Modelling reductions of pollutant loads due to improved management practices in the Great Barrier Reef catchments – Burdekin NRM region, Technical Report, Volume 4,

Technical Report · January 2014

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Modelling reductions of pollutant loads due to improved management practices in the Great Barrier Reef catchments

Burdekin NRM region

Technical Report

Volume 4

Australian Government

Queensland Government

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To reference this volume:

Dougall, C., Ellis, R., Shaw, M., Waters, D., Carroll, C. (2014) *Modelling reductions of pollutant loads due to improved management practices in the Great Barrier Reef catchments – Burdekin NRM region*, Technical Report, Volume 4, Queensland Department of Natural Resources and Mines, Rockhampton, Queensland (ISBN 978-0-7345-0442-5).

Acknowledgments

This project is part of the Queensland and Australian Government's Paddock to Reef program. The project is funded by the Queensland Department of Natural Resources and Mines '*Queensland Regional Natural Resource Management Investment Program 2013–2018'* with support from the Department of Science, Information Technology, Innovation and the Arts (DSITIA).

Technical support was provided by a number of organisations and individuals, including Environmental Monitoring and Assessment Science (DSITIA), Queensland Hydrology (DSITIA) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO). We would also like to thank three reviewers for providing feedback on this report.

Executive Summary

Contaminants contained in terrestrial runoff are one of the main issues affecting the health and resilience of the Great Barrier Reef (GBR). In response to a decline in water quality entering the GBR lagoon, the Reef Water Quality Protection Plan (Reef Plan) was developed as a joint Queensland and Australian government initiative. The plan outlines a set of water quality and management practice targets, with the long-term goal to ensure that by 2020 the quality of water entering the reef from broad scale land use has no detrimental impact on the health and resilience of the GBR. Progress towards targets is assessed through the Paddock to Reef Integrated Monitoring, Modelling and Reporting (P2R) Program. The program uses a combination of monitoring and modelling at paddock through to basin and reef scales.

To help achieve the targets, improvements in land management are being driven by a combination of the Australian Government's reef investments, along with Queensland Government and industry led initiatives in partnership with regional Natural Resource Management (NRM) groups.

Catchment modelling was one of the multiple lines of evidence used to report on the progress being made towards the water quality targets. Other components of the program include: paddock scale modelling and monitoring of the effectiveness of land management practices, monitoring of the prevalence of improved practices over time, catchment loads monitoring, catchment indicators and finally, marine monitoring. This report is a summary of the Burdekin NRM region modelled load reductions for sediment, nutrients and herbicides resulting from the adoption of improved management practices. The report outlines the progress made towards Reef Plan 2009 water quality targets from the baseline year 2008–2009 for four reporting periods: 2008–2010, 2010–2011, 2011–2012 and 2012–2013 (Report Cards 2010–2013).

The Burdekin region is one of six NRM regions adjacent to the GBR. It is approximately 34% (142,317 km^2) of the total GBR catchment area (423,134 km^2), and is characterised by grazing, occupying 90% of the total area. Intensive agriculture covers 1.6% of the total area. The Burdekin region is comprised of five drainage basins: Black, Ross, Haughton, Burdekin and Don. Previous studies have highlighted that the Burdekin region is a high risk to reef ecosystems due to runoff of herbicides, dissolved inorganic nitrogen and fine sediment from agriculture lands.

The eWater Ltd Source Catchments modelling framework was used to estimate the sediment, nutrient and herbicide loads entering the GBR lagoon. Major additions and improvements to the base modelling framework were made to enable the interaction of soils, climate and land management to be modelled. Enhancements include incorporation of SedNet modelling functionality to enable reporting of gully and streambank erosion, floodplain deposition, incorporation of the most appropriate paddock scale model outputs for major agricultural industries of interest and the incorporation of annual cover layers for hillslope erosion prediction in grazing lands.

The water quality targets were set against the anthropogenic baseline load (2008/2009 land use and management). Improved management practice adoption from 2008–2013 were modelled for four Report Cards covering management changes in sugarcane, grazing and cropping. These were compared to the anthropogenic baseline load and from this, a reduction in constituent loads was estimated. An ABCD framework (A = aspirational, D = unacceptable) was used for each industry to estimate the proportion of land holders in each region in each category for the baseline and then following implementation of the improved land management practices. In order to reduce the effect of climate variability, a representative climate period was used (1986–2009) for all scenarios. The average annual loads and the relative change in loads due to industry and

government investments were then used to report on the percentage load reductions for the four report cards. It is important to note that this report summarises the modelled, not measured, average annual loads and load reductions of key constituents and management changes reflected in the model were based on practice adoption data supplied by regional Natural Resource Management (NRM) groups and industry.

Fit for purpose models generated the daily pollutant loads for each individual land use. The paddock scale models, HowLeaky and APSIM, were used to calculate loads for a range of typical land management practices for cropping and sugarcane areas respectively. For grazing areas, the Revised Universal Soil Loss Equation (RUSLE) was used to calculate daily soil loss with the grazing systems model GRASP used to determine the relative changes in ground cover (C-factor) resulting from improved grazing management practices. An Event Mean Concentration (EMC) approach was used to calculate loads for horticulture, urban and the remaining minor land use areas.

Source Catchments was coupled to an independent Parameter EStimation Tool (PEST) to perform hydrology calibrations. .A multi-objective function that minimised differences between (1) modelled and observed daily discharges (2) modelled and observed monthly discharges and (3) exceedance curves of modelled and observed discharges were used. Once calibrated, three criteria were used to assess model performance: daily and monthly Nash-Sutcliffe and difference in total gauging station streamflow volumes. The Nash-Sutcliffe is a measure of how well modelled data simulates observed data, where 0.8-1 for monthly flows is considered a good fit. The modelled flows showed good agreement with observed flows with 80% of gauges having monthly Nash-Sutcliffe values >0.8 and the majority of modelled flow at gauges had total runoff volumes within 20% of observed flows. The Burdekin region average annual modelled flow (1986–2009) was 12 million ML, which accounts for 19% of the total GBR average annual flow. Of the six GBR regions, the Wet Tropics had the highest average annual runoff.

Four approaches were used to validate the GBR Source Catchments modelled loads. Firstly, a comparison was made with the previous best estimates in the first Report Card. Secondly, a long-term comparison was made with Burdekin basin load estimates derived from all available measured data for the 23 year modelling period. Thirdly, a short-term (4 year) comparison was made using load estimates from monitoring results that commenced in 2006. Finally, model performance was assessed against a range of other measured estimates at smaller time scales. At the Burdekin basin scale model performance was rated as “good” to “satisfactory” for TSS, TN and TP at the monthly time-step for the modelling period. In addition, the model was found to adequately represent the trapping of fine sediment within the Burdekin’s major reservoir when assed against loads derived from monitoring data.

The Burdekin region modelled total baseline load for Total Suspended Sediment (TSS) was 3,976 kt/yr, ~47% of the GBR export load with an anthropogenic load of 2,525 kt/yr (Table 1). The largest contributor of the TSS load in the Burdekin region was the Burdekin basin contributing ~80% of the total regional load. The Burdekin basin estimated TSS baseline load (3,173 kt/y) is a threefold increase over the predevelopment load.

A total nitrogen (TN) baseline load of approximately 10,110 t/yr is estimated to be exported to the GBR from the Burdekin region, with the Burdekin basin contributing ~70% of the total load. A total phosphorus (TP) baseline load of approximately 2,184 t/yr is estimated to be exported to the GBR from the Burdekin region, with the Burdekin basin contributing ~73% of the total load. TN and TP loads are estimated to have increased by two times over natural loads. The herbicide (PSII) load was approximately 2,091 kg/yr for the region, with 65% of the load coming from the Haughton catchment.

By land use, sugarcane contributed the largest PSII load, contributing 94% of the total baseline load with the remaining 6% from cropping. For DIN baseline load contribution, grazing had the highest proportion at 44% followed by sugar with 36%. While grazing and streambank erosion contributed the majority of the grazing baseline TSS load.

Table 1 Summary of Burdekin region total baseline and anthropogenic load and load reduction due to improved management practice adoption (2008–2013)

	TSS (kt/yr)	TN (t/yr)	DIN (t/yr)	DON (t/yr)	PN (t/yr)	TP (t/yr)	DIP (t/yr)	DOP (t/yr)	PP (t/yr)	PSIIs (kg/yr)
Total baseline load	3,976	10,110	2,647	3,185	4278	2,184	341	153	1,690	2,091
Anthropogenic baseline load	2,525	5,816	1,893	1,701	2,222	1,293	214	89	990	2,091
Load reduction (2008–2013) (%)	15.8	9.9	13.8	0.0	14.1	11.4	0.0	0.0	14.9	13.2

Across the GBR for Report Card 2013, TSS has been reduced by 11%, TN and TP by 10% and 13% respectively. The PSII herbicide load has had the greatest reduction of all constituents at 28%. The modelling shows that good progress has been made towards reaching the 2020 target of a 20% reduction in sediment load from the GBR. However, the target of a 50% reduction by 2013 as outlined in Reef Plan 2009 for nutrients and herbicides has not been met. The timeline for meeting this target has been revised in Reef Plan 2013, and Report Card 2014 and beyond will report against this. For Report Card 2013, in the Burdekin region, there has been a 13% reduction in PSII loads (Table 1) with the reductions attributed to investment in sugarcane. There has been a 14% reduction in DIN load due to improved management practice adoption in sugarcane. For PN and PP there were reductions of 14% and 15% reduction respectively. Most of the change was attributed to grazing for PN and PP. Suspended sediment loads were reduced by 16% with the major contribution in this reduction from grazing.

The modified version of the Source Catchments model has proven to be a useful tool for estimating load reductions due to improved management practice adoption. The underlying hydrological model simulates streamflow volumes that show good agreement with gauging station data, particularly at long-term average annual and yearly time-steps. At shorter time scales (weeks to days) the model tends to underestimate peak discharge and overestimate low flow. Future work will explore the potential to re-calibrate the model with greater emphasis on simulating high flows.

In general, the modelled average annual loads of constituents were lower than previous modelled estimates for the Burdekin region although in close agreement with load estimates derived from recently collected measured data. The differences in load estimates are due to different approaches used to derive the loads between studies, changes made to constituent generation and transport modelling methodologies and utilising the most recent data sets in this study.

Major recommendations for enhanced model prediction include:

- Re-calibration of the hydrological model to better simulate maximum discharge (includes improvements to rainfall data).
- For surface erosion it was observed that the BGI may not be delineating scalded areas at an optimal scale. Improvements would require the use of higher resolution remote sensing data to better delineate scalds and additionally the use of a variable hillslope delivery ratio.
- Improvements in the simulation of gully erosion were also identified. These included the use of mapped 1:100,000 drainage lines to better delineate gullies in some landscapes.

The current modelling framework is flexible, innovative and is fit for purpose. It is an improvement on previous GBR load modelling applications. The model is appropriate for assessing load reductions due to on-ground land management change.

Key messages, outcomes and products from the development and application of the GBR Source Catchments model include:

- Natural Resource Management groups, governments and other agencies now have a new modelling tool to assess various climate and management change scenarios on a consistent platform for the entire GBR catchment.
- Methods have been developed to implement and calibrate an underlying hydrological model that produces reliable flow simulations for gauged sites and increased confidence in modelled flows for un-gauged sites.
- Daily time-step capabilities and high resolution Source Catchments areas allow for modelled flow volumes and loads of constituents to be reported at catchment scale for periods ranging from events over a few days, to wet seasons and years.

Table of Contents

List of Figures

List of Tables

Acronyms

Acronym	Description
ANNEX	Annual Network Nutrient Export- SedNet module speciates dissolved nutrients into organic and inorganic forms
DERM	Department of Environment and Resource Management (now incorporated into the Department of Natural Resources and Mines)
DNRM	Department of Natural Resources and Mines
DS	Dynamic SedNet
DSITIA	Department of Science, Information Technology, Innovation and the Arts
DWC	Dry Weather Concentration – a fixed constituent concentration to base or slow flow generated from a functional unit to calculate total constituent load.
E2	Former catchment modelling framework – a forerunner to Source Catchments that could be used to simulate catchment processes to investigate management issues.
EMC	Event Mean Concentration –a fixed constituent concentration to quick flow generated from a functional unit to calculate total constituent load.
EOS	End-of-system
ERS	Environment and Resource Sciences
FRCE	Flow Range Concentration Estimator – a modified Beale ratio method used to calculate average annual loads from monitored data.
FU	Functional Unit
GBR	Great Barrier Reef
GBRCMLP	Great Barrier Reef Catchment Loads Monitoring Program (supersedes GBRI5)
HowLeaky	Water balance and crop growth model based on PERFECT
NRM	Natural Resource Management
NRW	Natural Resources and Water (incorporated in the Department of Environment and Resource Management, now incorporated into the Department of Natural Resources and Mines)
NSE	Nash Sutcliffe coefficient of Efficiency
Paddock to Reef Program	Paddock to Reef Integrated Monitoring, Modelling and Reporting program

PET	Potential Evapotranspiration
PSII herbicides	Photosystem-II herbicides – ametryn, atrazine, diuron, hexazinone and tebuthiuron
Reef Rescue	An ongoing and key component of Caring for our Country. Reef Rescue represents a coordinated approach to environmental management in Australia and is the single largest commitment ever made to address the threats of declining water quality and climate change to the Great Barrier Reef World Heritage Area.
Report Cards 2010–2013	Annual reporting approach communicating outputs of Reef Plan/Paddock to Reef (P2R) Program
RUSLE	Revised Universal Soil Loss Equation
SedNet	Catchment model that constructs sediment and nutrient (phosphorus and nitrogen) budgets for regional scale river networks (3,000-1,000,000 km^2) to identify patterns in the material fluxes
Six Easy Steps program	Integrated sugarcane nutrient management tool that enables the adoption of best practice nutrient management onfarm. The Six Easy Steps program forms part of the nutrient management initiative involving BSES limited, CSR Ltd and the Queensland Department of Environment and Resource Management (DERM). It is supported by CANEGROWERS and receives funding from Sugar Research and Development corporation (SRDC), Queensland Primary Industries and Fisheries (PI&F) and the Australian Department of the Environment, Water, Heritage and the Arts.
STM	Short term modelling project

Units

Units	Description
g/L	grams per litre
kg/ha	kilograms per hectare
kg/ha/yr	kilograms per hectare per year
L/ha	litres per hectare
mg/L	milligrams per litre
mm	millimetres
mm/hr	millimetres per hour
m^3	cubic metres
ML	megalitres
GL	gigalitres
t/ha	tonnes per hectare
t/ha/yr	tonnes per hectare per year
µg/L	micrograms per litre

Full list of Technical Reports in this series

Waters, DK, Carroll, C, Ellis, R, Hateley, L, McCloskey, GL, Packett, R, Dougall, C, Fentie, B. (2014) *Modelling reductions of pollutant loads due to improved management practices in the Great Barrier Reef catchments – Whole of GBR, Technical Report, Volume 1*, Queensland Department of Natural Resources and Mines, Toowoomba, Queensland (ISBN: 978-1-7423-0999).

McCloskey, G.L., Ellis, R., Waters, D.K., Carroll, C. (2014) *Modelling reductions of pollutant loads due to improved management practices in the Great Barrier Reef catchments – Cape York NRM Region, Technical Report, Volume 2,* Queensland Department of Natural Resources and Mines. Cairns, Qld (ISBN: 978-0-7345-0440-1).

Hateley, L., Ellis, R., Shaw, M., Waters, D., Carroll, C. (2014) *Modelling reductions of pollutant loads due to improved management practices in the Great Barrier Reef catchments – Wet Tropics NRM region, Technical Report, Volume 3,* Queensland Department of Natural Resources and Mines, Cairns, Queensland (ISBN: 978-0-7345-0441-8).

Dougall, C., Ellis, R., Shaw, M., Waters, D., Carroll, C. (2014) *Modelling reductions of pollutant loads due to improved management practices in the Great Barrier Reef catchments – Burdekin NRM region, Technical Report, Volume 4,* Queensland Department of Natural Resources and Mines, Rockhampton, Queensland (ISBN: 978-0-7345-0442-5).

Packett, R., Dougall, C., Ellis, R., Waters, D., Carroll, C. (2014) *Modelling reductions of pollutant loads due to improved management practices in the Great Barrier Reef catchments – Mackay Whitsunday NRM region, Technical Report, Volume 5,* Queensland Department of Natural Resources and Mines, Rockhampton, Queensland (ISBN: 978-0-7345-0443-2).

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Fentie, B., Ellis, R., Waters, D., Carroll, C. (2014) *Modelling reductions of pollutant loads due to improved management practices in the Great Barrier Reef catchments – Burnett Mary NRM region, Technical Report, Volume 7,* Queensland Department of Natural Resources and Mines, Brisbane, Queensland (ISBN: 978-0-7345-0445-6).

