speargrass (Heteropogon contortus)	Indian Couch (Bothriochloa pertusa)	Golden Beard Grass (Chrysopogon fallax); Wiregrass (Aristida spp.); Desert Bluegrass (Bothriochloa ewartiana)
Hillslope position and angle	Upper slope; 0-3%	Mid-slope ; 3-7%	Upper to mid-slope; 1-3%	Mid-slope; 3-7%	Upper to mid-slope; 5-8%	Mid-slope ; 0-2%
Geology	Cainozoic sediments	Devonian sedi-ments and sedimentary rocks	Metamorphic rocks and metasediments	Granite and granodiorite	Granodiorite	Cainozoic sediments
Dominant soil types [1]	Yellow Kandosol (Boston series)	Red Chromosol (Ceasar series); Brown/Yellow Chromosol (Greenvale series)	Red Chromosol (Rangeview series); Brown Sodosol (Warrawee series)	Brown and Yellow Chromosols (Bluff series)	Red Chromosol (Dalrymple series, eroded phase)	Brown-grey Sodosol (Liontown series)
Key attributes [2]						
Sand (%)	nd	68 – 88	68 – 79	86 – 89	48 – 79	58 – 76
Clay (%)	nd	6 – 22	14 – 23	5 – 7	11 – 41	11 – 18
Bulk dens. (g/cm^3)	1.53 – 1.90	1.51 – 1.72	1.46 – 1.67	1.36 – 1.57	1.43 – 1.61	1.48 – 1.90
OM content (% C)	nd	0.6 – 1.3	0.7 – 3.5	0.6 – 1.4	0.7 – 1.8	0.8 – 1.8
Moisture (%vol)	0.06 – 0.15	0.05 – 0.17	0.05 – 0.11	0.08 – 0.14	0.11 – 0.13	0.02 – 0.06
Ground cover (%)	8 – 98	0 – 100	0 – 100	75 – 100	1 – 96	3 – 100
Biological activity [3]	1 – 2	1 – 2	1 – 2	3 – 4	1 – 4	1 – 4

[1] As described in Rogers et al. (1999); [2] 1 – 5 cm soil depth; [3] Soil biological activity rated in four classes: 1 = low or negligible: no incorporation of litter, no castings, no or little visible soil biological activity; 2 = moderate: 0-50% of litter incorporated into surface; single macrofaunal pores visible; occasional castings; 3 = high: >50% of litter incorporated into surface; <50% of surface covered with castings; enhanced microrelief; 4 = very high: >50% of surface covered with castings; pronounced microrelief; surface uncrusted and friable.

7.2.3 Soil and water analyses and data analysis

Soil cores were taken from within each plot after the event for bulk density measurements at a depth 1 – 5 cm, as bulk density values were intended to reflect levels of hoof compaction rather than crust density. Antecedent soil moisture was determined gravimetrically on samples taken in 0 – 10 cm depth before the event. Particle size distribution, total N (Kjeldahl), bicarbonate extractable P and organic carbon contents (Walkley and Black) were determined for samples taken in 1 – 5 cm depth using standard procedures described by Rayment and Higginson (1992). During the rainfall event runoff was recorded to determine rainfall infiltration as the difference between rainfall and runoff rates. Runoff samples were analysed for concentrations of suspended solids (defined as the fraction <20 μm; clay and fine silt) using the pipette method. Bedload was discarded, as the small plot size does not allow for full entrainment of larger particles to occur. Total N and total P in runoff samples were determined by digestion using a Kjeldahl acid digest procedure and analysed for total Kjeldahl N and P using a segmented flow analyser.

In addition to the above quantitative measures, soil surface condition indices were determined for each plot based on the criteria and the scoring system proposed by Tongway and Hindley (1995). The only difference was that the soil surface condition assessment technique was restricted to the plot area itself, rather than the 10 m long transects prescribed by the original methodology of Tongway and Hindley (1995). The objective of this approach was to assess how well the their infiltration index INF and their soil stability index STAB related to measured infiltration and sediment concentration data, respectively.

Infiltration rates calculated from the difference between applied rainfall rate and measured runoff rate were plotted against rainfall depth to normalise for variation in rainfall intensity between individual plots. The Horton equation (Horton, 1940) was fitted to the data to calculate infiltration rates after 30 mm of rainfall as a standardized infiltration index, which is termed I_{30}. In most cases, I_{30} was close to final infiltration rate I_f as extrapolated by the Horton equation. At site 5, infiltration rates were significantly greater than the rainfall intensity able to be supplied by the simulator. In this case a hood permeameter (for details see UGT, 2000) was used as an alternative method to determine infiltration properties. The hood permeameter operates like a disc permeameter, except that water is supplied to the soil surface through a circular hood that is maintained at tensions than can be varied between 0 and 10hPa. The hood is placed onto the soil surface without any disturbance into an outer ring filled with fine sand. As the hood is filled with water under tension, the outer ring filled with sand acts as a seal. Two to four replicates were carried out for each condition class at tensions 0, 2 and 4 hPa. In order to assess comparability of the two methods, hood permeameter tests were conducted adjacent to rainfall simulator plots where runoff data had been obtained at site 5 in order to compare infiltration rates.

7.2.4 Hillslope runoff model

We used a hillslope model that had been developed for a similar project in the Defence Department's Dotswood military training area. In the study reported here, we built on this model and applied it to run selected grazing management scenarios to assess the relationship between hydrologic properties of patches, the grazing-induced distribution of patches, and hillslope delivery of runoff and suspended sediments. In brief terms, the model simulates overland flow by matching infiltration against rainfall on a pixel-by-pixel basis, and then routes any excess runoff downslope. Routing of runoff is two-dimensional to allow for runoff to flow around mounds or tussocks. The model accounts for surface roughness and patch infiltration characteristics (obtained from the rainfall simulation experiments). Scenarios can include changes to slope (angle and length), different rainfall intensity and duration and patch distribution characteristics. A rudimentary sediment transport routine is also included, that takes the equilibrium concentration of suspended sediments for each pixel (based on the data obtained from the rainfall simulation experiments) and routes the suspended sediment downslope together with the flow. Sediment discharge is obtained from the product of runoff and sediment concentration at each pixel. Details of the two-dimensional hillslope model developed to model overland flow and sediment delivery are provided in Appendix 9 (Volume II).

Following implementation and testing of the hillslope model, a series of scenarios were defined to assess the effect of grazing on runoff and sediment delivery. All scenarios were run on a 32 x 8 m large hillslope segment with a final pixel size of 1 x 1 m, this being seen as a reasonable compromise between minimum size of slope segment and computational demand (10 – 30 min per simulation run). The following scenarios were tested:

1. Hillslope segment heavily degraded by cattle grazing ('low cover'). Actual cover distribution was taken from low-altitude videography scans of site 2 (see Table 7.1) and relative pixel frequency of surface condition classes (see Figure 7.7 for codes) corresponded to 96% 1.1.1.1 and 4% 1.1.2.1, respectively.
2. Hillslope segment slightly less degraded by cattle grazing ('moderate cover'). Actual cover distribution was taken from low-altitude videography scans of site 2 (see Table 7.1) and relative pixel frequency of surface condition classes (see Figure 7.7 for codes) corresponded to 28% 1.1.1.1, 63% 1.1.2.1 and 9% 1.1.3.1, respectively.
3. Uniform, undisturbed hillslope segment, with no or little cattle impact, characterised by soil surface condition class 1.1.3.3 (100% of pixels).

A preliminary sensitivity analysis indicated that amongst other factors, degree of slope, rainfall event and pixel size were not important in terms of discerning relative effects of grazing impacts. In all cases slope was held constant at 5%. The rainfall event was chosen to deliver 30 mm of rain in 30 min and its rainfall intensity designed to follow a X^2 distribution, with a peak intensity of 114 mm/h. Further information regarding individual parameters required by the model is given in Appendix 9, (Volume II).

7.3 Results and discussion

7.3.1 The effect of grazing on soil surface condition

Soil surface condition is essentially determined by the quality and amount of ground cover, organic matter content of the surface soil and the soil structural condition at and near the surface. Ground cover generally is thought to consist of green material (grasses, forbs) and litter (leaves, twigs, dead grass). As discussed in Chapter 6, we found that ground cover varies significantly at any one site and in areas impacted by heavy grazing, cover typically occurs in patches (Figure 7.1). Examples of soil cover that we observed at the patch scale are shown in Figure 7.2. Excessive grazing pressure leads to removal of ground cover, opening up the soil surface to the direct impact of rain (crusting) and the loss of soil organic matter (reduction in soil biological activity). As bare patches develop, topsoil erodes leading to water and nutrient loss, leading to further rundown of the system.

Figure 7.1: Patchy nature of a site with a history of heavy grazing (Site 3, Table 7.1)

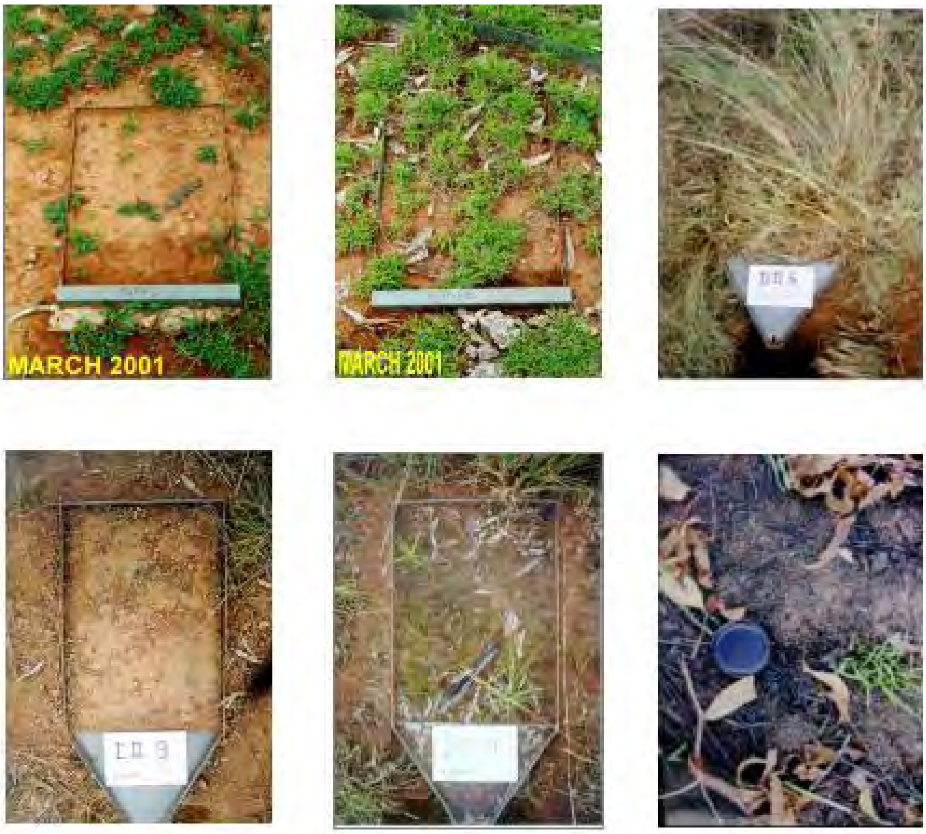


Figure 7.2: Examples of soils cover (top row), ranging from low (<25%) to high (>75%) and examples of soils surface condition (bottom row), ranging from erosional crust (left), cryptogam crust (middle) and surface uncrusted and reworked by soil macro-fauna (right).

Structural features of significance for the assessment of soil surface condition are presence and nature of surface seals (wet soils) or crusts (dry soils) capping the soil surface. These seals and crusts can prevent entry of rainwater, and were found to occur in a variety of forms, e.g. erosional, depositional, pavement or cryptogam crusts. Examples of such surface conditions are shown in Figure 7.2. Soil structure is also determined by the level of compaction near the surface (0-15 cm depth). In rangeland soils, this is primarily as a function of hoof compaction (Greene et al., 1994). Hoof compaction (contact pressure of a steer is ~1 kg/cm^2), particularly in the wet season when soils are wet and highly compactable, leads to loss of large pores and a significant reduction of infiltration. In most savanna soils with sandy-loamy topsoils that do not contain enough clays with shrink-swell properties, we observed that the only agents capable of reversing structural decline are soil macro-fauna such as termites and earthworms, which require sufficient organic matter to thrive.

7.3.2 The effect of soil surface condition on infiltration, sediment and nutrient generation

As an initial step in analysing the data, the infiltration index (I_{30}) and the concentration of suspended solids after 30 mm of rainfall (Sed_{30}) were plotted as a function of total ground cover (Figure 7.3). In general terms, an increase in infiltration rate and a decrease in sediment concentration with an increase in ground cover was noted, corroborating earlier work in the Burdekin on similar soils (McIvor et al., 1995; Scanlan et al., 1996). Although statistically significant, the relationships are characterised by considerable scatter. With respect to sediment concentration the scatter is greatest for cover ranges <25% (Figure 7.3B). In the case of infiltration scatter is particularly evident for cover levels >75% (Figure 7.3A). Indeed closer scrutiny of the data suggests no effect on infiltration for cover levels <75%, which would seemingly contradict the findings of Scanlan et al. (1996), who observed a more significant decrease in runoff with rising cover levels beginning at lower thresholds (40% cover). One possibility is that the reduction in runoff at lower cover levels observed by the above authors at the large plot scale is due to larger runoff residence times because of flow tortuosity and increased tussock-induced roughness, even though runoff generation at the point scale is probably not very different until significantly higher cover levels are achieved. However, McIvor et al. (1995) were able to show that cover has a close relationship to runoff only in low intensity rainfall, and that this relationship weakens with increased rainfall intensity until it breaks down completely at intensities >45 mm/h, corroborating the work presented here, which was conducted using rainfall intensities of ~60 mm/h.

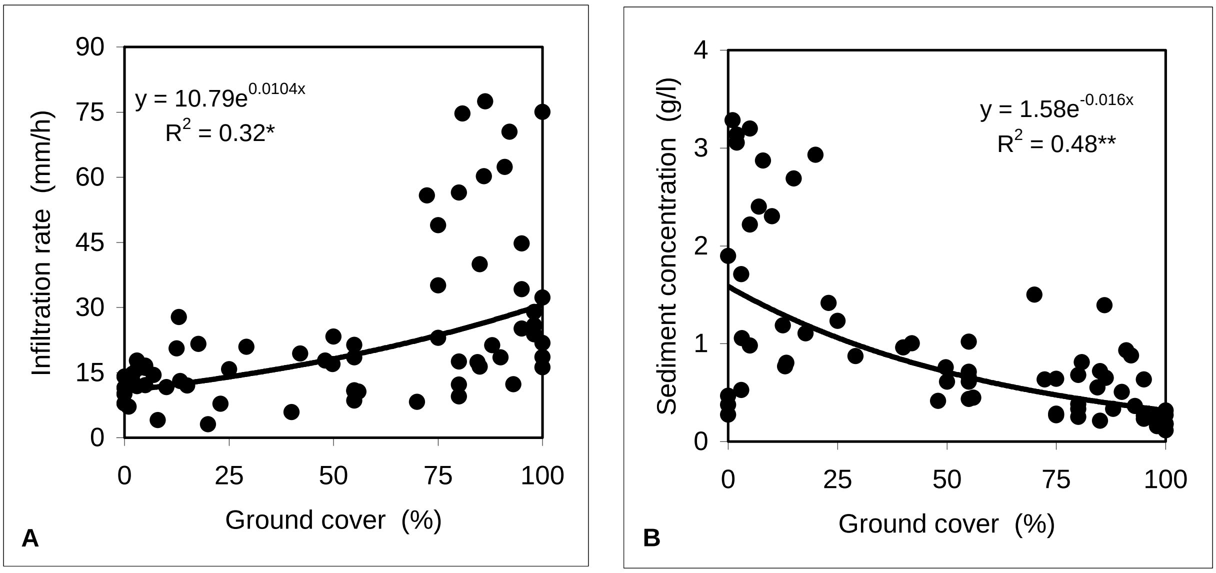
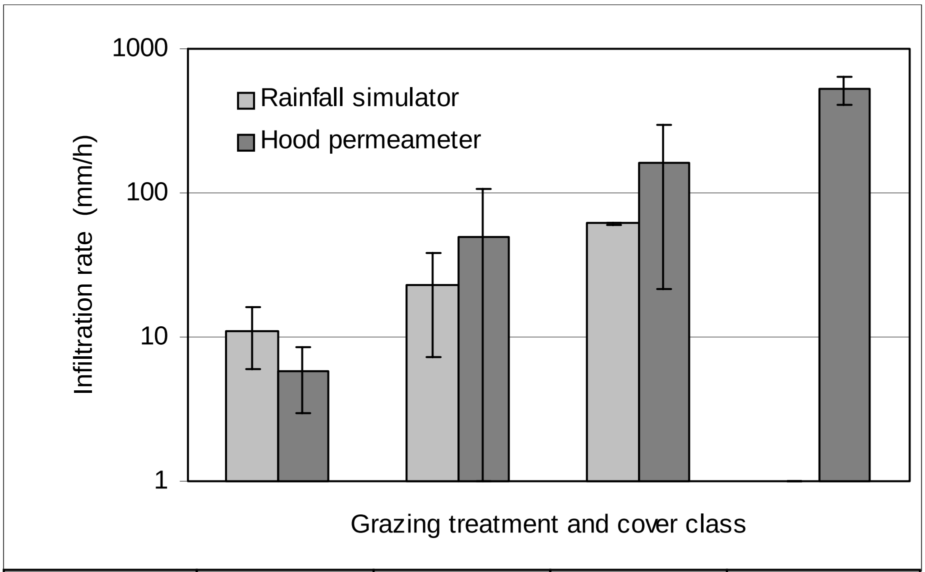


Figure 7.3: Effect of ground cover on infiltration rate (A) and concentration of suspended solids (B) after 30 mm of rainfall.

Clearly, cover alone is a poor predictor of infiltration. We therefore undertook a more detailed analysis on a site-by-site basis to determine which other factors may be affecting infiltration. Based on observations in patches that were well covered and had had little cattle impact for long periods, we hypothesised that indicators related to soil biological activity might help explain the variability of infiltration in the cover class >75%. Figure 7.4 shows results obtained for site 5 (Meadowvale), where we compared patches on heavily grazed hillslopes with patches in a cattle exclosure and a full grazing exclosure; hence the two right hand columns in Figure 7.4 relate directly to the runoff plots and the data presented in Table 5.5. This exclosure site at Meadowvale is one of the exclosure sites established by Scanlan et al. (1996) about 15 years ago. As can be gathered from Figure 7.4, high infiltration rates are primarily associated with indicators of higher macroporosity (indicated by the lower bulk densities) and absence of crusts in conjunction with increased levels of bioturbation, following the exclusion of cattle and the reintroduction of grazing at low intensities.

Total N and P in runoff were not well related to cover. This is because concentrations of N and P are primarily controlled by sediment concentration, as shown in Figure 7.5. Nutrient concentrations decrease significantly at sediment concentration smaller than 1 g/l (Figure 7.5), which corresponds to ground cover levels of 30 - 40% in Figure 7.3B. Plotting concentrations of particulate N and P against sediment concentration was found to further improve the relationship to suspended solids (Figure 7.6). On average, 85% of the total P and 75% of the total N contained in the analysed runoff samples was in particulate form, respectively (i.e. bound to clay and organic matter particles). This means that total suspended solids are a reasonable surrogate measure of nutrient export. However, determinations of nutrient concentrations in hillslope runoff and stream water samples being carried out as part of the current project will enable us to assess whether this holds for overland flow and flow in waterways as well.



	Low cover + high grazing pressure	High cover + high grazing pressure	High cover + low grazing pressure	Very high cover + no grazing pressure
Bulk density (g/cm^3)	1.55	1.49	1.44	1.34
Ground cover (%)	7	88	90	100
Presence of crusts	+++	++	+	-
Presence of castings	-	-	++	+++

Figure 7.4: Relationship between selected soil surface condition attributes and infiltration rates for site 5 (Goldfields country – Narrow-leafed Ironbark/Indian Couch on Red Duplex soils derived from granodiorite). Bars represent standard deviation.

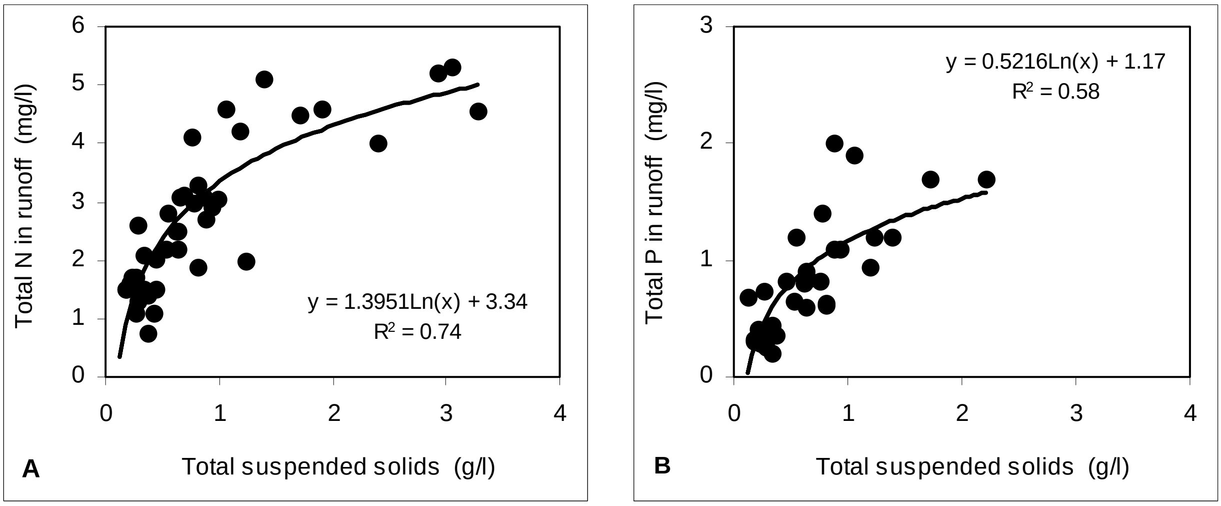


Figure 7.5: Relationship between concentration of suspended solids after 30 mm of rainfall and total nitrogen (A) and total phosphorous (B) concentrations in runoff, respectively.

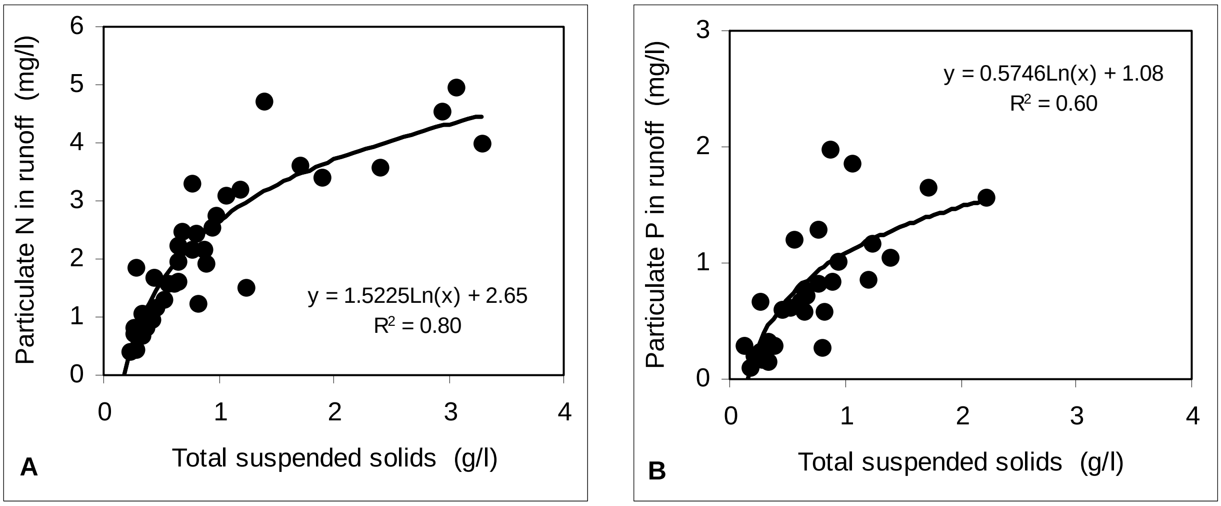


Figure 7.6: Relationship between concentration of suspended solids after 30 mm of rainfall and particulate nitrogen (A) and particulate phosphorous (B) concentrations in runoff, respectively.

7.3.3 A framework to assess soil surface condition

As shown in the two preceding sections, ground cover alone is not a sufficiently robust indicator of soil surface condition. Multiple regression analysis using a variety of predictor variables in addition to soil cover such as bulk density, soil texture etc. did not produce any useful regressions. However, in subsets of the data, where we measured basal area, we were able to derive pedotransfer regressions that accounted for up to 80% of the variation. Unfortunately, as basal area is not a readily available measure, we decided to develop a soil surface condition classification system based on easily distinguishable surface features, as shown in Figure 7.7. The classification is currently only developed for hard setting or crusting soils (class 1.1 in Figure 7.7), but it is conceivable that the classification will need to be expanded as data become available for other regions and soil types (e.g. self mulching and sandy soils).

Three cover classes were selected as the next category level (classes 1.1.1, 1.1.2 and 1.1.3 in Figure 7.7) based on the three scatter domains observed in Figures 7.3A and 7.3B (<25%, 25-75% and >75% cover). Four categories within the next level are distinguished, based on generic crust and surface morphological features, following features suggested by Tongway and Hindley (1995) and Casenave and Valentin (1992). In most cases, soil surface in bare to moderate cover conditions is erosional in nature, i.e. is characterised by the presence of erosional, structural or sedimentary crusts, often with small pedestals under individual pieces of litter or gravel. A thin, discontinuous layer of sand or fine gravel lag may also be present. This category has been termed ‘erosional surface’ (1.1.1.1 and 1.1.2.1 in Figure 7.7). On those areas of the hillslope where larger, bare runoff patches are located upslope of densely covered patches, patches with contiguous deposits of loose, mostly sandy material about 5 – 20 mm thick can be found, often with a layer of vesicles at the interface between the loose surface and the buried, relic crust. This second category is termed ‘depositional surface’ (1.1.1.2 and 1.1.2.2 in Figure 7.7). The third category, ‘pavement surface’ (1.1.1.3 and 1.1.2.3), represents a progression from erosional surfaces commonly observed in gravelly soils and is characterised by the dominance of loose or partially embedded gravel or stones at the surface. Cryptogam crusts, characterising the fourth category (1.1.1.4 and 1.1.2.4) are widespread features in more arid and patchy savanna systems with lower levels of grazing pressure. They are comprised of soil material, lichens and algae forming intricately intermixed biological crusts that are more resistant to sheet erosion than erosional surfaces.

In the cover class >75%, crust morphological criteria alone were not suitable to differentiate further soil surface condition categories. Rather, we found that criteria based on the level of biological activity offered a better basis for differentiation. Four additional categories were identified in this cover class based on differing levels of macroscopically visible bioturbation by soil macrofauna such as ants, termites and earthworms. Morphological criteria used to distinguish these categories are provided in Figure 7.7 and amongst other criteria include diagnostic criteria such as the degree of litter incorporation (following the reasoning of Tongway and Hindley, 1995); presence of macropores, and frequency of castings deposited at the soil surface.

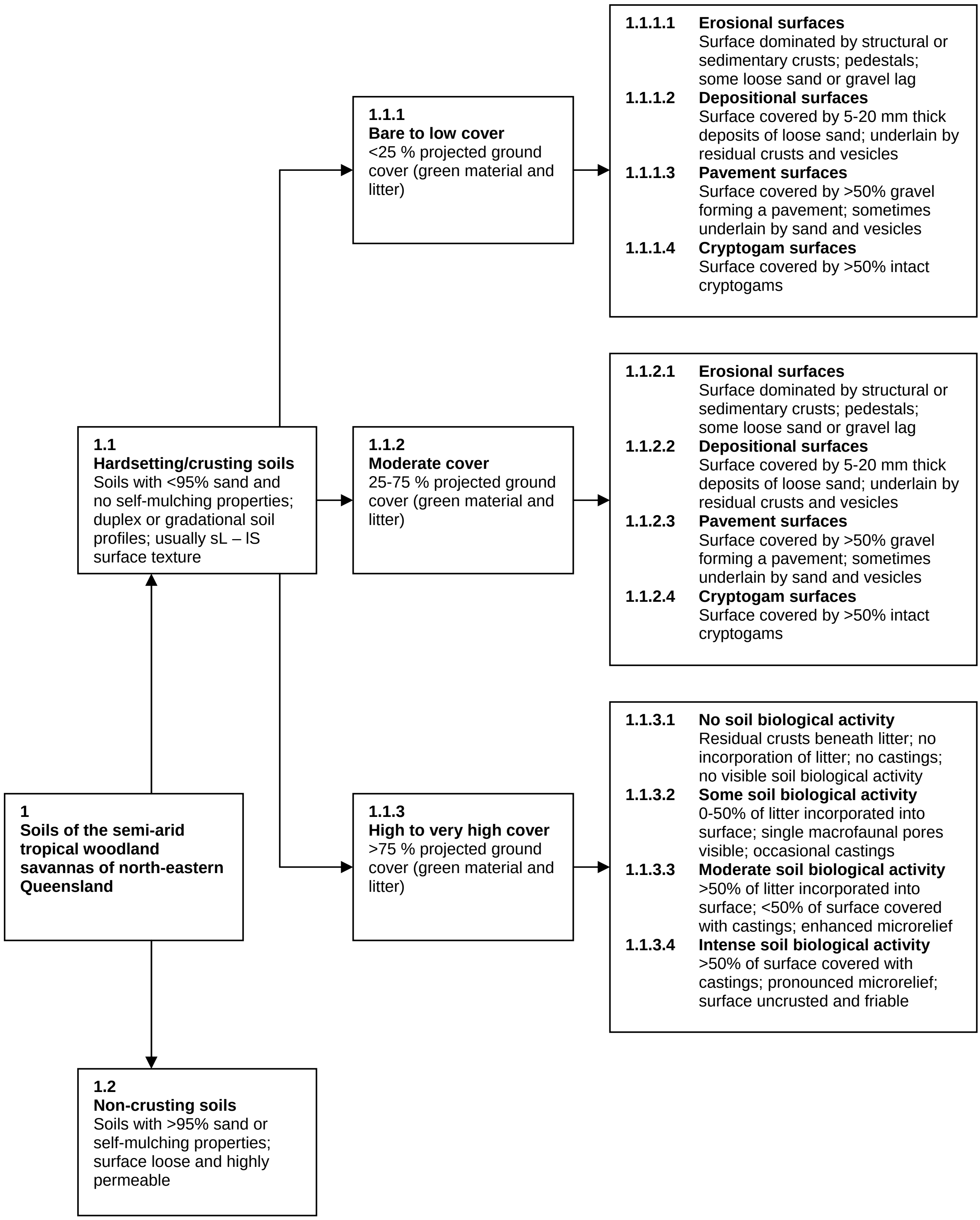


Figure 7.7: Classification of soil surface condition classes for crusting soils of semi-arid tropical savannas in the Burdekin, using easily distinguishable soil surface features.

Taking the classification proposed in Figure 7.7 as the basis, the data were clustered accordingly, to derive average values for I_{30}, Sed_{30} and total N and P concentrations in runoff. These data, together with the results of Student's t-test and the respective standard errors are presented in Figure7.8. In the cover class 1.1.1 (<25%), grouping into erosional (1.1.1.1), depositional (1.1.1.2), pavement (1.1.1.3) and cryptogam (1.1.1.4) surfaces clearly differentiated sediment concentration with erosional surfaces being associated with significantly higher Sed_{30} values than the other three surfaces. There was a tendency for lowest sediment concentrations to be associated with class 1.1.1.3, but due to insufficient replicates, differences could not be tested statistically. However, it is conceivable that armouring of the soil surface with gravel pavements in effect protects the soil surface from soil detachment by drop impact, leading to values similar to those at ground cover levels >75% (indeed gravel cover was 60 – 70%). The importance of cryptogam crusts in maintaining lower soil detachment rates on crusted soils compared to disturbed, erosional surfaces has been reviewed by Chartres (1992).

	I_{30} (mm/h)	Sed_{30} (g/l)	N_{tot} (mg/l)	P_{tot} (mg/l)
1.1.1	13.2 a *12*	1.8 a *0.2*	3.61 a *0.38*	1.06 a *0.21*
1.1.2	17.7 a *3.1*	0.8 b *0.1*	2.35 b *0.33*	1.04 a *0.21*
1.1.3	35.2 b *4.0*	0.4 c *0.1*	2.25 b *0.23*	0.65 b *0.08*

	I_{30} (mm/h)	Sed_{30} (g/l)	N_{tot} (mg/l)	P_{tot} (mg/l)
1.1.1.1	12.7 a *13*	2.2 a *0.2*	4.3 a *0.25*	1.24 a *0.28*
1.1.1.2	7.9 *	0.5 *	nd	nd
1.1.1.3	12.1 * *2.0*	0.3 * *0.1*	1.03 * *0.28*	0.31 * *0.05*
1.1.1.4	17.3 ab *4.1*	0.9 b *0.2*	3.27 ab *0.71*	1.32 a *0.36*
1.1.2.1	18.2 ab *5.0*	0.8 b *0.1*	2.21 bc *0.43*	0.86 ab *0.12*
1.1.2.2	nd	nd	nd	nd
1.1.2.3	nd	nd	nd	nd
1.1.2.4	16.9 ab *2.4*	0.7 b *0.1*	2.80 bc	1.40 ab
1.1.3.1	19.8 b *2.3*	0.3 c *0.0*	1.87 c *0.25*	0.52 b *0.16*
1.1.3.2	41.1 c *6.8*	0.5 c *0.1*	2.04 bc *0.30*	0.61 ab *0.12*
1.1.3.3	62.2 d *3.9*	0.7 bc *0.2*	3.08 b *0.52*	0.82 ab *0.15*
1.1.3.4	> 75	nd	nd	nd

* T-test not performed due to insufficient replicates

Figure 7.8: Mean infiltration rate at 30 mm of rainfall (I_{30}), concentration of suspended solids at 30 mm of rainfall (Sed_{30}) and concentrations of total N and P, for the soil surface condition classes proposed in Figure 7.7. Values in columns followed by different letters indicate significant differences at p = 0.05 using Student's t-test; values in italics are standard errors; nd = not determined.

Differences in the moderate cover class (1.1.2) are not as clear, partly because of absence of data in classes 1.1.2.2 and 1.1.2.3, but also because the nature of surface condition in this class does not differ greatly from cover class 1.1.1. The only noticeable difference is the significant decrease in sediment concentration between classes 1.1.1.1 and 1.1.2.1, which is related to higher cover. As more data become available, the need to discriminate between surface condition classes in cover class 1.1.2 should be reviewed.

In the cover class 1.1.3 (>75%), differentiation into different classes of soil biological activity significantly improves discrimination of infiltration, even though cover levels are essentially the same for all four classes. There is a tendency for a slight increase in sediment concentration with increasing biological activity, which is attributed to increased availability of loose soil material in the form of castings deposited on top of litter. In class 1.1.3.4, it was not possible to obtain runoff using the rainfall simulator, as the maximum achievable rainfall intensity was lower than the infiltration rate. However, using the hood permeameter at site 5, infiltration rates in the order of 500 mm/h were observed on class 1.1.3.4 plots (Figure 7.4; class 1.1.3.4 corresponds to the right column).

In order to relate the soil surface condition assessment framework developed as part of this project with the one proposed by Tongway and Hindley (1995), we compared the average I_{30} values and the average Sed_{30} values for each class in Figure 7.8 with averages of the infiltration index (INF) and the stability index (STAB), respectively, obtained by applying the method of Tongway and Hindley to each runoff plot. The results of these comparisons are presented in Figures 7.9 and 7.10.

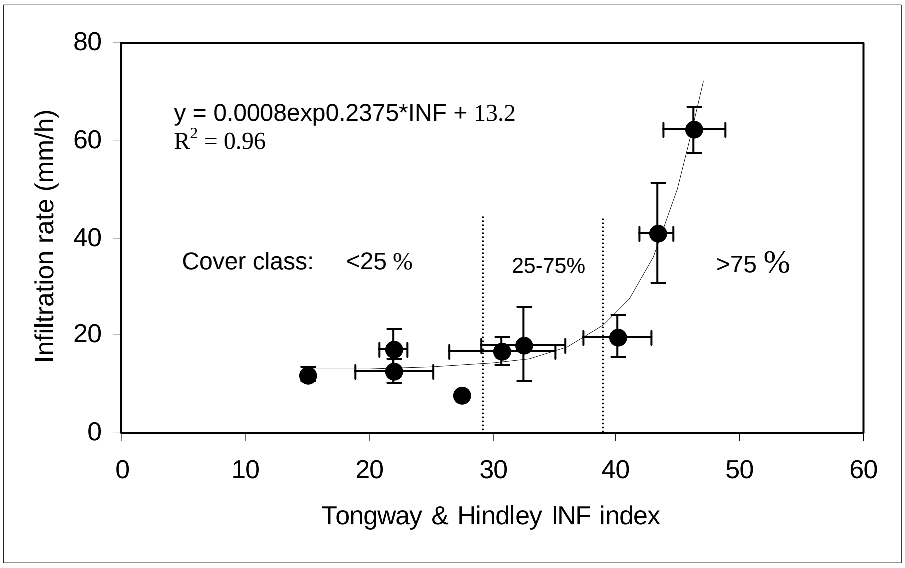


Figure 7.9: Comparison of clustered I_{30} values taken from Figure 7.8 with the infiltration index INF derived from the Tongway and Hindley (1995) soil surface condition assessment method.

In the case of infiltration, there is a very close statistical relationship, although it is highly non-linear (Figure 7.9). It appears that the INF index differentiates better between the various soil surface categories in the low to moderate cover classes, a differentiation however which is not borne out by the measured infiltration rates. Overall, there seems to be a general consistency between the two methods, although the Tongway and Hindley method is not necessarily designed to assess patches, and the relative spread between indices can vary between sites. Here, we have lumped all data from all sites, so it is actually surprising that the two methods compare so well. The non-linear relationship indicates that the scores making up the INF index might have to be weighted differently or other criteria introduced, to better match the actual infiltration rates.

The relationship between the measured concentration of suspended sediments and the STAB index is not so straightforward (Figure 7.10). A weaker, but statistically significant, non-linear relationship is only obtained when two soil surface categories (the two crosses in Figure 7.10; corresponding to soil surface condition classes 1.1.1.2 and 1.1.1.3 as defined in Figure 7.7 and 7.8) are excluded from the relationship. The bigger discrepancy was to be expected, as we only assess suspended solids in our framework, whilst STAB assess total soil and nutrient loss over hillslope segments rather than points or patches.

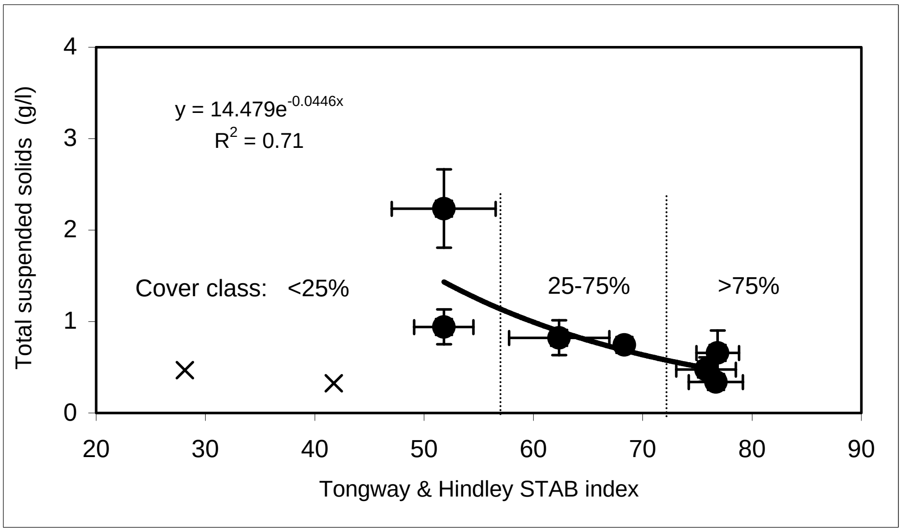


Figure 7.10: Comparison of clustered Sed_{30} values taken from Figure 7.8 with the stability index STAB derived from the Tongway and Hindley (1995) soil surface condition assessment method.

7.3.4 Using patch surface condition to model hillslope runoff

The basic assumption underlying the scaling up approach chosen is that in situations where runoff and sediment delivery are essentially surface driven processes (as is the case in many rangelands), it is possible to simplify hillslope hydrology in an additive approach by aggregating patch characteristics to larger scales. A similar approach has been successfully used in the West African Sahel (Casenave and Valentin, 1992), and is also consistent with theoretical considerations underpinning the rangeland condition and function assessment framework provided by Tongway and Hindley (1995).

Figure 7.11 presents the simulated hydrographs obtained for a hypothetical high intensity storm and a comparison of total runoff is presented in Table 7.2. As to be expected, the case with predominantly low cover and very poor surface condition resulted in a very peaky hydrograph with very high runoff rates. Increasing the cover, but with a surface condition still resulting in only marginally higher infiltration rates decreases the runoff rate, but leads to a longer recession phase, which can be interpreted to be a result of the increase in surface roughness between the two scenarios. In other words, a similar amount of runoff takes longer to flow down the hill. In contrast the hillslope where we assumed all patches to be in excellent condition practically reduces runoff to negligible amounts, and indeed runoff ceases before the storm ends as rainfall rate falls below infiltration rate (~75 mm/h).

Similar patterns can be observed for the discharge of suspended solids (Figure 7.11 and Table 7.2). However, the model oversimplifies sediment transport, in that it does not account for additional entrainment of sediment as a result of flow concentration in rills. This would be likely to happen in the case of poor surface condition and along longer slope segments, and the sediment discharge in this case is probably significantly underestimated.

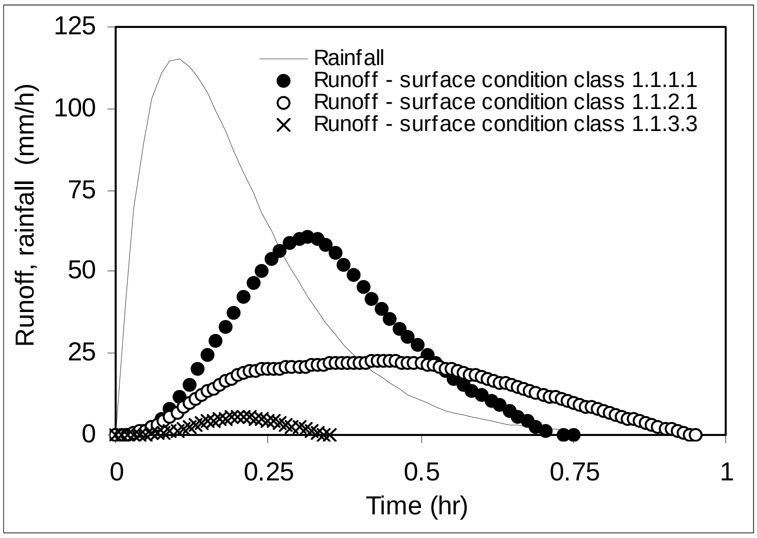


Figure 7.11: Runoff hydrographs modelled for three hillslope segments characterised by different soil surface conditions. Hillslope segment a plane with 5% slope and 8 x 32 m large, with pixel = patch sizes of 1x1 m.

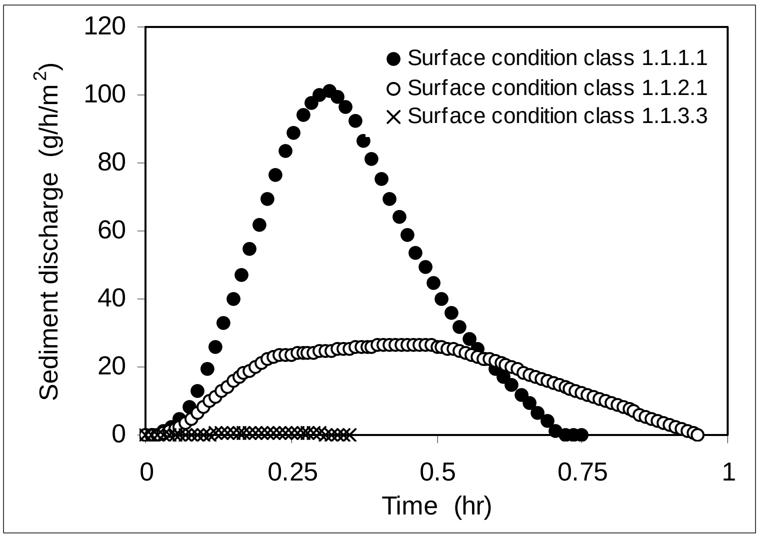


Figure 7.12: Sediment discharge modelled for three hillslope segments characterised by different soil surface conditions. Hillslope segment a plane with 5% slope and 8 x 32 m large, with pixel = patch sizes of 1x1 m. Design storm as in Figure 79.

The absolute values in Table 7.2 are well within the range of plausible results (runoff coefficients in the order of 65-43 % were measured with the rainfall simulator under similar rainfall amounts and intensities; 32 g/m^2 soil loss corresponds to 0.32 t/ha, which is also in the same order of magnitude of calculated erosion rates presented in Chapter 5). The model also meets the condition of conserving mass balance. In summary therefore, we believe the model is probably capturing the overland processes well enough in a relative sense and is therefore a useful tool to explore the relationships between cover, surface condition and hillslope discharge. However, the model now needs to be validated against actual runoff data being obtained from the hillslope runoff plots. This step has been deferred until we have more hillslope runoff and sediment discharge data from the Meadowvale plots and the newly installed hillslope flumes at Virginia Park, and also because we chose to focus our resources on the development of SubNet before pursuing more work on the hillslope model. The model also needs improved sediment transport and deposition routines, which currently are very rudimentary. This model refinement is due to be carried out as part of the current project to allow us to develop a better representation of hillslope erosion, which in turn will improve the hillslope routines in SubNet.

Table 7.2: Simulated total runoff and total sediment discharge for three hillslope segments characterised by different grazing regimes and soil surface condition classes. Hillslope segment a plane with 5% slope and 8 x 32 m large, with pixel = patch sizes of 1x1 m. Total rainfall 30 mm.

Grazing regime	Soil surface condition class (% pixels)	Runoff (mm)	Runoff coefficient (%)	Total discharge of suspended solids (g/m^2)
High grazing pressure; low cover	1.1.1.1 (96%); 1.1.2.1 (4%)	19.6	65	32.4
High grazing pressure; moderate cover	1.1.1.1 (28%); 1.1.2.1 (63%); 1.1.3.1 (9%)	12.9	43	15.5
Grazing excluded > 20 years	1.1.3.3 (100%)	0.9	3	0.1

7.5 Conclusions

Soil surface condition, as expressed by amount and quality of ground cover, and soil structural features at the surface (crusts) and near the surface (compaction), is clearly related to grazing impact. When soil surface condition is poor, i.e. low levels of cover, presence of crusts and generally compact A-horizons, runoff can be expected to be high because of low infiltration. Conversely, with enduring high levels of soil cover (>75%), soil macro-fauna will reverse some of the adverse conditions, leading to a recovery of soil hydrological function. Exclosure sites in the Burdekin have indicated that such recovery can occur within 10-15 years. However, further investigations on a wider range of sites across northern Australia are required to fully assess the relevance of earthworm activity in moderating these dynamics and additional work is warranted into quantifying the likely time periods to recovery under various improved grazing management regimes based on wet season spelling combined with lower stocking densities. As infiltration increases and runoff incidence decreases, sediment generation and nutrient mobilisation in runoff will decrease, particularly at cover levels > 40%. Two key principles for grazing management can be derived to achieve the desired level of soil recovery – the need for wet season spelling and the need for overall lower levels of grazing pressure.

It appears that a simple soil surface condition assessment framework for crusting/hard setting rangeland soils suitable for use by graziers and which encompasses a wide range of surface conditions can be based on as few as 12 categories using ground cover and easily distinguishable surface morphological features. The features selected seem robust enough to effectively differentiate infiltration and sediment concentration in runoff within three broad cover classes. From the analysis of the data and the preliminary hillslope scenario modelling, it is suggested that whilst the cover threshold of 40% previously suggested by McIvor et al. (1995) and Scanlan et al. (1996) is probably sufficient to significantly reduce soil and nutrient loss from hillslopes, a long term target cover level ranging between 75 and 95% cover for native tussock grasses or Indian Couch dominated pastures respectively, would be required to allow for recovery of soil hydrological and biological function with a significant increase in infiltration to reduce runoff reaching gullies and causing gully and bank erosion due to higher flow concentration.

Finally, the first version of a hillslope overland flow model that accounts for two-dimensional flow has been successfully developed and tested. It represents a tool that can be used in future studies to derive input functions that would enable us to eventually replace the USLE approach in SubNet and provide for better hydrological feedback between hillslope and gully processes. As part of the ongoing project, this model needs to be validated against data obtained from the hillslope runoff plots at Meadowvale, Virginia Park, Blue Range and Wambiana before it used in a more comprehensive scenario analysis.

8. Review of landscape remediation techniques

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8.1 Introduction and objectives

Grazing management options to maintain or rehabilitate pasture condition of areas that have not been degraded beyond State II conditions in the State and Transition model (i.e. moderately degraded pastures, that still retain a sufficient level of native perennial grasses to allow for natural rehabilitation) have now been well researched and recommendations have been provided through the EcoGraze manual (Ash et al., 2001) or are being disseminated through the Grazing Land Management (GLM) package. Further recommendations are discussed in chapter 9 of this report. These options generally involve grazing management decisions that affect the species composition and amount of biomass. These decisions have their basis in sound principles of rangeland ecology or plant physiology. For example, maintenance of native perennials is dependant on reducing their defoliation because of grazing (Ash et al.,1997; Ash et al., 2001; Ludwig et al., 1990) and thus stocking rates are dependent on pasture production (GRASP model; McKeon et al., 1990). Therefore, what is required to achieve rehabilitation and maintenance of pasture condition is reasonably well known (see EcoGraze manual and references therein).

However, based on reviews of land degradation in the Burdekin catchment (De Corte et al., Rogers et al., 1999), our own field observations and results obtained from the initial project phase (see Chapter 4), it can be concluded that there are portions of the catchment where past grazing practices have led to large land tracts being damaged beyond the natural ability of the land to recover. In particular, where extensive gully systems have developed in conjunction with widespread scald development, spelling and other grazing management options will not lead to recovery of the land within practical time scales. As discussed in Chapter 5, in the study area of this project, these badlands comprising scalds and gullies are often located along creek banks or on river frontage, and as the SubNet modelling results in section 5.6 and 5.7 indicate, these areas can be the main source of sediments in granodiorite country. In these areas, targeted revegetation measures might have to be employed to facilitate a more rapid regeneration and a more effective reduction of sediment export. In some instances, graziers have attempted this, experimenting with a range of techniques including ripping and seeding with Buffel grass, grading contour or water diversion banks, seed mulching and infilling and revegetation of gullies. In some cases these measures are successful and have resulted in increased pasture productivity, in other cases they have resulted in failures.

In any event, these measures are costly, and not always economic. However, based on feedback obtained from graziers in meetings and discussions, there is a clear request for developing more effective rehabilitation techniques. These were to build on results from the EcoGraze project using wet season spelling and conservative grazing regimes, as well as exploring direct rehabilitation or revegetation measures. In addition, there was a request to develop cost effective tools to assist graziers in identifying target areas. However, the required methodologies to rehabilitate severely degraded lands at the paddock or patch scale have not been studied systematically, especially in northern Australia. For this reason, this review will focus primarily on the limited information that is available on these methodologies.

Hence, this component of the project was designed to achieve the following objectives:

- To review existing grazier experience and to compile published information on landscape rehabilitation and to document key success factors.
- To scope and design a future project on rehabilitation of degraded grazing lands with active participation of graziers.

Originally, the second objective was to be the basis for the development of the current project following the completion of this study, but given that the development of the successive project began earlier than planned, it was decided to fold this objective into the new project and to focus on the literature review and compiling grazier's experiences. This review is limited to research in Australia and, as much as possible, to experience from northern Australia. It is a summary of methods rather than a critical review of results.

8.2 Results of literature review

There are a number of different strategies that have been successful in rehabilitating gullies and scalds. In general, they have one feature in common – slowing down, or even stopping, the flow of water to retain it in the landscape for a longer period of time - this is also seen to be a feature of fully functional landscapes (Tongway and Ludwig, 1997). The purpose of retaining water in the landscape longer is to allow it more time to infiltrate the soil. Another common feature is the creation of soil surface conditions that are more likely to retain seeds, whether from natural dispersion or active seeding operations. Fortunately, the soil conditions required are generally common to both of these features.

There are four strategies that are more common than others to achieve higher retention of flow in the landscape and to enhance infiltration and these are discussed below.

8.2.1 Furrowing/ploughing/ripping

There are a number of techniques that involve furrowing the soil in various patterns to encourage water infiltration and seedling establishment (Fitzgerald, 1976; Noble et al., 1984; Pressland et al., 1988).

Contour furrowing retards the movement of water downslope, thus reducing run off and subsequently increasing water infiltration. Usually the furrows are discontinuous to avoid a build up of water at low points leading to possible breakage of the furrow and subsequent erosion. Each row of these intermittent furrows is often offset so that the lower furrow covers the gap between the ends of two upper furrows. Furrow lengths range from 40 – 60 m with gaps of 1 m, to furrows of 10 – 15 m with gaps of 5 – 10 m. The soil from the furrows should be thrown down hill to allow water to infiltrate the plough line. This technique has been successful in a number of large scale operations (see Fitzgerald, 1976; Noble et al., 1984 and references therein).

Checkerboard furrows are a continuous contour furrow system with furrows at right angles to create rectangular cells. The soil from every second row or column is thrown in the opposite direction so that one in four rectangles is fully bunded and retains water.

On flat areas, which are scalded, spirals are ploughed from the centre of the scald outwards. This method not only increases the chance of infiltration but also slows the velocity of the water. In addition, any excess water is ponded in the interfurrows facilitating infiltration

Absorption banks are created by pushing soil uphill to form contour banks. The ends of the banks turn uphill slightly to allow water to flow in to the depression formed behind the bank – further facilitating infiltration. Similar to contour furrows, successive rows of banks should be staggered.

A critical aspect of all of these methods is the timing of the operations in relation to rainfall and the nature of the soils on which they are performed, as they all represent disturbances to the soil that can potentially trigger more erosion through furrow or bank failure when the retention capacity of these structures is surpassed.

Not all graziers would be in a position to implement these measures, as they require access to graders or bulldozers.

8.2.2 Pitting

Pitting is designed to create small depressions which allow water to remain and hence infiltrate before running off. They also create an area in which seeds collect (either naturally or manually spread).

Pits range in size, shape and separation depending on equipment used. For example, tined instruments on an off-centre axle produce furrows 1 – 2 m long whereas pitted disc ploughs (disc ploughs with sections cut out) produce much shorter furrows (Fitzgerald, 1976; Pressland et al., 1988). Other equipment, such as the Paech Pitter Tiller, create boat-shaped pits 150cm long, 50 cm wide and 20 cm deep which can hold about 40 L water (Noble et al., 1984). This technique has successfully enabled the re-establishment of native grasses on severely scalded areas.

In some areas of the Burdekin, the ‘Crocodile Seeder’ has also been successfully used, with an ability to store up to 10 L/m^2 of water, (Shepherd, personal communication).

In areas such as gully heads, that are difficult to manoeuvre in, Fitzgerald (1976) suggested a spiked roller to create pits.

8.2.3 Waterponding

On areas of low slope, building U-shaped banks to trap and pond water can be an effective way to rehabilitate large areas. Once again the purpose is to slow water movement and retain it in the landscape long enough to enhance infiltration.

Banks are designed to pond water at depths of up to 15 cm depending on the permeability of the soil. As with contour furrows, the banks must be designed such that the excess water escapes around the arms of the banks rather than breaching the bank at the lowest point. Thus where this technique is most useful (i.e. low slope), it is also the most difficult to get bank levels and shape correct. Noble et al. (1984) and Pressland et al. (1988) provide examples where waterponding has been used extensively and successfully. Alternatively shallow pits can be created by pushing depressions downslope into the soil surface using a bulldozer. This technique has been utilised in flatter topography such as the Mitchell grass plains. Bastin et al. (2001), have shown that plant nutrients, organic carbon, microbial activity and vegetation all increased in ponded areas compared to non-ponded areas.

8.2.4 Accumulation of dead vegetation

In undisturbed sites, dead wood often lies on the soil for substantial periods of time – providing both a barrier to water movement and a source of nutrients with decomposition. However, these features are often removed (raked, burned) in grazed landscapes.

Tongway and Ludwig (1996) and Ludwig and Tongway (1996) have clearly shown the benefit of these features in facilitating reestablishment of vegetation. These vegetation piles act by locally concentrating water and nutrients and thus serve as resource islands. Although nutrients are often a limitation to pasture production, it is of interest that additions of nutrients in inorganic form were less effective than piles of vegetation.

As there is often a source of appropriate vegetative material on most properties (i.e. materials that decompose slowly) from activities such as tree-clearing, management of regrowth or tree thickening, and presence of dead trees as a result of droughts, there is an opportunity to utilise such material for trapping water and nutrients in the landscape. Obstructions to flow in drainage lines, downstream of scalded areas or in gully heads can be created using these materials by pushing them together in appropriate locations.

However, there are also some risks involved in pushing dead trees into gullies. If the timber in the gully burns the resultant hot fire can sterilize the soil and trigger renewed gully erosion at that point. Also, flow around timber obstructions in the gully can lead to lateral undercutting. To avoid this, timber should not just be pushed into the gully but preferably placed on the gully floor or along the drainage line. An alternative to timber is the placement of old tyres on the gully floor secured with stakes and river gravel.

8.2.5 Critical success factors

Most authors agree that stock control is vital to the success of any rehabilitation scheme. Even small numbers of stock can cause significant damage (Fitzgerald, 1976) so total exclusion is usually recommended. It is also noted that nutrients, as well as water, are being identified as key aspects of the rehabilitation process.

Noble et al. (1984) have provided a useful table describing situations appropriate for some of the techniques described above (Table 8.1). Slope is the major determinant of which technique is appropriate.

Table 8.1: Application of rehabilitation methods (modified from Noble et al. 1984)

	Pitting	Furrowing	Waterponding
Where	On bare areas with slopes of < 2%, but can be used on slopes of up to 5%	Primarily used on slopes of greater than 1 in 50. Furrows usually staggered on steepest slopes	Essentially an erosion control and reclamation technique on bare scalded areas with a catchment area to ponded area ratio between 1:1 and 1:2. Restricted to low slopes of < 1%.
When	No time constraints but best undertaken shortly before rainfall is expected especially if reseeding is also being carried out.	Similar to pitting and best carried out prior to expected rains	No major constraints. Bank construction best undertaken during relatively dry periods.
How	Use of implements such as the Paech Pitting Tiller (eccentrically mounted tines form three rows of pits), or scalloped disc implements, or Crocodile Seeder.	Three-point linkage mounted implement with a central ripper tine and two opposed discs, one on either side of the ripper. Also mouldboard ploughs.	Ponding banks constructed by road grader or some alternative banking implement, e.g. opposed disc banker. Bank size will depend on ponding depth, which in turn depends on soil permeability.

8.2.6 Examples of techniques employed by practitioners

A cross-section of graziers with properties characteristic of a range of different landscapes mainly in the Burdekin was interviewed to obtain supplementary information on rehabilitation techniques being employed. In general terms, when discussing aspects of rehabilitation, most practitioners tended to focus the conversation on issues around fixing the “badlands”. This is an indication that there is awareness for the need to address the ‘hotspot’ areas within a property and that this usually requires additional inputs in terms of mechanical interventions, seeds and fertilisers, and in some cases this has been done with moderate to good success. Examples include:

Warren Matthews (Lassie Creek Station, Q) has successfully rehabilitated gullies by pushing in trees and back filling with soil to the top of the gully. This has slowed flow velocity and stopped gullies advancing, especially when seeded and fertilised with super phosphate. Scalded areas were successfully rehabilitated by discing, seeding and fertilising with super phosphate. As these operations were carried out on more fertile river frontage areas, they are reported to have been economically feasible, with a return on investment estimated to have occurred after 3 to 5 years following the intervention. The economic feasibility in this instance is mainly attributed to the higher productivity of the rehabilitated pasture because of the introduced pasture species, allowing for higher utilisation rates.

Rob and Sue Bennetto (Virginia Park, Q) have found ripping and seeding improved infiltration of water resulting in much better growth in the rip lines. In some smaller paddocks with more intensive grazing, super phosphate has been beneficial. However, the benefits of these techniques are only short-lived if grazing pressure is high following the intervention.

Ken Tinley (Western Australia Department of Agriculture) has used piles of brushwood in gullies. This has slowed the movement of water, resulting in deposition of soil on the downhill side. These areas subsequently become colonised and further stabilise the system.

Colin Healing (Warrawee, Q) and Kirk Smith (Dreghorn, Q), both on similar country (Goldfields country), have used a crocodile seeder and ripping to rehabilitate many scalded areas over a number of years. Buffel grass was the main grass seeded. Success of rehabilitation was only moderate, although germination was reportedly good. However, permanent establishment of the seeded grass was less satisfactory. This was attributed to the seasons following the intervention and the lack of cattle exclusion, so that preferential grazing of the freshly germinated grass inhibited better establishment.

There was a unanimous view from all graziers interviewed that exclusion of cattle following the ripping and seeding constitutes a critical success factor. However spelling is not always an easily implemented option, as in many instances, poor seasons, debt servicing requirements, small property size or large paddock size reduce the flexibility to spell the rehabilitated paddocks. Some graziers suggest that electric fencing may constitute an alternative to selectively spell rehabilitated areas within paddocks, as the costs are approximately only a third of conventional fencing.

8.3 Conclusions

There is a range of mechanical techniques available that can be targeted to degradation hotpots within paddocks to promote active landscape rehabilitation. The degree to which they are successful depends on local conditions such as slope (the flatter the slope, the more likely the measures are effective), soil type (the more dispersive and unstable the exposed subsoils are, the more likely the measure will have the opposite effect and increase erosion), the level of denudation (scalds that have lost the A-horizon are less likely to have a viable seed store and will take longer to be recolonised). The key to success of these techniques is that they effectively trap water, organic debris, nutrients and native seeds, either by mechanically opening the soil surface, or allowing more time to infiltrate (by slowing flow through greater surface roughness and placement of physical obstructions) and or both. Most often, additional resources such as seed or nutrients further increase the chance of successful rehabilitation. Exclusion from cattle grazing is also regarded as essential for success.

9. Synthesis, recommendations and project outcomes

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9.1 Synthesis and recommendations

9.1.1 An integrative framework

In this section we describe an integrative framework that attempts to encapsulate the key findings of the preceding chapters and place them into the broader context of hydrological response to grazing impacts. The framework is presented in Figure 9.1. It is structured into three rows, representing different soil and landscape states. The top row reflects the assumed pre-European conditions, the middle row the present situation and the bottom row a vision of how the landscape might be in the future. For each of the three states, we differentiate three different soil cover classes (which for instance could be those discussed in Chapter 7). The right hand column depicts the corresponding, hypothetical hydrographs for runoff (Q_{H20}) and sediment discharge (Q_{sed}).

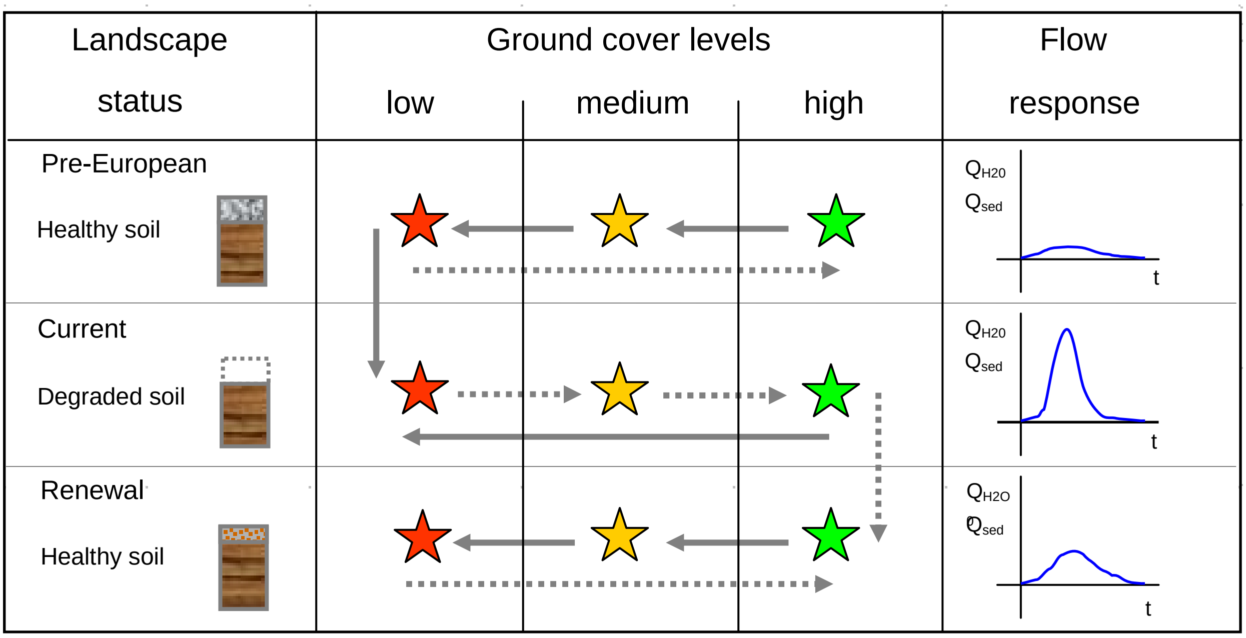


Figure 9.1: Proposed conceptual framework relating grazing-induced changes to soil health and ground cover to landscape hydrological response. Full arrows and schematic soil profiles denote the direction soil surface condition has evolved (pre-European and current) or may evolve (landscape renewal); dotted arrows denote recovery pathways (pre-European and landscape renewal status); Q_{H_20} and Q_{sed} denote water and sediment discharge, respectively.

