Water IP – water knowledge services

Improving how gully erosion and river sediment transport processes are represented in Queensland catchment models

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A report to the Queensland Water Modelling Network

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Preface and acknowledgements

This report is the product of Queensland Water Modelling Network Project 2.1.1: Conceptual Model R&D – gullies, streambanks and channels. Ian Prosser of *Water IP* – water knowledge services was contracted to complete the project. It was informed by discussions at a three-day workshop, which allowed a broader set of inputs and views to be expressed. General consensus was reached at the workshop. A draft of this report was produced prior to the workshop, and was then revised as a result of workshop discussions and other inputs. Contributors to the workshop and the report are listed on the previous page, and their input is much appreciated. However, the author is responsible for how those inputs were used and any judgements or mistakes that have been made. The final report benefited from reviews by Jon Olley, Ian Rutherfurd, Rebecca Bartley and James Grove. I am also grateful to Robin Ellis, Jenny Riches, Jean Erbacher and Jo Burton of the Dept. of Environment and Science for managing the project.

The views expressed in this report are those of the author, except where acknowledged. They are not necessarily the views of the Queensland Government or individual workshop participants.

Executive summary

The Queensland Government uses the Dynamic SedNet model to predict sediment and nutrient loads from catchments of the Great Barrier Reef, and it has the potential for broader uses across the state. The model is used to evaluate how well major catchment management programs are likely to improve water quality downstream in large regional catchments.

Dynamic SedNet is a further development of the SedNet model that was built about 15 years ago for the National Land and Water Resources Audit. The Queensland Government has customised the model to suit its purposes, particularly changing the way agricultural erosion is modelled. It has made incremental changes to the way river processes are modelled and put a lot of effort into improved spatial data inputs for the model, particularly for gully erosion.

Beyond these changes, the modelling of gully erosion and river processes remains largely unchanged since the model was first developed. SedNet is a sediment budget model, applying concepts developed in catchment geomorphology to water quality modelling. Since the model was first built, there has been a substantial body of research on geomorphology and sediment transport of Queensland catchments, so it is an appropriate time to review that research. Some of the research has already been included in the model through improvements mentioned above. This report examines the concepts coming out of the research and how they might be included in further improvements to catchment water quality modelling.

Multiple lines of evidence are used to understand and improve catchment water quality. The model is one line of evidence, used together with load monitoring, remote sensing, sediment tracing and field research. Full integration of these multiple lines of evidence will provide the best understanding. Incorporating research findings into the model is part of that integration, as is using the model to help determine future research priorities.

An earlier review of the model found that it is largely fit for purpose, and incorporates the main catchment processes and concepts. Inevitably, though, there are considerable uncertainties in the predictions and in individual sediment processes considered. Before any major improvements are made, an uncertainty analysis should be undertaken to identify the areas that will make the most difference to use of the model. Qualitative consideration of uncertainties during this project highlighted the following initial projects to improve the model:

- continued gully mapping
- evaluation of effectiveness of management
- current sediment yield from gully erosion
- riverbank erosion
- soil properties of gullies and riverbanks.

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1. Introduction

The Queensland Water Modelling Network (QWMN) is a four-year Queensland Government program focused on improving a broad suite of water models used in government. One of these models is the catchment water quality model used in the *Reef Water Quality Protection Plan* (Reef Plan), but the program also applies to other large catchments across Queensland. One aim of the QWMN is to review the current understanding of land and water transport processes and have them more accurately reflected in the models.

This report is the output from QWMN Project 2.1.1: Conceptual Model R&D – gullies, streambanks and channels. The aims of the project are to:

- review the current understanding of gully erosion and river sediment transport processes in Queensland catchments
- use that understanding to describe conceptual models for gully erosion and river sediment transport processes
- use this conceptualised understanding and knowledge of the current catchment sediment model to suggest improvements that could be made to the model.

The scope of possible model improvements that were considered is very broad. Improvements can mean:

- new spatial input data to better represent patterns in processes
- better parameter estimates to increase accuracy of the model
- new measurements that better define large-scale controls on poorly understood processes or constrain model predictions
- new model algorithms that better reflect the levels of process understanding
- better understanding of uncertainty and how to represent it
- new modelling approaches.

The project recognises that catchment models used to estimate pollutant load reductions are increasingly being used for purposes beyond their original design. The Queensland Government has made major changes to the modelling of hill-slope erosion processes. Some changes have been made to the modelling of river deposition, and a lot of work has gone into improved inputs of spatial data, but the basic approach to gully and riverbank erosion remains the same as in the original SedNet (Prosser et al. 2001a) model.

Meanwhile, there has been a substantial body of additional research into gully erosion and river sediment transport in Queensland. The recent Great Barrier Reef Scientific Consensus Statement reaffirms the major contributions of sediment from gullies and riverbank sources compared to erosion of agricultural land, and the same probably applies elsewhere. This report reviews that research to identify possible improvements to Queensland water quality modelling.

2. Current approach to catchment modelling

2.1 Introduction

The Queensland Government uses a version of the Dynamic SedNet model (Wilkinson et al. 2014) for catchment water quality modelling (Waters et al. 2014; Ellis and Searle 2014). The model is implemented using the Source platform (eWater Ltd 2017). For application to the Reef Plan, Queensland has:

- made incremental improvements to the model
- customised it through various add-ons
- linked it to paddock-scale models of sediment and nutrient generation from agricultural land.

Dynamic SedNet is a daily time-stepping model that was developed from the original steady state SedNet model built for the National Land and Water Resources Audit (NLWRA) (Prosser et al. 2001a). The basic structure of the model is that it is a sediment budget model, or could be described as a sediment mass accounting model or sediment mass balance model. It aims to account for the major sources (erosion) and stores (deposition) of sediment in a catchment, the residual of which is exported from the catchment. The major sources of sediment that are modelled are hill-slope erosion (surface wash erosion on agricultural land and other land uses), gully erosion and riverbank erosion (Figure 1). The major stores modelled are hill-slope deposition (modelled through a hill-slope sediment delivery ratio); floodplain deposition; and reservoir deposition (Figure 2). For Reef Plan modelling, within channel deposition and re-entrainment of fine sediment has been added as a source and sink (see Sections A6 and 3.9). Hill-slope erosion is predicted from finer scale “paddock” models such as USLE or models specific to particular land uses (Ellis and Searle, 2014). Improvements to paddock scale modelling will be considered by a parallel project so are not considered here.

SedNet is a large scale semi-distributed spatial model. It is structured around river reaches and their sub-catchments. A sub-catchment is further delineated into ‘functional units’ (FUs) which in Queensland applications are based on land use categories. The model aims to examine the first order patterns of sediment transport, based upon patterns in driving environmental factors such as hydrology, geomorphology, rainfall, vegetation cover, land use and soil properties. The influence of environmental factors on sediment transport is modelled by first order representations of physical processes where possible although there is inevitable use of empirical representations and calibrations against observations. SedNet was designed to be applied at the sub-continental scale (such as across all agricultural and pastoral catchments in Australia) down to large regional catchments containing diverse environments.

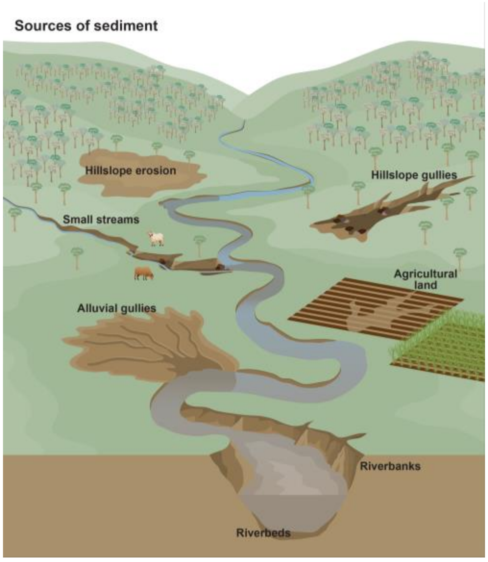

Figure 1. *Main sources of sediment identified in Queensland catchments. At present alluvial and hill-slope gullies are grouped together as gully erosion in the model and erosion of small streams is not modelled.*

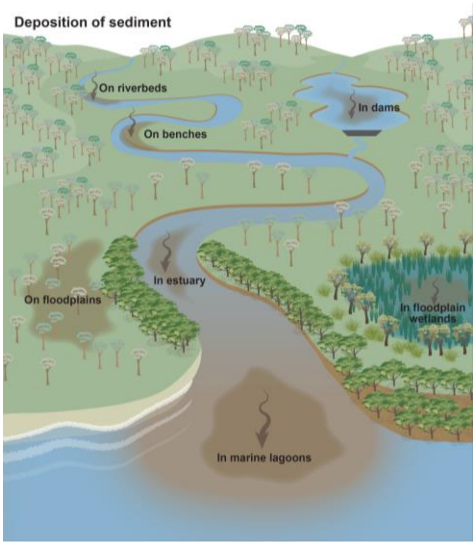

Figure 2. *Main locations of fine sediment deposition in catchments. Floodplain and wetland deposition are modelled together at present and the model does not extend to estuarine and marine processes so deposition in these areas is not modelled by the catchment model. Marine models can be used for those processes.*

SedNet started as a steady state model, predicting mean annual masses of the budget terms under particular conditions, such as recent or future land use. With Dynamic SedNet, it has evolved to be a daily time-stepping model that aims to produce annual sediment loads from catchments for comparison to monitoring of catchment loads, and for use as an input to marine water quality modelling.

The model produces separate budgets for fine and coarse sediment. The fine sediment budget focuses on processes of suspended sediment transport. The coarse budget focuses on bedload transport processes. The total mass of sediment derived from a source is apportioned between fine and coarse sediment, usually based on soil properties. The transport of fine and coarse sediment through the river network is then modelled independently. The coarse sediment budget is not analysed for the Reef Plan. It has potential applications for examining river channel aggradation and degradation, and major changes in in-stream habitat resulting from increased sediment transport such as ‘sand slugs’, but is less relevant for water quality.

Through application of nutrient concentrations, the model is used to examine loads of particulate nitrogen (N) and phosphorus (P) that come from erosion. These are coupled with catchment modelling of dissolved N and P and nutrient transformations to model catchment nutrient budgets. The scope of this project is to examine gully erosion and river sediment processes. It goes as far as considering nutrient concentrations in eroding sediments, but does not consider broader nutrient transport and transformations, which require quite different expertise.

For Reef Plan modelling, the fine sediment budget is restricted to particles finer than 20 µm, to focus on the size of particles that are transported far enough to have impact on the coral and seagrass marine environments of concern (Bainbridge et al. 2012). The use of 20 µm to define fine sediment represents the particle size range corresponding to clay and silt proportions of the international particle size classification system used in the Queensland Government's soil and land information database 'SALI', from which most soil data inputs for Reef Plan modelling are sourced. The coarser suspended sediment exported from rivers tends to be deposited in the vicinity of the river mouth.

2.2 Purpose of the model

All models are simplifications and generalisations of reality. The appropriateness of simplifications and the matters that a model addresses depend on the purpose or use of the model. Different purposes will be suited to quite different representations of the same processes. Therefore it is important to be very clear about the purpose of a model and to always use that purpose in evaluating the model.

A useful analogy is with maps, which also are simplifications (graphical models) of reality. Maps vary remarkably in their scale and what they portray depending on their intended use. There are no absolute right or wrong things to represent in a map, but there are differences in effectiveness at meeting different purposes. Maps and models can be inaccurate, however, which is critical if it leads to false conclusions.

A common purpose of most catchment models is to estimate discharge, sediment and nutrient loads in catchments where these are not monitored. Another common purpose is to predict discharges or constituent loads under future conditions. Essentially modelling is used to extrapolate from gauged circumstances to ungauged circumstances. The main purpose to which Dynamic SedNet is put in Queensland is to examine the effectiveness of Reef Plan catchment management at reducing future pollution of the Great Barrier Reef (GBR) from fine sediment and attached nutrients.

A secondary purpose of the model is to help guide management by identifying those parts of catchments and those catchment processes where management will be most effective at reducing sediment and nutrient loads. The model can be used to plan the scale and type of management program. The model has been used by the Queensland Government for this secondary purpose in the GBR catchments, and Queensland Murray Darling Basin catchments. It has potential to be used for both purposes in south-east Queensland catchments, although the addition of urban source areas would require a different approach to sub-catchment land use modelling.

To evaluate the effectiveness of catchment management, we need to know how much the management will reduce the rate of sediment generation, and how that local reduction in sediment generation is passed downstream to load reductions of fines (fine sediment and associated particulate nutrients) at the mouth. The latter is needed in addition to understanding the rate of erosion reduction because some parts of catchments have high sediment delivery efficiency, contributing disproportionate amounts of sediment to the river mouth, while others store most of the sediment, preventing it from passing downstream. So there are hotspots of sediment sources within catchments, and there are other parts of catchments that contribute little to the marine environment. This aspect of functionality is also what is required to identify priorities for management at the planning stage of a program.

The Reef Plan is a large government program with substantial investment of public funds, so it is good practice to evaluate progress to give governments and the public confidence that the money is being well spent and that reasonable progress is being made on such a large and 'wicked' problem. Not all government programs are well evaluated, but the effort that goes into program evaluation for the Reef Plan is a stand-out example (Jakeman et al. 2015).

Catchment modelling is used as one of multiple lines of evidence to report on progress towards the Reef Plan water quality targets. The Reef Plan is further evaluated through paddock-scale monitoring and modelling of the effectiveness of land management practices; monitoring of the prevalence of improved practices over time; catchment loads monitoring; catchment indicators; and marine monitoring. (McCloskey et al. 2017a).

The catchment modelling provides crucial links between on-ground management changes and load monitoring (such as seeing if catchment mouth targets can be met by management actions further up the catchment). It can also account for lags in management actions taking full effect, and for naturally high inter-annual variability in loads as a result of Australia's naturally high hydrological variability. Because of this hydrological variability, it would take decades to use monitoring alone to demonstrate with certainty that loads have reduced over time. Monitoring is required though, along with other measurements, to give confidence that model predictions have a basis in reality.

For the purposes of identifying priority places and actions for catchment management, a model needs to correctly apportion at least relative sediment loads between different sources, whether they be different sub-catchments, land uses and land use practices, or erosion processes. Modelling, coupled with measurements and advances in remote sensing analysis, is appropriate for the largest scales of prioritisation across large diverse catchments, but as the scale of assessment decreases and increased precision is required in design of management action, measurements and field observations become more important. It is not practical or efficient to make field measurements everywhere across large regions beyond the operational use of remote sensing.

Three scenarios are used in Reef Plan modelling to meet the model purposes, and similar approaches have been used elsewhere:

1. *Predevelopment scenario*—this is used as a foundation with which to compare the other two scenarios. It recognises that sediment transport is a natural process with natural variability across landscapes. Acceleration of erosion and increased sediment loads are the problem.
2. *Baseline scenario*—this represents recent sediment loads and erosion as a basis on which to evaluate improved land management practices. The model is used to identify places and processes for management attention by comparing the current baseline to the predevelopment scenario to show the degree of acceleration of sediment transport.
3. *Reef Plan 'implemented change' scenario*—recent management interventions aimed at reducing sediment transport are represented in this scenario. These are used to model reduced erosion rates which then follow through in the model to predictions of reduced sediment loads at river mouths. The Reef Plan

scenario is compared to the baseline scenario to measure annual progress compared to the target reductions of the Reef Plan.

To be useful to the Reef Plan and other catchment management programs, catchment sediment modelling needs to:

- be responsive to land management changes
- represent the effectiveness of land management changes
- be specific to the pollutants of concern (e.g. particle size, particulate nutrients)
- identify major sources of these pollutants
- scale from paddock to catchment mouth
- be consistently applied across all catchments covered by the program
- be able to report progress toward meeting targets (list modified from Jakeman et al. 2015).

These are quite onerous requirements, and it takes a concerted measurement and modelling program over many years to meet them. At the time that the Reef Plan was first being implemented, there were no available models that met all the requirements. An innovative combination of existing models and some further model developments were made to start meeting these requirements.

2.3 Concepts included in the model

SedNet was first developed about 15 years ago for the NLWRA. Its main innovation was to bring sediment budget concepts that were well developed in geomorphology to the topic of catchment modelling of water quality.

At the time, catchment water quality modelling largely used statistical or hydrological approaches. For example, in catchments where water quality and discharge were monitored, the mean concentration of sediment and nutrient was determined. In ungauged catchments, discharge was estimated using well developed empirical and conceptual models of rainfall to run-off. Applying mean concentrations of sediment and nutrient to the modelled discharge enabled loads of these pollutants to be estimated. Alternatively, statistical analysis of water quality data was used to determine the relationship between water quality and factors such as land use, and these relationships were then extrapolated to other catchments. These approaches assume that the concentrations measured or statistical relationships observed apply to unmonitored catchments even though, when extrapolated across large areas, these other catchments might be quite different in many ways to the monitored catchments. Predominantly, they focused on volume of run-off or land use as the predictors for catchment water quality. These models meet few of the requirements identified above by Jakeman et al. (2015).