Advancements and assumptions in Source Catchments modelling

The key modelling advancements to note are:

- The use of two regionally developed paddock models to generate the daily pollutant loads for each individual land use, with proven ability to represent land management change for specific GBR agricultural industries.
- Ability to run the models and interrogate the results, down to a daily time-step.
- Incorporation of annual spatial and temporally variable cover over the 23 year modelling period, rather than a single static cover factor for a particular land use.
- The incorporation of hillslope, gully and streambank erosion processes, with the ability to also use EMC/DWC approaches.
- The inclusion of small, coastal catchments not previously modelled.
- Integration of monitoring and modelling and using the modelling outputs to inform the monitoring program.
- The use of a consistent platform and methodology across the six GBR NRM regions that allows for the direct comparison of results between each region.

The key modelling assumptions to note are:

- Loads reported for each scenario reflect the modelled average annual load for the specified model run period (1986–2009).
- Land use areas in the model are static over the model run period and were based on the latest available QLUMP data.
- The predevelopment land use scenario includes all storages, weirs and water extractions represented in the current model, with no change to the current hydrology. Hence, a change to water quality represented in the model is due solely to a change in land management practice.
- Paddock model runs used to populate the catchment models represent “typical” management practices and do not reflect the actual array of management practices being used within the GBR catchments.
- Application rates of herbicides used to populate the paddock models were derived through consultation with relevant industry groups and stakeholders
- Practice adoption areas represented in the model are applied at the spatial scale of the data supplied by regional bodies, which currently is not spatially explicit for all areas. Where it is not spatially explicit, estimates of A, B, C and D areas (where A is cutting edge and D is unacceptable) are averaged across catchment areas. Depending on the availability of useful investment data, there may be instances where a load reduction is reported for a particular region or subcatchment that in reality has had no investment in land management improvement. Current programs aim to capture and report spatially explicit management change data.
- Water quality improvements from the baseline for the horticulture, dairy, banana and cotton industries are currently not modelled due to a lack of management practice data and/or limited experimental data on which to base load reductions. Banana areas are defined in the WT model, but management changes are not provided. Dissolved inorganic nitrogen (DIN) reductions are not being modelled in the cropping system, as there is no DIN model available currently in HowLeaky.

- For land uses that require spatially variable data inputs for pollutant generation models (USLE based estimates of hillslope erosion and SedNet-style gully erosion), data pre-processing captures the relevant spatially variable characteristics using the specific 'footprint' of each landuse within each subcatchment. These characteristics are then used to provide a single representation of aggregated pollutant generation per land use in each subcatchment.
- The benefits of adoption of a management practice (e.g. reduced tillage) are assigned in the year that an investment occurs. Benefits were assumed to happen in the same year.
- Modelling for Report Cards 2010–2013 represent management systems (e.g. A soil, A nutrient and A herbicides practices) rather than individual practices. The potential to overstate the water quality benefits of an A herbicide or nutrient practice through also assigning benefits from adoption of A practice soil management needs to be recognised.
- Gully density mapping is largely based on the coarse NLWRA mapping, with opportunities to improve this particular input layer with more detailed mapping.
- Within the current state of knowledge, groundwater is not explicitly modelled and is represented as a calibrated baseflow and 'dry weather concentrations' (DWC) of constituents. However, these loads are not subject to management effects.
- Deposition of fine sediment and particulate nutrients is modelled on floodplains and in storages. No attempt to include in-stream deposition/re-entrainment of fine sediment and particulate nutrients has been undertaken at this point.
- It is important to note these are modelled average annual pollutant load reductions not measured loads and are based on practice adoption data provided by regional NRM groups and industry. Results from this modelling project are therefore indicative of the likely (theoretical) effects of investment in changed land management practices for a given scenario rather than a measured (empirical) reduction in load.

1 Introduction

1.1 GBR Paddock to Reef Program Integrated Monitoring, Modelling and Reporting Program

Over the past 150 years Great Barrier Reef (GBR) catchments have been extensively modified for agricultural production and urban settlement, leading to a decline in water quality entering the GBR lagoon (Brodie et al. 2013). In response to these water quality concerns, the Reef Water Quality Protection Plan 2003 was initiated and updated in 2009 (Reef Plan 2009) and again updated in 2013 (Reef Plan 2013) as a joint Queensland and Australian Government initiative (Department of the Premier and Cabinet 2009, Department of the Premier and Cabinet 2013a). A set of water quality and management practice targets are outlined for catchments discharging to the GBR, with the long-term goal to ensure that the quality of water entering the Reef has no detrimental impact on the health and resilience of the Reef. A key aspect of the initiative is the Paddock to Reef Integrated Monitoring, Modelling and Reporting (P2R) Program (Carroll et al. 2012). This program was established to measure and report on progress towards the targets outlined in Reef Plan 2009. It combined monitoring and modelling at paddock through to catchment and reef scales.

Detecting changes in water quality through monitoring alone to assess progress towards targets would be extremely difficult due to variability in rainfall (rate and amount), antecedent conditions such as ground cover and changing land use and land management practices. The resultant pollutant load exported from a catchment can be highly variable from year to year. Therefore, the P2R Program used both modelling validated against monitoring data to report on progress towards Reef Plan 2009 targets.

Modelling is a way to extrapolate monitoring data through time and space and provides an opportunity to explore the climate and management interactions and their associated impacts on water quality. The monitoring data is the most important point of truth for model validation and parameterisation. Combining the two programs ensures continual improvement in the models while at the same time identifying data gaps and priorities for future monitoring.

Report Cards, measuring progress towards Reef Plan's goals and targets, are produced annually as part of the P2R Program. The first Report Card (2009) provided estimates of predevelopment, total baseline and total anthropogenic loads. The first Report Card was based on the best available data at the time and included a combination of monitoring and modelling (Kroon et al. 2010). It was always intended that these estimates would be improved once the Source Catchments framework was developed. Source catchments was used for subsequent model runs to report on progress towards the water quality targets outlined in Reef Plan 2009. Each year's model run represents the cumulative management changes occurring due to improved management practice adoption for the period 2008–2013. All report cards are available at www.reefplan.qld.gov.au.

The changes in water quality predicted by the modelling will be assessed against the Reef Plan targets. The Reef Plan water quality targets for Reef Plan 2009 (Report Cards 2010–2013)are:

- By 2013 there will be a minimum 50% reduction in nitrogen, phosphorus and pesticide loads at the end of catchment
- By 2020 there will be a minimum 20% reduction in sediment load at the end of catchment.

The water quality targets were set for the whole GBR and there are six contributing NRM regions: Cape York, Wet Tropics, Burdekin, Mackay Whitsunday, Fitzroy and Burnett Mary. This document outlines the Burdekin NRM region catchment modelling methodology and results used to report on the constituent loads entering the GBR for the total baseline, predevelopment, anthropogenic baseline (total baseline minus predevelopment) and post adoption of improved practices from the five regional basins: Black, Ross, Haughton, Burdekin and Don that make up the Burdekin region.

1.2 Previous approaches to estimating catchment loads

Over the past 30 years, there have been a series of empirical and catchment modelling approaches to estimate constituent loads from GBR catchments. These estimates can differ greatly due to the different methods, assumptions, modelling and monitoring periods covered and types of data used.

In an early empirical approach Belperio (1979), assumed a constant sediment to discharge relationship for all Queensland catchments based on data from the Burdekin River. This tended to overestimate sediment loads, particularly in northern GBR catchments. Moss et al. (1992) attempted to accommodate the regional difference in concentrations by assuming a lower uniform sediment concentration for the northern (125 mg/L) compared with southern (250 mg/L) Queensland catchments. In another approach Neil & Yu (1996) developed a relationship between unit sediment yield (t/km^2/mm/yr) and mean annual run-off (mm/yr) to estimate the total mean annual sediment load for the GBR catchments.

The SedNet/ANNEX catchment model has also been extensively used to provide estimates of average annual sediment and nutrient loads from GBR catchments (Brodie et al. 2003, Cogle, Carroll & Sherman 2006, McKergow et al. 2005a, McKergow et al. 2005b). Most recently, Kroon et al. (2012) collated modelling and monitoring information (Brodie et al. 2009), along with recent monitoring data to estimate natural and total catchment loads for Report Card 1 (RC1). For RC1 in the Burdekin region, (Kroon et al. 2012) estimated Total Suspended Sediment (TSS) load of 4,738 kt/yr, TP load of 2,555 t/yr, and TN load of 13,585 t/yr; representing a respective 7.9, 8.0 and 5.6 fold increase in constituent loads from predevelopment conditions. The estimated current PSII herbicide load was 4,911 kg/yr, with no increase factor since predevelopment conditions, as herbicides are not a naturally occurring compound (Kroon et al. 2012).

In considering the modelling approach required for the Paddock to Reef Program, there was no “off the shelf” modelling framework that could meet all of the modelling requirements. SedNet alone could not provide the finer resolution time-stepping required and the Source Catchments modelling framework, whilst used extensively across Australia, cannot inherently represent many variations of a spatially varying practice like cropping, to the level of detail required to allow subtle changes in management systems to have a recognisable effect on model outputs. To address these issues and answer the questions being posed by policy makers, customised plug-ins for the Source Catchments modelling framework were developed. These plug-ins allowed for the integration of the best available data sources and landscape process understanding into the catchment model. Purpose built routines were developed that enabled representations of processes such as; the effects of temporally and spatially variable ground cover on soil erosion, the aggregation of deterministic crop model outputs to be directly imported into the catchment model and the incorporation of SedNet gully and streambank erosion algorithms (Ellis & Searle 2013).

1.3 Burdekin region modelling approach

A consistent modelling approach was used across all regions to enable direct comparisons of export loads. A standardised 23 year representative climate period (1986–2009) was used for all scenarios. The eWater Ltd Source Catchments modelling framework was used to generate sediment, nutrient and herbicide loads entering the GBR lagoon, with SedNet modelling functionality incorporated to provide estimates of gully and streambank erosion and floodplain deposition (Wilkinson et al. 2010, Wilkinson et al. 2014). Specific and fit for purpose models were used to generate the daily pollutant loads for current and improved practices for each individual land use. This included paddock scale models HowLeaky (cropping) (Rattray et al. 2004) and APSIM (sugarcane) (Biggs & Thorburn 2012), the Revised Universal Soil Loss Equation (RUSLE) (grazing) (Renard et al. 1997) and Event Mean Concentration (EMC) approach used to generate loads for remaining minor land use areas.

The latest remotely sensed bare ground index (BGI) layers were used to derive annual ground cover (Scarth et al. 2006). Ground cover, riparian extent mapping (Goulevitch et al. 2002) and ASRIS soils information were all incorporated into the models. Model validation was done using water quality monitoring information from the Burdekin region. The small coastal catchments were also included into the Burdekin region catchment model to ensure the total area contributing loads to the GBR were captured in the model.

This report outlines the:

- Source Catchments hydrology and water quality model methodology
- Estimated predevelopment, total baseline and anthropogenic baseline loads for 1986–2009 climate period
- Progress towards meeting Reef Plan 2009 water quality targets following adoption of improved management practices.

2 Regional Background

This section provides brief context on the Burdekin region. A detailed outline of the Natural Resources of the region can be found at the NQ Dry tropics home page (http://www.nqdrytropics.com.au/). The Burdekin region (~140,000 km^2) is approximately 33% of the total Great Barrier Reef (GBR) area (423,134 km^2). The region is drained by five Australian Water Resources Council basins (AWRC) (basins 117–121) (Figure 1, Figure 2) (ANRA 2006). The Burdekin basin dominates in terms of area (93%), while the smaller basins the Black, Ross, Haughton, and Don make up the remaining (7%). Due to the size of the Burdekin basin, it is commonly discussed in terms of its subcatchments. Here we have subdivided the Burdekin into seven subcatchments. The Upper Burdekin, Cape, Belyando, Suttor are the headwater catchments that flow into the Burdekin falls dam (Figure 1). The area below these gauges and immediately upstream of the Burdekin falls dam has been labelled the ungauged area before dam (UGABD). Flow below the dam is contributed to by the Bowen and the area here referred to as below the dam and the Bowen (BDAB). The Burdekin irrigation area is also an area of importance (Figure 2) and the major crop here is sugarcane.

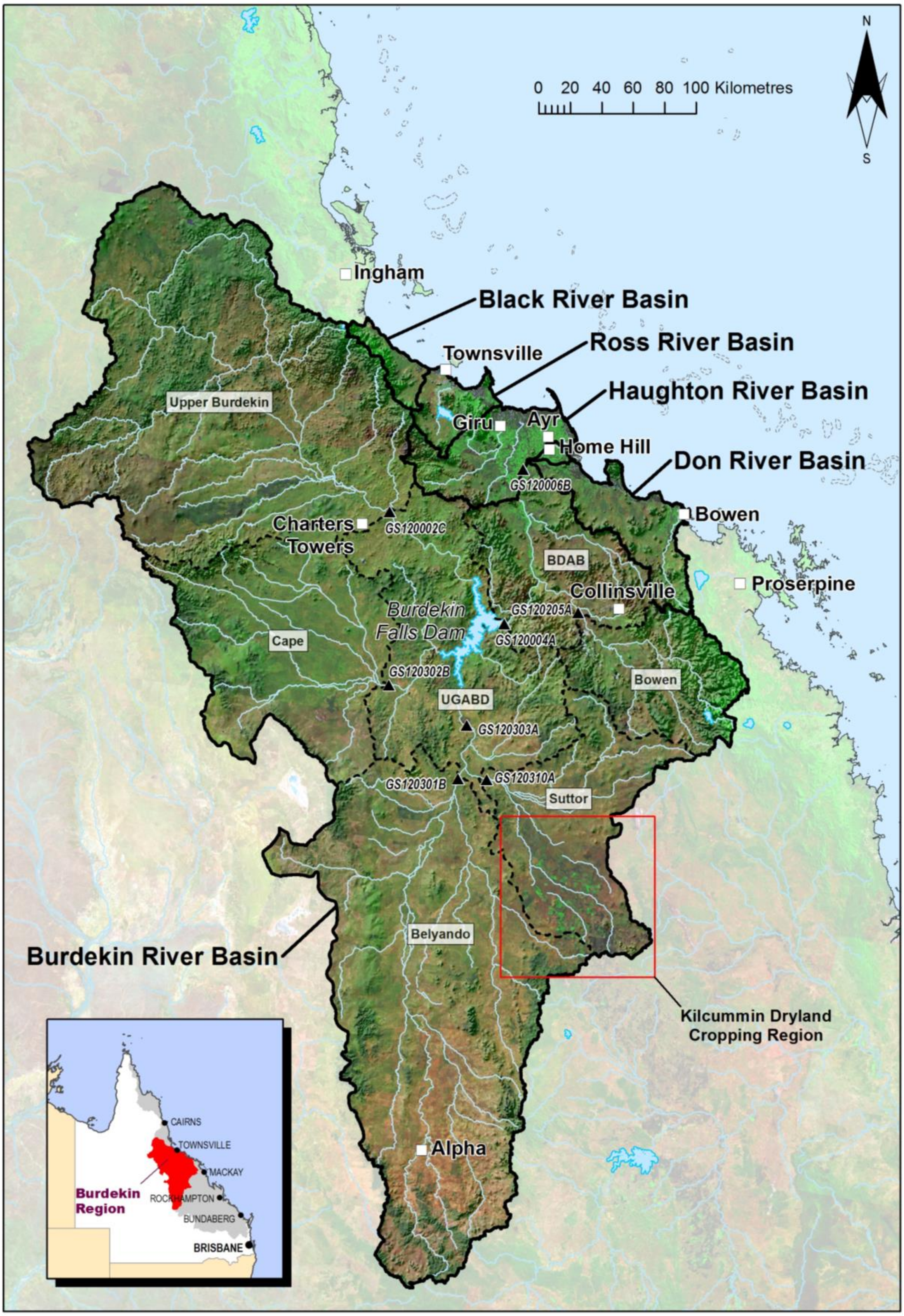

Figure 1 Burdekin region map, showing location of (AWRC) basins, Burdekin, Black, Ross, Haughton and Don. Map also includes Burdekin Subcatchments their end of valley gauges and the Kilcummin Dryland Cropping region