It is assumed that prior to European settlement and the widespread introduction of livestock in the late 1860's the landscape was in equilibrium, with soil hydrological function intact and patterns of runoff and sediment discharge in rivers dominated by base flow. There would have been greater variation in ground cover induced by droughts and fire, but generally, fully intact ecological processes would have enabled the landscape to recover rapidly from these disturbances. Following the introduction of livestock, the combined effect of hoof compaction and removal of ground cover would have caused deterioration in soil surface condition and led to accelerated hillslope erosion and the observable, widespread loss of the A-horizon (Rogers et al., 1999) in many parts of the Burdekin catchment. This, it is assumed, is likely to have been accompanied by a shift to higher runoff coefficients and discharge regimes dominated by peak flows. At the same time, some of the degradation will also have been a result of the intensive mining activities around the Mingela-Ravenswood-Charters Towers area in the 1870s to 1890s, but also in other areas of the catchment.

There is some evidence for the existence of more base discharge dominated flow regimes in the Burdekin River at the time of colonisation and the transition to the more peak flow dominated systems of the present. There are eyewitness accounts in unpublished diaries of early settlers that relate the introduction of cattle to the drying up of perennial springs and a shift from more perennially to more seasonally flowing rivers (White, unpublished). Recently, results obtained from dating and analysing fluctuations of the Ba/Ca ratio in growth bands in corals sampled in near-shore reefs in the GBRL suggest a marked and fairly abrupt increase in discharge from the Burdekin River at the time of colonisation in the late 1860s (McCulloch et al., 2003), lending support to the notion that the frequency and magnitude of peak flows increased after settlement. This period coincides with the introduction of initially great numbers of sheep and later, cattle (Holmes, 1963). These findings are further corroborated by the SedNet modelling for the Burdekin River catchment reported previously by Prosser et al. (2002) as part of this project and also with the results presented in Chapter 4 of this report (Figures 4.5 and 4.9), where we conclude that grazing has increased sediment delivery by about 5-fold. This matches up well with the 5- to 10-fold increase estimated by McCulloch et al. (2003).

The present day situation in many parts of the Burdekin River catchment is characterised by the middle row, where soils are degraded, and have lost much or all of their A-horizon, with poorer productivity and higher runoff. This is particularly true of the granodiorite-dominated landscapes to the east and south-east of Charters Towers. Whilst arguably there is probably a gradual shift from high grazing pressure systems with low cover to somewhat more moderate pressures leading to an increase in cover, the overall effect on discharge would be minor. This is borne out by the results in Figure 7.3, where we show that higher cover on degraded soils does not necessarily translate into higher infiltration and hence, less runoff.

However, we believe that there is scope for a reversal of this state. As clearly demonstrated by the results of the EcoGraze program, shifting grazing management regimes to systems that retain higher levels of cover for prolonged periods (25% utilisation rate), coupled to regular wet season spelling will rapidly (within three years under good rainfall conditions) lead to an improvement in ground cover and favourable pasture species composition (Ash et al., 2001; McIvor, 2001). This in turn is assumed to lead to an improved soil surface condition that allows for recovery of soil hydrological function, as evidenced by the results presented in Chapter 7. This process of renewal would correspond to the transition from the middle row to the bottom row in Figure 9.1. However, the time required to attain recovery of soil hydrologic function remains uncertain. Based on the results presented in this report, it can be assumed to be less than fifteen years on granodiorite-dominated landscapes, but requiring at least three to five years, because of the lag between build-up of root and cover biomass and the increase of soil biological activity.

Eventually, it is conceivable that the landscape more generally will be able to attain a new equilibrium, with a return to lower runoff coefficients and more base flow dominated discharge regimes. Early indications of this being the case are provided from the results obtained from the hillslope runoff troughs at Meadowvale (Table 5.5; Figures 5.19 to 5.21), as well as anecdotal evidence from other parts of the Upper Burdekin catchment, where long periods of conservative grazing regimes, coupled to wet season spelling have brought about widespread recovery of soil surface condition (e.g. on some of the sedimentary country around Blue Range station; see also Landsberg et al., 1998 for other landscape examples). However, in some cases, although soil health has been recovered some gullies that were triggered during earlier periods of degradation may continue to persist (e.g. Camel Creek area). Once the landscape has attained a new state of soil health, short term drought and fire induced variations in ground cover would again only have transient effects on soil hydrologic function, as it is likely that the system will have attained a higher level of resilience.

An important feature of the framework presented here is the explicit link between soil hydrology at a point or patch scale (which is strongly affected by grazing) and its relation to system response. In other words, grazing management regimes that place an emphasis on improving soil health are not only likely to provide benefits to pasture productivity, beef quality and turn-off rates, but are by default also reducing sediment and nutrient export.

9.1.2 General principles for developing sediment export management guidelines

Assuming the general validity of the framework presented in Figure 9.1, the next question that needs to be addressed is whether the proposed framework is applicable to all landscape types in the Burdekin River catchment, or whether certain landscapes are more disposed to degradation and sediment export than others. As we have demonstrated in Chapters 4 and 5, the use of spatial modelling to determine critical source areas and to construct sediment budgets is a feasible methodology to determine the spatial patterns of soil erosion, providing us with an indication of which parts of the landscape might be more vulnerable or where erosion and sediment export are a major problem, and hence, where the framework in Figure 9.1 might be most relevant. Also, as shown in the applications of SedNet and SubNet, this approach lends itself to a wide range of scales.

Based on these modelling results, which can be generalised for the catchment and hillslope scale as presented in Figure 9.2, it is clear that the majority of sediments (~85%) across a broad range of scales are generated in very localised hotspots (~10% of the area), offering significant opportunities for an effective management of sediment export by targeting these hotspots. However, as demonstrated in the sediment budgets presented in Tables 4.2 and 5.6, the relative proportion of sediments generated by sheet and rill erosion, gully erosion and riverbank erosion might vary quite significantly between scales and landscape types, and generalisations for one hotspot or for a particular scale might not hold for other cases.

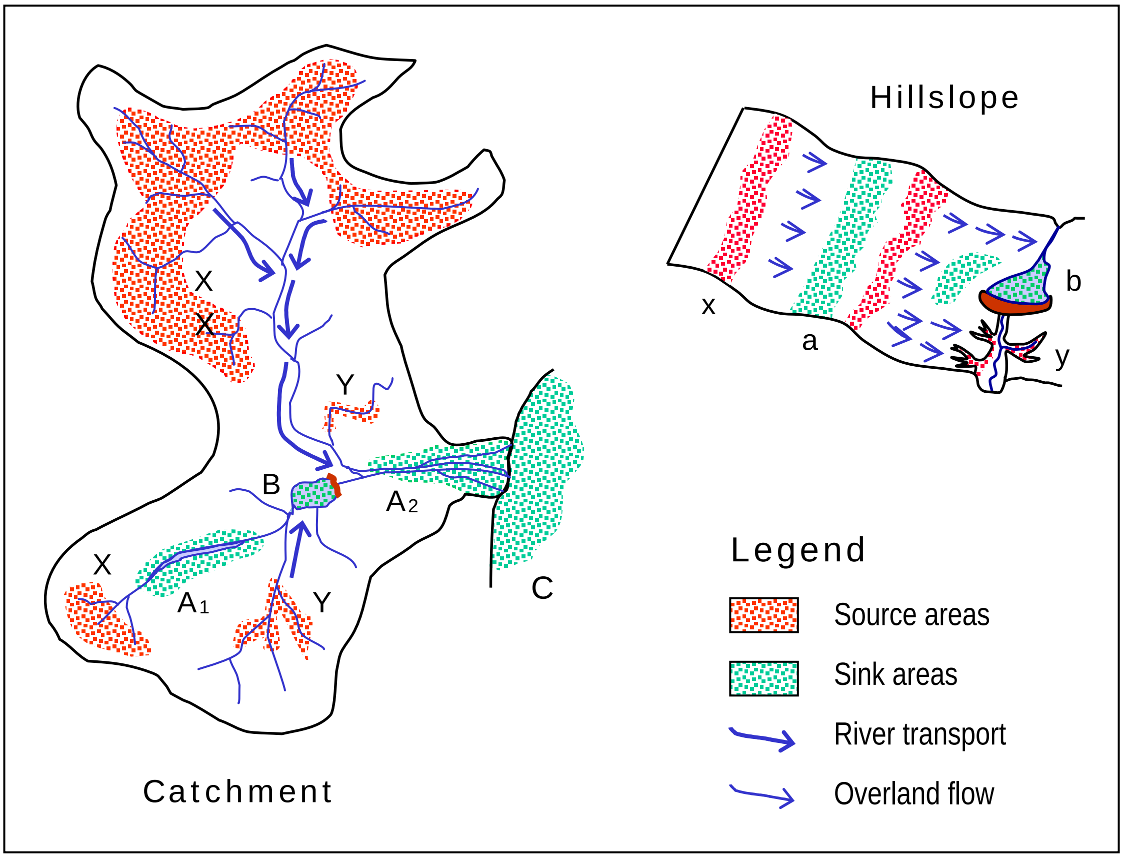


Figure 9.2: Generalisation of the sources and sinks of sediments at the catchment and at the hillslope scale. (Catchment sources: X = hillslope erosion in headwaters of 1st and 2nd order streams, Y = gully erosion in river frontage; catchment sinks: A_1 = internal floodplain, A_2 = coastal floodplain, B = dam, C = estuary and near-shore coastal zone; hillslope sources: x = hillslope erosion on convex heads of slope, y = gully erosion in drainage lines and creek banks; hillslope sinks: a = break of slope and creek frontage, b = farm dams).

For example, at the whole-of-basin scale, hillslope erosion clearly is the dominant source (Table 4.2), suggesting that in general terms, changing grazing management with the objective of increasing ground cover may be the best strategy in the Burdekin River catchment. However, this strategy might not necessarily be the most effective strategy at the sub-catchment or paddock scale, if, as is the case for the granodiorite (Goldfields) country, gully erosion is the predominant source of sediments (Table 5.6). However, if we take into consideration loss of suspended sediments only, which is more relevant to pasture productivity, then even in the granodiorite country managing hillslope erosion might still be the main issue. Consequently, to properly target the most appropriate management recommendations, once a particular hotspot region in the catchment has been selected for intervention, it would be desirable to establish a sediment budget for that region at a finer resolution, using the approaches illustrated in Chapter 5, before deriving more specific management guidelines.

Understanding the spatial pattern of erosional processes and sediment export, based primarily on inherent landscape attributes such as rainfall, topography, soils and vegetation more generally, constitutes only one information layer. As illustrated in Chapter 6, the spatial distribution of grazing pressure is the second information layer that has to be taken into account. Even though our ability at this point in time to predict the spatial distribution of grazing impacts is incomplete, the results in Chapter 6 indicate that factors like spatial distribution, total extent and timing of burning within a paddock are strong determinants of whether cattle are likely to be more randomly distributed, or will tend to congregate. We also conclude in Chapter 6 that other factors like seasonal pasture growth conditions, fencelines, heterogeneity of pasture species within a paddock and the spatial distribution and density of water (natural sources and artificial watering points) determine whether cattle are more evenly distributed or not.

This means that at a paddock level, management of sediment export is not as straightforward as one might have hoped for. It highlights the need for producers to more thoroughly understand landscape processes in the context of a temporally varying spatial distribution of grazing impacts, and how their management of cattle interacts with these processes. In situations where paddocks are smaller and more uniform, and cattle are evenly spread, the task may be easier and it may be sufficient to focus on generally reducing overall grazing pressure to reduce sediment export. In situations where paddocks are larger and more diverse and hence, cattle distribution uneven, it becomes a very challenging task, and trade-offs between feasible options and the ability to target sediment export hotspots will be inevitable.

On the other hand, even in smaller paddocks, there may be certain areas (soil type, vegetation units) that are preferentially grazed even at low overall paddock utilisation rates. These might also coincide with erosion hotspots e.g. sodic soils. Smaller paddocks, whilst providing more management flexibility, may also be more difficult to manage in terms of maintaining optimal utilisation rates, where small changes in animal numbers or biomass production can have a proportionally greater impact on overall utilisation, whilst also reducing the potential grazing diversity available to stock.

One of the options to reconcile these different considerations is placing the selection of appropriate management responses into a property planning context; i.e guidelines to manage sediment export need to be framed in a way that they assist decision making on a property scale and help prioritise where to implement what.

Finally, as has clearly emerged from the results presented in Chapter 7, runoff generation as the primary cause of soil erosion is not merely a function of soil cover, but is controlled by a complex set of factors that interrelate with cattle impacts and that govern soil health and infiltration. Recognising and understanding these implications will be a significant step towards addressing the problem of sediment and nutrient export in view of the link between soil health and catchment hydrological response as postulated in the framework presented in Figure 9.1.

Summarising the above discussion, we derive five guiding principles.

1. Target catchment rehabilitation efforts at the hotspot areas. The first principle is that efforts directed at rehabilitating landscapes to minimise sediment and nutrient export from grazing lands of the Burdekin River catchment should be aimed at those areas identified as a significant source **and** where intervention is likely to have a large impact on achieving reduced end-of-valley sediment export targets. To the best of our knowledge, based on Figure 4.9, it appears that the Bowen and Bogie River catchments, followed by some of the Goldfields country along the Upper Burdekin River upstream and downstream of the Burdekin Falls Dam would have to be the primary priority areas.

2. Design effective grazing management strategies based on an understanding of dominant erosional processes. To be effective within the priority intervention areas, there needs to be a thorough understanding of which erosional processes are the dominant source (i.e hillslope delivery vs. gully erosion vs. channel erosion), in order to design the most appropriate grazing management responses. In some instances, the feasibility of measures going beyond what is possible through manipulation of grazing pressure need to be assessed. Such measures may include engineering solutions to the targeted remediation of badlands and some of the more extensive gully networks located on river frontage (e.g. for the areas discussed in Appendix 1, Volume II).

3. Match the scale of grazing management to the scale of dominant erosional processes for management to be effective. Two steps are required. First, it is necessary to clarify which erosion process dominates where in a particular situation (i.e through the establishment of paddock scale sediment budgets like the one presented in Table 5.6). Then it is necessary to match the erosion processes and their spatial distribution against the spatial distribution of cattle. If there is significant overlap between where cattle tend to congregate and where the main sources of sediment have been identified, that would then clearly point to where the focus on intervention measures needs to be directed.

4. Develop and prioritise the guidelines for managing sediment export within a property management planning context. In order to assist producers in their decision making in relation to where to prioritise management intervention to reduce sediment export, it is necessary to place the principles enunciated above into a risk management framework that can underpin property scale trade-off and planning decisions.

5. Focus grazing management needs on soil health rather than simply on ground cover. In this principle we formulate the need for grazing management to shift from purely managing pasture cover and species composition to managing soil health. The key link between soil health and pasture management is not just ground cover, but pasture biomass, as this is assumed to be the key determinant of soil health. This shift in emphasis is entirely consistent with our recent understanding of pasture dynamics as enunciated in the EcoGraze work and the ensuing shift from managing stocking rates to manipulating cattle numbers to achieve desired utilisation rates. The challenge is to define new thresholds based on pasture biomass rather than ground cover to inform the selection of appropriate utilisation rates that allow for the recovery or maintenance of soil hydrological function in any given season. In the meantime, we believe that the threshold utilisation rates proposed by the EcoGraze program to achieve pasture recovery and long term sustainable grazing are useful starting points to achieve the objective of soil hydrological recovery as well.

Based on previous published work (e.g. the EcoGraze project results from Cardigan Station) and the results emanating from this study, we have now accumulated enough understanding to apply these principles in one of the critical hotspot landscapes in the Burdekin River catchment – the Goldfields country, characterised by red duplex soils and sodic duplex soils derived from granodiorite, with Narrow-Leafed Ironbarks and Bloodwoods as dominant tree layer, and Indian Couch with some residual native perennials as the predominant pasture species. Guidelines derived for this landscape type based on the above principles are presented in more detail in the following sections.

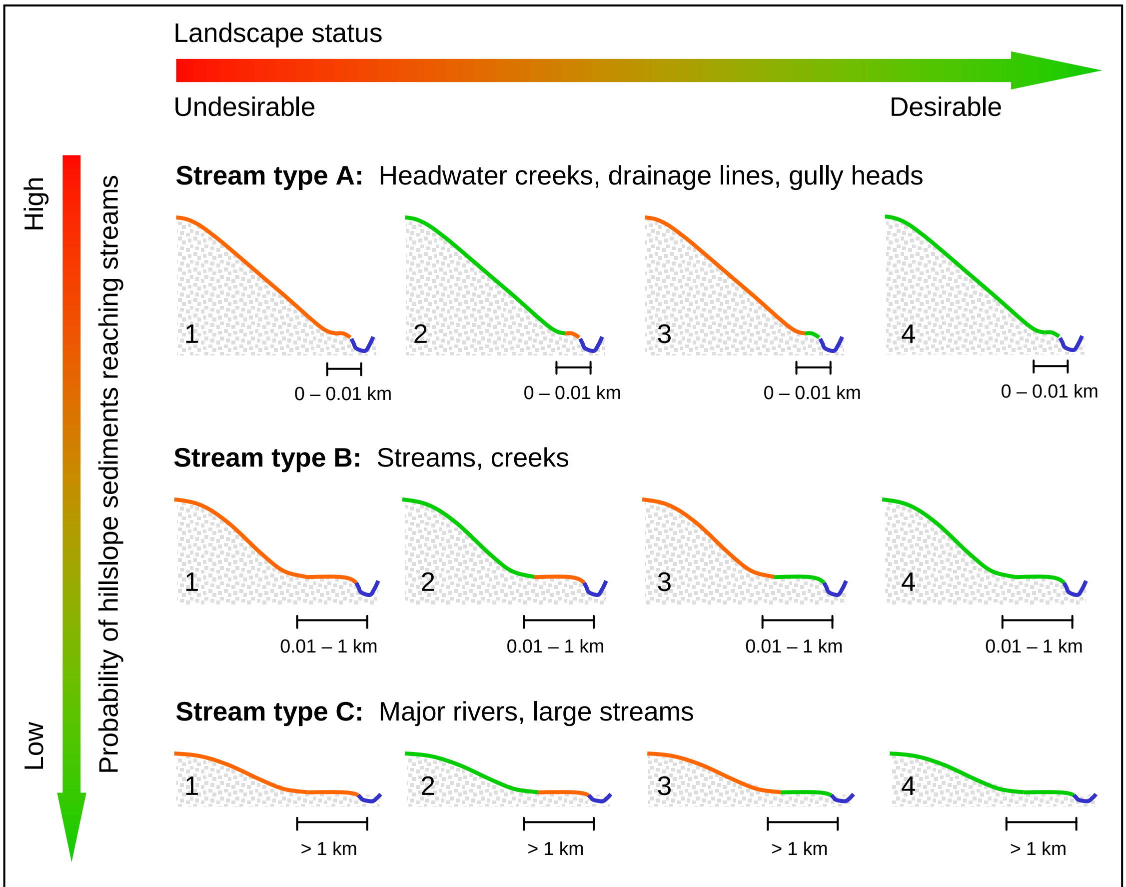
9.1.3 Managing sediment export from granodiorite landscapes

As a first step in deriving management guidelines for sediment export from granodiorite landscapes, we developed a risk assessment framework emanating from our improved landscape understanding presented in Chapters 4 to 8 and based on the principles outlined in the previous sections. This risk assessment framework, shown in Figure 9.3, helps delineate under which circumstances one might opt for a certain suite of management practices and with what level of priority, and thus could become a tool to assist in property management planning. At this stage it is preliminary, and requires testing and refining based on input we intend obtaining from experienced practitioners.

The framework is based on stream type and landscape condition as the key criteria to delineate five different levels of sediment export risk. Stream type is an indicator for 'landscape leakiness', i.e different probabilities that eroded material will reach streams and leave the landscape. For simplicity, stream types have been aggregated into three classes A, B and C. Each stream type class is broken down into four categories of landscape condition, ranging from poor (category 1) to good (category 4).

Stream type A comprises the headwater portions of catchments and the 1st order streams. In granodiorite landscapes, this class is characterised by slopes less than a kilometre long, with slope angles ranging between 3% and 10%. Drainage lines are often incised, with active gully heads and gullies that transition into the 1st order streams. Drainage lines or streams are associated with no or only very narrow riparian fringes (< 0.01 km in width). Due to the steeper slopes and the narrow or non-existent riparian zones, the probability that eroded hillslope materials reach streams is very high. Soils within this class are usually more uniform. Large sections of Wheel and Weany Creek (see e.g. Figure 5.16) are good examples of this stream type class.

In stream type B, the riparian zone widens to a more distinct river frontage unit, often with different vegetation (Box trees) and a change to either sodic duplex soils or better-drained and more fertile alluvial deposits. Width may vary between 0.01 and 1 kilometres. The hillslope areas can vary, either being similar to those of class A, but generally set back from the main creeks, or characterised by longer and flatter slopes. Examples of this stream type class in granodiorite country are Station Creek, Kirk River, Pandanus Creek, Broughton River and the upper reaches of Fanning River.



Stream type	**Landscape status**			
	1: Overall poor condition	2: Hillslopes in good condition; creek lines or river frontage in poor condition	3: Hillslopes in poor condition; creek lines or river frontage in good condition	4: Overall good condition
A	Very high	High	High	Low
B	Very high	High	High - moderate	Very low
C	High	High	High - low	Very low

Figure 9.3: A sediment export risk framework for granodiorite landscapes in the Burdekin catchment; risk criteria based on stream type and landscape condition (red = poor; green = good condition; thresholds for each condition discussed in section 9.1.4).

Class C, the class with the lowest probability of sediment leakage, is characterised by major streams and higher order rivers (stream type > 4) and is characterised by wide and distinct floodplains, which might be further differentiated into the immediate riparian zone and the broader, often more fertile river frontage country. An example of this class in granodiorite landscapes is the stretch of Burdekin River between its confluence with the Fanning River and the upper reaches of the Burdekin Falls Dam. The lower reaches of the Fanning and Kirk Rivers also have similar characteristics of flatter, undulating country with river frontage transitioning into floodplains.

Within each of these three stream type classes, landscape condition can vary quite markedly. In condition category 1, both slopes and riparian fringes or river frontage are degraded, with poor cover and active erosion. On the hillslopes of granodiorite landscapes, native perennial grasses (3P grasses) have often been replaced by Indian Couch. In contrast, category 4 represents optimum landscape condition, with intact riparian fringes or river frontage and hillslopes well grassed, the latter either by healthy stands of native perennials, the former with well-established native or improved pastures species (Buffel, Urochloa). Categories 2 and 3 represent intermediate conditions, where either hillslopes or riparian zones are in poor condition. Category 3 is rated with a lower risk because intact riparian zones or river frontages can filter sediments delivered from upslope areas before they reach the stream.

In general terms therefore, the risk of sediment being exported decreases with the transition from stream type class A to C, and decreases with improving condition of the landscape (moving from category 1 to category 4 in Figure 9.3). Combination A1 is rated as having the highest sediment export risk, followed by combinations B1, C1, A2, B2, C2 and A3, which are rated as having a high risk of sediment export. These are the landscape situations that need to be targeted for changes to grazing management and landscape remediation, as a reduction of soil erosion in these conditions is likely to have the greatest effect on reducing downstream sediment and nutrient loads. Where hillslopes are degraded (B3, C3), the risk of sediment export is intermediate. If runoff flows from the hillslopes are dispersed as overland flow, then intact riparian zones or river frontage should effectively trap sediments, minimising downstream impacts. If however the hillslopes in stream classes B3 and C3 are in fact characterised by stream classes A1 or B1, then the risk of export is high, as sediment would bypass the river frontage in streams or gully networks. In this case the same management priority needs to be in place as for stream classes A1and B1. The other combinations of landscape condition and stream type class (A4, B4 and C4) constitute a far lesser degree of risk, indicating that current grazing management regimes are well adapted to the landscape and require no or little change in relation to management of sediment and nutrient export. In the following therefore, we will focus on developing recommendations to minimise sediment export where the risk is very high or high.

Large cattle properties may comprise a range of different landscape types, covering the whole range of stream type classes in Figure 9.3. For instance, some of the properties on granodiorite bordering on the Burdekin River (e.g. Cardigan, Warrawee, Dreghorn) have parts of the property characterised by stream type class C in the immediate vicinity to the Burdekin River, which is in turn dissected by 2nd or 3rd order streams (Class B) flowing directly into the Burdekin River (e.g. Six Mile Creek on Dreghorn), which in turn are fed by headwaters and small creeks (Class A), only a few kilometres inland from the main river. In terms of prioritisation within a property, the framework presented in Figure 9.3 suggests that the highest emphasis be placed on degraded headwater areas (A1, followed by the less degraded headwater areas A2, A3) and those areas that have degraded river frontage (B1, B2, C1, C2).

In the following, we derive two sets of management guidelines, one set suited to addressing sediment export from degraded headwater areas, and one set targeting the rehabilitation of degraded river frontages.

Guidelines to manage headwater areas at risk

Management of degraded headwater areas (risk combinations A1, A2 and A3 in Figure 9.3) should receive the highest priority. Given that there are no or only negligible opportunities to trap sediments in riparian fringes, the emphasis has to be on reducing hillslope runoff and sediment delivery. This means that grazing pressure has to be reduced to levels that allow for gradual recovery of pasture condition (higher biomass, higher ground cover, higher proportion of 3P grasses). In time, this will also lead to recovery of soil hydrologic function. Based on the EcoGraze principles, this entails:

1. Initiating recovery with a complete wet season spell; subsequently

2. Managing grazing pressure to allow for no more than 25-35% utilisation of fodder in any given season; or
3. Managing grazing pressure to allow for no more than 50% utilisation in combination with annual wet season spelling.

Details on how to determine utilisation rates, strategies to enable regular wet season spelling etc. are discussed in the EcoGraze manual (Ash et al., 2001) and therefore need not be repeated here. To provide for the flexibility to wet season spell, large paddocks will need to be sub-divided. Where that is not an option, the alternative is to ensure grazing pressure at low rates is more evenly distributed. However, a completely uniform grazing pressure may not be desirable either, as some level of patchiness provides valuable refuges and biodiversity functions. Based on the results obtained in Chapter 6, this includes measures such as strategic placing of sufficient watering points and licks. This may be complemented by patch burning, although this recommendation is less certain as additional research is required to better define timing and effects of patch burning.

As a rule of thumb, depending on layout of the paddock, we recommend one water point every 500 – 1000 ha, located away from the drainage lines. In some circumstances this could mean a distance to water of greater than 2 - 3 km, depending on the paddock shape, which may not be desirable in terms encouraging evenly distributed utilisation. In such a case the number and location of watering points might have to be adjusted or have to be complemented by the judicious distribution of licks. If establishing dams is the means of providing watering points, care should be taken not to establish them on vulnerable soils (e.g. sodic soils in Box/Sandalwood patches) in order to avoid scald development that may trigger new gully erosion. Where a dam site on sodic soils is unavoidable, the dam needs to be fenced off and water from the dam pumped to watering points on more stable soils upstream of the dam.

Over time (5-10 years), as the hillslope areas recover, the amount of runoff delivered as run-on onto scalds and badlands and then concentrated into gullies will diminish, gradually leading to a halt in gully progression. More direct methods of scald or gully rehabilitation in headwater areas, whilst desirable, are not deemed practical in this situation, mainly because any ripped and re-seeded areas would require cattle exclusion to be successful. However, we recommend a number of ancillary measures to increase the rate of natural scald recovery and gully attenuation:

- Early dry season patch burning of ridgelines or upper hillslopes following their recovery to attract cattle away from preferred grazing patches in areas adjacent to scalds or within drainage lines;
- Raking or pushing of woody debris onto scalds or badlands to slow down surface flow and to provide more water, seed, and nutrient trapping opportunities for recolonisation of scalds.

The reduction of runoff from rehabilitated hillslopes will also reduce the amount of flow in the headwater creeks, decreasing the likelihood of bank erosion and reducing the rate of bedload transport.

Guidelines to manage risk areas adjacent to creeks and rivers

In dealing with sediment and nutrient export from degraded areas adjacent to higher order streams and rivers (i.e. risk combinations B1, B2, C1 and C2 in Figure 9.3), the emphasis of grazing management needs to shift from the hillslope areas to the riparian zone or river frontage, because enhancing the filter capacity of these areas offers the most efficient means of reducing sediment export in the short term. In the mid to longer-term, degraded hillslope areas will also need to be addressed.

The primary requirement to manage the frontage areas is to fence them off as a separate management unit. Preferably, this should entail fence lines between hillslope areas and frontage **as well as** between frontage and riverbanks. The latter is essential to stop cattle accessing waterholes, as cattle tracks leading to the streambed are often a trigger point for gully incision and bank erosion. In addition, restricting cattle access to waterholes is critical to maintain good ambient water quality, particularly during the dry season when streams contract into a series of waterholes that act as a refuge for aquatic organisms. Figure 9.4 presents a schematic view of the way in which river frontage areas can be delineated and fenced-off. As this is an onerous measure, one way of staging this management option could be to restrict grazing to river frontage in the dry season when long reaches of the creeks are dry and to only fence off the more permanent water holes.

Once the frontage areas have been fenced off, where they are degraded it is recommended to implement similar EcoGraze grazing management regimes as those discussed for the recovery of hillslope areas in the preceding section. The build-up of grass following the introduction of a more conservative stocking rates provides the additional benefit of being able to use fire as a tool to control rubber vine infestations along stream and riverbanks. Indeed, in some instances the ability to manage woody weeds on river frontage may be a more important reason for fencing off frontage country than controlling sediment export, but the two strategies are entirely compatible. Practical experience in fencing off river frontages of 3rd and 4th order streams in granodiorite country is being gained through a MLA funded PIRD project on Warrawee.

In some instances where the river frontage is wider and further differentiated into various land units (e.g. Cape and Mingela soil associations - Reid River Box and False Sandalwood on moderately to poorly drained floodplain soils on older alluvial deposits; alternating with Burdekin and Pandanus alluvial soil associations - tall Narrow-leafed Ironbarks and Long-leafed Grey Bloodwoods on younger, well drained and more fertile river banks soils; see Rogers et al. 1999 for more details on soil associations), it may be feasible to separate out more paddocks. On paddocks established on the more fertile, younger alluvial soils, the conversion of native pasture into improved pastures sown to exotic species (Buffel, Urochloa) may offer a technically and economically feasible alternative to rapidly regenerating soil cover in degraded areas, with the added benefit of higher productivity. Frontage areas characterised by Reid River Box on poorly drained duplex soils, that may also have dispersive subsoils (sodic duplex soils), are more vulnerable, and large scale mechanical disturbance on these soils should be avoided to minimise the risk of triggering new gully systems.

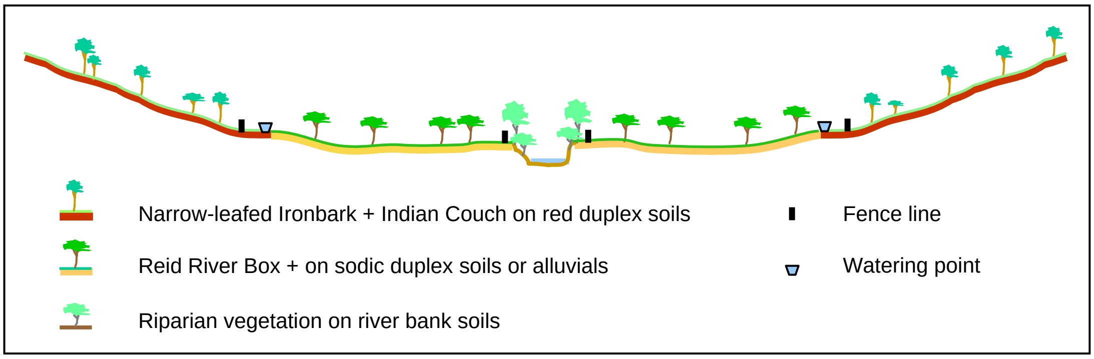


Figure 9.4: Schematic cross-section of a 3rd order stream valley in granodiorite country, indicating recommended positions of fencelines and watering points to manage frontage country.

If active gully systems are present in the frontage areas, it is recommended to fence these off to inhibit further access by cattle. This measure may have to be complemented by the judicious establishment of grassed, flow diversion banks along the contour line just upstream of the gully heads. This is aimed at 'starving' the gully heads of further runoff from upslope areas, thus more rapidly arresting gully head progression. Ultimately, as the upslope areas of the gully heads recover their soil hydrologic function, the banks should no longer be critical, and once the gullies have revegetated and stabilised themselves, it is possible to remove the fencing around the gully to recuperate paddock areas previously not available for grazing. An example of the implementation of such a gully control measure is shown in Figure 9.5. However, the design and construction of contours or flow diversion systems is a risky option if poorly designed; such systems can actually exacerbate gully erosion, particularly on vulnerable soils (sodic duplex soils). Hence, such approaches will require a properly engineered plan involving civil engineers. In many cases, simply fencing off badlands adjacent to gullies or upstream of gully heads may be the safest option.

On well-drained alluvial soils, gully remediation using earth-moving machines followed by mulching and seeding of improved pasture species into the in-filled gullies has been reported to be a feasible option to not only to stop further gully erosion, but also to recover gullied and dissected frontage areas for grazing.

Irrespective of the strategy used, any measures involving soil disturbance for contour bank construction, ripping of scalded areas to enhance seeding and in-filling of gully sections will require cattle exclusion for at least one if not several seasons to ensure a successful establishment of pastures. As discussed in

Chapter 8, the use of electric fences may be an economical alternative to conventional fencing for those situations where only temporary fencing-off is required. Costs of electric fences are about 1/3 of those for conventional fences.

As creeks and streams are progressively fenced off and new frontage paddocks established, it is necessary to provide artificial watering points. To reduce the risk of cattle pats being washed into streams (pats can significantly increase the accession of nutrients into waterbodies) and as cattle camps are formed in the vicinity of the watering points, to avoid these newly formed cattle camps being a source for sediments and nutrients, it is recommended to place the watering points well away from the stream banks. In some instances, an option may be to locate the watering points on the fenceline separating the hillslope areas from the frontage country, thus servicing two paddocks. The rule based grazing impacts framework provided in Figure 6.10 provides further guidance on factors to take into account when placing fencelines and watering points.

Once the frontage areas have been rehabilitated and risk combinations B1 and C1 have progressed to risk combination B3 or C3, sediment export risk will have diminished significantly. In the case of B3, there is still a residual, moderate risk of eroded materials leaving grazed landscapes. Hence, in this case the final step would be to implement a similar grazing management regime on the hillslopes as discussed for the headwater areas. However, to enable progressive adjustment, this can be done in a staged manner.

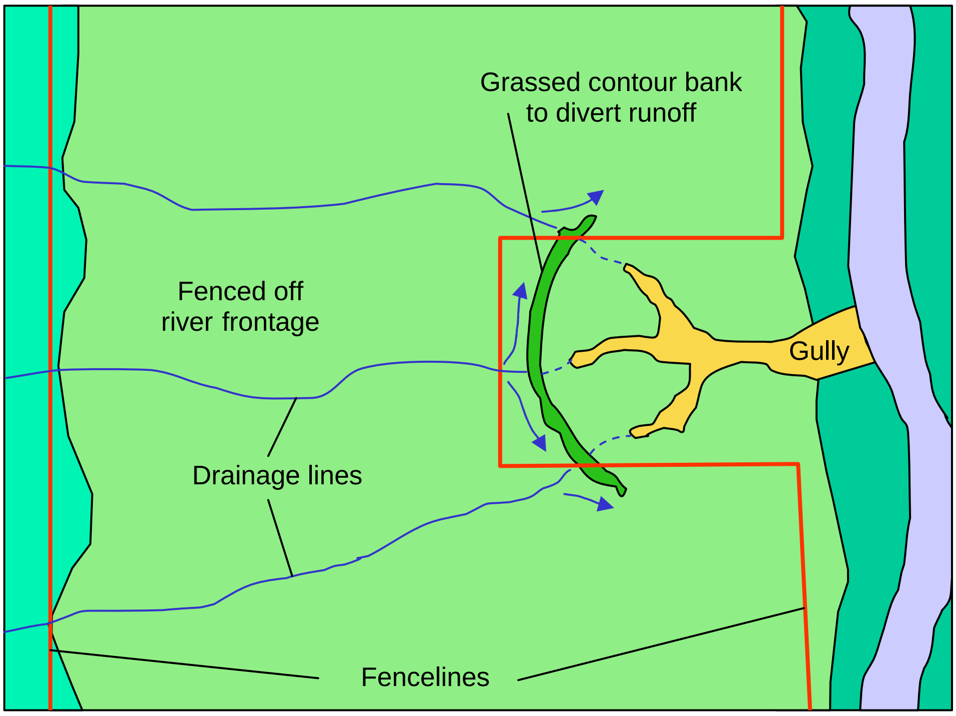


Figure 9.5: Schematic view of fencing layout to fence-off active gullies in river frontage. Note that in order to retain its effectiveness, the grassed flow diversion bank is located mainly within fenced-off perimeter to avoid damage by cattle trampling and preferential grazing of sown grasses.

In summary, a staged approach to achieve recovery of degraded river frontage with the aim of reducing sediment export should include the following steps:

1. Establish fencelines between hillslope areas and frontage country;
2. Initiate pasture recovery on frontage with a complete wet season spell, followed by the introduction of more conservative stocking rates to achieve utilisation rates of 25-35% (if grazing is to be continuous) or 50% (if regular wet season spelling is planned);
3. Relocate existing watering points near watercourses to the upslope fenceline;

4. Establish a fenceline on the stream or river bank to fence off the riparian vegetation and watercourses from the frontage paddock to stop cattle access to the watercourse;
5. Where necessary, fence off badland areas and/or gully systems;
6. On well-drained alluvial soils, this can be supplemented by active scald and gully remediation works, which in order of priority would include:
   - ripping, seeding and mulching of scalds directly adjacent and feeding into the gully system (provided these are not associated with sodic duplex soils, where ripping may only exacerbate the problem by accelerating soil dispersion);
   - construction of grassed flow diversion banks on following the contour lines immediately upslope of the gully heads (requires specialist advice);
   - infilling and levelling of gullies followed by establishment of improved pastures (requires specialist advice).
7. If the hillslope areas adjacent to the newly formed frontage paddocks are degraded, follow the guidelines as set out in the section on managing headwater areas.

If resources available to the producer are limited, these stages can be carried out sequentially, but it would be preferable for some of the stages to occur simultaneously (e.g. stages 2, 3 and 4). It is possible that government initiatives such as the NAPSWQ and NHT2 might provide incentives to producers to carry out some of the stages listed above, provided the areas needing rehabilitation are recognised as high priority intervention areas in the regional NRM plans being developed by the Regional NRM Bodies (e.g. the Burdekin Dry Tropics Board).

9.1.4 Spatial applicability of guidelines

Building on previous work carried out at Cardigan as part of the EcoGraze program, the bulk of the sub-catchment scale work carried out by this project and reported in Chapters 5 and 6 was focussed on locations characterised by granodiorite landscapes. As a consequence, sufficient data and process understanding has been acquired to enable us to derive the initial set of landscape scale grazing management guidelines aimed at addressing sediment and nutrient export. However, granodiorite landscapes, although constituting one of the hotspot landscapes as determined in Chapter 4, are only one of many landscape types in the Burdekin River catchment. This raises the question of the spatial extent and broader applicability of these guidelines.

Figure 9.6 provides an overview of the spatial distribution of granodiorite landscapes in the Dalrymple Shire, which covers most of the Upper Burdekin catchment and for which we have detailed soils information (Rogers et al., 1999). According to Figure 9.6, granodiorite landscapes cover about 6% of the Upper Burdekin catchment, concentrated mainly east and south of Charters Towers. The risk framework presented in Figure 9.3 and the guidelines discussed in section 9.1.3 are considered directly applicable to this area. A similar extent of granodiorite landscapes also exist in the parts of the Lower Burdekin, Bowen and Bogie catchments (Crack and Isbell, 1971), extending the applicability of the guidelines into the main sediment source hotspot as identified in Figure 4.9.

A certain degree of similarity exists between granodiorite country and sedimentary landscapes in terms of topography, vegetation and to a lesser extent, soil types, in particular for the region located in the Camel Creek and Douglas River sub-catchments in the northern section of the Upper Burdekin. These areas have historically been subjected to heavy grazing pressures, and gully erosion is a widespread occurrence in some areas, suggesting similar ratios of hillslope:gully erosion as for granodiorite landscapes. Consequently, we believe it is safe to extend the applicability of the guidelines to these areas as well, enlarging the area of applicability in the Upper Burdekin to about 20% (Figure 9.6).

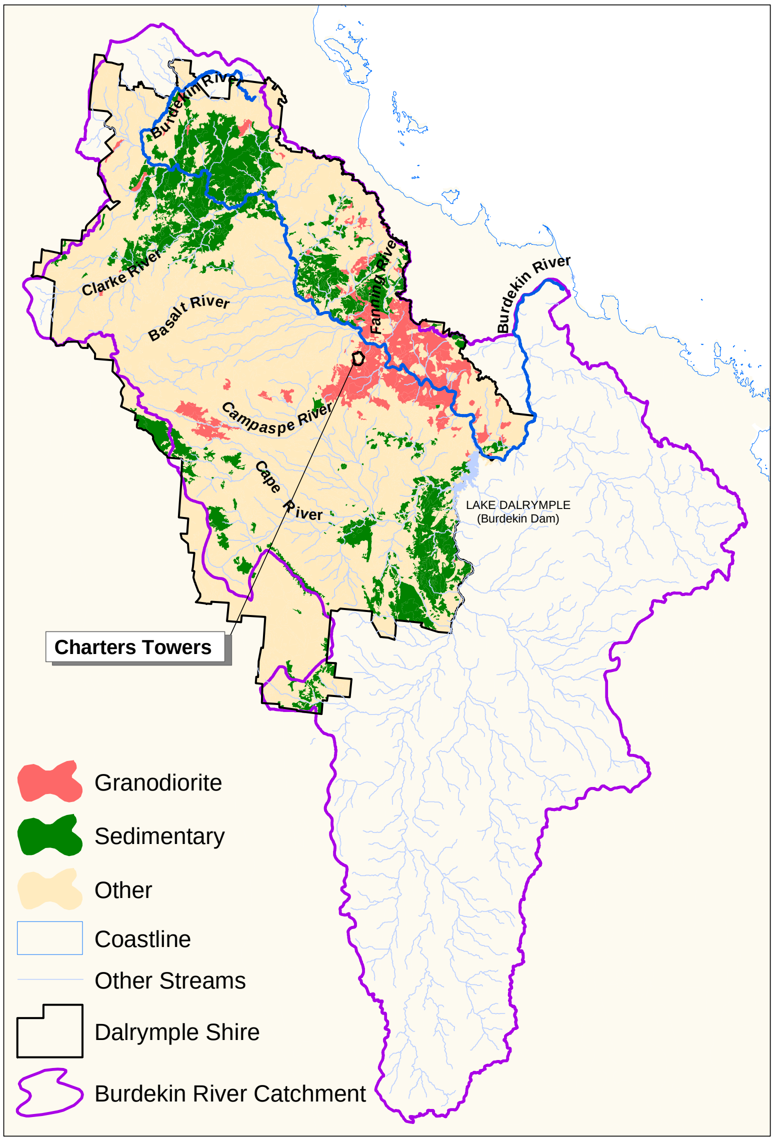


Figure 9.6: Extent of granodiorite and sedimentary landscapes in the Dalrymple Shire (extracted from Rogers et al., 1999).

In contrast, the soil surface condition assessment framework presented in Figure 7.7 has a broader applicability. In its current form, the framework is assumed to be applicable to all soils with a sandy-loam to loamy-sand surface texture. Therefore, excluding all sandy soils on granites and vertosols (cracking clays; derived from basalts or located in landscape depressions) the majority of soils occurring in the Upper Burdekin can be assessed using the framework. This corresponds to about 80% of the area of the Dalrymple Shire. Thus, in terms of managing the primary cause of soil erosion – i.e. runoff generation, we have produced a broadly applicable tool to assess soil condition as a basis for guiding grazing management decisions for soils occurring in most of the Upper Burdekin Catchment, irrespective of landscape type and location.

9.1.5 Critical knowledge gaps

Improvements to modelling tools

The modelling tools developed during the project constitute good prototypes of tools required to assist in the development of robust targets to reduce sediment and nutrient export from grazing lands. However, several critical gaps currently limit their usefulness for this purpose and constrain their broader application. Whilst SedNet has been successfully tested for plausibility and internal consistency (Prosser et al., 2002) and the AIMS sediment discharge data obtained at the mouth of the Burdekin River at Clare has been used as a calibration point, the lack of adequate gauging site data across the catchment has precluded a more systematic spatial calibration of the model. Some options to address this gap are summarised in Table 9.1, and some of the other critical data gaps to improve the model are also listed.

In addition to more investment into model calibration and additional data acquisition to further refine individual sediment budget components, there are a number of critical process components that need to be incorporated into the Burdekin SedNet model, most importantly the ability to provide estimates of nutrient discharge and a catchment scale nutrient budget. Prototypes from SedNet applications in other catchments are available (e.g. Mary River catchment; DeRose et al., 2002), and a strategy is in place to address this gap (Table 9.1). Data from the current MLA project and other NAP funded activities in the Burdekin will provide an initial set of calibration data.

The potential to expand SubNet into a property scale decision support tool was illustrated in Chapter 5. However, in its current version, SubNet has several major deficiencies that need to be addressed, before it could be utilised as a property and sub-catchment scale tool to assist target setting. The most important gap that needs to be addressed is the need for a hydrological feedback to be incorporated so that an increase in hillslope cover not only reduces hillslope sediment delivery, but also reduces gully erosion to the degree that higher cover levels reflect soil condition recovery and a concomitant decrease in runoff directed into gullies. Additional major gaps include the need to expand SubNet to include nutrient budgets, and the acquisition of additional data to improve our current estimates of some of the model components (e.g. measured sediment and nutrient enrichment ratios; measured stream bank erosion rates). All these gaps are seen as a high priority for the current MLA project.

Process understanding

One of the achievements of the project is the recognition of the importance of maintaining sufficient biomass to maintain or recover soil hydrological function. However, only sparse data or mainly anecdotal evidence at this stage backs up some of our statements, in particular in relation to the presumed role of macro-fauna like earthworms. A major gap continues to exist in our understanding of the factors that control earthworm activity in tropical savanna woodlands, which would be fundamental to develop thresholds of soil health. Not only do we not fully understand the factors involved, but our knowledge about rates of soil hydrological recovery for different soil and landscape types is also still very limited.

Nutrient cycling is closely related to soil biological activity. In fact, very little data exist on transformation and transfer rates of nutrients within the system compartments, and out of the systems. Nutrient balances for tropical woodland savannas are only partially quantified for very few sites in Australia. Although we know that soil erosion is a critical nutrient loss pathway, we do not know how significant erosional losses are in comparison to other loss pathways (e.g. leaching), or to what degree there are compensatory mechanisms such as ‘bio-pumping’ by trees, which could be replenishing nutrients at the soil surface through transfer of nutrients from the weathering zone by root uptake and subsequent litter deposition. The lack of data to establish spatially differentiated nutrient budgets and nutrient fluxes therefore continues to constrain our ability to fully ascertain the impact of grazing and soil erosion on system resilience and productivity at landscape scale. An overview of the knowledge gaps and some of the strategies in place to address these are summarised in Table 9.2.

Grazing management tools

Two critical knowledge gaps have been identified in relation to improving the uptake of the results and recommendations presented in this report – the lack of cost/benefit analysis of some of the proposed intervention measures, and tools that would enable graziers to monitor pasture biomass, pasture condition and associated management actions in near to real time for their entire property.

Table 9.1: Overview of key knowledge gaps, possible research approaches and strategies to improve the modelling tools developed in the project.

Knowledge gap	Research approach	Strategy to address knowledge gap
Need for additional data to refine and improve calibration of Burdekin SedNet	• Establish WQ gauging sites across the catchment • Employ geochemical tracers • Employ tracing methods using OSL and radio-isotopes • Determine bedload transport rates • Determine particle size composition of suspended solids • Determine rates of river bank erosion • Obtain measured values for sediment delivery and nutrient enrichment ratios	• BDTB to seek NAPSWQ and NHT2 funding to establish 6 automated gauging sites; opportunistic grab sampling currently underway; MLA and TFTA monitoring sites operating in Upper Burdekin • ACTFR/LWA funded project using geochemical tracers to determine fate of turbidity loads • No strategy currently in place • No strategy currently in place • Partly addressed by current MLA project and TFTA monitoring sites and ACTFR/LWA project • Partly addressed by current MLA project at Weany and Wheel Ck sites and future sedimentary site; no strategy in place for obtaining data elsewhere in the catchment • Partly addressed by current MLA project at Weany and Wheel Ck sites and future sedimentary site; no strategy in place for obtaining data elsewhere in the catchment
Incorporate new model components into Burdekin SedNet	• Incorporate nutrient export and budget modelling routines building on work done as part of the NLWRA • Develop a turbidity load modelling component by building on MDBC funded work • Incorporate alluvial river gully systems	• GBRMPA funded modelling of GBR catchments using SedNet to incorporate nutrient modelling (ACTFR/CSIRO/AIMS/NRM collaboration) • BDTB to seek NAPSWQ funding; potential to use data generated by ACTFR/LWA geochemical tracer project • BDTB to seek NAPSWQ Priority Action Funding
Refine SubNet	• Incorporate a hydrological feedback between hillslope processes and gully progression • Replace USLE with process based hillslope model (options: Scanlan model; incorporation of GRASP; further development of hillslope model developed by MLA project) • Determine spatially variable sediment and nutrient enrichment ratios • Determine rates of stream bank erosion • Incorporate nutrient budget routine by building on SedNet nutrient budget routines	• To be addressed as part of the current MLA project (Weany and Wheel Ck monitoring sites) • To be addressed as part of the current MLA project (Weany and Wheel Ck monitoring sites) • To be addressed as part of the current MLA project (Weany and Wheel Ck monitoring sites) • To be addressed as part of the current MLA project (Weany and Wheel Ck monitoring sites) • To be addressed as part of the current MLA project (Weany and Wheel Ck monitoring sites)
Improve the grazing impact models	• Broaden the database by sampling a larger cross-section of paddocks in the Burdekin catchment • Incorporate topographic attributes into model • Cross-calibrate LFA and vegetation sampling and modelling techniques with hydrological modelling and monitoring	• No strategy currently in place • To be addressed as part of the current MLA project (Weany Ck monitoring site) • To be addressed as part of the current MLA project (Weany and Wheel Ck monitoring sites)

Abbreviations: BDTB = Burdekin Dry Tropics Board; LWA = Land Water Australia; ACTFR = Australian Centre for Tropical Freshwater Research; TFTA = Dept of Defence Townsville Field Training Area

At this stage, the recommendations outlined in section 9.1.3 have been formulated largely in the absence of any cost/benefit assessment of their economic feasibility. There is some information on the cost-effectiveness of the EcoGraze recommendations, but what is lacking is a framework to assess property scale costs and benefits for all of the various management interventions a grazier might choose. Also lacking is specific data on the economic feasibility of direct rehabilitation measures such as earthworks to remediate scalded areas and gullies. The lack of more hard economic evidence of long-term benefits of investing in more sustainable grazing regimes is seen as one of the major impediments to achieving broader acceptance of some of the recommendations.

It follows from our discussion in section 9.1.4 on thresholds, that to move towards more effectively managing stock numbers to achieve desired utilisation rates as the main strategy to manage native pastures more sustainably, graziers would require knowledge of pasture biomass across their entire property, and that with a relatively high temporal resolution (once/twice a year would be enough). At this point in time, no readily available tools exist to implement property wide pasture biomass monitoring systems. However, remote sensing of rangeland condition has made significant progress in recent times, as has the development of efficient data delivery platforms (or ‘pipelines’). Given that many rural properties have significantly upgraded their Internet access capabilities in the wake of TELSTRA investments in the bush, it appears that there is scope in developing products that provide remotely sensed data on pasture condition (cover) on a property basis. Hopefully this can be complemented in the not too distant future by spatial estimates of biomass. Access to such information constitutes a key to assist implementation of the recommendations outlined in this report.

Table 9.2: Overview of key knowledge gaps, possible research approaches and strategies to improve our understanding of landscape processes and to underpin grazing management tools.

Knowledge gap	Research approach	Strategy to address knowledge gap
Factors governing soil macro-faunal activity and soil hydrology	• Carry out inventory of earthworm species in different land units and for different grazing pressures • Analysis of soil ecosystem factors controlling earthworm activity • Determine temporal relationships between earthwork species and abundance and recovery of soil hydrological function	• Partially addressed through Tropical Savanna CRC Project 1.1.3 • No strategy currently in place • No strategy currently in place
Nutrient fluxes and budgets in tropical savanna woodlands	• Determine C, N and P cycling and transfer rates at the point scale for selected sites with and without grazing impact (using Scanlan exclosures) • Determine hillslope and paddock scale transfer rates of C, N and P	• Partially addressed through Tropical Savanna CRC Project 1.1.3; • No strategy currently in place
Below-ground dynamics of paddock vegetation	• Determine root biomass and depth distribution • Determine below-ground response of native and introduced grasses to different levels of consumption • Evaluate rates of recovery of below-ground biomass of native and introduced grasses	• Partially addressed through Tropical Savanna CRC Project 1.1.4; • No strategy currently in place • Partially addressed in current project (above-ground biomass); no strategy for belowground aspects
Economics of landscape rehabilitation using grazing management and engineering solutions	• Design, test and assess engineering solutions to gully remediation • Develop trade-off analysis tools to assist property management planning	• Partially addressed in current project; to be complemented by BDTB Bowen project and new PAP project • No strategy currently in place
Develop property scale pasture condition and biomass assessment tools	• Develop remote sensing techniques to assess pasture biomass • Develop easy access data delivery platforms for use by graziers	• No strategy currently in place • No strategy currently in place

9.2 Project outcomes

Although the project's duration was only 3 ½ years, we believe that a number of significant outcomes have been achieved in that period – scientifically, for catchment management and for the beef industry.

9.2.1 Research outcomes

Before the project was initiated, very little catchment scale R&D had been carried out in the northern beef industry, as highlighted in the two earlier reviews commissioned by MLA (Hook, 1997; Roth et al., 1999). Consequently, few readily applicable methodologies had been established to study the impact of grazing on tropical savanna woodlands at landscape or catchment scale. From a research perspective therefore, a major outcome of the project has been the successful development, testing and implementation of methodologies suited to studying the interaction between cattle grazing and landscape response. This included a suite of new stream gauging and erosion monitoring techniques and the development of novel vegetation sampling protocols, which we report in detail in Volume II of this report.

Applying these new techniques allowed us to obtain baseline data hitherto lacking (e.g. actual erosion rates for a range of erosion processes, sediment discharge data, unique datasets on grazing distribution and paddock condition). This in turn enabled us to significantly advance our understanding of landscape processes, which we have been able to encapsulate in a suite of conceptual frameworks that will not only continue to guide and streamline our work in the current MLA project, but hopefully will inform and direct research in other regions of the northern beef industry (e.g. Northern Territory).

In several instances, we were able to take the conceptual models one step further and develop a suite of quantitative or more formal, rule-based modelling tools that allow us to model sediment transport through catchments and assess the impacts of sediment discharge, as well as providing us with the ability to better predict grazing impacts at landscape scale. The main potential future application of these models is to help select the best target areas for landscape rehabilitation and to test grazing management scenarios as part of more robust target setting processes likely to occur in the near future as part of government initiatives such as the National Action Plan for Salinity and Water Quality (NAPSWQ) and the Reef Protection Plan.

The Burdekin SedNet model is an example of this occurring. Since its initial application in the Burdekin catchment, SedNet has been modified and used in other GBR catchments, as well as being used nationally as part of the National Land and Water Resources Audit. It is constantly being refined and under the auspices of the CRC Catchment Hydrology, is currently being incorporated into a range of broader, more user-friendly catchment modelling tools.

9.2.2 Outcomes for catchment management

The reconnaissance scale sediment budget produced as part of the project and published as a separate MLA report (Prosser et al., 2002) has had a major impact on the prioritisation of investment of NAPSWQ funds in the Burdekin River catchment. The SedNet outputs formed a significant input to the Burdekin Catchment Condition Study (Roth et al., 2002), on the basis of which the Burdekin Dry Tropics Board (BDTB, the regional NRM body for the Burdekin accredited under NAPSWQ) prioritised its natural resource management issues and developed a suite of Priority Action Proposals. As part of this process, the BDTB was able to explicitly target the Bowen catchment for high priority investment of NAPSWQ funds to address sediment and nutrient discharge from grazed lands. The Bowen Priority Action Proposal has been successful, and it is anticipated that the project will commence shortly supported by a grant of over $ 500k from NAPSWQ.

A key objective of the Bowen project is to assess a range of incentives and management actions that graziers might adopt to restore degraded grazing lands and river frontage, with the specific objective of reducing sediment and nutrient discharge. The establishment of monitoring protocols, which will build on the techniques developed as part of this project, will be integral to the implementation of the on-ground works envisaged (fencing, relocation of watering points, gully rehabilitation, training and capacity building). The project also offers the first major opportunity to implement and test the landscape management guidelines developed and presented in section 9.1.3. As such, the Bowen project is seen as a pilot project to assess in what way NAPSWQ and other government funding can be most effectively delivered to graziers to achieve water quality outcomes in other hotspot regions of the Burdekin River catchment.

More generally, SedNet is finding widespread application in other catchments to assist in identifying key sediment and nutrient sources as the basis for investment prioritisation. The Great Barrier Reef Marine Park Authority (GRBRMPA) has commissioned a SedNet analysis for the GBR catchments to prioritise investment areas under the Reef Protection Plan, and other Regional NRM Bodies (Wet Tropics) and catchment groups (Herbert) have commissioned or are in the process of commissioning similar exercises as carried out for the Burdekin.

One of the main benefits resulting from the above is that the Regional NRM Bodies are now in a position to better target and justify strategic investments into managing sediment and nutrient export, thus meeting one of the key requirements to be eligible for future funding from NHT2, NAPSWQ and Reef Protection Plan. Tools like SedNet and SubNet are critical in demonstrating a more objective and scientifically robust approach to the delineation of hotspots, and are likely to be used as future tools to test likely resource management scenarios at regional and at property scales as part of the water quality target setting processes that many of the Regional NRM Bodies will have to embark on in the near future as part of their regional NRM planning processes.

9.2.3 Outcomes for the beef industry

Direct benefits for the northern beef industry have materialised in a number of ways. Given that 95% of the Burdekin River catchment is used for grazing, all of the catchment management benefits discussed in the preceding section also translate directly into positive outcomes for the beef industry in the Burdekin. At the same time, the substantial MLA investment into addressing sediment and nutrient export from grazing lands in the Burdekin is seen as a clear signal by government agencies and the community in general that the beef industry is responding to concerns about environmental impacts of extensive beef production. As a result, the industry has maintained a more positive image in the media and has received less negative exposure to the recent debate about potentially adverse impacts of land use on the Great Barrier Reef World Heritage Area.

Project results have been publicised through a very broad range of venues and panels and through a wide range of communication activities. These included numerous discussions and presentations to individual graziers in landcare group meetings, in industry-sponsored meetings (e.g. the recent NQBRC forums), and during field days. One of the main outcomes of these activities is that a greater proportion of graziers are not only more aware of the downstream impacts that grazing might trigger, but are now more readily embracing the need to change some of their management practices to ameliorate potential impacts. When we compare the industry’s attitude to sediment export and GBR issues as we experienced it five years ago (while conducting the reviews and scoping study that led to this project) to the attitudes now, we note a significant shift from denial towards engagement and willingness to change. This has promoted a positive image of the beef industry in comparison with other rural industries in the GBR region.

Finally, one of the most significant outcomes of the project is our ability to offer realistic solutions to address land degradation and sediment export problems. The solutions we offer will assist the industry in targeting hotspots across the region, and the suite of landscape management guidelines will help individual graziers more effectively target the hotspots on their properties within the context of property management planning. We developed guidelines that help identify those areas where interventions are most likely to achieve the greatest impact when limited resources are available. While recommendations in this report need to be tested further to ensure they are practical, economically feasible, and widely applicable, results from this project provide a firm basis for ongoing studies and for improved management of grazing enterprises.

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On farm

Reducing sediment export from the Burdekin Catchment

Volume II Appendices

Project number NAP3.224

Report prepared for MLA by:

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Natural Resources

List of appendices

Appendix 1. Distribution of alluvial gully systems along the Upper Burdekin River

Rebecca Bartley, CSIRO Land and Water, Atherton.

Background

Initial reconnaissance field work near 'Blue Range' in August 1999 alerted researchers to high levels of gully erosion along the Upper Burdekin River. Mapping of gully erosion in the Burdekin Catchment is limited to those areas investigated in Prosser et al (2001), and it was considered important to investigate further whether these erosion sites are a potential high source of sediment to the Burdekin River. Suggestions of how these erosion systems were formed and their role in contributing sediment to the Burdekin River are discussed below.

Approach

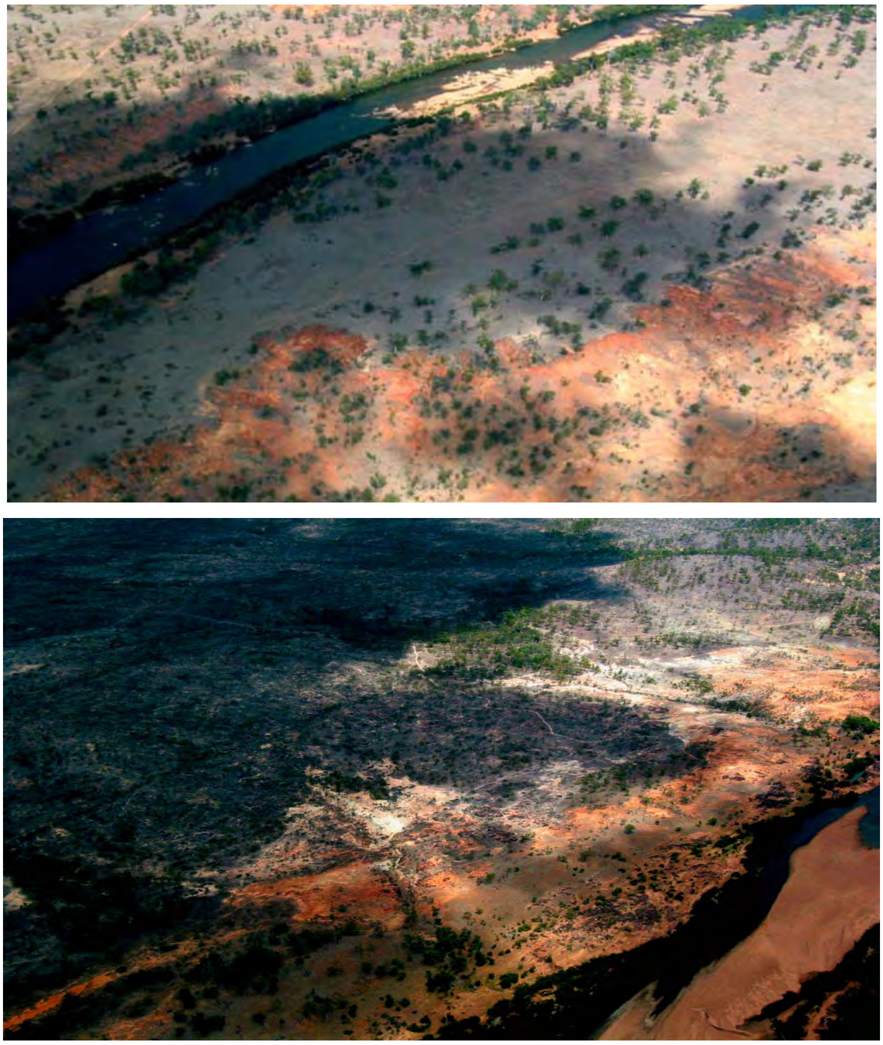
To assess the position and extent of gully erosion along the Burdekin River between the headwaters of the Burdekin River and Hillgrove we hired a plane and mapped erosion sites using a GPS. Photos of the sites were taken with a digital camera.

Results

Erosion sites within 500 m to 1000 m of the river banks were considered as potential sources of sediment. Any erosion sites further away from the river were not included. There were five different land types identified: bank erosion (e.g. Figure 1.1), gully bank erosion (e.g. Figure 1.2), erosion scalds (e.g. Figures 1.3), tributary sources of sediment (e.g. Figure 1.4) and wetlands (e.g. Figure 1.5). A map of the distribution of each of these erosion types is shown in Figure 1.6.