At the same time, there was a substantial body of work in geomorphology that showed, through a range of approaches, that much of the sediment eroded in catchments was stored on hill-slopes and in river networks for years to thousands of years before being exported from the catchment. Work also showed that there were multiple sources of sediment in catchments. In disturbed catchments, there was not just sheetwash and rill erosion of agricultural land; there were erosion gullies, landslides and major transformations of river channels that could be the source of sediment, in many cases yielding more sediment than agricultural land. These concepts were formalised through catchment sediment budgets that attempted to quantify the major sources and stores of sediment within a catchment. Efforts were made, with varying degrees of success, to incorporate these concepts into catchment management. Sediment budget concepts were extended into nutrient budgets for N and P, where sediment is a source of particulate nutrient that can be compared to sources of dissolved nutrients.

By incorporating sediment budget concepts, SedNet aims to model the large-scale spatial patterns of sources and stores of sediment, and use those to estimate catchment sediment loads. In catchments where sediment loads are measured, the sources and stores can be calibrated to match the loads, and the calibrated relationships can be applied to ungauged catchments. An example of the results that the model produces and how they differ between catchments is shown in Figure 3.

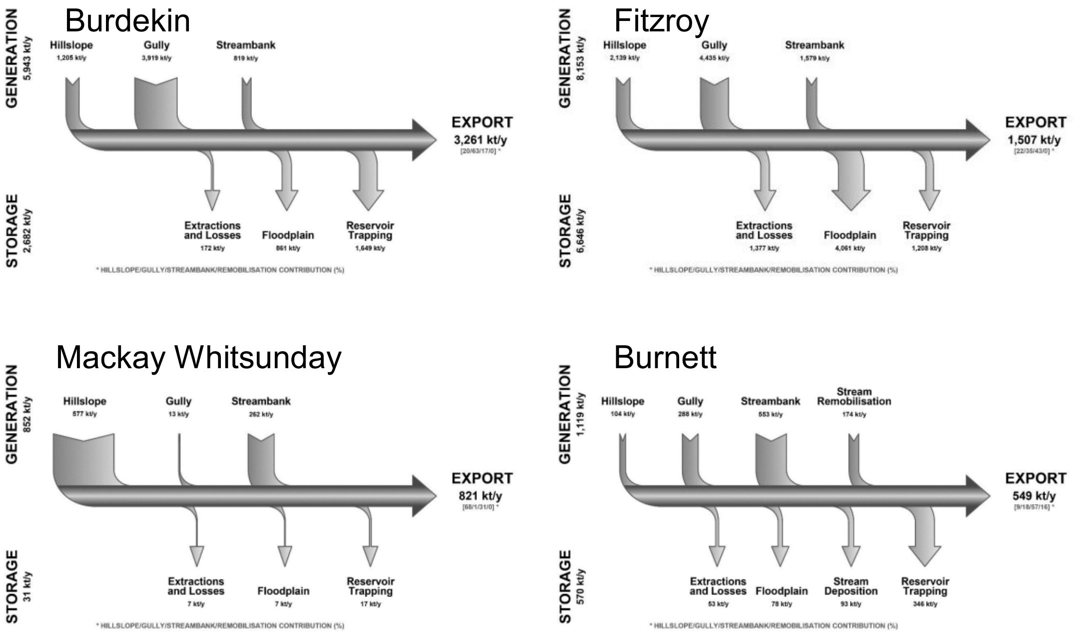

Figure 3. *Example of catchment sediment budgets produced by the SedNet model for GBR regions (from McCloskey et al. 2017b). There are very different sizes of sediment sources, stores and export between regions, which is the primary focus of the model.*

The advantages of taking a sediment budget approach to water quality modelling over the previous approaches are:

- It is more directly based on physical processes of erosion and theory or conceptual understanding of those processes, although empirical relationships are still used in part.
- Through a mass balance, it integrates and reconciles understanding of erosion processes across a range of scales from sources to export from very large catchments.
- Sediment load is expressed as a function of multiple environmental factors, through the modelling of individual processes of erosion and deposition.
- By forcing a mass balance of components, the model can be evaluated against multiple lines of evidence such as catchment load monitoring, sediment tracing studies, measurements of individual processes or physically realistic limits to individual processes.

The disadvantages of a sediment budget approach are:

- There are more variables in the model and it requires a much broader range of spatial input data.
- The higher number of variables make it harder to use as a calibrated model. If calibrated solely against loads at the mouth of a catchment, it is possible to get the correct load through an incorrect combination of catchment processes.

- It is more complicated so it has taken a lot of effort to develop software and is more computationally difficult.
- There is a risk of model complexity overstating the level of understanding of catchment processes.

A central question for a sediment budget model is whether the primary sources and sinks of sediment are represented in the model. SedNet models sources of sheetwash and rill erosion of hill-slopes, gully erosion, riverbank erosion and re-entrainment of sediment within river channels. Explicitly modelled sinks of sediment are floodplain deposition, in-stream deposition of bedload and deposition in reservoirs. For application to the Reef Plan, in-stream deposition and re-entrainment of fine sediment was added as a source and sink. For applications in New Zealand, landsliding has been added as a sediment source within the relevant modelling package.

Other sediment sources that could be considered in Queensland include erosion of small streams (see Section 3.5), unsealed tracks and roads, stock tracks and floodplain stripping. To justify inclusion of an additional sediment source, it needs to be of sufficient magnitude to make a significant difference to the interpretation of which catchments and processes are yielding the most sediment and what influence catchment management is having on sediment yields. The magnitude and patterns of the source need to be assessable across large and diverse environments, either by mapping the source or through spatial modelling of the primary controls on the sediment source. Inclusion of an additional source should bring a net improvement in information and a reduction in uncertainty, although this may be hard to assess.

Possible future approaches to catchment modelling, reflecting recent advances in conceptual understanding of sediment pollution, are considered in Section 3.17.

A more detailed description of the algorithms and approach used to represent gully erosion and river sediment transport processes is given in Appendix 1.

3. Recent research and possible model improvements

3.1 Introduction

This section discusses research and data collection that is relevant to improving the SedNet model and its application to Queensland catchments. It discusses what concepts emerge from the research that might be useful to include as improvements to the model. The section mostly refers to Queensland research conducted since the modelling started, but broader work is cited where it is particularly relevant. It includes discussion of unpublished submissions made in preparation for the workshop, and ideas for improvements to catchment modelling raised during the workshop itself.

Chapter 2 of the 2017 Great Barrier Reef Scientific Consensus Statement (Bartley et al. 2017) summarises much of the research for GBR catchments, and was a crucial starting point for considering how the model can be improved.

3.2 Gully erosion

The aspects of gully erosion that are of most significance to sediment budget modelling are:

1. spatial density of gullies, as there is very high variability of gullies across large catchments. It is important to correctly identify the major sub-catchments where gully erosion is most prevalent

2. estimates of the rate of gully erosion, which need to be certain enough to enable gully erosion to be ranked as a source of sediment relative to other sources in each major sub-catchment
3. characteristics of the eroding material, which are required to understand erosion as a potential source of marine pollutants such as fine sediment or nutrients
4. understanding of the effectiveness of gully management practices at reducing the rate of gully erosion, and how to scale that up to effectiveness at reducing marine pollution
5. understanding that the above aspects differ significantly between major types of gully erosion.

The ability of the catchment model to meet its defined purpose is probably most sensitive at present to uncertainties in:

- spatial density of gullies
- current erosion rate of different gully types
- effectiveness of management
- concentration of nutrients in the eroding materials.

3.2.1 Gully density

The foundation to gully erosion modelling is a map of gully density (length or area of gullies per area of land). The length of gullies is usually measured from aerial photographs or high resolution remote sensing. Gully erosion is fairly localised to particular soil types, terrains and land uses, and across an area as large as Queensland, it would be impractical and inefficient to map every gully. That has certainly been beyond the resources of any assessment of gully erosion to date. Consequently, sample areas are mapped and statistical models are built using environmental factors to predict gully density across wider regions.

This approach began with the NLWRA sediment modelling project, which used existing state government mapping of gullies and some mapping of its own, together with available national datasets of environmental variables, to produce a raster of gully erosion for one third of Australia. Within particular catchments, and in places where there was little mapping to constrain the model (such as all of Queensland), there is a high degree of uncertainty on gully density from the NLWRA model (Kuhnert et al. 2010).

More detailed mapping of gullies has since occurred in some catchments. In the Normanby catchment, gullies were mapped across the whole catchment from Google Earth imagery (Brooks et al. 2013). In the Burdekin and Fitzroy river basins, significant sub-catchments have been mapped and new statistical models have been built. All the more detailed mapping and modelling gave significantly higher gully densities than the NLWRA model, but significant uncertainties remain in some catchments.

Mapping has been simplified in places to record the presence or absence of gullies, and converting these indices to quantities of length or area of gully is problematic. Conversion of mapped gully presence to gully length in the Burdekin catchment (Tindall et al. 2014) may have resulted in an overestimate of gully length (Wilkinson et al. 2015; Darr and Pringle 2017). Reliable mapping requires high resolution imagery such as the Quickbird product available on Google Earth (Brooks et al. 2013; Tindall et al. 2014). Mapping from high resolution imagery has been compared to field mapping and very high resolution LiDAR digital elevation model (DEM) mapping, which show that, in areas of significant tree cover, gullies which have reasonable vegetation cover can be under-mapped (Brooks et al. 2013; Tindall et al. 2014). LiDAR imagery is expensive to obtain and analyse, so has only be applied to small proportions of regional catchments. Gully density mapped from imagery such as Google Earth should be considered a minimum estimate of gully extent.

The most recent detailed gully mapping under the Reef Plan is reported by Darr and Pringle (2017). Large sub-catchments of the Burdekin and Fitzroy basins were mapped using the approach of Tindall et al. (2014). The method takes 1 km^2 cells and divides them into a grid of 100 1 ha cells (100 m x 100 m) in which presence or absence of a gully is recorded. The number of 1 ha cells containing gullies is then recorded in each 1 km^2 cell. Darr and Pringle (2017) converted the percentage of gully presence to linear density (km/km^2) by measuring the average length of gully found in a subset of 1 ha cells. A total of 12,173 km^2 was mapped for percentage of gully presence covering the whole Bowen Broken Bogie sub-catchment of the Burdekin River. A subset of 1000 1 km^2 cells was used to train a statistical model based on a wide range of mapped environmental parameters. Comparing modelled gully density to mapped values showed no bias in the model, so overall gully length in the Bowen Broken Bogie sub-catchment is similar between modelling and mapping, and spatially the two maps are similar. However, there are still considerable differences between modelled values and mapped values in individual cells, and the model behaves similarly to other predictive models in that very few areas with no gully erosion are predicted, whereas mapping identified 27 per cent of the cells as having no gully erosion (Darr and Pringle 2017).

Total gully length mapped in the Bowen Broken Bogie sub-catchment was less than half that of earlier modelling by Tindall et al. (2014) using a smaller set of training data. Darr and Pringle (2017) also mapped gully presence in the Dawson River sub-catchment of the Fitzroy River, where the results were comparable to those of Trevithick et al. (2010); and their mapping of the Isaac River sub-catchment produced results of about two thirds of the density modelled by Trevithick et al. (2010). The Trevithick et al. (2010) model was built on a training set across the Fitzroy basin of 19 images of 64 km^2, within which 10 per cent of finer 1 ha cells were sampled for gully presence or absence.

Assessment of gully erosion in the GBR catchments (Wilkinson et al. 2015) suggests that the Normanby, Burdekin and Fitzroy river basins are the ones of significant concern for gully erosion, and within those basins there are areas of high concern and others of little known gully erosion. Some of these areas have not been mapped in detail, and therefore are highly reliant on spatial modelling. There are also significant areas of gully erosion in Queensland beyond the GBR, and most of these have not been mapped in detail. The current status of Queensland Government gully mapping is shown in Figure 4.

The work in the Bowen Broken Bogie sub-catchment suggests that 1000 km^2 of randomly located mapping is sufficient to build a model that gets total gully length and first order spatial pattern correct for a surrounding area at least ten times greater than that. This is probably of sufficient accuracy for the largest scale planning and evaluation work of the Reef Plan, and for similar programs. For work that is aimed at identifying finer scale hotspots or particular types of gullies for particular management actions, and for evaluating the effectiveness of local management, mapping from imagery and field observations will be more effective. The locations for this can be based on the modelling and other considerations. As mapping progresses and statistical models improve, the accuracy will improve as well. Earlier work suggests that models built on small samples of mapping (<10 per cent of the area of interest) or extrapolated to unmapped environments will not produce sufficient accuracy.

Continued mapping and spatial modelling have the potential to significantly reduce the uncertainty in extent of gullies as an input to catchment modelling.

One way of using a hybrid of spatial modelling with finer scale mapping might be to use the modelling to rule out large areas of catchments where gullies are not a significant source of sediment. The latest models appear capable of doing that. The density of gullies in areas where it is likely to be a significant sediment source could then be determined more precisely by mapping.
The current gully models suffer from the opposite problem of commission, predicting some gully erosion in cells where none is observed. This is not surprising, and could arise because other factors not used in the model have prevented gully erosion. Or it could indicate areas at risk of erosion where to date that risk has not been realised (Wilkinson et al. 2015).

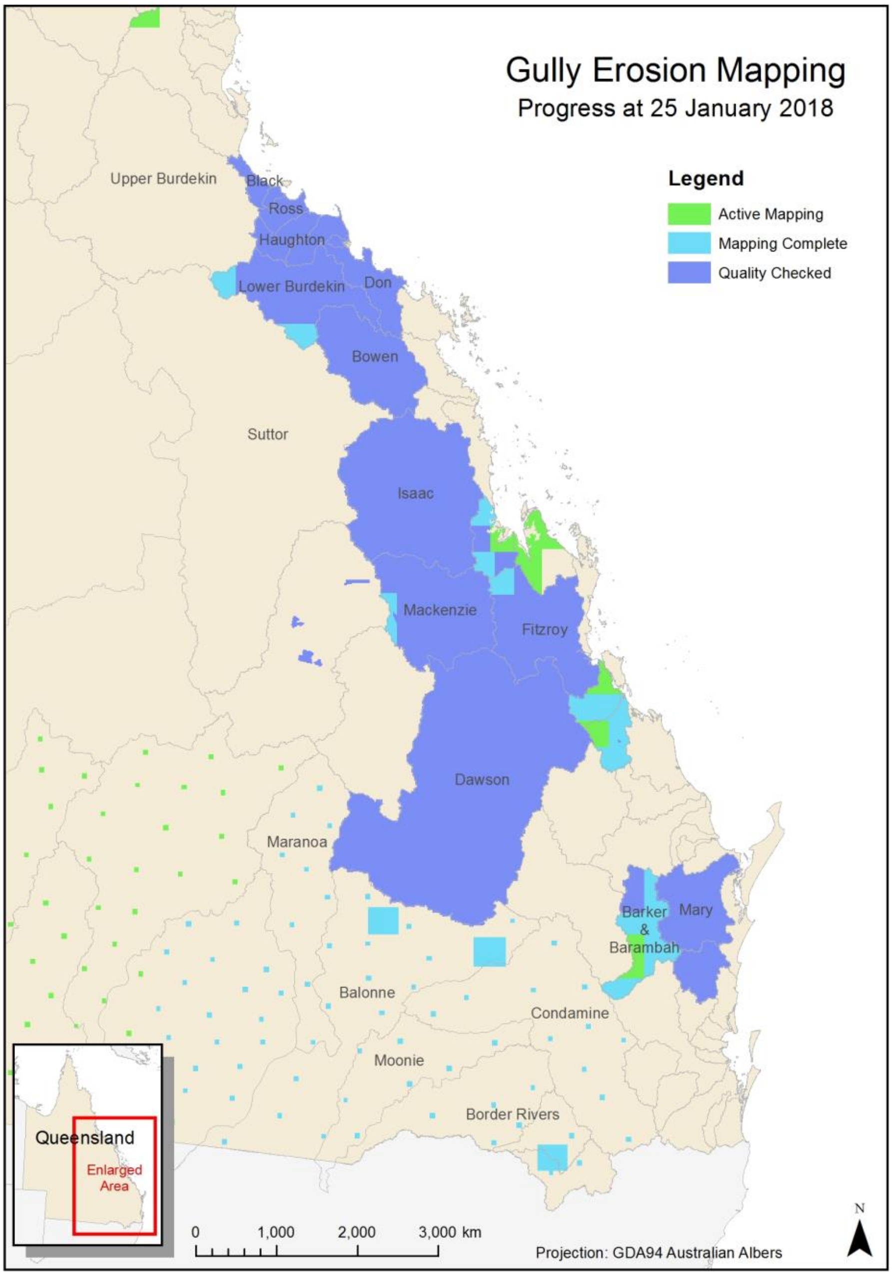

Figure 4. *Status of gully erosion mapping by Queensland Government (Shawn Darr, pers. comm.).*

3.2.2 Alluvial gullies

Work mapping gully erosion has identified a second broad type of gullies—alluvial gullies. These have been described and mapped in detail in the Mitchell (Brooks et al. 2009) and Normanby (Brooks et al. 2013) river catchments, and have also been identified in the Burdekin River catchment (Wilkinson et al. 2015). In these catchments, there are extensively gullied areas of many hectares occurring on alluvial plains. These are quite different environments to the hill-slope and upland-confined alluvial gullies that were the basis for mapping and modelling in the NLWRA. They are a useful distinction, as alluvial gullies are so different from hill-slope gullies that even simple attributes such as gully length don’t apply, as they are more spatially broad features. They might also have quite different erosion histories and erosion processes. Thus alluvial gullies should be separated from hill-slope gullies in mapping and modelling.