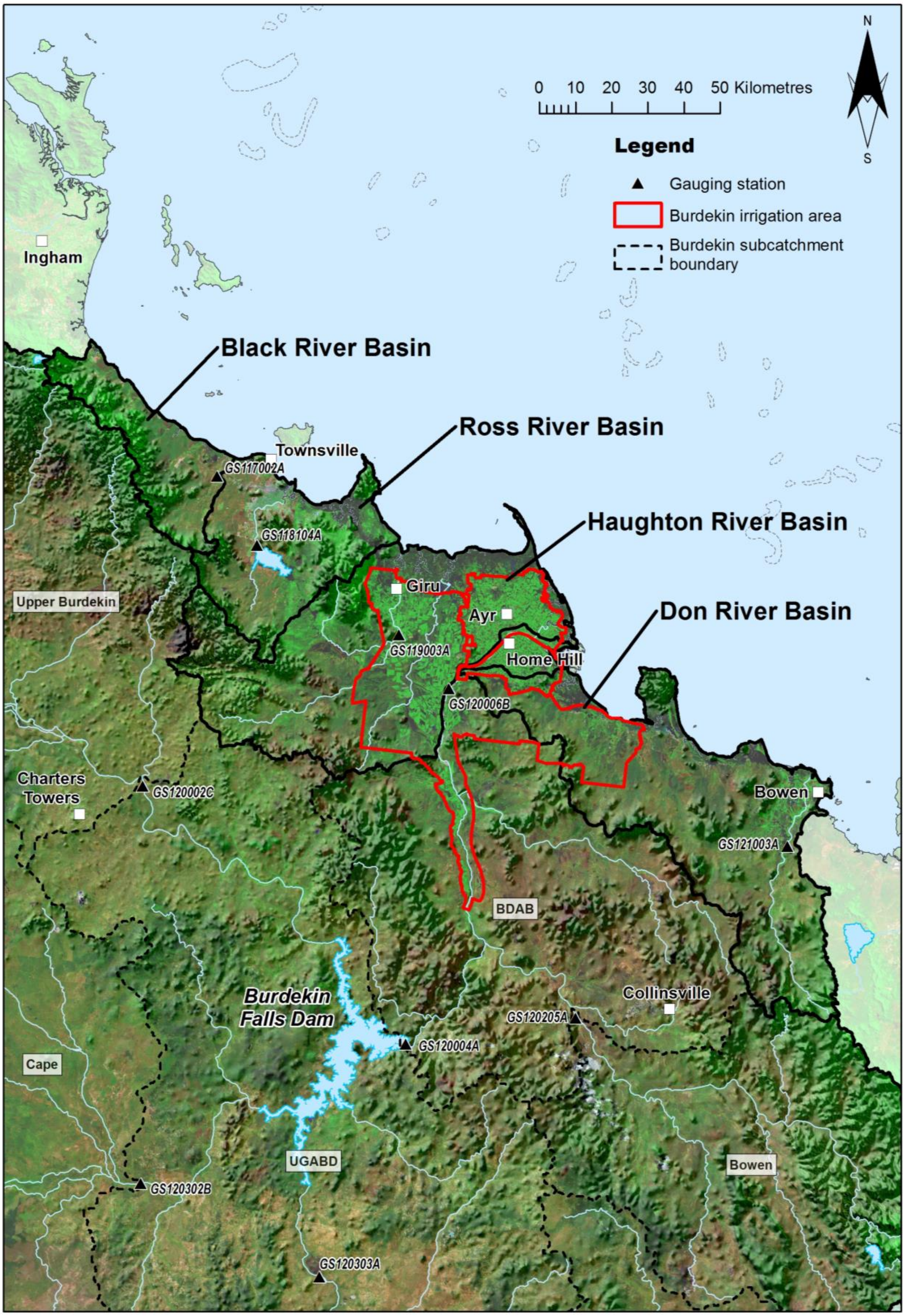

Figure 2 Map showing the coastal basins, Black, Ross, Haughton and Don in detail. Note location of largest coastal catchment river gauges and Burdekin irrigation area (within red boundary)

2.1 Climate

The region experiences a typical sub-tropical climate with humid, wet summers and mild, dry winters. Average yearly rainfall in the catchment ranges from over 2000 mm in north-eastern parts to less than 600 mm in south-western areas (Figure 3); however totals can be highly variable due to climatic drivers such as the EL Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Long-term rainfall and streamflow reconstructions (1600-2000) correlate well with ENSO records, indicating a long term climatic cycle of extended dry and wet conditions (Lough 2010, Lough 2007). This is further highlighted by the work of Lewis et al. (2006), showing large variation in the Burdekin streamflow record for an extended period (1920 – 2005).

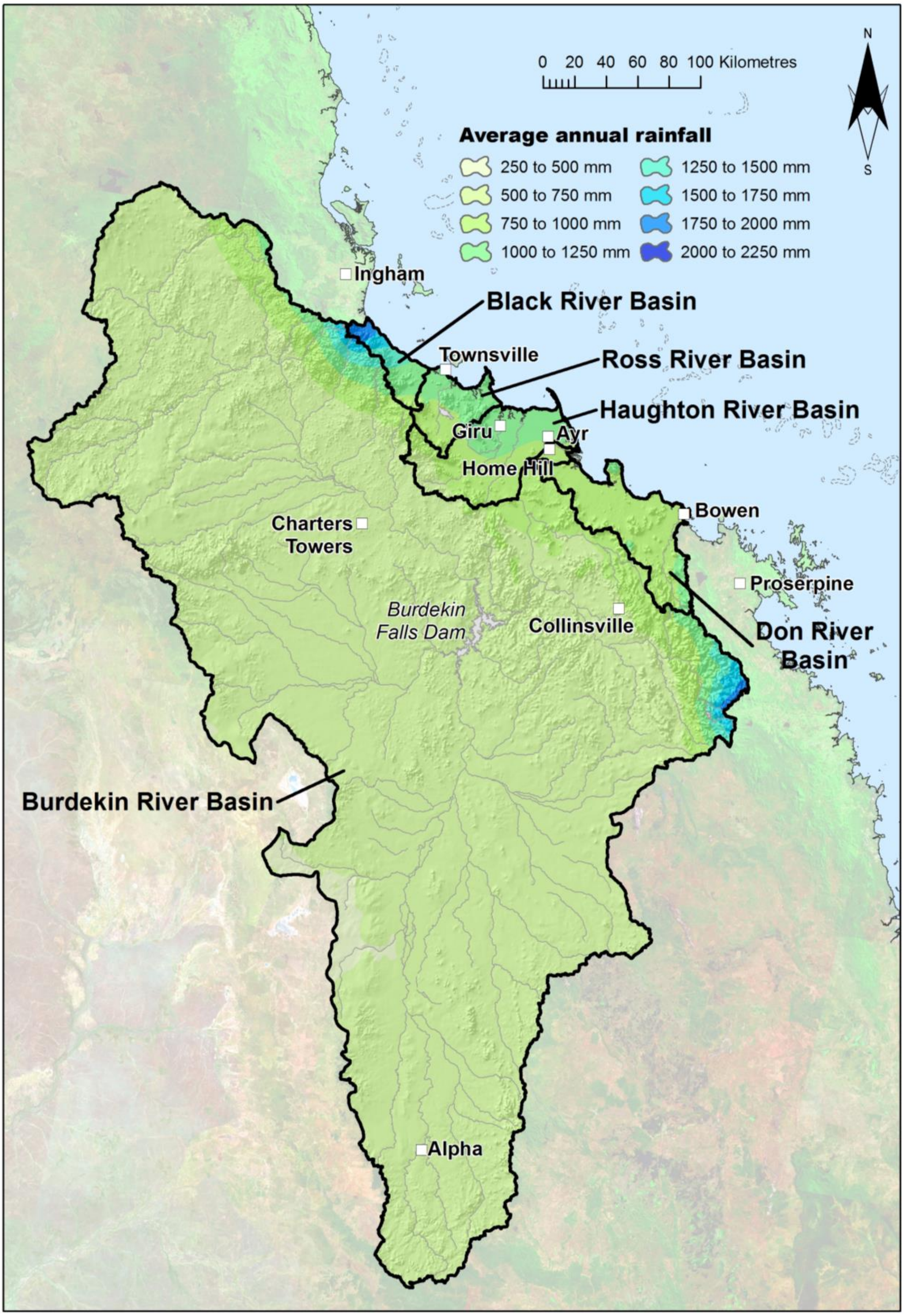

Figure 3 Burdekin Region average annual rainfall (mm/yr)

2.2 Hydrology

Broad hydrological characteristics for the region are described by Furnas (2003). Here mean annual flow is calculated as ~12,650 gigalitres (GL) (1968 – 1994), of this the Burdekin produces the majority of the discharge ~80%, with the coastal basins discharging the remaining 20% (Furnas 2003). Flows are summer/wet season dominant and are highly variable within, and between years. At end of valley, the Burdekin River discharges ~80% of water during event flow (Lewis et al. 2006) and a median event is characterised as ~3000 Gigalitres. A major hydrological feature of the region is the large Burdekin Fall's dam, with a full supply capacity of ~1860 Gigalitres. Surprisingly, following dam construction, the influence of the dam on end of valley discharge was not easily discernible (Lewis et al. 2006). This is likely a function of high reservoir water levels, long-term flow variability and high discharge at end of valley relative to dam capacity.

2.3 Land use and Industry Practice

European settlement began circa 1850, initially the principal farming practice was the grazing of sheep for wool production. After settlement, sheep numbers increased rapidly, with peak numbers approached by the 1870s (Lewis et al. 2007). Cattle numbers rose more steadily with a small peak before the federation drought and a substantial increase post World War II.

The setting up of the Queensland British Food Corporation (QBFC) following the Second World War provided the impetus for a grain cropping industry, in the Kilcummin region (Figure 1) of the Belyando basin. In this area, grain cropping began in the 1960s, with the majority of the land modification for cultivation occurring in the late 1970s and early 1980s. The Burdekin irrigation area comprises the majority of the irrigated land in the Burdekin region (Figure 2). This industry was largely initiated in the region through the construction of the Burdekin falls dam in 1986/1987.

Current major land uses are grazing (~90%), nature conservation (~5%), dryland cropping (~1%) and sugarcane (~0.7%) (Figure 4, Table 2). A comprehensive outline of land use and its condition has been compiled (Department of the Premier and Cabinet 2011). The report outlines the 2009 level of industry practice (e.g. A, B, C or D) for sugarcane, grazing (including ground cover values) and horticulture. In addition riparian and wetland condition are also assessed.

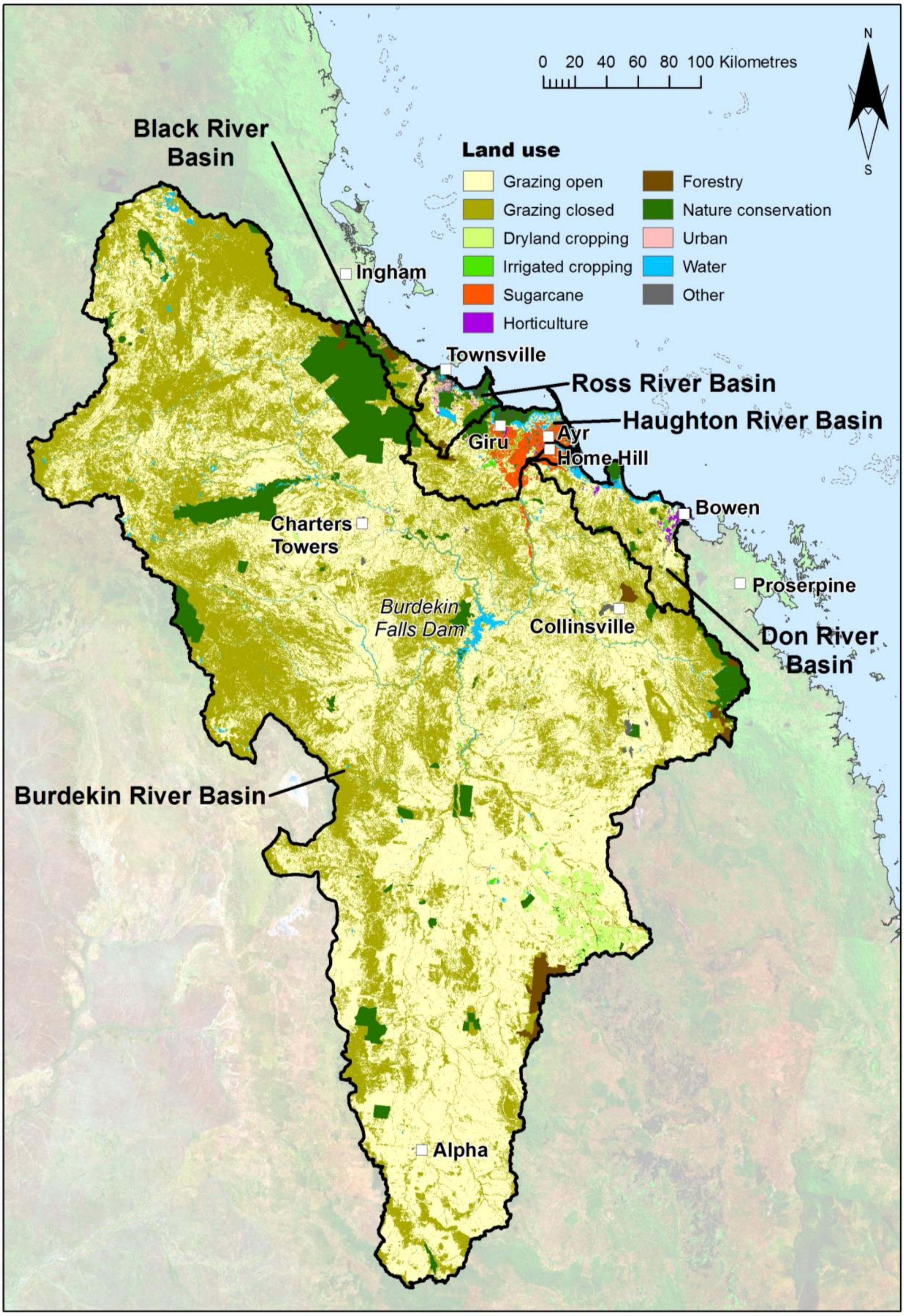

Figure 4 Burdekin Dry tropics NRM region land use classification

Table 2 Burdekin region QLUMP land use classification

Land use	Area (km^2)	Area (%)
Grazing open	87,034	61.2
Grazing forested	41,592	29.2
Nature conservation	7,732	5.4
Water	1,988	1.4
Dryland cropping	1,336	0.9
Sugarcane	1,063	0.7
Forestry	861	0.6
Other	267	0.2
Urban	219	0.2
Horticulture	155	0.1
Irrigated cropping	70	0.0

2.4 Water quality

The relative risk of reef pollutants to the GBR from agricultural land uses has recently been assessed (Waterhouse et al. 2012). This paper classifies the Burdekin region as a medium - high risk for suspended sediment, herbicide and dissolved inorganic nitrogen (DIN). Suspended sediments are dominated by grazing inputs while herbicides and anthropogenic DIN are mainly sourced from the Burdekin irrigation area. In the wet season, the Burdekin River can produce flood plumes that extend far into the GBR lagoon and Devlin et al. (2012) has rated the inshore area as having high exposure to sediment, DIN and PSII herbicides.

In the relative risk assessment report (Waterhouse et al. 2012), particulate N and P (PN, PP) were not considered as they would likely have a similar management response to sediment. Waterhouse identified dissolved organic nitrogen (DON) and dissolved organic phosphorus (DOP) as low risk and were classified as low importance as reef pollutants. Dissolved inorganic phosphorus (DIP) was not assed due to a scarcity of data but it was acknowledged as being potentially important.

In terms of suspended sediment Kroon et al. (2012) estimates the Burdekin region as contributing 4,738 t/yr of suspended sediment at end of valley, which is approximately 28% of total GBR export. The Burdekin basin is recorded as contributing the majority of the load. Within the Burdekin basin, the Bowen Broken and Upper Burdekin have been identified as suspended sediment hotspots in relation to sediment export to the GBR lagoon (Bainbridge, Lewis & Brodie 2007). Importantly these areas have been further delineated down to a subcatchment scale in an attempt to further define the spatial source. Here large suspended sediment generation areas include the Little Bowen river, Bogie river, Clarke river and Dry river (Bainbridge, Lewis & Brodie 2007). In the higher generating landscapes within the Upper Burdekin and Bowen Broken, sediment tracing has identified channel as the major erosion source (Wilkinson et al. 2013). However, some uncertainty still remains as to the exact weighting of surface and channel erosion (Hancock et al. 2013).

Sugarcane (1,063 km^2) and dryland cropping (1,336 km^2) are the major agricultural intensive land uses in the region, with high concentrations and loads of N reported from sugar crops in streams and groundwater in the Haughton basin (Bainbridge et al. 2008). Most DIN (primarily nitrate) in streams that drain sugarcane areas is considered to come from fertiliser residue, with 90% of DIN attributed to this source (Brodie et al. 2008).

The major source of herbicide loads from the Burdekin region is the Burdekin irrigation area. Here the major PSII herbicides used and found in receiving waters are atrazine, ametryn, hexazinone and diuron (Kroon et al. 2012, Davis et al. 2012, Davis et al. 2011). The herbicide tebuthiuron has been detected in runoff originating from grazing lands in the Burdekin river (Turner et al. 2012, Turner et al. 2013) but loads have been comparatively low when compared to the Fitzroy (Packett et al. 2009).

3 Methods

The Burdekin region model was built within the Source Catchments modelling framework. Source Catchments is a water quantity and quality modelling framework that has been developed by eWater Ltd. This framework allows users to simulate how catchment and climate variables (such as rainfall, land use, management practice and vegetation) affect runoff and constituents, by integrating a range of models, data and knowledge. Source Catchments supersedes the E2 and WaterCAST modelling frameworks (eWater Ltd 2012). A number of the model input data parameter sets are provided in Appendix D. A summary of input data sets are also available in (Waters & Carroll 2012).