Figure 1.1: Bank erosion along the Upper Burdekin

Figure 1.2: Gully erosion scalds within 200 m of the Burdekin River



Figures 1.3: Erosion scalds along the banks of the Burdekin River

Figure 1.4: Tributary sources of sediment

Figure 1.5: Valley of the Lagoons is an important wetland habitat along the Upper Burdekin

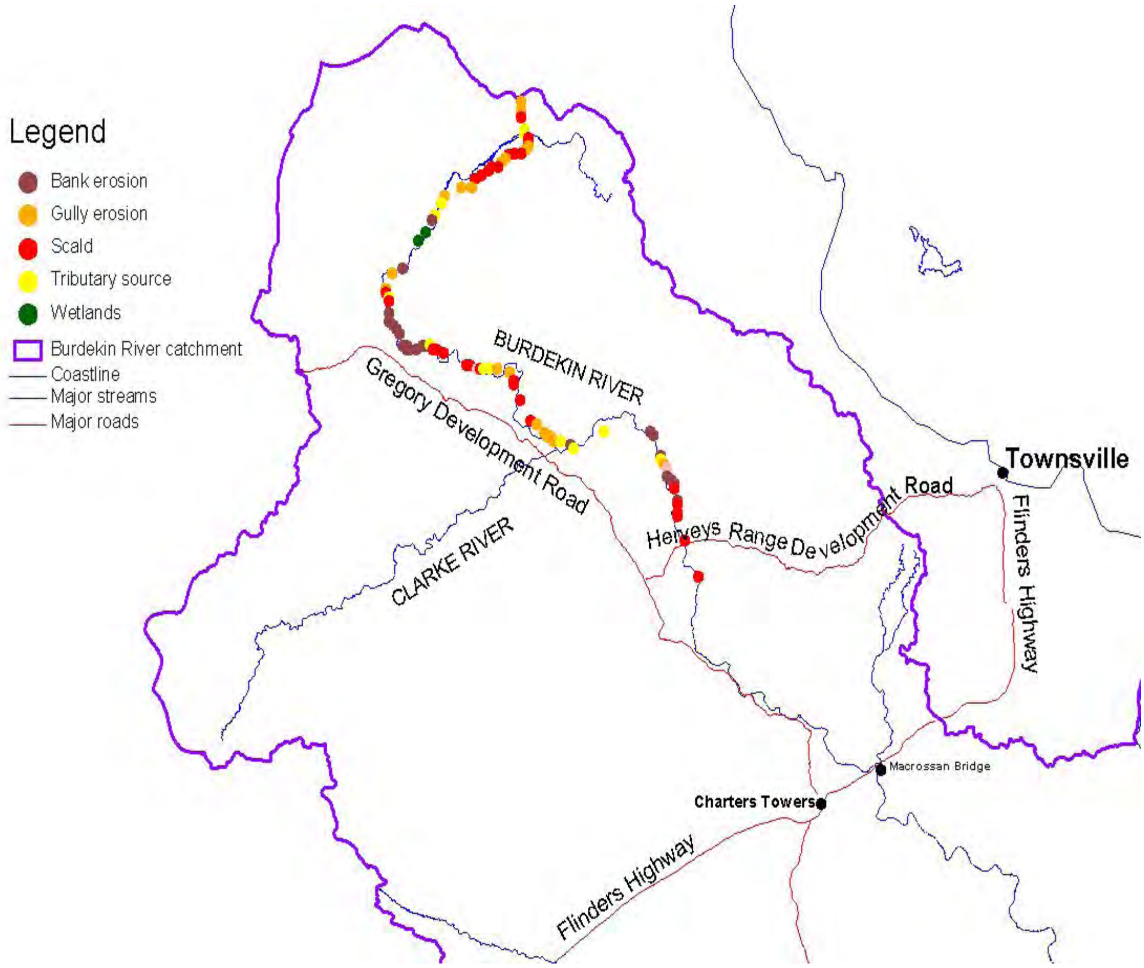


Figure 1.6: Map of location of gully systems along the Upper Burdekin

Estimating the impact of the erosion along the Upper Burdekin

It was initially proposed to estimate the contribution of these eroded sites to the overall sediment yield at Macrossan's Bridge. However, to do this, knowledge of erosion rates, dates of the erosion event, area of erosion surfaces and historical flow records would be required. Such a study would take considerable time and resources (even to make a rough calculation) and is therefore considered beyond the capacity of the project. Instead, a few qualitative suggestions as to the possible causes of this erosion and potential areas of further research are discussed.

The extent of erosion along the Upper Burdekin River is certainly more significant that originally mapped in Prosser et al., (2001). However, it is difficult to determine the causes of such extensive erosion. There are two probable causes:

1. excessive stocking rates on fragile soil and vegetation types; and
2. mining activities along the floodplains.

Based on the flight data, it seems that there are a number of large scalds located near and around stock watering points. Stock watering points are often located on the more vulnerable alluvial deposits of the floodplain or low-lying secondary channels (flood-runners), that when disturbed, can be stripped from the surface via floodwaters.

The bank erosion appears to be the result of a number of factors. In some cases the bank erosion looks to be directly related to high flood events that would cause scouring and slumping of the channel banks. In other cases it looks like miniature gullies ('badlands') have formed because of high surface runoff from hill-slopes running over the bank to the main channel. This process looks to be directly related to low vegetation cover in many areas. In some cases it does appear that bank erosion has been exacerbated by stock access to the main channel.

It is uncertain of the impact of mining along the floodplains and within the main channel. There is direct evidence of mine sites within a few kilometres of the main channel (Figure 1.7); however, it is difficult to determine to what level the rest of the landscape has been impacted by historical mining activities. It may be that some of the erosion is a function of sluicing activities related to tin mining.

Figure 1.7: Mine site located within a few kilometres of the Burdekin River

Suggested areas of further research

To fully understand the contribution of these erosion sites to the overall sediment yield from the Upper Burdekin River, a number of activities need to be carried out:

1. The erosion sites need to be mapped on aerial photos. Using stereo- photogrammetry estimates of soil volumes can be made. Such mapping would also need to be verified in the field.
2. Estimates of the date or time of erosion needs to be made so that a rate of soil loss can be determined. This may require the use of sophisticated techniques such as OSL (optical stimulated luminescence) dating or tracing techniques using ^{210}Pb or other radionucleide tracers. Without such information it is difficult to determine if these features are related to land-use (and which land-use has been the main cause).
3. An historical investigation into the extent of mining activities in the region would be an important exercise.
4. A general investigation into the flood history, stock management history and vegetation changes of the area would also assist in understanding when the erosion began in this area and which factors were the most important in triggering the erosion observed.
5. On the basis of the above, incorporate a new component with Sednet that models the contribution of these major riverine systems on sediment delivery and revise the Burdekin sediment budget.

Appendix 2. Using microplots to capture landscape runoff and suspended sediment characteristics

Aaron Hawdon, David Fanning, David Post & Christian Roth, CSIRO Land and Water, Townsville.

Summary

Microplots are designed to help describe surface hydrology characteristics and sediment transport for varying soil types and landforms.They are a cost effective, low maintenance tool that provides good seasonal response data about infiltration and suspended sediment transport for different vegetation coverage. A number of units dispersed around the major component types of the landscape can provide data diagnostic of the area.

Introduction

Microplots were primarily designed to capture quantitative data relating to hill slope runoff and associated suspended sediment loss, so that the relationships between these characteristics and vegetation cover may be investigated. Three vegetation cover classes were implemented for this study. Bare of scald (<25%), low-med cover (25-75%) and high cover (>75%). Two repetitions of each cover type were implemented at two separate sites (12 in total).

Microplots comprise of two main parts (figure 2.1), the frame and the Sample Collection Unit (SCU). Table 2.1 provides a breakdown of the individual components of the microplots.

The frame sits ~25mm above the soil surface, isolating the area inside, so that the characteristics of a fixed area (0.24 m^2) can be determined and compared against other plots. Runoff from the plot collects in the trough at the base of the frame and then drains to the Sample Collection Unit.

A small bund wall provides protection from upslope runoff that may compromise the frame walls, or result in hillslop flow overtopping into the microplot.

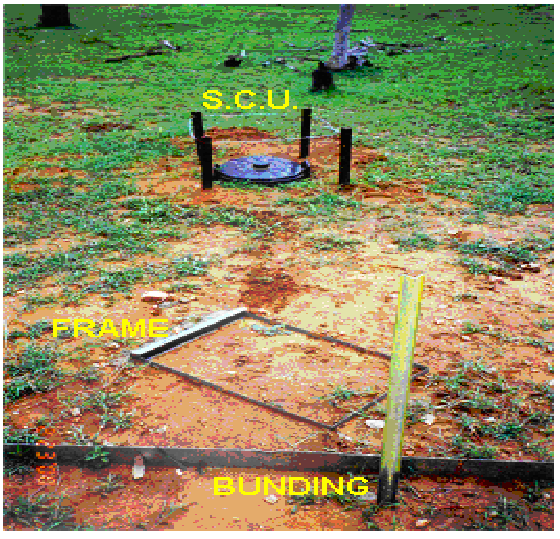


Figure 2.1: An installed microplot

Table 2.1: Microplot components & descriptions**.**

Component	Dimensions	Material / Description
Frame	600 x 400 x 50 (mm)	1.2mm zinc anneal
Trough	400 x 40 x 30 (mm)	1.2mm zinc anneal
Hose	16mm (diam) 2mm thick	Clear vinyl
Bin	44 L	Plastic garbage bin with lid
Drum	25 L	Plastic water storage
Fence		Star pickets (cut into 4 pieces) 1 strand of barbed wire
Rod	6 mm (diam)	Mild steel (cut into appropriate lengths)

Installation

Microplot frame

To insert the microplot frame into the soil, an angle grinder was used to cut around the outline of a solid template constructed out of sheet metal. The template also served to protect the area inside the microplot from disturbance. The microplot frame was then put into the resulting rectangular trench and a board, slightly larger in area than the frame, placed on top. Standing on the board, the frame was tapped into place with a hammer. Periodic rotation of strike points (eg clockwise from corner to middle to corner etc) above the frame edge ensured an even insertion. The frame was inserted so that the trough attachment would be flush with the ground surface.

At the downslope edge, a small hole was carefully excavated to allow for the emplacement of the trough. This excavation was made slightly deeper and wider to allow room for a mortar base (sand, cement & water). The trough was then inserted into the wet mortar, slotted into the frame and the cover emplaced. The frame walls were then repacked with soil of a similar type to form a tight seal between the frame and the soil surface. Figure 2.2 shows the microplot frame and trough after installation.

Figure 2.2: Microplot frame and trough

Sample collection unit

Downslope from the microplot a posthole auger was used to excavate a hole to the depth of the bin lip. A crowbar and a posthole shovel were needed to increase the diameter and to tidy up the excavation. With the bin in the excavation, the storage drum was placed inside and the bin marked at the top edge of the drum. This point should be slightly below ground level to allow for burial of the hose and flow of water from the microplot. After the drum and bin were removed from the excavation, a 20mm hole was drilled, at the marked point, to facilitate insertion of the hose to the drum.

When the mortar around the trough had set, a shallow trench of about 5cm was dug from the microplot to the SCU. The vinyl hose was attached to the trough and run along the trench and inserted into the drum through the hole in the bin wall. A small volume of water was run into the trough to ensure flow to the drum. When flow was achieved the drum was removed and the bin secured with 4 ‘L’ shaped steel rods through the sidewalls. 4 holes were punctured in the base of the bin to allow for faster drainage. With the hose free of kinks or creases the trench was backfilled to keep the hose free from bovine interference. After the drum was reinserted another rod was pierced through, the bin wall, passed under the handle of the drum and then pierced out the other side of the bin to hold the drum firmly in place.

The lid was placed on the bin and then excavated soil used to fill any voids between the outside bin wall and the soil. The rest of the excavated soil was used for constructing a raised bund wall on the upslope side of the SCU to deflect overland flow. A drainage trench was made on the downslope side of the bin unit to a depth just below the bin lip.

A small barbed wire fence was needed to protect the unit from trampling by cattle. This was constructed by cutting star pickets into approximately 500mm lengths. 4 lengths were driven into the ground around the SCU to form a square. Barbed wire was securely attached to the top of one star picket. A small groove about 10mm long and 5mm wide was cut into the outermost top edge of each of the other pickets. The barbed wire was loosely wrapped around the pickets, seated in the grooves, and then securely attached to the first picket. The wire was wrapped loosely enough to allow removal for easy access to the unit but not loose enough to come free when disturbed. Figure 2.3 shows an installed SCU.

Figure 2.3: The sample collection unit

Bund wall

A sheet metal bund wall was placed slightly upslope from the microplot frame to abate flooding of the microplots from upslope overland flow. (See Figure 2.1.) This metal strip was approximately 150mm high by 600mm long and was simply tapped into the soil with a hammer.

Measurements

Volume

A compilation of the data obtained from the microplots is provided in Table 2.2. To measure the volume of overland flow from the microplot, the barbed wire fence from around the sample unit was removed. The lid of the bin was removed, as was the hose from the drum. The drum was then shaken to disperse any settled sediments. The volume was determined using a measuring cylinder and a 250ml sub-sample was transferred to a labelled bottle (Plot Name, Date and Total Volume). The total volume, vegetation cover and any other relevant comments were recorded to the lab book and later added to an Excel Spreadsheet (see Table 2.2). Sub-samples were refrigerated on return to the laboratory. These were later analysed for total suspended sediments and turbidity.

Vegetation Cover

The amount of vegetation cover obstructing raindrop impact was estimated for each plot at every sample collection date. Estimates were in the form of percentage cover. Any litter that was thick enough to protect the soil from raindrop compaction was included. Results of the cover estimates are presented in Figure 2.4 and Table 2.2.

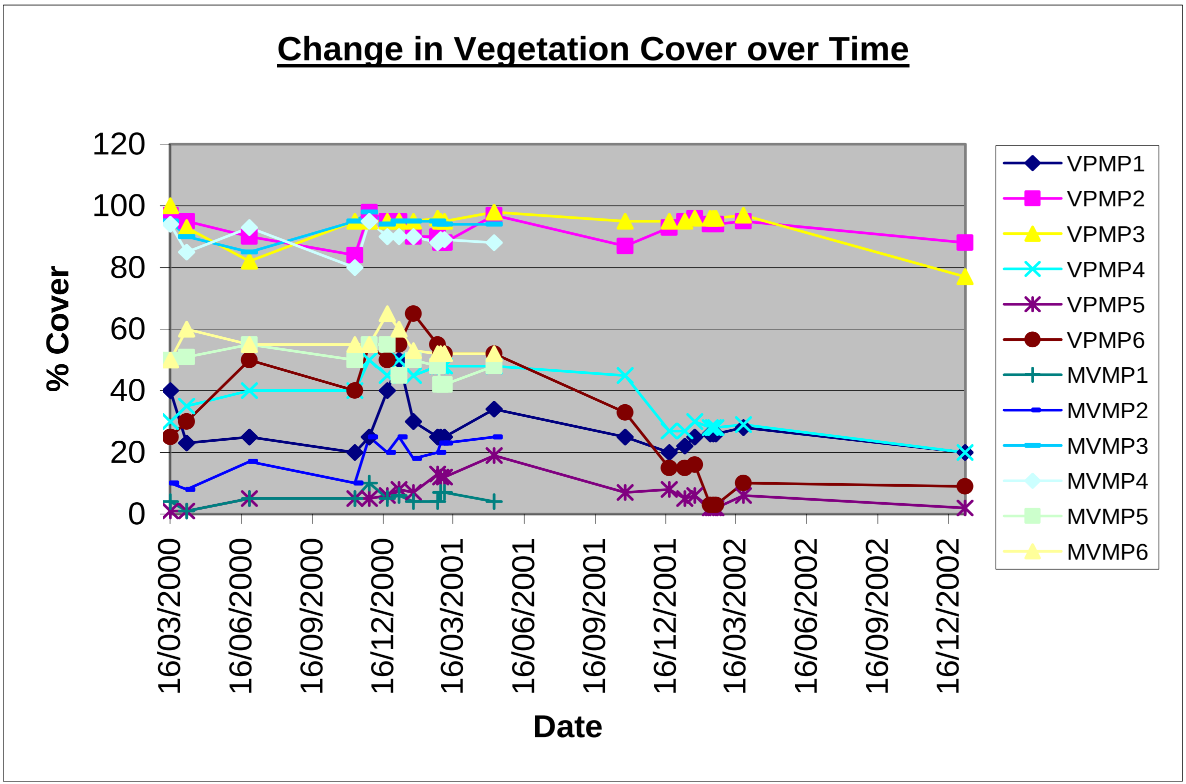


Figure 2.4: Overview of ground cover estimates for all microplots during the project life

Slope

The slope gradient for each microplot was taken by measuring the fall in ground level from the top of the plot, to the lip of the trough. A spirit level and tape measure was used.

Problems encountered

Cattle impacts

Residing cattle occasionally trampled the microplots. Damage from such events included, warped or flattened edges and skewing of the whole frame, to the total dislodgment of the trough. When frame warping had occurred, the frame was reshaped (in-situ if possible) and any gaps between the walls and the soil refilled and packed as per installation procedure. Trough dislodgment posed a more difficult problem. The troughs were cemented in and tend to dislodge with the cement base attached. To remedy the problem some further excavation was required, the trough reinserted and packed into place with stones and soil. A small amount of water was then run down the trough to ensure proper drainage.

Figure 2.5: Trampling caused by cattle

Figure 2.6: Coarse sediment trapped in trough

Blockages

It was discovered that periodically, the troughs would trap larger sediment particles (primarily sand) that would collect at the drainage hole, causing dysfunction. It is believed that these soil particles are moved by raindrop impact and that when they enter the trough, the runoff does not have enough energy to move the particles. This build up was easy to remove with the aid of a screwdriver (to break up cemented particles) and a small paintbrush (used in with dusting action), then washed out with water to ensure through flow. Some blockages extended a small way down the hose. Initially, when this occurred, the rod holding the drum in place was used to dislodge the blockage and then water was flushed down the line until it ran clear. A better method of unblocking the hose was then utilised. With one end blocked, the hose was then filled with water. Compressed air was applied to the hose ejecting the blockage with the water.

The drainage hole in the troughs and the troughs themselves provide excellent accommodation for spiders of the family *Lycosidae*. Redback spiders (*Lactrodectus hasselti)* were sometimes found with webs in the trough so care was taken when removing the trough cover. The webs built by both of these types of spiders created a barrier to throughflow, ultimately causing sediment build up and unit dysfunction. The spiders were removed with small twigs or screwdrivers and then the trough and drainage line cleaned out with water.

On one occasion, it was discovered that a cow had walked on the wet soil covering the drainage hose. The soil compacted considerably forcing the hose closed, effectively blocking flow. Barriers were then placed directly above the hose to mitigate future repeat occurrences.

Sealing

For the microplots to function correctly, the contact between the frame and the soil must be maintained. Natural erosion/deposition events and cattle interactions occasionally compromised the integrity of the contact. The contact was re-established by filling the gaps with a similar soil and which was then carefully packed to ground level. Moistening of the filled areas then allowed a tighter seal to be established. From time to time, erosion (primarily micro-rilling) compromised the contact between the trough lip and the ground.

Rainfall intensity effects

Rainfall events with an intensity >20mm/hr decreased the probability of the equipment capturing quantitative runoff samples. The results from these events were either high 25 litre counts or certain plots would have suspiciously low volumes due to early blockage (especially low cover plots). It was assumed that the 25 litre volumes resulted as a consequence of the plot-frame walls being compromised by excessive overland flow. Figure 2.7 compares the resulting outputs from moderately high and low intensity events for the microplots at Virginia Park & Meadowvale Stations near Mingela, Queensland, Australia. The TSS results also followed a similar trend as shown in Figure 2.8.

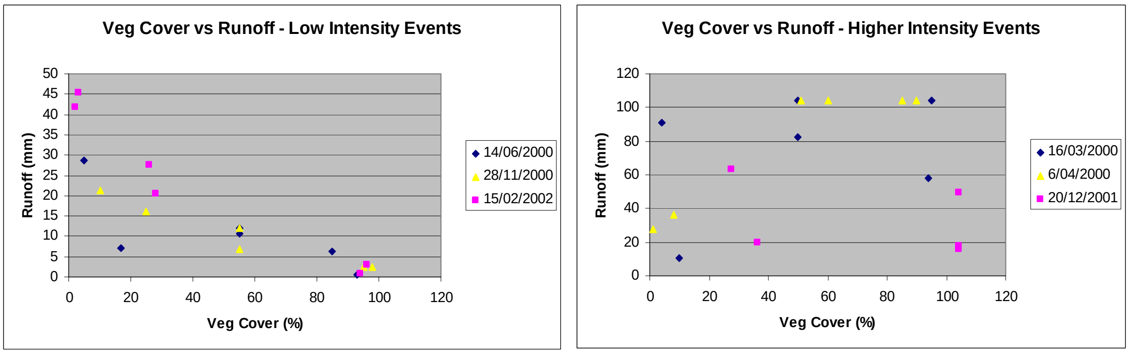


Figure 2.7: Rainfall intensity effects on veg Cover / runoff Volume relationships.

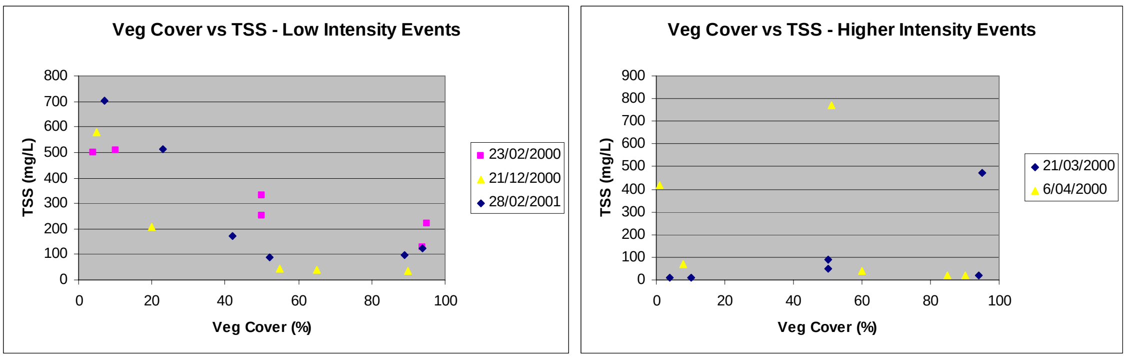


Figure 2.8: Rainfall intensity effects on TSS / Veg cover relationships.

Improvements

Frame

The thickness of the metal used for the frame could be increased. This would improve its ability to withstand trampling by cattle. It would also allow for the depth of the frame to be increased without impeding a clean install. An increase in frame depth may help to abate some problems associated with high intensity events.

Trough

A removable trough would greatly improve the access for cleaning and perhaps with frame realignment. It may also prove beneficial to locate the drainage hole centrally, rather than on the side, so that the drainage hose can be kept straight. This would improve the units' ability to 'self clean', minimising blockages by heavier soil particles.

Site selection/ alignment

Care should be taken to align the troughs directly downslope so that water and sediment does not have the potential to build up along the frame walls (i.e. the frame does not impede the flow of the water downslope). Microplots situated in depressions require extra bunding, which even then, may not provide adequate protection from overland flow (depending on the soil characteristics). For example, microplot MVMP3 was installed in a shallow drainage line and always seemed to be full or much fuller than it should be (especially on med-high intensity events). It was then discovered that increased overland flow was able to 'wrap around' the bunding and overtop the frame walls.

Table 2.2: Compilation of data obtained from the microplots

Date Collected	Sample	Cover (%)	Total Rainfall (mm)	MaxRain Intensity (mm/hr)	Runoff Volume (mm)	Runoff (%)	TSS (mg/L)	Turbidity (NTU)	TDS (mg/L)
23-Feb-00	VPMP3	100	118.2	42.80	63.63	53.83	0.00	47	24
23-Feb-00	VPMP4	30	118.2	42.80	75.95	64.26	773.20	2830	12
23-Feb-00	VPMP5	1	118.2	42.80	61.10	51.70	955.31	3475	12
29-Feb-00	MVMP2	10	70	5.70	12.92	18.45			
29-Feb-00	MVMP4	94	70	5.70	21.33	30.47			
01-Mar-00	VPMP1	40	48	12.10	5.63	11.72	110.00		30
01-Mar-00	VPMP6	25	48	12.10	38.75	80.73	432.00		18
21-Mar-00	MVMP1	4	145	19.40	91.25	62.93	226.00	865	6
21-Mar-00	MVMP2	10	145	19.40	10.63	7.33	0.00		12
21-Mar-00	MVMP5	50	145	19.40	82.71	57.04	0.00	478	12
21-Mar-00	VPMP2	97	110	22.70	4.77	4.34	2.00		48
21-Mar-00	VPMP3	100	110	22.70	8.19	7.44	0.00		18
21-Mar-00	VPMP4	30	110	22.70	42.50	38.64	18.00		12
21-Mar-00	VPMP6	25	110	22.70	91.04	82.77	348.00		12
06-Apr-00	MVMP4	85	230.7	36.40	104.17	52.08	8.00		12
06-Apr-00	MVMP5	51	230.7	36.40	104.17	52.08	16.00	1258	12
06-Apr-00	MVMP6	60	230.7	36.40	104.17	52.08	28.00		12
06-Apr-00	VPMP1	23	130	27.60	74.54	57.34	518.00		12
06-Apr-00	VPMP3	93	130	27.60	104.17		42.00		18
06-Apr-00	VPMP4	35	130	27.60	104.17		298.00		12
14-Jun-00	MVMP1	5	46.5	3.52	28.65	61.60			
14-Jun-00	MVMP2	17	46.5	3.52	7.17	15.41			
14-Jun-00	MVMP3	85	46.5	3.52	6.29	13.53			
14-Jun-00	MVMP4	93	46.5	3.52	0.46	0.99			
14-Jun-00	MVMP5	55	46.5	3.52	12.04	25.90			
14-Jun-00	MVMP6	55	46.5	3.52	10.58	22.76			
26-Jun-00	VPMP1	25	97	3.80	1.04	1.07			
26-Jun-00	VPMP2	90	97	3.80	0.50	0.52			
26-Jun-00	VPMP3	82	97	3.80	0.63	0.64			
26-Jun-00	VPMP4	40	97	3.80	0.71	0.73			
26-Jun-00	VPMP5	5	97	3.80	7.50	7.73			
26-Jun-00	VPMP6	50	97	3.80	0.92	0.95			
09-Nov-00	MVMP1	5	99	35.52	60.00	60.61			
09-Nov-00	MVMP4	80	99	35.52	16.46	16.62			
09-Nov-00	MVMP5	50	99	35.52	10.52	10.63			
09-Nov-00	VPMP 1	20	115.5	27.80	34.58	29.94	595.40	615	24.6
09-Nov-00	VPMP 2	85	115.5	27.80	9.58	8.30	135.80	56	124.2
09-Nov-00	VPMP 3	95	115.5	27.80	10.00	8.66	35.60	9	44.4
09-Nov-00	VPMP 4	40	115.5	27.80	26.56	23.00	520.80	526	19.2
09-Nov-00	VPMP 6	40	115.5	27.80	25.52	22.10	847.80	1070	22.2
17-Nov-00	MVMP1	5	30.5	18.69	21.46	70.36			
17-Nov-00	MVMP2	10	30.5	18.69	16.67	54.64			
17-Nov-00	MVMP4	80	30.5	18.69	19.27	63.18			
17-Nov-00	MVMP5	50	30.5	18.69	8.02	26.30			
17-Nov-00	MVMP6	55	30.5	18.69	5.63	18.44			

Date Collected	Sample	Cover (%)	Total Rainfall (mm)	MaxRain Intensity (mm/hr)	Runoff Volume (mm)	Runoff (%)	TSS (mg/L)	Turbidity (NTU)	TDS (mg/L)
17-Nov-00	VPMP 1	20	19.5	1.50	3.17	16.24	295.40	298	24.6
17-Nov-00	VPMP 4	40	19.5	1.50	3.29	16.88	199.00	197	21
17-Nov-00	VPMP 5	5	19.5	1.50	7.40	37.93	258.00	294	12
17-Nov-00	VPMP 6	40	19.5	1.50	2.06	10.58	258.40	288	21.6
28-Nov-00	MVMP1	10	43.5	6.66	21.25	48.85			
28-Nov-00	MVMP2	25	43.5	6.66	16.04	36.88			
28-Nov-00	MVMP3	98	43.5	6.66	2.46	5.65			
28-Nov-00	MVMP4	95	43.5	6.66	2.40	5.51			
28-Nov-00	MVMP5	55	43.5	6.66	6.75	15.52			
28-Nov-00	MVMP6	55	43.5	6.66	11.92	27.39			
28-Nov-00	VPMP 1	25	50	20.50	22.17	44.33	576.20	599	13.8
28-Nov-00	VPMP 2	98	50	20.50	6.25	12.50	100.60	13	59.4
28-Nov-00	VPMP 3	95	50	20.50	23.13	46.25	56.00	23	24
28-Nov-00	VPMP 4	50	50	20.50	14.48	28.96	645.00	695	15
28-Nov-00	VPMP 5	5	50	20.50	8.96	17.92	336.80	416	13.2
28-Nov-00	VPMP 6	55	50	20.50	13.33	26.67	594.40	751	15.6
21-Dec-00	MVMP1	5	92.4	9.90	52.08	56.37			
21-Dec-00	MVMP2	20	92.4	9.90	35.10	37.99			
21-Dec-00	MVMP4	90	92.4	9.90	20.73	22.43			
21-Dec-00	MVMP5	55	92.4	9.90	21.46	23.22			
21-Dec-00	MVMP6	65	92.4	9.90	26.88	29.09			
21-Dec-00	VPMP 1	40	129	19.80	60.63	47.00	270.10	280	9.9
21-Dec-00	VPMP 2	95	129	19.80	9.27	7.19	64.00	7.5	36
21-Dec-00	VPMP 4	45	129	19.80	22.08	17.12	113.20	102	16.8
21-Dec-00	VPMP 5	6	129	19.80	57.92	44.90	602.50	740	7.5
21-Dec-00	VPMP 6	50	129	19.80	58.23	45.14	192.20	225	7.8
05-Jan-01	MVMP1	6	72.5	26.83	53.96	74.43			
05-Jan-01	MVMP2	25	72.5	26.83	60.71	83.74			
05-Jan-01	MVMP4	90	72.5	26.83	49.79	68.68			
05-Jan-01	MVMP5	45	72.5	26.83	28.75	39.66			
05-Jan-01	MVMP6	60	72.5	26.83	45.63	62.93			
05-Jan-01	VPMP 1	50	66.4	33.70	22.50	33.89	671.00	614	9
05-Jan-01	VPMP 2	95	66.4	33.70	4.79	7.22	99.40	23	30.6
05-Jan-01	VPMP 3	95	66.4	33.70	40.00	60.24	65.60	15	14.4
05-Jan-01	VPMP 4	50	66.4	33.70	12.79	19.26	189.20	156	10.8
05-Jan-01	VPMP 5	8	66.4	33.70	67.50	101.66	919.80	920	10.2
05-Jan-01	VPMP 6	55	66.4	33.70	25.00	37.65	540.40	624	9.6
24-Jan-01	MVMP1	4	21.5	8.88	11.88	55.23			
24-Jan-01	MVMP2	18	21.5	8.88	6.88	31.98			
24-Jan-01	MVMP3	95	21.5	8.88	0.00	0.00			
24-Jan-01	MVMP4	90	21.5	8.88	0.10	0.48			
24-Jan-01	MVMP5	50	21.5	8.88	0.21	0.97			
24-Jan-01	MVMP6	53	21.5	8.88	5.21	24.22			
24-Jan-01	VPMP 1	30	30.6	15.70	4.27	13.96	211.10	163	18.9
24-Jan-01	VPMP 4	45	30.6	15.70	1.67	5.45	80.70	27.3	39.3
24-Jan-01	VPMP 5	7	30.6	15.70	7.50	24.51	1642.60	1795	17.4

Date Collected	Sample	Cover (%)	Total Rainfall (mm)	MaxRain Intensity (mm/hr)	Runoff Volume (mm)	Runoff (%)	TSS (mg/L)	Turbidity (NTU)	TDS (mg/L)
24-Jan-01	VPMP 6	65	30.6	15.70	1.67	5.45	128.80	117	31.2
22-Feb-01	MVMP1	4	44.25	12.58	7.92	17.89			
22-Feb-01	MVMP2	20	44.25	12.58	7.08	16.01			
22-Feb-01	MVMP3	95	44.25	12.58	0.10	0.24			
22-Feb-01	MVMP4	88	44.25	12.58	2.08	4.71			
22-Feb-01	MVMP5	48	44.25	12.58	2.71	6.12			
22-Feb-01	MVMP6	52	44.25	12.58	7.29	16.48			
22-Feb-01	VPMP 1	25	28.8	4.00	2.29	7.96	76.40	35	3.6
22-Feb-01	VPMP 2	90	28.8	4.00	1.25	4.34	92.00	16	78
22-Feb-01	VPMP 3	96	28.8	4.00	2.19	7.60	67.80	17	52.2
22-Feb-01	VPMP 4	48	28.8	4.00	2.29	7.96	64.60	43	35.4
22-Feb-01	VPMP 6	55	28.8	4.00	1.98	6.87	215.20	185	4.8
28-Feb-01	MVMP2	23	70.75	14.62	46.88	66.25			
28-Feb-01	MVMP3	94	70.75	14.62	44.79	63.31			
28-Feb-01	MVMP4	89	70.75	14.62	13.96	19.73			
28-Feb-01	MVMP5	42	70.75	14.62	22.92	32.39			
28-Feb-01	MVMP6	52	70.75	14.62	31.04	43.88			
28-Feb-01	VPMP 2	88	55.4	9.00	1.04	1.88	147.60	9	32.4
28-Feb-01	VPMP 3	95	55.4	9.00	2.71	4.89	55.40	4	24.6
28-Feb-01	VPMP 4	48	55.4	9.00	10.83	19.55	149.60	112	20.4
28-Feb-01	VPMP 5	12	55.4	9.00	22.71	40.99	729.20	840	10.8
28-Feb-01	VPMP 6	52	55.4	9.00	8.33	15.04	317.40	342	12.6
05-Mar-01	MVMP1	7	72.5	24.98	52.92	72.99			
05-Mar-01	MVMP2	23	72.5	24.98	62.71	86.49			
05-Mar-01	MVMP4	89	72.5	24.98	43.96	60.63			
05-Mar-01	MVMP5	42	72.5	24.98	45.63	62.93			
05-Mar-01	MVMP6	52	72.5	24.98	60.42	83.33			
05-Mar-01	VPMP 1	25	36.5	3.50	15.83	43.38	488.00	465	12
05-Mar-01	VPMP 2	88	36.5	3.50	1.88	5.14	54.00	8	36
05-Mar-01	VPMP 3	95	36.5	3.50	3.54	9.70	47.20	9	22.8
05-Mar-01	VPMP 4	48	36.5	3.50	16.04	43.95	183.20	163	16.8
05-Mar-01	VPMP 5	12	36.5	3.50	22.29	61.07	960.40	1140	9.6
30-Apr-01	MVMP1	4	52		38.96	74.92			
30-Apr-01	MVMP2	25	52		10.63	20.43			
30-Apr-01	MVMP4	88	52		18.33	35.26			
30-Apr-01	MVMP5	48	52		17.71	34.05			
30-Apr-01	MVMP6	52	52		10.42	20.03			
08-May-01	VPMP1	34	33.5	6.40	0.94	2.80			
08-May-01	VPMP2	97	33.5	6.40	0.63	1.87			
08-May-01	VPMP3	98	33.5	6.40	0.42	1.24			
08-May-01	VPMP4	48	33.5	6.40	0.52	1.55			
08-May-01	VPMP5	19	33.5	6.40	2.71	8.08			
08-May-01	VPMP6	52	33.5	6.40	0.52	1.55			
04-Dec-01	VPMP1	25	45	36.22	6.25	13.89			
04-Dec-01	VPMP2	98	45	36.22	1.67	3.70			
04-Dec-01	VPMP3	95	45	36.22	4.58	10.19			

Date Collected	Sample	Cover (%)	Total Rainfall (mm)	MaxRain Intensity (mm/hr)	Runoff Volume (mm)	Runoff (%)	TSS (mg/L)	Turbidity (NTU)	TDS (mg/L)
04-Dec-01	VPMP4	50	45	36.22	11.25	25.00			
04-Dec-01	VPMP5	5	45	36.22	20.42	45.37			
04-Dec-01	VPMP6	40	45	36.22	17.71	39.35			
20-Dec-01	VPMP1	20	237.25	54.90	63.33	26.69			
20-Dec-01	VPMP2	93	237.25	54.90	19.79	8.34			
20-Dec-01	VPMP3	95	237.25	54.90	49.17	20.72			
09-Jan-02	VPMP1	22	45	12.17	20.21	44.91			
09-Jan-02	VPMP2	95	45	12.17	4.17	9.26			
09-Jan-02	VPMP3	95	45	12.17	5.00	11.11			
09-Jan-02	VPMP4	27	45	12.17	25.63	56.94			
09-Jan-02	VPMP5	5	45	12.17	28.33	62.96			
09-Jan-02	VPMP6	15	45	12.17	27.50	61.11			
22-Jan-02	VPMP1	25	89.5	3.96	6.35	7.10			
22-Jan-02	VPMP2	96	89.5	3.96	1.88	2.09			
22-Jan-02	VPMP3	96	89.5	3.96	1.88	2.09			
22-Jan-02	VPMP4	30	89.5	3.96	3.54	3.96			
22-Jan-02	VPMP5	6	89.5	3.96	14.05	15.70			
22-Jan-02	VPMP6	16	89.5	3.96	12.50	13.97			
11-Feb-02	VPMP1	26	46.5	13.58	15.63	33.60			
11-Feb-02	VPMP2	94	46.5	13.58	2.29	4.93			
11-Feb-02	VPMP3	96	46.5	13.58	5.94	12.77			
11-Feb-02	VPMP4	28	46.5	13.58	19.38	41.67			
11-Feb-02	VPMP5	2	46.5	13.58	24.58	52.87			
11-Feb-02	VPMP6	3	46.5	13.58	29.17	62.72			
15-Feb-02	VPMP1	26	95	7.36	27.50	28.95			
15-Feb-02	VPMP2	94	95	7.36	0.83	0.88			
15-Feb-02	VPMP3	96	95	7.36	2.92	3.07			
15-Feb-02	VPMP4	28	95	7.36	20.63	21.71			
15-Feb-02	VPMP5	2	95	7.36	41.67	43.86			
15-Feb-02	VPMP6	3	95	7.36	45.42	47.81			
18-Feb-02	VPMP2	94	25.5	1.13	6.67	26.14			
18-Feb-02	VPMP3	96	25.5	1.13	20.00	78.43			
18-Feb-02	VPMP4	28	25.5	1.13	19.17	75.16			
18-Feb-02	VPMP5	2	25.5	1.13	12.71	49.84			
26-Mar-02	VPMP2	95	35	11.04	1.04	2.98			
26-Mar-02	VPMP3	97	35	11.04	2.50	7.14			
26-Mar-02	VPMP4	29	35	11.04	8.75	25.00			
26-Mar-02	VPMP5	6	35	11.04	19.17	54.76			
26-Mar-02	VPMP6	10	35	11.04	17.08	48.81			
06-Jan-03	VPMP1	20	20.94	20.94	18.54	88.55			

Appendix 3. Methods for monitoring ephemeral streams

David Fanning, Peter Fitch and David Post, CSIRO Land and Water, Townsville

Introduction

As part of the project it was necessary to construct and install stream guaging stations at three sites in the Mingela region. The purpose of these stations is to provide high temporal resolution data on the stream hydrograph and turbidity levels. Each site is equipped with an automated sampler to correlate suspended sediment with the turbidity measurements. The sites are at Weany, Wheel and Station Creeks. Turbidity measurements were also taken in the Burdekin River to be used in conjunction with existing discharge monitoring by NR&M.

This document has been prepared to describe a mechanical bottle sampler developed and deployed at Weany and Wheel Creeks. The construction of the gauging stations is also detailed and the instrumentation deployed is outlined.

Weany and Wheel Creeks

Mechanical bottle sampler

An automatic, mechanical in stream water sampling device was designed in response to a request for a robust, low cost, reliable method of sampling suspended sediment in ephemeral streams in the Burdekin catchment, North Queensland.

The instream bottle sampler is series of discrete modules each containing a single bottle (250 mL), a closing mechanism and a clamping system (Figures 3.1 and 3.2). It is constructed of a series of simple to manufacture components and "off the shelf" parts, as shown in Figures 3.3 to 3.6.

In operation the sampler is set at bottle open in a dry stream, when the stream rises the bottle fills then a float triggers a lever to seal the bottle bringing magnets together to hold the seal in place.

Figure 3.1: Single bottle sampler

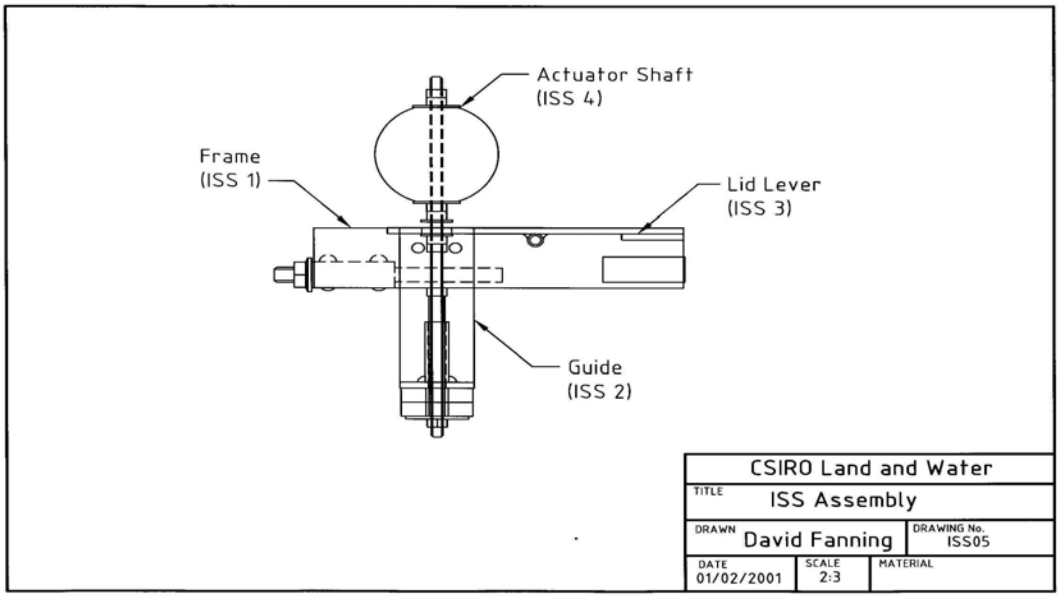


Figure 3.2: Assembly drawing of bottle sampler

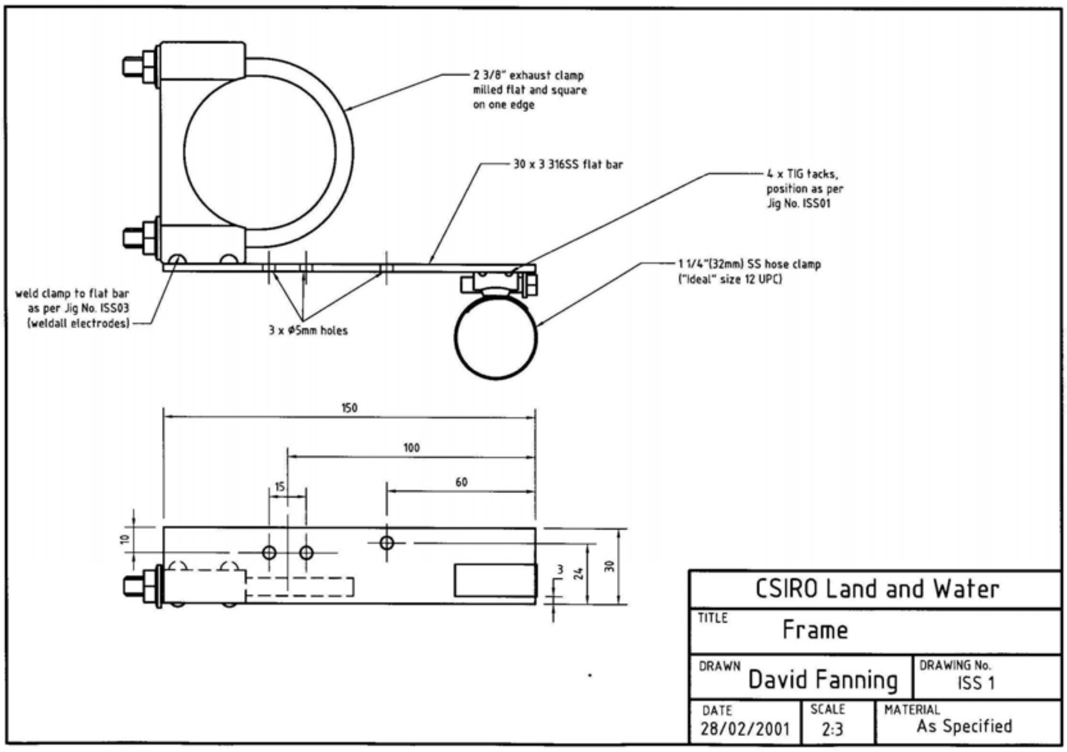


Figure 3.3: Drawing of frame component of bottle sampler (0.5 x scale)

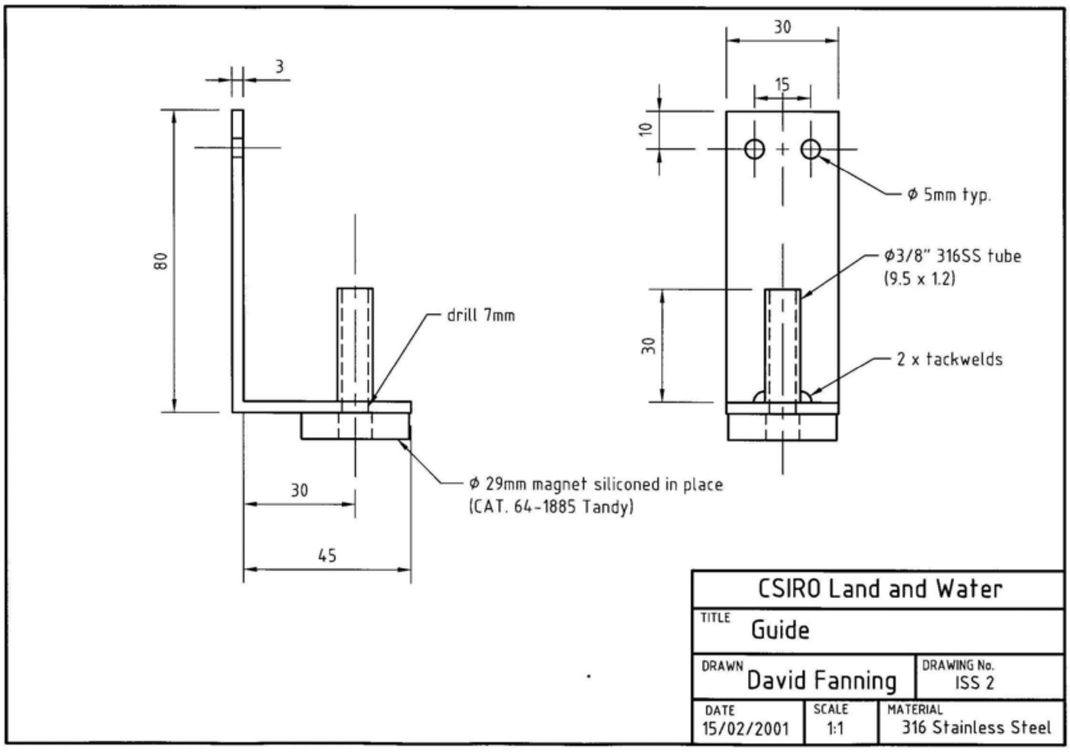


Figure 3.4: Drawing of guide component of bottle sampler (0.5 x scale)

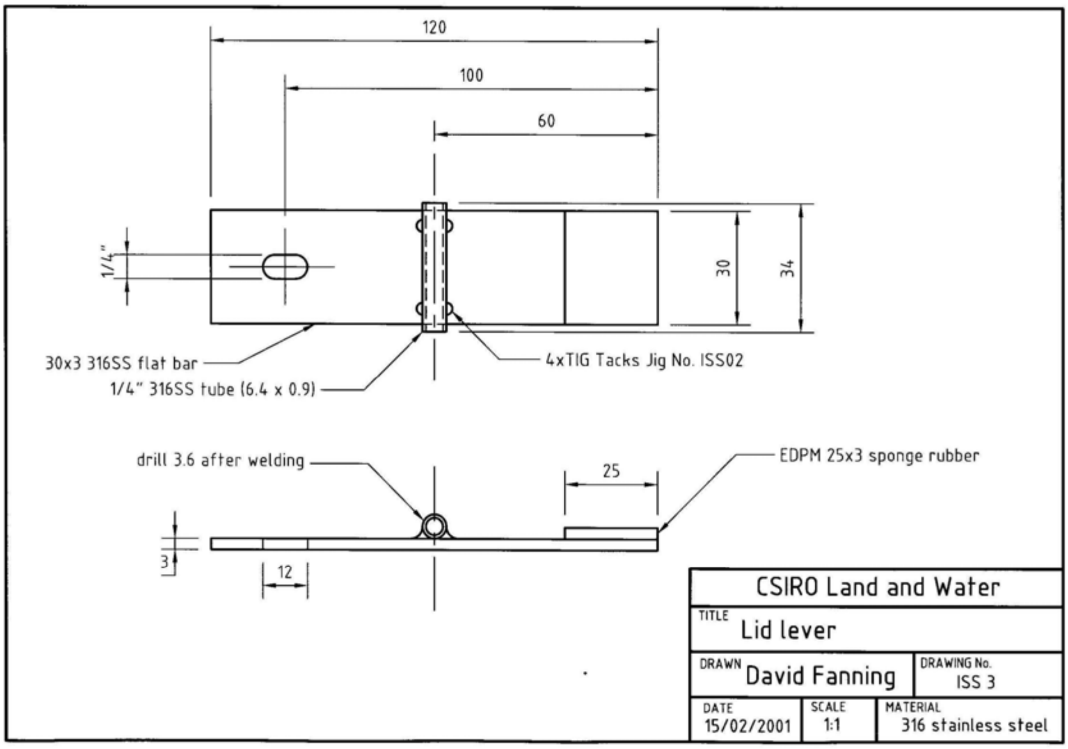


Figure 3.5: Drawing of lid lever component of bottle sampler (0.5 x scale)

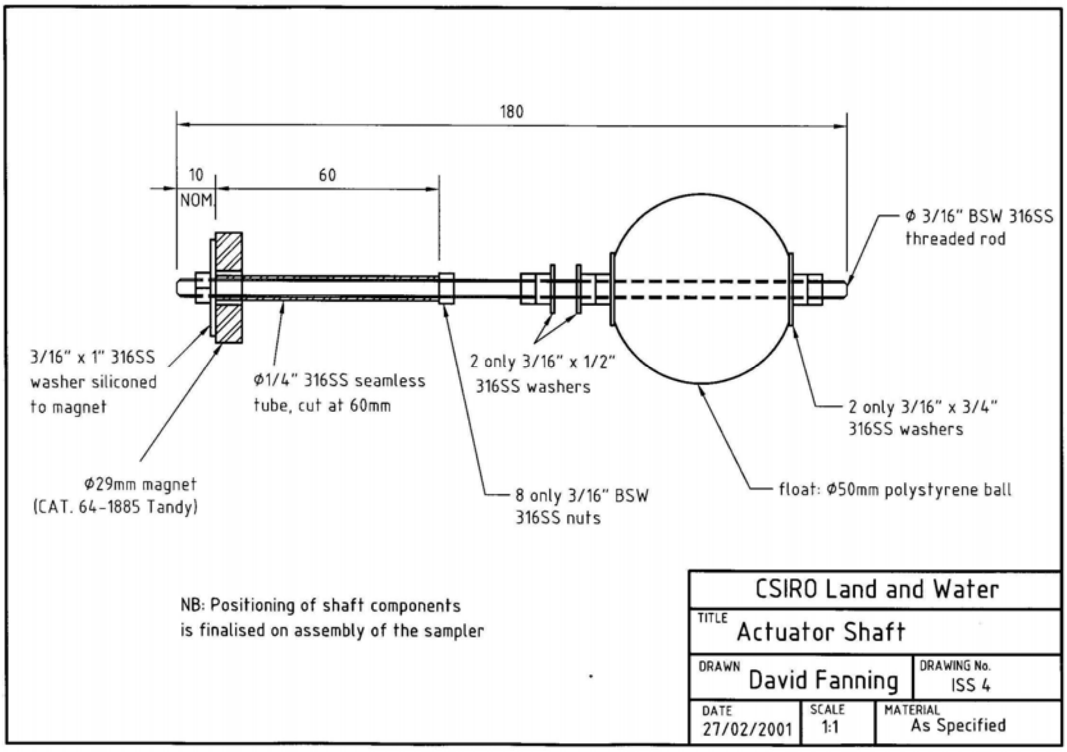


Figure 3.6: Drawing of actuator shaft component of bottle sampler (0.5 x scale)

Infrastructure and installation

The samplers are contained in a protective enclosure (Figure 3.7) consisting of a frame of two poles of 65 x 65 x 4 mm RHS and one central pole of 2" diameter medium wall water pipe. The shrouds are 460 mm diameter trench drain, which is supplied standard in half sections 1500 mm long with flanged sides, corrugated surface and slotted.

Figure 3.7: Arrangement of bottle samplers in enclosure at Weany Creek.

The two square outer poles and the round central pole were aligned and welded in place at top and bottom of 4 m sections with 65 x 6 mm flat bar on site (Figure 3.8). In order to key the frame into the concrete, eight sections of 25 x 25 mm RHS approximately 500 mm long were welded to the base of the outer poles from 0 to 1 m at right angles (Figure 3.9).

A small backhoe was maneuvered into the dry streams and a hole in each approximately 1.5 m deep x 1 m wide x 1.5 m long was excavated. The frame was jostled into position and concreted to a level about 0.5 m below surface using a sand (with limited gravel) mix from downstream. The top 0.5 m of the hole was refilled with the original sand and the site cleaned to represent the original streambed form.

Figure 3.8: Welding poles in place and cleaning out hole in preparation for concreting.

On the upstream side of the enclosure the shrouds were screwed into position then stainless steel through bolts were used to fix the downstream side, making the downstream side removable for sample recovery and servicing. To exclude precipitation an A-frame of 25 x 3 mm mild steel was welded to the top of the main frame and a low angle cone, manufactured in light gauge (0.55 mm) galvanized sheet steel, was screwed to this A-frame.

Figure 3.9: Frame with “keys” ready to be concreted into place.

Electronic Instruments

Water depth

A pressure transducer with a 392 single channel logger, supplied by Dataflow, Australia, was used initially with the bottle samplers to record water depth changes during stream-flow events.

The transducer was attached to the square section steel with conduit clips at streambed level and the logger was clipped inside the top of the enclosure for protection.

Turbidity

As a later addition a turbidity meter was added to both Weany and Wheel Creeks. The sensors used (supplied by Greenspan Technology, Australia) have a built in data logger to constantly record turbidity readings during stream-flow events.

The turbidity meters were housed in 316 stainless steel pipes oriented downstream for protection and attached to the outside of the enclosure at a height of 300 mm above the streambed. The cables were fed in and stored inside the top of the enclosure.

Velocity

The next addition was a Starflow ultrasonic Doppler velocity meter with a micrologger, supplied by Unidata, Australia.

The velocity meter was installed by knocking in a 1.5 m length of 2" galvanized, medium wall pipe with a sledgehammer, at a distance of 1.5m in front of the enclosure to minimise any flow disruption. The pipe had a section of 50 x 6 mm flat bar welded to the front top to enable bolting a support plate to mount the velocity meter at a height of 300m above the streambed (Figure 3.11). The cable was buried with the cable ends stored in the top of the enclosure for access for downloading.

Automatic Water Sampler

After the first year of sampling, an automated water sampler (ISCO 3700 series sampler, supplied by John Morris Scientific) was added to the system along with a Campbell CR10X logger (Campbell Scientific, Australia). The sampler has a capacity of 24 1L sample bottles.

Logging Regime

All instruments were connected to the Campbell logger, simplifying operation of the station and allowing greater control of the water sampler activation according to depth changes recorded. The logger is setup to scan for level changes every 60 seconds and log parameters every hour. When the water level increases over 30cm, the system goes into "event mode" and logs parameters every minute. The sampler is configured to take a sample each 100 mm rise and each 200 mm fall in the hydrograph.

The new system has also facilitated the direct transfer of the data back to Davies Laboratory via mobile phone. Since the ISCO water sampler and the Campbell logger must be kept dry they have been placed on platforms.

Platforms

Platforms were constructed on site to raise the new equipment above flood level and support a solar power supply and telemetry. At Weany Creek the platform is about 1.2 m high (Figure 3.10) and at Wheel Creek it is 2 m high (Figure 3.11). The wiring is suspended on steel cable and protected in corrugated conduit.

Figure 3.10: Platform at Weany Creek. Box containing auto sampler is on left; datalogger, control unit and solar panel on right hand corner of platform. Sampling device is seen in the background.

Figure 3.11: Gauging station at Wheel Creek. Sampling device with attached turbidity sensor and stand alone flow velocity meter in foreground; platform with autosampler in background.

Station Creek

The Station Creek monitoring site (Figure 3.12) required a different design than the smaller creeks, particularly since the sand depth is greater than 4 m and the water table is shallow all year.

Instruments

Three instruments are being used in the stream to measure water depth, velocity and turbidity. An ISCO water sampler is used to collect samples during stream-flow events. A tipping bucket rainguage is attached to the platform to measure rainfall intensity and totals.

Water depth

The water level instrument at Station Creek differs to those at Wheel and Weany Creeks being a PS700 supplied by Greenspan Australia. This instrument has a closed venting system allowing for improved reliability compared to the vented depth sensors. This sensor also has better immunity to extreme temperature variations than the Dataflow sensor. The full-scale range of the PS700 is 5 meters.

Turbidity

The turbidity instrument used at Station creep is an Analite NEP180 180 degree backscatter fibre optic nephelometer (McVan Instruments). This instrument has a full-scale range of 10,000 NTU.

Other instruments

The rest of the system is similar to that used at Weany and Wheel Creeks.

Figure 3.12: Station Creek instruments in the stream, with 3 m high platform in the background.

Infrastructure and installation

At Station Creek a series of four pipes were jack hammered as deep as possible to support the instruments. This was done by sharpening one end of 2 m sections of 2 inch medium wall, galvanized pipe and pushing them in with the jack hammer, then welding on another 2 m section and hammering that in. The result was four pipes in a square arrangement at a depth of 3.5 – 4 m (Figure 3.13). The pipes to the sides were then cut off to be below the streambed for burying, the front pipe was cut at 300 mm above the surface and the back pipe was cut at 600 mm above the surface.

Straps ("pole ties") were manufactured from 75 x 6 mm flat mild steel with 2" tight fit clamps to suit the distances between the poles to tie the structure together, as shown in Figure 3.13 and Figure 3.14. An "angle strap" tie plate (Figure 3.15) was manufactured to help support the back pipe and deflect debris.

Figure 3.13: Instrument supports in Station Creek

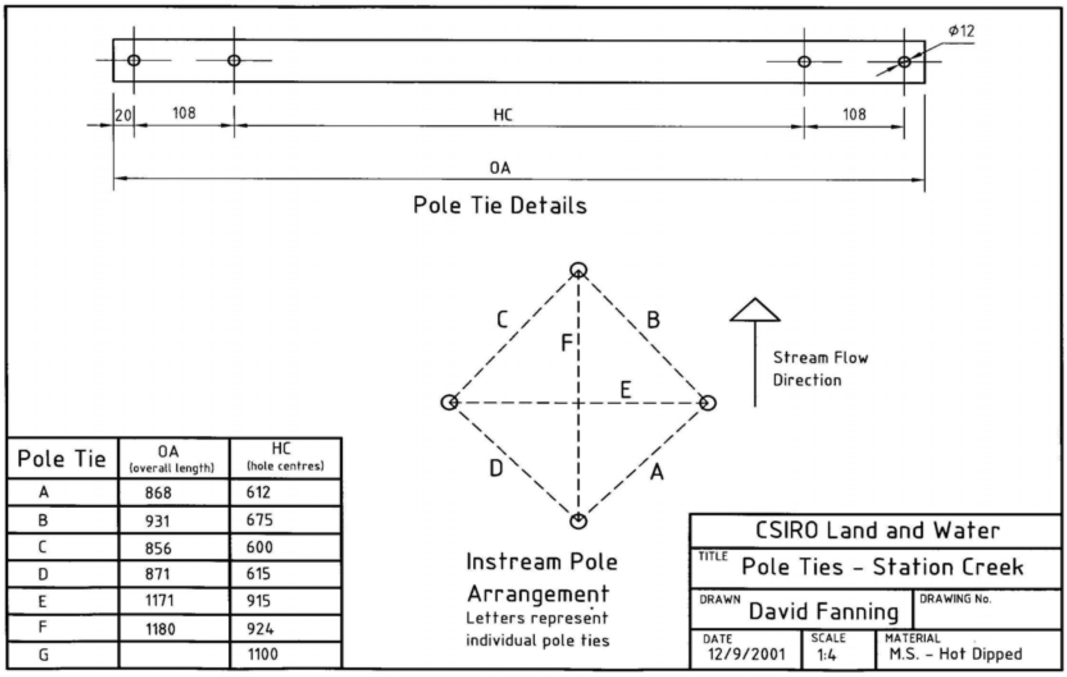


Figure 3.14: Drawing of pole ties for Station Creek

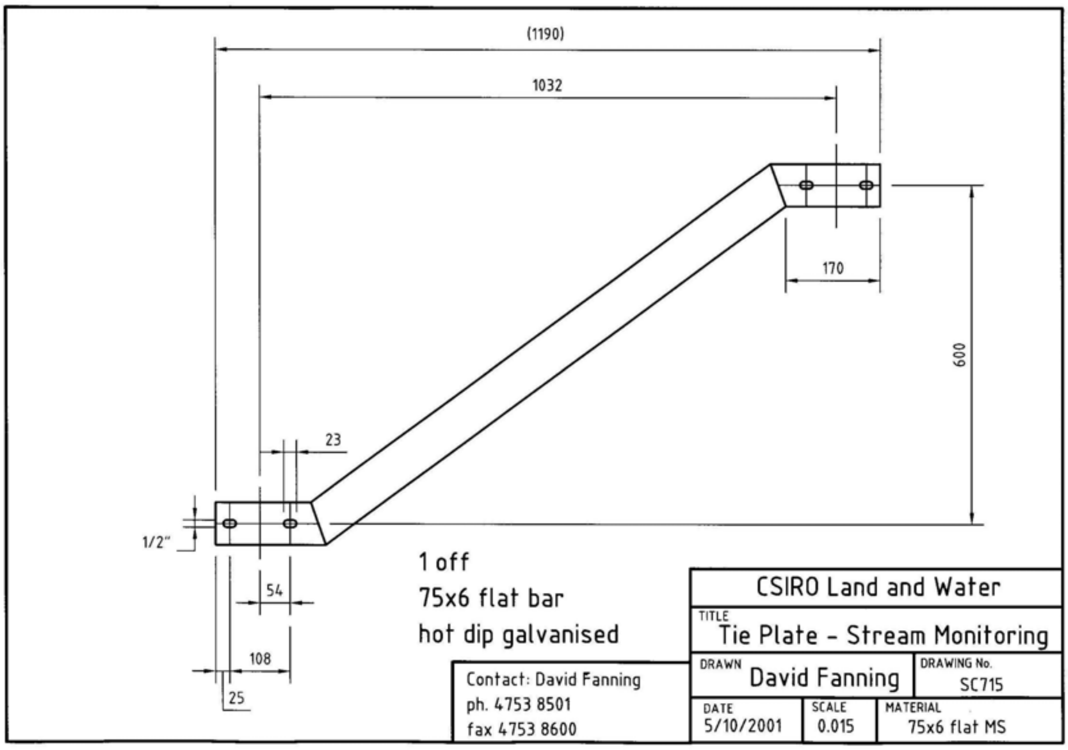


Figure 3.15: Drawing of tie plate for Station Creek

Support frames to attach and protect the instruments were designed, manufactured and galvanised, as shown in Figure 3.12, and the drawings in Figures 3.16 and 3.17. The frames were held in place with 2" tight fit clamps and tack welded to prevent turning.

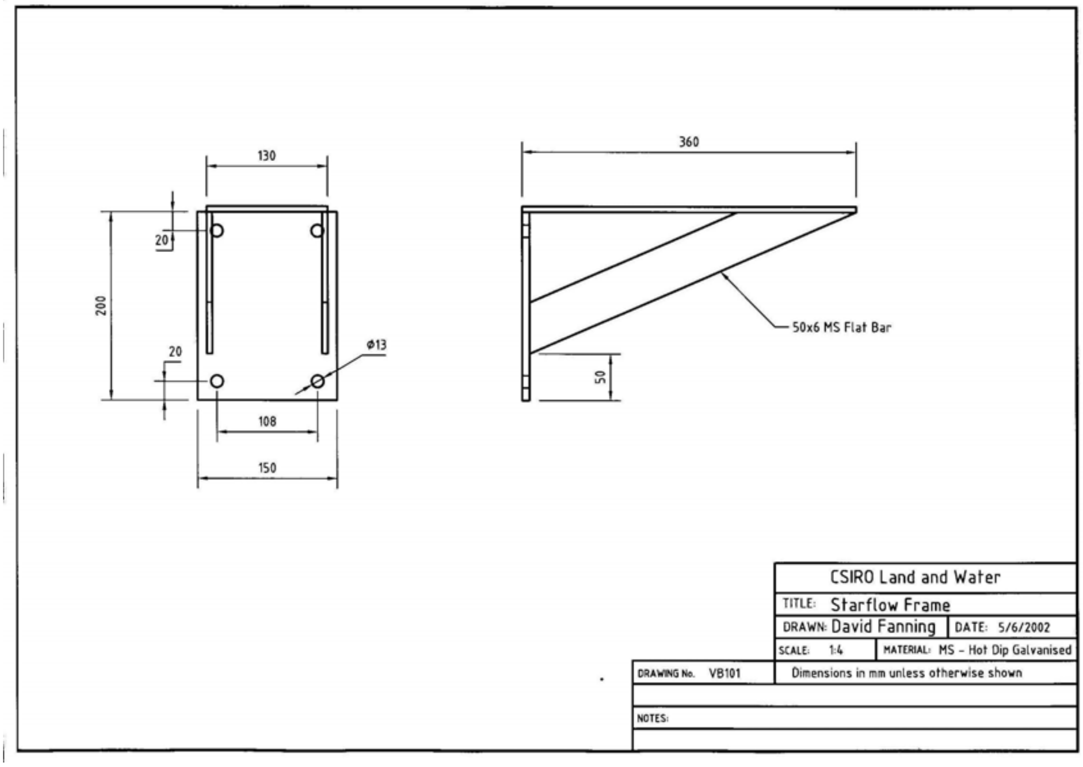


Figure 3.16: Drawing of support frame for the velocity meter (0.5 x scale)

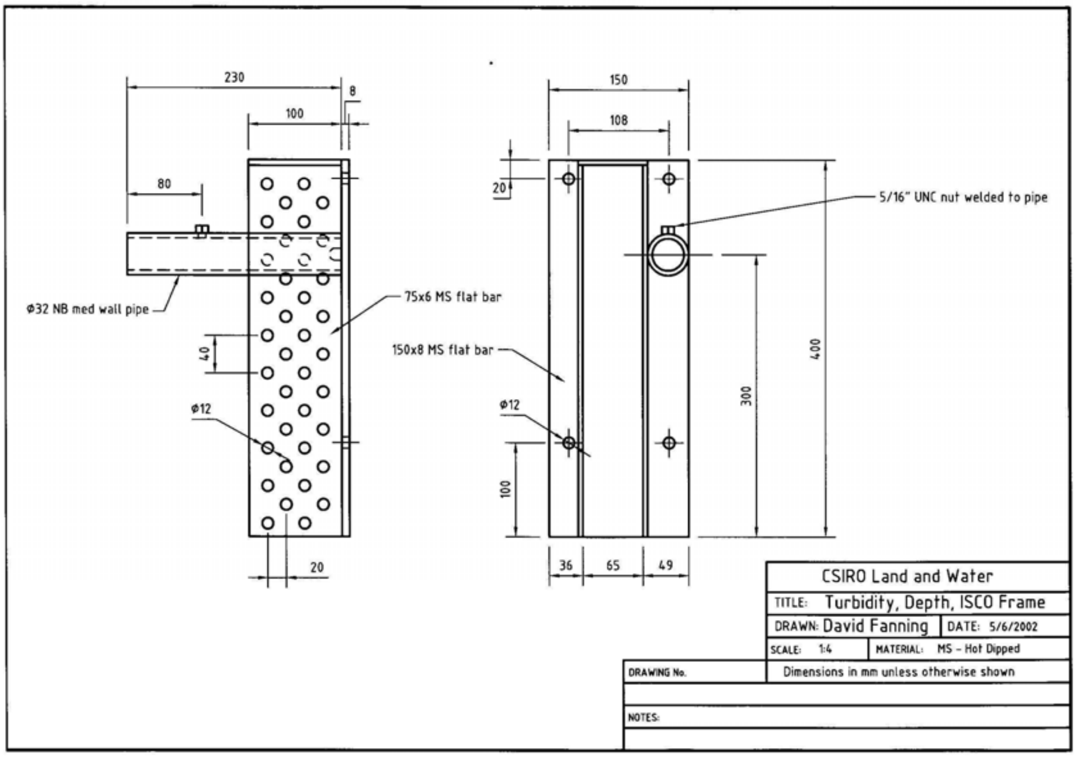


Figure 3.17: Drawing of support frame for velocity and depth meters, and ISCO uptake (0.5 x scale)

Burdekin River

In the Burdekin River two turbidity meters were deployed, to be used in conjunction with the existing NR&M gauging station. With permission from Queensland Rail these were bolted to the old railway bridge at Macrossan. The instruments are protected inside stainless steel housings, as shown in Figures 3.18 and 3.19, and fixed at heights of 1 m and 3 m above the streambed. The housings were fixed to the bridge support using chemical anchors, since they create no expansion forces and once cured the resin provides a stress free bond with the surrounding materials.