3.2.3 Gully geometry

Estimates of gully width and depth are used in modelling to turn linear gully density into eroded volume, or for places where gully surface area is mapped, as an estimate of mean gully depth. There is less uncertainty in gully geometry than there is in the presence and length of gullies. The values used for the NLWRA modelling were 2 m depth and 5 m width for a cross-sectional area of 10 m^2 (Prosser et al. 2001a). Measured cross-sections in a sub-catchment of the Burdekin River have a mean gully width of 10 m and a depth of 2 m (Wilkinson et al. 2018). Elsewhere, a mean width of 5.5 m was recorded (Bartley et al. 2010). An analysis of gully cross-sectional area in a catchment south of Sydney found a representative value of 23 m^2 (Rustomji 2006).

Mapping from high resolution imagery seems to include bare scalded land at the margins of gullies, so care is needed when selecting an average depth for the gully area to create a volume of gully eroded. From the Tindall et al. (2014) LiDAR mapping, average depth is 04–0.6 m, but areal extent in that analysis might be from LiDAR mapping, and no comment is made on how that compares to the Google Earth mapping of areal extent. Either way, average gully depth may be quite low.

Although model results are not particularly sensitive to gully geometry, it is relatively easy to measure, so it would be worthwhile making some measurements to estimate an average cross-sectional area or mean depth for finer resolution studies.

3.2.4 Gully age

In the initial NLWRA model, the volume of eroded material was divided by an average age of gullies to give a mean annual rate of gully erosion under historical conditions. An age of 100 years was used, reflecting that most gullies started forming soon after land was cleared or significant numbers of stock were introduced. The same approach is still used now, but for modelling of current and future scenarios, an activity parameter is sometimes used to scale down the current and future rate of erosion where there are reasons to believe that gullies are now largely stabilised and are producing less than historically average volumes of sediment. The age is also changed based on knowledge of the history of clearing and grazing in particular catchments.

A typical conceptual model of gully development is shown in Figure 5. Gullies might rapidly develop by lengthening and widening, and then gradually stabilise, producing less sediment over time. The degree of slowing and its timing are often poorly known. The initial acceleration of gully development may also be very quick, so the general form of Figure 5 can be simplified into a straight line. Alternatively, a parabolic form of monotonic slowing erosion, emphasising the upper part of the curve, could be used if there is evidence to support that.

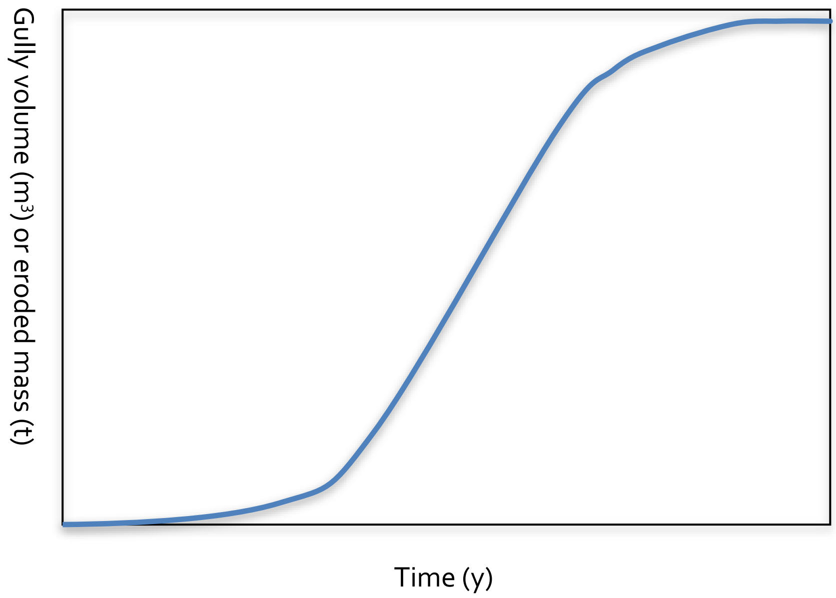

Figure 5. *Conceptual model of volume of mass of material eroded from a gully over time.*

There has been limited examination of rates of gully development in Queensland. It is difficult to find evidence of early rates of erosion before aerial photography became available in the 1940s. There is much more evidence for recent erosion, but within the overall pattern of Figure 5, rates of gully erosion are likely to be episodic, with much faster rates during extreme storms and very wet years than under dry conditions, especially as gullies mature and the average rate declines, so caution needs to be applied when extrapolating measurements over a few years to average rates over the wide range of climatic conditions that can be experienced. It is also important to note that, for sediment budgets, it is the volume or mass of sediment released from the whole gully over time that is required, not the rate of extension of gully head in linear gullies. Gullies can still produce large volumes of sediment from widening and other sidewall processes after the gully length has stabilised.

Wilkinson et al. (2015) provide a summary of the history of gully erosion in the GBR catchments. Aerial photographs have been available at repeated times since 1945, and have been used to extrapolate rates of gully headcut extension back in time to estimate that erosion started between 1850 and 1900, shortly after the introduction of cattle grazing in those catchments (Brooks et al. 2013; Wilkinson et al. 2013). In some areas, it is likely that historical alluvial mining (mainly gold and tin) contributed to gully initiation in the Upper Burdekin catchment and the Mitchell catchment (Shellberg et al. 2016). Both livestock grazing and mining expanded at similar times to the initiation of gully erosion. Mercury, which is used in gold mining, appeared in coral cores and coastal sediment cores around 1870 (e.g. Lewis et al. 2014; Bartley et al. 2018).

The present approach to gully erosion in the model assumes that current erosion is on the steep straight section of Figure 5. As many of the gullies are now quite old, erosion rates may be declining, in which case an alternative modelling approach, outlined below, would be better.

3.2.5 Other methods for estimating sediment yields from gullies

An alternative to using gully volumes and ages to estimate erosion rates is to use measurements of gully sediment yields (Figure 6) or erosion over the last few decades to build a simple model of gully sediment yield. This may involve fewer assumptions over the history of the gullies, but introduces its own challenges of applying the limited data on rates across diverse catchments, and requires some additional data on gully catchment areas. Modelling of erosion rates can be applied to the mapped and modelled extent of gullies described above.

Rose (unpublished a,b) proposes a method for such modelling. It distinguishes between alluvial gullies, where it is assumed sediment yield conforms with transport limiting conditions (Figure 7), and hill-slope gullies, where soil resistance to erosion results in entrainment limited sediment yields (Figure 8). In both cases, simplifications are made to physical erosion theory for regional scale application where detailed data is not available but where calibrations can be made against measured gully erosion rates or sediment yields.

For alluvial gullies, Rose (unpublished a) proposes that:

$$L_i = \gamma_i A_i R_i^2 \quad (1)$$

where L_i is daily sediment yield from a gully or set of gullies; γ_i is a modelling parameter to be obtained by fitting the model to data, such as sediment yield or erosion data; A_i is the plan area of the gully or group of alluvial gullies in sub-catchment i; and R_i is daily rainfall in the sub-catchment. The approach is a further simplification of that developed and evaluated for the Mitchell River alluvial gullies (Rose et al. 2015). Figure 6 illustrates a relationship between gully sediment yield and daily rainfall that can be used to fit Equation (1).

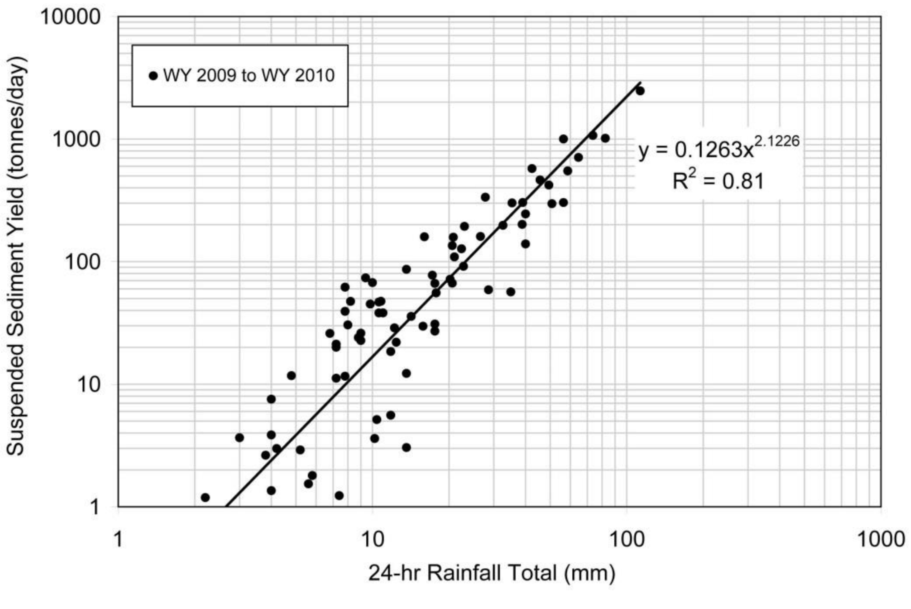

Figure 6. *Relationship between L and R for the alluvial gully reported in Shellberg et al. (2013). From Rose (unpublished a).*

The same approach can be used for entrainment limited gully erosion, but the modelling parameter γ_i will be smaller by the degree of material resistance to erosion. Rose et al. (2014) give more detail on the development of such a model for colluvial gullies.

The suggested approach has some parallels with the event mean concentration approach used to represent hill-slope erosion from some land use classes in the Reef

Plan modelling. It can be extended to include erosion of small river channels as discussed in Section 3.4 below.

Measured sediment yields from gullies (e.g. Bartley et al. 2007; Shellberg et al. 2013) provide the best data to fit the Rose model, but surveys of gully growth over time from aerial photographs, LiDAR imagery, unmanned aerial vehicles, (drones) or field surveys could also be used (e.g. Bartley et al. 2007; Brooks et al. 2013, 2016; Wilkinson et al. 2013; Tindall et al. 2014; Shellberg et al. 2016; Jarihani et al. 2017; Koci et al. 2017). There may thus be sufficient data to test the approach.

Compared to the current gully modelling, the Rose approach has the advantages of fewer parameters, a focus on current rates of erosion, and strong alignment of the model to measured rates of erosion. It has disadvantages of limited datasets across some regions on which to calibrate the model. The current modelling approach and that proposed by Rose (unpublished a, b) can be combined by using the mapped size of gully and inferred history to help constrain the Rose (unpublished a,b) model in data poor areas, based on the conceptual model of Figure 5.

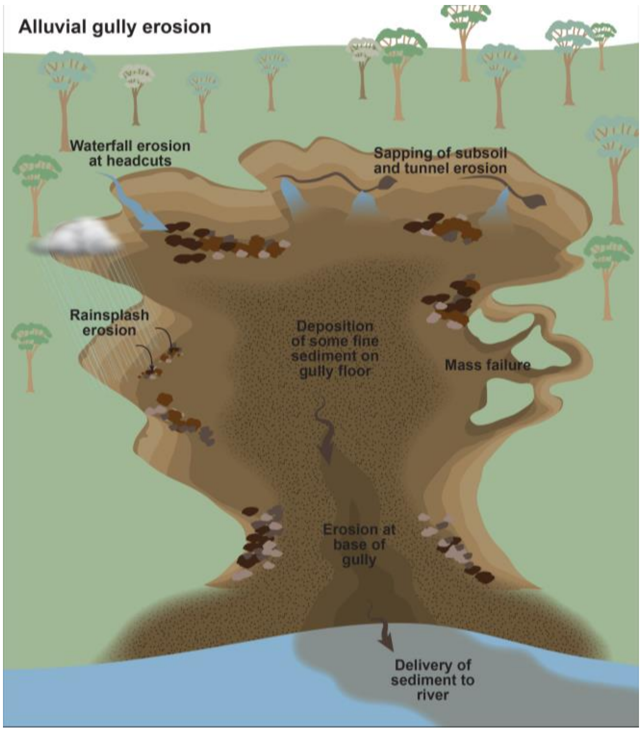

Figure 7. *Processes of erosion in an alluvial gully. Because sediment yield from an alluvial gully is limited by the ability of flows to export sediment from the gully, that is all that needs to be modelled for that purpose. It is an example of where a model can effectively simplify the result of an apparently complex set of individual processes.*

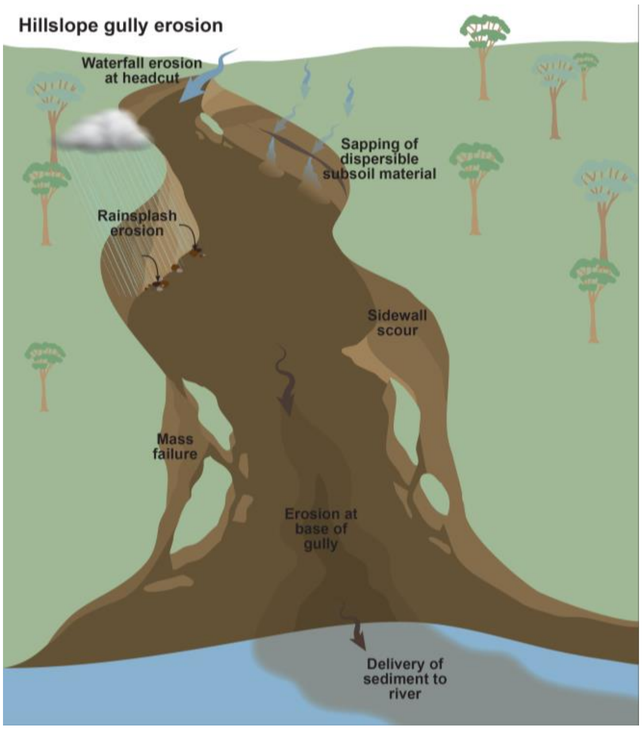

Figure 8. *The main water erosion and mass movement processes in a hill-slope gully.*

At finer spatial scales, head and sidewall erosion of gullies can be modelled to determine which process is more important and help plan appropriate remediation works. Rose et al. (2014) took this approach in a way that can be applied with relatively simple data inputs, and Allen et al. (2018) give a relatively simple model for gully head cut erosion.

3.3 River reach processes

A network of small to large river channels in a catchment transports flow and sediment from its sources to the river mouth, with varying efficiency. River channels and their associated alluvial floodplains can be a source of sediment themselves through riverbank erosion, channel change and floodplain stripping, or most importantly they can be stores of sediment preventing it from reaching the river mouth, at least for some considerable time (Figure 9). Large floodplains can store fine sediment for thousands to tens of thousands of years, while in-stream features tend to store sediment for tens to hundreds of years. Being higher energy environments, in-stream features are predominantly stores of coarser sediment, but under the right conditions can store a significant proportion of fine sediment. Croke et al. (2017) present a good general framework for in-stream features and cite several examples.

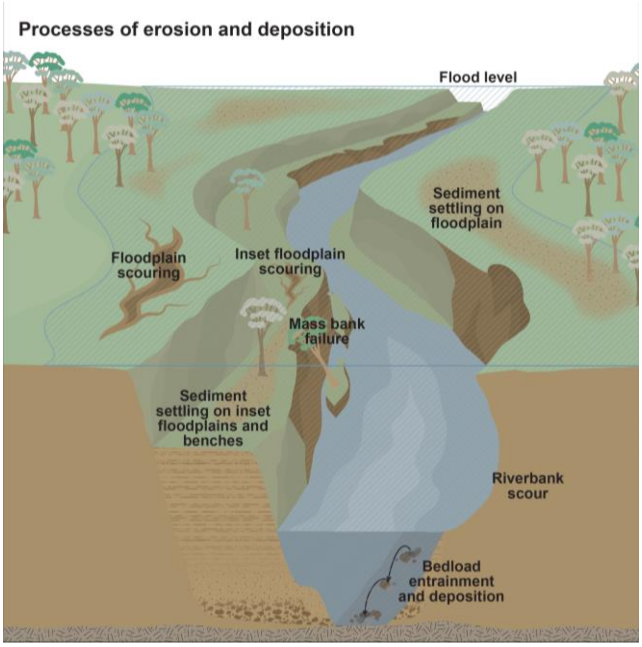

Figure 9. *Conceptual diagram of processes on a river reach. Bank erosion can occur by sub-aerial processes, scour or mass failure but the model just predicts the overall rate of erosion based upon stream power. Deposition can occur on floodplains or in the channel. Inset channel features can have deposition but are not represented in the model explicitly. Floodplains scour under some circumstances but this is not considered a big enough source of sediment across large catchments to be included in the model.*

The description above makes river sediment processes sound quite simple; however, the situation is confounded by the variable history of rivers being reflected in their current morphology. Often apparently active floodplains are relicts of past conditions no longer receiving flows or storing sediment, as flows are now confined within the main channel. Confinement of flows within channels will only increase the propensity to erode sediment and transport it downstream. In-channel features can include benches and bars that form by channel processes of sediment entrainment and deposition. They can also include small inset floodplains that accumulate via deposition from sediment settling out of low velocity flows, and later erode by lateral scour and mass failure of the banks.