3.1 GBR Source Catchments framework

A Source Catchments model is built upon a network of subcatchments, links and nodes (Figure 5). Subcatchments are the basic spatial unit in Source Catchments. A subcatchment is further delineated into 'Functional Units' (FUs) based on common hydrologic response or land use, (eWater Ltd 2013). In the case of the GBR Source Catchments Framework FUs were defined as land use categories.

In the GBR Source Catchments Framework there are two modelling components assigned to each FU representing the processes of:

- Runoff generation
- Constituent generation

Nodes and links represent the stream network and runoff and constituents are routed from a subcatchment through the stream network via nodes and links.

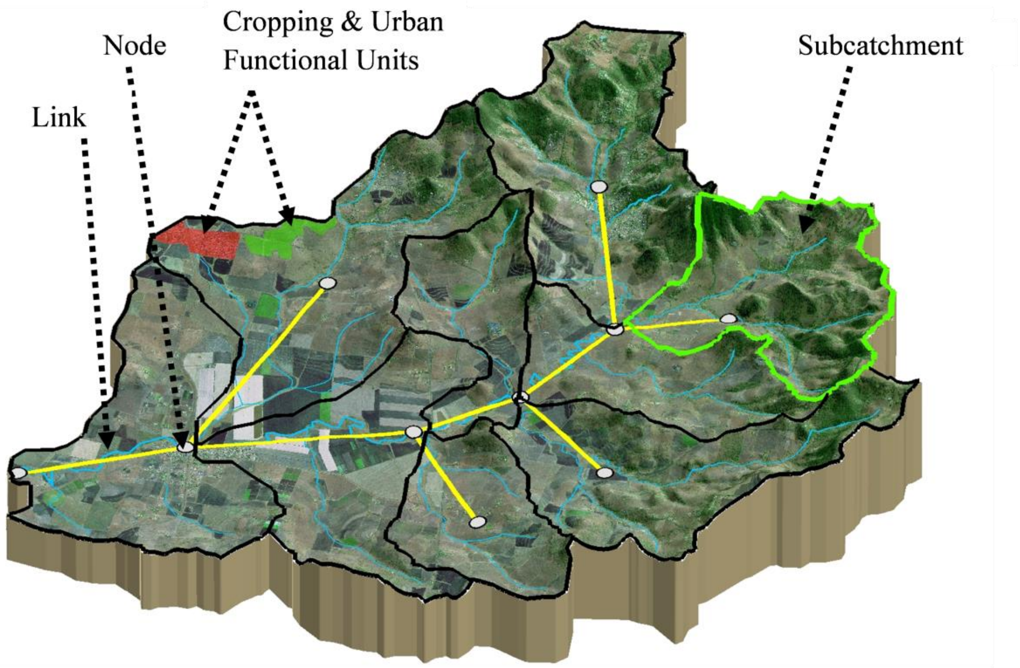

Figure 5 Example of a Functional Unit and node link network generated in Source Catchments. These components represent the subcatchment and stream network

3.1.1 Land use based functional units

In the Burdekin region the most recent land use mapping from the Queensland Land Use Mapping Project (QLUMP) (DSITIA 2012a) was used to define the Functional Units (FUs) which were mapped using 2009 imagery. The original detailed QLUMP categories were reclassified into 11 major land uses (Table 2). Grazing land use was spilt into open and closed (timbered) to enable differences in runoff and constituent generation to be reflected in the model. To differentiate between open and closed grazing, closed areas with Foliage Protective Cover (FPC), with a FPC >= 20% (National Committee on Soil and Terrain 2009). Differentiation was made between these two grazing systems to enable representation of different hydrological response units during calibration. Any given land use within a subcatchment is aggregated and represented as a single area in the model hence is not represented spatially within a subcatchment.

3.1.2 Subcatchment generation

The Burdekin Source Catchments model encompasses five drainage basins (Figure 1). These basins are delineated into smaller subcatchments using a Digital Elevation Model (DEM). A 270 metre, hydrologically enforced DEM and 50 km^2 drainage threshold was used to identify the major stream network and contributing subcatchments. In this process, some flat coastal areas were not captured. In order to rectify this, the flat coastal areas not captured were manually added to the DEM derived subcatchment layer in a GIS environment, based on drainage data and imagery. In addition to aid delineation of coastal streams and catchments, coastal streams were burnt into the DEM. The final subcatchment map was then re-imported into Source Catchments. A total of 1,568 subcatchments were generated with an average subcatchment area of 89 km^2 (Figure 6). The addition of these flat coastal areas, some of which were not included in previous models, will improve the overall load estimates to the end-of-system (EOS). An arbitrary node was created in the ocean as an ‘outlet’ node to enable the aggregation of loads for the entire region for reporting purposes. The selection of the most appropriate stream threshold value for subcatchment, node and link generation is based on several factors, namely: the resolution of the DEM, the distribution and length of the stream network required to represent bank erosion (Wilkinson, Henderson & Chen 2004) and available computing resources.

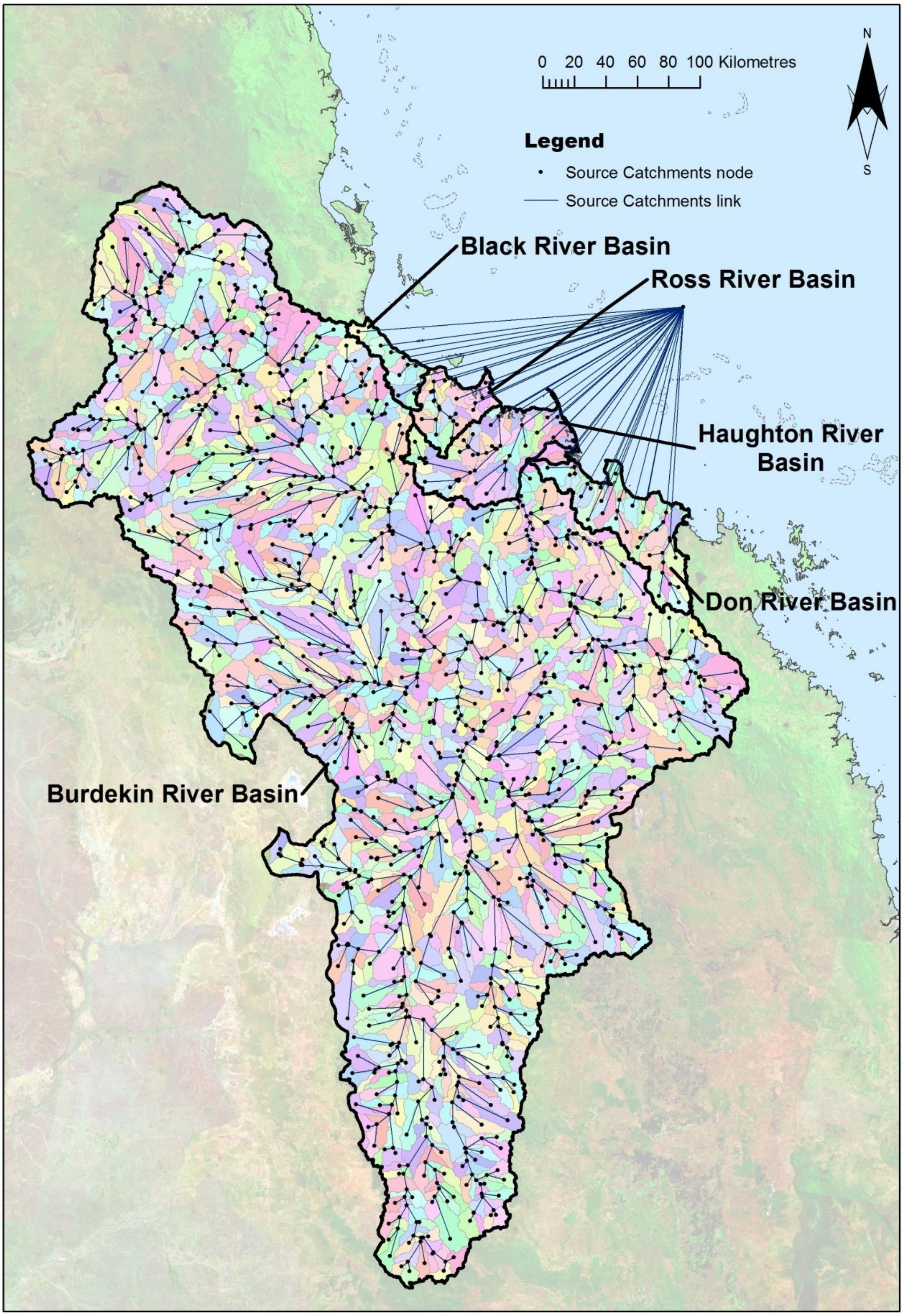

Figure 6 Burdekin region subcatchment, node and link network

3.1.3 Runoff generation

Six rainfall-runoff models are available within Source Catchments. A comparison of the six models (Vaze et al. 2011) concluded that there is little difference between these six models for broad scale application. SIMHYD is a catchment scale conceptual rainfall-runoff model that estimates daily streamflow from daily rainfall and areal potential evapotranspiration (PET) data (eWater Ltd 2013).The SIMHYD rainfall-runoff model was chosen due to its extensive application and proven performance to satisfactorily estimate streamflow across Australia (Chiew & Scanlon 2002) and in particular for a large catchment in the GBR (Ellis et al. 2009). An investigation of the performance of a number of other models available in Source Catchments was undertaken (Zhang et al. 2013) following the release of Report Card 2010 and Report Card 2011. As a result of this work, the Sacramento model will be applied in future model calibration due to its improvement in runoff predictions.

Each FU possesses a unique instance of the SIMHYD rainfall-runoff and constituent generation models (Chiew & Scanlon 2002). Typically, a rainfall-runoff model converts time series climate inputs to runoff, with a constituent load created by the generation model 'carried' by the runoff. Water and constituent loads are routed through the node-link network to the catchment outlet. Nodes represent stream confluences, features such as gauging stations, storages and subcatchment outlets. Links connect nodes and represent streams. A range of models can be applied to links to route or process water and constituents throughout the network (eWater Ltd 2013).

3.1.4 Constituent generation

In the GBR Source Catchments framework, there is the ability to link to external models and/or add your own component models as specific 'plug ins' to customise for particular modelling objectives. This capability has been extensively used to incorporate the most appropriate constituent generation models across the GBR (Figure 7). SedNet/ANNEX modelling functionality has been incorporated to generate gully and streambank erosion and floodplain deposition, within the daily time-step model. This relies upon the daily disaggregation of annual estimates of generation, or even long-term average annual estimates of generation in some cases. Whilst the methods used to perform daily disaggregation of the long-term estimates are mathematically sensible, it is recognised that simple disaggregation of the long-term estimates means that analysis of model outputs at a sub-annual resolution will yield results that are difficult to reconcile with observed events or data.

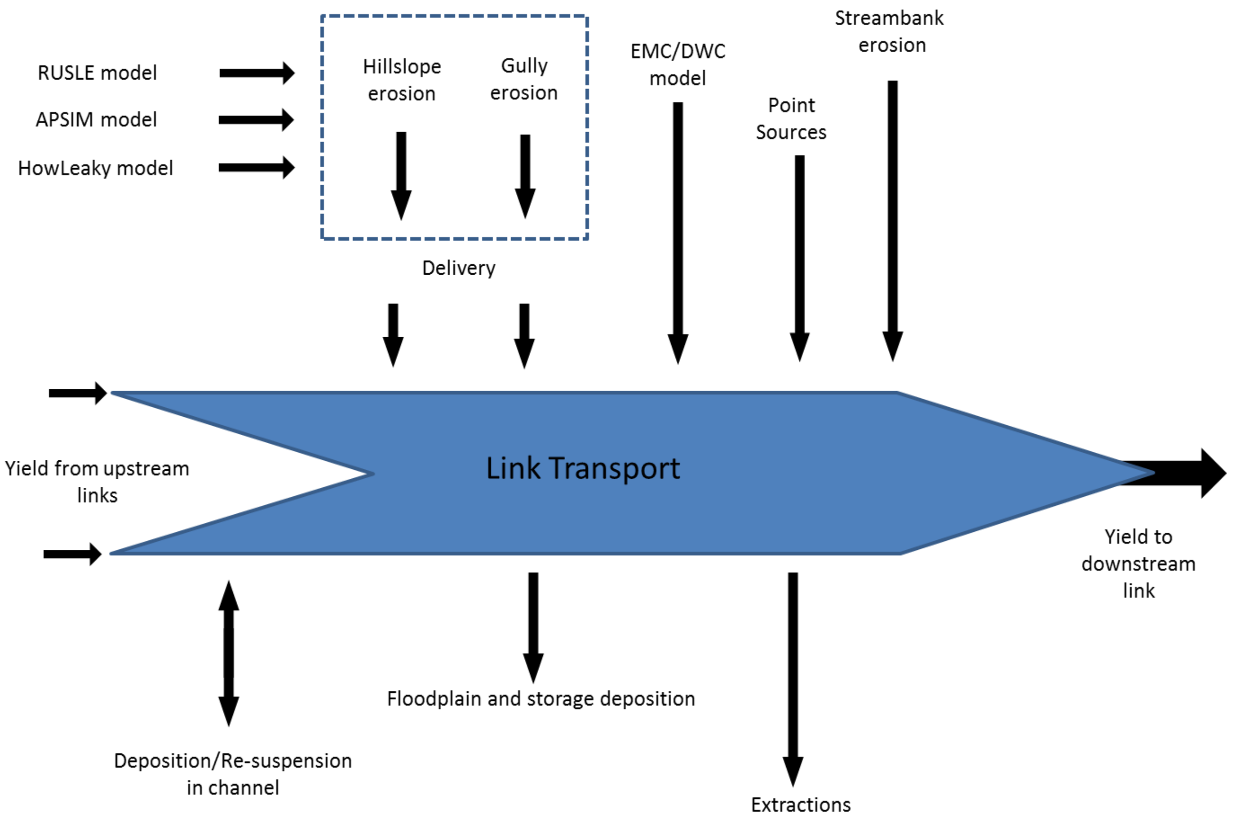

Figure 7 Conceptual diagram of GBR Source Catchments model

The APSIM (Agricultural Production Systems Simulator) model was chosen for modelling sugarcane (Keating et al. 2003), particularly for dissolved inorganic nitrogen in runoff. The HowLeaky model, with some enhancements, was used to model herbicides and phosphorus in sugarcane and all constituents for cropping areas cropping areas (Rattray et al. 2004, Robinson et al. 2010). The Source Catchments framework was selected to meet the increasing demand to improve and re-interpret the models at sub-annual (seasonal, monthly, recognised event) scales. Future work will look to examine the underlying concepts and available daily input data with the aim that these models become more robust at sub-annual time-steps.

3.1.5 Climate simulation period

A 23 year climate simulation period was chosen (1/7/1986–30/6/2009). The modelling was constrained to this period for three reasons: 1) it coincided with the availability from 1986 of bare ground satellite imagery, required in the calculation of hillslope erosion, 2) the average annual rainfall for the simulation period was within 5% of the long-term average rainfall for the majority of the regions and 3) at the time of model development in 2009, this period included a range of high and low flow periods which is an important consideration for hydrology calibration. The climate period will be extended for Reef Plan 2013 to include the extreme wet years post 2009.

Daily climate input files generated for each subcatchment were used to calculate daily runoff. Rainfall and PET inputs were derived from the Department of Natural Resource and Mines (DNRM) Silo Data Drill database (Queensland Government 2011). The data drill accesses grids of data derived by interpolation of the Bureau of Meteorology's station records. The data are supplied as a series of individual files of interpolated daily rainfall or PET on a 5 km grid. Source Catchments then interrogates each daily grid and produces an 'averaged' continuous daily time series of rainfall and PET data for each subcatchment, over the modelling period (1986–2009).

3.2 Hydrology

Hydrology calibration is a major aspect of constituent load modelling, given that constituent generation is driven by rainfall and runoff. Thus it was imperative that the hydrology calibration process was rigorous, and achieved the best possible results. The calibration process was developed building on previous calibration work in the GBR (Ellis et al. 2009). The SIMHYD rainfall-runoff model was selected as the preferred model. The rationale for selecting SIMHYD is outlined in section 3.1.3. Runoff and 'slow flow' (sub-surface seepage and low energy overland flow) aggregated at a subcatchment outlet, are transferred to the stream network then routed through the link system via the Laurenson flow routing model (Laurenson & Mein 1997). Storage dynamics (dams/weirs) were simulated, as well as irrigation extractions, channel losses and inflows such as sewage treatment plant discharges, through specific node models.

3.2.1 PEST calibration

Hydrology calibration was undertaken using PEST, a model-independent parameter estimation tool (Doherty 2005). Parameter optimisation incorporated both the SIMHYD rainfall-runoff parameters and the two Laurenson flow routing parameters within a subcatchment. The estimation of rainfall-runoff and flow routing parameters was undertaken simultaneously.