The instruments used at the Macrossan railway bridge were two Greenspan logging TS300 Turbidity meters (Greenspan Australia). These combination logger and sensor units have an integral battery pack that can supply power for extended periods of time (greater than 6 months). This allows for fully self-contained immersed operation. The full-scale range of these units is 2500NTU. The logging regime was set to log every 20 minutes and to event mode log every 10 minutes if the turbidity measurement had changed by more than 10NTU.

Figure 3.18: Turbidity meter inside the stainless steel housing, fixed to the old railway bridge at Macrossan on the Burdekin River.

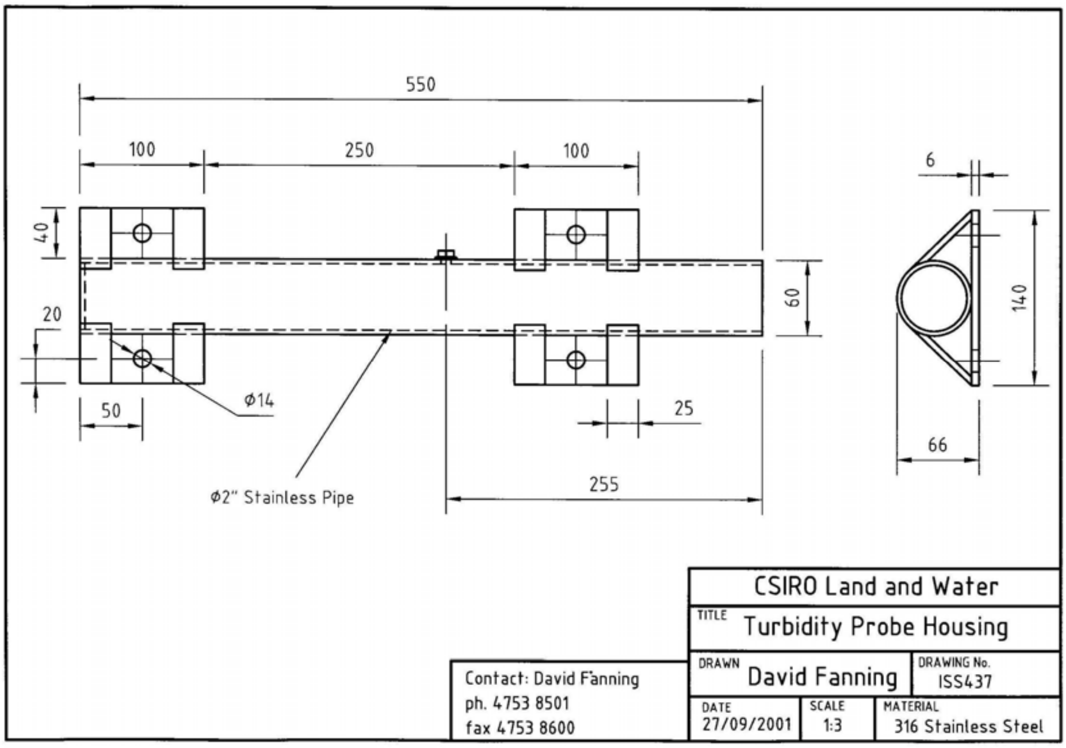
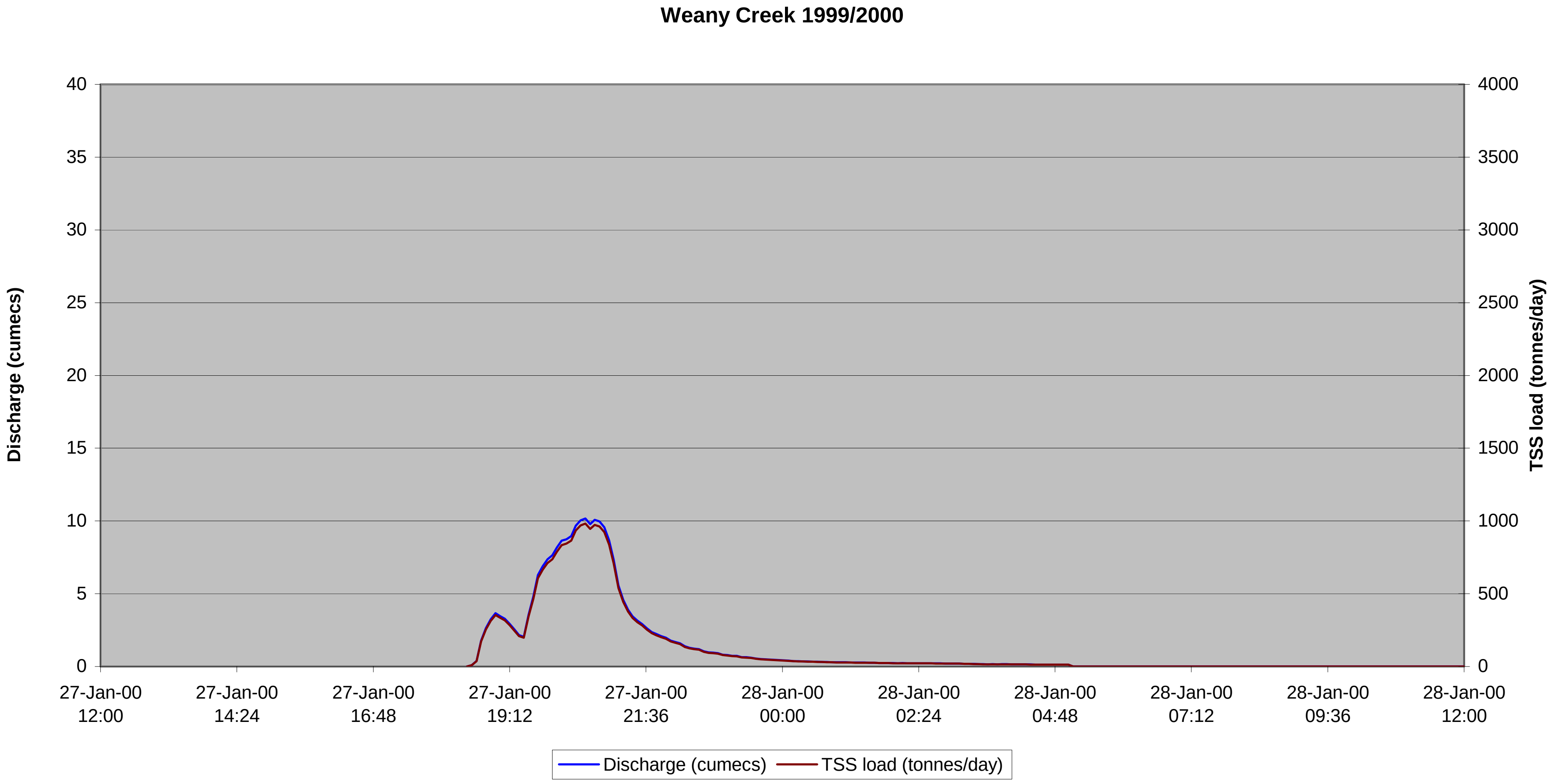


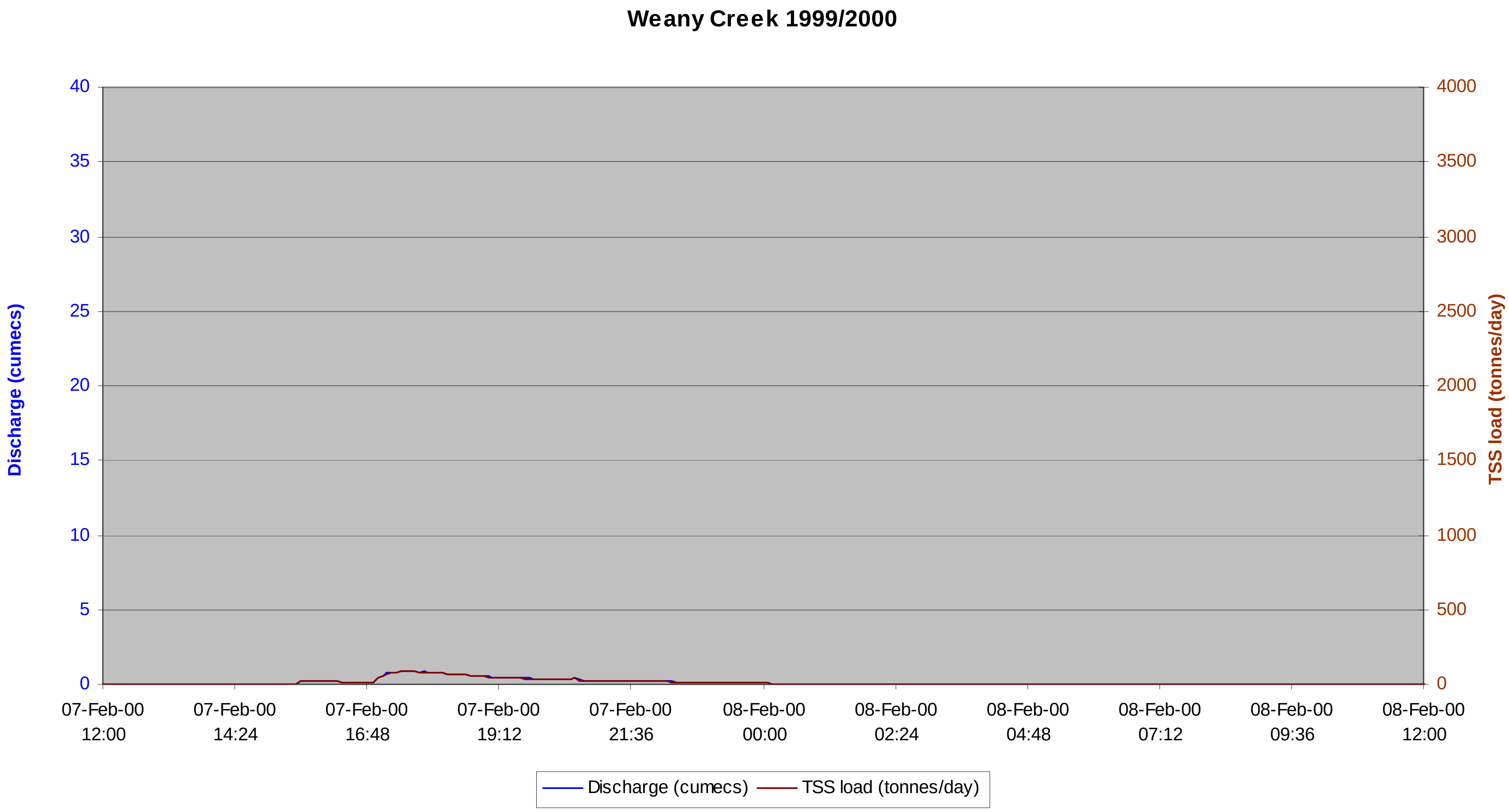
Figure 3.19: Drawing of the housing for the Greenspan turbidity meters.

Appendix 4. Compilation of stream gauging data for the period 1999-2002 for the MLA gauging sites, Upper Burdekin

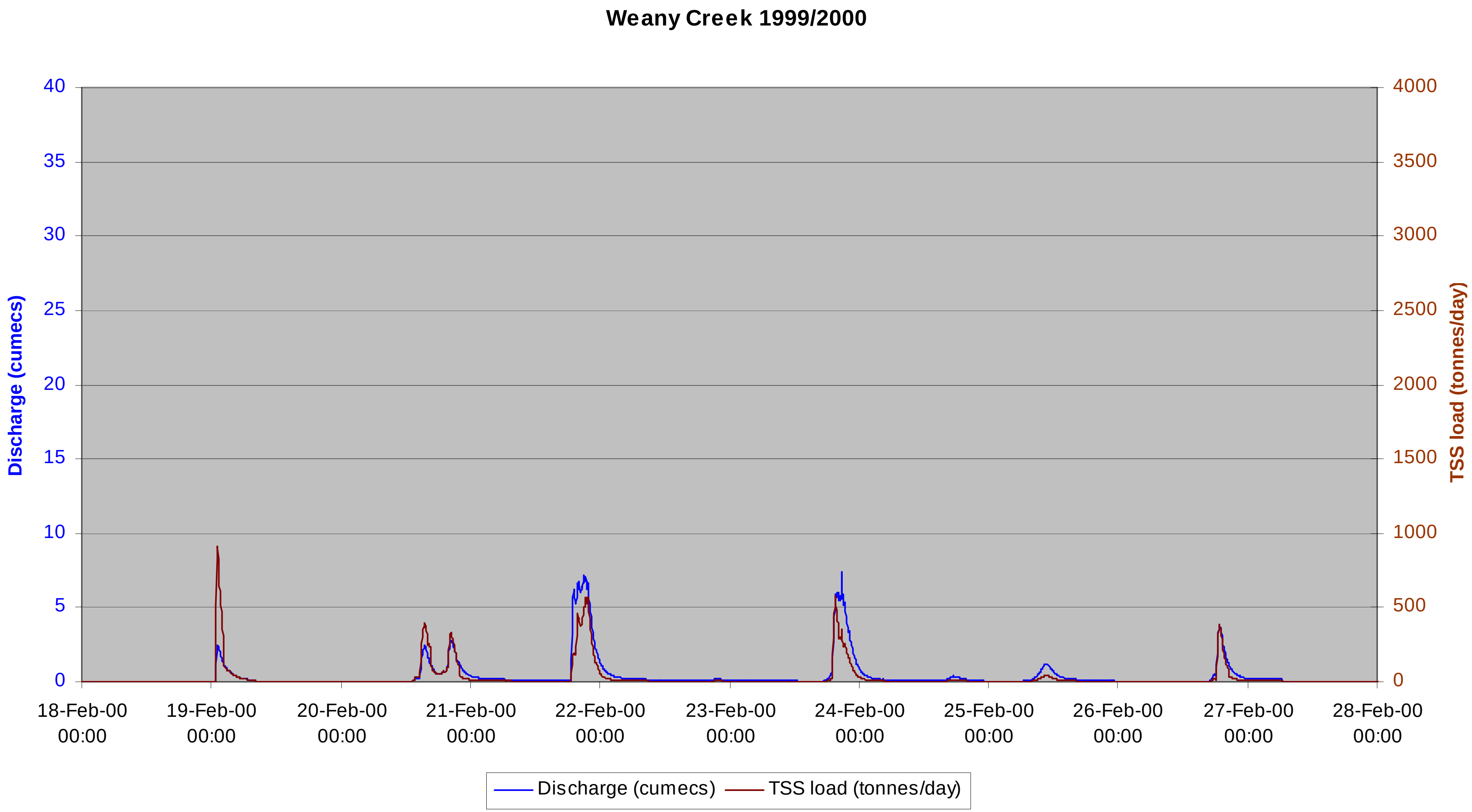
David Post, CSIRO Land & Water, Townsville

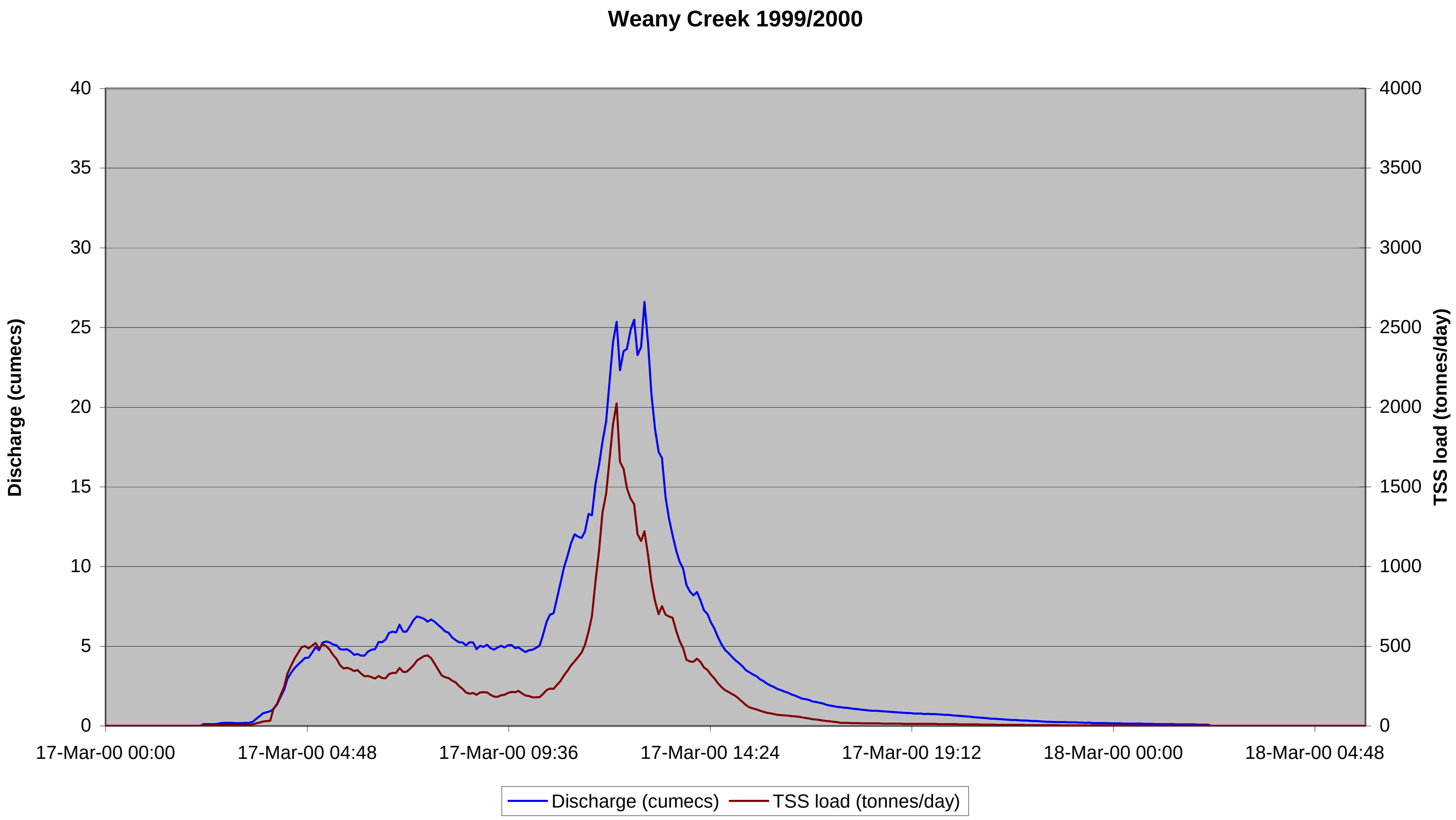
The purpose of this appendix is to provide a compilation of all recorded flow events for the Weany, Wheel and Station Creek gauging stations. Details on the instrumentation are provided in Appendix 3, and the methodology used to derive flow and sediment discharge is discussed in Chapter 5, Volume I. Data in this appendix is presented in the form of hydrographs and sedigraphs.

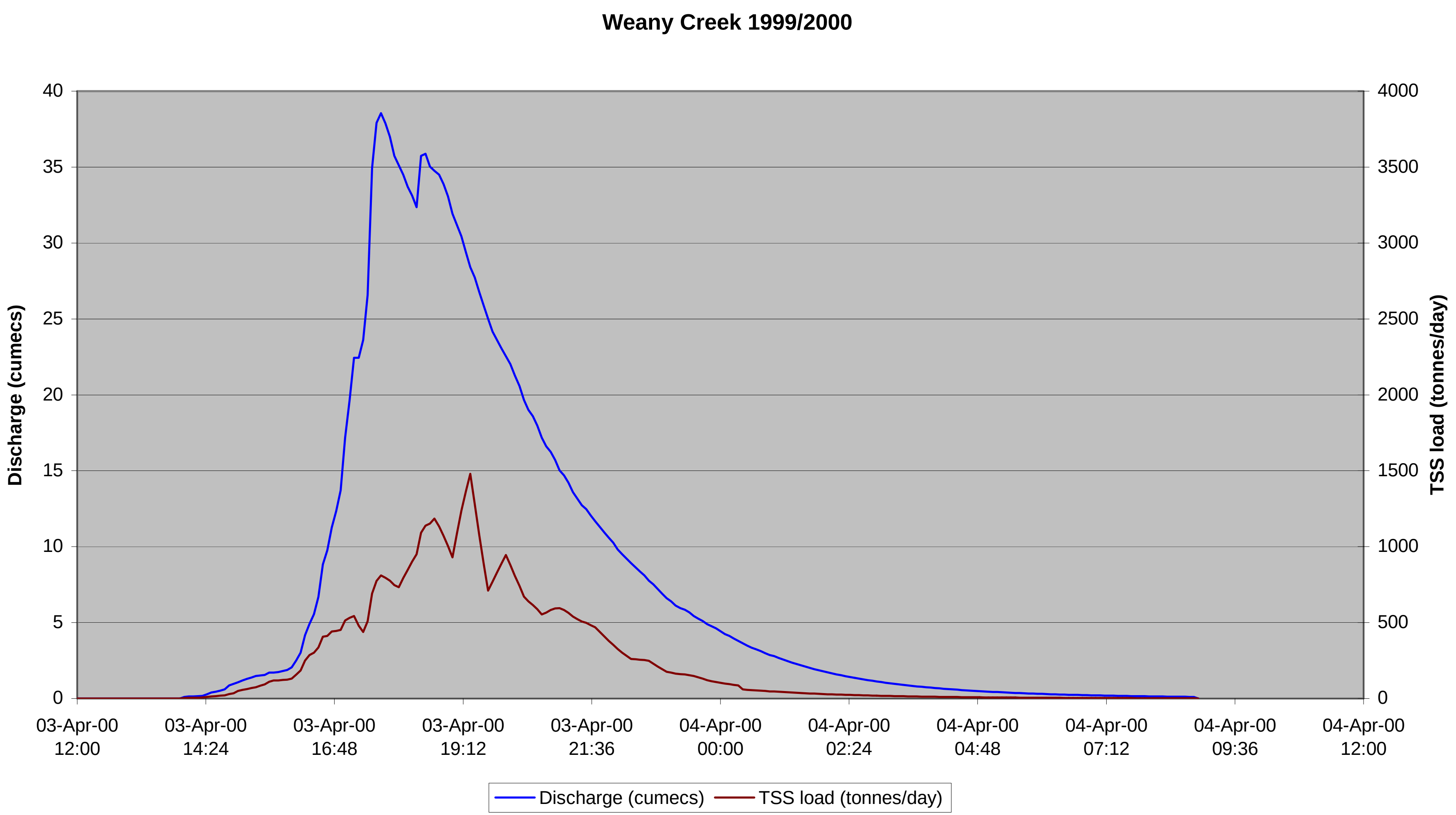

Weany Creek 1999/2000
Discharge (cumecs)
TSS load (tonnes/day)
0
5
10
15
20
25
30
35
40
0
500
1000
1500
2000
2500
3000
3500
4000
27-Jan-00 12:00
27-Jan-00 14:24
27-Jan-00 16:48
27-Jan-00 19:12
27-Jan-00 21:36
28-Jan-00 00:00
28-Jan-00 02:24
28-Jan-00 04:48
28-Jan-00 07:12
28-Jan-00 09:36
28-Jan-00 12:00
Discharge (cumecs)
TSS load (tonnes/day)

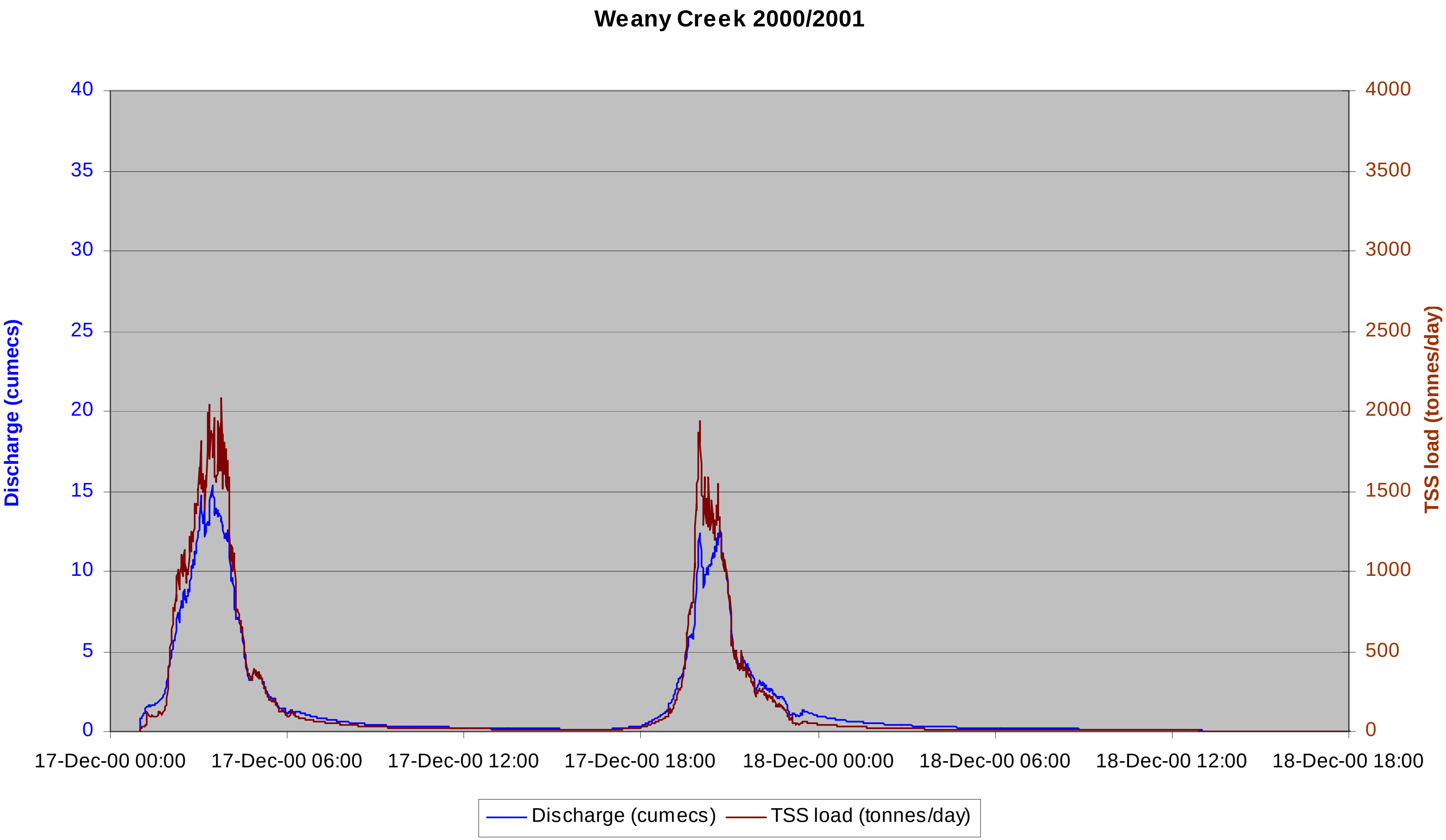


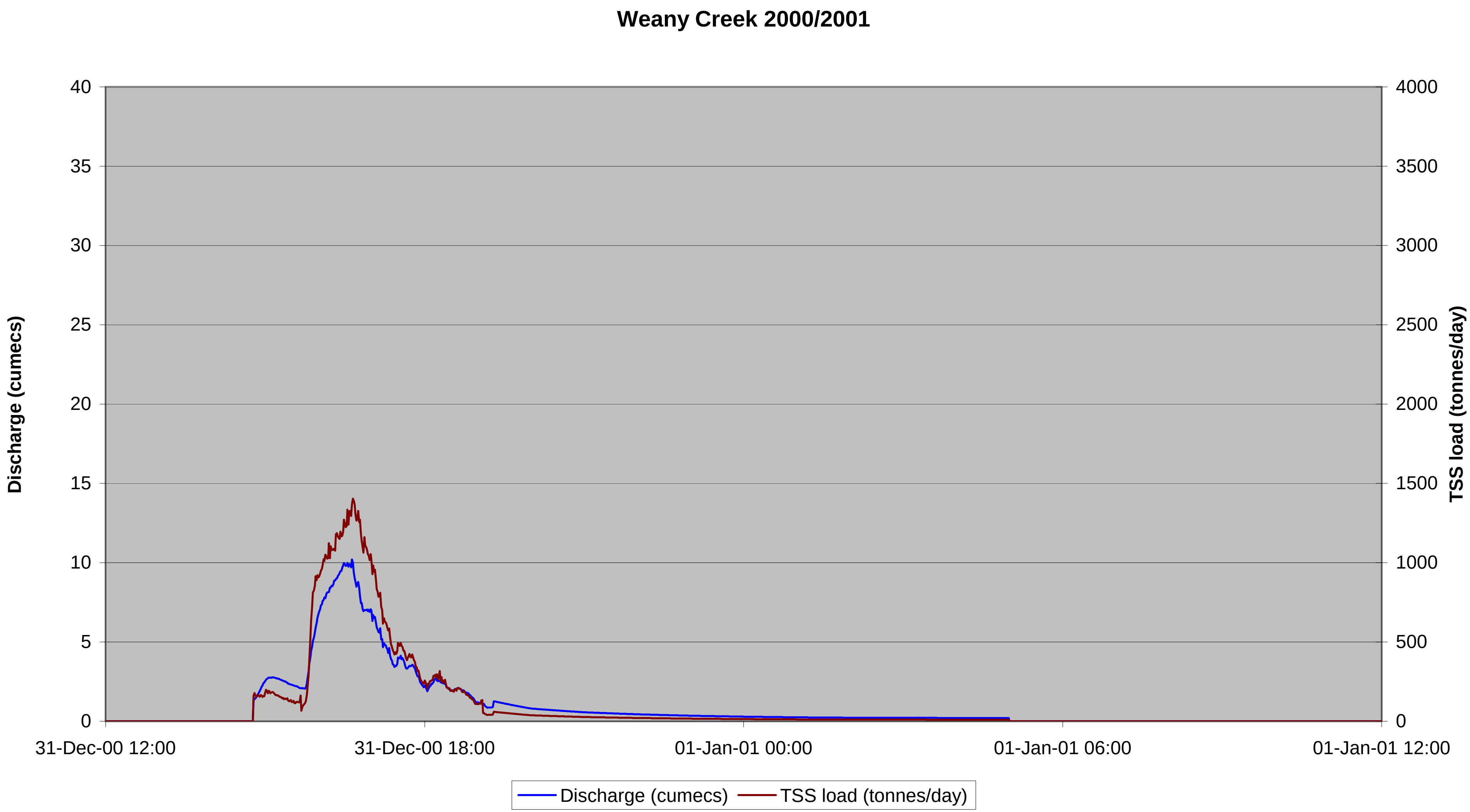
Weany Creek 1999/2000
Discharge (cumecs)
TSS load (tonnes/day)
40
35
30
25
20
15
10
5
0
4000
3500
3000
2500
2000
1500
1000
500
0
07-Feb-00 12:00
07-Feb-00 14:24
07-Feb-00 16:48
07-Feb-00 19:12
07-Feb-00 21:36
08-Feb-00 00:00
08-Feb-00 02:24
08-Feb-00 04:48
08-Feb-00 07:12
08-Feb-00 09:36
08-Feb-00 12:00
Discharge (cumecs)
TSS load (tonnes/day)


Weany Creek 1999/2000
Discharge (cumecs)
TSS load (tonnes/day)
0
5
10
15
20
25
30
35
40
0
500
1000
1500
2000
2500
3000
3500
4000
18-Feb-00 00:00
19-Feb-00 00:00
20-Feb-00 00:00
21-Feb-00 00:00
22-Feb-00 00:00
23-Feb-00 00:00
24-Feb-00 00:00
25-Feb-00 00:00
26-Feb-00 00:00
27-Feb-00 00:00
28-Feb-00 00:00
Discharge (cumecs)
TSS load (tonnes/day)

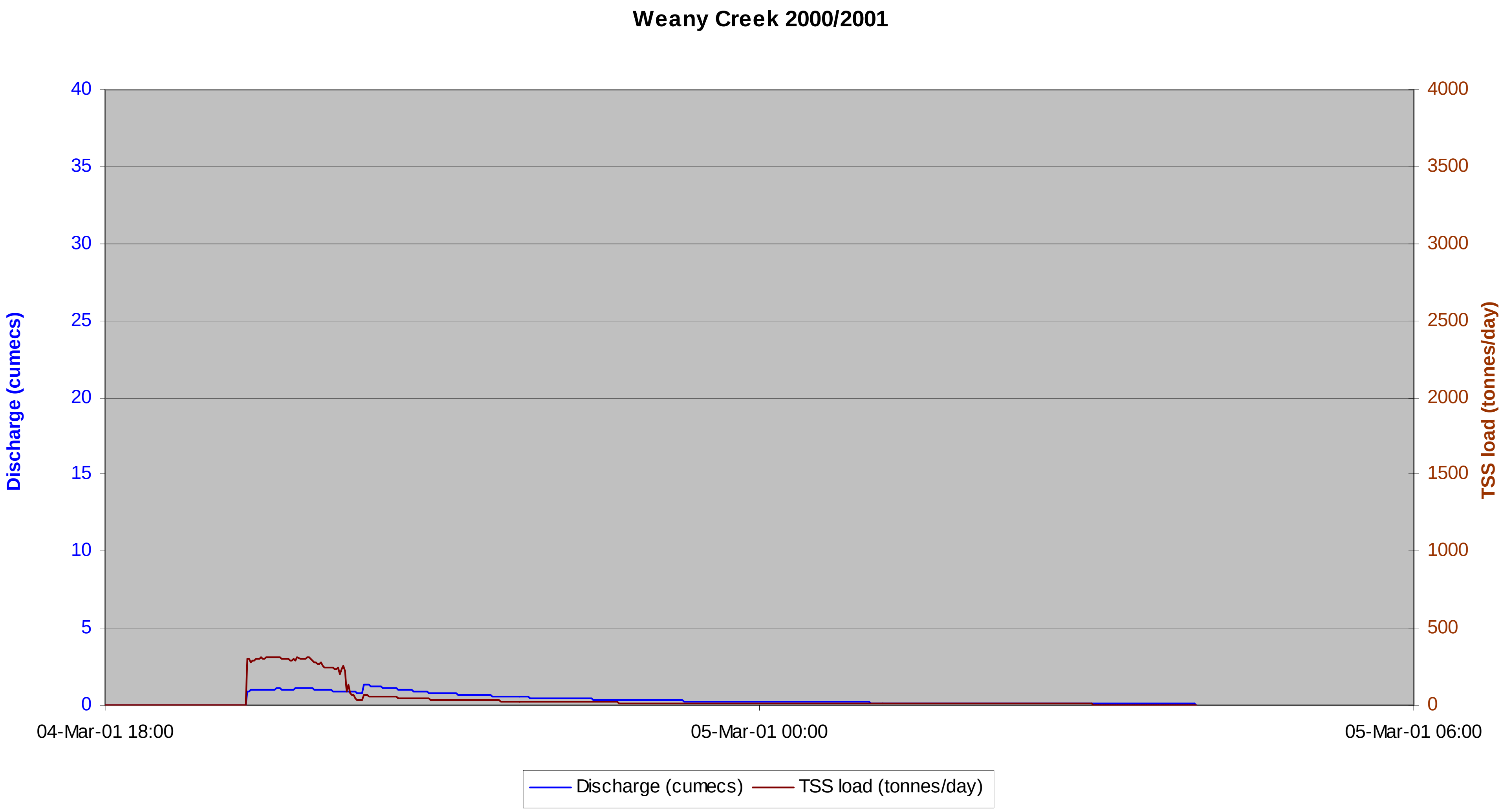

Weany Creek 1999/2000
Discharge (cumecs)
TSS load (tonnes/day)
0
5
10
15
20
25
30
35
40
0
500
1000
1500
2000
2500
3000
3500
4000
17-Mar-00 00:00
17-Mar-00 04:48
17-Mar-00 09:36
17-Mar-00 14:24
17-Mar-00 19:12
18-Mar-00 00:00
18-Mar-00 04:48
Discharge (cumecs)
TSS load (tonnes/day)

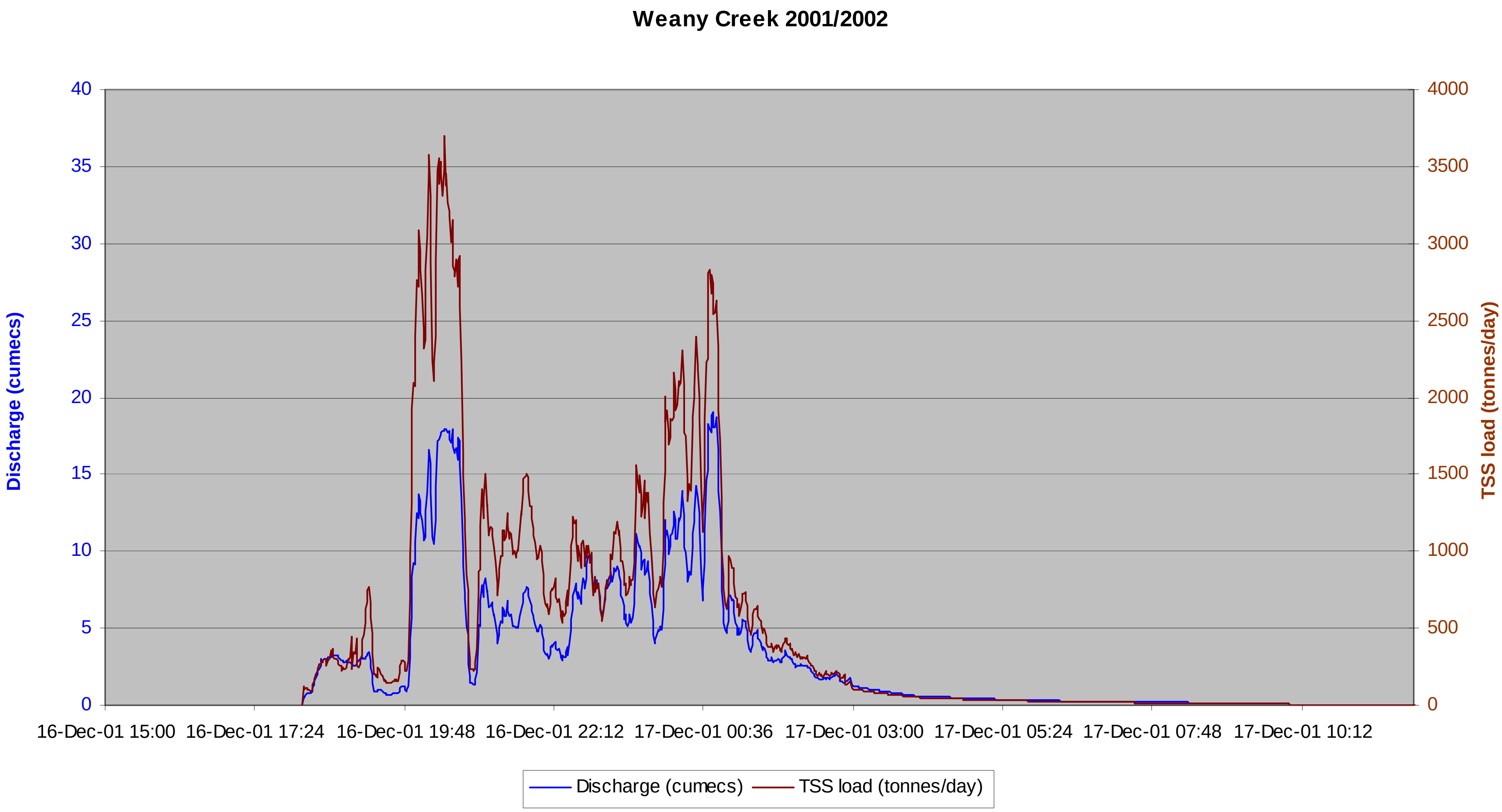

Weany Creek 1999/2000
Discharge (cumecs)
TSS load (tonnes/day)
40
35
30
25
20
15
10
5
0
4000
3500
3000
2500
2000
1500
1000
500
0
03-Apr-00 12:00
03-Apr-00 14:24
03-Apr-00 16:48
03-Apr-00 19:12
03-Apr-00 21:36
04-Apr-00 00:00
04-Apr-00 02:24
04-Apr-00 04:48
04-Apr-00 07:12
04-Apr-00 09:36
04-Apr-00 12:00
Discharge (cumecs)
TSS load (tonnes/day)

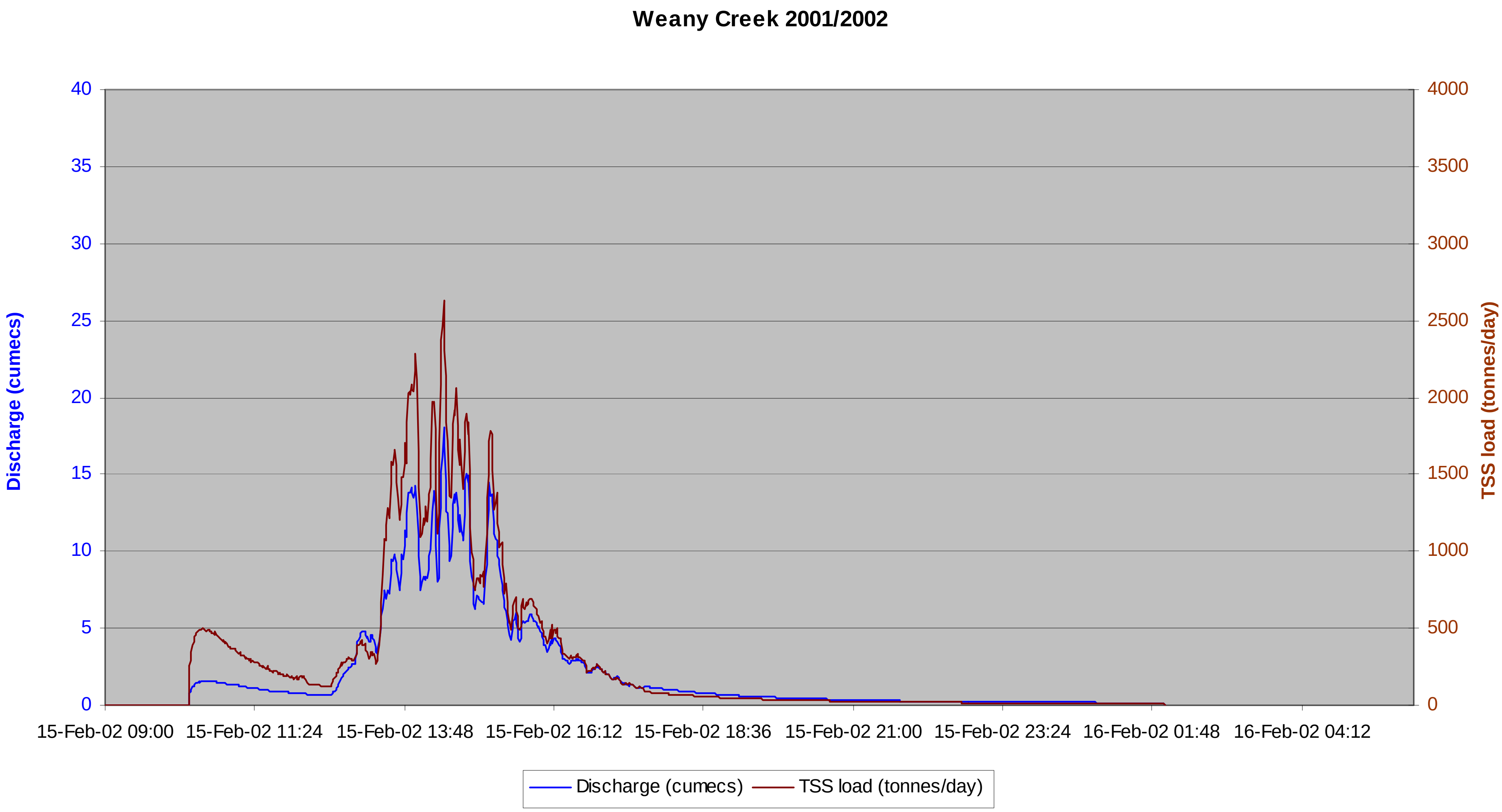

Weany Creek 2000/2001
Discharge (cumecs)
TSS load (tonnes/day)
0
5
10
15
20
25
30
35
40
0
500
1000
1500
2000
2500
3000
3500
4000
17-Dec-00 00:00
17-Dec-00 06:00
17-Dec-00 12:00
17-Dec-00 18:00
18-Dec-00 00:00
18-Dec-00 06:00
18-Dec-00 12:00
18-Dec-00 18:00
Discharge (cumecs)
TSS load (tonnes/day)

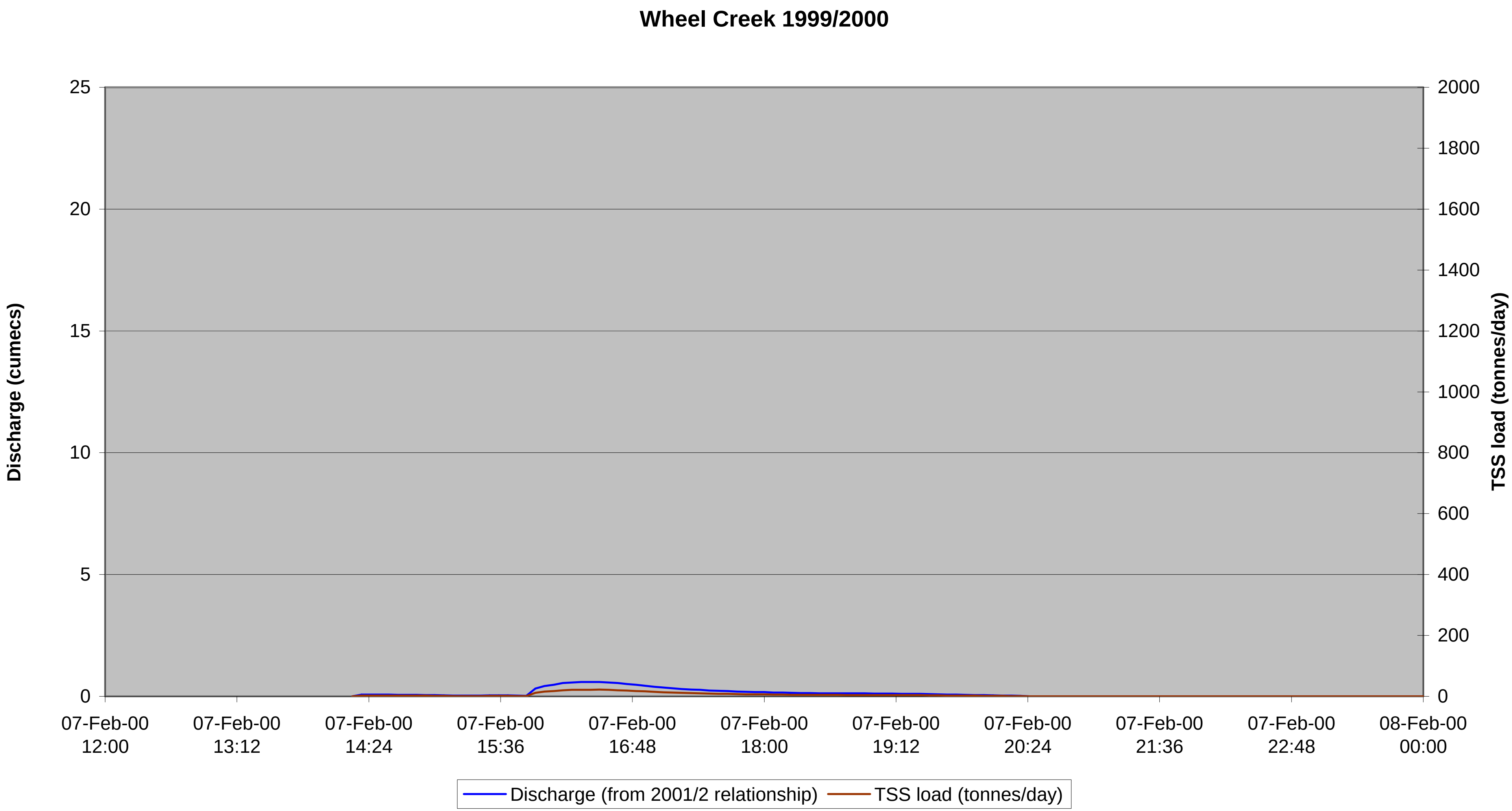


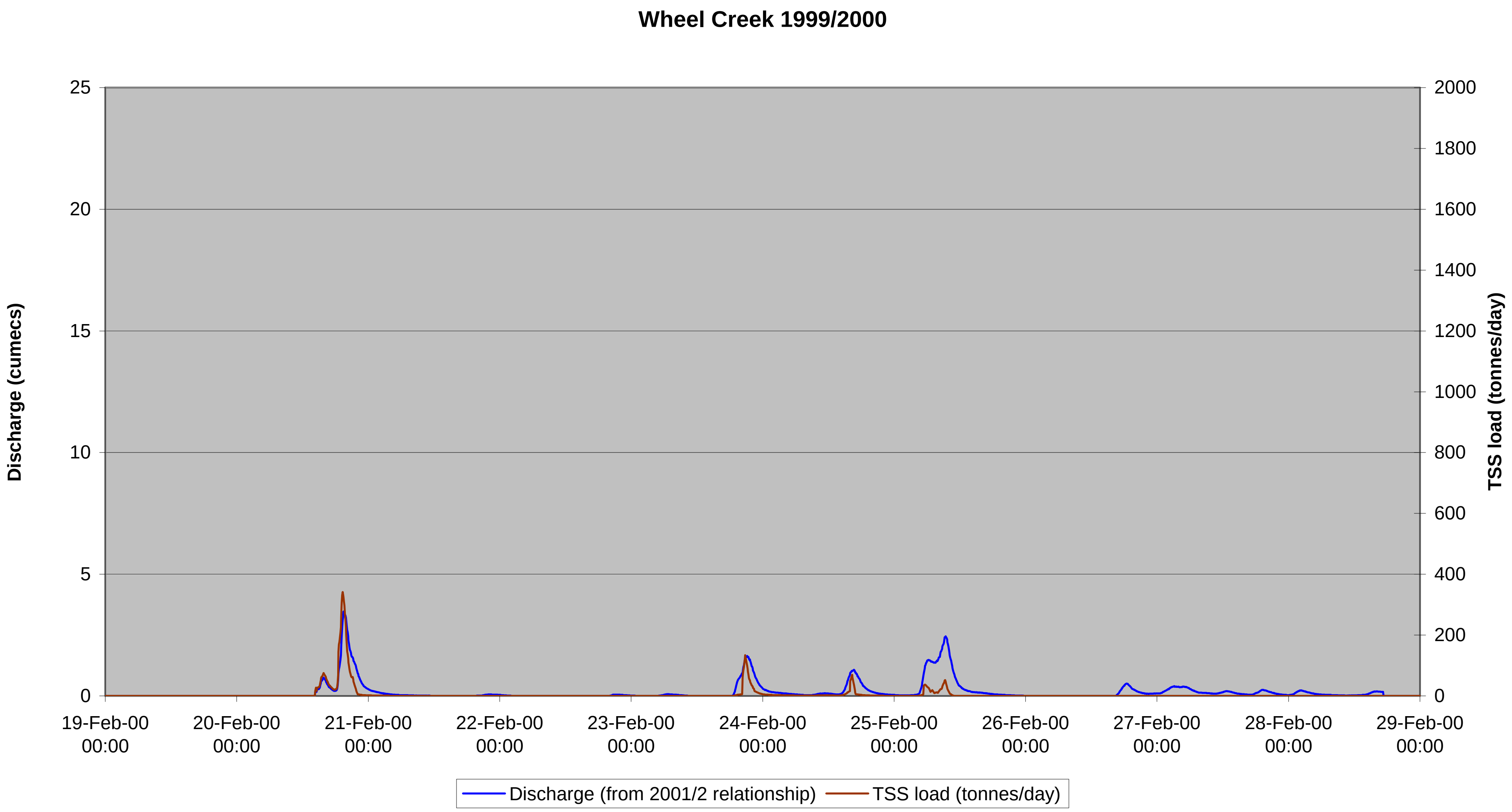
Weany Creek 2000/2001
Discharge (cumecs)
TSS load (tonnes/day)
0
5
10
15
20
25
30
35
40
0
500
1000
1500
2000
2500
3000
3500
4000
31-Dec-00 12:00
31-Dec-00 18:00
01-Jan-01 00:00
01-Jan-01 06:00
01-Jan-01 12:00
Discharge (cumecs)
TSS load (tonnes/day)

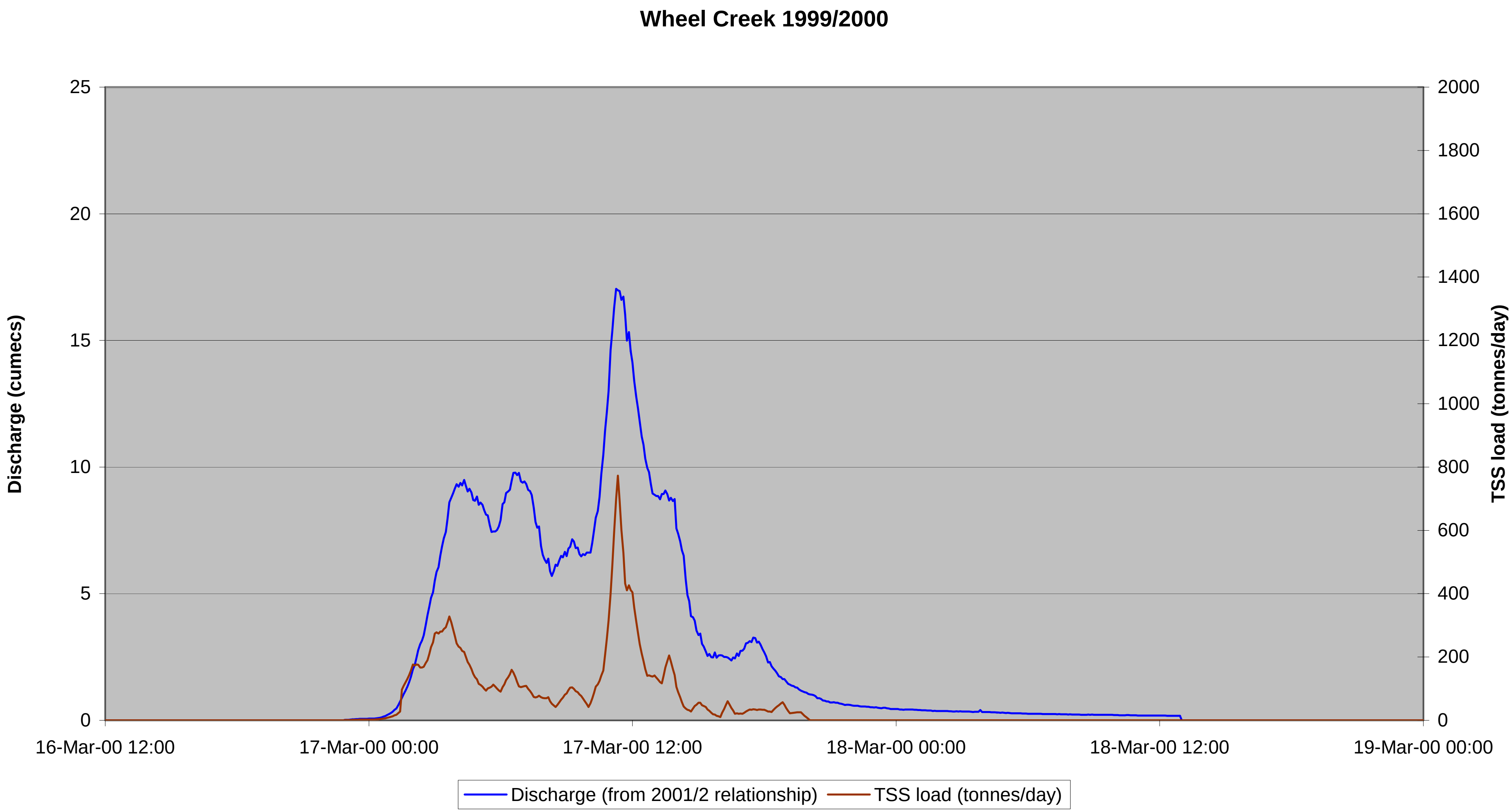

Weany Creek 2000/2001
Discharge (cumecs)
TSS load (tonnes/day)
0
5
10
15
20
25
30
35
40
0
500
1000
1500
2000
2500
3000
3500
4000
04-Mar-01 18:00
05-Mar-01 00:00
05-Mar-01 06:00
Discharge (cumecs)
TSS load (tonnes/day)

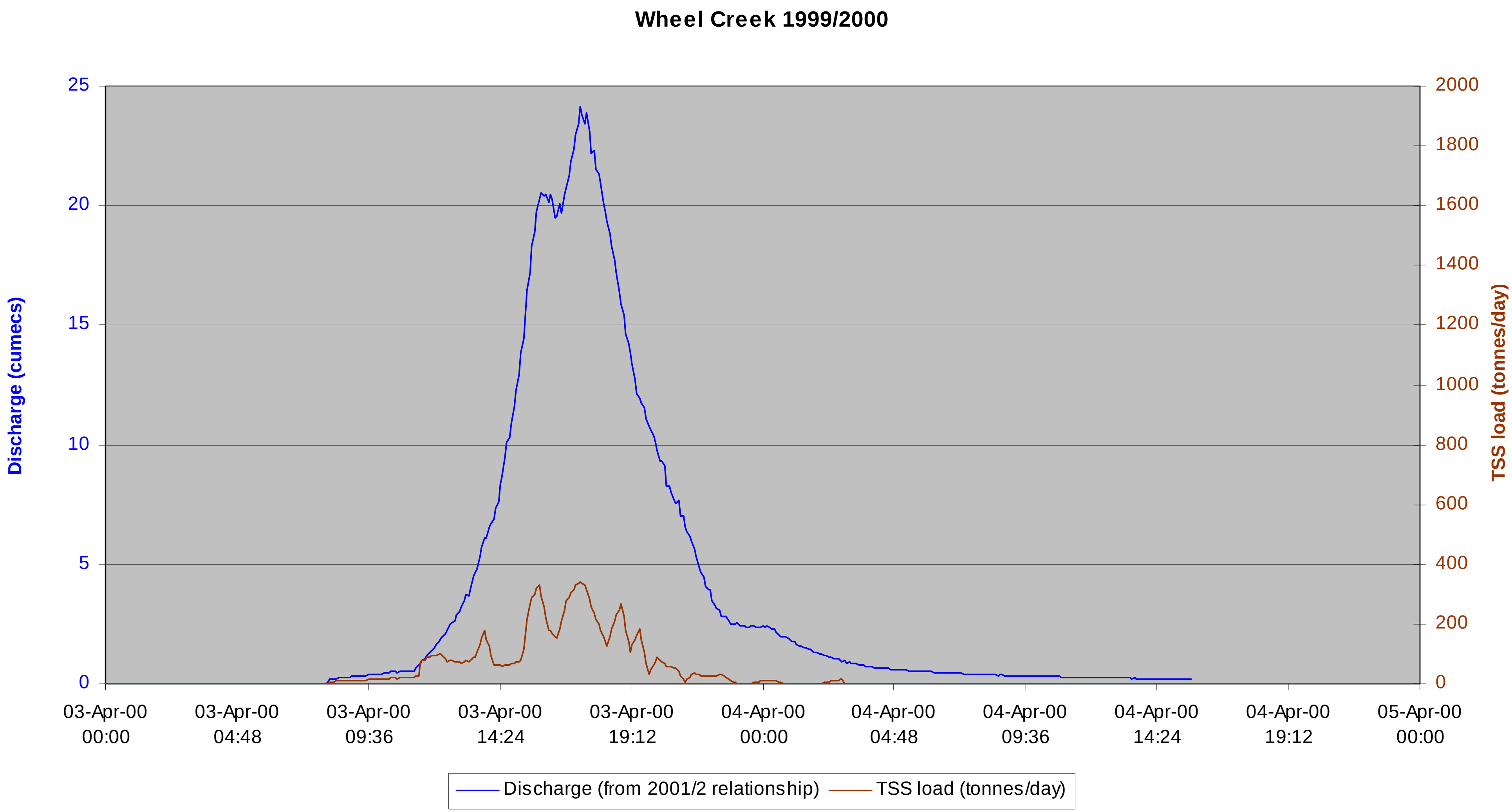

Weany Creek 2001/2002
Discharge (cumecs)
TSS load (tonnes/day)
40
35
30
25
20
15
10
5
0
4000
3500
3000
2500
2000
1500
1000
500
0
16-Dec-01 15:00
16-Dec-01 17:24
16-Dec-01 19:48
16-Dec-01 22:12
17-Dec-01 00:36
17-Dec-01 03:00
17-Dec-01 05:24
17-Dec-01 07:48
17-Dec-01 10:12
Discharge (cumecs)
TSS load (tonnes/day)


Weany Creek 2001/2002
Discharge (cumecs)
TSS load (tonnes/day)
0
5
10
15
20
25
30
35
40
0
500
1000
1500
2000
2500
3000
3500
4000
15-Feb-02 09:00
15-Feb-02 11:24
15-Feb-02 13:48
15-Feb-02 16:12
15-Feb-02 18:36
15-Feb-02 21:00
15-Feb-02 23:24
16-Feb-02 01:48
16-Feb-02 04:12
Discharge (cumecs)
TSS load (tonnes/day)

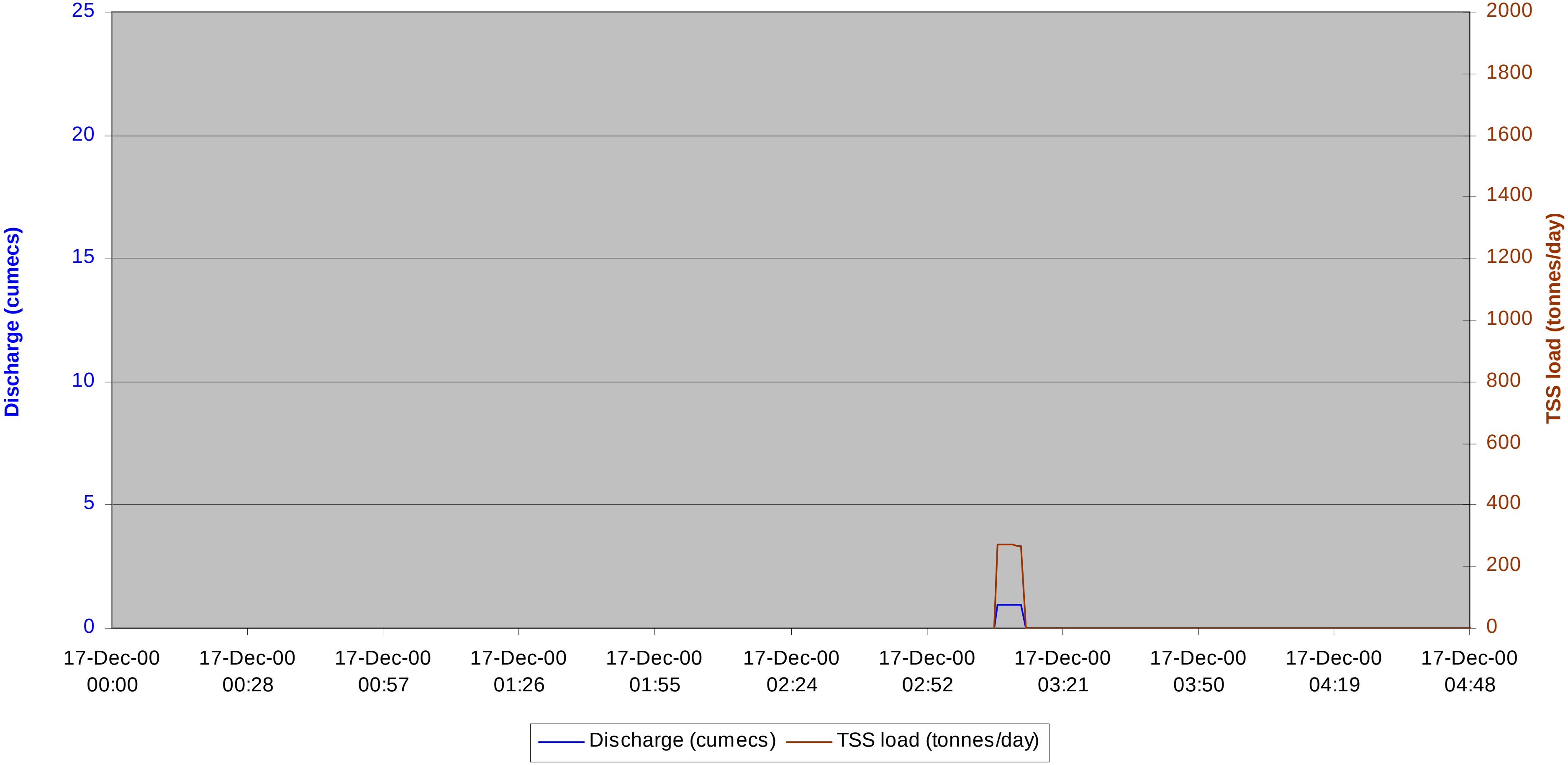

Wheel Creek 1999/2000
Discharge (cumecs)
TSS load (tonnes/day)
25
20
15
10
5
0
2000
1800
1600
1400
1200
1000
800
600
400
200
0
07-Feb-00 12:00
07-Feb-00 13:12
07-Feb-00 14:24
07-Feb-00 15:36
07-Feb-00 16:48
07-Feb-00 18:00
07-Feb-00 19:12
07-Feb-00 20:24
07-Feb-00 21:36
07-Feb-00 22:48
08-Feb-00 00:00
Discharge (from 2001/2 relationship)
TSS load (tonnes/day)