Thus many rivers have a complex morphology often characterised by a megachannel within which may sit a number of in-stream features of varying age and type (Figure 10). Megachannels and largely abandoned floodplains can form as a result of:

- climate change over the last hundred thousand years or so (e.g. Croke et al. 2011)
- changes in sea level over the last 10,000 years (Rustomji et al. 2006; Brooks et al. 2009)
- changed flood regime over the last few thousand years (Rustomji 2008) or
- historical clearing of rivers and floodplains (e.g. Brooks et al. 2003).

Complete metamorphosis of rivers during extreme floods has been attributed to Australia's highly variable river hydrology (Rustomji et al. 2009), although the susceptibility to high energy floods has probably been increased by clearing of riparian vegetation. Benches may then be part of channel contraction in periods of lower magnitude floods. Alternatively, benches have formed in response to changed flooding regime and post-European increases in erosion (Pietsch et al. 2015; Bartley et al. 2018). In summary, there are several possible causes and types of complex channel features.

There needs to be caution when extrapolating inferred behaviour from one river to another because of the different causes and river histories. For example, several researchers invoked highly variable flood magnitudes as the predominant driver of river morphology before Rustomji et al. (2009) showed that not all rivers, and even not all sub-catchments of the one river, experience such high variability as the few case studies from where this process is invoked. Worse still, Rustomi *et al.* (2009) is cited as evidence of high variability in Australian rivers even though it contains just as many examples of low or modest flood variability and it questions this ubiquitous conclusion of others. The MacDonald River near Sydney is perhaps the Australian river with the most studies of floodplain and channel history yet the inferred causes of change have altered markedly over several studies. For sediment transport modelling it is important to know the morphology of the rivers modelled but fortunately it is not essential to understand how that morphology formed. It would seem much easier to measure the required features of the morphology for the model, than infer them from such a wide range of possible histories and hypotheses.

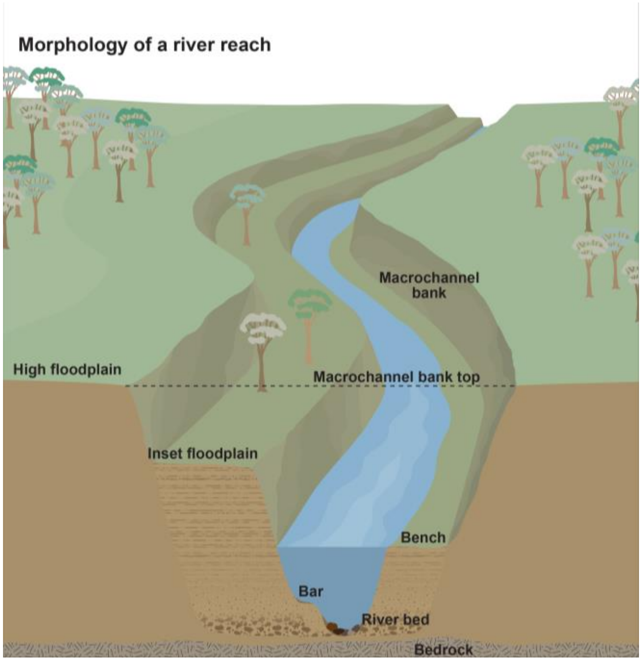

Figure 10. *Inset features of river channels arising from their complex history.*

Confusion around in-channel features is compounded by lack of agreement on terminology, and at times the same term is used for features with quite different behaviour. Thus, a first step to better incorporating in-channel morphology into the model would be to define and classify different features specifically for the purpose of understanding catchment sediment transport. To do this, the classification needs to consider not just the morphology and frequency of inundation of the features, but their sediment composition and the processes that form and erode them. These attributes will be interrelated. For example, not all benches are significant stores of fine sediment. Where in-channel features are relatively small, of short residence time (less than a few decades) and predominantly coarse-textured, they can be neglected (e.g. Bartley et al. 2018). In other circumstances, they can be a significant store of fine sediment, such as in the Normanby River basin (Pietsch et al. 2015). How widespread these circumstances are is unknown. It is important to know whether these features form by the same sediment settling processes as occur on floodplains, or whether they result from sediment exceeding the transport capacity of flow, because these two types of process are modelled and behave quite differently.

The modelling of river processes has changed more than the modelling of gully erosion since the original NLWRA model. The changes include:

- in-stream deposition and re-entrainment of fine sediment have been introduced
- stream power has replaced bankfull discharge in the bank erosion algorithm
- daily modelling has brought with it a change from modelling the net impact of accelerated post-European erosion to modelling actual sediment yield from bank erosion.

3.4 Bank erosion of river reaches

Riverbank erosion is the most uncertain of the sediment sources in the catchment model. In several catchments, it is the largest of the three sources of fine sediment modelled, while in others it may be quite small as a source of fine sediment. There are few well-established approaches for assessing bank erosion between basins and between major sub-catchments within basins.

Riverbank erosion was included in the original SedNet model because it was known to be a nationally significant source of sediment from accelerated erosion. However, there was little data at the national scale on which to define it, the only relationship available being a simple empirical rule for meander migration and bank erosion proposed by Rutherfurd (2000) following a review of global literature. This defined streambank erosion as a function of bankfull discharge, characterised as the 1.58 year recurrence interval event. While this was the only readily available algorithm at the time, it fails to recognise the complexities of historical accelerated bank erosion and its differences to meander migration. The original algorithm has been substantially modified using theoretical considerations as explained below, but at the cost of it being closely tied to empirical data.

Recognising that natural rates of bank erosion can be very low in Australian rivers with intact riparian vegetation, and that erosion is greatly accelerated with removal of riparian vegetation (see Section 3.4.2), the modelled erosion rate was scaled by proportion of the reach that contains intact riparian vegetation. This essentially assumes that erosion rate under full riparian cover is so low that it can be neglected for the broadest scale modelling. The algorithm was similarly modified to only erode the proportion of bank in the reach that has alluvial material. This was based on mapping of floodplain extent and an empirical relationship between that and proportion of alluvial bank (see Hughes and Prosser (2003) for a full description of bank erosion modelling at that time).

The algorithm was modified by subsequent developers to replace bankfull discharge with bankfull stream power, introducing the river link slope as a surrogate for the energy gradient of flow (see Appendix 1, Section A3 for a full description of the algorithm). This was a significant improvement, as it avoids unrealistically high bank erosion rates in flat lowland rivers.

In summary, the first order patterns of riverbank erosion are modelled as a function of stream power, and the extent of high cover of woody riparian vegetation and valley confinement as surrogates for resistance to erosion. These are all variables that have been suggested in the past as principal controls on bank erosion. The influence of stream power and riparian vegetation on erosion is discussed further below. Other variables not included in the algorithm that have been invoked as controls on bank erosion include river bend curvature and alluvial bank material properties. These can be investigated further to see if they should be included.

The bank erosion algorithm in SedNet has been evaluated against measured bank erosion rates over several reaches of individual rivers. Most recently, Binns (2017) found over 150 km of the middle reaches of the Mary River where the mean overall rate of erosion was similar between measurement and model, but at the scale of individual 10 km river reaches, there was no relationship between modelled and measured bank erosion rate. Sinuosity of the river was the factor most correlated with erosion rate, with weak influence of woody riparian vegetation and no influence of riverbank height. It was not clear how much each of these factors varied among the reaches studied, and how that compared to broader scale variations in the factors used to predict bank erosion. The same general conclusions have been reported for three other rivers—that the bank erosion algorithm does not reflect patterns in measured bank erosion rates (Brooks et al. 2014). However, the studies differ as to what the controlling factors are at the 10 km or finer scale, and there is much unexplained variation and no alternative algorithms have been proposed for broad application.

Bank erosion is a highly episodic process. Quite significant erosion occurs during infrequent big events (e.g. Thompson and Croke 2013; Grove et al. 2013), with much lower erosion rates during years of average or below average discharges (Bartley et al. 2016). Thus, while the most accurate measurements of bank erosion have been made over periods of two to 10 years, those measurements may not be representative of all the flow conditions experienced over several decades. River restoration aims to be effective for decades, so we need to examine bank erosion under a wide range of conditions. The work on rare extreme events (>100 year recurrence interval) such as the south-east Queensland floods of 2011 has produced findings that can improve catchment modelling (see below), but such large floods may not be amenable to bank protection works, and are not the main problem for marine pollution, which is experienced during more frequently occurring events.

Recent work measuring bank erosion rates in Queensland rivers has used various techniques. The most detailed and accurate measurements come from LiDAR, other high resolution imagery, and scanning technologies (e.g. Grove et al. 2013; Bartley et al. 2016; McMahon et al. 2017), but because they have only recently become available, the measurements span short time periods from two to 10 years. They usually only cover relatively short lengths of river. Measurements from aerial photographs and historical sources have the advantage of spanning several decades, but are less detailed and accurate, especially where small changes in channel width still release large volumes of sediment. The longer term measurements also pick up some of the long-term channel adjustments as a result of past changes such as bank protection and restoration alluded to above, confounding their use in elucidating controls on rates of bank erosion (Bartley et al. 2016).

3.4.1 Stream power

Some have questioned the use of stream power as a basis for predicting bank erosion; however, it has a strong theoretical basis that has led to its widespread use in river sediment modelling in a variety of forms. The questions have arisen as stream power does not always have a statistically significant association with measured bank erosion (e.g. McMahon et al. 2017; Brooks et al. 2014). This may be a result of limits to the statistical analysis that include:

- limited ranges of stream power being investigated relative to its natural variability in time and space across larger regions
- high natural variability in other factors such as resistance to erosion at the local scales of measurements, relative to the larger scale patterns that are the aim of modelling
- other confounding factors that may be auto-correlated with stream power.

So it is premature to conclude that stream power can be dismissed as a controlling variable. A more extensive dataset and controlled statistical design would be required for that.

Questioning of the influence of stream power has focused on spatial patterns of erosion. Its importance as a control on temporal patterns of erosion at a site has not been questioned, and is universally implied by authors because they all consider measured rates of erosion against the magnitude of discharge events experienced, and accept that rare high magnitude events result in much more erosion than smaller events. There should be theoretical consistency between space and time controls on erosion, or at least an explanation of why a theory that applies in time does not apply in space. Substitution of space for time is an accepted technique used by many in geomorphology, within the limits of its assumptions.

If the argument is over the relative influence of stream power compared to that of riparian vegetation or other bank resistance to erosion, that is addressed by the coefficient in the equation relating erosion rate to stream power (e.g. *k* in Equation A5, Appendix 1, Section A4). The current algorithm is more sensitive to the extent of intact riparian vegetation, highly resistant non-alluvial banks and bed slope than it is to spatial variations in discharge. Work to better understand the relationships between stream power and erosion rate at the broadest spatial scales would be worthwhile as it is a major source of uncertainty in the model at present, but that is quite a different hypothesis to removing stream power completely from consideration.

Stream power as a predictor of bank erosion has been characterised in various ways. As described above, Dynamic SedNet uses bankfull discharge to calculate bankfull stream power on the assumption that bankfull discharge is the discharge most effective at shaping river channels, an assumption supported by geomorphic theory. More commonly, unit stream power per unit area of stream bed (ω, W/m^2) is used, which is total stream power divided by the width of flow (*W*, m):

$$\omega = \frac{\rho g Q S}{W} \qquad (2)$$

Erosion rate may be a power function of stream power with a range of exponents on discharge (*Q*, m^3/s)and slope (*S*) used (Prosser and Rustomji 2000), or have more complicated relationships using the more complete theory of Rose et al. (2014). In broad simplified regional applications, such as SedNet, flow width is often expressed as a power function of Q, through what are known as hydraulic geometry relationships (see Section 3.7) reducing spatial patterns of unit stream power back to a function of *Q* and *S*.

Broad regional studies are interested in bank erosion over a series of discharge events, not at an instantaneous discharge. Time-integrated unit stream power is a useful measure of this (McMahon et al. 2017), obtained by cumulating daily unit stream power calculations. It was found that a threshold power needed to be introduced to reflect that very frequent occurrences of low stream power did little effective geomorphic work, and therefore should be ignored. Stream power integrated over time is a measure of the work done on the channel. Modelling bank erosion based on cumulative stream power would be better than the assumptions and difficulties of using bankfull stream power. It requires a better understanding of the effectiveness of stream power at creating erosion, as does the current algorithm.

Strictly speaking, stream power theory applies to the entrainment of sediment from the base of a flow, so it applies to scour of the riverbed or floodplain surface. In bank erosion, we are interested in the lateral erosion of sloping or vertical banks of a river. Bed and bank erosion are related. Scouring of the bed can increase bank height or angle, resulting in mass failure of bank material onto the bed, which can then be entrained by flow. Banks can also erode by direct scour of the bank toe or a particularly weak layer of the bank, which may cause the overlying material to fail. The power exerted on the bank will be some fraction of the power exerted on the bed. Mass failure of a bank with no fluvial erosion of the failed material will not contribute to river sediment loads. So while bank erosion may be related to stream power, there may be indirect or complex aspects of the relationship. These can be incorporated by empirical relationships between stream power, or total work, and the mass of bank eroded (see Section 3.4.2 below).

The discussion above has implications for how flow width is applied to modelling of stream power and bank erosion. For flows fully contained within a channel, it is clearly flow width in the channel that is relevant. For flows where some proportion goes beyond the banks and where the depth of flow on the broader floodplain or bench features is small compared to depth in the channel, then using the full width of flow will give an average unit stream power across the valley. That average is smaller than the power of flows in the main channel (where power will be similar, but slightly higher than at bankfull discharge) and larger than that being exerted on the floodplain, where discharge and flow depths are low. If the interest is in erosion of the banks within the main channel, then it is main channel unit stream power that is relevant, not the average power across the valley. If the interest is in floodplain or inset bench processes, then it is the work carried out on those features that is relevant.

There are problems with estimating low gradient river slopes from coarse resolution DEMs. DEM construction methods using splines produce artefacts in stream slope to which stream power calculations are quite sensitive (see Wilkinson et al. 2006; Bartley et al. 2008). Higher resolution DEMs that rely less on splines may not have such a problem, but this should be checked. Methods have been developed to overcome these problems when calculating river slopes.

3.4.2 Role of riparian vegetation and bank material strength

Brooks et al. (2003) identified massive changes in channel form and bank erosion as a result of the historical removal of riparian vegetation. The changes recorded in that paired river study in Victoria involved more than the role of woody vegetation along riverbanks, but they do demonstrate how important continuous intact riparian vegetation can be to river stability. Bartley et al. (2008) found in the Daintree River catchment that the mean erosion rate of banks with woody riparian vegetation was 6·5 times lower than that of banks without woody riparian vegetation. In a broader study of three coastal Queensland rivers, Brooks et al. (2014) concluded that thresholds of <40 per cent and >70 per cent riparian vegetation cover are useful for each producing an order of magnitude reduction in erosion rate. A statistical analysis of river sediment data from Moreton Bay catchments (Olley et al. 2015) showed that sub-catchments with degraded riparian vegetation had sediment yields 50 to 200 times those of sub-catchments with full cover of remnant riparian vegetation, in a catchment where bank erosion is the largest source of sediment. The role of vegetation in preventing bank erosion is illustrated in Figure 11.

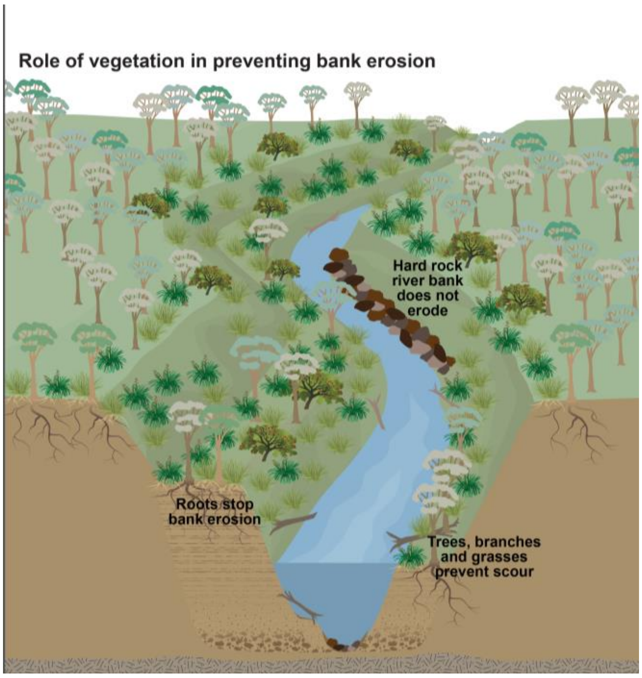

Figure 11. *Conceptual diagram of the role of vegetation in limiting riverbank erosion. Also shown is how bedrock or artificially emplaced rocks can prevent bank erosion.*

These results do not conflict with McMahon et al. (2017), where riparian vegetation was not a strong factor in a multi-factorial statistical analysis of reach scale bank erosion. In that study, woody cover was almost always <40 per cent, and there was a strong influence of confounding factors such as sand and gravel extraction, which is not found everywhere. Bartley et al. (2016) were unable to find any statistical relationship with woody riparian vegetation cover from a relatively small dataset of historical aerial photograph analysis confounded by other factors. Again, no statistical relationship does not mean no cause and effect, just that one was not detected. Overall there is good evidence that near complete or complete cover of woody riparian vegetation provides significant resistance to bank erosion.