A three-part objective function was employed, using log transformed daily flows, monthly flow volumes and flow exceedance curves to achieve an optimum calibration. The monthly flow volume component ensures that modelled volumes match measured volumes over long periods, the exceedance values ensure the flow volumes are proportioned well into baseflows and event flows, while the log transformed daily flows replicates the hydrograph shape (Stewart 2011). The three objective functions have been used successfully in other modelling applications (Stewart 2011). The absolute value of components will vary widely for all observation groups, depending on the magnitude of the values contained within each component and the number of values in each time series. However, this does not mean those small value components are not as important as large value components (Stewart 2011). To overcome this inadvertent weighting, each component of the objective function has been weighted equally.

Regularisation was added prior to running PEST. This ensures numerical stability resulting from parameter non-uniqueness, by introducing extra information such as preferred parameter values. Parameter non-uniqueness occurs when there is insufficient observation data to estimate unique values for all model parameters and is an issue in large models such as those in the GBR (Stewart 2011).

Once calibration was completed, model performance was assessed for the gauges used in the calibration process. Performance was assessed for the simulation period 01/07/1986-30/06/2009.

The model performance was assessed against observed flow data using the following criteria:

- Daily Nash Sutcliffe coefficient of Efficiency (NSE) >0.5
- Monthly NSE >0.8
- Percentage volume difference ±20%

Values for NSE can range from 1 to negative ∞ values. If NSE = 0, then the model prediction is no better than using average annual runoff volume as a predictor of runoff. Results between zero and one are indicative of the most efficient parameters for model predictive ability and NSE values of 1 indicate perfect alignment between simulated and observed values (Chiew & McMahon 1993). The PEST setup, operation and linkage with Source Catchments can be found in Appendix B – PEST calibration approach.

3.2.2 Stream gauge selection for calibration

Flow data were extracted from DNRMs Hydstra Surface Water Database to provide the 'observed' flow values for calibration. In the Burdekin region, a total of 110 gauging stations were initially identified as potentially suitable for PEST calibration. As outlined below it was not practical to use all gauge data for calibration. The following criteria were used to select appropriate gauging stations for calibration:

- Located on the modelled stream network
- Minimum of 10 years of flow record (post 1970) with suitable corresponding quality codes
- Little or no influence from upstream storages (subjective)

Gauges that had been moved and had <10% contributing area difference to its predecessor were merged into one continuous dataset.

These criteria reduced the number of gauges available for calibration to 51. However due to PC and software limitations (excessive run times and memory errors) it became necessary to condense the number of gauges further. This was done by identifying gauges that are closely gauged upstream or downstream by other gauges. In general, this resulted in the identification of gauges that added little in terms of area coverage to the calibration. This process was somewhat subjective in that involved visually looking at the gauge area coverage in GIS. This process further reduced the number of gauges to 37.

3.2.3 Rainfall-runoff model parameterisation approach

The SIMHYD rainfall-runoff model contains nine parameters. Seven of these were made 'adjustable' for each SIMHYD instance exposed to PEST for calibration. The Pervious Fraction parameter was fixed to 1 (assuming no impervious areas of significance), therefore making the Impervious Threshold parameter redundant and also fixed. Default SIMHYD and Laurenson flow parameters were used as the starting values (see Appendix B – PEST calibration). The final set of SIMHYD and Laurenson flow routing parameters used to generate runoff can also be found in Appendix B – PEST calibration, along with SIMHYD starting parameters and parameter range.

3.2.4 Model regionalisation

To further simplify the number of adjustable parameters assessed by PEST during calibration, FUs deemed to have similar hydrologic response characteristics were grouped into three broad 'hydrologic response units' (HRUs); forest, grazing and cropping (see Appendix B – PEST calibration). These broad groupings were selected from previous research across Queensland which suggested these land uses have measurably different hydrologic characteristics between virgin scrub, and land that has been cleared for grazing and cropping (Yee Yet & Silburn 2003). Flow routing models were also grouped according to the same regions. FUs, links and nodes continued to operate as discrete units within the Source Catchments structure. Each gauging station included in the calibration represented its own region and modelled subcatchments were therefore divided into 37 regions. Regions were based on the contributing area to a gauge. Nested gauge (gauged upstream or downstream by other gauges) regions had contributing areas minus the contributing area of the upstream gauge. The nearest neighbour approach was used to derive parameters for ungauged subcatchments (Chiew & Siriwardena 2005). After calibration, the 37 parameter sets were applied to the 37 regions (Figure 8) which included the ungauged areas. Ungauged catchments comprised 17% of Burdekin region area and are shaded grey in Figure 8. There are a few gauging stations located within the grey shaded area and were not included during the calibration. For the purposes of the modelling, this area is deemed ungauged.

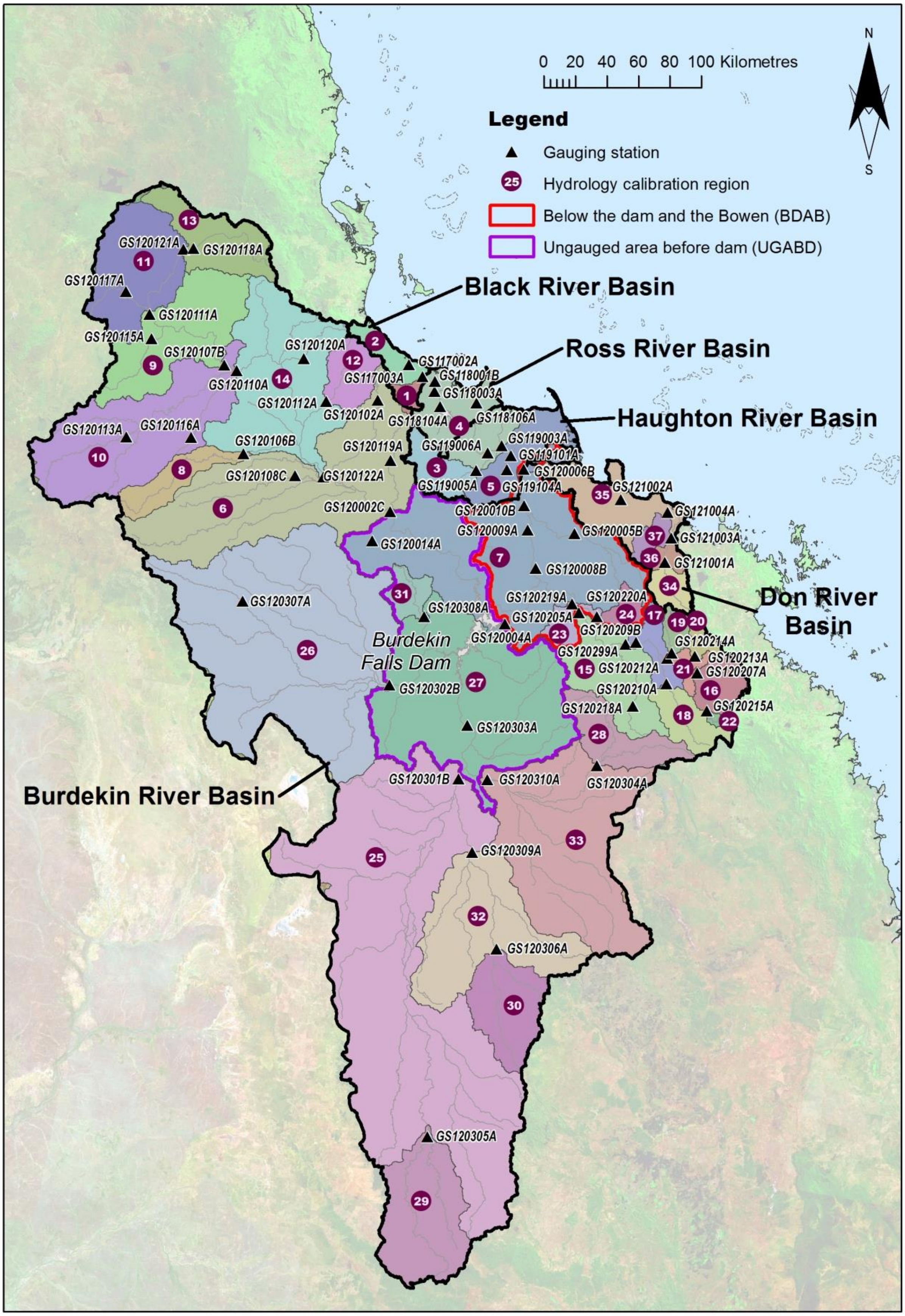

Figure 8 Hydrology calibration regions for Burdekin region

3.3 Constituent modelling

The key water quality constituents outlined in Reef Plan and for Reef Rescue are shown in Table 3. Total suspended sediment (TSS) is based on the international particle size fraction classification and is restricted to the <20 µm fraction (National Committee on Soil and Terrain 2009). Fine sediment (<16 µm) is the fraction most likely to reach the Great Barrier Reef lagoon (Scientific Consensus statement, Brodie et al. 2013). The choice of a <20 µm to determine the fine sediment fraction is also consistent with previous SedNet modelling studies, which used a clay percentage layer from the ASRIS database based on the International particle size fraction classification, to calculate particulate nutrient (PN and PP) loads. Moreover, Packett et al. (2009) found that for the in-stream sediment sampled for some subcatchments, and at the Fitzroy basin outlet, 95% of the (TSS) was very fine sediment (<20 µm). With regard to herbicides, Reef Plan focuses on the reduction in loads of herbicides considered 'priority'; atrazine, ametryn, diuron, hexazinone and tebuthiuron. These are Photosystem II (PSII) inhibiting herbicides, which are applied for residual herbicide control, collectively they are referred to as PSIIs. They are considered priority pollutants due to their extensive use and frequent detection in GBR waterways and in the GBR lagoon (Lewis et al. 2009, Shaw et al. 2010, Smith et al. 2012).

The catchment models were set up to include tebuthiuron as one of the five PSIIs, however due to the availability of application data it was only modelled in the Fitzroy and the Burnett Mary catchments. Ametryn was considered but not reported in WT as it was not part of a typical application profile. The Mackay Whitsunday region was the only area where ametryn was used and was modelled along with atrazine. The herbicide application scenarios also include the knockdown herbicides paraquat, glyphosate and 2,4-D, as well as the alternative residual herbicide, metolachlor although they were not required for reporting. It should be noted that many alternative herbicides are in use in the GBR catchment and have not been represented in the current modelling. The focus on reducing the use of these PSII herbicides has anecdotally led to increasing use of 'alternative' residual herbicides which fulfil a similar weed control role. In future modelling it may be necessary to include the alternative residual herbicides due to changing land management practices.

Table 3 Constituents modelled

Sediment	
Total suspended sediment (TSS)	
Nutrients	
Total nitrogen (TN)	Total phosphorus (TP)
Particulate nitrogen (PN)	Particulate phosphorus (PP)
Dissolved inorganic nitrogen (DIN)	Dissolved inorganic phosphorus (DIP)
Dissolved organic nitrogen (DON)	Dissolved organic phosphorus (DOP)
PSII herbicides	
Ametryn, atrazine, diuron, hexazinone, tebuthiuron	

The most appropriate paddock scale model outputs were used to generate data for Source Catchments. These were APSIM for sugarcane, with the HowLeaky model for pesticides and phosphorus, HowLeaky for cropping, RUSLE for grazing and EMC/DWC models for the remainder. A detailed summary of the models used for individual constituents for sugarcane, cropping and grazing are shown in Table 4. In addition, SedNet functionality was incorporated to model the contribution of gully and streambank erosion and floodplain deposition processes. A detailed description of the models used at the FU and link scale can be found in Ellis & Searle (2014) and Shaw & Silburn (2014).

Table 4 Summary of the models used for individual constituents for sugarcane, cropping and grazing

Constituents	Sugarcane	Cropping	Grazing
TSS	APSIM + Gully	HowLeaky + Gully	RUSLE + Gully
DIN	APSIM	EMC	EMC
DON	EMC	EMC	EMC
PN	Function of sediment	Function of sediment	Function of sediment
DIP and DOP	HowLeaky functions on APSIM water balance	HowLeaky	EMC
PP	Function of sediment	Function of sediment	Function of sediment
PSII herbicides	HowLeaky functions on APSIM water balance	HowLeaky	EMC

Dynamic SedNet is a Source Catchments 'plug-in' developed by DERM/DSITIA specifically for this project. The plug-in provides a suite of constituent generation and in-stream processing models that simulate the processes represented in the SedNet/ANNEX catchment scale water quality model (that is, gully, streambank erosion, as well as floodplain deposition processes) at a finer temporal resolution than the original average annual SedNet model. The Dynamic SedNet plug-in has a variety of data analysis, parameterisation and reporting tools. These tools are an important addition, as the complexity of a Source Catchments model (both spatially and temporally) representing SedNet processes across many landscapes makes it difficult to adequately populate and communicate in a traditional water quality modelling sense. The following sections describe the Source Catchments Dynamic SedNet model configuration. The description includes:

- How constituents are generated at the FU and link scale
- The data requirements of each of the component models
- The methodology used to simulate constituent generation and transport process for each FU within a subcatchment, link (in-stream losses, decay, deposition and remobilisation) and node (extractions and inputs to the stream).

3.3.1 Grazing constituent generation

Rainfall and ground cover are two dominant factors affecting hillslope runoff and erosion in the GBR. Previous studies report that gully erosion is also a significant source of sediment to the GBR (Wilkinson et al. 2013, Dougall et al. 2009, Wilkinson et al. 2005). Given grazing occupied over 75% of the GBR, it was important that the models chosen represented the dominant erosion processes occurring in these landscapes and the spatial variability observed across such a large area.

The component model referred to as the *SedNet Sediment (RUSLE & Gully)* combines two sub-models; the *Hillslope Dynamic RUSLE* model and the *Dynamic Gully Model*, representing hillslope and gully contributions to sediment supply respectively.

3.3.1.1 Hillslope sediment, nutrient and herbicide generation

Sediment generation model

A modified version of the Universal Soil Loss Equation (USLE) was used to generate hillslope erosion on grazing lands (Renard et al. 1997, Lu et al. 2001, Renard & Ferreira 1993) (Equation 1). This modified version is based on the Revised Universal Soil Loss Equation and is referred to as the RUSLE in this document (Lu et al. 2001, Renard & Ferreira 1993). The RUSLE model was chosen due to its proven ability to provide reasonable estimates of hillslope erosion worldwide including various GBR SedNet models, the ability to apply the model across a large spatial extent and at the same time incorporate detailed spatial and temporal data layers including cover and rainfall components. The model is:

$$A = R * K * S * L * C * P \qquad (1)$$

Where

A = soil erosion per unit area (t/ha) (generated as a daily value)

R = Rainfall erosivity EI30 (MJ.mm/ha.h.day) (generated as a daily value)

K = Soil erodibility (t.ha.h/ha.MJ.mm) (static value)

L = Slope length (static value)

S = Slope steepness (static value)

C = Cover management factor (one value generated per year for each 25 m x 25 m grid cell)

P = Practice management factor (static value)

In the GBR Source Catchments Framework, a daily time-step, spatially variable RUSLE was used to generate hillslope sediment predictions in grazing areas. The spatial data inputs were assessed at a fine resolution, with results accumulated up to a single representation of the particular grazing instance within each subcatchment. The spatial and global parameter values applied for the Burdekin model are shown in Appendix D.

Rainfall erosivity factor (R) values were calculated using the generalised rainfall intensity method (Yu 1998). Catchment daily rainfall used in the hydrology modelling provided the daily rainfall input (Queensland Government 2011).

Soil erodibility factor (K) raster was calculated using methods of (Loch & Rosewell 1992). Soil data for these calculations was sourced from the Queensland ASRIS database using the best available soils mapping for spatial extrapolation (Brough, Claridge & Grundy 2006).

Slope factor (S) was calculated by methods outlined in (Lu et al. 2003). The slope values for these calculations are derived from the 1 second DEM (Farr et al. 2007). The use of a shuttle DEM has been found to miscalculate slopes on floodplain areas or areas of low relief. The slope map produced from the 1 second DEM was therefore modified for the defined floodplain areas, with a value more appropriate for floodplains, in this case a slope of 0.25%. This was value was approximated from the measurement of slope values produced from a range of high resolution DEM's, covering floodplains in the Fitzroy region.

Length factor (L) was set to 1 for grazing areas and is only applicable where rill erosion can occur. The assumption was that rill erosion is generally not found in low intensity grazing systems.

The K, S and L factors are temporally constant and combined into one raster. The raster is a product of the best resolution K, S and L factors linear multiplied, then resampled to a grid resolution of 100 m.

Cover factor (C) can be applied in Source Catchments at three time-steps: monthly, annual and static. An annual time stepping representation of the C-factor was selected due to the availability of the relevant satellite imagery at an annual scale at the time of model development. Using an annual time-step for the C-factor ensures that extended wet and dry periods are reflected in hillslope erosion processes. This is an improvement on previous modelling approaches where a single static C-factor was applied both spatially and temporally for each land use. Seasonal cover will be incorporated to further improve erosion estimates when data is available, as it will better represent inter-annual variability in RUSLE predictions. Ground cover is estimated using Bare Ground Index (BGI) (Scarth et al. 2006) (version CI2). This product is derived from Landsat TM Satellite (25 m) imagery. BGI values were subtracted from 100 to provide a ground cover index (GCI). The GCI was calculated each year using a single NRM region BGI mosaic of images captured between July and October (dry season). The GCI is currently only considered to be accurate in areas where the Foliage Projected Cover (FPC) (Goulevitch et al. 2002) is <20%. To deal with this, the GCI was classified into 'no tree' areas (FPC <20%) and 'tree' areas (FPC >20%) (Equation 2). The 2009 FPC coverage was used to represent the 'tree' coverage, for all years. 2009 was chosen to correspond with the latest land use mapping, also mapped to 2009.