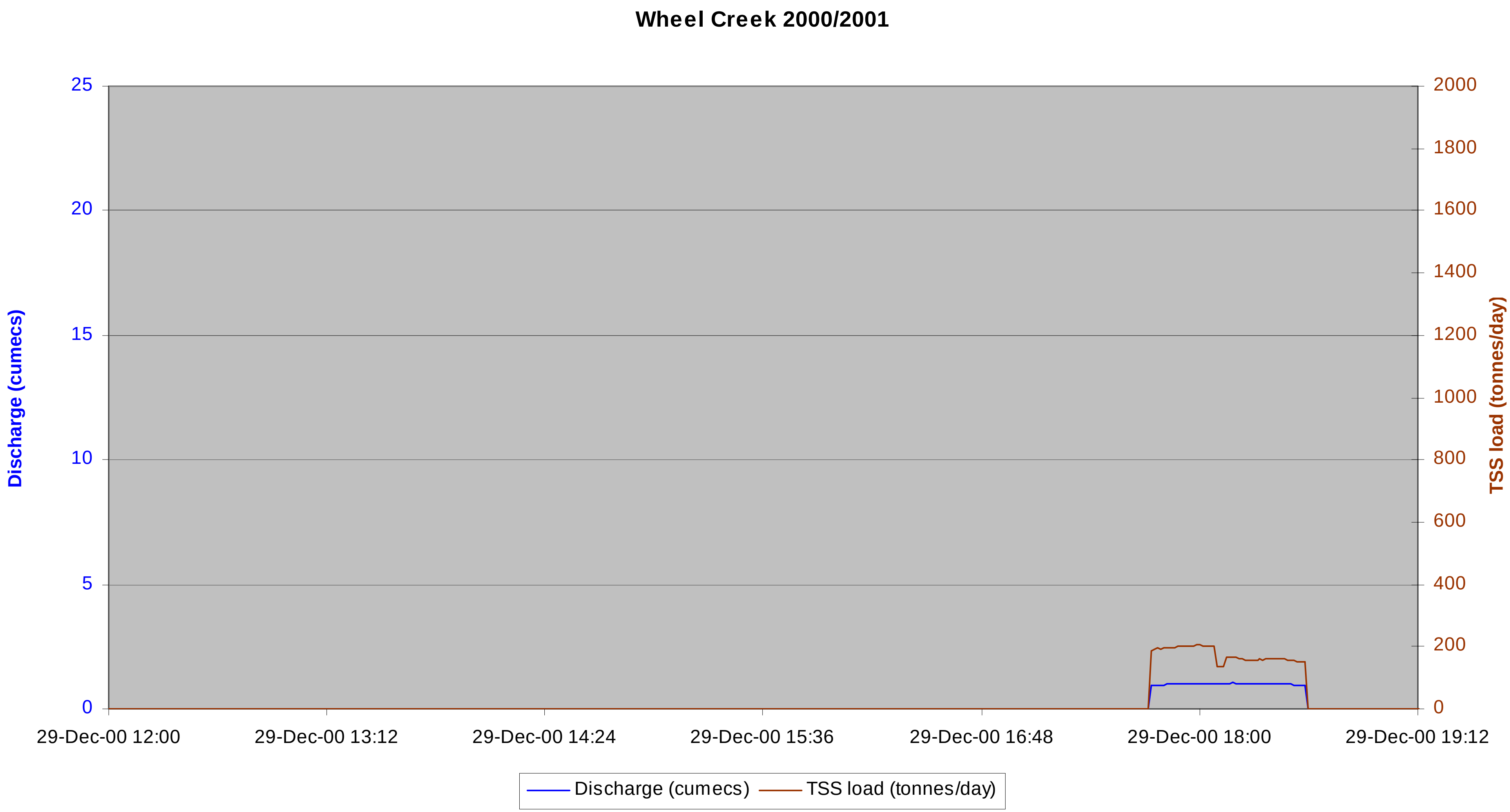

Wheel Creek 1999/2000
Discharge (cumecs)
TSS load (tonnes/day)
25
20
15
10
5
0
2000
1800
1600
1400
1200
1000
800
600
400
200
0
19-Feb-00 00:00
20-Feb-00 00:00
21-Feb-00 00:00
22-Feb-00 00:00
23-Feb-00 00:00
24-Feb-00 00:00
25-Feb-00 00:00
26-Feb-00 00:00
27-Feb-00 00:00
28-Feb-00 00:00
29-Feb-00 00:00
Discharge (from 2001/2 relationship)
TSS load (tonnes/day)

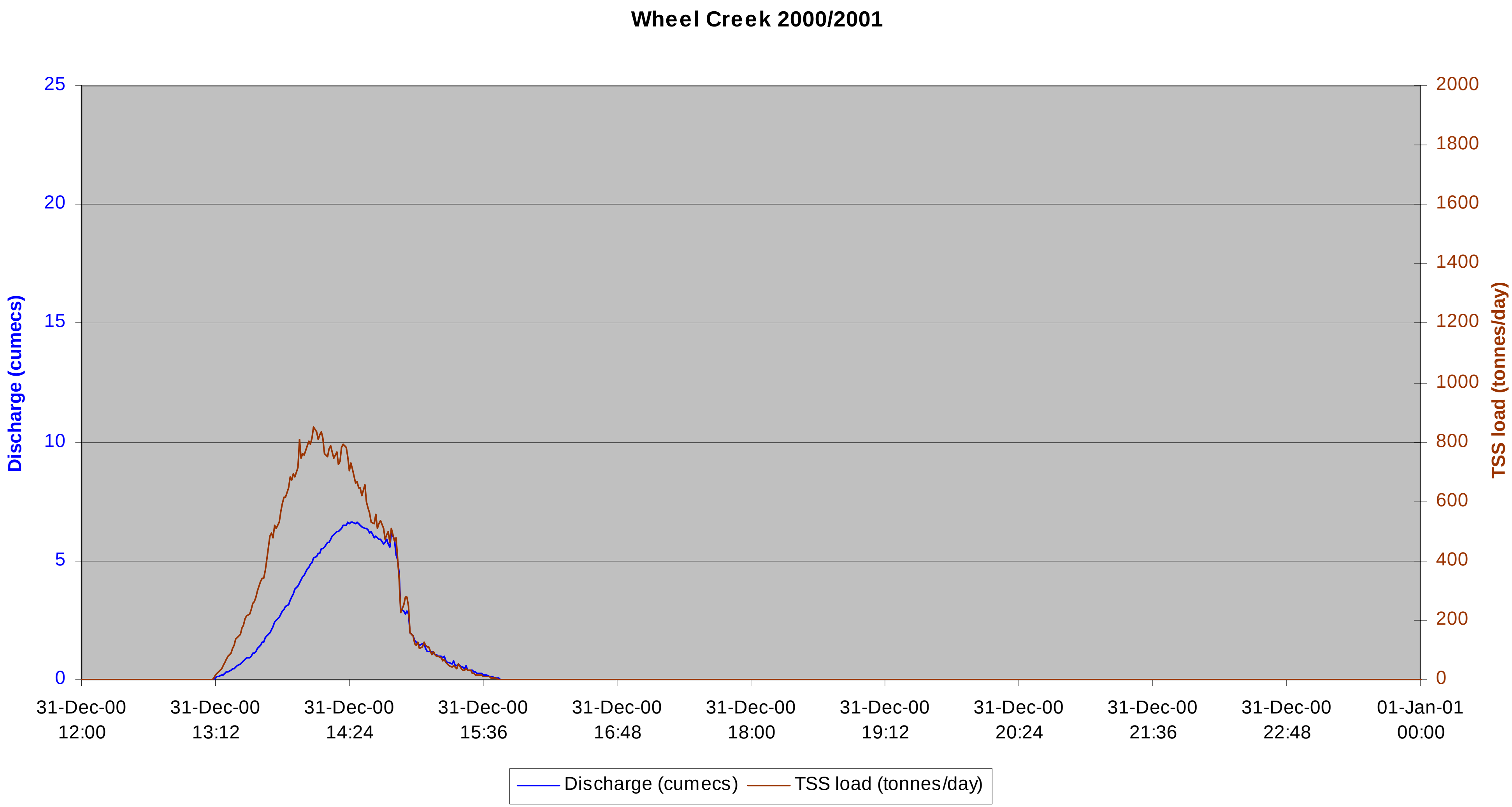

Wheel Creek 1999/2000
Discharge (cumecs)
TSS load (tonnes/day)
25
20
15
10
5
0
2000
1800
1600
1400
1200
1000
800
600
400
200
0
16-Mar-00 12:00
17-Mar-00 00:00
17-Mar-00 12:00
18-Mar-00 00:00
18-Mar-00 12:00
19-Mar-00 00:00
Discharge (from 2001/2 relationship)
TSS load (tonnes/day)


Wheel Creek 1999/2000
Discharge (cumecs)
TSS load (tonnes/day)
0
5
10
15
20
25
0
200
400
600
800
1000
1200
1400
1600
1800
2000
03-Apr-00 00:00
03-Apr-00 04:48
03-Apr-00 09:36
03-Apr-00 14:24
03-Apr-00 19:12
04-Apr-00 00:00
04-Apr-00 04:48
04-Apr-00 09:36
04-Apr-00 14:24
04-Apr-00 19:12
05-Apr-00 00:00
Discharge (from 2001/2 relationship)
TSS load (tonnes/day)

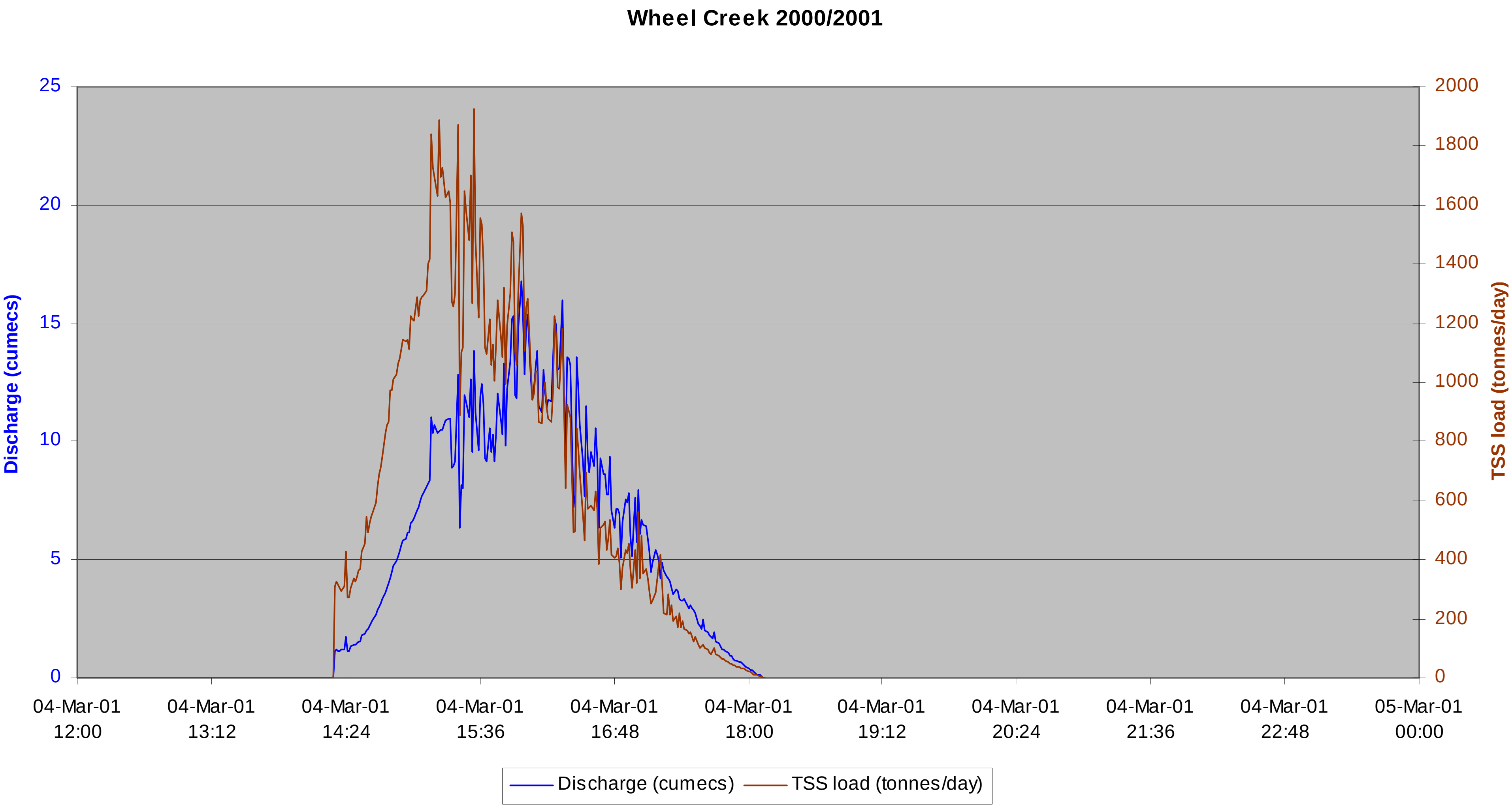
Wheel Creek 2000/2001



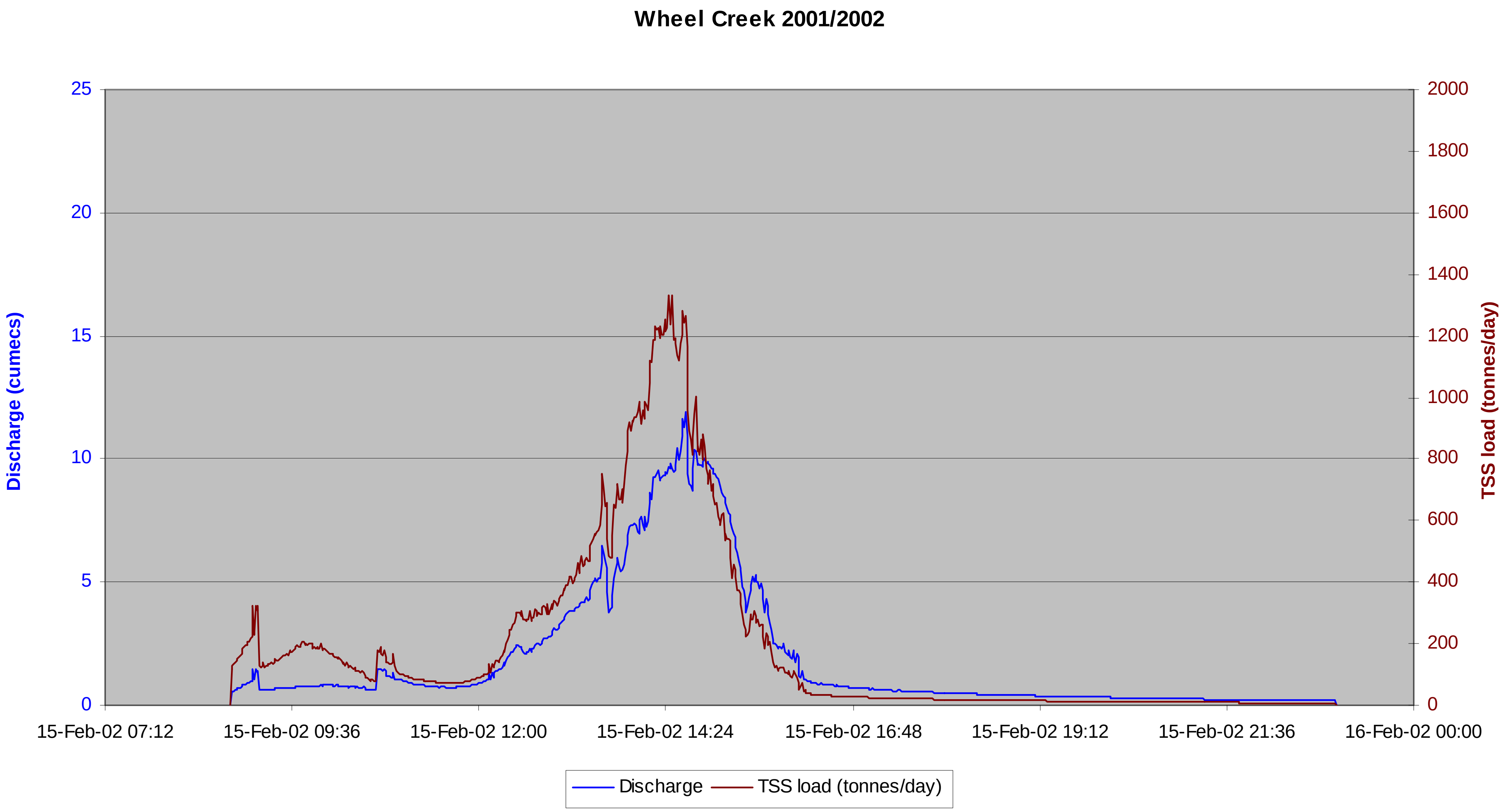

Wheel Creek 2000/2001
Discharge (cumecs)
TSS load (tonnes/day)
0
5
10
15
20
25
0
200
400
600
800
1000
1200
1400
1600
1800
2000
29-Dec-00 12:00
29-Dec-00 13:12
29-Dec-00 14:24
29-Dec-00 15:36
29-Dec-00 16:48
29-Dec-00 18:00
29-Dec-00 19:12
Discharge (cumecs)
TSS load (tonnes/day)

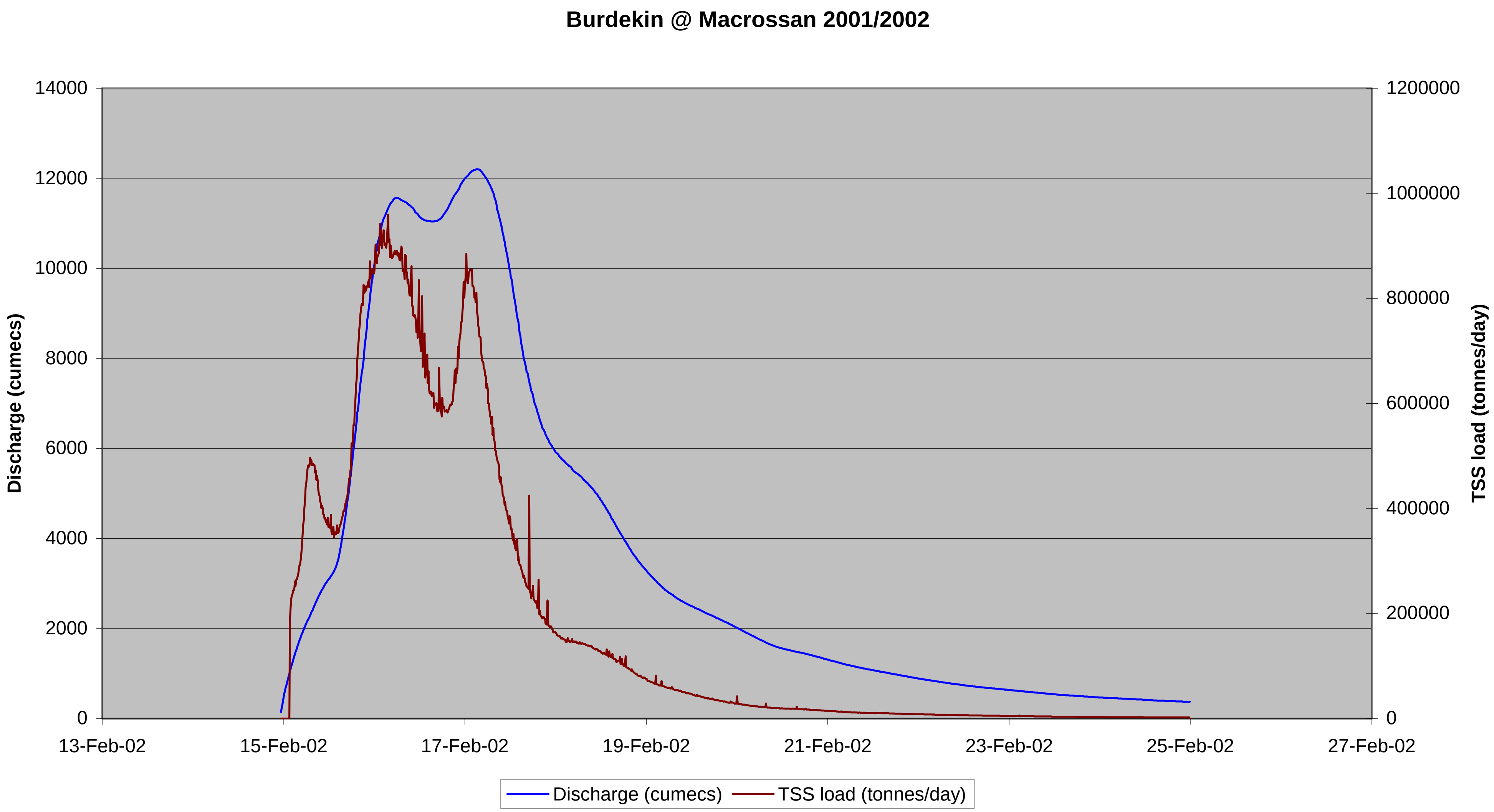


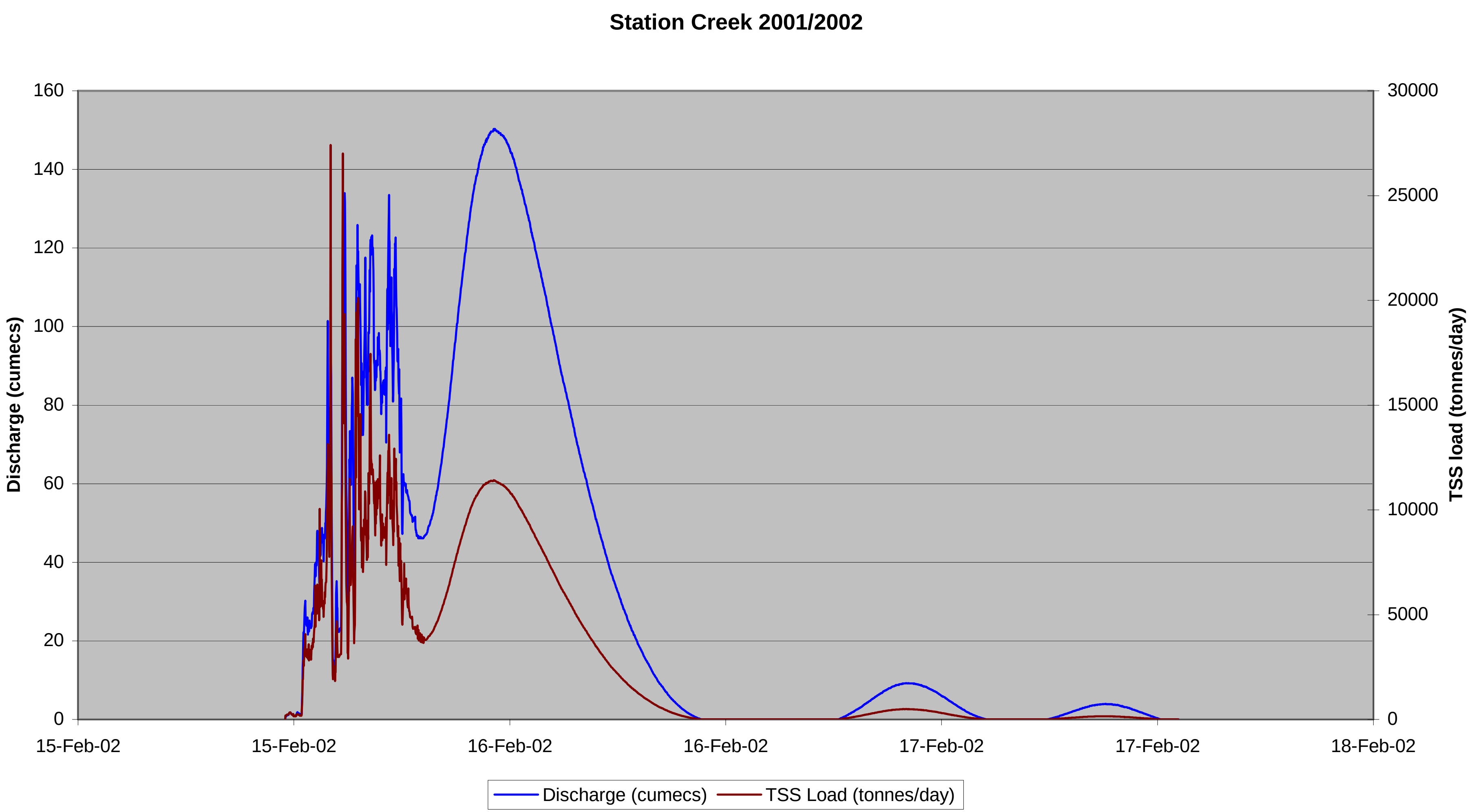
Wheel Creek 2000/2001
Discharge (cumecs)
TSS load (tonnes/day)
25
20
15
10
5
0
2000
1800
1600
1400
1200
1000
800
600
400
200
0
31-Dec-00 12:00
31-Dec-00 13:12
31-Dec-00 14:24
31-Dec-00 15:36
31-Dec-00 16:48
31-Dec-00 18:00
31-Dec-00 19:12
31-Dec-00 20:24
31-Dec-00 21:36
31-Dec-00 22:48
01-Jan-01 00:00
Discharge (cumecs)
TSS load (tonnes/day)



Wheel Creek 2000/2001
Discharge (cumecs)
TSS load (tonnes/day)
0
5
10
15
20
25
0
200
400
600
800
1000
1200
1400
1600
1800
2000
04-Mar-01 12:00
04-Mar-01 13:12
04-Mar-01 14:24
04-Mar-01 15:36
04-Mar-01 16:48
04-Mar-01 18:00
04-Mar-01 19:12
04-Mar-01 20:24
04-Mar-01 21:36
04-Mar-01 22:48
05-Mar-01 00:00
Discharge (cumecs)
TSS load (tonnes/day)


Wheel Creek 2001/2002
Discharge (cumecs)
TSS load (tonnes/day)
25
20
15
10
5
0
2000
1800
1600
1400
1200
1000
800
600
400
200
0
15-Feb-02 07:12
15-Feb-02 09:36
15-Feb-02 12:00
15-Feb-02 14:24
15-Feb-02 16:48
15-Feb-02 19:12
15-Feb-02 21:36
16-Feb-02 00:00
Discharge
TSS load (tonnes/day)


Burdekin @ Macrossan 2001/2002
Discharge (cumecs)
TSS load (tonnes/day)
0
2000
4000
6000
8000
10000
12000
14000
0
200000
400000
600000
800000
1000000
1200000
13-Feb-02
15-Feb-02
17-Feb-02
19-Feb-02
21-Feb-02
23-Feb-02
25-Feb-02
27-Feb-02
Discharge (cumecs)
TSS load (tonnes/day)



Station Creek 2001/2002
Discharge (cumecs)
TSS load (tonnes/day)
0
20
40
60
80
100
120
140
160
0
5000
10000
15000
20000
25000
30000
15-Feb-02
15-Feb-02
16-Feb-02
16-Feb-02
17-Feb-02
17-Feb-02
18-Feb-02
Discharge (cumecs)
TSS Load (tonnes/day)

Appendix 5. Grazing distribution study methods

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Overview

Studies in this project component consisted of vegetation measurements at three primary scales, and aerial surveys to document the distribution of cattle in the focal paddocks. Vegetation measurements at the two largest scales employed transects, while we used digital photographs to determine small scale pattern. In this Appendix, we provide detailed descriptions of the study paddocks and the methods used to collect data. Appendix 6 contains metadata for this component, and it includes descriptions of each variable, values for coded variable values, and notes on software used to analyze data.

In addition to data collected specifically for this study, we also used data from Fletcherview Paddock that was previously acquired, and we used a trend analysis conducted under the supervision of Bob Karfs. This Appendix also documents this information as appropriate.

Study paddocks

Three study paddocks – Virginia Park, Fanning River, and Fletchervale - were selected for cattle grazing and vegetation monitoring in December 1999 and January 2000.

Virginia Park – stud paddock (240 ha)

Location: 40k NE of Charters Towers, QLD, adjacent to Flinders Highway

Latitude 19 54’ 00” Longitude 146 30’ 36”

Soils/land system: Largely granodiorite soils of the moderately fertile Goldfields association, on gently undulating landscapes, with small alluvial components on lower slopes and flats associated with Weany Creek. Some exposed granite and stony areas associated with steeper gullies. Significant loss of A horizon on upper to mid slopes and active gully head erosion in places. Some extensive scalds associated with sodic soils on lower slopes.

Vegetation: Overstory vegetation dominated by Ironbark / Bloodwood (*E. crebra / C. erythrophloia*) and some ghost gum *(Corymbia dallachiana*) and few mid story shrubs on slopes, with areas of box (*E.Brownii*) and associated mid story shrubs (*Carissa, Erimophola, Atalaya, Cryptostegia*) on lower slopes and along major gully lines. Alluvial flats have an overstory of *E. Platyphylla* and some *E.teriticornis,* with *Allocasuarina sp* and some broad leaf species along creek lines. Riparian zones have significant infestations of rubber vine (*Cryptostegia).*

Understory herbage vegetation, once dominated by native perennial tussock grasses *(Heteropogon contortus, Bothriochloa ewartiana, Dicanthium sericeum, Chrysopogon fallax*), now largely replaced by Indian couch (*Bothriochloa pertusa*) in southern half of paddock especially. Some areas of tussock perennials remain in the north-west sector of the paddock.

Land condition and grazing management: Moderate to heavy stocking over many years, exacerbated by prolonged drought during the mid 1990s has degraded overall paddock to state II and state III land condition (Andrew et al, 2001). The paddock has been stocked at around 4-5ha / beast for most of the study period, though there have been several periods of de-stocking, mainly in the late wet/early dry, during this time. Early wet season grazing, following a late dry season burn in the southern half of the paddock in 1999/2000, concentrated grazing in this area for the following season. Early wet season grazing in 2000/2001 further weakened this area. Current annual dry matter production from this paddock is between 800-1200 kg/ha.

Fanning River - Mt Success paddock (2883ha)

Location: 27 north of Mingela on the Fanning River/Dotswood road adjacent to Mt Success.

Latitude 19 45’ 36” Longitude 146 30’ 00”

Soils/land system: Largely granodiorite soils of the moderately fertile Goldfields association, on gently undulating landscapes, with smaller areas of sandy alluvial soils on lower slopes and flats, associated with major creek and gully systems, which feed into the Fanning River catchment. Some exposed granite and stony areas associated with steeper gullies and some steep rocky hillslopes and ridges in the northern half. A major rocky limestone ridge system also marks the northern boundary, whilst Mt Success marks most of the western boundary. Significant gully systems occur throughout the paddock, with some scald areas associated with sodic soils also present on lower slopes adjacent to gully systems.

Vegetation: Overstory vegetation dominated by Ironbark / Bloodwood (*E. crebra / C. erythrophloia*) and some ghost gum (*Corymbia dallachiana)* with few mid story shrubs on slopes. Small areas of box (*E.Brownii*) and associated mid story shrubs (*Carissa, Erimophola, Atalaya, Cryptostegia)* on lower slopes and along major gully lines. Sandy alluvial flats between creek lines also have significant mixed shrub cover, dominated by *Carissa, Atalaya, Bursaria Erythroxylum, Planchonia and Petalostigma* species. Some areas of heavy alluvials have an overstory of *E. Platyphylla* and some *E.teriticornis* with *Allocasuarina, Melaleuca bracteatus, Lophostemon along* creek lines. Riparian zones have significant infestations of rubber vine (*Cryptostegia) in places.*

The Limestone ridge area is dominated by broadleaf, often semi-deciduous dry rainforest/ vine scrub upper and mid story species such as *Brachychiton, Lysophyllum, Terminalia, Owenia, Cocholospermum, Sterculia*, with an understory of vines such as *Canavalia* and other legume species. Steep rocky hillslopes and ridges also carry some a mixture of broadleaf tree and shrub species alongside ironbark and mixed bloodwood associations.

Understory herbage vegetation for the granodiorite areas is a mixture of native perennial tussock grasses *(Heteropogon contortus, Bothriochloa ewartiana, Dicanthium sericeum, Chrysopogon fallax*), with significant areas of Indian couch (*Bothriochloa pertusa*) in southern half of paddock especially, where the A horizon has been lost from mid and upper slopes and ridges.

Land condition and grazing management: The paddock is in a recovery phase from the impacts of past heavy stocking and prolonged drought. Extensive gully systems and sheet erosion in places, confirms its previously degraded state. The paddock has been moderately stocked at around 8-9ha / beast and is currently in an advanced state II land condition with some areas in state I (Ash et al, 2001). Though Indian Couch dominates significant areas, much of the paddock has good 3P perennial tussock grass cover, though tussock grass basal area is still <2% overall. Whilst some grazing is concentrated along ridges, the presence of six water points distributed around the paddock serves to spread grazing. Use of early wet season mosaic burning has also helped to shift the grazing distribution within the paddock. Mean paddock annual dry matter production is around 1500-1800 kg/ha

Fletchervale - Allingham Creek paddock (2500ha)

Location: 60km north of Charters Towers on the Lynd Highway

Latitude 19 53’ 24” Longitude 146 12’ 00”

Soil type/land system: The paddock is comprised of fertile basaltic red ferrosol soils and associated basaltic vertisols (heavy grey-brown cracking claysoils) and basalt sediments and colluvial soils typical of the “basalt country” to the north west of Charters Towers. The paddock includes red basalt plateaux areas to the west – part of a more recent basalt flow, which ends in a rocky “jump-up” areas just west of Allingham Creek, which divides the paddock longitudinally. There are extensive claysoil flats either side of the Allingham Creek, intersected by small anabranches and billabongs, which form part of an extensive channel system associated with the creek. Extensive areas of basalt sediments (a mosaic of rock free brown loams and cracking clay depressions) adjoin the claysoil flats to the east of Allingham Creek. The areas occur in several longitudinal bands, separated by low rocky basalt outcrops or ridges and adjoining stony colluvial margins and areas rocky red basalt plains.

Vegetation: The red basalt plateaux and plains are dominated by narrow leaf ironbark/bloodwood (*E. crebra / C. erythrophloia)* overstory, with few mid story shrubs. The rocky basalt ridges and slopes carry a significant mid-story shrub complex of *Carissa, Atalaya, Erythroxylum, Flindersia .* Claysoil flats are dominated by a box/coolibah overstory, whilst basalt sediments carry a mixed eucalypt overstory of silver leaf ironbark, (*E. Melanophloia*) ghost gum (*C.dalachiana*), box (*E. Brownii*) and bloodwood (*E. erythrophloia).* Basalt margins are dominated by a shrubby mid-story of false sandalwood (Eromophola mitchellii), Carissa and *Flindersia.* The riparian zone along Allingham Creek supports an overstory of *E. coolibah*, *Allocasuarina* sp. and *Melaleuca bracteata.* At the southern end of the paddock, Allingham Creek runs into Alligham Swamp, and extensive ephemeral wet land area, which is partly infested by *Parkinsonia* and restricts cattle access.

The herbaceous understory of the red basalts is dominated by 3P tussock grasses such as *Bothriochloa ewartiana, Heteropogon contortus* and *Dicanthium sericeum*, with significant invasion of buffel grass (*Cenchrus ciliaris*) and sarbi grass (*Urochloa mosambicensis),* along with an array of legume and non-legume forb species*.* Basalt ridges and outcrops are characterized by the presence of giant spear grass (*Heteropogon triticeus*). Cracking claysoil flats are dominated by perennial tussock grasses such as *Dicanthium sericeum, Dicanthium aristatum, Panicum decompositum* and *Eriochloa* spp. Basalt sediments support the range of both red soil and black soil species listed above. Stony colluvial margins have support a limited grassy under-story dominated by *Sporobolus, Eragrostis*, and other annual or short lived perennial species.

Land condition and grazing management: The paddock has been lightly stocked over many years and despite the impact of prolonged drought during the 1990s remains in good (state I) condition overall. A program of mosaic early wet and late wet season burning shifts grazing pressure around the paddock. Unlimited access to the perennial Allingham Creek limits potential grazing gradient impacts. Even so, most grazing tends to occur on the basalt plateau adjacent to a mill and also over the basalt sediment areas on the north-eastern side of the paddock. Production is about 1500-2000 kg/ha.

Fletcherview - Sandalwood paddock (467ha)

Location: Approximately 30k north of Charters Towers on Lynd Highway

Latitude: 19° 53' 24" Longitude 146° 12' 0"

Soil type/land system: The paddock is comprised of fertile basaltic rocky red ferrosol soils and associated basaltic vertisols (heavy grey-brown cracking claysoils) and basalt sediments and colluvial soils typical of the “basalt country” to the north west of Charters Towers. There are also small areas of exposed underlying granodiorite and sedimentary soils and sandy alluvial flats associated with Hann Creek, which marks the southern boundary of the paddock. The paddock includes several low basalt ridges and “walls” associated with a more recent basalt flows, which terminated at the border of Hann Creek. There are extensive claysoil flats on the northern side of the paddock adjacent to Lynd Highway separated from the red basalt soils by stony colluvial “margins” – a mosaic of brown basalt sediments and grey claysoil depressions and gilgais. Extensive areas of basalt sediments - a mosaic of rock free brown loams and cracking clay depressions) adjoin the western boundary. Significant areas of sheet, rill and gully erosion occur adjacent to Hann Creek, within both alluvial soils and adjacent sedimentary and granite derived soils.

Vegetation: The red basalt plateaux and plains are dominated by narrow leaf ironbark/bloodwood (*E. crebra / C. erythrophloia)* overstory, with few mid story shrubs. The rocky basalt ridges and slopes carry a significant mid-story shrub complex of *Carissa, Atalaya, Erythroxylum, Flindersia .* Claysoil flats are generally treeless or carry a scatttered box overstory, whilst basalt sediments carry a mixed eucalypt overstory of silver leaf ironbark, (*E. Melanophloia*) ghost gum (*C. dalachiana*), box (*E. Brownii*) and bloodwood (*E. erythrophloia).* Basalt margins are dominated by a shrubby mid-story of false sandalwood (*Eremophola mitchellii*), *Carissa* and *Flindersia.* The Hann Creek riparian zone supports an overstory dominated by *Melaleuca leucodendron*, *Eucalyptus tesserlaris*, *Allocasuarina* sp. Rubbervine (*Cryptostegia*) is a significant weed of both the riparian and gully areas, colluvial margins and basalt ridges.

The herbaceous understory of the red basalt areas is dominated by perennial tussock grasses such as *Bothriochloa ewartiana, Heteropogon. Contortus* and *Dicanthium sericeum*, with significant amounts of buffel grass (*Cenchrus ciliaris*) and sarbi grass (*Urochloa mosambicensis),* along with an array of legume and non-legume forb species. Basalt ridges and outcrops are characterized by the presence of giant spear grass (*Heteropogon triticeus*) and red natal grass (*Melenis repens*). Cracking claysoil flats carry perennial tussock grasses such as *Dicanthium sericeum , Panicum decompositum* and *Eriochloa* spp., with some bull mitchell (*Astrebla squarrosa*) and an array of legume and non-legume forbs. Where prolonged heavy grazing has reduced the perennial grass component, these flats are dominated by annual grasses such as *Brachyanche convergens* and *Sporololus spp*. Basalt sediments and colluvial margins support the range of both red soil and black soil species listed above, with the more scalded/shrubby areas carrying a limited grassy understory dominated by *Sporobolus, Eragrostis*, and other annual or short lived perennial species.

Land condition and grazing management: The paddock has been moderately stocked over many years and despite the impact of prolonged drought during the 1990s remains in generally good condition. Despite this, several areas of the paddock have been preferentially grazed over sustained periods resulting in localized degradation, scalding and significant erosion, especially along the Hann Creek frontage. The cracking claysoil plains fronting Lynd Highway have also suffered preferential prolonged grazing, especially through the 1990s drought, which significantly altered the pasture composition from tussock perennial to annual in character. Overall paddock dry matter production was around 1300 kg/ha throughout the mid-1990s drought, when this paddock was under study.

The paddock at Meadow Vale that was used for sub-catchment studies in this project was not included in the grazing / vegetation studies because of its small size, uniform vegetation, and uniformly heavy grazing regime. For selected paddocks, a GPS-based survey was conducted to record paddock boundaries, water points, major veg and soil types were completed in January/February 2000. This information formed the basis for paddock GIS maps, which were later refined using information from subsequent veg surveys.

Full-paddock vegetation measurements – methodology

Vegetation sampling using transects was based roughly on BOTANAL protocols (Tothill et al, 1978). However, to evaluate spatial pattern it was necessary to devise a protocol that could be used over large areas, such at entire paddocks, and that would detect patterns that resulted from grazing, which might be at scales or 10s to 100s of meters. To sample full paddocks, we evaluated two basic protocols. The first, used for sampling in June and July 2000, was based on the concept of sampling “active” and “inactive” sites, as determined from aerial sampling of cattle. Our initial vegetation sampling (June/July 2000) used four-armed, non-aligned transects placed at locations where we observed cattle (“active” sites) and at locations where no cattle were observed (“inactive” sites). The sampling technique yielded high-resolution data at sampled sites, but it was too labour-intensive to sample the full range of spatial locations and vegetation zones in large paddocks. In particular, it took a long time to travel to and locate each specific site using a hand-held GPS, and a considerable effort was necessary to lay out the transect tapes for the four-arm sampling protocol. We therefore evaluated alternative sampling schemes, and adopted the use of linear non-aligned transects. Vegetation sampling relied on linear transects, typically 1-2 km long, with quadrats placed at random locations within each 20 m segment of the entire transect. Using this technique, we were able to measure spatial patterns in the vegetation (see below) and the technique proved to be highly efficient.

Initial full paddock vegetation sampling methodology

Following initial aerial cattle distribution surveys of all three paddocks in May-June 2000, the following Botanal-based vegetation sampling methodology was used.

1. A set of pre-determined sampling points representing “active” (grazed) and “inactive” (ungrazed) areas across the paddock were selected, using data from recent aerial cattle distribution surveys. The aim was to cover both grazed and un-grazed areas across the range of major vegetation communities, soil types and significant landscape features in each paddock, within the time and resources available.

At each of these GPS located sampling points, observers, working in pairs, scored eight 2m*2m virtual quadrats at positions located in a stratified random manner, along each of four * 100m transect arms radiating out in cardinal directions from the central point. For Virginia Park, the direction of each was: 1: up-slope from site centre, 2: cross-slope to right of centre, 3: down-slope from centre, 4: cross-slope to left of centre. For the other paddocks, the arms were (in order of 1-4) north, east, south, and west.

2. 2m*2m quadrat positions were located at a random point within each 15m stratum (measured from the centre; Figure 5.1) along each transect arm, allocated on a stratified random basis as follows.

Quadrat	Distance Stratum	Actual Distance
1	0 (site centre)	always 0 m
2	0-15m	random within category (1m intervals)
3	16-30m	random within category (1m intervals)
4	31-45m	random within category (1m intervals)
5	46-60m	random within category (1m intervals)
6	61-75m	random within category (1m intervals)
7	76-90m	random within category (1m intervals)
8	91-105m	random within category (1m intervals)

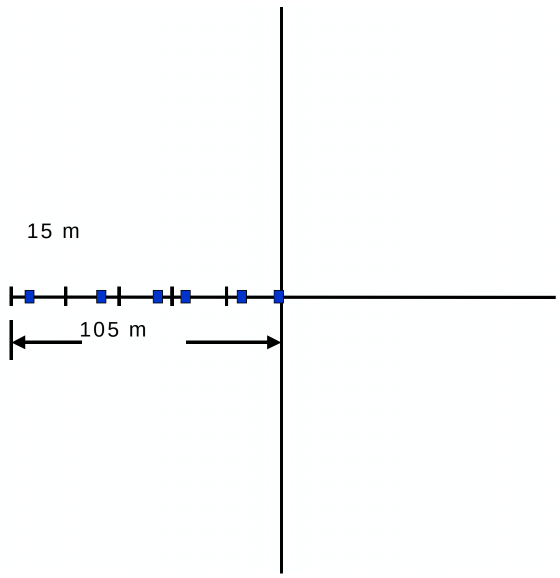

Figure 5.1: Quadrat placement design for sampling in April 2000.

Quadrat numbering was always 1-8 from centre to last quadrat along each arm. Quadrat 1 (site centre) was scored at least once by each observer (for comparison purposes), but where sites were scored by teams of 2 observers (scoring 2 arms each), quadrat 1 was not scored the second time around.

3. GPS locations at the start and end of each arm were recorded to enable accurate recording of quadrat positions on paddock GIS. 100m tapes were used to accurately locate the transect lines and quadrat positions for scoring.

Non-aligned transects methodology

An important observation from our July 2000 sampling was the large amount of time it took to locate, set up, and complete sampling at each site. We therefore modified the protocol for the November 2000 sampling and onwards to increase efficiency of sampling. From this sampling on we began using linear non-aligned transects that intersected actively grazed and un-grazed areas of each paddock. The location, direction and length of these transects was determined from paddock vegetation maps derived from aerial photography (Virginia Park), satellite imagery and accumulated paddock GIS data. Again, the aim was to intersect as many grazed and un-grazed areas as possible, across the range of major vegetation communities, soil types and landscape features in each paddock, within the time and resources available.

Sampling design for non-aligned transects

The non-aligned transects methodologies was used for all subsequent samplings. Each transect was divided into 200m (240 pace) sections (or parts thereof, where transects met fence lines or finished at the intersection with other transects). Within each 200m section, ten (10) quadrat positions were allocated to pre-determined random positions stratified between ten 20m (24 pace) sub-sections. Thus no quadrat could be more than 40m from its neighbour, but could be as close as 1m.

Pre-determined transect start and end positions and directions were located and followed using “go-to” and “routes” GPS functions. Observers mostly worked in pairs, “leap-frogging’ each other as they scored alternate 200m sections. Distances to quadrat positions were paced out – not measured by tape as previously. GPS locations were recorded at the START (0 paces) and END (240 paces) positions of each section, so that paced quadrat distances could be normalized. Where transects intersected fences, impassable waters etc. the last full quadrat position was scored and the remaining distance to the obstruction recorded as the END distance and GPS position, in place of the next quadrat distance listed on the HP spreadsheet program. Details of sampling instructions sheets can be found in Appendix 6 of this document.

The following variables were scored during the course of this study, with some variables being adapted or replaced and others added as sampling methodology evolved.

Variables recorded for each quadrat – all sampling periods

PAD:	Paddock (VPark=Virginia Park, FVale=Fletchervale, FRiv=Fanning River)
DATE:	ddmmyy
SITE:	1-N
OBS:	Observer initials: (JC, PA,PF,TK)
TOPO:	Local Topography (1-7)
BURN:	1=unburnt, 2=burnt
SP1-SP3:	3 dominant pasture species (as spec. nos. in Botanal biomass rank order)
YIELD:	Yield estimate - Botanal comparative yield estimate (0-100)
DEF:	Defoliation rating (O-5) 0=nil, 1=<5%, 2=5-25%, 3=25-50%,4=50-75%, 5=>75%)
COV:	Total projected cover estimate (0-100) – calibrated estimates
BAS:	Perennial tussock grass basal area category (0=nil, 1=<1%, 2=1-2.5%, 3=>2.5%
GRN_PC:	Green % of pasture (0-100%) – calibrated estimates
ER_TYPE:	Dominant soil surface erosion (0-3) 0=none, 1=sheet, 2=rill, 3=gully – visual assessment
ER_SEV:	Severity of erosion (0-3) 0=nil, 1=some, 2=moderate, 3=severe - visual assessment
COMMENTS	Any comments about the quadrat or site for future reference

Variables scored for June/July 2000 sampling only

ARM: Sampling Arm no. (1-4) in clockwise direction

DIR: Arm direction (NESW)

QUAD: Quadrat no. (1-8 from 0-105m along transect)

VEGCOM: Dominant vegetation community/land type within 10m radius (1-8) –see Appendix 6

Variables added or substituted from November 2000 onward sampling

T_SECT: Main transect number

SECTION: Sampling section number along each transect (1-n)

WAY_PT: GPS waypoint number (recorded at START or END of section)

QUAD: Quadrat no. (1-10 from 0m-200m along SECTION)

TOPO: Local topgraphy (1=flat, 2=ridge, 3=mid-slope, 4=downslope, 5=gully, 6=swale, 7=creek)

VEGCOM: Vegetation community (1-5) – consolidated paddock lists, see Appendix 6

Variables added or modified -- April 2001 onwards

VEG Dominant vegetation community within10m radius (code 1-8) see list Appendix 6

When initially established for the November 2000 sampling, the three study paddocks had the following number of non-aligned transects.

Table 5.1: Overview of transect sampling intensity

Paddock	Number of Transects	Total Length	Total Quadrats
Virginia Park	13	~12k	~ 598
Fanning River	15	~19k	~ 794
Fletchervale	14	~20k	~1018

At subsequent samplings in April 2001 and October 2001 additional transects were added at Fanning River (transects 16,17,18). These increased total transect length by 6k to 25k and total quadrats by 300 to approx. 1100. At Virginia Park there was also some re-alignment of transects from April 2001, which altered total length and number of quads slightly, whilst at Fletchervale, the total transect length and number of quads varied seasonally, according to the impact of Allingham swamp on transects 7 and 8. On some sampling occasions certain transects were not scored due to time constraints, whilst on other occasions some transect data was lost due to equipment problems (details in Appendix 6 of this document).

Data collection varied slightly between paddocks in June/July 2000, as the field sampling techniques were refined during the sampling exercise. Such variations were as follows:

1. At Virginia Park there was initially no discrete TOPO field recorded, but comments on topography were recorded.
2. At Virginia Park an additional field recording whether site/quadrat was previously burnt was included here. This variable was subsequently added to all study paddock data sets from November 2000 on.

3. At Virginia park perennial tussock grass basal area was recorded as a direct % estimate, but this was changed on subsequent paddocks to a rating, due to difficulty in obtaining accurate direct % estimates in thick pasture.
4. At Virginia Park, arms were not located north, east, south and west but up-slope, cross-slope (right), cross-slope (left) and down-slope). On other sites they were located N, E, S, W.

Reference quadrat establishment and observer training

Immediately prior to the initial paddock vegetation surveys in July 2000, sets of 4 m^2 permanent reference quadrats, covering a range of biomass, cover, species composition and defoliation combinations were established at strategic locations in all three study paddocks, for the purpose of on-going observer training and standardization and as photo points for on-going reference. At Virginia Park and Fanning River a total of 11 such reference quadrats were established, while 13 were established at Fletchervale. These quadrats were used both for initial training in scaling between 1 m^2 and 4 m^2 quadrats and also for on-going training, standardization and calibration at every subsequent sampling. Photos of all reference quadrats were taken by Taoufik KsiKsi, or Jeff Corfield, at each sampling and are held by Jeff Corfield. Details of reference quadrat training and calibration methods can be found in Appendix 6.

Hillslope-scale patchiness measurements - methodology

Whilst non-aligned Botanal based transects provided good data on the broad spatial relationships between observed grazing patterns and factors such as vegetation type, soil type, distance from water, fences etc. little information was gained on the actual size or dynamics of grazed patches across the paddock. Understanding patch dynamics may be a key to linking broader scale grazing impacts with plant/soil/hydrological processes and landscape function. Thus, in July 2001, a series of “intermediate scale” (100m) transects was established along sections of selected non-aligned transect lines in Mt Success study paddock, Fanning River Station, to record temporal changes in the dynamics of grazed and ungrazed patches at sub-10m scales.

Initial patch transect establishment

Patch transects were initially established along three 100m sections of transects 12 and 15 in Mt Success study paddock, to intersect a range of cover, species composition and grazing patterns, in particular, sections that included distinct bare (scald) patches, creek/gully lines, light, moderate and heavily grazed patches (see Appendix 6 for descriptions and locations). Patch transect start points were located by trees flagged with coloured surveyor’s tape, or wooden pegs, whilst end points were usually marked by wooden pegs. GPS waypoint positions were recorded at the start and end points of each 100m transect section. The initial 6 patch transect sections (3 along Transect 12 and 3 along transect 15) were not contiguous. 100m survey tapes were used to mark out patch transect lines and patch information was scored within a 1m belt transect located centrally along the tape.

Initial patch measurements, variable descriptors and definitions – July 2001 scoring

A number of “patch types” were identified and recorded along each 100m tapeline. A full list and description of patch codes used at all scoring occasions appears in Appendix 6 of this document. Main patch types included bare ground, grazed patches, un-grazed patches, intermittent grazed and ungrazed patches, cattle pads and camps, creek and gully banks and beds. Scoring was continuous along tape-lines, with every portion of each 100m transect assigned a “patch” category. Linear boundaries of each “patch” were recorded in an HP 200 spreadsheet, along with date of scoring, transect, section and scores for the following list of variables.

Changes to recording methodology at second scoring – September 2001

At the second scoring occasion, the following changes were made to variables recorded and recording methodology.

1. Standing crop herbage biomass (Botanal comparative yield method, Tothill et al 1978)) was added

2. Bare and grazed patch maximum and minimum diameters were abandoned
3. Dominant species variables increased from first two to first three
4. Herbage defoliation rating (Andrew 1988) was added
5. Estimation of all variables was confined to a 1m wide belt transect along tape centre line
6. Additional patch types were also recorded (see consolidated list below)

The following variables were scored during the course of this study, with some variables replaced or modified and others added as the sampling methodology evolved.

Variables scored for each transect - all sampling occasions

SITE	Catchment study paddock FRIV = Fanning River (Mt Success Paddock)
DATE	Sampling Date (DD-month-YY)
TRANSECT	Paddock veg survey Botanal transect number (1-19)
SECTION	100 m section of transect bounded by start and end waypoints
WAY_PT	GPS way point number marking beginning or end of section
PATCH	Patch Type - see separate code and description list
DISTANCE	Distance (in meters and decimeters) from start of 100m section to point measured
COVER	Mean total projected cover estimate for patch (%)
PAST_HT	Mean pasture height (cm) for patch - to flag leaf , excluding inflorescences
DOM_SP1	First dominant species (Botanal DWR method)
SP1_PERC	Estimated % contribution of first dominant species (%)
DOM_SP2	Second dominant species (Botanal DWR method)
SP2_PERC	Estimated % contribution of second dominant species (%)

Variables scored July 2001 only

MAX_DIAM	Diameter of longest axis of significant bare or grazed patch (cm)
MIN_DIAM	Diameter of shortest perpendicular axis of significant bare or grazed patch (cm)

New variables added September 2001 onward

DOM_SP3	Third most dominant species or species group in patch (Botanal DWR method)
SP3_PERC	Estimated percentage biomass of dom_sp3
YIELD_EST	Standing Crop Biomass (Botanal comparative yield estimate) -scale 0-100
DEFOL	Mean defoliation rating for patch on a 0-5 scale (Andrew 1986)
BURN	1=unburnt, 2=recently burnt

Detailed descriptions of variables and patch types can be found in Appendix 6 of this document.

Small scale patch measurements - methodology

Digital imagery was used to capture small scale measurement of patch attributes along existing sections of the hillslope patch transects, both for comparison with intermediate scale observations and to better understand patch and sub-patch dynamics.

We used a digital camera (5 mega-pixel) attached to a boom affixed to a quad bike, which yielded images of a 4.6m x 3.5m area. Imagery was classified into green foliage, cover and bare ground elements using standard image processing methodology. Patterns of bare ground were described quantitatively using statistical distributions and landscape metrics to derive connectance, lacunarity percolation and "landscape leakiness" – all of which are indicators of landscape hydrological function. Patterns of cover at the small-scale were related to vegetation type, soil characteristics, defoliation and topography.

Table 5.2: Variables and attributes measured

Variable	Method / definition	Reference	Unit
Classification	Supervised maximum likelihood		
Green foliage	Foliage greenness		% of image
Cover	Any grass (including green foliage) or litter element.		% of image
Bare ground	Bare earth not covered by a grass or litter element		% of image
Statistical distributions			
Mean, variance etc	Computed from the number of patches (soil and cover) and patch sizes		
Landscape analysis			
Leakiness	Measure of leakiness of a landscape unit	Ludwig et al (2001)	Directional leakiness index (DLI)
Patch metrics	Various descriptive metrics used to describe landscapes. Lacunarity, percolation and connectance are a few examples.	APACK and FRAGSTATS software packages	Descriptive indexes

See Appendix 6 of this document for detailed descriptions of variables and data obtained.

Aerial surveys for determining cattle distribution

Cattle distributions were documented in the three focal paddocks (Virginia Park, Fanning River, and Fletchervale) by conducting low altitude aerial surveys of paddocks at Virginia Park, Fanning River, and Fletchervale. Cattle locations were determined by flying low-elevation (approximate 150 m above ground) linear transects approximately 400 m wide and to record the size and location of each mob observed. For each mob of cattle, the location was recorded as a GPS waypoint, and the number of animals in the mob was recorded. As necessary, the aircraft circled area to ensure that all animals were observed or to provide a longer period to count large mobs. Locations were determined from GPS data and notes made at the time of observation. After transects were completed, locations were refined by comparing notes and GPS locations to aerial photographs and/or TM images. To emphasize spatial distributions while animals were feeding, morning flights began as soon as light permitted; evening flights were scheduled to occur during period when animals were active. Because of the long distance between some paddocks, surveys of Virginia Park and Fanning River were generally conducted during the same flight, and Fletchervale was surveyed as a separate flight. Flights were scheduled for the period of about 1 month before vegetation sampling to facilitate comparison of aerial locations to vegetation attributes.

Appendix 6. Grazing distribution studies metadata

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Overview

The purpose of this appendix is to provide a compilation of the metadata of all of the measurements conducted in the grazing distribution component of NAP3.224. The metadata information has been organised into a series of tables listing variables captured and their description.

Paddock scale vegetation sampling - main metadata

Table 6.1: Descriptions of all variables recorded in paddock-scale vegetation sampling, 2000-2002

Variable	Description / Definition	Reference	Units or categories
PAD	Paddock ID – 4 letter code	NA	VPARK=Virginia Park, FVALE=Fletchervale, FRIV=Fanning River
DATE	Sampling date	NA	dd-Mon-yy
OBS	Observer code	NA	JC=Jeff Corfield PA=Peter Allen TK=Taoufik KsiKsi PF=Peter Fry LW=Lindsay Whiteman CH=Chris Holloway BA=Brett Abbott
ARM	Sampling arm number. There were four*100m long sampling arms arrange at right angles to each other at each sampling site. Applicable for July 2000 sampling only	NA	1-4 for all sites For Virginia Park only 1=upslope 2=downslope 3=cross-slope left of centre 4=cross-slope right of centre
DIR	Direction of each sampling arm. Applicable for July 2000 sampling only at Fletchervale and Fanning River	NA	N=north of centre S=south of centre E=east of centre W=west of centre
TREAT	Category of selected sampling site (actively grazed or ungrazed) - used for July 200 sampling design only	NA	Categorical variable 1=selected active (grazed) site 2=selective inactive (ungrazed) site
T_SECT	Transect number (used from Nov. 2000)	NA	1-n
SECT	200m Section number (used from Nov. 2000)	NA	1-n
WAY_PT	GPS waypoint number each ARM centre and end (July 2000) or for start and end of each section (from Nov 2000)	NA	1-n – corresponds with GPS waypoint recorded as UTMs in GWS84

QUAD	$4m^2$ quadrat number	NA	1-10
PACES	Number of paces from START of section or previous quadrat to next quadrat or END of section	NA	0-40 paces. Start position recorded as START or "0"; end point recorded as END or "999"
VEG or VEGCOM	Code number recorded for dominant veg community or landtype within a 10m radius of quadrat – see separated detailed descriptions below	NA	1-n - number of categories varied with sampling date as methods evolved
TOPO or SOIL_TOPO	Code number recorded for dominant topographical feature and / or soil type within a 10m radius of quadrat – see detailed descriptions below	NA	1-n - number of categories varied with sampling date as methods evolved
BURN	Status of quadrat in relation to recent burning	NA	1=unburnt 2=burnt
SP1	Code number for most dominant herbage layer species or group – Botanal comparative yield estimate method	BOTANAL Tothill et al (1978)	Species ID number 1-26 See separate ID list in this document
SP2	Code number for second most dominant herbage layer species or group - Botanal comparative yield estimate method	BOTANAL Tothill et al (1978)	Species ID number 1-26 See separate ID list in this document
SP3	Code number for third most dominant herbage layer species or group - Botanal comparative yield estimate method	BOTANAL Tothill et al (1978	Species ID number 1-26 See separate ID list in this document
YIELD	Calibrated estimate of total standing dry biomass of herbage present in quadrat – Botanal comparative yield estimate method	BOTANAL Tothill et al (1978)	Rating scale of 0-100, converted to kg/ha dry matter using regressions derived from calibration standards
COV	Calibrated estimate of total projected cover (folia + litter + rocks) of quadrat		0-100% - data adjusted by regressions derived from calibration standards
DEF	Visual rating of defoliation within quadrat, using an un-calibrated 0-5 rating scale	Andrew (1986)	Categorical variable 0-5 scale 0=nil, 1=<5% 2=5-25% 3=25-50% 4=50-75% 5=>75% - converted to mid-point percentage
BAS	Perennial tussock grass basal area category. Note B. pertusa BA not included in this as not a tussock grass	Tongway (1995)	Categorical variable 0-3 scale 0=nil, 1=<1% ba 2=1-2.5%, 3=>2.5%
GRN_PC	Calibrated Estimate of percentage of standing biomass which is green at each sampling		0-100% in units of 1%

ER_TYPE	Dominant erosion category for each quadrat, loosely based on Tongway LFA system	Tongway (1995)	Categorical variable 0=no erosion 1=sheet erosion 2=rill erosion 3=gully erosion
ER_SEV	Erosion severity category for each erosion type – loosely based on Tonway LFA system	Tongway (1995)	Categorical variable 0=no erosion 1=slight 2=moderate 3=severe
COMMENTS	Any comments specifically related to quadrat, section or transect, recorded at time of scoring each quadrat		Text

Table 6.2: Consolidated species shortlist for transect Botanal data 2000-2002

BOTNUM	SPECIES	Functional group 1	Functional group 2	Functional group 3
1	*Aristida* spp.	perennial grass	native	increaser
2	*Bothriochloa decipiens*	perennial grass	native	decreaser
3	*Bothriochloa ewartiana*	perennial grass	native	increaser
4	*Chrysopogon fallax*	perennial grass	native	intermediate
5	*Dichanthium spp.*	perennial grass	native	decreaser
6	*Enneapogon sp*	perennial grass	native	increaser
7	*Heterogon contortus*	perennial grass	native	decreaser
8	*Heteropogon triticeus*	perennial grass	native	decreaser
9	*Themeda triandra*	perennial grass	native	decreaser
10	*Sorghum plumosum*	perennial grass	native	decreaser
11	Other native per. grasses	perennial grass	native	intermediate
12	*Bothriochloa pertusa*	perennial grass	exotic	increaser
13	*Melenis repens*	perennial grass	exotic	increaser
14	*Cenchrus ciliaris*	perennial grass	exotic	increaser
15	*Urochloa mosambicensis*	perennial grass	exotic	increaser
16	Other exotic grasses	perennial grass	exotic	increaser
17	*Dactylocteneum radulans*	annual grass	native	increaser
18	*Sporobolus* sp.	annual grass	native	increaser
19	*Tragus austalianus*	annual grass	native	increaser
20	Other annual grasses	annual grass	native	increaser
21	Legumes	legume	mixed	mixed
22	Sedges	sedge	native	mixed
23	Forbs	forb	mixed	mixed
24	*Panicum* spp.	perennial grass	native	decreaser
25	*Eulalia aurea*	perennial grass	native	intermediate
26	*Dichanthium aristatum*	perennial grass	native	increaser

Detailed descriptions of VEGCOM, VEG and TOPO codes used in paddock scale sampling

VEGCOM field indicated broad land type – a combination of vegetation community, soil type and landscape features broadly equivalent to the system of land types used in the Fletcherview study and comparable to land units. VECOM codes and identities used for each study paddock at the July 2000 sampling are listed in Table 6.3 below. Both VEGCOM and TOPO variables were recoded as the dominant feature within a 10m radius of the quadrat centre.