The question is how best to quantify or model resistance to bank erosion. Brooks et al. (2014) used the same theoretical foundation as Hairsine and Rose (1992) and Rose et al. (2017) to express resistance to bank erosion as the amount of work required to erode unit mass of material (*J*, J/kg), noting that most work is lost in other ways such as friction and heat. At the geomorphic scale of a river reach, Brooks et al. (2014) back-calculated an effective *J* from observations of volume eroded and total work done by the flow. By this method, they showed that, while there are orders of magnitude variation in *J* with similar levels of woody vegetation cover, when woody cover levels are <40 per cent there is at least an order of magnitude lower *J* than when woody cover >70 per cent. Note that this is the author's interpretation of the data, not that which was presented in the paper.

The bank erosion algorithm in the model approximates this result. It calculates erosion rate over several kilometres of river, and scales the rate down by proportion of reach with intact riparian vegetation cover. Although not defined explicitly, intact cover would be >70 per cent cover in most environments. This is essentially a threshold criteria of no significant erosion under intact riparian vegetation, and significant erosion occurring under degraded woody riparian cover. Still, the algorithm can be improved to ensure it conforms exactly with the Brooks et al (2014) or other empirical data and explicitly includes *J*, and if necessary a threshold stream power for significant work to occur.

Research that demonstrates the resistance of forested riverbanks to erosion comes from coastal streams where there is naturally complete cover of woody vegetation. Many rivers flow through semi-arid to arid environments where naturally woody cover is not complete, and where degradation of riparian vegetation produces fewer dramatic changes in cover. Differences in erosion resistance are likely to be more subtle in these circumstances, and this situation was part of the Bartley et al. (2016) study that found no overwhelming influence of woody bank vegetation on erosion.

Alluvial bank materials and soils have cohesion that provides resistance to erosion, which again can be characterised by the work required to erode unit mass of bank material (*J*). A standard jet scour tester can be used to calculate *J* for different materials (Rose et al. 2017; Haddadachi et al. 2017). Data collected to date shows that *J* can vary from 47 J/kg for a clay-silt to a high 6421 J/kg for an indurated Pleistocene age soil (Rose, unpublished b). The data suggests that in contemporary alluvial material, *J* is small and relatively constant compared to the order of magnitude variations resulting from woody bank vegetation. It may still be an important factor where woody riparian cover is low, and is worth understanding better for inclusion in modelling at finer scales. Given the variability of alluvial materials with depth in a riverbank, it might be better to calculate an effective value of *J* at a larger scale from calculated stream power and measured mass of erosion than to measure it in each layer of alluvial material.

Most of the work discussed above characterises resistance to bank erosion as resistance to stream power, thus assuming that it is fluvial scour and resistance to scour that are the driving processes. This ignores mass failure of riverbanks, which is a common process (e.g. Grove et al. 2013). Tree roots can effectively prevent mass failure of riverbanks (Abernethy and Rutherfurd 2000). There are models of bank mass failure that have been applied locally in Queensland (e.g. BSTEM; Simon, 2014), but there are challenges in obtaining the data required to apply these at a regional scale.

It is possible that the best prospect to predict bank erosion at finer scales is to treat it as a combination of two processes: mass failure and fluvial scour, which can interact with each other. There will be significant spatial variation in these two processes (Abernethy and Rutherfurd 1998), including the way in which riparian vegetation influences the processes at different scales. The interaction should also include situations where bed and bench deposition is occurring (e.g. Bartley et al. 2008) as result of sediment supply from upstream exceeding the capacity of the river to transport it. This deposition can effectively protect channel banks from mass failure and scour that would otherwise occur. The skill is to have simple representations of these processes that can be applied at the regional scale.

3.4.3 Improving modelling of bank erosion

Unless the current predictions are wildly wrong, bank erosion is a much smaller overall sediment source than hill-slope or gully erosion, but it is still significant and can be the major source in some catchments. The current bank erosion algorithm incorporates some of the first order controls on bank erosion that come out of research, but it is not strongly tied to good empirical data. It is not clear whether it gets the patterns of bank erosion in large catchments broadly correct or not.

As noted above, there have been several studies of bank erosion rates, but they have largely looked at more local patterns of erosion than the very large-scale focus of SedNet. To overcome this problem and to improve the bank erosion algorithm, a useful start would be to conduct a meta-analysis of all the Queensland bank erosion data by combining it into a single database to examine patterns against factors such as cumulative stream power, riparian vegetation, valley confinement, channel morphology and so forth. The next step would be to determine the full range of all those factors in the modelled catchments and compare that to the range captured in the meta-analysis. That would reveal missing situations which would be the focus for additional data collection on bank erosion rates, such as through aerial photographs or LiDAR data analysis. The collection of additional data should also focus on more rigorous statistical design so that the influence of individual factors can be isolated, and so that specific hypotheses coming from erosion and sediment transport theory can be tested. For example, Abernethy and Rutherfurd (1998) provided a theory on various ways that riparian vegetation can control bank erosion in different situations, and that theory can be tested by well-designed observations. Focus should be on catchments where bank erosion seems to be most significant, and on processes that generate the most sediment.

3.5 Erosion of small streams

At present erosion in small tributary streams is not modelled. Streambank erosion only covers erosion of the stream or river along the links represented in the node link network. Gully erosion covers the smallest scale catchments, which naturally contained no well-defined channels, but now have incised channels as a result of land degradation.

There is a gap between these two scales of erosion, the magnitude of which is determined partly by the catchment size used to define first order links. At present this is 20 km^2, so erosion of all streams with smaller catchment areas than that, but larger than the mapped gullies, is not assessed. The Queensland Government gully mapping (see Section 3.2.1) extends as far downstream as the top of third order streams as defined in the Queensland mapping of stream networks. The total length of unassessed small streams will be high where streams extend close to drainage divides, as in those cases third order streams will have catchment areas quite a bit lower than 20 km^2.

These streams may not all present problems of accelerated erosion that is a significant source of sediment pollution. In hilly and wet environments the streams are likely to be confined in bedrock with little erodible alluvial material. In other situations stream power and bank size could be insufficient to generate much scour or mass failure and sub-aerial processes could predominate (Abernethy and Rutherfurd 1998). However, in other circumstances where there are deep alluvial materials and degraded vegetation cover, these streams could be a major source of sediment. Such a situation was found in the Normanby River catchment (Brooks et al. 2013). In a sediment budget constructed for a small degraded catchment within the Burdekin River basin, Bartley et al. (2007) found that erosion of small streams produced about 10–15 per cent of the total sources of fine sediment. The first step to including these streams is to better understand the circumstances where they are a significant sediment source that needs to be assessed.

There are three broad options for modelling sediment from these streams:

1. Extend gully erosion modelling to include all channel erosion up to the scale of the first defined river link. Rose (unpublished a) suggests this approach for the alluvial gully systems of the Normanby River and catchments, where there are highly eroded streams of small catchment areas that have similar characteristics to the alluvial gullies. The same argument can be made for streams that naturally had small channels atop an alluvial fill, but now are deeply incised and have similar erosion histories to the hill-slope gullies above them (e.g. Finlayson and Brizga 1993). They could be mapped as part of the gully mapping in future.

2. Extend the use of bank erosion algorithms upstream into smaller catchment areas. It is not practical to do this by defining a very small threshold area for river links, as this produces a cumbersome number of sub-catchments that makes for very long model run times. Instead the total length of stream channel or eroding stream channel in river link catchment areas should be estimated and used with the bank erosion algorithm. This method would be justified where there is evidence that the same erosion processes and rates extend further upstream. At present there may be little data to evaluate this approach for streams of this scale.
3. Model small catchment area streams using a separate algorithm recognising them as quite distinctive in form, process and erosion rate to either riverbanks or gullies. Again this would require sufficient data to support the claim that they are different and to characterise their erosion.

3.6 Floodplain deposition

The contribution of a source of sediment to downstream sediment loads declines with distance downstream of the source because of deposition of part of the load. At its simplest level this can be represented in catchment modelling as a power function with distance, which might vary with type of sediment source (Rose unpublished a). Others have used simple sediment yield relationships with catchment area to capture the effect of deposition (Wasson 1994). However, there is over an order of magnitude unexplained variation in sediment yield beyond the effect of catchment area, so predictive skill of this relationship is negligible.

Croke et al. (2013) identify very different zones of sediment connectivity depending on valley and channel morphology. Along a single river, such as Lockyer Creek, there are confined reaches where little deposition occurs, and broader reaches with substantial floodplains where deposition occurs. The dimensions of the macro-channel vary systematically with this valley confinement, as well with larger channels near the end of the confined reaches and smaller channels near the end of the floodplain reaches. The recurrence interval of bankfull discharge of the macro-channel varies from tens of years to over 3000 years. Patterns of sediment transport in the 2011 flood reflect these patterns, with net erosion in confined reaches and net deposition in the floodplain reaches. If the patterns observed by Croke et al. (2013) are widespread, there will be very different sediment delivery through the river network depending on type of valley. This is not represented by a uniform distance variable.

The SedNet model represents part of the behaviour observed by Croke et al. (2013) by modelling floodplain deposition as a function of floodplain area along a river reach. It produces declining sediment contribution with distance downstream, but the strength of that decline is a function of the floodplain area. SedNet does not incorporate other aspects of the features of confined and floodplain reaches, however, such as variations in bankfull discharge and bank erosion. Improvements are needed to estimates of bankfull discharge beyond the default recurrence interval of 1.58 years, as discussed below.

Strictly speaking, the mapping of floodplain area as an input to the model is an innovative approach to mapping of flat valley bottoms from DEMs (Gallant and Dowling 2003). This is the maximum possible extent of land that gets inundated during floods. Putting aside issues of defining bankfull discharge, which are discussed below, in places, flat valley bottoms will include finer scale topography such as higher terrace surfaces so that not all the flat land is inundated by floods. To improve estimation of flooded area, the actual extent of floodwaters during high magnitude events can be derived from flood maps or determined from a hydraulic model of flood inundation set up with observed channel and floodplain topography and vegetation cover.

Representing deposition of inset features within the macro-channel may or may not be required depending on whether they are likely to be a significant store of fine sediment over several years. It is relatively easy to find out though through reconnaissance surveys and rough calculations. If found significant, they can be modelled by examining their aerial extent and the discharge at which they get inundated.

It may be useful to introduce large-scale hydrodynamic modelling of floods through river networks to explore how valley and channel morphology might influence erosion, deposition and the formation of channel and floodplain features. This might identify backwater zones, for example, which will be focal areas for floodplain deposition (Thompson et al. 2011), or it might identify where benches form as a type of in-stream deposition. It will reveal patterns of stream power that might provide insights into patterns of bank erosion.

There is relatively little data with which to evaluate rates of floodplain deposition predicted by the model. There are first order limits that deposition must at most be of the order of millimetres per year when averaged over many decades of flow variability, as it takes thousands of years to accumulate metres of floodplain by overbank deposition. That still leaves room for significant variability on individual floodplains. Hughes et al. (2009) used ^{137}Cs depth profiles to record contemporary floodplain deposition rates of 0.7 to 2.1 mm/year in a tributary of the Fitzroy River, well within the first order limits applied to the model, and three to four times higher than natural rates of deposition on those floodplains (Hughes et al. 2010). Amos et al. (2009), in a study of the broader Fitzroy Basin, measured floodplain deposition from ^{137}Cs and found no measurable deposition in some sites, and 13 mm/year deposition in a flood swale of the lower Fitzroy River.

If we can be confident about first order controls of valley morphology on sediment delivery through a river network, it should be possible to represent those in the model. Otherwise, the fundamental uncertainty on controls on sediment delivery can be reflected by using the more parsimonious approach of travel distance decay of sediment yield.

Acknowledging the significance of deposition in the river network is important because it opens up a completely different set of management possibilities. Catchment sediment yields could be reduced by reducing catchment erosion or by increasing floodplain and in-stream deposition. Restoring the connection between rivers, floodplains and wetlands could be quite effective. Croke et al. (2017) first raised this prospect and provided a framework to enhance flooding and deposition. The catchment model could be used to explore floodplain management possibilities just as it has been used to examine scenarios of erosion control.

3.7 River types

There are a broad range of river plan forms across environments as diverse as those found in Queensland. The modelling of river processes in SedNet makes assumptions that do not apply to all river types, so it is worth considering what broader types of rivers exist and how to include them in catchment modelling. SedNet assumes a single thread channel that occurs in either a confined or unconfined valley setting. Current river types may also be quite different to, and more relevant than, pre-European types of river plan form.

Anabranching rivers are a quite different river plan form of multiple river channels separated by stable alluvial islands. Individual anabranches are hydraulically independent and only meet at points of splitting and rejoining, which are usually several to many kilometres apart (Figure 12). Almost a quarter of the higher order channel length in the Fitzroy River basin has anabranching form (Amos et al. 2008), and it is common in the Murray-Darling Basin. Anabranching rivers can be mapped from 1:250,000 topographic mapping and satellite imagery, but are not easily amenable to prediction from catchment characteristics (Amos et al. 2008). Within channel discharge, bank erosion and deposition processes will all differ if an anabranching river system is assumed to be a single thread. It is quite possible that anabranching systems have lower bank erosion, more floodplain deposition and less effective sediment delivery than single thread rivers. Distributary systems in river deltas such as the lower Burdekin River are a separate form, with some similar characteristics to anabranching rivers (Figure 12).

Channel avulsion is another important distinction in river form. It is the sudden erosion of a new course cutting across a floodplain as opposed to the incremental migration assumed in bank erosion modelling. The risk of avulsion on a floodplain may be amenable to simplified process modelling, but it has not been investigated, nor has its frequency of occurrence in Queensland.

The same principles of classifying river types apply to identifying different types of inset channel features or floodplains that need to be modelled in a way consistent with their sediment composition and formative processes.

There are numerous classification systems for rivers, with very different aims. It would be worthwhile adapting one to classify major behavioural types relevant to patterns of sediment transport in Queensland. Then quick assessment techniques should be explored to map these types. The techniques would explore how well they can be mapped from topographic maps, remote sensing, DEMs or catchment attributes. The aim would be to identify major river types which have significant implications for large scale sediment transport. Once rivers were classified, some modelled processes could be omitted or modified for particular river types. For example, anabranching reaches are depositional with very little bank erosion.

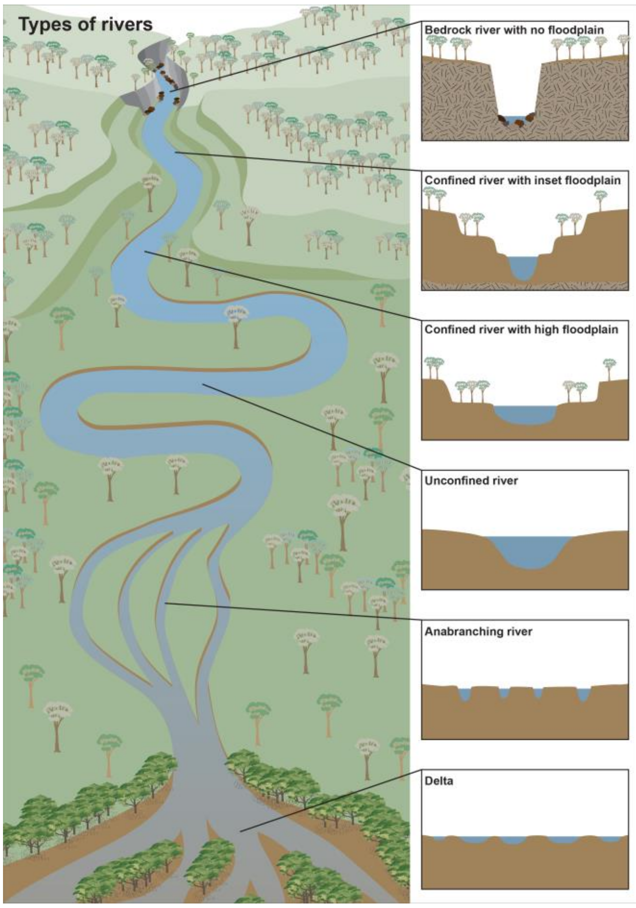

Figure 12. *Different types of river reaches which will have implications for large-scale patterns of erosion and sediment transport.*

3.8 Channel geometry

Channel geometry properties of flow width, bank height and bankfull discharge are used in the model to predict bank erosion and floodplain deposition.

The most important of these for catchment sediment transport is bankfull discharge. The degree to which flows are confined within a channel exerts a strong control on river erosion and sediment deposition. The greater the size of flows that are confined by riverbanks, whether that be confined within a mega-channel or within inset features, the greater the potential for those flows to erode within channel sediment, erode the riverbanks, or continue to transport water and sediment downstream without depositing it on floodplains.

The default setting for bankfull discharge in the model is that it is equal to the magnitude of the 1.58 year recurrence interval flood. This is an empirical relationship derived from global rivers with active floodplains. As mentioned in Section 3.3 there is much evidence that higher discharges are confined within channels in many Australian rivers as a result of their history. Reflecting this, higher recurrence intervals of bankfull discharge are often set in the model, but in places they may not be high enough to reflect observed values. Given the importance of bankfull discharge to both erosion and deposition, it is a key parameter that should be better understood, perhaps first through systematic measurement across modelled regions.