'No tree' (where FPC <20%) C-factors (C_f) were derived as follows (Rosewell 1993):

$$C_f = EXP\left[-0.799 - (0.0474 \times GC) + (0.000449 \times GC^2) - (0.0000052 \times GC^3)\right] \quad (2)$$

Where GC is the percentage cover in contact with the soil.

Where FPC >20%, the C-factor was calculated using methods outlined in Kinsey-Henderson, Sherman & Bartley (2007) (Equation 3). This took the form of the following equation:

$$C_f = 1.0286 \times 10^{-8}\left[(100 - FPC)^{3.3907}\right] \quad (3)$$

Practice management factor (P) is the support practice factor, a measure of the effect on erosion of soil conservation measures such as contour cultivation and bank systems (Rosewell 1993). There was insufficient information available to apply P factors in this study, therefore P was set to 1 in all regions.

The daily RUSLE soil loss calculation provides an estimate of the sediment generation rate at the hillslope scale. To estimate the suspended fraction of the total soil loss, the RUSLE load is multiplied by the clay and silt fraction (%) located in the ASRIS layers (the best data source available to generate this layer at the GBR scale). The clay and silt fraction (%) is based on the International particle size fraction classification (<20 µm) (National Committee on Soil and Terrain 2009). The use of a particle size distribution raster in the current modelling to determine the fine sediment fraction (and calculate fine sediment load transported to the stream network) is a likely improvement from previous modelling studies that used SedNet (e.g. Brodie et al. 2003 and Cogle et al. 2006). These SedNet studies used a hillslope delivery ratio (HSDR) to alter the RUSLE-estimated eroded soil mass into a 'suspended sediment' in-stream mass, rather than the product of the fine fraction and HSDR as applied in this study (Equation 4). The clay and silt proportion values in the ASRIS data layer are derived as a function of many laboratory analysed soil samples from a range of soil types, hence the data incorporates the spatial variability of fine fractions across the GBR.A sediment delivery ratio (SDR) was then applied to this load and was selected based on past research using a standard 10% delivery ratio (Cogle, Carroll & Sherman 2006). However, in some regions the SDR was increased so that the generated fine sediment load better matched monitored data, or to counter the per cent cover generated by the BGI layers which was thought to be too high. The equation takes the form:

Total suspended sediment load (kg/day) = RUSLE sediment load (kg/day) * (silt proportion + clay proportion) * SDR (4)

This estimates the TSS load which reaches the stream.

Nutrient generation models

Hillslope particulate nutrient generation was derived as a function of the clay fraction of the daily RUSLE soil loss, the surface soil nutrient (total nitrogen and phosphorus) concentration and an enrichment ratio (Young, Prosser & Hughes 2001) (Equation 5). This algorithm assumes that all nutrients in the soil are attached to the clay fraction where:

Hillslope particulate nutrient load (kg/ha) = RUSLE sediment load (kg/day) * clay proportion * Surface nutrient concentration (kg/kg) * Enrichment factor * Nutrient Delivery Ratio (NDR) (5)

This estimates the total suspended nutrient load, which reaches the stream. For the dissolved nutrient load, an EMC/DWC value (mg/L) is multiplied by the quick and slow flow output (model values are listed in Appendix D). These models are described in (Ellis & Searle 2014) and replicate the original SedNet approach to dissolved and particulate nutrient generation, modified to a daily time-step. Enrichment ratios and load conversion factors are outlined in (Appendix D). Three rasters are required as inputs to these models, two nutrient rasters (surface nitrogen and phosphorus), as well as a surface clay (%) raster. The surface soil nutrient layers were from the Queensland ASRIS database.

Herbicide generation models

Tebuthiuron, a PSII herbicide, is the main herbicide used in grazing lands for control of regrowth. Tebuthiuron is applied to selected areas of land and is not reapplied on a regular basis. This makes it difficult to model an accurate representation of the usage pattern across a 23 year climate period. Because of this, a static EMC/DWC concentration model was used, based on measured in-stream data from the Fitzroy basin to ensure a very conservative estimate of the average annual load was generated in the model. Tebuthiuron was not modelled in the Burdekin region due to a lack of data at the time of the Burdekin region model build.

3.3.1.2 Gully – sediment and nutrient generation models

Gully modelling was based on well published SedNet gully modelling methodology (Prosser et al. 2001a) applied extensively used across the GBR (McKergow et al. 2005b, Hateley et al. 2005).

Gully sediment contribution to the stream was calculated as a function of the gully density, gully cross sectional area and likely year of initiation. Once the volume of the gullies in each FU was calculated for a subcatchment, this volume is converted to an 'eroded' soil mass. This eroded mass is then distributed over the model run period as a function of runoff (Equation 6). The gully average annual sediment supply (AASS) is calculated by:

$$AASS\ (t/year) = (P_s * \alpha_{xs} * GD_{FU} * A_{FU}) / Age \qquad (6)$$

Where:

P_s = Dry soil bulk density (t/m^3 or g/cm^3)

α_{xs} = Gully cross sectional area (m^2)

GD_{FU} = Gully density (m/m^2) within FU

A_{FU} = Area of FUs (m^2)

Age = Years of activity to time of volume estimation (e.g. year of disturbance to year of estimation)

To derive a daily gully erosion load, the long-term average annual gully erosion load is multiplied by the ratio of daily runoff to annual runoff to apportion a daily gully load. Spatial raster inputs and parameter global values are shown in (Appendix D). A statistically modified National Land and Water Resources Audit (NLWRA) gully density layer (Kuhnert et al. 2012) was used as the input raster (km/km^2) for gully density in the Burdekin basin. However the coastal basins are not covered by this product, here the only available mapping was the original National Land and Water Resources Audit (NLWRA) gully density layer (Hughes et al. 2001). Much of the Australian research on gully erosion has occurred in south-eastern Australia, and measurements of gully cross sectional area suggest a value of 10-23 m^2 would be appropriate in SedNet modelling (Hughes & Croke 2011, Prosser & Winchester 1996, Rustomji et al. 2010). Recent research from northern Australia indicates that a value of 5 m^2 is more appropriate (Hughes & Croke 2011) and this value was originally applied in the Burdekin, however modelled results indicated insufficient erosion when compared with measured sites. A cross sectional value of 10m^2 was applied matching earlier values used in SedNet modelling in the Burdekin. The soil bulk density (g/cm^3) and b horizon clay plus silt (%) rasters were both created from the Queensland ASRIS dataset. The year of disturbance can either be input as a raster or as a uniform value. In the Burdekin model, a uniform value of 1900 was applied. This value was chosen as it coincides with new work on gully initiation in the upper Burdekin at the Weany Creek research catchment (Silburn et al. 2012).

Similar to the hillslope nutrient generation, gully nutrients were derived as a function of the gully particulate sediment load. Sub-surface nutrient concentrations are multiplied by the gully sediment load to provide an estimate of the gully nutrient contribution and the sub-surface clay (%). Raster inputs to these models, were two nutrient rasters (sub-surface nitrogen and phosphorus), and a sub-surface clay raster (%).

3.3.2 Sugarcane constituent generation

In the GBR Source Catchments framework, the component model referred to as the *Cropping Sediment (Sheet & Gully) model* combined the output from two sub-models; the *Cropping Soil Erosion* model and the *Dynamic Gully* model. The time series loads of daily hillslope erosion (t/ha), calculated by APSIM are combined with the daily gully erosion estimate as outlined in section 3.3.2.2.

3.3.2.1 Hillslope-sediment, nutrient and herbicide generation

Daily time series loads of fine sediment and DIN in runoff were supplied from APSIM model runs for sugarcane FUs. Hillslope erosion was predicted in APSIM using the (Freebairn & Wockner 1986) form of the RUSLE described in (Littleboy et al. 1989). Erosion estimates from APSIM were adjusted for slope and slope length before being run in Source Catchments. Slope and slope length were derived from the intersected DEM and slope values were capped at 8%. Further explanation for this is provided in 3.3.3.1.

Runoff in APSIM was modelled using the curve number approach. Model runs for the soil types were assigned to mapped soils in the Burdekin on the basis of similarity of surface texture and curve number in an effort to assign appropriate runoff estimates. Runoff drives the offsite transport of other constituents (sediment, herbicides and nutrients) in the APSIM and HowLeaky functions. The APSIM generated runoff was analysed when APSIM timeseries data are transferred to Source Catchments, to ensure that loads are transferred to the Source Catchments streams only when Source Catchments has runoff generated. This analysis attempts to ensure pollutant load mass balance is consistent on a monthly basis.

DIN loads modelled by APSIM were imported directly as supplied (under the procedure for runoff analysis above). Herbicide and phosphorus loads were modelled using HowLeaky functions based on the outputs of the APSIM model of sugarcane systems for water balance and crop growth. The HowLeaky herbicide and phosphorus models are described for dryland and irrigated cropping below. DON is an EMC model. Further details on the APSIM and HowLeaky models and the parameters used to define simulations of sugarcane are provided in Appendix D and in (Shaw & Silburn 2014).

There were differences between the industry supplied sugarcane areas (hectares) and the QLUMP derived sugarcane area used for the modelling. This indicated that the QLUMP data was most likely representing more area than the industry recognises as actually growing sugarcane at any given time, due to consideration of crop rotations, headlands, infrastructure and other factors. Comparison with industry supplied estimates of sugarcane area indicated that the QLUMP over estimate may be in the order of 10%, and an area correction factor was applied to the APSIM pollutant loads accordingly.

3.3.2.2 Gully – sediment and nutrient generation

Gully modelling for sugarcane used the same methodology as for grazing lands (3.3.1.2). Similarly to the grazing areas, the total subcatchment contribution for sugarcane FUs combined the hillslope and gully loads. Gully nutrients are derived as a function of the gully particulate sediment load, the sub-surface clay (%) and the sub-surface soil nutrient concentrations.

3.3.3 Cropping constituent generation

In the GBR Source Catchments framework, the component model referred to as the *Cropping Sediment (Sheet & Gully)* model combined the output from two sub-models; the *Cropping Soil Erosion model* and the *Dynamic Gully* model. The time series loads of daily hillslope erosion (t/ha), calculated by HowLeaky (Rattray et al. 2004) are combined with the daily gully erosion estimate as outlined in section 3.3.3.2.

3.3.3.1 Hillslope sediment, nutrient and herbicide generation

Daily time series loads of fine sediment, phosphorus and herbicides in runoff were supplied from HowLeaky model runs for the dryland and irrigated cropping FUs (Shaw & Silburn 2014). DIN and DON were modelled using an EMC. Simulations of a range of typical cropping systems in the Burdekin region were run in the HowLeaky model to represent each unique combination of soil, climate and land management.

Runoff was modelled in HowLeaky using a modified version of the Curve Number approach (Shaw & Silburn 2014, Littleboy et al. 1989). Soils were grouped according to hydrologic function and assigned a curve number parameter to represent the rainfall versus runoff response for average antecedent moisture conditions, for bare and untilled soil. This curve number was modified in HowLeaky model daily to account for crop cover, surface residue cover and surface roughness.

Hillslope erosion was predicted in HowLeaky using the modelled runoff, USLE K, L and S and a cover-sediment concentration relationship (Freebairn & Wockner 1986). This generalised equation applies anywhere where the cover-sediment concentration relationship holds. In addition, the Freebairn & Wockner equation has been tested and calibrated for 14 sites, predominantly in the GBR refer http://www.howleaky.net/index.php/library/supersites for detailed summary of results. For each of the unique combinations of soil and climate an average slope value was derived from the intersected digital elevation map (DEM) and applied in the soil loss equation.

Dissolved phosphorus in runoff was modelled in HowLeaky as a function of saturation of the soil P sorption complex while particulate phosphorus was modelled as a function of sediment concentration in runoff and the soil P status (Robinson et al. 2011). As the HowLeaky model did not differentiate between forms of dissolved P, a ratio was applied to the dissolved P on import to the catchment model. While the fractions of DIP/DOP are known to vary by site and situation, a value was selected from the limited available literature (e.g. Chapman et al. 1997) which showed that DOP could represent up to 20% of dissolved P in leachate/soil water. Dissolved P is not explicitly modelled for management practice change, however within the model, dissolved P changes with runoff, so less runoff results in less offsite transport of dissolved P. With regard to particulate P, management practices affect suspended sediment movement and thus affect PP runoff. This is because a) there is no GBR P management practice framework, and b) there is no reporting on P management investments.

Herbicide mass balance and runoff losses were modelled using HowLeaky (Shaw & Silburn 2014), an enhanced version of Rattray et al. (2004). Modelling of herbicide applications at the paddock scale was based on theoretical scenarios that represent a ‘typical’ set of applications under an A, B, C or D set of management practices. The scenarios modelled describe the products applied and the timing and rates of those applications. An emphasis was placed on modelling the PSII herbicides considered priority under Reef Plan. Half-lives of herbicides of interest were taken from available studies in the literature or from Paddock to Reef field monitoring results where possible. Partitioning coefficients between soil and water were calculated from both soil and herbicide chemistry. Further details on the HowLeaky model and the parameters used to define simulations of cropping and sugarcane are provided in Shaw & Silburn (2014).

3.3.3.2 Gully sediment and nutrient generation

Gully modelling for cropping used the same methodology as for grazing lands (3.3.1.2). Similarly to the grazing areas, the total subcatchment contribution for cropping FUs combined the hillslope and gully loads. Gully nutrients are derived as a function of the gully particulate sediment load, the sub-surface clay (%) and the soil nutrient concentrations.

3.3.4 Other land uses: Event Mean Concentration (EMC), Dry Weather Concentration (DWC)

For the remaining land uses (horticulture and urban), Event Mean Concentration/Dry Weather Concentration (EMC/DWC) models were applied (Equation 7). In comparison to grazing, cropping and sugarcane areas, these land uses had a small relative contribution to region loads. In the absence of specific models for these land uses, EMC/DWC models were applied to give an estimate of the daily load, where:

$$\text{Daily Load (kg)} = \text{EMC (mg/L)} \times \text{quickflow runoff} + \text{DWC (mg/L)} \times \text{baseflow runoff} \quad (7)$$

Where quickflow represents the storm runoff component of daily runoff, the remainder is attributed to baseflow. A constituent EMC/DWC model was applied for a particular FU; an estimate was made using available monitoring data, or where monitored data was not available, with best estimates from previous studies (Bartley et al. 2012, Rohde et al. 2008, Waters & Packett 2007). An EMC constituent value was calculated directly from the load and flow data for the entire period when reliable long-term monitoring data were available.

3.3.5 Subcatchment models

3.3.5.1 Point sources

Sewage Treatment Plants (STPs) were deemed to be a significant point source contribution to nutrient loads exported to the GBR. The larger STPs with an arbitrary criterion of a minimum 10,000 equivalent person's (EP) capacity were included. STP details and data were provided by DERM's (formerly Environment Protection Agency) Point Source Database (PSD). All STP's are maintained by the Cairns City Council. Annual flow and loads data was provided for 2000-2004. The flows and load data were then used to calculate an average annual flow volume and load.

Table 5 Sewage Treatment plants >10,000 equivalent persons

STP	Discharge point	Catchment	Lat	Long	EP
Ayr Sewage Treatment Plant	KALAMIA CREEK	Haughton	-19.556	147.388	10,000-50,000
Cleveland Bay Water Purification Plant	CLEVELAND BAY	Ross	-19.290	146.853	> 100,000
Condon Sewage Treatment Plant	BOHLE RIVER	Ross	-19.337	146.706	10,000-50,000
Mt St John Wastewater Treatment Plant	BOHLE RIVER	Ross	-19.254	146.744	> 100,000

The Source Catchments model required average annual loads (kg/yr) of DIN, DOP, DIP and DOP. However, the majority of the nutrient data in the PSD database was reported as TN, TP and Ammonia (as N-NH3). Twelve STPs from Queensland with recorded concentrations of DIN, DON, DIP, DOP, TN and TP were used to calculate the mean percentage of each constituent to the total. Of the 12 STPs, eight were tertiary and four were secondary treatment plants. No differentiation was made between tertiary and secondary treatment plants, as there was a 10% difference in N speciation and 4% difference in P speciation. Moreover, STP sources only account for a small fraction of the total nutrient budget. Out of the 12 STP plants, 550 samples were used to calculate N speciation mean percentages and 469 samples used to calculate P speciation, see Table 6 for percentages. Data pairs were discarded where the speciation concentration added together was greater than the TN or TP concentration. The fixed percentages were applied to 2010 TN and TP concentration data from each STP to get the speciation. Annual loads (kg/yr) were then calculated by multiplying the average annual flow (2007-2010) from each STP by the average 2010 daily concentration of DIN, DON, DIP and DOP. To reflect the recent upgrades to STPs in the region only the 2010 nutrient concentrations were used.