Table 6.3: VEGCOM codes - July 2000 sampling

VEGCOM	VIRGINIA PARK	FANNING RIVER	FLETCHERVALE
1	Ironbark/bloodwood	Ironbark/bloodwood	Ironbark/bloodwood
2	Gully systems	White Gum Flats	Basalt colluvium
3	Riparian	Sandalwood/ shrubby	Black Soil
4	Box/Carissa	Box Flats	Box flats
5	Sandalwood (*Eremophola*)	Riparian	Riparian
6	Stony Goldfields	Mixed Euc./rocky hills	Basalt ridges
7		Limestone ridge	
8		Gully systems	

Detailed VEGCOM code descriptions – July 2000 sampling

Virginia Park vegetation communities

1. Ironbark/bloodwood. — *E. crebra/C. erythrophloia* over *B .ewartiana, H. contortus, C. fallax*, now dominated by B.pertusa. Undulating topography on Dalrymple neutral red duplex soils).

2. Gully Systems — Mixed Eucalypt and shrubs (*Atalaya, Carissa, Eromophola, Cryptostegia*) over annual and perennial grasses mostly dominated by *B. pertusa*. Associated bare scalds, rills and gullies.

3. Riparian – creeks — Major creek lines dominated by *E. tesserlaris, E. teriticornis, E. platyphylla* and *Melaleuca sp*. over mixed perennial grasses. Exotic grasses such as *B. pertusa* and *U. mosambicensis* dominate open areas whilst *Cryptostegia* and other exotic weeds occupy mid-story.

4. Box/Carissa — *E. brownii, Carissa sp., Cryptostegia* over *H. contortus, Aristida sp., Sprobolus sp.* on heavy clay loams in lower slopes adjacent to creeks. Associated scalds and bare patches and heavy rubber vine infestation in places.

5. Eremophola — Scattered *E. brownii* and *C. dallachiana* over E.*mitchellii/Atalaya/Carissa* mid story and *Sporoblus/Aristida/Enneapogon* understory. Significant bare scalds, sheeting, rills, gullies.

6. Stony Goldfields — *E. Crebra/C. erythrophloia/C. dallachiana* over *B. ewartiana, Enneapogon spp., H. contortus* on undulating topography with rocky/stony surface – goldfields neutral red duplex soils.

Fletchervale vegetation communities- July 2000

1. Red Basalt — *E. Crebra/C. erythrophloia/C. dallachiana* (Ironbark/bloodwood) over *B. ewartiana , D. sericeum, H. contortus* (with significant invasion of *Cenchrus and Urochloa* spp) on rocky red basalt soils in flat to undulating topography. Generally well covered with minor scalds.

2. Basalt colluvium — Mixed Eucalypt (*E. crebra, C. erythrophloia, E. melanophloia, C. dallachiana*) over *B. ewartiana, B. decipiens, D . sericeum , D. aristatum*. On flat to slightly undulating country, almost rock free, with associated blacksoil depressions and gilgais. Usually in margins between red basalt and box areas.

3. Black Soil — Scattered *E. brownii* over *D. sericeum/D. aristatum, P. decompositum* on heavy grey cracking clay soils in almost treeless, lower lying areas between red basalt areas and riparian zones.

4. Box flats	*E. brownii* over *D. sericeum, D. aristatum, B. decipiens* on heavy grey-brown clay loams – flat to swale areas adjacent to riparian channels of Allingham Creek.
5. Riparian	Areas associated with Allingham Creek channels- *E.* tesselaris, E.brownii, *M. bracteatus, Allocasuarina spp*. over *D. sericeum/D. aristatum/B. decipiens*. Numerous creek channels, some with semi-permanent water, and associated heavy loam stream levees.
6. Basalt ridges	Rocky basalt ridges and walls –*E. crebra/C.erythrophloia /C. dallachiana* with shrubby mid-story of *Carissa spp., Bursaria incana, Erythroxylum* spp., *Atalaya* spp. over *B. ewartiana, H. contortus, H. triticeus and Melenis repens.* Large basalt rocks present.

Fanning River vegetation communities – July 2000

1. Ironbark/bloodwood	*E. crebra/C. erythrophloia* over *B. ewartiana, H. contortus, C. fallax*. Dominated in some areas by *B. pertusa*. Undulating topography on Dalrymple neutral red duplex soils).
2. White Gum Flats	*C. tessellaris, E. playphylla, E. tereticornis, C. dallachiana* over B. *ewartiana, H. contortus, B. decipiens, D. sericeum* . Sandy loam alluvial flats adjacent to larger creeks.
3. Sandalwood/ shrubby	*E. brownii, C. clarksonii* over mid-story of *Eremophola mitchellii, Bursaria spp., Atalaya* spp., *Carissa* spp. in gullies and hillslope breakaways on skeletal soils or eroded landscapes.
4. Box Flats	*E.brownii* and scattered *C. dallachiana* over mid story of scattered *Carissa, Atalaya* and *E. mitchellii*. Usually heavy soils on lower slopes, associated with middle order streams.
5. Riparian	Creek line areas – *Melaleuca bracteata, Allocasuarina* spp*. Lophostemon* spp., often with mid-story of rubbervine (*Cryptostegia*) over *Arundinella* sp., *B. decipiens* and forbs.
6. Mixed Euc./rocky hills	*E. crebra, C. clarksoniana, C. erythrophloia, C. dallachiana* with mid story of *Bursaria, Petalostigma* spp., *Carissa* and *Atalaya* over *H. contortus*, *Enneapogon* spp., *Aristida* spp., *Themeda* spp. on rocky/stony hill-slopes around Mt. Success and other hilly areas.
7. Limestone ridge	Broadleaf vine thicket scrub associated with limestone ridge in NW section of paddock. Over-story of *Brachychiton* spp., *Acacia brewsteri*, *Lophostemon* spp. *Owenia* spp, *Terminalia* spp, over mid-story of vines, *Cajanus* spp. *Indigofera* spp and grass layer dominated by *H. contortus, Melenis repens, B. ewartiana, T. triandra* and *B. pertusa*.
8. Gully systems	Mixed Eucalypt and shrubs (*Atalaya, Carissa, Eromophola, Cryptostegia*) over annual and perennial grasses mostly dominated by *B. pertusa* but also *H. Contortus, B. ewartiana*, *M. repens*. Associated bare scalds, rills and major gully systems.

VEGCOM codes used at November 2000 Botanal transect sampling

At the November 2002 sampling the previously separate VEGCOM codes for each study paddock were consolidated into a single VEGCOM code list for standardization purposes. The new codes were as follows. Reconciliation tables linking the July 2000 and November 2000 VEGCOM codes can be found below and also in the "main_data_notes" worksheets of November 2000 Botanal data files.

Table 6.4: List of VEGCOM codes and descriptors used at November 2000 sampling

VEGCOM	Description	Virginia Park	Fanning River	Fletchervale
1	IBBW- granodiorite systems	yes	yes	no
2	IBBW – stony granodiorite	yes	yes	no
3	IBBW - red basalt plains	no	no	yes
4	BOX flats - granodiorite systems	yes	yes	no
5	BOX flats - red basalt system	yes	yes	no
6	RIPARIAN - granodiorite systems	yes	yes	no
7	RIPARIAN - red Basalt system	no	no	yes
8	GULLY SYSTEMS – granodiorite	yes	yes	no
9	S/WOOD SCALDS - granodiorite	yes	yes	no
10	WHITEGUM/ALLUV granodiorite	yes	yes	no
11	BLACKSOIL PLAINS - basalt soils	no	no	yes
12	BASALT COLLUVIUM - basalt soils	no	no	yes
13	BASALT RIDGES - red basalt system	no	no	yes
14	STONY HILLS/MIXED EUC	no	yes	no
15	LIMESTONE/VINE SCRUB	no	yes	no

Detailed VEGCOM code descriptions – November 2000 sampling

1. Ironbark/bloodwood granodiorite systems (Vpark and Friver) — *E. crebra/C. erythrophloia* over *B. ewartiana, H. contortus, C. fallax,* now dominated by *B. pertusa*. Undulating topography on Dalrymple neutral red duplex soils.

2. Ironbark/bloodwood Stony Goldfields (Vpark and Friver) — *E. Crebra/C. erythrophloia/C. dallachiana* over *B.ewartiana, Enneapogon spp., H. contortus* on undulating topography with rocky/stony surface – goldfields neutral red duplex soils.

3. Ironbark / bloodwood basalt systems (Fvale only) — *Crebra/C. erythrophloia/C. dallachiana* (Ironbark/bloodwood) over *B. ewartiana*, *D. sericeum, H. contortus* (with significant invasion of *Cenchrus and Urochloa* spp) on rocky red basalt soils in flat to undulating topography of basalt plains or plateaux.

4. Box Flats granodiorite systems (Vpark and Friver) — *E. brownii* and scattered *C. dallachiana* over mid story of scattered *Carissa, Atalaya* and *E. mitchellii*. Usually heavy soils on lower slopes, associated with middle order streams.

5. Box flats basalt systems (Fvale only) — *E. brownii* over *D. sericeum, D. aristatum, B. decipiens* on heavy grey-brown clay loams – flat to swale areas adjacent to riparian channels of Allingham Creek.

6. Riparian – creeks granodiorite systems (Vpark and Fvale) — Major creek lines dominated by *E. tesserlaris, E. teriticornis, E. platyphylla* and *Melaleuca leucodendron, Melaleuca bracteata, Allocasuarina* spp. and *and Lophostemon* spp. over mixed perennial grasses. Grasses such as B. *pertusa* and *U. mosambicensis* dominate open areas whilst *Arrundinella* sp. occupies creek banks. *Cryptostegia* and other exotic weeds often prevalent in mid-story.

7. Riparian – creeks basalt systems (Fvale only) — Areas associated with Allingham Creek channels- E. tesselaris, *E.brownii*, *M. bracteatus, Allocasuarina spp*. over *D. sericeum/D. aristatum/B. decipiens*. Numerous creek channels, some with semi-permanent water, and associated heavy loam stream levees.

8. Gully systems granodiorite systems (Vpark and Fvale) — Deep gullies often characterized by mixed Eucalypt and overstory and shrubby understory of *Carissa, Atalaya, Eromophola mitchellii and cryptostegia.* Understory grasses usually dominated by *B. pertusa* but *B*.

	ewartiana, H. contortus and *M. repens* may also be present where little grazing.
9. Sandalwood scalds granodiorite systems (Vpark and Fvale)	Usually scalded or eroded sodic soil areas dominated by box (E brownie) overstory, false sandalwood (*E. mitchellii*) and *Carissa (*mid-story with poor grass cover usually dominated by *B. pertusa, Sporobolus* spp. and other annuals. Highly susceptible to erosion from grazing impacts.
10. White Gum Flats granodiorite systems (Vpark and Fvale)	Alluvial flats close to major creek systems, dominated by an overstory of *C. tessellaris, E. playphylla, E. tereticornis, C. dallachiana* over B*. ewartiana, H. contortus, B. decipiens, D. sericeum* .
11. Black Soil Plains basalt systems (FVale)	Scattered *E. brownii* over *D. sericeum/D. aristatum, P.decompositum* on heavy grey cracking clay soils in almost treeless lower lying areas between red basalt areas and riparian zones.
12. Basalt colluvium basalt systems (FVale only)	Mixed Eucalypt (*E. crebra, C. erythrophloia, E. melanophloia, C.dallachiana)* over *B. ewartiana, B. decipiens, D .sericeum ,D aristatum.* On flat to slightly undulating country, almost rock free, with associated blacksoil depressions and gilgais and box areas. Usually in margins between red basalt. NOTE. These were later renamed basalt sediments – a more correct term.
13. Basalt ridges basalt systems (FVale only)	Rocky basalt ridges and walls –*E. crebra/C. erythrophloia /C. dallachiana* with shrubby mid-story of *Carissa spp., Bursaria incana, Erythroxylum* spp., *Atalaya* spp. over *B. ewartiana, H. contortus, H .triticeus and Melenis repens.* Large basalt rocks present.
14. Stony Hills/mixed Euc granodiorite systems (Friver only)	*E. crebra, C. clarksoniana, C. erythrophloia, C. dallachiana* with mid story of *Bursaria, Petalostigma* spp.*Carissa* and *Atalaya* over *H. contortus*, *Enneapogon* spp., A*ristida* spp. *Themeda* spp. on rocky/stony hill-slopes around Mt. Success and other hilly areas of Fanning River.
15. Limestone ridge granodiorite systems (Friver only)	Broadleaf vine thicket scrub associated with limestone ridge in NW of paddock. Over-story of *Brachychiton* spp., *Acacia brewsteri*, *Lophostemon* spp. *Owenia* spp., *Terminalia* spp, over mid-story of vines, *Cajanus* spp. *Indigofera* spp and grass layer dominated by *H.contortus, Melenis repens, B. ewartiana, T. triandra* and *B. pertusa*.

VEGCOM codes used from April 2001 Botanal transect sampling onwards

From the April 2001 Botanal transect sampling the old system of VEGCOM codes and TOPO or landscape position codes was replaced with a separate codes for dominant vegetation community (VEG) and soil type / topographic feature (SOIL/TOPO) within a 10m radius of each quadrat. This system was adopted to provide more discrimination or resolution in regard to landscape features, which may contribute to observed grazing patterns and impacts and to overcome anomalies encountered in use of broad scale VEGCOM descriptors. New codes and descriptors are listed below.

Changes from the previous coding system of July and November 2000

1. The previous VEGCOM codes, which were a combination of vegetation over-story and soil type, have now been separated into VEG and SOIL/TOPO fields for better definition of vegetation maps and interpretation of data attributes scored.

2. The previous TOPO field was removed as most of the critical info from this field will be incorporated into the SOIL/TOPO field.

Table 6.5: VEG codes and descriptors - April 2001 onwards.

VEG	DESCRIPTION	VIRGINIA PARK	FANNING RIVER	FLETCHERVALE
1	Ironbark/Bloodwood	yes	yes	yes
2	Box	yes	yes	yes
3	Whitegum	yes	yes	yes
4	Sandalwood	yes	yes	yes
5	mixed Euc/ shrubby	yes	yes	yes
6	riparian	yes	yes	yes
7	mixed Eucalypt/broadleaf	yes	yes	yes
8	broadleaf scrub/vine thicket	no	yes	no

Table 6.6: SOIL/TOPO codes and descriptors - April 2001 onwards

SOIL/TOPO	DESCRIPTION	VIRGINIA PARK	FANNING RIVER	FLETCHERVALE
1	goldfields – granodiorite	yes	yes	no
2	stony goldfields – granodiorite	yes	yes	no
3	gully systems – granodiorite	yes	yes	no
4	scalded areas – granodiorite	yes	yes	no
5	alluvials/creek banks - granodiorite	yes	yes	no
6	sandy creek beds - granodiorite	yes	yes	no
7	steep rocky slopes/ridges	no	yes	no
8	limestone ridges	no	yes	no
9	red basalt plains/plateaux	no	no	yes
10	rocky Basalt ridges or outcrops	no	no	yes
11	basalt sediments – few rocks	no	no	yes
12	Stony colluviums / basalt margins	no	no	yes
13	blacksoil plains - almost treeless	no	no	yes
14	scalded areas / basalt margins	no	no	yes
15	gully systems – not channels	no	no	yes
16	allluvials – creek/channel banks	no	no	yes
17	creek /channel beds	no	no	yes
18	brown clay loams / box-coolibah	no	no	yes

Detailed description of VEG and SOIL/TOPO codes

NOTE: Both VEG and SOIL TOPO codes contribute to overall description of category

A. VEG Codes - all systems

VEG 1. Ironbark/ Bloodwood with little shrubby mid-story, over mixed perennial tussock grasses (in less disturbed state) dominated by *B.ewartiana, H.contortus, D.sericeum* , plus native annual grasses, legumes and forbs. In disturbed state can be dominated by exotic perennial grasses such *as B.pertusa* (granodiorite) *or C.ciliaris/U.mosambicensis* (basalt). This veg type can occur on GRANODIORITE SOIL/TOPO 1,2 and occasionally 3 and 4 and BASALT SOIL/TOPO 9 and 10 (see SOIL/TOPO descriptions for details).

VEG 2. Box - Over mixed perennial and annual grasses dominated by *B.decipiens* and *D.sericeum* in less disturbed states on both granodiorite and basalt (more *Dichanthium* in basalt systems). On grano diorite BOX areas associated mainly with heavy clay/loam poorer drained lower slope areas which are subject to surface scalding and gully erosion when highly disturbed. On basalt systems BOX areas associated with blacksoil and basalt quarternary sediment areas. Rubbervine often significant.This VEG type can occur on GRANODIORITE SOIL/TOPO 1-4 or BASALT SOIL/TOPO 11, 13, 16 and 17.

VEG 3. Whitegum – *C. tesserlaris* and/or *C.dalachiana*, and/or *C. platyphylla* and/or *E. teriticornis* over mixed perennial and annual grasses dominated by *B.decipiens, D.serecium/fecundum*, *E.procera* in undisturbed state and replaced by exotic perennials in response to sustained heavy grazing. Usually associated with sandy-loam levee areas associated with higher order streams, particularly in granodiorite systems but occasionally adjacent to riparian areas in basalt systems. This VEG type can occur on GRANODIORITE SOIL/TOPO 4/5 and BASALT SOIL/TOPO 11 and 16

VEG 4. Sandalwood – Shrubby areas dominated by *E.mitchellii* and *Carissa spp*, with *Atalaya, Flindersia* and other shrubs often present. On granodiorite systems usually associated with heavily scalded lower slope areas and bigger gully systems. On basalt systems, usually associated with stony colluvial margins between red basalt and heavy claysoil areas, often at bottom on basalt ridges. Rubbervine often present. This VEG type associated with GRANODIORITE SOIL/TOPO 3 and 4 and BASALT SOIL/TOPO 12.

VEG 5. Mixed Shrubby - Usually Ironbark/bloodwood or mixed Eucalypt overstory with significant mixed shrubby mid-story dominated *by Carissa, Atalaya, Erythroxylum , Eremophola mitchellii* and other shrubs. On granodiorite systems usually associated with dissected country, characterized by significant gully systems. May be confined to actual gully areas or skeletal slopes in upper/mid-slope areas but more extensive in lower slope dissected areas. Has similar characteristics to SANDALWOOD VEG 4 but not confined to scalded areas or dominated by *E. mitchellii*. On basalt systems can be associated with rocky basalt outcrops and ridges or colluvial margins. This VEG type associated with GRANODIORITE SOIL/TOPO 3 and 7 and BASALT SOIL/TOPO 11 and 12.

VEG 6. Riparian - Mixed creek bank and adjacent new levee veg community with overstory dominated on granodiorite systems *by M. bracteatus, M. leucodendron, Allocasuarina spp., Lophostemon spp* and *E.teriticornis* over mixed perennial and annual grasses dominated by *D. fecundum, B. decipiens, E. procera* and *Arundinella* in less disturbed states and *B. pertusa* in heavily grazed areas. On basalt systems overstory dominated by *M.bracteatus, Allocasuarina spp, E. brownii, C. tesserlaris* and other Euc species over mixed perennials dominated by *D. fecundum, D.aristatum, B. decipiens, Arindinella* and *Capilipedium spp* (replaced by *B.pertusa, U. mosambicensis* and other exotics with heavy grazing). This VEG type associated with GRANODIORITE SOIL/TOPO 5 and 6 and BASALT SOIL/TOPO 16 and 17.

VEG 7. Broadleaf Scrub/Vine Thicket - Mixed broadleaf overstory dominated by Lyspohyllum, Brachychiton, Owenia, Terminalia, Alphitonia and other species with mid-story of leguminous shrubs such as Cajanus, Indigofera and Tephrosia spp and malvaceous shrubs such as Hibiscus, Sida, Abelmoschus and other. Understory either absent under closed canopy or dominated by twining legumes and forbs and mixed native and exotic grasses where opened by disturbance. This veg type almost exclusively associated with limestone ridge areas and isolated hills within the Fanning River study paddock. Although some of these tree and shrub species occur in isolation on basalt ridges, this Veg type Fanning River only, TOPO 7.

VEG 8. Mixed Eucalypt/Broadleaf – Mixed Eucalypt and broadleaf overstory associated with steep rocky slopes or hilltops, mainly on granodiorite systems. Overstory usually dominated by a mixture of bloodwoods (C. erythrophloia, C. clarksoniana), scattered E.crebra, C. dalachiana and box (E. Normantensis) plus some broadleaf species such as Petalostigma, Brachychiton and others. It is often an integrade between Ironbark/bloodwood and broadleaf scrub veg types on Fanning River. Mid-story can be shrubby (Atalaya, Erythroxylum etc) or open, over mixed perennial tussock grass. This VEG type associated with GRANODIORITE SOIL/TOPO 8 only.

SOIL/TOPO codes – Granodiorite systems

SOIL/TOPO 1. Goldfield/Dalrymple – normal/undulating - Granodiorite duplex soils over mixed native perennial grasses, which are usually replaced by *B. pertusa* after sustained heavy grazing. Usually undulating country with sandy/loamy surface and little stone, though occasional granite outcrops occur. Usually dominated by VEG 1 (ironbark bloodwood).

SOIL/TOPO 2. Stony Goldfields - Similar to SOIL/TOPO 1 but with distinct stony soil surface and frequent rocky outcrops. May be associated with areas of increased slope and/or gullying and sol surface loss in upslope areas.VEG overstory mainly ironbark/bloodwood with understory often characterized by presence of *Enneapogon* species and other increaser perennial and annuals, unless dominated by *B. pertusa*.

SOIL/TOPO 3. Gully systems - On upper and mid-slope these may be deep but narrow systems, where the overstory and mid-story veg is basically ironbark/bloodwood while the understory is degraded and either bare or dominated by exotics. On the lower slopes extensive gully systems may be characterized by a degraded box and/or whitegum overstory and a mid-story dominated by *Carissa, Atalaya, Eromophola mitchellii* and othershrubs. Understory grasses are usually dominated by pertusa.

SOIL/TOPO 4. Scalded Areas - Usually severely degrade lower slope areas characterized by extensive sheet, rill and gully erosion. Overstory often scattered (or dead) box with shrubby mid-story dominated by *E.mitchellii* and *Carissa spp.* Where scalds are severe there are few live trees and only scattered shrubs. Grass layer is absent or dominated by *B. pertusa* or *Sporobolus spp*. with occasional islands of perennial tussock grasses

SOIL/TOPO 5. Alluvial Soils/ Creek Banks - Sandy/loamy levee areas adjacent to mid/ higher order streams. Usually associated with mixed whitegum veg system (VEG 3) over a grassy understory of mixed perennial grasses. These areas are often dominated by exotic perennials and weedy forbs, due to proximity to water points. They can be associated with VEG type 3 and 4 on granodiorite system. These areas can also contain significant rubbervine and broadleaf weed infestation.

SOIL/TOPO 6. Sandy Creek Bed - Associated exclusively with granodiorite riparian (VEG 6) this SOIL/TOPO is provided to discriminate between creek bank (riparian) and usually bare sandy creek beds in larger streams.

SOIL/TOPO 7. Steep Rocky Hillslopes or Ridges - Basically restricted to the steeper hillslopes of Fanning River paddock – but excluding the limestone ridge (SOIL/TOPO 8). The slopes of Mt. Surprise are also included in this code.VEG type 8 is almost exclusively associated with this system, but it can also contain some VEG 1 (IB/BW) or VEG 7 (broadleaf scrub) on some hilltops.

SOIL/TOPO 8. - Limestone Ridge – Restricted to Fanning River paddock only and associated exclusively with VEG 7 (broadleaf scrub/vine thicket). Rocky limestone ridge and hills supporting dry rainforest closed canopy forest.

SOIL / TOPO codes - Basalt systems

SOIL/TOPO 9. Basalt Plains/Plateau - Basaltic red clay loams on flat to slightly undulating terrain with some surface rock and rocky outcrops, supporting mainly IB/Bwwith scattered mid-story *of Carissa, Bursaria, Maytenus* and *Atalaya* over mixed perennial tussock grasses dominated by *B. ewartiana*. Where disturbed, exotic species *U.mosambicensis* and *C.ciliaris* often dominate.

SOIL/TOPO 10. Rocky Basalt Ridges And Outcrops - Includes basalt wall areas and outcrops within SOIL/TOPO 9. Similar IB/BW overstory with addition of scattered *C.dalachiana , Petalostigma, Alphitonia, Bursaria* and shrubby mid-story species such as *Carissa, Atalaya, Erythroxylum, Maytenus* and *Santalum*. Grassy layer often characterized by presence of *H.triticeus*. The exotic grass *M.repens* is often prominent in these areas.

SOIL/TOPO 11. Basalt Sediments - Formally described as **basalt colluvium**. These are areas of depositional basalt derived soils characterized by a mosaic of almost stone free brown loams and heavy clay gilgais or swales supporting a mixed Eucalypt overstory of *E. crebra, E. melanophloia, E.brownii, C.erythrophloia* and *C.dalachiana*. over an open mid-story and grassy layer dominated by *B.decipiens, D.sericeum* and *D.aristatum* with some *B.ewartiana*.

SOIL/TOPO 12. Basalt Margins - These areas are stony colluvial margins between red basalt soils an transitional basalt sediment areas (SOIL/TOPO 11). They support a mixed Eucalypt overstory of *E.crebra, C.dallachiana, C.erythrophloia* and *E.brownii* over a usually shrubby mid-story of *Atalaya, Bursaria, Carissa, E.mitchellia, Flindersia* and *Maytenus*. The grass layer is often scattered and dominated by Enneapogon, Sporobolius, Eragrostis and Melenis along with native forbs and legumes.

SOIL/TOPO 13. Black Soil – Almost treeless cracking claysoil plains or depressions dominated *by D. sericeum, P.decompositum, A. squarosa, D.aristatum* and *Eriochloa spp*.

SOIL/TOPO 14. Scalded Areas - Rare in basalt systems, but occasionally associated with SOIL/TOPO 9 and 12 where surface erosion has removed loamy top layer exposing heavier sodic clay subsurface after sustained heavy patch grazing.

SOIL/TOPO 15. Gully Systems - Rare in basalt systems but does occur in small areas adjacent to basalt margins associated with VEG 4 and 5.

SOIL/TOPO 16. Alluvial Soils – Assocated with creek or channel banks adjacent to higher order streams. Usually loamy sediments rather than sandy. Overstory usually box but occasionally whitegum (VEG 3).

SOIL/TOPO 17. Creek/Channel Bed – Mid-stream dry channel beds – usually heavy soil – mostly bare, but occasionally supporting couch lawns.

SOIL/TOPO 18. Brown Clay Loams - Associated with box veg communities (veg 2) which occur on lower slopes between basalt margins , basalt sediments and riparian areas bounding Allingham Creek. Overstory dominated by Reid River Box (*E.brownii)* and Coolibah (*E.coolibah*?) with understory dominated by *D. sericeum, P.decompositum, A. squarosa, D.aristatum* and *Eriochloa spp*.

Table 6.7: Reconciliation of VEGCOM, VEG and SOIL/TOPO codes from all samplings

	JULY 2000	NOV. 2000	APRIL 2001 ONWARD	
PADDOCK	***VEGCOM***	**VEGCOM**	**VEG**	**SOIL/TOPO**
VPARK	1	1	1	1
FRIV	1	1	1	1
FVALE	1	3	1	9
VPARK	2	8	5	3
FRIV	2	10	3	5
FVALE	2	12	5	11
FVALE	2	12	2	11
VPARK	3	6	6	5
VPARK	3	10	3	5
FRIV	3	9	4	4
FVALE	3	11	2	13
VPARK	4	4	2	4
FRIV	4	4	2	4
FVALE	4	5	2	18
VPARK	5	9	4	4
FRIV	5	6	6	5
FRIV	5	6	6	6
FVALE	5	7	6	16
FVALE	5	7	6	17
VPARK	6	2	1	2
FRIV	6	14	7	7
FVALE	6	13	1	10
FVALE	6	13	5	10
FRIV	7	15	8	8
FRIV	8	8	5	3

Use of 4 m^2 reference quadrats for training and calibration

At each of the three (3) study paddocks (Virginia Park, Fletchervale and Fanning River) a set of 2m*2m reference quadrats were established for initial and ongoing observer training and to generate a series of photo standards. The number of quadrats varied slightly between paddocks but was at least 10 in each case. Actual numbers were:- Virginia Park = 13, Fletchervale = 11, Fanning River = 11.

OBSERVERS - Jeff Corfield, Peter Allen, Peter Fry, Taoufik Ksiksi, with John Gross present for Virginia Park.

Quadrats were selected to try and cover the range of biomass yields, projected covers, defoliation and pasture types likely to be encountered within the paddock – within the constraint of easy accessibility for reference during each sampling exercise.

Each quadrat was initially marked by placing metal fence droppers in each corner and a permanent steel picket at the centre, on which was recorded the quadrat number. At the conclusion of the calibration exercise the temporary metal droppers were removed for stock safety reasons.

Each reference quadrat was photographed (by Taoufik KsiKsi, QDPI, Charters Towers) both obliquely from one side and as close to vertical as possible from the back of a quad bike (same direction) for future reference and for generation of photo standards to use in future sampling exercises. Taoufik retains this photo record.

Observer training and calibration using reference quadrats

This involved 3 components in a “double sampling” approach

1. All observers, in the process of choosing the range of reference quadrats, arrived at a mutually acceptable scale for yield estimates (to cover the range of yields likely to be encountered). Other variables such as cover, defoliation and greenness were either scored as a percentage or on a pre-determined rating scale. For each quadrat, observers then settled on a consensus score for the major variables to be recorded. Individual observer scores were also recorded for future reference.

2. Within each 2m*2m quadrat each observer then scored each 1m*1m sub-quadrat in the same order, recording variable scores on the same scales used for the 2m*2m quadrats. This exercise was to derive individual observer relationships between the more familiar $1m^2$ quadrat size and $4m^2$ reference quadrat size and also to provide immediate “in the field” feedback to observers about effects of spatial scale on observations. At the end of this exercise observers compared their component $1m^2$ scores with the corresponding $4m^2$ scores and adjusted their individual estimations accordingly.

3. At the end of exercise 2 a set of $1m^2$ standards were scored by each observer. A sub-set of these 1m standards was photographed to derive cover and greenness values and the full set was harvested to derive biomass values. This data was then used to generate individual observer regressions for biomass yield, cover and greenness. Defoliation ratings could not be calibrated in this way, but between-observer variation could be monitored . Results from this calibration exercise were then fed back to observers to assist in refining estimation techniques, and reducing between observer variation.

On-going use of reference standards

At each field sampling exercise, each observer re-scored the full set (or a sub-set) of reference standards as part of the “double sampling” training and calibration process. If possible, both separate whole quadrat and component sub-quadrat scores are recorded as in initial calibration exercise. During the first sampling exercise (June/July 2000) This latter exercise was unnecessary, as field sampling followed straight on after establishment of reference quadrats.

If structure or biomass yield of any reference quadrat changes significantly during the season, due to heavy grazing or disturbance, consideration should be given to adding additional reference quadrats to original set. Reference quadrats were also re-photographed at each sampling period as a record of phenology and seasonal conditions.

Note: The herbage species list established in July 2000 and added to in November 2000 continued to be used at all subsequent samplings.

Vegetation sampling instruction sheets

Burdekin Catchment Study – Sampling Procedure – 1st Sampling July 2000

1. Locate sample site using “go to” facility for predetermined weigh point
2. Place dropper close to centre of sample site
3. Each observer to run 100m tape out in opposite directions (either NSEW or Dslope/upslope or cross-slope)
4. Walking back along 100m tape line, locate each pre-determined quad position
5. Using HP spreadsheet program, record parameters & variables listed below
6. Repeat procedure for 2nd set of sampling arms at sample site

Burdekin Catchment Study – Sampling Procedure – 2nd Sampling Nov 2000

1. A set of predetermined TRANSECTS will be selected, each with START (A) and END (B) waypoints already loaded into each GPS as waypoints and / or routes.
2. The entire length of each transect will be scored in SECTIONS of 200m each (or part thereof at the end of each transect).
3. Observers will work in pairs, with each observer scoring 2*200m sections at a time, leap-frogging along each transect, using the quad-bike and GPS “go-to” facility to locate each new start point.
4. Within each transect SECTION, observers will score TEN 2m*2m quadrats whose locations have been pre-selected in a stratified random fashion. The START and END of each 200m SECTION will be recorded as GPS waypoints using the MARK facility on each GPS. The associated waypoint number MUST be recorded against the START and END records on the HP.
5. Distances between QUADRATS along transect sections will be PACED. Quadrat position sets will be in PACES not metres. Observers MUST write their NAMES on each quadrat position sheet they use and MARK OFF each quadrat set with TRANSECT and SECTION number and RETAIN SHEET for later use.
6. If there is less than 200m in the last SECTION scored, just score up to the number of quadrats within the distance available and record the END GPS weigh point at the end of the transect.
7. Using HP spreadsheet program, record parameters & variables listed. Fill in each variable cell to ensure no data is missed and avoid ambiguity in data interpretation.

Note: November 2000 instructions remained the same for subsequent scorings

Table 6.8: Description of variables recorded in hillslope-scale vegetation measurements

Variable	Description	Reference	Units or Categories
SITE	Study paddock code		FRIVPAT=Fanning River patch study
DATE	Sampling date		dd-Mon-yy
TRANSECT	Patch transect number - refers to paddock scale transects on which patch study transects located		1-13
SECTION	100 m section of transect bounded by start and end waypoints		1-3
BURN	Status of quadrat in relation to recent burning in paddock		Categorical variable 1=unburnt, 2= burnt
WAYPOINT	GPS waypoint number – recorded at start and end of each 100m patch transect		UTM GW84 datum 55k zone
PATCH	Patch Type - see separate code and description list		Categorical. See code descriptions in this appendix.
DISTANCE	Distance from start of patch transect section		(meters and decimetres)
COVER	Mean total projected cover (foliar plus litter cover + rocks) for patch		percent
PAST_HT	Mean pasture height for patch - to flag leaf, excluding inflorescences		centimetres
DOM_ SP1	Most dominant pasture species or species group in patch (Botanal DWR method)	BOTANAL Tothill et al (1978)	ID number
SP1_PERC	Estimated percentage biomass of dom_sp1		percent
DOM_SP2	Second most dominant species or species group in patch (Botanal DWR method)	BOTANAL Tothill et al (1978)	ID number
SP2_PERC	Estimated percentage biomass of dom_sp2		percent
DOM_SP3	Third most dominant species or species group in patch (Botanal DWR method) – used from Sep 2001 onward	BOTANAL Tothill et al (1978)	ID number
SP3_PERC	Estimated percentage biomass of dom_sp3 – used from Sep 2001 onward		percent
YIELD_EST	Mean standing crop biomass (comparative yield estimate) – used from Sep 2001 onward	BOTANAL Tothill et al (1978)	0-100 rating scale
DEFOL	Mean defoliation rating for patch on a 0-5 scale – used from Sep 2001 onward	Andrew (1986)	0-5 scale 0=nil, 1=<5% 2=5-25% 3=25-50% 4=50-75% 5=>75%
MAX_DIAM	Diameter of longest axis of significant bare or grazed patch – used for July 2001 only		centimeters
MIN_DIAM	Diameter of shortest perpendicular axis of significant bare or grazed patch - used for July 2000 only		centimeters

Table 6.9: Record of variables recorded at each scoring – July 2001 - September 2002

VARIABLE	JULY 2001	SEPT 2001	JAN 2002	APRIL 2002	SEPT 2002
SITE	yes	yes	yes	yes	yes
DATE	yes	yes	yes	yes	yes
TRANSECT	yes	yes	yes	yes	yes
SECTION	yes	yes	yes	yes	yes
PATCH	yes	yes	yes	yes	yes
DISTANCE	yes	yes	yes	yes	yes
WAY_PT	yes	yes	yes	yes	yes
COVER	yes	yes	yes	yes	yes
PAST_HT	yes	yes	yes	yes	yes
DOM_SP1	yes	yes	yes	yes	yes
SP1_PERC	yes	yes	yes	yes	yes
DOM_SP2	yes	yes	yes	yes	yes
SP2_PERC	yes	yes	yes	yes	yes
DOM_SP3	no	yes	yes	yes	yes
SP3_PERC	no	yes	yes	yes	yes
YIELD_EST	no	yes	yes	yes	yes
DEFOL	no	yes	yes	yes	yes
MAX_DIAM	yes	no	no	no	no
MIN_DIAM	yes	no	no	no	no

Changes to recording methodology at second scoring – September 2001

At the second scoring occasion, the following changes were made to variables recorded and recording methodology.

1. Standing crop herbage biomass (Botanal comparative yield method) was added
2. Bare and grazed patch maximum and minimum diameters were abandoned
3. Dominant species variables increased from first two to first three.
4. Herbage defoliation rating (Andrew 1986) was added
5. Estimation of all variables was confined to a 1m wide belt transect along tape center line
6. Additional patch types were also recorded (see consolidated list below)

Addition of further patch transects – January 2002 scoring

Further patch transects were established along Botanal transects 8, 9 and 13 during the January 2002 scoring, to record temporal changes in patch dynamics around water point locations. For both transects 8 and 9 these took the form of 3 contiguous 100m patch transects running out from the water trough near where both botanal transects commence. On botanal transect 13, they consisted of two contiguous running along the transect line from transect waypoint 13A towards 13B, and a further two 100m patch transects placed on both unburnt and recently burnt sections several hundred meters further along the Botanal transect (see transect descriptions and location details in appendix 1 of this document). As with previously established patch transects, start and end locations were marked by trees or wooden pegs marked with flagging tape and GPS position waypoints recorded.

Data variables recorded remained the same as for September 2001, with further patch types added to cover the impact of burning and influence of previously grazed or recovering bare patches on patterns of subsequent patch grazing (see consolidated list and description of patch types at the end of this document). A WAYPOINT field was also added to the data collection spreadsheet from January onwards.

Detailed Descriptions of Pasture/ Patch Characterization Variables

DIAM_MAX and DIAM_MIN - Bare and grazed patch diameters

At the July 2001 scoring the longest and shortest diameters of each bare or grazed patch encountered within each transect were recorded as a measure of patch dimensions. Variables associated with all other patch types were recorded only within the 1m belt transects along the tapeline.

PAST_HT - Mean pasture height

Mean pasture height was estimated by averaging several height measurements across each patch. Pasture height was taken from the top of the vegetative layer, excluding inflorescences.

COVER - Mean total projected cover

Mean total projected cover - the total of foliar and litter cover – was estimated across the entire patch in the case of bare and grazed patches and the 1m wide belt transect in the case of all other patch types.

DOM_SP1, DOM_SP2, DOM_SP3 - Dominant species or species groups

The identity code of the first three dominant pasture species or groups (determined by Botanal dry weight rank method (Tothill, 1978) was recorded (see species list below).

SP1_PERC, SP2_PERC, SP3_PERC - Estimated percentage contribution of dominant 3 species or species groups using Botanal percentage rank method (Tothill et al., 1978)

YIELD_EST - Estimated standing dry biomass – using Botanal comparative yield estimate technique (Tothill et al., 1978). Estimates converted to kg/ha dry matter using regressions derived from calibration standards.

DEFOL – Estimated herbage defoliation **–** using 0-5 rating scale (Andrew, 1988)

Definitions and descriptions of patches

For the purposes of this study a “patch” was defined as an area usually exceeding 1m in diameter along the length and breadth of the belt transect, which exhibits common definitional features in respect to cover, biomass, species composition and grazing score across the majority of the patch area. The exceptions to this were when cattle pads, small gullies, rocks and large logs were recorded along transects – these being commonly <1m in width.

Thus, in the case of **bare patches**, these usually exceeded $1m^2$ and the majority of the area contained was bare ground (<10% TPC), whilst **grazed patches** usually exceeded $1m^2$, with the majority of the area contained being grazed to score 3 or more (> 50% defoliated) on the defoliation index used.

The **intermittent grazed and intermittent ungrazed patches** were defined as patches within which grazing was occurring to a greater (IG) or lesser (IU) extent across the whole area contained, but at a scale of $<1m^2$ in any portion. Intermittent grazed and ungrazed patches thus consisted of a mosaic of sub $1m^2$ grazed and ungrazed patches, with the proportion of grazed to ungrazed defining the patch type.

Transition zone patches were defined as areas straddling the margins of bare and grassed areas, where bare patch expansion often occurs in response to preferential grazing. Transitional zones can be either recovering or degrading.

Table 6.10: Description of all patch types used to date in patch transect study At Fanning River

PATCH	PATCH DESCRIPTION
GP	Grazed patch - currently being grazed TO >= 50% defoliation
UP	Ungrazed patch – < 5-10% defoliated
IG	Intermittent grazed patch (currently more grazed than ungrazed)
IU	Intermittent ungrazed patch (currently more ungrazed than grazed)
BG	Bare ground (largely scalded areas) - little herbage cover
TZ	Transition zone between edge of bare scald and grassed areas – can be degrading or recovering
CP	Cattle pad - usually bare but sometimes trampled grass if new
CC	Cattle camp - grass usually flattened or destroyed by cattle trampling
SG	Small gully –usually little herbage cover
CB	Creek bed - little herbage cover
EB	Eroded bank - usually upper creek bank damaged by erosion or cattle
LB	Lower bank - adjacent to creek bed – can have green “lawn” cover
RD	Roadway or track – little herbage cover
RK	Rock
LG	Large log or fallen tree
OGP	Old grazed patch - previously grazed patch but no recent grazing
OIG	Old intermittent grazed patch - previously impacted by intermittent heavy grazing - but no recent grazing
OIU	Old intermittent ungrazed patch - previously impacted by intermittent light-moderate grazing - but no recent grazing

Table 6.11: Species and species group codes and IDs used throughout patch transect study

BOTNUM	SPECIES	Functional group 1	Functional group 2	Functional group 3
1	*Aristida* spp.	perennial grass	native	increaser
2	*Bothriochloa decipiens*	perennial grass	native	decreaser
3	*Bothriochloa ewartiana*	perennial grass	native	increaser
4	*Chrysopogon fallax*	perennial grass	native	intermediate
5	*Dichanthium spp.*	perennial grass	native	decreaser
6	*Enneapogon sp*	perennial grass	native	increaser
7	*Heterogon contortus*	perennial grass	native	decreaser
8	*Heteropogon triticeus*	perennial grass	native	decreaser
9	*Themeda triandra*	perennial grass	native	decreaser
10	*Sorghum plumosum*	perennial grass	native	decreaser
11	Other native per. grasses	perennial grass	native	intermediate
12	*Bothriochloa pertusa*	perennial grass	exotic	increaser
13	*Melenis repens*	perennial grass	exotic	increaser
14	*Cenchrus ciliaris*	perennial grass	exotic	increaser
15	*Urochloa mosambicensis*	perennial grass	exotic	increaser
16	Other exotic grasses	perennial grass	exotic	increaser
17	*Dactylocteneum radulans*	annual grass	native	increaser
18	*Sporobolus* sp.	annual grass	native	increaser
19	*Tragus austalianus*	annual grass	native	increaser
20	Other annual grasses	annual grass	native	increaser
21	Legumes	legume	mixed	mixed
22	Sedges	sedge	native	mixed
23	Forbs	forb	mixed	mixed
24	*Panicum* spp.	perennial grass	native	decreaser
25	*Eulalia aurea*	perennial grass	native	intermediate
26	*Dichanthium aristatum*	perennial grass	native	increaser

Appendix 7. Time-series analysis using Landsat TM in the Burdekin Catchment, Qld

Kate Richardson and Robert Karfs, NT Dept. of Lands Planning and Environment

Time-series Landsat TM imagery

The purpose of this appendix is to report on an evaluation of time-series analysis as applied in the Burdekin River in selected areas, i.e. focal paddocks: Fanning River, Virginia Park and Fletchervale. Separate 1: 100,000 scale trend summary image maps have been provided for each pastoral property.

Characteristics of the imagery utilized:

- Pixel size of imagery (ie. feature resolution) – 25m.
- Projection: TMAMG55, Datum: AGD66.
- Dates analysed in the time-series – 1991, 1993, 1995, 1996, 1997 and 1998.
  - All imagery was acquired in the late dry season (August to October).
- A cover index derived from Landsat TM band 3 (visible red) was used in the analysis.

Landscape characteristics and landsat cover index

All landscapes that had relief more than 90m and a slope greater than 10% were classed as ‘rugged country’. These landscapes were not included in the analysis as grazing impact in these areas is normally minimal. In the remaining areas, land type stratification was done using land system data to separate inherently different landscapes with different surface features (eg. light versus dark coloured soils) allowing for more accurate interpretation of cover.

Over time landscapes dominated by ephemeral cover often experience greater fluctuations in cover compared to landscapes dominated by perennial cover. By examining the brightness and variation in cover indices derived from time-series Landsat satellite data, ephemeral-perennial vegetation compositions are interpreted. Cover indices summarised in graphical plots or as maps are a ‘first’ interpretation of land cover trend and condition. Ground truthing and data collection at monitoring sites are necessary to refine the relationship between land condition and cover indices.

Cover indices are numeric values derived from calibrated Landsat images that are adjusted to the regional response of a specific land type. Cover change detected by the satellite data may be due to either grazing impact, seasonal variability, fire or unmapped landscape heterogeneity. Interpretation of these data in relation to distance from water and the location of fences, roads and land types assist in determining the cause of change. Knowledge of management history gained from archived reports, photographs, and from discussion with land managers are further important sources with which to interpret cover indices and select monitoring sites.

Light coloured soils - the soils of the Goldfields land system (Fanning River and Virginia Park) were classified as bright corresponding to high spectral reflectance in TM band 3. When bright soils are covered by dry ground vegetation, the spectral reflectance is lowered, resulting in low cover index values.

Dark coloured soils - the soils of the basaltic area (Fletchervale) were classed as dark corresponding to low spectral reflectance. When these soils are covered by dry ground vegetation, the spectral reflectance is increased, resulting in high cover index values.

Finally it must also be understood that Landsat cover indices used in this analysis range from 1991 to 1998. Hence, landscape change in response to recent good rainfall years over the region is not represented.

Fanning River and Virginia Park

There are five broad land type classes within the Fanning River and Virginia Park properties based on descriptions from the Land Systems of the Dalrymple Shire. These land types are listed below and percentage area of each land type shown in Figure 7.1.

- Alluvial
- Cainozoic
- Granodiorite
- Igneous
- Sedimentary

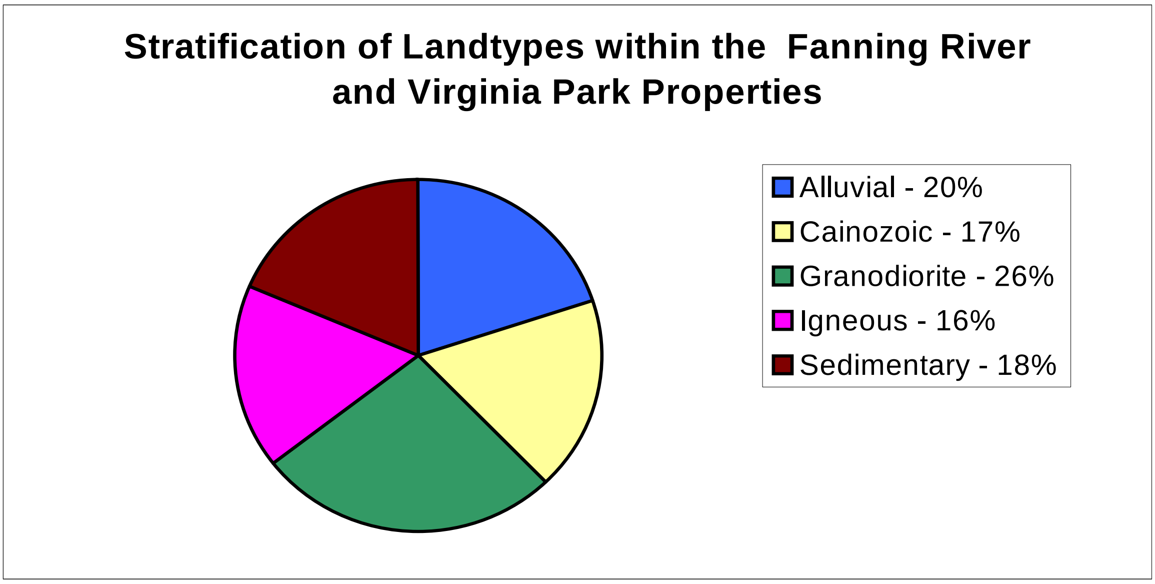


Figure 7.1: Stratification of the Fanning River and Virginia Park.

For understanding the impacts of land management and for providing representative data which to relate to Landsat cover indices, ground-based monitoring sites would need to be located on all five land types. If grazing impact is the focus, then concentrating on one or two productive land types may be the best option with less attention focused on 'natural' low productive land types. Figure 7.2 shows the spatial distribution of these land types over Fanning River and Virginia Park.

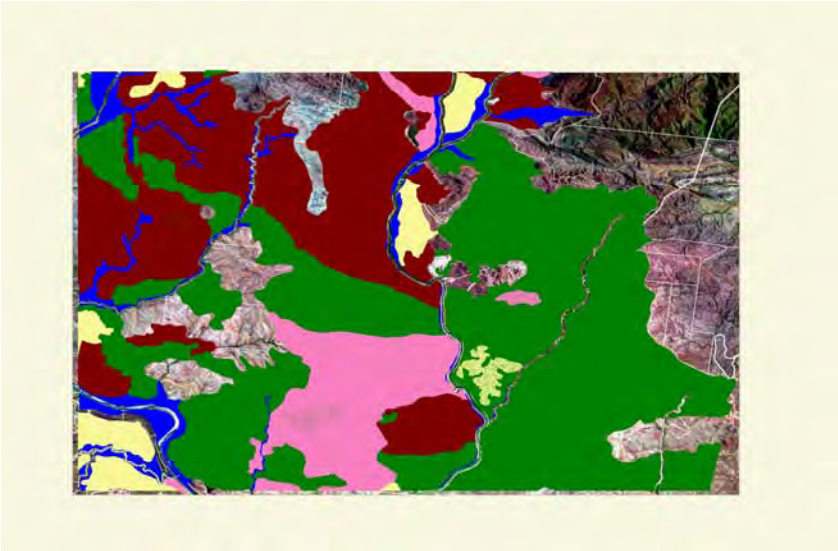


Figure 7.2: Spatial distribution of land types in the Fanning River and Virginia Park. Blue depicting alluvial soils, pink the igneous derived soils, yellow the Cainozoic soils, brown the sedimentary soils and green the granodioritic soils.

Time traces for the five land types on Fanning River and Virginia Park are shown in Figure 7.3. Our interpretation is that the Alluvial and Cainozoic land types had more cover during the 1993-96 drought compared with the other land types. But ground truthing needs to confirm that the soil colour for the Alluvial and Cainozoic land types is light coloured, similar to the three other land types.

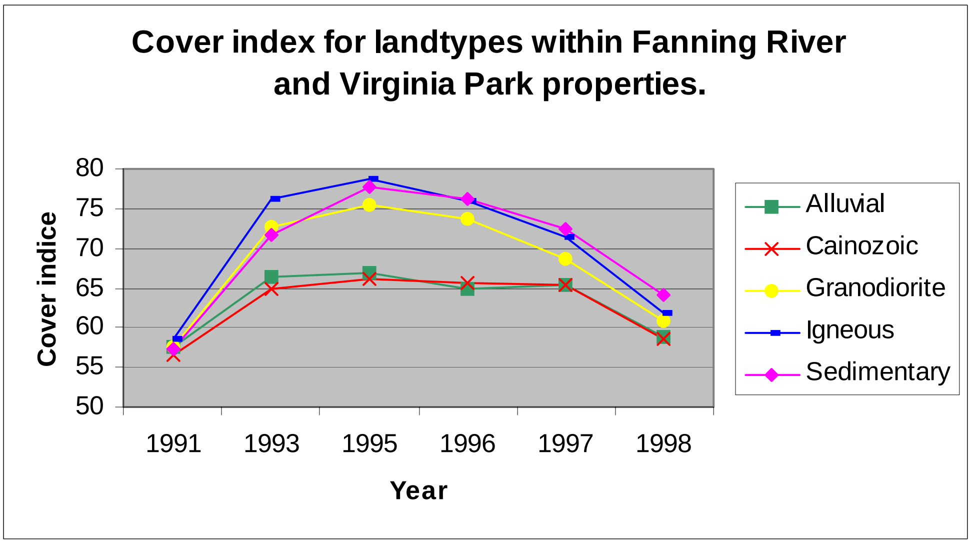


Figure 7.3: Low vegetation cover in the drought period of 1993-96, results in high cover indices for light coloured soils in Fanning River and Virginia Park.

Fletchervale

Two significant soil types were analysed within the basalt land type that comprises the Fletchervale property. These soil types are listed below and percentage area for each soil type is shown in Figure 7.4. The spatial distribution of these land types over Fletchervale is shown in Figure 7.5.

Ferrosol

Vertosol

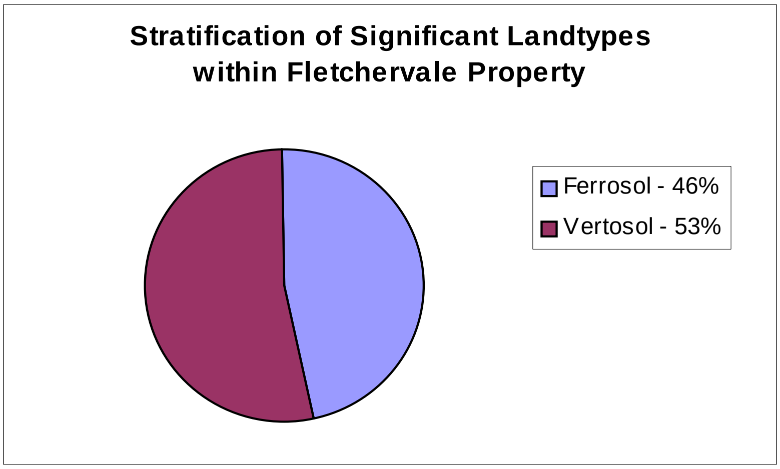


Figure7.4: Stratification of Fletchervale.

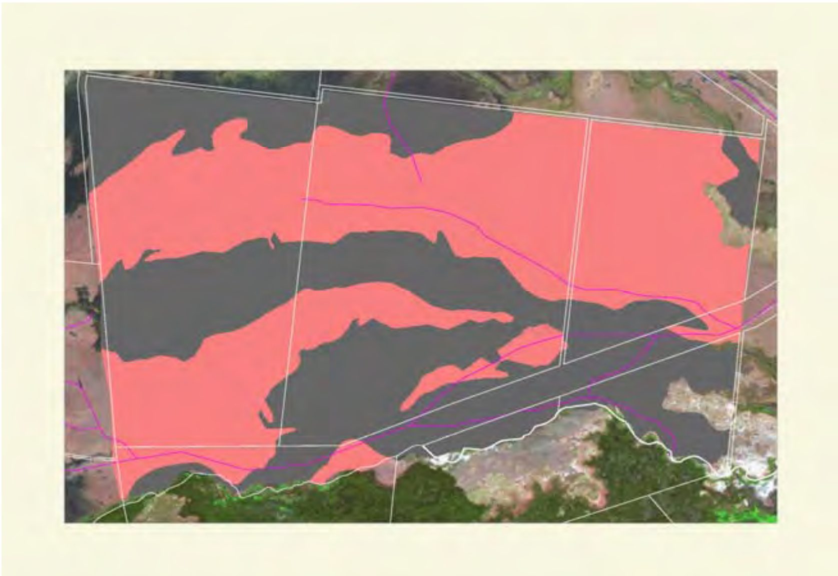


Figure 7.5: Spatial distribution of soil types in the Fletchervale. Ferrosol soils are coloured orange and the vertosol soils dark grey.

A comparison of ferrosols and vertosols on Fletchervale with similar landscapes over the entire Dalrymple Shire is shown in Figure 7.6. The time traces indicate Fletchervale had vegetation cover similar to that of the greater Dalrymple Shire before the drought period began in 1993. During the drought, cover levels over Fletchervale were slightly higher than the regional average and by 1998, two years after the drought; cover was significantly higher compared with the rest of the Shire. This relationship suggests that on Fletchervale there may have been relatively more perennial grasses on the basalt land type that survived drought and responded as seasonal conditions improved. The sharp increase in cover in 1998 is likely due to a flush of annual grasses infilling between perennial patches. Ground truthing, Landscape Function Analysis and examination of management history are required to verify this hypothesis.

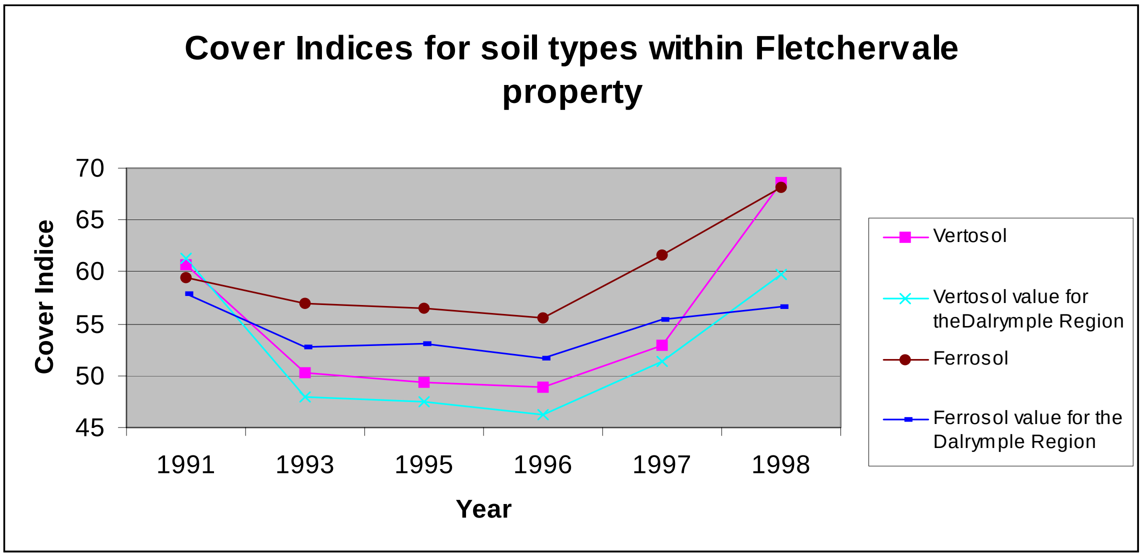


Figure 7.6: A comparison of vegetation cover on dark coloured soils of the basalt land type of Fletchervale compared with mean values for the Dalrymple Shire.

By comparing cover indices of a specific area (eg. property, paddock) with regional averages, differences in management in the context of seasonal variation may be identified. This type of intelligence assists in deciding where to look for possible monitoring sites with a key objective of finding a suite of monitoring sites on the same land type ranging in condition from poor to good from which to compare ground data and historical cover.

Trend summary image maps

Cover indices can also be summarised spatially as ‘trend summary image maps’ for discriminant analysis of vegetation cover change within stratified land types. A schematic explaining the ‘colours’ on trend summary images is shown in Figure 7.7. Table 7.1 provides further explanation of trend summary colour representation.

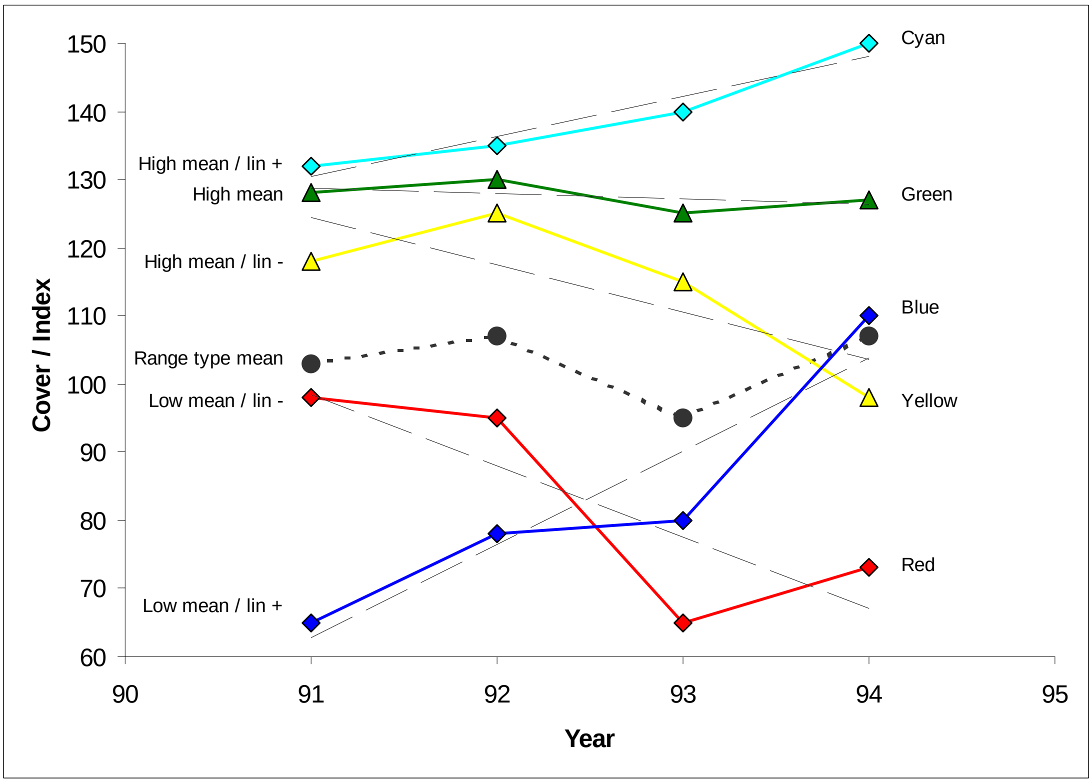


Figure 7.7: Schematic diagram of different cover responses through time, which may apply, to a pixel, or larger area. Land type mean (black dashed line) is the broad spectral response from a stratified landscape. Summaries are listed on the left and the colour equivalent is listed on the right of the diagram. Linear trend lines as thin black dashed lines are represented for each summary.

Table 7.1: – Trend summary imagery colour summation

Mean Brightness over period (displayed in intensity of green) RELATIVE to regional annual response.	**Slope**- linear trend over time RELATIVE to regional mean trend (positive trend in Blue negative trend in red).	Combined map colour using additive colour scheme – **Interpretation** based on an assumption of uniform soil colour.
GREEN: High **+**	BLUE: Positive **=**	CYAN: High cover, increasing trend over period
GREEN: High **+**	BLACK: Steady **=**	GREEN: High cover, trend close to regional average
GREEN: High **+**	RED: Negative **=**	YELLOW: High cover, trend decline over period
BLACK: Low **+**	BLUE: **Positive** **=**	BLUE: Low initial cover, increasing trend over period
BLACK: Low **+**	BLACK: Steady **=**	BLACK: Low cover relative to regional average, steady
BLACK: Low **+**	RED: Negative **=**	RED: Low cover, trend decline over period

Examples of areas over the Fletchervale property responding differently to neighbouring areas are shown in Figure 7.8. The following discussion is related to Figure 7.8.

- Fence effects and fire history are highlighted on the trend summary map. To provide a complete understanding of the area, ancillary data such as TRAPS and QGRAZE data would best be incorporated. Ancillary data such as stocking rates, location of old stock routes and fire history as well as present day infrastructure data, including watering points, fencing, and roads also need to be consulted.
- Areas showing a high cover response over time need to be assessed to determine if they are comprised of perennial grasses. A high cover response interpreted from the cover indices sometimes may be confused with weed infestation or an annual grassland with an anomalous soil surface (eg. high stoniness, silty veneer, etc.).
  - Figure 7.8a. – This example represents a fire affected landscape where the dark blue area was burnt in 1991 and the yellow area unburnt, probably separated by a fenceline. Since the blue area was burnt at the beginning of the 1990's drought, this landscape may have had little chance to establish vegetative cover until 1997 or 1998. Looking at this area now after recent good seasons would be worthwhile to identify differences (if any) on how the fire may have affected vegetation.
  - Figure 7.8b. – A fence effect is highlighted in a low cover response area (red) and no fire was mapped for this area. This area needs ground truthing.
  - Figure 7.8c. - The red area probably represents a rocky outcrop or geological difference due to the shape and intensity of the cover indices.
  - Figure 7.8d. – This area is interpreted as a stable area with relative high vegetative cover (green and cyan) requiring field verification.

Final comments

Confidence in the interpretation of Landsat time-series involves ground verification particularly at monitoring sites over a period of years. Since the relationship between ground cover and spectral data varies annually an estimate of condition using a single Landsat date, or even by comparing two dates, is problematic. Thus, sequences of Landsat imagery are used. Important landscape attributes also need to be considered such as soil type and colour, dominant vegetation type, percentage cover and amount of litter as well as surface stoniness. In addition, by examining the spatial arrangement of long-lived vegetation and soil features, Landscape Function Analysis can provide a basis which to further interpret the relationships between temporal cover indices and vegetative cover. The identification of 'desirable species' is less important as the resolution of Landsat sensors is often too coarse to detect change at the species level.

Once relationships are understood for landscapes at the site scale, rapid assessments are possible along property or regional transects to verify cover indices. The extension of detailed knowledge from sites to rapid field verification allows for a confident extrapolation across the broad landscape using only Landsat data, with less sites needed in the monitoring system.

Detecting vegetation change using time-series cover indices is a useful tool for rangeland management. Maps that can be used to help identify where grazing has resulted in poor condition landscapes or where pasture is under utilised by stock may significantly alter property management planning. Cover change histories also have useful application in research for determining rates of ecological change and understanding patterns of change over time and space.