Bank height is used to scale rates of bank retreat to a volume of sediment, which is then converted to a mass of sediment. As argued above for gully erosion, the mass of sediment is not very sensitive to such scaling factors relative to other factors. Channel or flow width is used to calculate unit stream power as discussed in Section 3.4.1 above. Within channel stream power is less sensitive to channel width than it is to discharge or slope. Both bank height and width can be estimated from crude hydraulic geometry relationships that relate first order patterns in channel geometry to the discharges they carry. There is much unexplained variation within these empirical relationships, so direct measurement of properties in reaches is an alternative, and there are good prospects to achieve this through LiDAR data. There is a relationship between bankfull discharge recurrence interval and channel height and width, because channels that confine high discharges are larger than those that do not. Croke et al. (2013) show an example of systematic differences in channel width with bankfull discharge and valley confinement. Channel bed slope also varies by over an order of magnitude between reaches in this case. If cross-sectional geometries that are more complex than a rectangle are to be considered in the model because of inset features, then multiple flow widths and bankfull discharges may need to be considered.

3.9 In-channel deposition and re-entrainment of fine sediment

Observations of in-stream deposition of large quantities of fine sediment in inset bench features in the Normanby River catchment led to the introduction of modelling of in-stream deposition and re-entrainment for Reef Plan applications (see Appendix 1, Section A6).

Modelling of in-stream deposition and re-entrainment at present is conceptually a riverbed process, but the benches are discontinuous channel margin features. Channel margin processes are probably hard to model at a large scale, but it does raise questions about the appropriateness of the current approach. The modelling includes an artificial cap on deposition to prevent the river channel from infilling completely with sediment. If this cap is widely invoked, in-stream deposition degenerates to a large fixed value, and suggests that the approach or the values for sediment transport are not physically realistic. The modelling of in-stream fine sediment is based on a quite different sediment transport capacity for deposition than for re-entrainment. The theoretical basis for this has not been made clear, and there are alternatives such as probabilistic methods or the use of a single sediment transport capacity equation.

More fundamentally, research on in-channel benches suggests they are fairly temporary features and can be completely removed in a large flood after a hundred or more years of deposition. Not only will removal provide a significant pulse of sediment, it will change the morphology of the river channel and thus have indirect consequences for bank erosion and floodplain deposition. It might be more important for large-scale sediment budgets to model these major changes of bench formation and destruction than it is to model the more frequent processes of deposition and re-entrainment

Overall, this new aspect of modelling should be more fully investigated to ensure that it produces realistic and theoretically sound results. If not, alternative approaches should be considered. If in-stream deposition and re-entrainment of fine sediment is a relatively small or temporally constant sediment budget term, then it is not required to meet the model purposes.

3.10 Temporal patterns of sediment loads

It is important first to consider the best temporal resolution for the model. Floodplain deposition, in-channel deposition and re-entrainment and hill-slope erosion (modelled outside SedNet) are modelled as daily processes. For gully and riverbank erosion, the daily rates are temporally downscaled from mean annual results according to daily discharge, so are not truly modelled as daily processes. Moving from mean annual to daily predictions makes it easier to model episodic processes such as floodplain deposition. It also brings either a lot of additional assumptions or requires the modelling of additional processes that are significant at the daily resolution, such as short-term sediment stores that even out or can be neglected at the macro mean annual scale. The purpose of the model is to guide and evaluate catchment management programs that are designed to be effective over several decades and across a wide range of conditions, so this does not require results at daily resolution or even yearly resolution. Wilkinson et al. (2014) showed that Dynamic SedNet produced temporal patterns of sediment yields that were comparable to those produced by a rating curve at a gauging site, but they did not show that the model accounted for daily variation around the rating curve and therefore that the model explained any of the daily details. Jakeman et al. (2015) recommended that model results not be shown at any finer temporal scale than annual loads. So the best temporal resolution for the model remains an open question.

For gully and riverbank erosion, the daily rates are temporally downscaled from mean annual results according to daily discharge. There are various ways of temporally downscaling sediment loads proportional to discharge, and more than one method is used in the model at present, but they have not been well tested against data or sediment transport theory. Erosion and sediment yield can be linearly scaled with discharge, or as a power function with exponents greater than 1 (exaggerated response to high flows) or less than 1 (damped response to high flows). River sediment monitoring data can be used to show the actual sensitivity of daily load to discharge, and then be used to determine what daily temporal scaling rules should be implemented in the model to best reproduce these observed patterns. The same can be applied to data on, and theory of, the temporal patterns of gully and riverbank erosion processes to guide how the model temporally downscales these processes, or alternatively they can be modelled directly from daily discharge (see Section 3.2.5 and 3.4.1). This work should also consider whether thresholds of resistance to erosion need to be introduced for low discharges. However, the purposes for which the model is designed do not require daily results, so daily modelling of these processes is not automatically an improvement.

Another consideration of temporal patterns is the magnitude of events or river discharges that are of concern. For pollution of the GBR, what size events cause pollution? Extreme floods will carry more sediment further, but only occur occasionally. Is marine pollution a problem of these rare events or of more chronic pollution from smaller, more frequent events? The evidence from the marine record and marine modelling can be used to answer this question and provide a focus for improved catchment modelling. Work to date suggests that, in historical times, flood discharges reached the reef on average 1:6 years (Lough et al. 2015).

Understanding the temporal patterns of sediment transport and pollution better will answer the questions posed in the paragraph above. It will show the type of events that should be the focus for modelling and better understanding of processes such as riverbank erosion, floodplain deposition and in-channel erosion and deposition, which is important because these processes can be quite different between smaller and larger floods. It will also enable questions such as the influence of historical climate variability and future climate change to be considered against changes to catchment land uses (e.g. Bartley et al. 2018).

3.11 Modelling pre-European conditions

Reducing accelerated erosion is the focus of catchment management and associated modelling; however, it is also recognised that erosion is a natural process. Thus places of high erosion or sediment yield are not necessarily the places with the greatest problems. Erosion or sediment yield need to be put in the context of natural rates. In the model, pre-European rates of gully and bank erosion are very rough estimates based on scaling down the extent of gullies or management factors to reflect good natural vegetation cover. There is little to no data on actual natural rates of these processes with which to constrain the model. Other factors such as bankfull discharge and floodplain deposition are not varied for pre-European model scenarios, even though they may also have changed in historical times. So while there is a need to have baseline modelling of pre-European sediment yields, there is large uncertainty in the methods applied.

There is an alternative that recognises this uncertainty by using a simpler approach. Instead of trying to model each source and deposition process, an event mean concentration applied to a whole catchment could be used. This is already applied to modelling current sediment sources under largely natural forested land cover. The same approach could be extended by using those event mean concentrations for the whole catchment under pre-European conditions. These measurements can be supplemented by the results of studies of long-term erosion rates or natural sediment yields (e.g. Croke et al. 2015; Bartley et al. 2017). A disadvantage of applying this quite different approach to the pre-European scenario is that the relative differences in results with the post-European scenarios could reflect methodological differences as well as actual differences in sediment yields. This can be explored in the model to examine uncertainty as a result of different modelling methods. In other words, it might be best to use multiple approaches and multiple lines of evidence to reveal the uncertainty of pre-European estimates of sediment loads. Considerable expert judgement will be required to reconcile or choose erosion rates from the disparate evidence.

3.12 Management effectiveness

The primary aim of the Reef Plan modelling is to evaluate the effectiveness of catchment management actions in reducing delivery of pollutants to the GBR. To do this we need to understand patterns of sediment sources and sediment transport through river networks. However, the only aspect of modelling that differs between the baseline and implemented change scenarios is the management effectiveness. For the paddock scale models, this includes changes to quite a few factors. By contrast, in gully and riverbank erosion modelling, all that is changed is the management effectiveness parameter that simply scales down erosion rate by an estimate of the effectiveness of gully management (Figure 13) or riparian management (Figure 11). To model the effectiveness of the Reef Plan, we need to have confidence in the degree to which management reduces gully and riverbank erosion.

The current approach for gully erosion (see Section 2.5) is based on the effectiveness of grazing management in the surrounding catchment, and the scaling is based on values from the international literature (see Thorburn and Wilkinson 2013). Where gullies are fenced off and riparian vegetation is established, it is assumed that these measures will eventually reduce gully erosion to its natural rate. There are several other ways of managing gully erosion, such as by engineering methods, but how widely they are implemented is uncertain. It is only worth including large-scale management in the catchment model as it is that scale of change that is needed to have any discernible impact on catchment yields.

Management effectiveness in alluvial gullies was recently investigated by Brooks et al. (2016). They found that revegetation and stock exclusion were likely to take over a decade to have a significant positive impact, and are probably not effective in treating the most active sites in these highly erodible gullies. A combination of engineering works, soil treatment and revegetation were found to be more effective at controlling gully headwalls and sidewalls, reducing erosion by up to 90 per cent. Additional bed control engineering would also be required to prevent renewed bed incision.

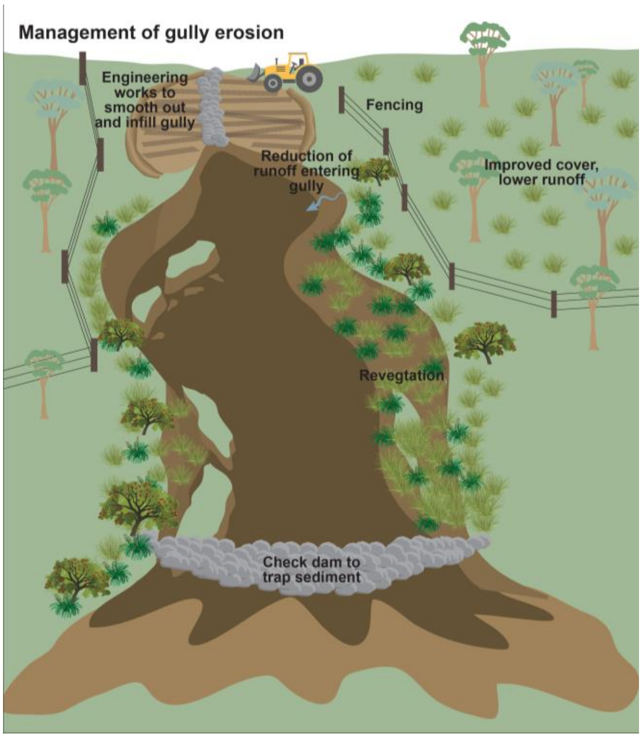

Figure 13. *Some techniques used to reduce sediment yield from gullies.*

Wilkinson et al. (2013) found some similarities in their results for hill-slope gullies in the Burdekin River catchment, where engineering works were more effective than stock exclusion. More recent evaluation of gully sediment yields under different grazing pressures (Wilkinson et al. 2018) shows that grazing exclusion can significantly reduce sediment yields from gullies as a result of improved vegetation cover. It is also likely that grazing management can further reduce erosion by reducing run-off, as there was a strong relationship between annual run-off and sediment yield, and high levels of ground cover have been found to be associated with lower catchment run-off. Based on expert opinion and a review of the literature, Wilkinson et al. (2016) estimated the effectiveness of a wide variety of gully remediation techniques for both alluvial and hill-slope gullies. The findings of all of these studies on effectiveness could be used to improve its representation in the model recognising alluvial and hill-slope gullies separately.

For bank erosion, the management factor is determined by restoration of riparian vegetation and improvement of adjacent grazing land management. It is assumed that riparian fencing and vegetation planting will reduce the bank erosion rate back to that of fully vegetated banks. These rates are assumed in the model to be so low that they are insignificant sources of sediment. From the discussion in Section 3.4.2, there are good reasons to believe that riparian revegetation programs should be successful, but there is scant quantitative evidence to demonstrate this (Bartley et. al. 2015). A Victorian project designed precisely to do that found that restoration projects that resulted in quality native riparian vegetation reduced bank erosion by 80 to 95 per cent. It might take 10–15 years to realise these benefits, and in some cases structural works may be needed as well to provide required levels of protection. These are similar conclusions to those for the effectiveness of gully erosion controls (Hardie et al. 2012).

There is now much better data and knowledge on management of gully and bank erosion than was available when Table A1 was derived to evaluate management effectiveness. There is a calculator (Scott Wilkinson, pers. comm.) used to estimate the effectiveness of management in the Reef Plan, and this and the model should be updated to reflect current knowledge on decreases to erosion rates following restoration efforts.

3.13 Gully and riverbank soil properties

There are a few soil properties of gullies and riverbanks that are used in the catchment modelling:

- Soil bulk density is used to convert volumes of eroded material to mass.
- The proportion of fine sediment is used to convert total mass eroded to the mass of fine particles that are significant for pollution.
- Soil nutrient concentrations are used to convert mass of erosion to particulate nutrient concentration in flows.

The list is in order of increasing uncertainty. The bulk density of mineral soils varies little compared to the uncertainties in other inputs to the sediment budget model, and does not require further attention.

For particle size distribution and soil nutrient concentration, it is mainly the subsoil properties and variations of properties with depth that are required, as subsoil constitutes the majority of the soil eroded by gullies and rivers. Surface nutrient concentrations can matter as well, because if they are several times higher than subsoil concentrations and the erosion is shallow in depth, they will significantly increase the average concentration of eroded soil.

Soil nutrient concentrations are particularly poorly understood, and are a significant source of uncertainty in nutrient modelling. Concentrations and particle size distribution are generally obtained from landscape mapping of soil properties (from the SALI database); however, there are few measurements of subsoil properties, and the spatial extrapolation of these properties in the Australian Soil Resource Information System (ASRIS) can produce high uncertainties and biases (Sherman and Read 2008). Furthermore, gullies and rivers occur in the lower part of landscapes where colluvial and alluvial processes predominate, so their soil properties will be quite different to those of the surrounding landscape. It is hard to reconcile ASRIS soil properties with measured nutrient concentrations in sediments (McCloskey et al. 2017b). For all these reasons, there could be substantial improvements in model performance if particle size distribution and soil nutrient concentration of colluvial and alluvial materials were better understood. Field measurements of these properties in Queensland gullies has begun (Garzon-Garcia et al. 2016) and, when combined with proposed development of pedo-transfer functions (Burton, pers. comm.), the new data should result in improved modelling.

3.14 Other aspects of nutrient transport

Sometimes Dynamic SedNet seems to get fine sediment loads approximately right, but gets attached nutrients quite wrong. This may in part reflect the problems of soil nutrient concentrations described above, but can also be the result of broader limitations to the nutrient budgets. Nutrient transport was not a focus of this project and deserves a project of its own, but several issues were raised at the workshop for further consideration.

One of these is the degree to which the very fine sediment that creates marine pollution is enriched in nutrients. This can occur if nutrients are preferentially attached to fine mineral and organic matter. Data was also presented (Mark Silburn, pers. comm.) to show that in some soil types, aggregates of clay and organic matter were being eroded, so these materials do not necessarily produce river sediment loads of very fine-grained dispersed particles. The fate of eroded soil aggregates and their nutrient enrichment needs to be investigated further.

There are additional complexities in nutrient transport that need to be considered in nutrient modelling. For example:

- NH_4 released from particles in saline water
- mineralisation and dissolution processes mean there are interactions between particles and dissolved nutrient pollution
- groundwater can be a significant source of dissolved N, with the possibility of transformations when it interacts with riparian zones and surface waters.

At present, prioritisation of works in the Reef Plan is largely around fine sediment, dissolved N and pesticides, but particulate nutrients could be considered too, and could quite easily lead to additional priorities for rehabilitation. Mobile water quality monitoring points could be used to bring monitoring further up into catchments for specific purpose of testing hypotheses about sources and transport of nutrients.

3.15 Modelling processes at a finer spatial scale

There are a range of spatial scales of interest in catchment management, and it is unreasonable to expect that a single approach to catchment modelling will best suit all these scales. The aim of SedNet is to identify major differences between large river basins, and between the major sub-catchments of those basins. This scale is used for broad level design and evaluation of catchment management programs such as the Reef Plan.

There is now interest in finer scales, such as the hotspots of erosion within particular sub-catchments, or patterns and sources of sediment in catchments of 10^3 km^2 area (instead of 10^4 to 10^5 area at the broadest scale). Research has shown that riverbank erosion is unable to be modelled at anything other than the broadest scale at present, while hill-slope erosion, gully erosion and deposition processes can conceptually be modelled down to 10^3 km^2 catchment scales if supported by suitably accurate spatial input data. Sometimes SedNet is used at finer scales simply because it is available and well-known among the agencies. Catchment models suitable to the finer scale have either not been developed into usable well supported software or the agencies have no experience with them.

At the finest scale, there is interest in designing and evaluating rehabilitation works within the 10 to 10^2 km^2 catchment area, or along single river reaches of several kilometre scale. The questions being posed at the finest scale are often about where exactly erosion is occurring, by what process and how best to control it. This does not require a sediment mass balance approach and may not even require erosion rates to be quantified. SedNet is completely unsuitable at these scales and for these purposes. At this scale, direct field measurements or observations become the best primary data source.