Table 6 TN, TP speciation ratio's

	DIN of Total N	DON of Total N	DIP of Total P	DOP of Total P
% of total	79%	21%	78%	22%
No. samples	550		469	

3.3.6 In–stream models

The in-stream processes represented in the model are streambank erosion, in-stream deposition, decay, remobilisation and floodplain deposition. The models that have been applied are: the

SedNet Stream Fine Sediment model and *SedNet Stream Coarse Sediment* model which simulate sediment generation, deposition and remobilisation in-stream and coarse sediment deposition. The *SedNet Stream Particulate Nutrient* model has been applied to generate, deposit and remobilise particulate nutrients in-stream. Dissolved nutrients and herbicides were not generated at a link scale. Coarse sediment was not reported.

3.3.6.1 Streambank erosion

The *SedNet Stream Fine Sediment* model calculates a mean annual rate of fine streambank erosion (t/yr) as a function of riparian vegetation extent, streambank erodibility and retreat rate. The mean annual streambank erosion is disaggregated as a function of the daily flow. For a full description of the method refer to (Ellis & Searle 2014) also see Appendix D for a list of the parameters used. The *SedNet Stream Particulate Nutrient* model calculates the particulate N and P contribution from streambanks by taking the mean annual rate of soil erosion (t/yr) from the stream network multiplied by the ASRIS sub-surface soil N and P concentrations.

3.3.6.2 In-stream deposition, decay and remobilisation

The implemented in-stream model allows both the deposition and remobilisation of fine and coarse sediment. However with limited data available to validate this component at the time of model development, remobilisation and in-stream deposition was not included in any of the GBR models. The assumption was made that all coarse sediment deposits in the main stream with no remobilisation occurring. Hughes et al. (2010) note that in-channel benches are an important store of large volumes of sediment in the Fitzroy catchment, however these benches are predominantly comprised of sand. A small fraction of fine sediment may be trapped in these coarse (bedload) deposits, however the time scale for fine sediment movement is much shorter and thus this fraction is ignored in the bedload budget (Wilkinson, Henderson and Chen, 2004). For fine sediment it was assumed that there was no long-term fine sediment deposition in-stream, and that all suspended sediment supplied to the stream network is transported (Wilkinson, Henderson and Chen, 2004). As new science becomes available on fine sediment in-stream deposition (and remobilisation) processes, applying these models will be investigated. Currently research is being undertaken in the Fitzroy, Burdekin and Normanby catchments (Brooks et al. 2013) which may help to validate this component. Furthermore, in-stream deposition and remobilisation are both influenced by stream flow energy, which itself is controlled by stream geometry parameters that are difficult to determine across a large model. Details on the in-stream deposition and remobilisation models can be found in Ellis et al. (2014).

The in-stream decay of dissolved nutrients was not implemented in the Burdekin region model. Monitoring data suggests that dissolved nutrient concentrations showed little reduction from source to the catchment outlet therefore no decay model was applied. However further research is required to improve our understanding of in-stream decay process for dissolved nutrients.

Herbicides were decayed in-stream using a first order exponential decay function (Ellis & Searle 2013). Half-lives were taken from the DT_{50} values for water from the Pesticide Properties Database (PPDB) (PPDB 2009). Before these values were selected for use in the modelling, they were checked against predicted half-lives based on the physical and chemical properties of the herbicides being considered and against field monitoring data of events to determine whether the order of magnitude reported in the database was consistent with field observations in the GBR catchment (e.g. (Smith et al. 2011) and Bob Packett, 2012, pers. comm.). Monitoring in the Fitzroy River designed to target the same 'parcel' of water in the upper catchments and again at the mouth of the Fitzroy River indicated that the half-life of atrazine and diuron in-stream was in the order of three to six days, while for tebuthiuron the half-life estimates ranged from approximately 15-60 days (Bob Packett, 2012, pers. comm.). Where values were not available for a specific herbicide, a value was assigned from a compound with similar chemical properties or derived from the monitored data. The herbicide half-life parameters are presented in Appendix D.

3.3.6.3 Floodplain (deposition)

Floodplain trapping or deposition occurs during overbank flows. When floodwater rises above rivers banks the water that spills out onto the rivers' floodplain is defined as overbank flow. The velocity of the flow on the floodplain is significantly less than that in the channel allowing fine sediment to deposit on the floodplain. The amount of fine sediment deposited on the floodplain is regulated by the floodplain area, the amount of fine sediment supplied, the residence time of water on the floodplain and the settling velocity of the sediment (Wilkinson et al. 2010, Ellis & Searle 2014, Prosser et al. 2001b). The *SedNet Stream Particulate Nutrient* model also calculates the particulate nutrients deposited on the floodplain as a proportion of fine sediment deposition. The loss of dissolved nutrients and herbicides on the floodplain was not simulated.

3.3.6.4 Node models

Nodes represent points in a stream network where links are joined (eWater Ltd 2013). Catchment processes can also be represented at nodes. In the GBR Source Catchments model, irrigation extractions, STP inflows, losses from channels and storages were represented at nodes. For the description of these models refer to (eWater Ltd 2013).

Extraction, Inflows and loss node models

To simulate the removal of water from storages and/or rivers, daily extraction estimates for a river reach were incorporated at relevant nodes. The data was obtained from previous integrated quantity and quality models (IQQM). Extraction time series data for the Source Catchments model were obtained from the following integrated quality and quantity models (IQQM):

1. Burdekin Model – Developed for the Burdekin Resource operations plan (DERM 2009)

2. Ross Model-Regional Water Supply Strategy modelling (DERM 2009)

Extraction points were lumped using data from the IQQM node-link network. Here extractions were interrogated at each link and assessed for inclusion via the following criteria:

1. If >5% of the mean annual flow was extracted, then extraction points were lumped and placed on the immediate downstream node; and,

2. At the end of each sub-basin all extractions not accounted for in Criteria 1, were lumped and extracted at the sub-basin node.

Using this approach, 11 extraction points were selected for inclusion in the model. Each extraction point was assigned to the corresponding Source Catchments node (Table 7).

Table 7 Extraction ID, and corresponding IQQM and Source Catchments nodes

Extraction	IQQM Nodes	Source Node	Description
1	1-8	56	Far upper Burdekin
2	68	113	Paluma dam extraction
3	8-170 (excluding 68)	501	Upper Burdekin
4	706-265	1247	Upper Belyando 1
5	266-267	1145	Upper Belayando 2
6	All Belyando excluding extraction points 4 and 5	748	Belyando
7	384	120215A	Eungella Dam (water removed completely from system)
8	All Bowen (excluding 384)	653	Lower Bowen
9	509	403	Haughton pump station
10	All Lower Burdekin (excluding 509)	120006b	All Lower Burdekin, excluding Haughton Pump Station (node 509)
11	824	118104A	Ross river dam

As the Burdekin Resources Operations Plan IQQM extractions' only extend to the end of 2006, it was necessary to extend the extraction time series to the extent of the model run; in this case 2010. The time series was extended by selecting an average rainfall year. For this model the 2001 year was chosen. The extractions for that year were then used to fill the years without data, through applying the daily extraction from the representative year. However, this process resulted in over extraction for the lower Burdekin, and as such observed extraction data was obtained from the Queensland Government gauging station data.

3.3.6.5 Storage models

Storages (dams and weirs) with a capacity >10,000 ML (Table 8) were incorporated into the model at nodes. Only storages of significant capacity were incorporated as it was impractical to include all storages into the model and it was assumed the smaller storages would have minimal impact on the overall water balance and pollutant transport dynamics. Storage locations, dimensions and flow statistics were used to simulate the storage dynamics on a daily basis. Additional storage information is located in Appendix D.

Table 8 Burdekin region storage details (>10,000 ML capacity)

Storage	Construction Date	Capacity (ML)
Paluma Dam	1958	12,300
Ross River Dam	1973	417,000
Clare Weir	1986	15,600
Burdekin Falls Dam	1987	1,860,000
Eungella Dam	1969	131,000

Trapping of fine sediment and particulate nutrients in storages is simulated by the *SedNet Storage Lewis* model and the *SedNet Storage Particulate Nutrient Deposition* model, respectively. Here fine sediment and particulate nutrient is captured using a 'trapping' algorithm based on daily storage capacity, length and discharge rate. The implemented trapping algorithm is a daily modification of the Churchill fine sediment trapping equation (Churchill 1948). Lewis et al. (2013) reviewed and tested an annual weighted version of this equation against measured data for the Burdekin Falls dam and storages in the USA, in general, predictive capability improved with use of daily data. Dissolved constituents are decayed in storages using the *SedNet Storage Dissolved Constituent Loss* model, which applies a first order decay. Storage details are presented in Appendix D, Table 36.

3.4 Progress towards Reef Plan 2009 targets

Water quality targets were set under Reef Plan 2009 in relation to the anthropogenic baseline load. The predevelopment load refers to the period prior to European settlement; hence the anthropogenic baseline load is the period since European settlement (Equation 8, 9 and Figure 9).

$$\text{Anthropogenic baseline load} = \text{total baseline load} - \text{predevelopment load} \tag{8}$$

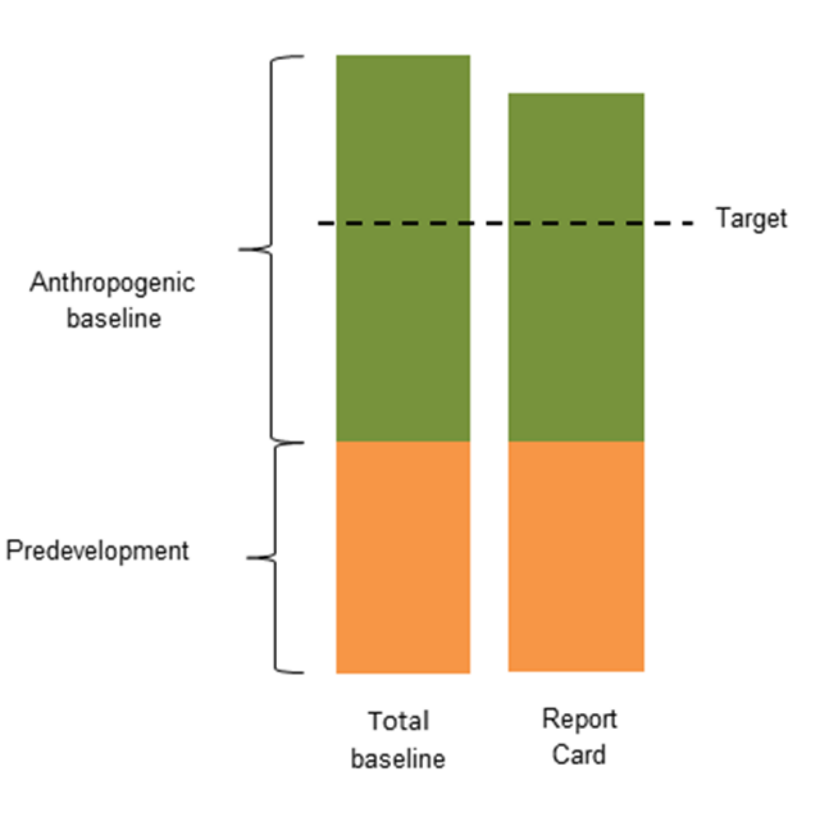

Figure 9 Example of how modelling results will be reported to demonstrate the estimated long-term load reduction resulting from adoption of improved management practices for Report Cards 2010–2013 against the target

The percentage reduction in load for Report Card 2013 is calculated from:

$$\text{Reduction in load (\%)} = \frac{(\text{Total baseline load} - \text{Report Card 2013 load}) * 100}{\text{Anthropogenic baseline load}} \qquad (9)$$

The progress made towards water quality targets due to investments in improved land management are therefore reported as a reduction in the anthropogenic baseline loads. In this section the approach and series of assumptions used to derive the total baseline and predevelopment loads and the process to represent management practice change are outlined.

Report Cards, measuring progress towards Reef Plan's goals and targets, are produced annually as part of the Paddock to Reef Program. The first Report Card was released in August 2011 (Kroon et al. 2010). Report Cards 2010–2013 represent management changes based on a yearly period, usually financial year to financial year. The total and anthropogenic baseline load was based on land use and management status at the start of the 2008/2009 financial year. All scenarios were run using the same modelling period 1986–2009 (23 years) see Table 9 for details of the total and anthropogenic baseline scenarios and Report Card scenarios. Note that Report Card 2010 includes two years of management change. Report Card 2011 and beyond represent cumulative change each year.

Table 9 Total and anthropogenic baseline and Report Card model run details

Scenario	Reporting period	Land use	Model run period
Total and anthropogenic baseline	2008-2009	2009	1986–2009
Report Card 2010	2008-2010	2009	1986–2009
Report Card 2011	2008-2011	2009	1986–2009
Report Card 2012	2008-2012	2009	1986–2009
Report Card 2013	2008-2013	2009	1986–2009

3.4.1 Modelling baseline management practice and practice change

State and Australian government funds were made available under Reef Plan to the six Regional NRM groups and industry bodies to co-fund landholder implementation of improved land management practices. The typical practices that were funded under the Reef Rescue Program for grazing include fencing by land type, fencing of riparian areas and the installation of off-stream watering points, all of which aim to reduce grazing pressure of vulnerable areas and improve ground cover in the longer term.

For sugarcane, typical practices included adoption of controlled traffic farming, modification of farm machinery to optimise fertiliser and herbicide application efficiency, promoting the shift from residual to knockdown herbicides and reduced tillage. These identified management changes were (subject to review) attributed with achieving improvements in land management which would result in improvements in off-site water quality. It is important to note that not all reported investments are assumed to have achieved this management system change. This is particularly the case in cropping systems where several specific and inter-related practice changes are often required to complete the transition to a new management system. For a summary of typical management practice changes attracting co-investment, refer to Table 37 Appendix D, (K McCosker, 2014, pers. comm.).

To model management practice change, the baseline management practice was identified and incorporated into the total baseline model through the development of an ABCD framework. This framework was developed for each industry (sugarcane, cropping and grazing) and was used to describe and categorise farming practices within a given land use according to recognised water quality improvements for soil, nutrient and herbicide land management (Drewry, Higham & Mitchell 2008). Farm management systems are classed as:

A-Cutting edge practices, achievable with more precise technology and farming techniques

B-Best management practice, generally recommended by industry

C-Code of practice or common practices

D-Unacceptable practices that normally have both production and environmental inefficiencies

The proportion of each industry was established in A, B, C or D condition. The area of A,B,C or D was then reflected in the total baseline model. The proportion of area of A,B,C or D then changed each year between 2008 and 2013 based on adoption of improved practices. “For more information on the ABCD framework and associated management practices see the Reef Plan website: www.reefplan.qld.gov.au.

The total baseline load was modelled using 2009 land use and land management practices. The most recent Queensland land use mapping program (QLUMP) map was used to define the spatial location of the major land uses in the region (DSITIA 2012b). Land use categories in QLUMP were amalgamated to represent broader land use classes including: nature conservation, forestry, open and closed grazing, sugarcane, cropping, and horticulture (Table 2).

For each of the major industries where investment occurred in the Burdekin region (sugarcane and grazing) there were a suite of specific management practices and systems defined under the ABCD framework relevant to soil, nutrient and herbicide management. The prevalence and location of management practice is central to the modelling and reporting on progress towards the reef water quality targets. The variety of sources of information collected in the baseline year (start of 2008/2009 financial year) and adoption of improved management practices from industry and government programs are outlined in Reef Plan (Department of the Premier and Cabinet 2013b).

Management changes funded through the Reef Rescue Caring for Our Country investment program were provided as the numbers of hectares that have moved ‘from’ and ‘to’ each management class level. In the Burdekin region, baseline and management change data was provided at a River Basin scale (e.g. Black and Ross River basins). The threshold and progress towards target definitions are provided in Table 10.

Table 10 Pollutant load definitions of the status/progress towards the Reef Plan 2009 targets

Status/progress	**Pesticides, nitrogen and phosphorus**			**Sediment**		
	Target – 50% reduction in load by 2013			**Target – 20% reduction in load by 2020**		
	June 2011 reductions	**June 2012 reductions**	**June 2013 reductions**	**June 2011 reductions**	**June 2012 reductions**	**June 2013 reductions**
Very poor progress towards target – 'Increase in the catchment load'	None	0–5%	5–12.5%	None	0–1%	1–3%
Poor progress towards target – 'No or small increase in the catchment load'	0–5%	5–12.5%	12.5–25%	0–1%	1–3%	3–5%
Moderate progress towards target – 'A small reduction in catchment load'	5–12.5%	12.5–25%	25–37.5%	1–3%	3–5%	5–7%
Good progress towards target – 'A significant reduction in catchment load'	12.5–25%	25–37.5%	37.5–49%	3–4%	5–6%	7–8%
Very good progress towards target – 'A high reduction in catchment load'	>25%	>37.5%	>50%	>4%	>6%	>8%

3.4.1.1 Sugarcane

To represent the effects of A,B,C or D management practices for sugarcane daily timeseries files of loads in runoff per day per unit area were generated from the APSIM or HowLeaky model for combination of soil type, climate, constituent and management system. These daily loads were then accumulated into a single timeseries (per constituent) according to spatially relevant weights and loaded into the Source Catchments model for each subcatchment. This process allowed the inclusion of spatial (and management) complexity that the Source Catchments model was unable to represent. The impact of fertiliser and soil management practices on DON has not been modelled. For further details on this methodology see Shaw & SIlburn (2014).