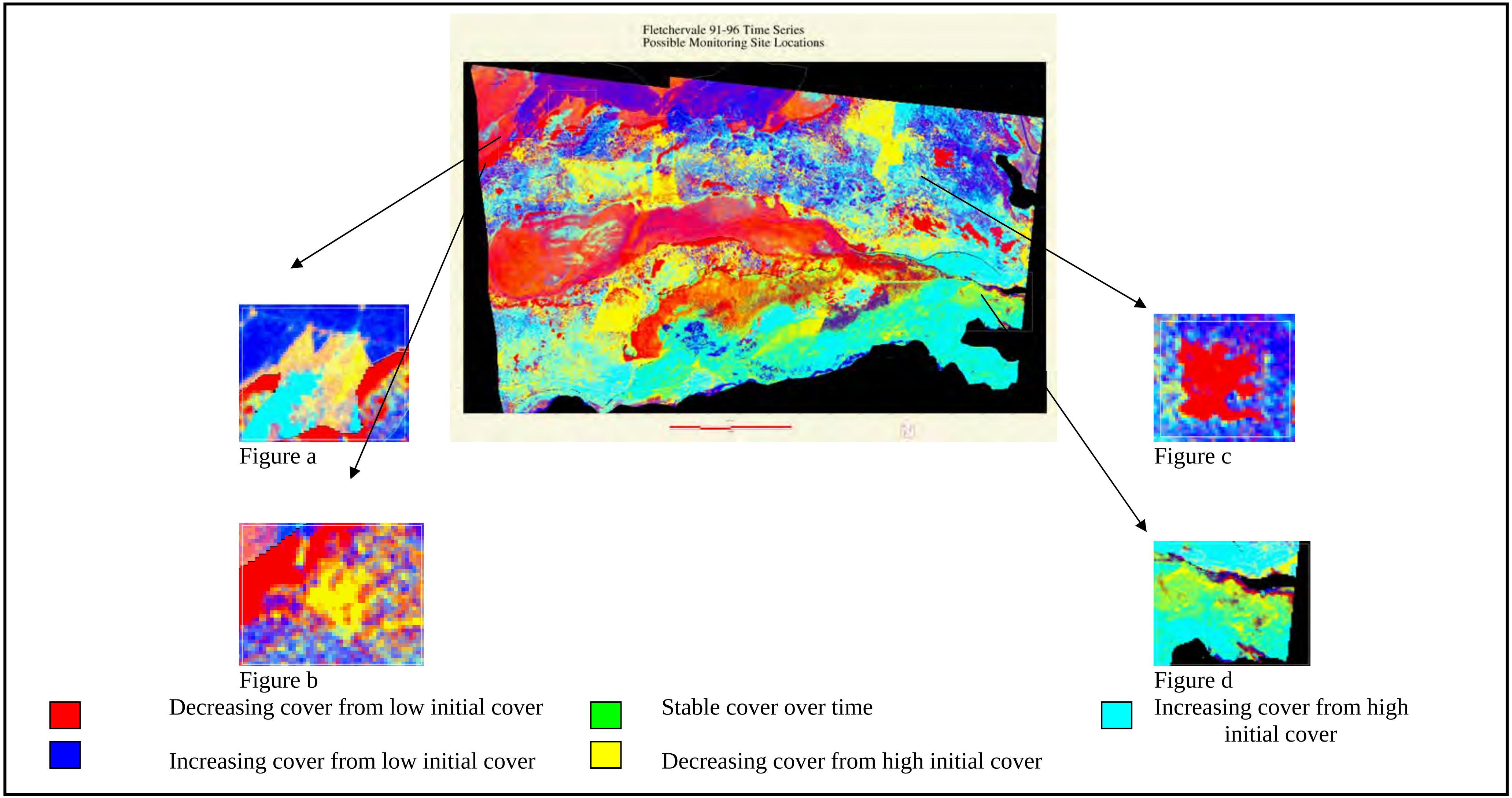


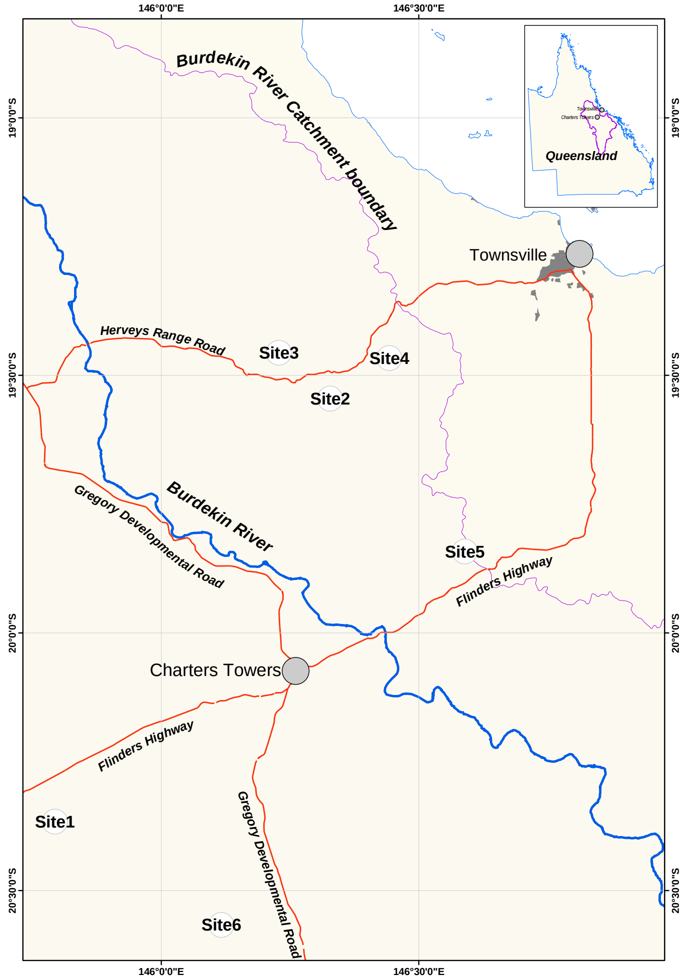
Figure 7.8: Trend summary map of Fletchervale 1991-96

Appendix 8. Rainfall simulation experiments conducted in the Upper Burdekin 1998-2002 – methodology and documentation of results

Joseph Kemei, Aaron Hawdon, David Fanning, Christian H. Roth and Roger Penny,
CSIRO Land and Water, Townsville.

Introduction

The purpose of this document is to provide a detailed description of the rainfall simulator developed at CSIRO Davies Laboratory, its equipment and operation. In addition, this report also provides a compilation of relevant site information and the main data obtained from all rainfall simulation experiments carried out in the period 1998 to 2001, as part of various MLA and LWRRDC/Defence Dept. funded research projects. In total, six sites ranging from 80 to 180 km east to south-east of Townsville were studied. Map 8.1 provides an indication of their location in the Upper Burdekin catchment.



Map 8.1: Locations of the six rainfall simulation sites studied in the period 1998 to 2001.

Rainfall simulator description and operation

General description

The rainfall simulator is an easily erected, mobile unit requiring only 2-3 people to setup and run. It is a capillary drop type model, capable of applying rainfall at constant rates of 25 mm/hr to ~85 mm/hr. A minimum of three experiments per day can be run with ease, with the main limitation being the amount of water that can be carried to the site. Experiments are generally run for 30 minutes per site.

A unique trailer mounted lifting device, as shown in Figure 8.1, is the key to the mobility of the unit. This is lightweight and quickly erected on site. The other major components of the system are: the top chamber, the support frame, the pumps and water supply (including a generator), and the runoff plot.

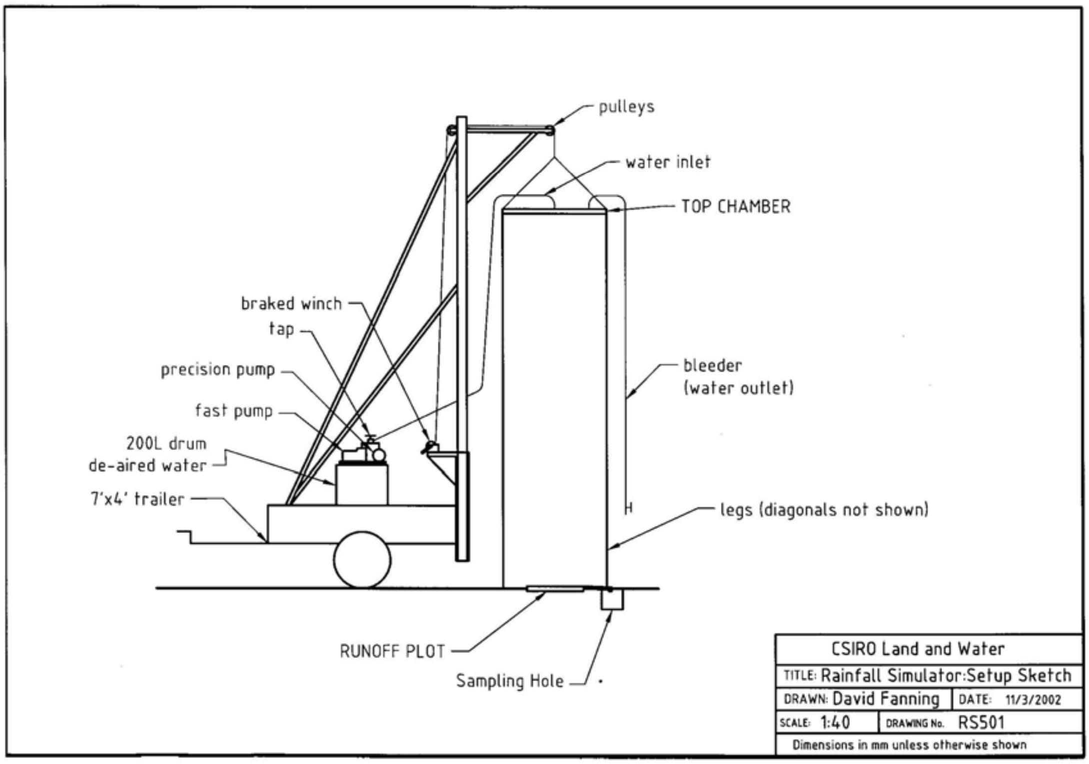


Figure 8.1: Overview sketch of rainfall simulator setup.

Top chamber

The drop-forming unit (Figure 8.2) is an air-tight aluminium chamber (1m x 1m x 0.035 m) with a density of 1300 capillaries/m^2 acting as drop formers. The capillaries are made from single lumen polyethylene tube (OD 1.0 mm x ID 0.50 mm x10 mm long) providing drops of approx. 3.2 mm diameter. The chamber is mounted 4 m above ground on an aluminium frame. It has a water inlet hose, an outlet hose, and a drain tap. The inlet hose supplies/feeds the water while the outlet hose is used to bleed the chamber when filling up.

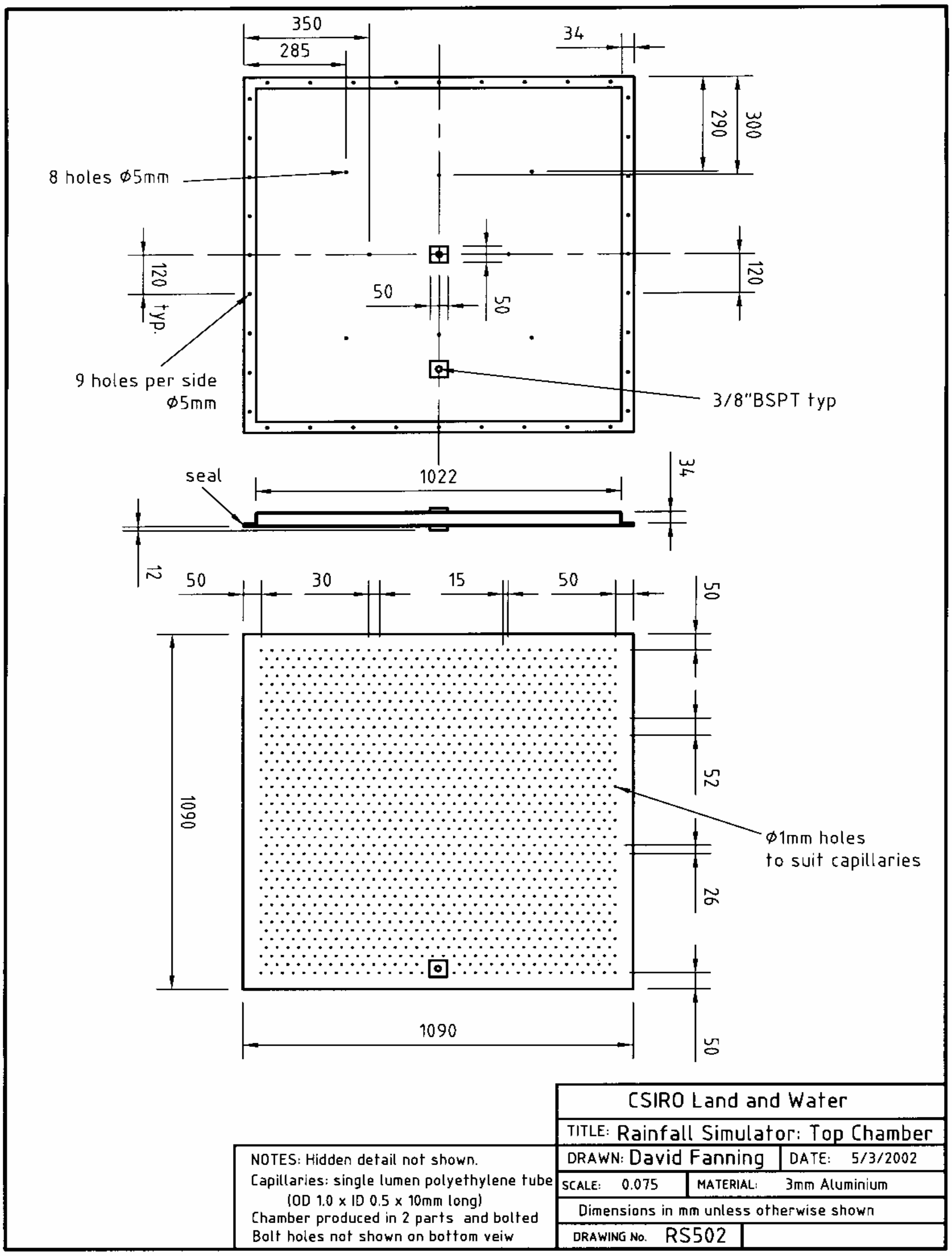


Figure 8.2: Construction details of the top chamber (drop forming unit).

Support frame

For ease of assembly the simulator is broken into three parts: the top frame (supporting the chamber and windshields); the middle leg section (2 m long); and the lower leg section (2 m long). The leg sections include diagonals that maintain rigidity and level operation.

Pumps and water supply

De-aired water is used for the rainfall experiments to minimise clogging of capillaries by air bubbles. The water is stored in three 200 L drums and a single stage vacuum pump is used to de-air the water the day before the experiments is run.

Power to drive the water pumps is supplied from a 2.5 kW generator located away from the experiment site to minimise noise. A fast pump is utilised to fill the drop-forming chamber (0.4 hp; 2800 l/min) until excess waters drains from the outlet. This ensures all the air inside the chamber is forced out. After filling the chamber, the fast pump is stopped and a high precision diaphragm pump with a micrometer control activated that allows for accurate setting of rainfall intensity (Figure 8.3).

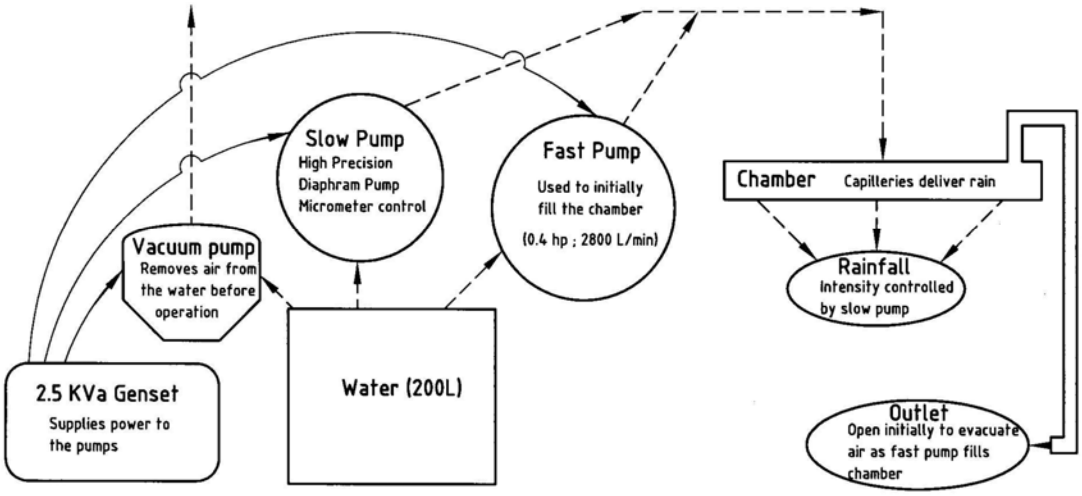


Figure 8.3: Schematic of pump set up.

Runoff plot

The runoff plot is a simple zinc anneal steel frame with a collection area of 0.24 m^2, 600 mm x 400 mm (Figure 8.4). It consists of an open runoff area, a runoff tray that has a clear perspex cover during operation, a drain hole and a front lip.

After the site has been chosen, the sides and bottom of the plot are marked with a spade and a small pit is excavated along the front lip to facilitate sample collection.

There are two methods used for inserting the frame. If the soil is soft enough the plot frames can be tapped directly into the soil. If the soil is very hard, an angle grinder and template need to be used to cut grooves approximately 25 mm deep. The frame is then inserted into these grooves and the edges are sealed by backfilling with loose soil. Careful attention must be given to the front lip of the plot to maintain a good seal with the soil.

It is possible to use preinstalled microplots (of the same surface area; see Appendix 2 in this volume) in the experiments. As there is no installation required, there is little or no disturbance of the soil surface when using these plots.

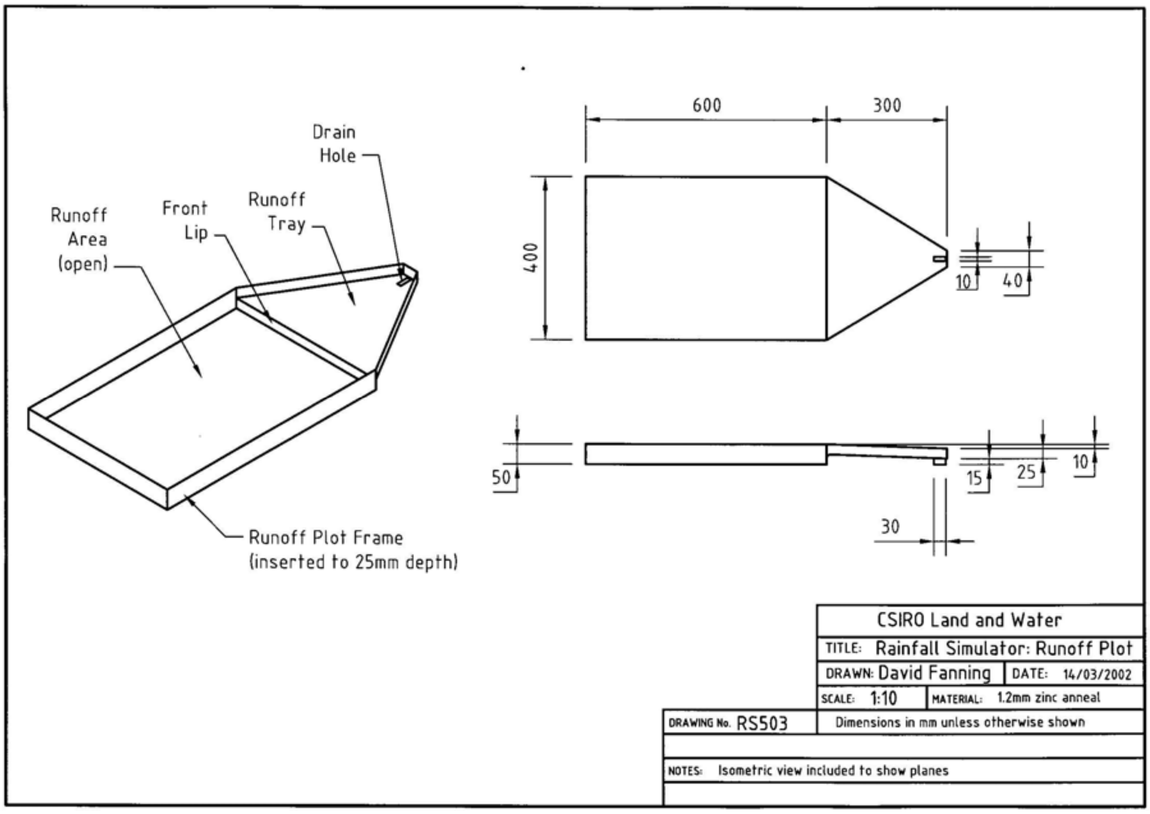


Figure 8.4: Schematic view and dimensions of runoff plot.

Setup

Once experimental sites have been selected the rainfall tower is assembled in the vicinity of the first runoff plot. The top chamber has four multi-stranded cables attached to the four corners for lifting/winching the chamber and the tower into position. Using the trailer mounted 220 kg braked winch and pulley system the chamber is successively lifted and the supports attached. The use of a braked winch is important since the lift can be stopped or lowered at any point with safety.

Once assembled, the entire tower is lifted to at least 20 cm above ground. The trailer is then towed forward, making sure the wheels straddle the plot until the simulator is correctly positioned above the plot. A spirit level is used, and by digging out under the feet and adding packers as necessary the simulator is levelled, ensuring an even distribution of rainfall intensity across the plot area.

To avoid the plot area getting wet before the start of the experiment and to exclude any foreign matter during setup the plot area is covered. To reduce wind effects roll-down vinyl windshields are attached on all four sides of the rainfall tower. These cover 0.1 m under the chamber to 1 m above ground.


Figure 8.5: Views of the rainfall simulator in operation. Wind shield can be lowered in response to main direction of wind.

Experimental procedures

Plot sites were selected to represent the range of soil surface condition found in each landscape. This range was divided into 3-5 classes with 2-3 replicates for each. For example, the range of condition at Meadowvale Station was divided using vegetative cover classes of ‘low, medium, high, very high and ungrazed’.

A plastic trough of similar dimension to the runoff plot was used as a rain gauge to check the rainfall intensity over duration of 2 minutes. At least 2 rainfall calibration measurements are necessary, taken at the beginning and at the end of each rainfall run. To start the experiment, the cover over the runoff plot is removed, a clock timer started and a sample-collecting cup placed under the drainage snout.

Runoff samples were collected at 2-minute intervals and samples collected over a cumulative time of 6 minutes were collected into the same sample bottle (1L plastic bottles). The experiments were let to run for 30 minutes at target intensities of 60 mm/hr. At the end of the experiment, a cover was placed over the plot and the final rainfall intensity measured. A 2 cm diameter auger was used to take soil samples for gravimetric water content before and after the rainfall experiments. In some cases, thin clear perspex sheetings were used to trace the plot features such as tussocks to be digitised in the laboratory to determine basal area. The vegetation within the plot was clipped and separated into green litter and dry matter for biomass determination. Core rings of (7.3 cm by 5 cm) were used to take 3 replicate cores for the determination of bulk density from within each runoff plot and to provide soil material for the determination of key nutrients and particle size distribution.

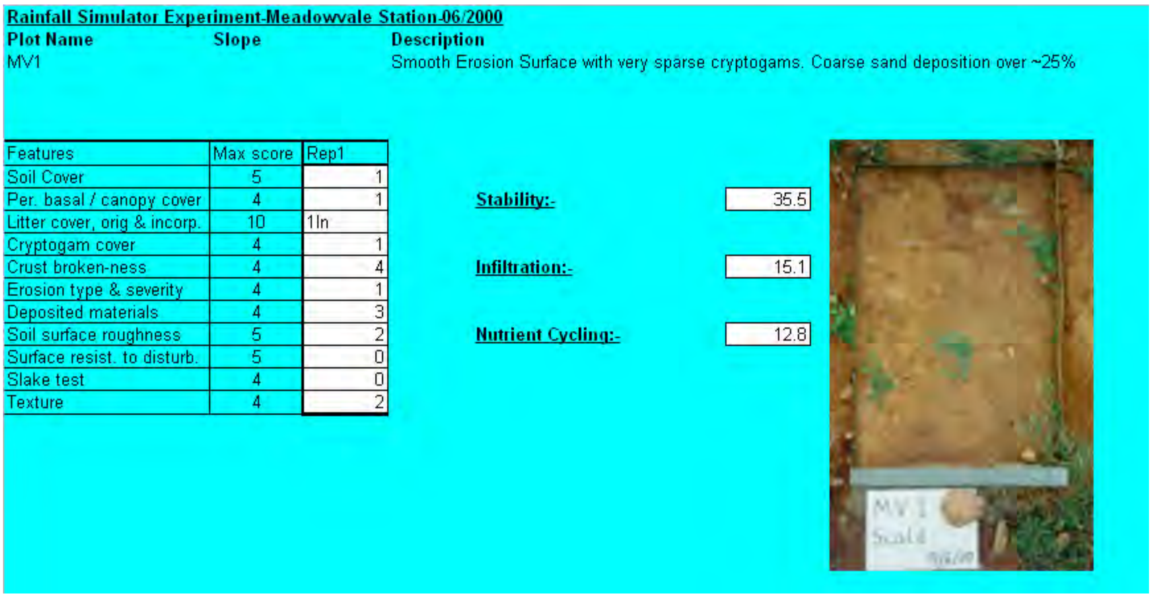
Plot surface description

Apart from the first two experiment sites (Thalanga and Pinnacle Transect), each test plot was photographed and a description of the general characteristics and slope was noted. Soil surface condition of each plot was estimated using a variation of the method proposed by Tongway and Hindley (1995). The procedure was modified to accommodate estimates for area ($0.24m^2$) rather than using the transect method. All of the suggested indicators were used to determine indices for Infiltration (INF), Nutrient Cycling (NUT) and Stability (STAB; see Tongway and Hindley (1995) for more details.

In addition to the Tongway and Hindley indices, all plots were described in terms of soil surface morphological features. These included:

- nature and extent of crusts (loosely following the terminology of Valentin and Bresson, 1992);
- litter, stone/pebble and standing ground cover estimates;
- classes of soil biological activity. These consisted of the following: 1 = low or negligible: no incorporation of litter, no castings, no or little visible soil biological activity; 2 = moderate: 0-50% of litter incorporated into surface; single macrofaunal pores visible; occasional castings; 3 = high: >50% of litter incorporated into surface; <50% of surface covered with castings; enhanced microrelief; 4 = very high: >50% of surface covered with castings; pronounced microrelief; surface uncrusted and friable.

All of the descriptive data collected was then entered into an Excel workbook using the Soil Surface Condition Assessment Trainer (V2 010807) as a template (Tongway and Hindley (2001)). Examples of how the images and the Tongway and Hindley indices were stored are provided in Figure 8.6. Similar data can be obtained from the authors for all microplots in spreadsheet format (except the Thalanga and Pinnacle Transect sites).



Rainfall Simulator Experiment-Meadowvale Station-06/2000

Plot Name	Slope	Description
MV1		Smooth Erosion Surface with very sparse cryptogams. Coarse sand deposition over ~25%

Features	Max score	Rep1
Soil Cover	5	1
Per. basal / canopy cover	4	1
Litter cover, orig & incorp.	10	1In
Cryptogam cover	4	1
Crust broken-ness	4	4
Erosion type & severity	4	1
Deposited materials	4	3
Soil surface roughness	5	2
Surface resist. to disturb.	5	0
Slake test	4	0
Texture	4	2

Stability:- 35.5

Infiltration:- 15.1

Nutrient Cycling:- 12.8

Figure 8.6: Example of the format in which plot descriptions and the Tongway & Hindley indices are stored in an Excel spreadsheet.

Field sampling protocols

In overview, the following additional parameters recorded for each runoff plot:
- actual rainfall intensity before and after experiment
- soil moisture before and after (0-5, 5-10, 10-20 cm depth, respectively)
- runoff amount every 2 min approx.
- bulk density 1-5 cm (3 reps)
- particle size distribution 1-5 cm
- total C, N and available P 1-5 cm
- sediment concentration every 10 min approx.
- surface condition assessment using Tongway and Hindley (see preceding section)
- macroscopic morphological description of crusts (extent and crust type - erosional, depositional, structural, cryptogam; see preceding section)
- total percentage cover, split into litter, standing material, cryptogam
- brief soil profile description for each plot (texture, horizons, colour, structure)

For some of the sites we also recorded the following parameters:
- total N and total P in runoff (every 10 min)
- total grass and forb basal area
- particle size distribution 0-1 cm
- total C, N and available P 0-1 cm

Laboratory Analysis

The runoff samples were immediately stored in a cold room (at –18 degrees C) as soon as they were brought in from the field. On completion of the planned experiments, the runoff samples were shaken thoroughly and an aliquot of 125ml taken to be analysed for total N and P (Dissolved and Particulate) as per EPA (1993a, 1993b). The remainder of the sample was left to stand overnight at room temperature. On the second day, the sample was shaken thoroughly and an aliquot analysed for suspended sediment concentrations using the pipette method described by Coventry and Fett (1979).

The bulk density and gravimetric moisture soil samples were immediately weighed and dried at 105^{o}C. The oven-dried bulk density samples were bulked together and a sub-sample used for particle size analysis. The 0 – 1cm soil layer was air-dried and analysed for total nitrogen, total phosphorous and texture. A dehydrator set at 60^{o}C degrees was used to dry the biomass material.

Data Analysis

All the data were stored and analysed in Excel spreadsheets.

(i) Concentration total suspended sediment
Concentration of total suspended sediment (g/L) = Weight of suspended sediment
in aliquot (g) * 1000/Volume of aliquot ml) Eq. 1

(ii) Calculation of rainfall intensity
The rainfall intensity over the complete run was assumed to scale gradually from the initial to the final measured intensity:

Scaled rainfall intensity (mm/hr) = [Volume of water (ml) collected in time t (min)* 60]
/[(time t (min) * Cross sectional area of rain gauge (cm^2)]*10. Eq. 2

(iii) Calculation of infiltration rate
The collected runoff was converted to runoff rate:

Runoff rate (mm/hr) = [Volume of runoff (ml) in time t (min) *60 min]/[time t (min) * plot area (cm^2)] * 10   Eq. 3

Hence, the infiltration rate at a particular time (t) is:

Infiltration rate (mm/hr) = [Scaled rainfall intensity (mm/hr) – Runoff rate (mm/hr)]   Eq. 4

Infiltration rate was then plotted as a function of time (see Figure 8.7) and also total rainfall. The latter procedure allowed the determination of a normalised infiltration index I_{30} (infiltration rate at 30 mm rainfall depth). In both cases, the data were fitted to a modified Horton equation using Excel SOLVER:

Instantaneous infiltration rate (mm/hr) = a * exp [b * time (min)] + I_f (mm/hr)   Eq. 5

Alternatively

Instantaneous infiltration rate (mm/hr) = A * exp [B * rainfall depth (mm)] + I_f (mm/hr) Eq. 6

Where a, b A and B are fitting parameters, and I_f is final infiltration rate.

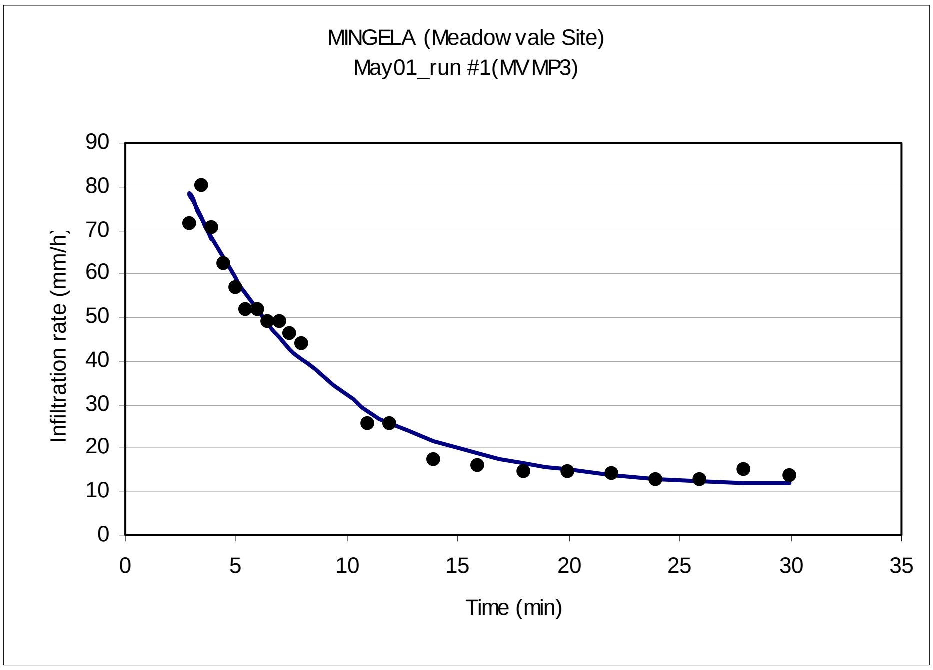


Figure 8.7: Example of measured infiltration rates derived using Equation 4 plotted against time and fitted using Equation 5.

Site descriptions

Site 1: Thalanga

General description:
A. Noble's Stylo monitoring site (NAP project 3.218) paired site with native pasture (moderately to heavily grazed, plots 1-6) and a Stylo dominant pasture (plots 7-9), in which all trees had died off; paired sites about 50m apart. Ground cover very patchy; general condition of both paired sites moderate to poor.

Site code:	TH
Date Studied:	July 1998
Dominant trees:	Silver-leafed Ironbark (*Eucalyptus melanophloia*)
Dominant grasses:	Wiregrass *(Aristida spp.)* Stylo *(Stylosanthes spp.)*
Hillslope position:	Upper slope
General slope:	0-3%
Geology:	Cainozoic sediments
Soil type:	Yellow Kandosol (Boston series)
Longitude: **Latitude:**	E145°47'38.27" S20°21'57.91"

Site 2: Pinnacle Transect, TFTA

General description:
Site on Dotswood military training area; heavily degraded, grazed site with signs of initial recovery (State II/III; plots 1-12); ground cover patchy with large scalds interspersed; some military vehicle activity (APC swerve tracks; plots 13-15).

Site code: PT
Date Studied: November 1998

Dominant trees: Narrow-leafed Ironbark (*Eucalyptus crebra*)

Dominant grasses: Desert Bluegrass *(Bothriochloa ewartiana)* Wiregrass *(Aristida spp.)*

Hillslope position: Mid-slope

General slope: 3-7%

Geology: Devonian sediments Sedimentary rocks

Soil type: Red Chromosol (Ceasar series) Brown/Yellow Chromosol (Greenvale series)

Longitude: E146°19'40.66"
Latitude: S19°32'42.71"

Site 3: Simpson's Dam, TFTA

General description:
Site on Dotswood military training area; heavily degraded, grazed site with signs of recovery (more pronounced than site 1 as cattle already removed, State II); ground cover patchy, with some large gravel covered scalds. No military activity.

Site code: SD

Date Studied: April 1999

Dominant trees: Reid River Box
(*Eucalyptus brownii)*

Dominant grasses: Desert Bluegrass
(*Bothriochloa ewartiana)*
Golden Beard Grass
(Chrysopogon fallax)
Hairy Panic
(Panicum effusum)

Hillslope position: Upper to mid-slope

General slope: 1-3%

Geology: Metamorphic rocks
Metasediments

Soil type: Red Chromosol
(Rangeview series)
Brown/Yellow Sodosol
(Warrawee series)

Longitude: E146°13'41.87"
Latitude: S19°27'22.47"

Site 4: High Range, TFTA

General description:
Site on Dotswood military training area (TFTA section); site with no grazing over the past 20 years; general site condition excellent, except permanent tracks from APC's; high level APC activity; one section of site burned (plots 1-10); plots 11-14 unburnt.

Site code:	HR
Date Studied:	November 1999
Dominant trees:	Narrow-leafed Ironbark (*Eucalyptus crebra*)
Dominant grasses:	Kangaroo grass *(Themeda triandra)* Black Speargrass *(Heteropogon contortus)*
Hillslope position:	Mid-slope
General slope:	3-7%
Geology:	Granite/Granodiorite
Soil type:	Brown Chromosol (Bluff series) Yellow Chromosol (Bluff series)
Longitude:	E146°26'33.42"
Latitude:	S19°27'58.07"

Site 5: Meadowvale

General description:
Main NAP 3.224 erosion monitoring site (microplots; hillslope runoff plots, stream gauging); history of heavy stocking and overall condition poor (State III/IV), with loss of perennial grasses replaced by *Bothriochloa pertusa*; 500 m from monitoring site one of Pressland/Scanlan exclosure sites; plots 9B-12B on grazing exclosure, that now has some grazing. Two series: series A in 2000 and series B in 2001, including some of the permanent microplots.

Site code:	MNA and MNB
Date Studied:	June 2000 (A); May 2001 (B)
Dominant trees:	Narrow-leafed Ironbark (*Eucalyptus crebra*)
Dominant grasses:	Indian couch *(Bothriochloa pertusa)*
Hillslope position:	Upper to mid-slope
General slope:	5-8%
Geology:	Granodiorite
Soil type:	Red Chromosol (Dalrymple series) (eroded phase)
Longitude: **Latitude:**	E146°35'19.81" S19°50'30.67"

Site 6: Wambiana

General description: Paddock 1 in DPI Wambiana grazing trial; fairly heavily stocked over the last 5 years; good cover of perennials; some patches with less desirable species; clumps of Carissa (~25% of area) ungrazed for many years; general site condition moderate.

Site code:	WB
Date Studied:	May 2002
Dominant trees:	Reid River Box (*Eucalyptus brownii*) Current bush (*Carissa ovata*)
Dominant grasses:	Golden Beard Grass (*Chrysopogon fallax*) Wiregrass (*Aristida spp.*) Desert Bluegrass (*Bothriochloa ewartiana*)
Hillslope position:	Mid-slope
General slope:	0-2%
Geology:	Cainozoic Sediments
Soil type:	Brown-grey Sodosol (Liontown series)
Longitude: **Latitude:**	E146°07'02.62" S20°33'19.42"

Individual plot infiltration and sediment concentration data on a site-by-site basis

Thalanga TH1

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.0	57.6	6.0	4.7
4.0	42.0	10.0	4.8
6.0	18.3	14.0	4.1
8.0	4.6	18.0	3.7
10.0	4.6	22.0	3.5
12.0	7.1	26.0	4.0
14.0	5.3	30.0	2.9
16.0	4.7		
18.0	3.5		
20.0	4.0		
22.0	6.1		
24.0	4.2		
26.0	4.3		
28.0	3.7		
30.0	9.3		

Thalanga TH2

Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
5.8	39.9	9.0	1.884
6.5	14.7	11.5	1.316
7.9	18.4	14.0	1.452
9.1	10.7	17.0	1.488
10.3	8.3	20.0	0.856
11.4	9.8	24.0	0.800
12.6	9.9	30.0	0.660
13.8	11.3		
14.9	8.9		
16.0	7.6		
17.1	7.8		
18.2	6.4		
19.2	3.3		
20.3	8.1		
21.4	8.2		
22.5	9.7		
23.6	8.5		
24.8	10.0		
25.8	7.3		
26.9	8.9		
28.1	10.4		
29.1	7.7		
30.0	14.8		

Thalanga TH3

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.6	40.5	6.0	0.852
3.7	43.5	11.0	0.580
4.5	29.3	16.0	0.496
5.9	23.6	21.0	0.332
7.2	19.9	26.0	0.276
8.9	16.1	30.0	0.252
10.1	17.9		
11.3	16.8		
12.5	18.1		
13.7	18.2		
14.9	19.5		
16.1	18.5		
17.3	18.6		
18.5	18.7		
19.7	17.6		
20.8	16.4		
22.0	17.8		
23.1	17.9		
24.3	18.1		
25.4	16.9		
26.6	18.3		
27.7	15.7		
28.8	17.2		

Thalanga TH7

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
10.9	60.5	6.0	1.448
11.4	46.4	12.0	1.068
12.4	44.6	18.0	0.924
13.7	42.1	24.0	0.720
14.5	40.6	30.0	0.636
16.1	39.8		
18.3	39.5		
20.3	37.1		
22.2	35.9		
24.0	34.1		
25.6	32.0		
27.2	32.2		
28.9	33.0		
30.0	33.8		

Thalanga TH8

Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
3.1	51.6	6.0	1.236
4.6	52.7	12.0	1.056
6.3	49.0	17.0	0.844
8.3	47.5	22.0	0.784
9.7	42.3	26.0	0.728
12.3	40.9	30.0	0.720
15.9	40.2		
19.4	40.2		
22.9	40.3		
26.5	41.0		
30.9	43.9		

Thalanga TH9

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
4.7	60.3	8.0	2.364
5.5	42.0	12.0	1.368
6.6	35.0	16.0	0.824
8.5	27.7	20.0	0.944
10.5	29.8	24.0	0.696
11.8	25.5	30.0	0.612
13.1	23.4		
15.1	20.2		
15.9	20.8		
16.9	22.0		
17.9	20.6		
19.0	25.3		
20.1	22.9		
21.2	25.1		
22.3	22.6		
23.4	23.7		
24.5	23.5		
25.6	23.4		
26.7	23.3		
27.8	23.1		
29.0	27.1		
30.0	26.2		

Pinnacle transect
PT1

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
1.5	41.5	6.0	6.300
2.0	5.7	12.0	3.836
3.0	18.3	18.0	3.264
4.0	14.6	24.0	2.956
6.0	19.2	30.0	3.200
8.0	15.6		
10.0	13.8		
12.0	12.7		
14.0	17.9		
16.0	17.4		
18.0	22.5		
20.0	16.4		
22.0	16.6		
24.0	17.4		
26.0	16.3		
28.0	18.3		
30.0	15.3		

Pinnacle transect
PT2

Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
3.5	51.3	6.0	3.880
4.0	41.6	12.0	2.004
5.0	32.8	18.0	1.528
5.3	14.9	24.0	1.420
6.0	33.2	30.0	1.500
8.0	22.5		
10.0	16.7		
12.0	14.0		
14.0	11.4		
16.0	11.8		
18.0	10.4		
20.0	10.2		
22.0	8.8		
24.0	8.0		
26.0	6.5		
28.0	4.5		
30.0	4.9		

Pinnacle transect
PT3

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
6.0	57.8	6.0	
8.0	30.8	12.0	1.704
10.0	24.6	18.0	1.124
12.0	20.3	24.0	0.728
14.0	18.6	30.0	0.712
16.0	19.3		
18.0	16.9		
20.0	17.0		
22.0	16.4		
24.0	15.3		
26.0	14.7		
28.0	14.8		
30.0	12.4		

Pinnacle transect
PT4

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
5.5	52.9	12.0	1.216
6.5	30.4	18.0	0.704
7.0	28.0	24.0	0.608
8.0	23.1	30.0	0.508
9.0	22.1		
12.0	20.5		
14.0	18.5		
16.0	22.0		
18.0	20.5		
20.0	15.8		
22.0	17.4		
24.0	16.5		
26.0	16.9		
28.0	17.8		
30.0	16.9		

Pinnacle transect
PT5

Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
10.0	56.5	12.0	
11.0	41.6	17.0	0.684
12.0	37.5	23.0	0.420
13.0	37.2	29.0	0.340
15.0	35.3	35.0	0.320
17.0	29.6	41.0	0.260
19.0	25.8		
21.0	23.9		
23.0	23.3		
25.0	21.4		
27.0	24.5		
29.0	24.4		
31.0	26.9		
33.0	23.1		
35.0	26.8		
37.0	23.7		
39.0	22.4		
41.0	21.7		

Pinnacle transect
PT6

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
3.0	49.5	6.0	2.884
3.5	22.1	12.0	2.064
4.0	17.2	18.0	1.528
4.5	17.3	24.0	1.536
5.0	7.4	30.0	1.416
5.5	12.5		
6.0	12.5		
6.5	5.1		
7.0	5.2		
7.5	7.8		
8.0	5.4		
8.5	5.4		
9.0	5.5		
9.5	10.6		
10.0	8.2		
10.5	3.3		
11.0	13.4		
11.5	3.4		
13.0	19.5		
14.0	8.8		
15.0	5.3		
16.0	5.4		
18.0	7.0		
20.0	7.3		
22.0	10.2		
24.0	5.5		
26.0	8.3		
28.0	5.5		
30.0	7.1		

Pinnacle transect PT7

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
4.0	59.2	6.0	1.632
4.5	7.3	12.0	1.036
5.5	8.4	18.0	0.692
6.0	9.6	24.0	0.656
7.0	13.2	30.0	0.468
8.0	11.8		
9.0	9.1		
10.0	10.3		
11.0	10.1		
12.0	8.7		
14.0	10.3		
16.0	5.0		
18.0	6.6		
20.0	6.9		
22.0	7.3		
24.0	7.0		
26.0	6.7		
28.0	8.3		
30.0	8.6		

Pinnacle transect PT8

Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.0	44.6	6.0	6.048
2.5	16.0	12.0	3.880
3.0	26.0	18.0	3.320
3.5	16.1	24.0	3.180
4.0	13.7	30.0	3.136
4.5	13.8	36.0	3.520
5.0	18.9		
5.5	14.0		
6.0	14.1		
8.0	15.0		
10.0	13.5		
12.0	13.8		
14.0	14.2		
16.0	14.5		
18.0	15.5		
20.2	19.2		
22.0	13.6		
24.0	14.0		
26.0	12.5		
28.2	15.9		
30.0	17.7		
32.0	14.1		
34.0	13.8		
36.0	13.5		

Pinnacle transect PT9

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
3.5	56.8	6.0	
4.5	48.4	12.0	1.068
5.0	44.6	18.0	0.632
5.5	42.1	24.0	0.452
6.0	39.6	30.0	0.384
6.5	34.5		
7.0	29.5		
7.5	24.5		
8.0	24.5		
10.0	20.1		
12.0	12.5		
14.0	12.4		
16.0	11.1		
18.0	11.7		
20.0	11.0		
22.0	11.6		
24.0	10.9		
26.7	9.1		
28.3	9.9		
30.0	9.1		
32.0	9.4		

Pinnacle transect PT10

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
3.5	62.8	6.0	
4.0	58.0	12.0	0.608
4.5	52.9	18.0	0.848
5.0	52.8	24.0	0.404
5.5	50.2	30.0	0.316
6.0	45.2		
6.5	40.1		
7.0	37.5		
7.5	32.4		
8.0	29.8		
10.0	28.2		
12.0	25.3		
14.0	24.9		
16.3	27.0		
18.0	23.7		
20.0	22.6		
22.0	21.0		
24.0	22.5		
26.0	22.7		
28.0	20.5		
30.0	20.1		

Pinnacle transect PT11

Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
8.0	53.1	12.0	0.780
8.5	51.0	18.0	0.440
9.0	48.4	24.0	0.360
9.5	43.3	30.0	0.272
10.0	40.7		
11.0	33.1		
12.0	29.1		
14.0	29.4		
16.0	27.9		
18.0	26.3		
20.0	22.8		
22.0	21.2		
24.0	21.5		
26.0	18.7		
28.3	18.5		
30.0	13.9		

Pinnacle transect PT12

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
5.5	61.0	12.0	0.432
6.0	56.2	18.0	0.252
6.5	43.7	24.0	0.208
7.0	36.2	30.0	0.176
7.5	28.7		
8.0	26.2		
8.5	23.7		
9.0	23.7		
9.5	21.2		
10.0	21.2		
12.0	21.8		
14.0	18.7		
16.0	12.4		
18.0	11.8		
20.0	16.8		
22.0	16.2		
24.0	17.4		
26.0	14.9		
28.0	18.1		
30.0	16.8		

Pinnacle transect				Pinnacle transect				Pinnacle transect			
PT13				PT14				PT15			
time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)	Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)	time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
0.5	36.9	6.0	1.536	3.5	51.8	6.0	1.788	2.5	48.8	6.0	4.156
1.0	31.9	12.0	1.224	4.0	28.9	12.0	1.212	3.0	28.7	14.0	2.624
1.5	24.5	18.0	1.052	4.5	23.9	18.0	1.140	3.5	18.7	18.0	2.904
2.0	22.0	24.0	0.936	5.0	16.4	24.0	1.068	4.0	13.6	24.0	2.676
2.5	17.0	30.0	0.960	5.5	13.9	30.0	1.020	4.5	13.5	30.0	2.304
3.0	14.5			6.0	11.4			5.0	13.5		
3.5	12.1			6.5	11.3			5.5	10.9		
4.0	9.6			7.0	11.3			6.0	15.9		
4.5	7.1			7.5	11.3			8.0	12.5		
5.0	7.1			8.0	11.3			10.0	14.8		
5.5	4.7			10.0	12.5			12.0	10.2		
6.0	4.7			12.0	12.4			14.0	11.2		
8.0	9.8			14.0	13.0			16.0	12.3		
10.0	4.9			16.0	11.7			18.0	12.7		
12.0	6.2			18.0	16.0			20.0	10.6		
14.0	3.8			20.0	14.0			22.0	12.2		
16.0	8.3			22.0	10.2			24.0	12.0		
18.0	5.9			24.0	8.3			26.0	8.0		
20.0	7.2			26.0	9.5			28.0	8.4		
22.0	6.1			28.0	7.5			30.0	11.3		
24.0	5.5			30.0	4.9						
26.0	5.6										
28.0	5.7										
30.0	8.9										

Simpson's dam				Simpson's dam				Simpson's dam			
SD1				SD2				SD3			
time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)	Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)	time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
1.7	56.3	7.7	1.900	2.8	56.4	8.2	1.844	3.7	56.1	9.2	0.504
2.2	40.0	12.0	1.172	3.2	45.9	12.2	1.192	4.2	46.9	14.2	0.336
2.7	35.8	16.0	0.964	3.7	41.9	16.2	0.924	4.7	39.0	20.2	0.276
3.2	30.1	22.0	0.796	4.2	38.4	20.2	0.808	5.2	33.0	24.2	0.248
3.7	29.1	26.0	0.784	4.7	33.9	24.2	0.732	5.7	32.0	28.2	0.228
4.2	25.5	30.0	0.732	5.2	28.9	28.2	0.688	6.2	30.6	32.2	0.232
4.7	29.4	34.0	0.768	5.7	27.9	30.2	0.612	6.7	26.2		
5.2	31.0			6.2	27.4			7.2	24.7		
5.7	28.1			6.7	23.9			7.7	23.3		
6.2	25.5			7.2	21.7			8.2	25.8		
6.7	30.4			7.7	20.9			8.7	24.9		
7.2	30.8			8.2	16.9			9.2	25.4		
7.7	32.7			9.2	17.9			10.2	22.6		
8.9	31.0			10.2	16.6			11.2	23.9		
10.0	33.5			11.2	12.9			12.2	24.0		
11.0	32.7			12.2	15.4			13.2	22.9		
12.0	30.3			14.2	14.1			14.2	23.0		
13.0	27.8			16.2	12.9			16.2	23.9		
14.0	27.8			18.2	10.4			18.2	26.0		
16.0	28.5			20.2	11.0			20.2	25.6		
18.0	31.9			22.2	10.1			22.2	27.1		
20.0	30.4			24.2	9.3			24.2	29.2		
22.0	31.1			26.2	9.1			26.2	26.3		
24.1	26.3			28.2	10.4			28.2	27.1		
26.0	22.2			30.2	10.4			30.2	27.3		
28.0	20.6							32.2	27.6		
30.0	20.6										
32.0	20.4										
34.0	19.8										

Simpson's dam SD4

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
3.1	60.0	5.6	0.664
3.6	33.4	9.1	0.484
4.1	25.8	14.1	0.384
4.6	25.8	18.0	0.320
5.1	20.3	24.0	0.284
5.6	18.8	30.0	0.276
6.1	19.8		
7.1	16.0		
8.1	17.2		
9.1	16.4		
10.1	16.4		
12.1	14.8		
14.1	15.1		
16.0	13.6		
18.0	12.4		
20.0	12.3		
22.0	13.5		
24.0	10.9		
26.0	10.2		
28.0	11.4		
30.0	10.7		

Simpson's dam SD5

Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.0	51.0	8.0	0.548
2.5	45.7	12.0	0.376
3.0	45.8	18.0	0.316
3.5	37.0	24.0	0.324
4.0	35.5	30.0	0.268
4.5	35.5		
5.0	32.0		
5.5	27.0		
6.0	24.5		
6.6	25.7		
7.0	24.3		
8.0	23.3		
9.0	24.6		
10.0	23.3		
12.0	22.6		
14.2	24.4		
16.0	22.4		
18.0	23.4		
20.0	22.2		
22.0	23.5		
24.0	22.9		
26.0	23.5		
28.0	24.2		
30.0	25.5		

Simpson's dam SD6

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.3	61.6	8.2	0.592
2.8	59.1	12.2	0.348
3.2	57.6	16.2	0.296
3.7	53.2	20.2	0.248
4.2	45.2	26.2	0.208
4.7	44.2	30.2	0.184
5.2	42.3		
5.7	42.3		
6.2	37.3		
6.7	34.9		
7.2	37.4		
8.2	35.0		
9.2	33.5		
10.2	32.6		
11.2	32.7		
12.2	32.7		
14.2	32.9		
16.2	33.6		
18.2	33.1		
20.2	32.6		
22.2	32.1		
24.2	36.0		
26.2	31.1		
28.2	31.3		
30.2	30.8		

Simpson's dam SD7

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.8	56.0	6.3	1.128
3.3	26.1	10.3	0.704
3.8	21.6	14.3	0.580
4.3	15.6	18.3	0.488
4.8	15.6	24.3	0.428
5.3	11.6	30.3	0.376
5.8	8.6		
6.3	13.7		
7.3	9.4		
8.3	9.7		
9.3	10.8		
10.3	9.8		
12.3	9.2		
14.3	9.9		
16.3	10.0		
18.3	10.1		
20.3	8.9		
22.3	9.6		
24.3	9.6		
26.3	10.3		
28.3	8.5		
30.3	9.2		

Simpson's dam SD8

Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
1.6	56.4	6.1	2.888
2.1	27.8	12.1	2.092
2.6	19.3	18.1	1.804
3.1	22.8	24.1	1.728
3.6	12.9	30.2	1.712
4.1	15.4		
4.6	13.9		
5.1	11.4		
5.6	17.9		
6.1	10.4		
8.1	13.6		
10.1	11.1		
12.1	11.8		
14.1	12.4		
16.1	12.4		
18.1	12.5		
20.1	10.0		
22.1	11.9		
24.1	10.7		
26.1	10.1		
28.1	8.3		
30.1	7.1		

Simpson's dam SD9

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
1.5	55.6	5.5	3.076
2.0	36.0	10.5	2.432
2.5	29.5	16.5	2.272
3.0	21.0	24.5	2.200
3.5	16.5	30.5	1.896
4.0	15.1		
4.5	15.6		
5.0	14.1		
5.5	12.6		
6.5	10.3		
7.5	14.1		
8.5	11.3		
9.5	10.1		
10.5	8.6		
12.5	11.1		
14.5	10.5		
16.5	13.0		
18.5	11.1		
20.5	11.2		
22.5	9.9		
24.5	12.4		
26.5	13.1		
28.5	11.8		
30.5	11.8		

Simpson's dam
SD10

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
8.6	53.0	15.6	0.320
9.1	42.4	20.6	0.216
9.6	45.9	26.6	0.184
10.1	41.4	32.6	0.172
10.6	40.9		
11.1	38.9		
11.6	37.9		
12.6	36.4		
13.6	34.8		
14.6	32.6		
15.6	33.8		
16.6	33.8		
18.6	32.8		
20.6	32.6		
22.6	29.5		
24.6	29.1		
26.6	28.3		
28.6	28.2		
30.6	28.2		
32.6	27.3		

Simpson's dam
SD12

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
3.5	52.7	10.0	0.600
4.0	44.5	16.0	0.360
4.5	42.9	22.0	0.284
5.0	39.9	28.0	0.256
5.5	37.3	32.0	0.212
6.0	35.7		
6.5	33.1		
7.0	30.5		
7.5	29.4		
8.0	27.9		
9.0	26.9		
10.0	26.0		
12.0	21.6		
14.0	19.4		
16.0	19.0		
18.0	18.7		
20.0	18.4		
22.0	18.3		
24.0	16.5		
26.0	14.9		
28.0	15.8		
30.0	16.1		
32.0	15.1		

Simpson's dam
SD13

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
3.3	56.8	7.8	0.972
3.8	43.5	13.8	0.764
4.3	35.9	19.8	0.688
4.8	34.4	23.8	0.588
5.3	33.3	27.8	0.540
5.8	33.8	31.8	0.528
6.3	32.2		
6.8	29.7		
7.8	25.9		
9.8	23.8		
11.8	20.9		
13.8	21.3		
15.8	19.5		
17.8	20.0		
19.8	18.9		
21.8	18.1		
23.8	17.5		
25.8	17.0		
27.8	16.6		
29.8	14.4		
31.8	14.1		

High Range (TFTA)
HR1

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
3.5	58.2	12.0	1.376
4.0	57.0	18.0	1.008
4.5	57.1	24.0	0.832
5.0	54.6	30.0	0.600
5.5	48.1		
6.0	43.1		
6.5	40.6		
7.0	40.1		
7.5	38.1		
8.0	38.1		
9.0	37.4		
10.0	37.4		
11.0	35.4		
12.0	32.4		
14.0	33.7		
16.0	31.2		
18.0	29.4		
20.0	30.1		
22.0	30.7		
24.0	32.0		
26.0	30.2		
28.0	30.8		
30.0	27.1		

High Range (TFTA)
HR2

Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
3.0	64.3	12.0	2.308
3.5	56.6	18.0	1.888
4.0	50.5	24.0	1.580
4.5	46.3	30.0	1.600
5.0	40.6		
5.5	37.4		
6.0	34.8		
6.5	32.1		
7.0	34.9		
7.5	34.8		
10.0	37.9		
12.0	26.6		
14.0	28.4		
16.0	27.1		
18.0	28.9		
20.0	25.7		
22.0	25.0		
24.0	28.1		
26.0	24.3		
28.0	23.6		
30.0	22.9		

High Range (TFTA)
HR3

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.0	62.4	6.0	1.708
2.5	37.2	12.0	1.084
3.0	28.8	18.0	0.940
3.5	16.3	24.0	1.216
4.0	18.8	30.0	0.784
4.5	18.9		
5.0	21.4		
6.0	17.7		
7.0	6.6		
8.0	10.4		
9.0	10.5		
10.0	13.0		
12.0	21.3		
14.0	7.1		
16.0	9.7		
18.0	7.4		
20.0	12.5		
22.0	12.7		
24.0	12.8		
26.0	11.7		
28.0	9.4		
30.0	14.5		

High Range (TFTA)
HR4

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.5	54.5	6.0	1.632
3.0	26.4	12.0	1.160
3.5	20.9	18.0	0.956
4.0	21.4	24.0	0.932
4.5	20.4	30.0	0.868
5.0	18.3		
5.5	16.3		
6.0	16.8		
7.0	14.8		
8.0	19.7		
9.0	18.5		
10.0	18.9		
11.0	17.9		
12.0	16.9		
14.0	18.5		
16.0	17.2		
18.0	20.0		
20.0	17.6		
22.0	17.0		
24.0	19.0		
26.0	17.3		
28.0	17.6		
30.0	17.0		

High Range (TFTA)
HR5

Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.5	60.2	6.0	1.628
3.0	50.8	12.0	1.340
3.5	46.2	18.0	1.308
4.0	41.7	24.0	1.168
4.5	39.7	30.0	1.028
5.0	35.2		
5.5	31.2		
6.0	33.6		
7.0	31.3		
8.0	29.8		
9.0	31.0		
10.0	29.7		
11.0	29.4		
12.0	28.6		
14.0	28.8		
16.0	29.2		
18.0	27.9		
20.0	29.6		
22.0	30.4		
24.0	28.3		
26.0	29.9		
28.0	27.3		
30.0	26.9		

High Range (TFTA)
HR6

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.5	72.7	6.0	1.592
3.0	65.7	12.0	1.336
3.5	63.6	18.0	1.080
4.0	59.6	24.0	0.976
4.5	54.6	30.0	0.880
5.0	51.1		
5.5	47.0		
6.0	48.0		
7.0	44.9		
8.0	44.1		
9.0	42.3		
10.0	44.5		
11.0	44.9		
12.0	40.6		
14.0	45.6		
16.0	43.9		
18.0	41.8		
20.0	45.0		
22.0	43.5		
24.0	42.9		
26.0	40.6		
28.0	41.6		
30.0	42.1		

High Range (TFTA)
HR7

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
3.5	63.8	6.0	1.088
4.0	52.0	12.0	0.812
4.5	51.1	18.0	0.580
5.0	49.1	24.0	0.576
5.5	47.6	30.0	0.412
6.0	47.7		
7.0	50.3		
8.0	53.4		
9.0	53.5		
10.0	54.1		
11.0	54.4		
12.0	53.7		
14.0	56.0		
16.0	56.8		
18.0	57.0		
20.0	57.1		
22.0	57.8		
24.0	57.5		
26.0	59.6		
28.0	59.4		
30.0	59.4		

High Range (TFTA)
HR8

Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.5	72.8	6.0	1.340
3.0	69.8	12.0	0.944
3.5	65.8	18.0	0.856
4.0	62.8	24.0	0.784
4.5	56.4	30.0	0.872
5.0	51.4		
5.5	45.0		
6.0	50.5		
7.0	47.9		
8.0	39.7		
9.0	39.3		
10.0	35.4		
11.0	41.5		
12.0	39.1		
14.0	40.8		
16.0	39.5		
18.0	37.2		
20.0	37.3		
22.0	35.0		
24.0	35.5		
26.0	40.2		
28.0	43.1		
30.0	22.4		

High Range (TFTA)
HR9

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.0	72.8	12.0	1.184
4.0	70.1	22.0	0.996
6.0	70.1	30.0	0.820
8.0	70.0		
10.0	69.8		
12.0	70.5		
14.0	70.1		
16.0	68.2		
18.0	68.7		
20.0	68.3		
22.0	68.1		
24.0	68.0		
26.0	67.8		
28.0	67.0		
30.0	66.5		

High Range (TFTA) HR10				High Range (TFTA) HR12				High Range (TFTA) HR13			
time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)	time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)	time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.0	69.3	6.0	1.388	2.5	87.7	8.0	0.344	4.5	64.2	12.0	0.520
2.5	58.5	12.0	1.248	3.0	71.1	16.0	0.256	5.0	57.6	18.0	0.344
3.0	55.7	18.0	0.888	4.0	73.6	24.0	0.148	5.5	55.5	24.0	0.336
3.5	49.3	24.0	0.844	5.0	72.3	32.0	0.116	6.0	56.0	34.0	0.284
4.0	44.5	30.0	0.852	6.0	72.3			6.5	54.4		
4.5	42.2			7.0	71.8			7.0	54.3		
5.0	40.9			8.0	71.5			8.0	52.2		
5.5	40.0			9.0	70.7			9.0	52.1		
6.0	37.7			10.0	73.2			10.0	51.8		
7.0	37.6			12.0	79.6			12.0	49.3		
8.0	33.4			14.0	76.3			14.0	47.8		
9.0	31.3			16.0	74.8			16.0	47.6		
10.0	30.4			18.0	75.2			18.0	48.7		
12.0	27.1			20.0	77.1			20.0	47.8		
14.0	38.0			22.0	75.2			22.0	48.2		
16.0	34.9			24.0	76.1			24.0	48.0		
18.0	36.9			26.0	77.4			26.0	49.0		
20.0	37.6			28.0	77.6			28.0	49.4		
22.0	36.4			30.0	77.6			30.0	50.5		
24.0	35.0			32.0	77.5			32.0	50.3		
26.0	35.3							34.0	51.9		
28.0	36.6										
30.0	34.2										

High Range (TFTA) HR14			
time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
4.0	66.2	12.0	0.580
5.0	64.2	18.0	0.376
6.0	62.7	24.0	0.284
7.0	60.3	32.0	0.332
8.0	58.0		
9.0	58.7		
10.0	57.9		
11.0	57.3		
12.0	56.7		
14.0	56.1		
16.0	55.3		
18.0	55.2		
20.0	55.7		
22.0	56.2		
24.0	57.3		
26.0	59.0		
28.0	58.3		
30.0	55.6		
32.0	56.7		

Meadowvale Site
MN1A

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
1.75	65.6	6.0	2.636
2.25	52.2	10.0	2.844
2.75	16.7	12.0	2.804
3.25	11.8	18.0	2.540
3.75	16.8	24.0	2.400
4.25	14.3	30.0	2.232
4.75	16.9		
5.25	11.9		
5.75	11.9		
6.75	12.0		
7.75	14.6		
8.75	14.7		
9.75	14.7		
10.75	14.8		
11.75	16.1		
13.75	16.3		
15.75	17.7		
17.75	17.2		
19.75	15.5		
21.75	15.6		
23.75	16.4		
25.75	13.4		
27.75	14.2		
29.75	14.3		

Meadowvale Site
MN2A

Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.0	74.1	6.0	2.376
2.5	52.8	12.0	1.328
3.0	39.9	18.0	1.060
3.5	25.0	24.0	0.980
4.0	22.6	30.0	1.012
4.5	20.3		
5.0	20.4		
5.5	18.0		
6.0	18.1		
7.0	15.9		
8.0	14.9		
9.0	16.4		
10.0	16.6		
11.0	16.9		
12.0	17.1		
14.0	17.6		
16.0	16.8		
18.0	17.3		
20.0	16.6		
22.0	18.3		
24.0	17.6		
26.0	16.8		
28.0	16.0		
30.0	15.3		

Meadowvale Site
MN3A

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
1.5	71.8	6.0	5.136
2.0	19.4	12.0	3.964
2.5	17.0	18.0	3.448
3.0	12.1	24.0	3.056
3.5	17.2	30.0	2.908
4.0	9.8		
4.5	12.4		
5.0	12.5		
5.5	10.1		
6.0	10.1		
7.0	12.8		
8.0	13.0		
9.0	12.0		
10.0	13.4		
11.0	12.4		
12.0	13.8		
14.0	12.3		
16.0	12.1		
18.0	12.4		
20.0	15.3		
22.0	12.6		
24.0	14.8		
26.0	12.7		
28.0	15.6		
30.0	13.5		

Meadowvale Site
MN4A

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
1.5	75.7	6.0	7.108
2.0	57.7	12.0	4.156
2.5	49.2	18.0	3.328
3.0	38.7	24.0	2.932
3.5	28.7	30.0	2.816
4.0	15.7		
4.5	13.2		
5.0	10.7		
5.5	5.7		
6.0	3.2		
7.0	3.2		
8.0	3.2		
9.0	2.0		
10.0	2.0		
11.0	-0.5		
12.0	3.3		
14.0	2.0		
16.0	2.1		
18.0	0.8		
20.0	1.5		
22.0	-1.0		
24.0	1.5		
26.0	0.3		
28.0	0.3		
30.0	0.9		