A good start at this finest scale would be a simple classification of processes and attributes as is done for riverbank condition in the Victorian Index of Stream Condition (James Grove, pers. comm.), and has been done for qualitative reach scale assessment in south-east Queensland (Tony Weber, pers. comm.). For bank erosion, this might start with planform classifications and get finer scale from there, using stream power and analysis of factors such as bank height, mass failure mechanisms, deposition patterns and riparian vegetation. For gully erosion, it might start with morphological indicators of erosion processes, assessment of vegetation cover and connectivity of run-off (Sidle et al. 2017) and modelling of individual processes in gullies (see last paragraph of Section 3.2.5).

3.16 Sediment tracing and multiple lines of evidence

Isotopes and other geochemical tracers have been used as a very useful line of evidence to examine sources of sediment. The traditional approach is to find distinctive geochemical signals in two sources, such as two tributaries, and also measure the geochemical signature downstream of the tributary junction, then use a mixing model to determine what proportion of the downstream sediment load comes from each tributary. The same mixing model approach has been used extensively to distinguish surface sediment sources (such as sheetwash and rill erosion) from sub-surface sediment (such as eroded from gullies and riverbanks) based on different geochemical signatures of surface soils and subsoils. ^{210}Pb excess and ^{137}Cs are widely used for this tracing, and more recently ^{7}Be (Hancock et al. 2014) and OSL (Haddadchi et al. 2016) have been added to the suite of tracers. It is always better to use multiple tracers than single tracers. This body of work has been important in the last two decades for broadening the emphasis of catchment sediment and nutrient studies from sheet and rill erosion of agricultural land to include riverbank and gully erosion as substantial sources (see Prosser et al. 2001b for a national review). Bartley et al. (2017) present a summary of these studies in the GBR catchments and show that in most catchments, sub-surface soil sources predominate. They form part of the multiple lines of evidence of patterns of sediment transport, along with field measurements of erosion and sediment yields, and catchment modelling. The three techniques are largely independent of each other and complementary, providing different types of information. Comparisons between the different techniques have been largely qualitative at present.

It might be tempting to quantitatively use sediment tracing studies to determine the percentage of individual erosion sources and force the model to match those results, or precisely plan management around those results. That fails to recognise the uncertainties in sediment tracing. Like catchment models and load estimates from monitoring, there are assumptions, unaccounted for sources of variation and possible bias in sediment tracing studies, particularly for interpreting surface vs sub-surface sources. Thus the results should not be taken as a precise measurement, but like the model, they are an estimate with a hard-to-determine band of uncertainty. When field observations and monitoring, catchment modelling and tracing studies broadly agree within reasonable bands of uncertainty for each, then there is some confidence about sources of sediment. When they don't, further investigation is warranted. Both situations are found in the current understanding of GBR catchments as discussed by Bartley et al. (2017).

3.17 Sediment quality

Research identifying the characteristics of sediments that pose problems of marine pollution has already resulted in a focusing of catchment work on finer sized suspended particles. No longer is it gross erosion that is of concern, but erosion of <20 µm particles, as discussed earlier. This might mean that some areas of significant erosion that erode mainly sandy soils might be of concern for other reasons, but they are not contributing to marine pollution. That concept is being extended to identify other properties of sediment that contribute to it being a marine pollutant. This work, currently being led by Zoe Bainbridge, Stephen Lewis and colleagues at James Cook University, is summarised in Bartley et al. (2017). It shows that expandable clays are more likely to produce problems for marine pollution, although the dynamics are complicated by factors such as interaction with terrestrial organic matter. There are yet to be understood differences in the behaviour of particular types of expandable clay, and there are some other materials that may pose a problem. Nevertheless, there is now emerging a tighter focus on the sediments of concern. Basaltic terrains are emerging as a key source of these materials.

A related area of work in the marine environment has been to use marine water quality modelling to work backwards from water quality indicators of health of marine ecosystems. Targets of chlorophyll and turbidity for coral and sea grasses were then modelled back to the mouths of particular catchments to determine the sediment and nutrient load reductions required to meet the marine water quality targets (Brodie et al. 2017). This provides more detail and better justification of catchment load targets than the current uniform approach. Catchment modelling can then be used to investigate how to achieve the new targets and evaluate progress in achieving them.

Thus, in the long term, a productive line of research might be a combination of identifying sediment quality attributes, tracing their origin through geochemical methods, and using catchment models designed specifically around these types of sediment and their transport.

4. Discussion

4.1 Introduction

There are lots of possible improvements to the model raised above. Some are quite small and easy to implement, but probably with modest consequences as well. Others are major changes that require quite a bit of additional investigation before they are ready to include in the model and be applied widely. They have potential to make substantial improvements to the model if there is sufficient data to support their broad application. Finally, there is a third class of improvement, which is to undertake a whole new approach to modelling, to move away from a sediment budget approach to more direct modelling of just the type of sediments that pose problems of water pollution. To make that change now might be premature, as the nature of sediment pollution is still being investigated, but it could be fruitful to start to model this pollution as part of those investigations to explore the implications of that research.

Few of the potential improvements are ready to be implemented now or are proven to better meet the model purposes. They mostly require some further development, and to maximise potential for transfer of broader research into the model, the researchers should work closely with experienced modellers. Research has to be presented in a suitable way to be included in the model. Research results need to be generalised at the scale of large diverse catchments to make them applicable, preferably through conformity with wider theory of sediment transport. Input variables for any new algorithms needs to be obtained and processed or be interpreted from ancillary environmental data.

Improvements to the model should be done as a parallel program to its operational use in the Reef Plan and other government programs. There may be good operational reasons to not change versions midway through a highly public government program. Also, any potential improvements need to be properly tested and documented, and users trained, before a new version of software is adopted for operational use. This is not an argument to delay making improvements, just to separate research and development (R&D) on a model from operational use of the model.

4.2 Uncertainty analysis

Before making any major model improvements, the first thing that should be undertaken is an analysis to determine the critical sources of uncertainty that impact on how well the model meets its purpose. The model is used for two purposes—to evaluate the effectiveness of large-scale catchment management programs, and to identify the predominant sources of sediment in terms of which sub-catchments and which sediment sources (hill-slope, gully and riverbank) are significant sources of accelerated sediment loads. The model makes predictions of annual catchment sediment yields in tonnes/year, and these predictions are compared to measured sediment yields as part of evaluating how well the model is doing, but that is not the purpose of the model and should not be the sole basis for assessing how well the model is doing. If the purpose was only to predict annual yields, then the best approach would be to calibrate the model to the measurements as is done for rainfall–run-off models.

Uncertainty analysis aims to address a much more fundamental question: how wrong is the model? It is probably wrong in many ways, as all models are, but the only way that really matters is how wrong it is for the uses to which it is put. For example, how much would the model and its inputs need to change in order to significantly change the ranking of accelerated sediment yield from catchments along the coast of

Queensland or the ranking of sediment sources in each region, as illustrated in Figure 3.

The analysis should explore uncertainty arising from:

- the concepts and assumptions used in the model
- the choice of algorithms used
- the spatial and temporal input data
- parameter values in algorithms.

A small part of uncertainty analysis is to conduct a sensitivity analysis for parameters used in the model algorithms. There are many parameters used in SedNet, but quite a few are used just for scaling and unit conversion. They are generally spatially and temporally fixed and have little influence on interpretation of the results for the questions posed above. Newham et al. (2003) undertook a sensitivity analysis for all the parameters that were in the original steady state SedNet model, but they only evaluated the sensitivity of mean annual catchment sediment yield, and only in the Murrumbidgee River catchment. Bennett and Fentie (2017) and Fentie and Bennett (2017) conducted a more limited sensitivity analysis on the current Dynamic SedNet model, selecting six spatially uniform parameters to explore against annual sediment yield over five years of simulation for the Mary River basin. Globally changing parameters will increase or decrease the predicted sediment yield from all catchments, but it may not change which sub-catchments or which sediment sources are important. Nor will it significantly change the evaluation of the effectiveness of catchment management, because the parameters stay the same for both present and post-management scenarios, so the absolute difference in yield between scenarios stays the same. Therefore, changing these parameters will not make the model's contribution to catchment management programs significantly better or worse.

SedNet is essentially a spatial model. Much of its usefulness rests on its ability to predict large-scale spatial patterns of sediment sources. It is highly likely that uncertainty in spatial input data and the way sediment transport processes are modelled will have a significant influence on the spatial patterns of the results. Spatially variable inputs that have considerable uncertainties include factors such as the extent of gullies; their current rate of erosion; the power of streamflow; bankfull discharge; the condition of riparian vegetation; the extent of floodplains; channel geometry; the slope of the riverbed and the proportion of fine sediment being eroded. There are broader concerns such as the ability to spatially model patterns of riverbank erosion or floodplain deposition, or the effectiveness of various management actions. At the most fundamental level is the question of whether additional sources and sinks of sediment should be added to the model. Uncertainty in many of these spatial inputs and model components has been addressed descriptively in the review of Section 3 above, but a formal uncertainty analysis is needed to properly evaluate them and compare between them.

As an example, riverbed slope varies by about three orders of magnitude across Queensland rivers. It is used to predict riverbank erosion and in-channel deposition and re-entrainment of sediment. Riverbed slope is derived from DEMs, and there are known to be errors in values of bed slope obtained from DEMs, but there are methods to correct for these errors. Do these errors matter for the predicted spatial patterns of bank erosion, or are they small compared to the variability in bed slope between reaches?

At the coarsest scale, when the model is evaluated against multiple lines of evidence (see Bartley et al. 2016), it appears to predict relative load differences between catchments reasonably well, and the main sources of sediment. There is less confidence about how well management effectiveness is modelled, and how well it performs in individual basins such as the Normanby River, and drier basins that differ substantially from the types of basins around which it was designed.

4.3 Turning research into model software

This project was focused on reviewing catchment research to see how the model can be improved, but new algorithms of modelling approaches are only one half of what is required to improve the model. The other half is to develop professional, well-supported software, and the history of SedNet is a good example of the importance this, as outlined below. This second half is often ignored, and is why many models developed in a research environment are never used in private consultancy practice or in major government programs.

SedNet was developed purely for NLWRA projects that aimed to assess the downstream impacts of agriculture and other land uses on river habitat and water quality. Over 130 catchments had to be assessed in a relatively short time, so a repeatable modelling process was required, and the project team wanted to bring the geomorphological concepts of sediment budgets to the assessment (as described in Section 2.3). Following the NLWRA, several catchment management agencies realised that the model could be used to identify sources of sediment from catchments in a more targeted way, or to use the model to predict how effective particular management actions might be. The model had to be manually modified to do this, and it was at best a prototype so only the research team was able to apply it.

It may have ended there, as many projects of research organisations do. But the CRC for Catchment Hydrology, and then the eWater CRC, developed a software platform of a suite of approaches to various catchment and water modelling problems. For water quality, this included Dynamic SedNet. The CRCs brought professional software engineering and dedicated collaboration with catchment management agencies to complement catchment research. Software engineering, model testing and development in real applications, and capacity building in government agencies took several million dollars and about ten years to turn research concepts and models into routinely applicable operational models that were well enough supported for government programs to fully adopt them. Queensland undertook several years of further work itself on SedNet to build capacity, customise the model, obtain input data and introduce its own models for agricultural sources. That significant level of time and investment commitment (or more) required to transform a research model into an operational application is mirrored in several other related areas, such as water planning, hydrological forecasting, seasonal climate prediction and fisheries management models. In some ways, the research is the easy bit compared to adoption as an operational model.

What is easily forgotten is the transformation that has taken place in Queensland. Fifteen years ago, geomorphology was at the periphery of catchment water quality science, and now for a range of reasons it has a central role. This is not to say that the traditional disciplinary approaches to water quality are no longer needed. It is now recognised that it is a more multidisciplinary problem, and the best understanding is coming from combining disciplinary perspectives, such as is seen in compiling multiple lines of evidence.

That geomorphology is now central to questions of catchment management can be seen in the research publications of the last 15 years. I suspect there have been more papers published on sediment tracing, sediment budgets, sediment quality, nutrient transport, gully erosion and riverbank erosion in Queensland catchments over the last 15 years than for the rest of Australia, and more than over the previous 15 years. Most of these papers begin with the context of the management issues being addressed by the Queensland Government programs.

5. Conclusions

The Dynamic SedNet model is fit for the purposes of identifying the main sources of sediment in large river basins and evaluating reductions in sediment loads resulting from major efforts at catchment management (Jakeman et al. 2015). Relative to previous large-scale modelling, its emphasis on spatial sediment budgets means it better identifies the major sources and sinks of sediment in large catchments, and is able to estimate catchment sediment yields. It is based on simple conceptualisations of the main processes, and uses a large amount of spatial data to estimate the broadest scale spatial patterns of the processes. It adds catchment geomorphology to the disciplines used in water quality assessment. Being targeted at catchment management that aims to be effective over decades, the model is less focused on daily details of sediment yields, and at best should only be used to estimate yearly loads.

At times, SedNet has been used to predict finer scale patterns of processes in smaller catchments to guide local restoration efforts, simply because it is readily available and is well known. It is not suited to these purposes. Often, instead of a sediment budget, what is needed at the finer scale is a qualitative assessment of processes or a site attribute classification.

Modelling sediment sources and yields in widely different catchments inevitably has a high degree of uncertainty, and knowledge of the uncertainties should be paramount when making interpretations from the model. Queensland has made major improvements to modelling hill-slope erosion and the extent of gully erosion across catchments. A formal uncertainty analysis should be undertaken to identify those aspects where improvements to the model could significantly change the conclusions made.

In the absence of a formal uncertainty analysis, I suggest that the first priority for major improvement would be to change the modelling of gully erosion to focus on current gully sediment yields. Gully erosion seems to be the biggest source of sediment across modelled catchments. There is good, simplified erosion theory that can be applied at the large scale, and there is probably sufficient data on contemporary rates of gully erosion to support the approach (see Section 3.2.5).

There is quite a contrasting situation for riverbank erosion. It would seem to be the smallest of the three major sediment sources, and is the most episodic and hardest to measure. While there is simplified erosion theory, it is harder to apply because of a lack of good quality datasets and empirical relationships to constrain the theory. Nevertheless, there should be a concerted effort to improve modelling of this sediment source.

For transport through river systems, improvements have been made to predicting floodplain inundation and deposition, but more improvements are needed as bankfull discharges are clearly larger and more variable than are represented in the model. Similarly, there is a greater diversity of river planforms than represented in the model, and these may have quite a different mix of processes. Within river channels, there are circumstances where benches temporarily store large volumes of fine sediment. The model has been modified to simulate these processes, but further work is needed to evaluate this component. A useful first step would be to establish a typology of rivers in modelled catchments, and to use the types to determine which processes should be modelled and to help set appropriate parameter values for rivers.

There are some relatively easy incremental improvements to the model listed below, but most substantial improvements will take further work to generalise and quantify research concepts and present them in the form of algorithms and input data that can be used in the model. Further work is needed to demonstrate that new concepts will lead to improved model predictions.

Investments in research, improved data and model development should more than pay for themselves in benefits of improved effectiveness of government programs. Hundreds of millions of dollars are being spent on catchment management on the assumption that it effectively targets the sources of pollution. Investments in R&D are generally one or two orders of magnitude lower, so do not have to improve the effectiveness of management much to be worthwhile. However, to achieve this, R&D does have to contribute directly to catchment management and produce broadly applicable conceptual models. Putting this knowledge into assessment techniques and quantitative modelling is an effective way of applying and transferring the knowledge.

Multiple lines of evidence are used to understand and improve catchment water quality and all lines should continue to be used. Modelling is one line of evidence, which is used together with load monitoring, remote sensing, sediment tracing and field research. Fuller integration of these multiple lines of evidence will provide the best understanding. Incorporating research findings into the model is part of that integration, as is using the model to identify the key uncertainties and thus help prioritise and design future research. To achieve this there should be more collaboration between researchers and experienced modellers.

5.1 Summary of recommended model improvements

For convenience, the potential improvements identified in this review are summarised here as a set of projects, with a very brief description and reference to where they are discussed in more detail.

Within each of the three bands of project size, the projects are listed in declining order of impact in my judgement. Projects on uncertainty analysis, gully mapping and effectiveness of management are essential in my view, as they could make quite a difference to use of the model with relatively little effort required. To start bigger projects on modelling current rates of gully erosion, improved modelling of bank erosion and soil properties of eroding materials is highly recommended. These could be PhD or similar projects that, if undertaken, could well make a major difference.

Short-term projects of 1 year or less

1. **Uncertainty analysis** (Section 4.2). Determine the critical sources of uncertainty that impact on how well the model meets its purposes. Do this before any major investments in model improvements to help design those improvements.

2. **Gully mapping** (Section 3.2). Continue mapping and spatial modelling of gullies in catchments where gully erosion is of concern. Separate alluvial from hill-slope gullies.

3. **Effectiveness of management** (Section 3.12). Review the table of management parameters used for gully and riverbank erosion, and possibly use more sophisticated ways of representing management effectiveness.

4. **Improve daily scaling of model processes** (Section 3.10). Use river sediment monitoring data, erosion rate data and erosion theory to enable the model to best reproduce observed patterns.