Meadowvale Site
MN6A

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
1.0	72.8	2.5	4.900
1.5	30.8	6.0	5.672
2.0	17.9	12.0	4.164
2.5	10.4	18.0	3.660
3.0	10.5	29.0	3.284
3.5	10.5	32.0	3.068
4.0	8.0		
4.5	8.1		
5.0	8.1		
5.5	5.6		
6.0	5.7		
7.0	7.0		
8.0	9.6		
9.0	7.2		
10.0	6.0		
11.0	4.8		
12.0	2.4		
14.1	4.7		
16.0	4.9		
18.0	6.0		
20.0	7.4		
22.0	8.8		
24.0	7.7		
26.0	9.1		
28.0	8.0		
29.0	10.0		
30.0	6.8		
31.0	7.4		
32.0	7.7		

Meadowvale Site
MN7A

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.0	71.2	9.0	0.792
2.5	70.3	12.0	0.508
3.0	68.9	16.0	0.440
3.5	66.6	22.0	0.364
4.0	64.7	30.0	0.332
4.5	62.8		
5.0	61.9		
5.5	59.5		
6.0	52.1		
7.0	42.4		
8.0	31.3		
9.0	24.1		
10.0	21.8		
11.0	18.3		
12.0	18.5		
13.0	16.2		
14.0	16.5		
16.0	14.4		
18.0	14.9		
20.0	14.1		
22.0	12.7		
24.0	11.9		
26.0	13.0		
28.0	10.9		
30.0	12.6		

Meadowvale Site MN8A

Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
4.0	81.7	12.0	0.800
4.5	80.7	18.0	0.732
5.0	79.8	24.0	0.612
5.5	79.4	30.0	0.496
6.0	73.0		
7.0	63.1		
8.0	58.8		
9.0	53.7		
10.0	50.8		
11.0	49.0		
12.0	45.4		
14.0	40.0		
16.0	36.6		
18.0	31.9		
20.0	33.4		
22.0	31.2		
24.0	32.7		
26.0	29.3		
28.0	29.0		
30.0	29.9		

Meadowvale Site MN9A

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.0	83.2	6.0	0.892
2.5	58.8	12.0	0.580
3.0	41.9	18.0	0.444
3.5	38.0	24.0	0.436
4.0	33.6	30.0	0.440
4.5	27.6		
5.0	28.7		
5.5	26.3		
6.0	22.4		
7.0	20.3		
8.0	18.0		
9.0	16.9		
10.0	22.0		
11.0	23.4		
12.0	21.1		
14.0	25.8		
16.0	24.9		
18.0	19.5		
20.0	19.9		
22.0	20.2		
24.0	20.5		
26.0	22.1		
28.0	21.1		
30.0	21.5		

Meadowvale Site MN11A

Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.75	68.48	6.0	1.460
3.00	42.48	12.0	0.840
3.50	39.96	18.0	0.740
4.00	30.45	24.0	0.680
4.50	23.44	30.0	0.584
5.00	18.43		
5.50	13.42		
6.00	15.90		
7.00	22.13		
8.00	18.35		
9.00	9.58		
10.00	13.30		
11.00	20.78		
12.00	19.51		
14.00	17.58		
16.00	17.53		
18.00	14.98		
20.00	9.93		
22.00	6.76		
24.00	5.46		
26.00	5.41		
28.00	2.86		
30.00	4.06		

Meadowvale Site MN2B

Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.9	58.9	6.0	0.648
3.4	37.6	12.0	0.472
3.9	35.6	18.0	0.408
4.4	30.5	24.0	0.416
4.9	27.0	30.0	0.416
5.4	24.0		
5.9	22.4		
6.9	21.6		
7.9	20.3		
8.9	19.0		
9.9	18.9		
10.9	20.1		
11.9	18.8		
13.9	20.6		
15.9	19.2		
17.9	17.2		
19.9	16.5		
21.9	15.1		
23.9	14.3		
25.9	14.8		
27.9	15.3		
29.9	16.5		

Meadowvale Site MN3B

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
1.9	45.2	6.0	0.944
2.9	9.0	12.0	0.624
3.9	7.2	18.0	0.544
4.9	8.9	24.0	0.448
5.9	8.9	30.0	0.384
6.9	13.2		
7.9	13.4		
8.9	12.9		
9.9	10.7		
10.9	10.4		
11.9	4.4		
12.9	5.6		
13.9	8.9		
14.9	8.1		

Meadowvale Site MN4B

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.4	68.0	6.0	2.832
2.9	30.6	12.0	2.740
3.4	19.6	18.0	2.580
3.9	16.6	24.0	2.216
4.4	11.6	30.0	2.244
4.9	20.6		
5.4	14.6		
5.9	12.6		
6.9	11.8		
7.9	10.6		
8.9	10.6		
9.9	10.1		
10.9	9.3		
11.9	12.8		
12.9	12.1		
13.9	10.1		
14.9	12.1		
15.9	11.6		
16.9	11.1		
17.9	11.6		
19.9	12.3		
21.9	11.6		
23.9	13.5		
25.9	12.5		
27.9	12.5		
29.9	11.5		

Meadowvale Site
MN5B

Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.4	68.6	6.0	2.580
2.9	43.6	12.0	1.624
3.4	34.6	18.0	1.364
3.9	24.6	24.0	1.232
4.4	23.1	30.0	1.196
4.9	20.1		
5.4	17.6		
5.9	18.6		
6.9	19.1		
7.9	14.4		
8.9	18.6		
9.9	17.4		
10.9	13.9		
11.9	13.6		
13.9	17.5		
15.9	17.8		
17.9	15.3		
19.9	17.5		
21.9	14.8		
23.9	15.0		
25.9	13.8		
27.9	13.2		
29.9	12.9		

Meadowvale Site
MN6B

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.4	73.2	12.0	0.452
2.9	71.5	18.0	0.356
3.4	71.9	24.0	0.332
3.9	71.9	30.0	0.300
4.4	71.3		
4.9	69.8		
5.4	69.3		
5.9	66.7		
6.9	60.1		
7.9	48.1		
9.2	42.0		
9.9	36.2		
10.9	31.6		
11.9	31.5		
13.9	30.7		
15.9	26.8		
17.9	25.4		
20.2	22.6		
21.9	23.3		
23.9	22.4		
25.9	21.6		
27.9	20.2		
29.9	18.8		

Meadowvale Site
MN7B

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
6.9	71.1	12.0	0.340
7.4	63.0	18.0	0.300
7.9	59.4	24.0	0.264
8.4	56.9	30.0	0.256
8.9	54.8		
9.4	52.8		
9.9	51.8		
10.9	51.2		
11.9	47.6		
13.9	47.6		
15.9	46.8		
17.9	46.3		
19.9	44.5		
21.9	44.7		
23.9	44.3		
25.9	43.8		
27.9	44.3		
29.9	42.5		

Meadowvale Site
MN8B

Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
1.9	71.4	8.0	1.912
2.4	68.0	12.0	1.012
2.9	65.9	18.0	0.760
3.4	63.9	24.0	0.640
3.9	59.9	30.0	0.596
4.4	57.9		
4.9	55.3		
5.4	54.3		
5.9	52.3		
6.9	49.5		
7.9	44.7		
8.9	43.1		
9.9	41.3		
10.9	41.5		
11.9	40.7		
13.9	40.7		
15.9	39.9		
17.9	39.8		
19.9	38.2		
21.9	37.1		
23.9	35.7		
25.9	34.0		
27.9	35.6		
29.9	32.3		
31.9	30.2		

Meadowvale Site
MN9B

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.4	71.9	12.0	3.296
2.9	70.3	26.0	1.572
3.4	70.3	32.0	1.040
3.9	69.8	40.0	0.932
4.4	69.7	46.0	0.732
4.9	68.7		
5.4	68.2		
5.9	67.7		
6.9	66.6		
7.9	65.6		
8.9	65.8		
9.9	65.7		
10.9	65.7		
11.9	65.6		
13.9	65.0		
15.9	65.1		
17.9	64.8		
19.9	64.4		
21.9	63.8		
23.9	63.4		
25.9	63.2		
27.9	62.7		
29.9	61.1		
31.9	61.4		
33.9	60.7		
35.9	60.2		
37.9	59.3		
39.9	58.6		
41.9	57.7		
43.9	56.6		
45.9	56.2		

Meadowvale Site
MN10B

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.9	70.8	12.0	3.012
3.4	67.3	24.0	1.392
3.9	65.8	30.0	0.996
4.4	65.3		
4.9	64.3		
5.4	63.4		
5.9	63.4		
6.9	62.9		
7.9	63.5		
8.9	63.5		
9.9	63.5		
10.9	63.3		
11.9	62.6		
13.9	62.4		
15.9	61.3		
17.9	62.5		
19.9	61.4		
21.9	60.1		
23.9	59.5		
25.9	59.5		
27.9	59.1		
29.9	59.2		

Wambiana Site WB1

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
5.5	66.4	8.5	3.292
6.0	56.3	12.0	2.360
6.5	45.8	18.0	1.500
7.0	34.8	24.0	1.052
7.5	24.9	30.0	0.804
8.0	23.4		
8.5	23.4		
9.0	17.9		
9.5	23.4		
10.0	27.4		
10.5	26.0		
11.0	10.0		
11.5	12.5		
12.0	17.5		
13.0	13.8		
14.0	13.8		
15.0	16.4		
16.0	11.4		
17.0	11.5		
18.0	12.7		
19.0	10.3		
20.0	11.6		
22.0	12.3		
24.0	11.7		
26.0	13.0		
28.0	11.9		
30.0	13.2		

Wambiana Site WB2

Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
3.5	64.5	12.0	1.704
4.0	62.3	18.0	0.988
4.5	60.7	24.0	0.816
5.0	58.7	30.0	0.760
5.5	56.2		
6.0	53.2		
6.5	51.7		
7.0	50.6		
7.5	48.6		
8.0	46.1		
9.0	43.8		
9.5	39.5		
10.0	39.0		
10.5	33.0		
11.0	31.4		
11.5	28.9		
12.0	25.4		
13.0	27.8		
14.0	25.3		
15.0	24.0		
16.0	22.7		
17.0	21.4		
18.0	20.1		
20.0	20.0		
22.0	19.9		
24.0	18.5		
26.0	17.8		
28.0	18.3		
30.0	17.6		

Wambiana Site WB3

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
3.0	63.3	10.0	1.260
3.5	55.8	15.0	0.840
4.0	55.8	19.0	0.728
4.5	55.7	24.0	0.668
5.0	53.2	30.0	0.552
5.5	51.7		
6.0	50.7		
6.5	49.7		
7.0	49.6		
7.5	48.6		
8.0	47.6		
8.5	45.6		
9.0	45.0		
9.5	44.0		
10.0	43.5		
11.0	41.7		
12.0	37.9		
13.0	35.3		
14.0	32.8		
15.0	31.5		
16.0	28.9		
17.0	22.6		
18.0	28.8		
19.0	21.3		
20.0	20.0		
21.0	22.4		
22.0	22.4		
23.0	21.1		
24.0	18.5		
25.0	18.5		
26.0	18.4		
27.0	19.6		
28.0	18.3		
29.0	18.3		
30.0	18.2		

Wambiana Site WB4

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
6.0	77.5	18.0	1.428
6.5	75.7	30.0	0.880
7.0	76.2		
7.5	76.2		
8.0	75.7		
8.5	76.2		
9.0	75.7		
9.5	74.7		
10.0	74.7		
10.5	74.7		
11.0	75.2		
11.5	73.7		
12.0	74.2		
12.5	73.7		
14.0	74.2		
16.0	73.4		
18.0	72.7		
20.0	71.7		
22.0	70.9		
24.0	69.9		
26.0	69.5		
28.1	69.2		
30.0	68.7		

Wambiana Site WB5

Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
3.0	64.6	8.0	2.976
3.5	58.4	12.0	1.804
4.0	53.4	18.0	1.624
4.5	47.9	24.0	1.348
5.0	44.3	30.0	1.188
5.5	42.8		
6.0	39.8		
7.0	34.5		
8.0	30.8		
9.0	30.7		
10.0	28.2		
11.0	25.7		
12.0	25.7		
14.0	22.5		
16.0	21.8		
18.0	19.3		
20.0	20.5		
22.0	20.4		
24.0	16.6		
26.0	17.2		
28.0	19.0		
30.0	18.4		

Wambiana Site WB6

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
3.5	87.7	12.0	1.564
4.0	86.1	20.0	0.808
4.5	84.0	26.0	0.984
5.0	83.5	30.0	0.644
5.5	81.5		
6.0	82.0		
6.5	81.5		
7.0	82.0		
7.5	81.4		
8.0	80.9		
8.5	78.4		
9.0	79.4		
9.5	78.4		
10.0	78.4		
10.5	77.9		
11.0	78.3		
11.5	77.8		
12.0	77.8		
14.0	76.9		
16.0	75.6		
18.0	75.5		
20.0	75.4		
22.0	74.1		
24.0	73.4		
26.0	72.7		
28.0	72.0		
30.0	71.4		

Wambiana Site WB7

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
7.5	84.2	18.0	1.076
8.0	81.8	30.0	0.652
8.5	80.8		
9.0	80.7		
9.5	80.2		
10.0	80.1		
10.5	80.1		
11.0	79.6		
11.5	80.0		
12.0	80.0		
12.5	79.5		
13.0	78.4		
13.5	78.4		
14.0	78.9		
14.5	78.8		
15.0	79.3		
16.0	79.7		
17.0	78.9		
18.0	78.8		
19.0	77.8		
20.0	77.4		
22.0	77.3		
24.0	77.4		
26.0	76.6		
28.0	76.1		
30.0	76.0		

Wambiana Site WB8

Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
5.5	65.3	12.0	2.056
6.0	54.5	18.0	1.532
6.5	48.6	24.0	1.276
7.0	49.1	30.0	1.104
7.5	44.6		
8.0	35.6		
8.5	42.1		
9.0	40.1		
9.5	31.1		
10.0	33.6		
10.5	33.6		
11.0	35.1		
12.0	30.4		
14.0	29.9		
16.0	27.4		
18.0	25.6		
20.0	23.7		
22.0	21.9		
24.0	20.6		
27.0	20.9		
28.0	19.6		
29.0	19.8		
30.0	19.6		

Wambiana Site WB10

time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
7.0	75.6	12.0	1.436
7.5	66.7	18.0	1.012
8.0	64.6	24.0	0.760
8.5	64.1	30.0	0.636
9.0	64.1		
9.5	62.0		
10.0	63.0		
10.5	61.5		
11.0	61.4		
11.5	60.9		
12.0	61.4		
13.0	61.8		
14.0	60.7		
15.0	60.2		
16.0	59.4		
17.0	59.3		
18.0	58.7		
20.0	58.3		
22.0	57.0		
24.0	56.2		
26.0	54.8		
28.0	53.4		
30.0	52.7		

Wambiana Site WB13

Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
3.0	73.3	6.0	2.77
3.5	59.3	12.0	1.39
4.0	56.8	18.0	1.04
4.5	54.9	24.0	0.94
5.0	51.9	30.0	0.87
5.5	49.9		
6.0	46.0		
7.0	41.5		
8.0	39.1		
9.0	35.6		
10.0	33.5		
11.0	31.0		
12.0	28.1		
14.0	27.0		
16.0	24.6		
18.0	25.3		
20.0	22.6		
22.0	20.6		
24.0	20.7		
26.0	19.0		
28.0	20.6		
30.0	19.2		

Wambiana Site WB14

Time (min)	Inf. Rate (mm/h)	Time (min)	Sed. Conc. (g/l)
2.0	77.2	6.0	2.844
2.5	72.7	12.0	1.668
3.0	62.7	18.0	1.260
3.5	53.6	24.0	1.200
4.0	44.1	30.0	1.056
4.5	35.6		
5.0	29.0		
5.5	24.0		
6.0	24.0		
7.0	22.4		
8.0	21.8		
9.0	22.3		
10.0	18.5		
11.0	20.4		
12.0	18.3		
14.0	17.6		
16.0	15.0		
18.0	16.1		
20.0	14.7		
22.0	15.2		
24.0	13.2		
26.0	14.3		
28.0	14.2		
30.0	11.6		

Main data tables for data collected from rainfall simulation experiments

Table 8.1: Abbreviations and units

Abbreviation inTable 8.2	Variable	Unit
No	Running number	
Class	Soil surface condition classification code (see Chapter 7, Volume I)	
Date	Date of rainfall simulation experiment	
Plot code	Original plot code	
Int mean	Mean rainfall intensity	mm/h
RunTime	Total duration of rainfall simulation	min
Slope	Average microplot slope	%
WC	Initial water content in 0-5 cm	Vol %
STAB	Tongway stability index	
INF	Tongway infiltration index	
NUT	Tongway nutrient cycling index	
BIOM	Total ground cover biomass (green and litter)	g/m^2
COV	Projected ground cover (green and litter)	%
BD	Bulk density 1-5 cm	g/cm^3
CS 1-5	Coarse sand content in 1-5 cm depth	%
FS 1-5	Fine sand content in 1-5 cm depth	%
Z 1-5	Silt content in 1-5 cm depth	%
C 1-5	Clay content in 1-5 cm depth	%
G 1-5	Gravel content in 1-5 cm depth	%
N 1-5	Total N content 1-5 cm depth	%
P 1-5	Total P content 1-5 cm depth	mg/kg
C 1-5	Total C content 1-5 cm depth	%

Abbreviation inTable 8.2	Variable	Unit
If HOR	Final infiltration rate - Horton fitted	mm/h
R^2 HOR	Coefficient of determination of Horton fit	
SE HOR	Standard error of Horton fit	mm/h
I30 Hor	Infiltration rate at 30 mm of cumulative rainfall - Horton	mm/h
R30 Hor	Runoff rate at 30 mm of cumulative rainfall - Horton	mm/h
Sed30	Concentration of suspended solids (particles <20 m) at 15 mm of cum rainfall	g/l
PFIL	Concentration of soluble P in runoff at approx 30 mm rainfall	mg/l
NFIL	Concentration of soluble N in runoff at approx 30 mm rainfall	mg/l
PUF	Concentration of total P in runoff at approx 30 mm rainfall	mg/l
NUF	Concentration of total N in runoff at approx 30 mm rainfall	mg/l
PPART	Concentration of particulate P in runoff at approx 30 mm rainfall	mg/l
NPART	Concentration of particulate N in runoff at approx 30 mm rainfall	mg/l

Table 8.2A: Main data table

No	Class	Date	Plot code	Int mean	RunTime	Slope	WC	STAB	INF	NUT	BIOM	COV	BD	S 1-5	CS 1-5	FS 1-5	Z 1-5	Cl 1-5	G 1-5	N 1-5	P 1-5	C 1-5
1	1.1.1.1	23/11/1998	PT1	61.7	30	2.0	0.06	55	19	9	0	5	1.587	69.9	44.8	25.1	13.1	16.9	5.4	0.035	8	0.71
2	1.1.2.1	23/11/1998	PT2	55.7	30	2.5	0.16	80	43	39	191	70	1.645	78.4	52.0	26.4	10.2	11.4	5.9	0.04	4	0.73
3	1.1.2.4	23/11/1998	PT3	58.3	30	2.3	0.14	68	37	28	224	55	1.643	75.2	51.1	24.1	10.6	14.2	5.8	0.038	5	0.66
4	1.1.3.1	24/11/1998	PT4	59.3	30	3.8	0.15	80	41	37	205	90	1.618	82.6	56.0	26.6	8.3	9.1	7.2	0.031	5	0.64
5	1.1.3.1	24/11/1998	PT5	56.5	30	3.3	0.15	83	44	42	677	98	1.582	84.4	55.8	28.6	7.7	7.8	5.7	0.043	5	0.75
6	1.1.1.4	24/11/1998	PT6	56.5	30	3.8	0.09	50	25	23	43	23	1.617	80.9	45.4	35.5	8.5	10.6	8.8	0.036	7	0.66
7	1.1.1.2	24/11/1998	PT7	58.3	30	1.7	0.10	28	28	12	0	0	1.724	67.9	42.5	25.4	10.5	21.6	12.8	0.045	4	0.78
8	1.1.1.1	24/11/1998	PT8	58.6	36	3.8	0.05	50	19	16	13	2	1.647	72.9	40.1	32.8	10.5	16.6	11.9	0.036	5	0.75
9	1.1.3.1	26/11/1998	PT9	56.8	32	3.7	0.29	78	43	37	1403	80	1.704	74.6	46.9	27.7	11.5	13.9	4.7	0.061	6	0.95
10	1.1.3.2	26/11/1998	PT10	61.0	30	3.3	0.24	83	44	42	706	100	1.505	84.3	53.3	31.0	7.8	7.9	2.6	0.059	8	1.08
11	1.1.3.1	26/11/1998	PT11	52.4	30	1.7	0.23	80	43	39	835	100	1.533	87.8	62.0	25.8	5.9	6.3	2.6	0.044	8	0.77

No	Class	Date	Plot code	Int mean	RunTime	Slope	WC	STAB	INF	NUT	BIOM	COV	BD	S 1-5	CS 1-5	FS 1-5	Z 1-5	Cl 1-5	G 1-5	N 1-5	P 1-5	C 1-5
12	1.1.3.1	26/11/1998	PT12	61.2	30	3.0	0.22	80	44	39	1254	100	1.575	79.8	52.4	27.4	9.4	10.8	5.5	0.068	7	0.99
13	1.1.2.1	27/11/1998	PT13	52.6	30	3.3	0.25	60	34	28	169	40	1.538	82.3	62.7	19.6	8.2	9.4	1.3	0.07	8	1.34
14	1.1.2.1	27/11/1998	PT14	53.6	30	2.0	0.23	63	32	28	213	55	1.705	76.9	51.4	25.5	10.6	12.4	13.5	0.045	5	0.74
15	1.1.1.1	27/11/1998	PT15	52.4	30	2.0	0.24	45	21	12	49	10	1.603	84.2	57.3	26.9	6.8	9.0	8.1	0.037	5	0.62
16	1.1.1.4	19/04/1999	SD1	57.9	30.0	3.0	0.12	58	23	21	46	13	1.670	72.2	27.4	44.8	10.3	17.5	9.8	0.06	15	1.30
17	1.1.2.4	19/04/1998	SD2	57.9	30.2	1.9	0.13	70	34	28	393	55	1.626	67.8	27.5	40.3	9.0	23.2	30.0	0.05	20	2.00
18	1.1.3.1	20/04/1999	SD3	58.2	32.2	5.2	0.09	73	47	35	558	95	1.466	75.6	28.3	47.3	8.7	15.8	23.6	0.1	16	2.90
19	1.1.1.3	20/04/1999	SD4	61.9	30.0	2.2	0.15	43	15	10	0	0	1.591	73.0	25.2	47.8	8.7	18.4	13.1	0.05	15	0.79
20	1.1.3.1	20/04/1999	SD5	52.2	30.0	4.5	0.07	81	40	38	335	75	1.546	79.0	28.9	50.1	7.3	13.7	19.2	0.05	12	2.10
21	1.1.3.2	21/04/1999	SD6	62.9	30.2	3.7	0.21	78	44	39	903	100	1.455	72.0	29.9	42.1	9.8	18.2	22.6	0.14	22	3.50
22	1.1.1.3	21/04/1999	SD7	60.0	30.3	3.0	0.05	41	15	10	0	0	1.602	78.1	27.2	50.9	8.2	13.7	13.5	0.03	9	0.66
23	1.1.1.1	21/04/1999	SD8	60.6	30.1	1.7	0.07	55	23	12	0	3	1.589	76.0	32.1	43.9	7.8	16.1	24.2	0.05	15	1.60
24	1.1.1.1	22/04/1999	SD9	58.6	30.5	3.3	0.07	58	23	16	0	0	1.586	77.0	30.4	46.6	7.9	15.2	13.6	0.04	15	1.20
25	1.1.3.2	22/04/1999	SD10	53.3	32.6	2.8	0.08	80	44	42	760	98	1.503	72.2	25.3	46.9	10.7	17.1	7.7	0.08	17	1.70
26	1.1.3.1	22/04/1999	SD12	51.5	32.0	2.5	0.22	83	46	46	526	85	1.470	74.0	32.5	41.5	9.6	16.4	15.1	0.11	18	2.20
27	1.1.1.4	23/04/1999	SD13	57.4	31.8	1.0	0.09	60	21	19	0	3	1.505	73.2	31.6	41.6	11.9	15.0	0.8	0.08	14	1.50
28	B 1.1.1.1	11/10/1999	HR1	58.7	30.0	5.0		50	34	14		8	1.511	81.4	49.1	32.3	7.9	10.7	1.8	0.08	19	0.99
29	B 1.1.1.1	12/10/1999	HR2	61.2	30.0	3.3	0.16	50	34	14		10	1.621	87.5	52.6	34.9	6.0	6.6	2.2	0.05	10	0.70
30	B 1.1.1.1	12/11/1999	HR3	69.7	30.0	2.0	0.11	48	21	9	0	0	1.771	87.5	52.2	35.3	5.9	6.6	2.8	0.03	17	0.38
31	B 1.1.1.1	12/11/1999	HR4	57.0	30.0	2.5	0.15	53	21	12	0	0	1.791	85.3	44.9	40.4	6.4	8.2	4.9	0.04	13	0.52
32	B 1.1.2.1	13/11/1999	HR5	60.7	30.0	4.2	0.14	50	27	12		4	1.565	86.7	51.4	35.3	6.3	7.0	1.7	0.04	10	0.74
33	B 1.1.2.1	13/11/1999	HR6	72.9	30.0	3.0	0.12	55	34	21		8	1.505	86.0	51.4	34.6	6.3	7.7	0.8	0.04	13	0.63
34	B 1.1.3.4	14/11/1999	HR7	66.0	30.0	5.0	0.07	58	40	21		10	1.284	84.8	52.3	32.5	7.8	7.4	1.2	0.10	27	1.30
35	B 1.1.2.1	14/01/1900	HR8	74.4	30.0	2.5	0.12	58	32	21		14	1.562	86.5	54.0	32.5	6.7	6.8	1.0	0.04	13	0.71
36	B 1.1.3.4	14/11/1999	HR9	76.3	30.0	6.7	0.07	50	41	23		12	1.187	85.2	54.7	30.5	8.0	6.8	0.8	0.10	21	1.30
37	B 1.1.2.1	15/11/1999	HR10	75.8	30.0	5.8	0.09	53	32	18		8	1.605	86.7	49.1	37.6	6.0	7.3	1.1	0.04	12	0.61
38	1.1.3.4	15/11/1999	HR11	88.1	24.0	3.3	0.12	80	50	37	1635	100	1.356	86.5	58.8	27.7	7.2	6.3	0.8	0.07	16	1.20
39	1.1.3.3	15/11/1999	HR12	90.9	32.0	3.3	0.14	80	50	37	1364	100	1.410	85.6	53.4	32.2	7.5	6.9	1.3	0.09	18	1.40
40	1.1.3.3	16/11/1999	HR13	63.8	34.0	5.6	0.08	70	43	35	808	75	1.503	89.3	55.9	33.3	6.2	4.6	1.2	0.04	10	0.68
41	1.1.3.3	16/11/1999	HR14	66.0	32.0	5.0	0.10	75	41	33	919	80	1.570	89.0	56.4	32.6	6.1	4.9	1.6	0.04	6	0.60
42	1.1.1.1	13/07/1998	TH1	57.5	30.0	2.0	0.07				50	8	1.626									
43	1.1.2.4	13/07/1998	TH2	54.3	30.0	2.0	0.10				191	55	1.902									
44	1.1.3.1	14/07/1998	TH3	61.2	30.0	2.0	0.10				856	80	1.735									

No	Class	Date	Plot code	Int mean	RunTime	Slope	WC	STAB	INF	NUT	BIOM	COV	BD	S 1-5	CS 1-5	FS 1-5	Z 1-5	Cl 1-5	G 1-5	N 1-5	P 1-5	C 1-5
45	1.1.2.4	14/07/1998	TH4	59.1	28.2	2.0	0.06				179	42	1.691									
46	1.1.1.1	14/07/1998	TH5	53.7	30.0	2.0	0.07				70	15	1.527									
47	1.1.3.2	14/07/1998	TH6	53.5	30.0	2.0	0.15				750	98	1.700									
48	1.1.3.2	15/07/1998	TH7	61.8	30.0	2.0	0.08				900	95	1.656									
49	1.1.3.2	15/07/1998	TH8	55.4	26.5	2.0	0.07				2946	85	1.562									
50	1.1.2.4	15/07/1998	TH9	62.5	30.0	2.0	0.06				384	50	1.769									
51	1.1.1.1	13/06/2000	MN1A	72.6	30.0	4.3	0.31	52	26	26		7	1.592	50.4	30.6	19.8	8.9	40.7	2.7			
52	1.1.1.1	13/06/2000	MN2A	80.3	30.0	4.0	0.28	35	15	13		5	1.610	60.4	35.5	24.9	9.0	30.6	7.0			
53	1.1.1.1	13/06/2000	MN3A	74.4	30.0	8.0	0.15	39	13	10		2	1.542	66.2	40.4	25.8	9.6	24.2	2.5			
54	1.1.1.1	14/06/2000	MN4A	78.1	30.0	7.3	0.26	45	15	13		20	1.570	52.7	32.4	20.3	10.4	36.8	1.7			
55	1.1.1.1	14/06/2000	MN6A	74.0	32.0	7.0	0.17	42	17	10		1	1.551	58.3	32.0	26.3	9.3	32.5	2.3			
56	1.1.3.1	15/06/2000	MN7A	74.2	30.0	9.8	0.28	68	28	26		93	1.513	69.0	42.2	26.8	11.7	19.3	3.0			
57	1.1.2.1	15/06/2000	MN9A	85.3	30.0	5.7	0.15	61	28	28		55	1.612	79.2	48	31.2	9.6	11.1	3.1			
58	1.1.3.1	16/06/2000	MN11A	68.2	30.0	5.2	0.32	71	33	35		80	1.477	50.7	8.6	42.2	18.4	30.8	0.7			
59	1.1.2.1	30/04/2001	MN2B	59.9	29.9	8.7		63	30	21		48	1.483	47.9	31.3	16.6	11.1	41.0	8.2	0.05	3	0.97
60	1.1.2.1	1/05/2001	MN3B	71.4	23.9	4.0		50	25	14		56	1.612	79.3	48.0	31.2	9.6	11.1	3.1	0.04	2	1.00
61	1.1.1.1	1/05/2001	MN4B	72.6	29.9	5.0		68	30	26		5	1.610	60.3	35.5	24.9	9.0	30.6	7.0	0.02	2	0.71
62	1.1.2.1	2/05/2001	MN5B	70.7	29.9	2.5		50	23	12		25	1.592	50.4	30.6	19.8	8.9	40.7	2.7	0.05	2	0.91
63	1.1.3.1	2/05/2001	MN6B	72.5	29.9	5.8		70	35	27		88	1.429	54.6	28.8	25.7	15.5	30.0	3.0	0.11	4	1.80
64	1.1.3.1	2/05/2001	MN7B	70.9	29.9	3.3		75	37	35		95	1.483	69.6	42.0	27.6	11.0	19.4	6.4	0.07	4	1.50
65	1.1.3.2	3/05/2001	MN8B	71.8	31.9	5.5	0.13	68	39	33		75	1.464	67.3	36.8	30.6	9.3	23.4	1.6	0.07	5	1.30
66	1.1.3.3	3/05/2001	MN9B	71.3	45.9	3.7	0.11	81	48	44		91	1.605	75.2	44.7	30.5	9.4	15.4	0.8	0.06	5	1.10
67	1.1.3.3	3/05/2001	MN10B	71.7	29.9	4.2	0.12	78	54	44		86	1.521	67.6	37.9	29.6	10.1	22.3	1.2	0.07	8	1.40
68	1.1.3.4	4/05/2001	MN11B	71.1	39.9	1.7	0.13	78	61	54		96	1.547	73.4	40.2	33.3	13.5	13.1	3.2	0.07	8	1.40
69	1.1.3.4	4/05/2001	MN12B	70.8	39.9	3.3	0.12	75	50	38		92	1.571	73.8	43.7	30.1	12.1	14.1	1.4	0.05	3	1.10
70	1.1.1.1	20/05/2002	WB1	67.6	30.0	0.17	0.09	60	23	15	54	13	1.673	57.8	33.7	24.1	18.1	24.1	12.7	0.04	6	1.10
71	1.1.2.1	20/05/2002	WB2	65.2	30.0	0.33	0.10	68	41	35	203	50	1.757	63.6	39.8	23.7	12.8	23.7	4.7	0.06	5	1.30
72	1.1.3.1	20/05/2002	WB3	65.2	30.0	0.33	0.09	78	41	36	542	84	1.661	63.6	37.5	26.1	14.3	22.0	4.7	0.09	6	1.80
73	1.1.3.3	21/05/2002	WB4	77.7	30.0	0.17	0.08	78	43	38	659	92	1.685	68.5	37.6	30.9	12.3	19.2	6.1	0.05	7	1.20
74	1.1.1.1	21/05/2002	WB5	65.6	30.0	1.67	0.10	63	32	23		13	1.794	67.3	37.5	29.8	14.9	17.8	4.3	0.04	6	1.30
75	1.1.3.2	21/05/2002	WB6	88.7	30.0	0.17	0.04	75	41	36	599	81	1.500	71.8	38.8	33.0	13.8	14.4	1.6	0.05	6	1.40
76	1.1.3.2	22/05/2002	WB7	84.3	30.0	1.17	0.03	72	47	36	772	86	1.544	71.8	42.4	29.4	13.4	14.9	1.8	0.05	2	1.30
77	1.1.1.1	22/05/2002	WB8	66.2	30.0	2.5	0.05	60	32	23	68	18	1.723	70.9	43.8	27.2	12.0	17.0	4.5	0.05	5	0.98

No	Class	Date	Plot code	Int mean	RunTime	Slope	WC	STAB	INF	NUT	BIOM	COV	BD	S 1-5	CS 1-5	FS 1-5	Z 1-5	Cl 1-5	G 1-5	N 1-5	P 1-5	C 1-5
78	1.1.3.4	22/05/2002	WB9	87.1	40.0	3.33	0.06	78	50	41	705	94	1.492	74.5	38.9	35.6	11.3	14.2	2.9	0.05	5	1.40
79	1.1.2.1	22/05/2002	WB10	76.2	30.0	0.83	0.04	68	37	30	355	72	1.747	68.9	41.1	27.9	12.6	18.5	5.4	0.05	4	1.10
80	1.1.3.4	23/05/2002	WB11	89.3	32.5	3.33	0.03	78	47	36	3099	100	1.511	75.4	47.4	28.0	12.9	11.8	1.7	0.07	5	1.50
81	1.1.3.4	23/05/2002	WB12	88.5	30.0	0.83	0.04	78	47	36	2726	100	1.483	73.5	46.1	27.4	12.9	13.7	5.1	0.05	5	1.50
82	1.1.2.4	23/05/2002	WB13	77.0	30.0	0.83	0.04	68	21	21	120	29	1.905	73.0	42.9	30.1	13.2	13.8	2.7	0.04	6	0.82
83	1.1.1.4	23/05/2002	WB14	76.9	30.0	0.83	0.05	63	19	19	4	3	1.704	73.7	44.2	29.5	13.0	13.3	4.1	0.04	5	1.10
84	1.1.3.4	24/05/2002	WB15	96.9	30.0	0.83	0.07	78	61	44	615	91	1.686	76.5	44.1	32.4	10.6	12.9	3.9	0.05	5	1.30
85	1.1.3.4	24/05/2002	WB16	96.4	30.0	0.83	0.05	78	61	44	768	95	1.626	72.6	43.1	29.5	12.1	15.3	2.5	0.04	7	1.20

Table 8.2B: Main data table

No	Class	Date	Plot code	If HOR	R^2 HOR	SE HOR	I30 Hor	R30 Hor	Sed30	PFIL	NFIL	PUF	NUF	PPART	NPART
1	1.1.1.1	23/11/1998	PT1	16.1	0.662	3.4	16.1	45.6	3.2						
2	1.1.2.1	23/11/1998	PT2	8.2	0.871	4.8	8.2	47.3	1.5						
3	1.1.2.4	23/11/1998	PT3	18.5	0.961	1.9	18.5	39.7	0.7						
4	1.1.3.1	24/11/1998	PT4	18.5	0.961	1.9	18.5	40.9	0.5						
5	1.1.3.1	24/11/1998	PT5	23.7	0.932	2.4	23.8	32.4	0.3						
6	1.1.1.4	24/11/1998	PT6	7.8	0.836	3.4	7.8	48.8	1.4						
7	1.1.1.2	24/11/1998	PT7	7.9	0.824	4.5	7.9	50.3	0.5						
8	1.1.1.1	24/11/1998	PT8	14.7	0.948	1.8	14.7	44.0	3.1						
9	1.1.3.1	26/11/1998	PT9	9.5	0.988	1.7	9.5	47.2	0.4						
10	1.1.3.2	26/11/1998	PT10	21.8	0.977	2.1	21.8	39.2	0.3						
11	1.1.3.1	26/11/1998	PT11	18.4	0.961	2.5	18.5	33.5	0.3						
12	1.1.3.1	26/11/1998	PT12	16.2	0.971	2.4	16.2	45.0	0.2						
13	1.1.2.1	27/11/1998	PT13	5.9	0.963	1.7	5.9	46.8	1.0						
14	1.1.2.1	27/11/1998	PT14	10.9	0.942	2.4	10.9	42.6	1.0						
15	1.1.1.1	27/11/1998	PT15	11.7	0.961	1.8	11.7	40.5	2.3						
16	1.1.1.4	19/04/1999	SD1	27.8	0.682	3.3	27.8	30.1	0.8	0.11	0.84	1.40	3.00	1.29	2.16
17	1.1.2.4	19/04/1998	SD2	10.7	0.987	1.5	10.7	47.1	0.6	0.12	0.91	0.80	2.50	0.68	1.59
18	1.1.3.1	20/04/1999	SD3	25.2	0.947	1.8	25.2	33.1	0.2	0.12	1.30	0.30	1.70	0.18	0.40
19	1.1.1.3	20/04/1999	SD4	14.1	0.938	2.7	14.1	47.9	0.3	0.05	0.85	0.26	1.30	0.21	0.45
20	1.1.3.1	20/04/1999	SD5	23.0	0.961	1.7	23.0	29.2	0.3	0.07	0.98	0.74	1.70	0.67	0.72

No	Class	Date	Plot code	If HOR	R^2 HOR	SE HOR	I30 Hor	R30 Hor	Sed30	PFIL	NFIL	PUF	NUF	PPART	NPART
21	1.1.3.2	21/04/1999	SD6	32.2	0.971	1.6	32.3	30.6	0.2			0.33	1.50		
22	1.1.1.3	21/04/1999	SD7	10.1	0.972	1.7	10.1	49.9	0.4	0.06		0.36	0.75	0.30	
23	1.1.1.1	21/04/1999	SD8	11.9	0.927	2.7	11.9	48.7	1.7	0.04	0.89	1.70	4.50	1.66	3.61
24	1.1.1.1	22/04/1999	SD9	11.5	0.983	1.4	11.5	47.2	1.9	0.07	1.20		4.60		3.40
25	1.1.3.2	22/04/1999	SD10	28.9	0.928	1.8	29.0	24.3	0.2	0.21		0.31	1.50	0.10	
26	1.1.3.1	22/04/1999	SD12	16.3	0.990	1.1	16.3	34.8	0.2	0.21		0.41	1.60	0.20	
27	1.1.1.4	23/04/1999	SD13	17.7	0.940	2.6	17.7	39.6	0.5	0.03	0.88	0.65	2.20	0.62	1.32
28	B 1.1.1.1	11/10/1999	HR1	30.2	0.959	2.0	30.2	28.6	0.6	0.70	2.10	4.70	10.60	4.00	8.50
29	B 1.1.1.1	12/10/1999	HR2	26.6	0.939	2.8	26.6	34.7	1.6	0.31	1.50	1.10	8.30	0.79	6.80
30	B 1.1.1.1	12/11/1999	HR3	12.3	0.900	3.8	12.3	57.2	1.0	0.32	1.90	3.20	4.60	2.88	2.70
31	B 1.1.1.1	12/11/1999	HR4	17.8	0.964	1.5	17.8	39.2	0.9	0.21	1.80	1.40	5.50	1.19	3.70
32	B 1.1.2.1	13/11/1999	HR5	28.9	0.983	1.1	28.9	31.9	1.0	0.05	0.21	5.40	5.00	5.35	4.79
33	B 1.1.2.1	13/11/1999	HR6	42.7	0.968	1.6	42.7	30.4	0.9		0.84		7.50		6.66
34	B 1.1.3.4	14/11/1999	HR7	54.4	0.139	1.4	54.4	11.5	0.4	0.79	1.80	1.70	6.60	0.91	4.80
35	B 1.1.2.1	14/01/1900	HR8	36.4	0.890	4.0	36.4	37.7	0.9	0.39	1.60	1.10	5.80	0.71	4.20
36	B 1.1.3.4	14/11/1999	HR9	41.5	0.844	0.6	67.8	8.4	0.8	0.33	1.20	2.70	7.60	2.37	6.40
37	B 1.1.2.1	15/11/1999	HR10	34.5	0.932	2.5	34.5	40.3	0.9	0.40	1.40	4.10	4.00	3.70	2.60
38	1.1.3.4	15/11/1999	HR11				> 75								
39	1.1.3.3	15/11/1999	HR12	75.1	0.661	2.4	75.1	15.9	0.1	0.40		0.69		0.29	
40	1.1.3.3	16/11/1999	HR13	48.9	0.903	1.3	48.9	14.9	0.3	0.23	0.75	0.40	2.60	0.17	1.85
41	1.1.3.3	16/11/1999	HR14	56.5	0.889	1.0	56.5	9.6	0.3	0.12	1.40	0.44	2.10	0.32	0.70
42	1.1.1.1	13/07/1998	TH1	4.1	0.947	3.7	4.1	53.2	2.9						
43	1.1.2.4	13/07/1998	TH2	8.5	0.902	2.1	8.5	45.9	0.7						
44	1.1.3.1	14/07/1998	TH3	17.5	0.895	2.2	17.5	43.6	0.3						
45	1.1.2.4	14/07/1998	TH4	19.4	0.794	1.0	19.4	39.7	1.0						
46	1.1.1.1	14/07/1998	TH5	12.0	0.601	3.4	12.0	41.6	2.7						
47	1.1.3.2	14/07/1998	TH6	24.2	0.984	1.1	25.8	27.8	0.2						
48	1.1.3.2	15/07/1998	TH7	34.1	0.877	2.6	34.2	27.5	0.6						
49	1.1.3.2	15/07/1998	TH8	40.0	0.946	1.1	40.0	15.5	0.7						
50	1.1.2.4	15/07/1998	TH9	23.3	0.951	2.1	23.3	39.3	0.6						
51	1.1.1.1	13/06/2000	MN1A	14.4	0.898	3.9	14.4	58.0	2.4		0.42		4.00		3.58
52	1.1.1.1	13/06/2000	MN2A	16.6	0.991	1.4	16.6	62.8	1.0		0.30		3.07		2.76
53	1.1.1.1	13/06/2000	MN3A	12.9	0.977	1.8	12.9	60.9	3.1		0.34		5.30		4.96

No	Class	Date	Plot code	If HOR	R^2 HOR	SE HOR	I30 Hor	R30 Hor	Sed30	PFIL	NFIL	PUF	NUF	PPART	NPART
54	1.1.1.1	14/06/2000	MN4A	3.1	0.987	2.4	3.1	74.7	2.9		0.65		5.20		4.55
55	1.1.1.1	14/06/2000	MN6A	7.1	0.982	1.8	7.1	66.6	3.3		0.56		4.57		4.01
56	1.1.3.1	15/06/2000	MN7A	12.1	0.983	2.4	12.3	61.2	0.4		0.56		1.40		0.84
57	1.1.2.1	15/06/2000	MN9A	21.4	0.976	2.4	21.4	63.2	0.4		0.36		2.03		1.67
58	1.1.3.1	16/06/2000	MN11A	12.3	0.847	5.5	12.3	56.0	0.7		0.66		3.13		2.47
59	1.1.2.1	30/04/2001	MN2B	17.8	0.949	2.3	17.8	42.1	0.4		0.14		1.10		0.96
60	1.1.2.1	1/05/2001	MN3B	10.6	0.923	3.6	10.6	60.8	0.4	0.22	0.34	0.82	1.50	0.60	1.16
61	1.1.1.1	1/05/2001	MN4B	12.1	0.968	2.1	12.1	60.4	2.2	0.13	0.29	1.70		1.57	
62	1.1.2.1	2/05/2001	MN5B	15.8	0.978	1.9	15.8	54.9	1.2	0.02	0.47	1.20	2.00	1.18	1.53
63	1.1.3.1	2/05/2001	MN6B	20.5	0.984	2.3	21.3	51.4	0.3	0.06	0.44	0.21	1.50	0.15	1.06
64	1.1.3.1	2/05/2001	MN7B	44.8	0.975	1.2	44.8	26.3	0.3	0.03	0.26	0.28	1.10	0.25	0.84
65	1.1.3.2	3/05/2001	MN8B	34.6	0.980	1.7	35.1	36.8	0.6	0.13	0.22	0.91	2.20	0.78	1.98
66	1.1.3.3	3/05/2001	MN9B	36.5	0.945	1.0	62.3	9.2	0.9	0.09	0.34	1.10	2.90	1.01	2.56
67	1.1.3.3	3/05/2001	MN10B	59.9	0.814	1.1	60.2	11.4	1.4	0.14	0.37	1.20	5.10	1.06	4.73
68	1.1.3.4	4/05/2001	MN11B				> 75								
69	1.1.3.4	4/05/2001	MN12B				> 75								
70	1.1.1.1	20/05/2002	WB1	13.0	0.889	3.8	13.0	54.5	0.8	0.33	0.84	0.61	3.30	0.28	2.46
71	1.1.2.1	20/05/2002	WB2	16.0	0.970	2.1	16.9	48.4	0.8		0.79	0.82	4.10	0.82	3.31
72	1.1.3.1	20/05/2002	WB3	9.1	0.954	2.1	17.4	47.9	0.6		1.20	1.20	2.80	1.20	1.60
73	1.1.3.3	21/05/2002	WB4	64.0	0.991	0.2	70.5	7.2	0.9	0.25	0.77	1.10	2.70	0.85	1.93
74	1.1.1.1	21/05/2002	WB5	20.5	0.969	1.3	20.6	45.1	1.2	0.07	0.99	0.94	4.20	0.87	3.21
75	1.1.3.2	21/05/2002	WB6	19.7	0.959	0.4	74.7	14.2	0.8	0.05	0.65	0.64	1.90	0.59	1.25
76	1.1.3.2	22/05/2002	WB7	72.6	0.882	0.5	77.5	7.1	0.7	0.11	0.86	0.84	3.10	0.73	2.24
77	1.1.1.1	22/05/2002	WB8	21.4	0.949	2.8	21.6	44.5	1.1						
78	1.1.3.4	22/05/2002	WB9				> 75								
79	1.1.2.1	22/05/2002	WB10	20.5	0.983	0.4	55.8	20.6	0.6	0.01	0.89	0.60	2.50	0.59	1.61
80	1.1.3.4	23/05/2002	WB11				> 75								
81	1.1.3.4	23/05/2002	WB12				> 75								
82	1.1.2.4	23/05/2002	WB13	19.5	0.995	0.9	20.9	55.9	0.9	0.01	0.94	2.00	3.10	1.99	2.16
83	1.1.1.4	23/05/2002	WB14	16.0	0.969	2.4	16.0	61.2	1.1	0.04	1.50	1.90	4.60	1.86	3.10
84	1.1.3.4	24/05/2002	WB15				> 75								
85	1.1.3.4	24/05/2002	WB16				> 75								

Appendix 9. Description of the hillslope overland flow model

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Introduction

The purpose of this document is to describe a mathematical model that calculates the discharge at the base of a hillslope segment during a rainfall event. We are only concerned with Hortonian overland flow, which occurs when rainfall intensity exceeds the infiltration rate. The hillslope is idealised by a plane of slope S with patches of different soil surface conditions representing the variable vegetation covers or the grazing induced-disturbances that occurred on the hillslope. Because of the variation in physical properties imposed by the patchiness of the hillslope, the overland flow process has to be modelled by a two-dimensional approach.

Modelling the overland flow process with a two-dimensional approach

Zero inertia equations

Generally, overland flow problems are simplified to one-dimensional process in which concentrated flow is assumed to occur in straight channels, and sheet flow is expressed in terms of a discharge per unit width. Because we want to study the influence of variations in surface cover and physical properties on overland flow, we need to follow a two-dimensional approach. The continuity equation for broad shallow two-dimensional sheet flow is written as

$$\frac{\partial h(x_1, x_2, t)}{\partial t} + \nabla \cdot \mathbf{q} = p(x_1, x_2, t) - i(x_1, x_2, t) = s(x_1, x_2, t) \quad (1)$$

where t [T] is time, x_1 [L], x_2 [L] are the spatial coordinates (x_1 across the hillslope and x_2 down the hillslope), h [L] is the mean depth of water above the soil surface h_s [L], $\mathbf{q}$ [L^2T^{-1}] is the vector of flow rate per unit width, p [LT^{-1}] is the precipitation rate and i [LT^{-1}] is the infiltration rate.

We will assume that the inertial and acceleration terms in the momentum equation are negligible. For the majority of overland flow problems, these terms can indeed be neglected (Moore and Foster, 1990). With these assumptions, the momentum equation is written as

$$\nabla h = \mathbf{S} - \mathbf{S_f} \quad (2)$$

where **S** is the slope vector and $\mathbf{S_f}$ is the friction slope vector. We introduce the water heights h_w [L] defined as

$$h_w(x_1, x_2, t) = h(x_1, x_2, t) + h_s(x_1, x_2) \quad (3)$$

Noting that $\mathbf{S} = -\nabla h_s$, we get

$$\nabla h_w = -\mathbf{S_f} \quad (4)$$

The general relationship between friction slope and flow rate (resistance relationship) is of the form

$$\mathbf{S_f} = k(h)\, \mathbf{q.q} \quad (5)$$

where k is some function of the hydraulic radius. Because we are dealing with broad shallow overland flow, the hydraulic radius can be approximated by the water depth. By combining Eqs. (4) and (5) we get

$$\mathbf{q} = -k(h)^{1/2} \left| \nabla h_w \right|^{-1/2} \nabla h_w = -K(h) \nabla h_w \tag{6}$$

where K plays the role of an hydraulic conductivity. Combining Eqs. (1) and (6) yields the system of equations

$$\begin{aligned} \frac{\partial h}{\partial t} &= -\left(\frac{\partial q_1}{\partial x_1} + \frac{\partial q_2}{\partial x_2} \right) + p - i \\ q_1 &= -K(h) \frac{\partial h_w}{\partial x_1} \\ q_2 &= -K(h) \frac{\partial h_w}{\partial x_2} \end{aligned} \tag{7}$$

Resistance relationship

The relationship between flow rate and friction slope (Eq. (5)) is expressed in terms of the dimensionless Darcy-Weisbach resistance coefficient f and of the acceleration due to gravity g [L^2T^{-1}]

$$\mathbf{S_f} = \frac{f}{8gh} \frac{1}{h^2} \mathbf{q.q} \tag{8}$$

so that in this particular case

$$k(h) = \frac{8gh^3}{f} \tag{9}$$

Numerical solution

General equations

A hillslope of width $X1$ and length $X2$ can be divided into ($nx1$+1)×($nx2$+1) rectangles of area $\Delta x1 \times \Delta x2$. We introduce the grid indices i and j such that $x_1 = i\Delta x_1$ and $x_2 = j\Delta x_2$. The index i runs from 0 to nx_1 and the index j runs from 0 to nx_2 (Figure 9.1). We use the following notations

$h_{i,j}$: water depth at ($i\Delta x_1$, $j\Delta x_2$)

$hw_{i,j}$: height of water surface above reference plane at ($i\Delta x_1$, $j\Delta x_2$)

$hs_{i,j}$: height of soil surface above reference plane at ($i\Delta x_1$, $j\Delta x_2$)

$s_{i,j}$: source/sink term due to precipitation and infiltration at ($i\Delta x_1$, $j\Delta x_2$)

$q^1_{i,j}$: x_1 component of flow rate to the right of ($i\Delta x_1$, $j\Delta x_2$), i.e. at ((i-1/2)Δx_1, $j\Delta x_2$)

$q^2_{i,j}$: x_2 component of flow rate under ($i\Delta x_1$, $j\Delta x_2$), i.e. at ($i\Delta x_1$, (j-1/2)Δx_2)

$K_{i,j}$: conductivity at ($i\Delta x_1$, $j\Delta x_2$)

$ghw^1_{i,j}$: x_1 component of gradient of water heights at ($i\Delta x_1$, $j\Delta x_2$)

$ghw^2_{i,j}$: x_2 component of gradient of water heights at ($i\Delta x_1$, $j\Delta x_2$)

With these notations (see Figure 9.1 for more information on where the parameters are defined), we discretise Eqs. (7) in space to obtain a set of ordinary differential equations (ODEs) valid for $0 \le i \le nx_1$ and $0 \le j \le nx_2$

$$\begin{aligned}&\text{If}\quad \left(-\frac{q^1_{i+1,j}-q^1_{i,j}}{\Delta x_1}-\frac{q^2_{i,j+1}-q^2_{i,j}}{\Delta x_2}+s_{i,j}\right)\le 0 \quad\text{And}\quad h_{i,j}\le 0 \quad\text{Then}\quad \frac{\mathrm{d}h_{i,j}}{\mathrm{d}t}=0\\ &\text{Else}\quad \frac{\mathrm{d}h_{i,j}}{\mathrm{d}t}=-\frac{q^1_{i+1,j}-q^1_{i,j}}{\Delta x_1}-\frac{q^2_{i,j+1}-q^2_{i,j}}{\Delta x_2}+s_{i,j}\end{aligned} \tag{10}$$

with

$$q^1_{i,j}=-\frac{K_{i,j}+K_{i-1,j}}{2}\frac{hw_{i,j}-hw_{i-1,j}}{\Delta x_1} \tag{11}$$

$$q^2_{i,j}=-\frac{K_{i,j}+K_{i,j-1}}{2}\frac{hw_{i,j}-hw_{i,j-1}}{\Delta x_2} \tag{12}$$

$$K_{i,j}=\sqrt{\frac{8g}{f}}h_{i,j}^{3/2}\left(\left(ghw^1_{i,j}\right)^2+\left(ghw^2_{i,j}\right)^2\right)^{-1/4} \tag{13}$$

For $1 \le i \le nx_1 - 1$ and $1 \le j \le nx_2 - 1$, $$ghw^1_{i,j}=\frac{1}{2\Delta x_1}\left(hw_{i+1,j}-hw_{i-1,j}\right) \qquad ghw^2_{i,j}=\frac{1}{2\Delta x_2}\left(hw_{i,j+1}-hw_{i,j-1}\right)$$

For $1 \le i \le nx_1 - 1$ and $j = nx_2$, $$ghw^1_{i,nx_2}=\frac{1}{2\Delta x_1}\left(hw_{i+1,nx_2}-hw_{i-1,nx_2}\right) \qquad ghw^2_{i,nx_2}=\frac{1}{\Delta x_2}\left(hw_{i,nx_2}-hw_{i,nx_2-1}\right) \tag{14}$$

For $i = nx_1$ or $i = 0$ or $j = 0$, $$ghw^1_{i,j}=0 \qquad ghw^2_{i,j}=0$$

The If statement in Eqs. (10) ensures that the model does not calculate negative water depths.

Initial and boundary conditions

We assume that initially, there is no water on the hillslope (dry soils) so that the initial conditions are

For $0 \le i \le nx_1$ and $0 \le j \le nx_2$, $$\frac{\mathrm{d}h_{i,j}}{\mathrm{d}t}=0,\ t=0 \tag{15}$$

We assume that there is no flow at the x_1 boundaries (side boundaries) and at the top of the hillslope so that

For $0 \le j \le nx_2$, $$q^1_{0,j}=-q^1_{1,j} \text{ and } q^1_{nx_1+1,j}=-q^1_{nx_1,j} \tag{16}$$

For $0 \le i \le nx_1$, $$q^2_{i,0}=-q^2_{i,1} \tag{17}$$

At the bottom of the hillslope, we impose a drainage line so that h = 0 at j = nx_2. This gives the last boundary condition

$$\text{For } 0 \le i \le nx_1, \quad q^2_{i,nx_2+1} = \frac{\Delta x_2}{\Delta x_1}\left(q^1_{i,nx_2} - q^1_{i+1,nx_2}\right) + q^2_{i,nx_2} + \Delta x_2 s_{i,nx_2} \qquad (18)$$

The set of ODEs (10) was numerically solved using the function NDSolve in Mathematica 4.0™.

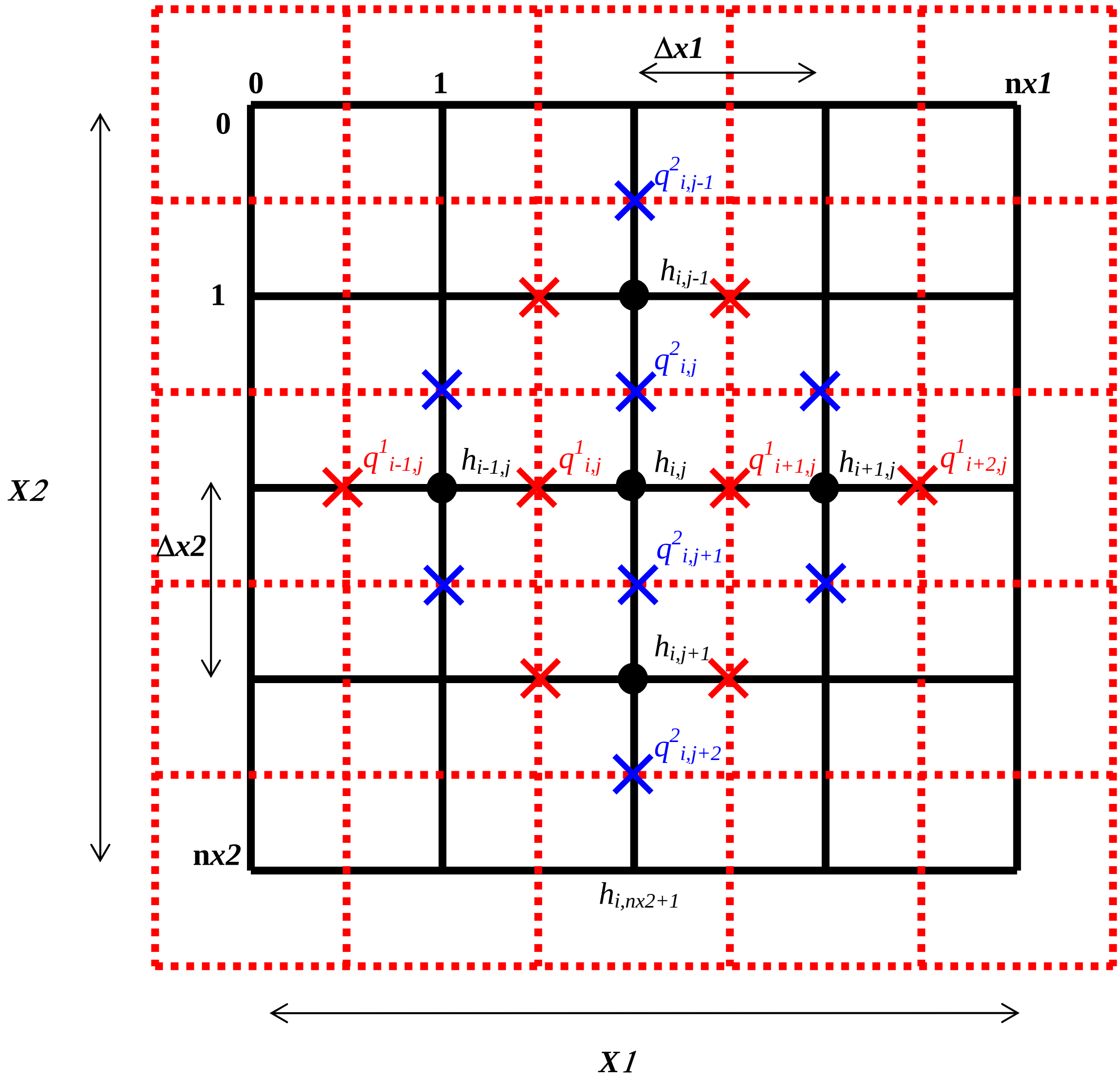

Figure 9.1: Discretisation of hillslope into ($nx1$+1)×($nx2$+1) rectangles of area $\Delta x1 \times \Delta x2$.

Model implementation

Model testing

We first evaluated the performance and accuracy of the overland flow model. As at the time of development there was no available data against which we were able to compare the model's results, we carried out basic verifications of the numerical model, including mass balance checks. We carried out runs for various hillslope surface conditions, and checked the soundness and consistency of the results. The next important stage of modelling overland flow will be to compare model's calculations with field data.

To simplify the model and reduce calculation time, we further assumed that the gradient factor in Eq. (6) could be ignored and that the flow rate could be calculated with

$$\mathbf{q} = -k(h)^{1/2} \nabla h_w \qquad (19)$$

Since the laws governing flow under the conditions we are dealing with are not well established, this simplification may be acceptable. To test this hypothesis, we compared model's calculations obtained using Eq.(6) to model's calculations obtained using Eq.(19). The difference in total runoff calculated by either of these two methods was less than 10%. Calculation times were up to 20 times faster using the simplified Eq.(19). Hence, for all of our calculations, flow rates were computed using Eq.(19).

Hillslope parameterisation

The model was initially run on two hillslopes representative of the area under study. To characterise the vegetation cover of the area, visible and near-infrared aerial videography data with a 0.5m $\times$ 0.5m pixel resolution were used. An area was selected within the available data and analysed to determine ground cover type and distribution.

The slope was uniform and equal to 0.05 m/m. Trees and bushes were ignored from the ground cover map, as were their shadows. We used a combination of albedo and greenness to distinguish dry grass cover from bare soil. An albedo threshold value combined with a greenness ratio (ratio of green to red channels) threshold value were used to separate bare ground from grass cover. Within the pixels classed as grass covered, the greenness ratio was used to further discriminate between high, moderate and low vegetation covers.

We chose two hillslope samples from the analysed videography data. Both samples were 8 m wide by 32 m long. One hillslope sample had degraded ground cover (referred to as "low cover" sample) and the other sample had moderate ground cover (referred to as "moderate" samples).

Hillslope characterisation

The sampling of ground cover from the two images generated four cover classes: bare, low, moderate and high. In the model, we used infiltration characteristics determined directly for each cover class at Site 2 (Pinnacle Transect), rather than class averages. The bare and low cover class correspond to the soil surface condition; class 1.1.1.1, the moderate class 1.1.2.1 and the high cover class to 1.1.3.1, defined in Figure 7.7 (Volume 1, respectively).

In addition, we defined an additional slope scenario in which all pixels correspond to soil surface condition class 1.1.3.3.

To simulate the effects of microtopography on surface runoff, we associated specific heights with each surface condition, based on the observations made in the field. These heights are given in Table 9.1. Microtopography for the very high cover scenarios was set to 0, as the whole surface consisted of the same pixels.

Table 9.1: Microtopography associated with the surface conditions of the representative hillslopes

Surface type	Soil surface condition class	Height (m)
Bare area	1.1.1.1	0
Low vegetation cover	1.1.1.1	$1\ 10^{-3}$
Moderate vegetation cover	1.1.2.1	$3\ 10^{-3}$
High vegetation cover	1.1.3.1	$5\ 10^{-3}$
Very high vegetation cover	1.1.3.3	0

Resistance relationship

The values of the Darcy-Weisbach resistance coefficient *f* for the various surface conditions were computed from the literature (Parsons et al., 1994). These values are given in Table 9.2.

Table 9.2: Value of the Darcy-Weisbach resistance coefficient f for the surface conditions of the representative hillslopes

Surface type	Soil surface condition class	*f*
Bare area	1.1.1.1	5
Low vegetation cover	1.1.1.1	20
Moderate vegetation cover	1.1.2.1	40
High vegetation cover	1.1.3.1	60
Very high vegetation cover	1.1.3.3	5

Infiltration

Infiltration rates depend on surface conditions. We described infiltration rates with Philip's equation and obtained the parameters for Philips equation for each surface condition by analysing data from rainfall simulation experiments carried out at the Pinnacle Transect in Dotswood (see Appendix 8 this volume). The Phillip's equation was used rather then the Horton equation as it is easier to linearize, simplifying the mode. The values of these parameters are given in Table 9.3.

Table 9.3: Values of the Philips equation parameters for the surface conditions of the representative hillslopes

Surface type	Soil surface condition class	*A* (m/hr)	*S* (m/hr$^{1/2}$)
Bare area	1.1.1.1	6.7 10^{-3}	6.7 10^{-3}
Low vegetation cover	1.1.1.1	6.3 10^{-3}	7.6 10^{-3}
Moderate vegetation cover	1.1.2.1	10.1 10^{-3}	8.0 10^{-3}
High vegetation cover	1.1.3.1	13.9 10^{-3}	12.3 10^{-3}
Very high vegetation cover	1.1.3.3	79.6.10^{-3}	0 8 10^{-3}

Sediment concentration

Sediment concentrations selected represent the equilibrium sediment concentrations at ~ 30mm of rainfall obtained from the rainfall simulation experiments. The corresponding values are given in Table 9.4.

Table 9.4: Values of sediment concentrations *C* for the surface conditions of the representative hillslopes

Surface type	Soil surface condition class	*C* (g/m^3)
Bare area	1.1.1.1	2.4 10^3
Low vegetation cover	1.1.1.1	1.5 10^3
Moderate vegetation cover	1.1.2.1	0.6 10^3
High vegetation cover	1.1.3.1	0.3 10^3
Very high vegetation cover	1.1.3.3	0.15 10^3

Precipitation

The precipitation rate we have chosen for modelling runoff reproduced a heavy storm characteristic of the rainfall in the area of interest. It was assumed the precipitation rate was uniform over the entire surface area of the hillslope. We considered a storm which delivered 0.03 m of rain in 0.5 hr. The precipitation rate during each storm was assumed to follow a X^2 distribution with the maximum precipitation rate obtained at 1/5$^{\text{th}}$ of the total storm duration. Hence, the precipitation rate is given by the equations

$$\begin{aligned} &t \le 0.5, \quad p(t) = 3.127\ \mathrm{Exp}(-10\,t)\,t \\ &t > 0.5, \quad p(t) = 0 \end{aligned} \qquad (20)$$