5. **In-stream deposition and re-entrainment** (Section 3.9). Investigate the behaviour of the in-stream deposition and re-entrainment algorithms against field data to evaluate if they are physically realistic and, if not, explore alternative approaches.

6. **Pre-European sediment loads** (Section 3.11). Use an event mean concentration approach to model pre-European loads from the whole catchment, analogous to how low impact land uses are modelled in the baseline scenario.

Intermediate scale projects of 2–3 years duration
7. **Modelling current rates of gully erosion** (Section 3.2.5).
Model current gully sediment yields based on their size, discharge and resistance to erosion, which could be more accurate than using just gully volume. Use LiDAR or other remote sensing to determine current rates of erosion.

8. **Measuring and modelling riverbank erosion** (Section 3.4). This is a significant but highly uncertain source of sediment. Reduce the uncertainty at the larger scale through more systematic measurements and algorithm design.

9. **Gully and riverbank soil properties** (Section 3.13). Data and pedo-transfer models are needed for gully and riverbank soil particle size and nutrient content, because they will be quite different to hill-slope soils.

10. **River typology** (Section 3.7). Design a typology of river reaches specifically for the purposes of choosing which processes need to be modelled in which rivers, and for varying parameter values.

11. **River channel morphology** (Sections 3.6, 3.8). Better define flow confinement, flooding extent and channel cross-section morphology to more accurately predict erosion and sediment transport through river reaches.

12. **Erosion of small streams** (Section 3.5). There are small streams which are larger than erosion gullies, but smaller than river links, and in places these may be a significant source of sediment and so need to be modelled.

Longer term projects of 4–5 years duration
13. **Small catchment, high resolution model** (Section 3.15). At a finer scale of catchment than can be modelled by SedNet, there is interest in designing and evaluating rehabilitation works. A new model or assessment processes are required for this purpose.

14. **Sediment quality model** (Section 3.17). Research is showing that particular types of clay minerals are responsible for marine pollution. Future modelling might focus on the sources and transport of those particular types of sediment, requiring a quite different model conceptualisation.

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Appendix 1 Description of the Dynamic SedNet model

A1 Introduction

The description of the catchment modelling given below is based on Waters et al. (2014); Ellis and Searle (2014); Wilkinson et al. (2010; 2014); and McCloskey et al. (2017a, b), and on discussion with members of the modelling team. The author is responsible for any mistakes in the description.

A2 Gully erosion modelling

Gully erosion is modelled as a source of sediment to streams in grazing land uses, and is beginning to be represented within the conservation and forestry land uses as models are updated. Cropping and sugarcane land use areas have the potential to also include gully processes; however, in most cases, this contribution is considered negligible. It is not explicitly modelled in urban, horticulture, dairy, bananas and ‘other’ land use categories where a flow mean concentration approach is used.

The total volume of gully eroded in a functional unit is calculated from a raster of gully density across a region. The mean annual gully erosion rate (*G*, t/y) is determined from the area of the functional unit (*A*, m^2), gully density in the functional unit (*D*, m/m^2), mean cross-sectional area of gully (a_g, m^2), the bulk density of sediment in gullies (ρ_g, t/m^3), and an estimate of mean gully age (T_g, y):

$$G = A\ D\ \rho_g\ a_g / T_g \qquad \text{(A1)}$$

Alternatively, if gully density is expressed as an area of gullies, as is more appropriate for alluvial gullies, an estimate of mean gully depth instead of cross-sectional area is used to calculate the volume eroded (Wilkinson et al. 2014).

Daily gully erosion (G_i; t/d), is calculated from mean annual gully erosion by temporal scaling (see Ellis and Searle 2014). Dividing mean annual gully erosion by 365 gives mean daily gully erosion. Two methods can be used to weight daily gully erosion by discharge from the functional unit: the CSIRO and DERM methods. The CSIRO method weights by the daily proportion of discharge raised to power Q_i^a (where Q_i is daily discharge in m^3/d) over the number of days modelled (*n*):

$$G_i = \frac{G}{365} \frac{{Q_i}^a}{\frac{1}{n}\sum_{i=1}^{n} {Q_i}^a} \qquad \text{(A2)}$$

The DERM method weights proportionally to daily discharge. Annual gully erosion is weighted by the ratio of total discharge (QT_j ; m^3/y) in each year (*j*) to the long-term average discharge over the number of modelled years (*y*). Within each year, daily gully erosion is weighted by the ratio of daily discharge to the total discharge for the year. So:

$$G_i = \frac{G}{365} \frac{QT_j}{\frac{1}{y}\sum_{j=1}^{y} QT_j} \frac{Q_i}{QT_j} \qquad \text{(A3)}$$

The two methods are near identical when *a* = 1 in Equation (A2). A default value of *a* = 1.4 is used to reflect stream power and disproportionately high erosion at high discharges. The same temporal scaling is also applied to bank erosion (Equation A7 below) so an appropriate value of *a* can be obtained by using rating curves of sediment concentration with discharge at monitoring stations in rivers where gully and streambank erosion are the main erosion processes.

Total daily gully erosion is converted to daily erosion of fines (G_{if}; t/day) by the proportion of fines in the gully soils (F_g). The generated daily fine sediment load is further modified by (dimensionless) gully management (M_g) and gully activity factors (A_g). Activity level reflects the relative stabilisation of gullies over time. Without considering activity level, the average rate of gully erosion will just be the volume of gully eroded material divided by the mean age of gullies in the region. The activity level factor is used for short contemporary modelling periods, such as in the annual report card modelling, to reflect that current rates of erosion will be less than average, especially for mature gullies that are largely fully developed. Usually $A_g = 1$ except where there is evidence to suggest that gullies are mature.

Section 2.5 below describes the gully management factor.

The delivery of fine sediment from gully erosion to the river network is further modified by a dimensionless gully sediment delivery ratio (SDR_g). This represents the situation that not all gullies are connected hydrologically to the river network. So:

$$G_{if} = G_i F_g SDR_g M_g A_g \qquad \text{(A4)}$$

Particulate N and P derived from gully erosion are obtained by multiplying the generated sediment load from gullies by sub-surface nutrient concentration. The transport of particulate nutrients to the stream is assumed to occur in a similar process to the finest sediment particles (i.e. clay).

Nutrient concentrations and other required soil properties are derived from the SALI database, spatially extrapolated using ASRIS mapping protocols.

Gully density mapping in Reef Plan modelling uses the NLWRA mapping, with more recent data used for the Burdekin, Fitzroy and Normanby catchments (see Section 3.1.1).

There are many parameters in the modelling of gully erosion. However, most are just scaling or unit conversion factors that are kept constant over time and space, or vary little over the modelled regions. The parameter that varies most in space is gully density, followed by soil nutrient concentration and particle. Daily discharge is the only time varying parameter.

A3 Modelling streambank erosion

Streambank erosion is modelled for each river reach in a catchment (see Ellis and Searle 2014; Wilkinson et al. 2010; 2014). Mean annual bank erosion (B; t/y) represents lateral retreat of banks along a river reach (m/y), which is modelled as a function of bankfull stream power and bank erodibility (E) in each reach. The lateral retreat rate is converted to a mass erosion rate of fine sediment in each reach through the length (L; m) and height of streambanks (h; m), and the bulk density (ρ_b; t/m^3) and proportion of fines (F_b) in bank materials. So:

$$B = F_b \rho_b h\, L(k\, \rho_w\, g\, S\, Q_b)\, E \qquad \text{(A5)}$$

The term inside the brackets is an expression for stream power at bankfull stage. It consists of channel slope (S), bankfull discharge (Q_b ; m^3/s), acceleration due to gravity (g; m/s^2), density of water (ρ_w; kg/m^3) and an empirical constant (k) used to scale long-term bank erosion rate to bankfull stream power, often through calibration with measurements or estimated values of bank erosion.

Bank erodibility is modelled as a function of proportion of riparian vegetation cover (V_R), maximum effectiveness of riparian cover (V_{max}), bank material erodibility (E_b; 0 for bedrock, 1 for alluvium) and streambank management (M_b, see Section A2.5).

$$E = 1 - (\min(V_R , V_{max}))E_b M_b \qquad \text{(A6)}$$

The daily rate of bank erosion of fines (B_i ; t/d) is temporally downscaled by the ratio of daily Q_i^a in the river link to the mean daily Q_i^a over the modelling period of *n* days, similarly to Equation (A2) for gully erosion. Therefore:

$$B_i = \frac{B}{365} \frac{Q_i{}^a}{\frac{1}{n}\sum_{i=1}^{n} Q_i{}^a} \qquad \text{(A7)}$$

Particulate N and P contribution from streambanks was estimated by taking the mean annual rate of streambank erosion (t/yr) multiplied by the ASRIS sub-surface soil N and P concentrations. For 2015 Reef Plan reporting, the sub-surface nutrient concentration in the Cape York and Wet Tropics regions was replaced with surface nutrient concentration to produce higher nutrient concentrations and results for nutrient export that better match observations.

For Queensland applications, bank height is estimated from the same simple hydraulic geometry relationships used in the NLWRA (see Prosser et al. 2001a). The recurrence interval of bankfull discharge is modified spatially based on estimated values. Daily discharge is obtained from calibrated rainfall–run-off modelling using the Sacramento method. The cover of woody riparian vegetation is derived from Queensland mapping using a range of Landsat satellite imagery (1984–2013), which has a spatial resolution of 30 m. The riparian area is defined as a 100 m buffer based on the Australian Hydrological Geospatial Fabric drainage layer.

A4 Modelling land use management practices

Land use management practice is a factor that determines rates of gully and streambank erosion in the model. It is crucial to the purpose of evaluating progress on the Reef Plan, as it is the only factor that changes between baseline and implemented management scenarios.

For each of the major land uses that are the focus of the Reef Plan, management practices that influence pollutant delivery are divided into four classes (Waters et al. 2014):

A. cutting edge practices, achievable with more precise technology and farming techniques for cane, and highly likely to maintain land in good condition for grazing
B. best management practice, generally recommended by industry for cane, and likely to maintain land in good/fair condition for grazing
C. code of practice or common practices for cane, and likely to degrade some land for grazing
D. unacceptable practices that normally have both production and environmental inefficiencies, and highly likely to degrade land to poor condition in grazing.

In order to allow sediment generation rates to reduce in scenarios (thus representing improved management), it was necessary to provide some means to estimate baseline management distribution of grazing land uses impacting on hill-slope, gully and riverbank erosion. Non-spatial regional estimates were made of the proportion of area subject to each management practice class for the baseline year of 2008–09. Management practice class was modelled spatially using satellite observations of ground cover during two dry years, assuming that the best covered land under these conditions reflected the best managed land. For future management scenarios, the proportions of each management class were changed based on the investments made under the Reef Plan.

The rate of gully erosion is scaled by grazing management class, recognising that better landscape cover reduces landscape run-off, which together with lower stocking density is likely to result in lower erosion rates (Table A1).

Table A1. *Gully and streambank erosion rates relative to C class practice. Waters et al. (2014) derived from Thorburn and Wilkinson (2013).*

Grazing practice change	**A**	**B**	**C**	**D**
Relative gully erosion rate	0.75	0.90	1	1.25
Relative streambank erosion rate	0.6	0.75	1	1.1

The rate of streambank erosion in grazed land use areas is scaled by management practice class (i.e. vegetation cover) within 100 m of the stream.

Where management practice change under the Reef Plan included riparian fencing of streambanks, it is assumed that the fencing will increase vegetation cover sufficiently to reduce riverbank erosion rates to natural levels.

For the predevelopment scenario, it is now assumed that all riverbanks were naturally in A class condition, or in other words, the assumption is that A class riparian cover results in a similarly low erosion rate to the natural rate.

For gully erosion, the predevelopment cross-sectional area of gully is assumed to be 10 per cent of the current cross-sectional area, based on studies in northern Australia, so predevelopment erosion rates are 10 per cent of those under C class management. This recognises that gully erosion has occurred sporadically prior to European settlement, although its frequency and extent is poorly known and very hard to determine.

A5 Modelling floodplain deposition

When floodwater rises above riverbanks, the water that spills out onto the river's floodplain is defined as overbank flow. Floodplain trapping or deposition occurs during overbank flows. The velocity of the flow on the floodplain is significantly less than that in the channel, allowing fine sediment to deposit on the floodplain (Waters et al. 2014). In the model, along each river reach, the amount of fine sediment deposited on the floodplain on each day (F_i; t/day) is regulated by the proportion of daily discharge that goes overbank, floodplain area along the reach (A_f ; m^2), the amount of fine sediment supplied to the reach (I_i; t/day), the residence time of water on the floodplain, and the mean settling velocity of the fine sediment (υ; m/sec). Floodplain deposition is calculated from (Prosser et al. 2001a; Wilkinson et al. 2010, 2014; Ellis and Searle 2014):

$$F_i = I_i \left({}^{Q_f}\!/_{Q_i} \right) \left(1 - e^{-(\upsilon A_f / Q_f)} \right) \qquad \text{(A8)}$$

where the proportion of daily discharge that goes overbank:

$${}^{Q_f}\!/_{Q_i} = Q_b - Q_i \text{ if } Q_f > Q_b$$

$${}^{Q_f}\!/_{Q_i} = 0 \text{ if } Q_f < Q_b \qquad \text{(A9)}$$

where Q_f (m^3/s) is daily floodplain discharge and Q_b (m^3/s) is bankfull discharge.

For particulate nutrients, the proportion of load deposited on the floodplain is the same as the proportion of fine sediment deposition. That just assumes that the flow is fully mixed.

Floodplain area in each river reach was estimated in the NLWRA by analysis of the 9" DEM. This has been updated for Queensland using 1:100,000 scale landscape mapping, with some checking through aerial photograph interpretation.

A6 In-stream deposition

In stream deposition and re-entrainment of fine sediment was first introduced into Dynamic SedNet for the Cape York region for the 2014 Reef Plan report card. It was introduced there because of the availability of measured sediment data in the Normanby basin, which provided a source of data to constrain the model parameters (McCloskey et al. 2017b). For the 2015 report card, it was expanded to the Mackay Whitsunday and Burnett Mary regions, using the constraints from the Normanby catchment. It was not implemented for the Burdekin and Fitzroy regions. The conservative approach (in Burdekin and Fitzroy) assumes that deposition and re-entrainment are in equilibrium. The effect of this constraint is that there is no net source of suspended sediment from the riverbed, but some proportion of the load exported from the catchment will have come from the riverbed during the reporting year.

It is widely assumed that there will be a long-term approximate equilibrium between re-entrainment and deposition of suspended sediment on riverbeds, otherwise the river channels will reduce in size to zero over time, or become ever larger. However, where supply of suspended sediment to channels has greatly increased in recent times, there may be a period of disequilibrium as the channel network adjusts to the changed supply.

The within channel deposition/remobilisation model for fine sediment requires the calculation of two daily sediment transport capacity values for each link. The sediment transport capacity for deposition (STC_d; t/day) in a river link is (Ellis and Searle 2014, following Wilkinson et al. 2010):

$$STC_d = \frac{1}{10} \frac{Q_i^{1.4} S^{1.3}}{v_d w^{0.4} n^{0.6}} \quad \text{(A10)}$$

and for remobilisation (STC_m; t/day) it is:

$$STC_m = \frac{1}{10} \frac{Q_i^{1.4} S^{1.3}}{v_m w^{0.4} n^{0.6}} \quad \text{(A11)}$$

where *S* is channel slope along the link; v_d is the average terminal fall velocity (m/s) for fine sediment (default 0.0007), v_m is the terminal fall velocity (m/s) for larger particles (default 0.1, based on particles mid-way between fine and coarse sediment); *w* is channel width (m); and *n* is Manning's channel roughness factor (default 0.04). This is the same formulation for STC as is used in the coarse sediment budget, and is based on the Yang (1973) relationship for bedload transport as a function of stream power (see Prosser et al. 2001a).

Once STC values have been calculated, in-stream deposition and remobilisation (D_i; t/day) are determined from the incoming sediment load to the link (I_i; t/day) according to these rules:

1. If $I_i > STC_d$ then $D_i = I_i - STC_d$;
2. If $I_i < STC_m$ then $D_i = I_i - STC_m$ and D_i will be < 0, indicating remobilisation, limited by M_i (the mass of in-stream fine sediment stored; t)
3. If $STC_m \le I_i \le STC_d$ then $D_i = 0$, and M_i remains unchanged.

In the model, the amount of in-stream fines that can be stored within each link (M_i) is capped at an upper limit, represented as a proportion of the bank height parameter. Once the channel store is 'full', no more deposition can occur unless remobilisation removes some material from the store first (Ellis and Searle 2014). The greater the difference between STC_d and STC_m, the more likely that sediment stores will need to be artificially capped.

A7 Reservoir deposition

Deposition of fine sediment in reservoirs on each day (T_i; t) is modelled according to the empirical equation (Lewis *et al.*,2013):

$$T_i = 112 - 800 \left(\frac{Cap^2}{3.28\, Len\, Q_i^2} \right)^{-0.2} \quad \text{(A12)}$$

where *Cap* (m^3) is the reservoir capacity; *Len* (m) is the longest impounded length from the wall at full capacity; Q_i (m^3/s) is reservoir outflow on day *i* of the model run; and the numeric parameters include unit conversions from the original formulation (Wilkinson et al. 2014).