For sugarcane nutrient, soil and herbicide management, the majority of the nutrient baseline management was C practice (72%), for soil and herbicide C practice (92%) and (55%) respectively (Table 11).

Table 11 Summary of the baseline management and management changes for sugarcane (% area) for the baseline and Report Cards 2010–2013

Management system	Period	A	B	C	D
		(%)			
Nutrient	Baseline	5	7	72	16
	2008-2010	13	31	42	15
	2008-2011	13	33	39	15
	2008-2012	13	34	38	14
	2008-2013	15	36	35	14
Herbicide	Baseline	0	35	55	10
	2008-2010	6	34	51	9
	2008-2011	7	36	48	8
	2008-2012	8	37	47	8
	2008-2013	8	38	46	8
Soil	Baseline	0	0	92	8
	2008-2010	2	2	90	7
	2008-2011	2	3	89	6
	2008-2012	5	1	88	5
	2008-2013	7	2	86	5

3.4.1.2 Grazing

In grazing lands, for the baseline condition, the ABCD management practice was represented by different ground cover classifications. Cover for the grazing areas were derived from the Ground Cover Index (GCI), which was then translated into a C-factor. The C-factor is required in the RUSLE equation, used for sediment generation in grazing lands.

In grazing the GRASs Production model (GRASP) (McKeon et al. 1990) provided scaling factors for adjusting RUSLE C-factors where management practice changes occur. These C-factor scaling factors have been derived for a range of climates and pasture productivity levels or land types that occur within the GBR catchments. The GRASP model was chosen for grazing given it has been extensively parameterised for northern Australian grazing systems (McKeon et al. 1990). The C-factor decreases (ground cover increases) related to an improvement in management practice were then applied to the GCI derived C-factor values used to model the baseline. For management changes (e.g. from C to B) to be assigned in a reportable and repeatable fashion, the farms ('properties' as discernable from cadastral data) representing grazing needed to be spatially allocated into a baseline A, B, C or D management class according to the average GCI conditions observed at that property over time. A methodology was adopted which compared GCI in properties for two very dry years a decade apart (Scarth et al. 2006). Properties that maintained or increased cover over this time were considered to be well managed while properties where cover decreased were considered to have been poorly managed. Higher ranked properties were assigned into 'A' management until the area matched the required regional baseline area, and this was repeated for B, C and finally D management classes. Changes were assigned within the relevant management class in each region. For example, changes from C to B were assigned randomly to areas defined as 'C' management for the baseline year within the river basin specified.

For further detail on the GRASP modelling and spatial allocation of the derived cover factor changes refer to Shaw & Silburn (2014). The paddock model outputs from changed management are then linked to Source Catchments to produce relative changes in catchment loads. For grazing, the majority of the baseline management practice for soil was in B class, Table 12 provides area (%) of the ABCD framework for the baseline, Report Cards 2010–2013.

Table 12 Summary of the baseline management and management changes for grazing (% area) for the baseline and Report Cards 2010–2013

Management system	Period	A	B	C	D
		(%)			
Soil	Baseline	16	55	27	2
	2008-2010	17	56	25	2
	2008-2011	17	57	23	2
	2008-2012	20	55	23	2
	2008-2013	22	56	20	2

Riparian fencing

Improved grazing management (in particular cover management) can have both a direct and indirect effect on gully and streambank erosion rates. Indirect effects of improved grazing management or increasing cover on hillslopes can reduce runoff rates and volumes from upstream contributing areas to a gully or stream. This process is represented in the model by implementing relative reductions in rates of erosion per management class, as described by (Thorburn & Wilkinson 2012), Table 13. The direct effects of riparian fencing are a result of increased cover on the actual stream or gully. Both have a beneficial effect on erosion rates from these areas.

Table 13 Gully and streambank erosion rates relative to C class practice. (Adapted from Table 4, (Thorburn & Wilkinson 2012)

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

To represent this indirect effect on streambank erosion, a spatial analysis was conducted identifying the proportion of each Source Catchments' stream associated with each grazing management class. These proportions were used to produce a weighted streambank erosion rate adjustment factor, with this adjustment factor applied to the bank erosion coefficient for the relevant stream.

Similarly, the gully erosion model implemented by Dynamic SedNet has a management factor parameter, to which the area-weighted average of relative gully erosion rates (based on predicted distribution of grazing management practices) was applied for both the total baseline and Report Cards 2010–2013 scenarios.

Indirect effects have been applied in Burdekin for Report Cards 2011–2013 only and riparian fencing data to represent direct effects was only provided to the modelling team for Burdekin for Report Card 2012 and beyond. For assessing the direct effect of riparian fencing, where investment in riparian fencing were identifiable, the riparian vegetation percentage for the stream was increased linearly with respect to the proportion of the stream now excluded from stock.

3.4.2 Predevelopment catchment condition

A series of assumptions on the catchment condition and erosion attributes were used to derive the predevelopment load. The predevelopment load and hence anthropogenic baseline load, refers to the prior to European settlement. The assumptions made to represent predevelopment conditions were:

- ground cover was increased to 90% on all land uses except for those in the Black basin were cover was increased to 95% to represent higher rainfall values and thus cover in this area. conservation land use retain its original cover values
- a Foliage Projected Cover (FPC) was created to represent 100% riparian cover in the Stream parameteriser, and
- gully cross-section area was reduced from 10 m^2 to 1 m^2 (90% reduction)

To be consistent with previous catchment modelling undertaken in the GBR, the hydrology, storages and weirs were left unchanged in models in which they are present. Therefore, the load reductions reported were solely due to land management change. As per Table 9 the predevelopment scenario was run from 1986 to 2009.

3.5 Constituent load validation

Four approaches were used to validate the GBR Source Catchments modelling. Firstly, a comparison was made with the previous best estimates in Report Card 1 (Kroon et al. 2012). Secondly, a long-term comparison was made with catchment load estimates derived from all available measured data for the high priority catchments for the 23 year modelling period (Joo et al. 2014) and thirdly, a short-term comparison was made using load estimates from monitoring results that commenced in 2006 in ten high priority catchments (Turner et al. 2012, Joo et al. 2012). Fourthly, a range of other measured datasets at smaller time scales were also included, see section 3.5.4.

3.5.1 Previous best estimates-Report Card 1

Kroon et al. (2012) reported current, Pre-European and anthropogenic loads from the 35 reef catchments (in six NRM regions) (Table 22), using published and available loads data. The best estimates for the Burdekin region of the ‘current’ loads (except PSIIs) were either from Post et al. (2006) which was based on SedNet modelling or loads generated from the Loads Regression Estimator (LRE). For the Burdekin, the Load Regression Estimator (LRE) methodology was used (Kroon et al. 2012) to estimate annual pollutant loads with uncertainties for each water year where GBR catchment monitoring data was collected by using a four step process outlined in (Wang, Kuhnert & Henderson 2011). The remaining catchments had loads from the last round of SedNet modelling in the area (Post et al. 2007). The Pre-European loads described were from (McKergow et al. 2005a, McKergow et al. 2005b). Both of these studies also used the SedNet model, but with different input data sets and parameters to the SedNet modelling (Post et al. 2007). The PSII catchment load estimates reported in Kroon et al. (2012) were derived from (Maughan, Brodie & Waterhouse 2008) and (Brodie, Mitchell & Waterhouse 2009). Lewis et al. (2011) has also estimated PSII loads and has been included in the graph showing PSIIs. The difference between the (Kroon et al. 2012) current and Pre-European load resulted in the ‘anthropogenic’ load. Anthropogenic loads are not compared in this report due to large differences in the methodology used to derive the loads and the differing periods modelled. The Report Card 1 loads by catchment are presented in Appendix A – Previous estimates of pollutant loads. It should be noted that any comparisons made with RC1 are indicative only, as no information was provided on the dates or time period over which these average annual loads are derived.

3.5.2 Long-term FRCE and LRE loads (1986 to 2009)

Annual sediment and nutrient load estimates were required to validate the GBR Source Catchments outputs for the period July 1986 to June 2009 (23 years). Prior to the GBR Catchment Loads Monitoring Program (GBRCLMP), water quality data was collected sporadically and often was not sampled for critical parts of the hydrograph. There have been previous attempts to calculate long-term load estimates from this sporadic data. (Joo et al. 2014) has collated all appropriate data sets to generate estimates of daily, monthly, annual and average annual loads for a range of EOS gauging stations across the GBR. The standard approaches were examined including averaging, developing a concentration to flow relationship (regression) and/or the Beale Ratio (Joo et al. 2014, Marsh & Waters 2009, Richards 1999). It is acknowledged that these can result in large errors in the load estimates especially when extrapolating far beyond the sampled flow ranges due to a lack of representative data (Joo et al. 2014, Marsh & Waters 2009). (Joo et al. 2014) has applied a Flow Range Concentration Estimator (FRCE) method (a modified Beale ratio method) to provide estimates of annual loads. The mean modelled loads were compared with the likely upper and lower, and mean, FRCE load for TSS, TN, DIN, TP and DIP across 23 water years (1/7/1986 to 31/6/2009). In the Burdekin the Burdekin Basin LRE (Kuhnert et al. 2012) and Burdekin FRCE (Joo et al. 2014) loads are compared with the Source Catchments EOS outputs. These two estimates the have also been combined into a “Kuhnert_Joo” average adding to the Source Catchments comparison dataset.

In addition to the average annual comparison, Moriasi et al. (2007) developed statistical model evaluation techniques for streamflow, sediment and nutrients. Three quantitative statistics were recommended: Nash-Sutcliffe coefficient of efficiency (NSE), percent bias (PBIAS) and the ratio of the root mean square error to the standard deviation of validation data (RSR). Model evaluation performance ratings were established for each recommended statistic, and are presented in Table 14. Modelled and measured monthly loads were then assessed against these ratings.

Table 14 Performance ratings for recommended statistics for a monthly time-step (from Moriasi et al. 2007)

Performance rating	RSR	NSE	PBIAS	
			Sediment	N,P
Very good	0.00-0.50	0.75-1.00	<±15	±25
Good	0.50-0.60	0.65-0.75	±15-±30	±25-<±40
Satisfactory	0.60-0.70	0.50-0.65	±30-±55	±40-±70
Unsatisfactory	>0.70	<0.50	>±55	>±70

3.5.3 GBR Catchment Loads Monitoring Program (GBRCLMP) – (2006 to 2010)

In 2006, the Queensland Government commenced a GBR Catchment Loads Monitoring Program (GBRCLMP) designed to measure sediment and nutrient loads entering the GBR lagoon (Joo et al. 2012). The water quality monitoring focussed at the end-of-system (EOS) of ten priority rivers; Normanby, Barron, Johnstone, Tully, Herbert, Burdekin, O’Connell, Pioneer, Fitzroy, Burnett and 13 major sub-basins. Water sampling of herbicides commenced in 2009/2010 in eight GBR catchments and three subcatchments (Smith et al. 2012). Analysis of water samples was conducted to test for numerous pesticides including the five priority PSII herbicides that are commonly detected from GBR catchments: diuron, atrazine, hexazinone, ametryn and tebuthiuron and also organochlorine and organophosphate insecticides (e.g. Endosulfan). In general, the EOS sites capture freshwater flows from 40% to 99% of total basin areas and do not include tidal areas and small coastal catchments (Joo et al. 2012). In the Burdekin region, modelled and GBRCLMP load estimates are compared for the Burdekin catchment for the 2006 to 2010 period at the EOS for TSS, TP, DIP, TN, DIN, (Turner et al. 2012, Joo et al. 2012).

3.5.4 Other datasets

The Burdekin Falls Dam load dataset (2005-2009) is used for model comparison and is outlined in Lewis et al. (2013). Here, estimates of sediment loads and flow into and out of the dam are estimated. Lewis has used load calculation data and techniques outlined in Kuhnert et al. (2012). Importantly some of the loads are based on limited sampling data, so the various years have various levels of uncertainty and accuracy afforded to them.

A sediment tracing study in the Burdekin basin using fall out radionuclides (FRN) and geochemistry has been under taken by Wilkinson et al. (2013). The study uses these techniques to identify the spatial source, and the contributions of surface and subsurface soil to fine sediment export. The study area consists of three smaller catchments within the Burdekin, two of the catchments, Keelbottom Creek (1,200 km^2) and Weany Creek (14 km^2), are located in the Upper Burdekin catchment. The other study site comprises the majority of the Bowen River catchment (9,400 km2). Source samples were obtained from hillslope top soil and gully walls within the catchments. Riverine samples were obtained in two ways: in 2007 they were sourced from deposition on trees and banks ~ 1-8 m above the river bed and are representative of sediment transported in February 2007 events; and in January and March 2008 bulk river samples (~100 L) were taken for large events over the rising and falling stages of the hyrdrographs. More detail on this method is outlined in Wilkinson et al. (2013).

4 Results

This section is separated into hydrology and water quality. For hydrology, the results of the calibration process will be presented, as well as a general summary of the hydrology of the GBR regions. The water quality results section includes modelled sediment, nutrient and herbicide total baseline loads, and the anthropogenic baseline and predevelopment loads. Progress towards Reef Plan 2009 targets is reported against the 2009 anthropogenic baseline for Report Card 2013. . The validation of the Burdekin results is then presented using load estimates from measured data and previous modelled data. The focus is around those constituents that are identified as high risk to the GBR from the Burdekin region namely TSS, DIN and PSII herbicides (Waterhouse et al. 2012). For a full list of the Burdekin region loads for Report Cards 2010–2013 refer Appendix E-H.

4.1 Hydrology

4.1.1 Calibration performance

Model performance was assessed for the gauges used in the calibration and active during the modelling period (01/07/1986–30/06/2009), plus a number of other gauges not used in the calibration. These extra gauges can be viewed as independent of the calibration and are therefore useful as validation sites for model performance assessment in ungauged locations.

The calibration results for key sites within the Burdekin and Coastal basins are shown in Table 15. Here key sites are defined as the sub catchment sites in the Burdekin, the Burdekin Falls Dam and the EOV Burdekin River at Clare (Figure 1) (GS 120006b). While for the coastal basins; gauges with the largest catchment area were selected (Figure 2). The results for the three performance criteria daily Nash-Sutcliffe (>0.5), monthly Nash-Sutcliffe (>0.8) and total modelled volume difference ± 20% of observed volume are listed. A 'traffic light' colour scheme identifies those gauges that met criteria as green and gauges that did not meet criteria as red. Six of eleven gauges (54%) met all three of the above criteria. In terms of daily and monthly Nash Sutcliffe Coefficient of Efficiency, 72% and 81% of gauges respectively met the criteria. For the Percentage volumetric error, 81% of gauges met the criteria. Large difference in percentage volume occurred for 120301b, Belyando River at Gregory Development Rd.

Table 15 Model Performance; Burdekin region hydrology calibration. Red = criteria not met, Green = Criteria met, Blue = Gauge used in calibration

Basin	Gauge name	Gauge ID	Catchment area (km^2)	Daily NSE	Monthly NSE	Total volume difference (%)
Burdekin	Burdekin River at Sellheim	120002C	36,260	0.73	0.97	2%
Burdekin	Cape River at Taemas	120302B	16,074	0.65	0.88	6%
Burdekin	Belyando River at Gregory Development Rd.	120301B	35,411	0.52	0.67	-61%
Burdekin	Suttor River at St Anns	120303A	50,291	0.64	0.78	-18%
Burdekin	Burdekin Falls Dam	120004	114,654	0.80	0.96	6%
Burdekin	Bowen River at Myuna	120205A	7,104	0.35	0.88	22%
Burdekin	Burdekin River at Clare	120006B	129,876	0.80	0.96	2%
Black	Black River at Bruce Highway	117002A	256	0.35	0.83	-9%
Ross	Ross River at Ross River Dam Headwater	118104A	747	0.63	0.85	-14%
Haughton	Haughton River at Powerline	119003A	1,773	0.44	0.90	-6%
Don	Don River at Reeves	121003A	1,016	0.76	0.88	11%

A full list of calibration results for all gauges active during the modelling period are shown in Table 25, Appendix C. In the Black basin, all three calibration criteria were met for gauge 117003a despite a relatively small catchment area (86 km^2). The Ross basin recorded good calibration for gauges 118106a and 118104a. In contrast, performance statistics were poor for 118003a and 118001b. The Haughton basin recorded good calibration for gauges 119006a and 119005a. All performance criteria were met in the Don basin apart from daily and monthly NSE for gauge

121001a.

In the Upper Burdekin catchment, all performance criteria were met when catchment area was greater than 2000 km^2. Three gauges had an area less than 2000 km^2. Poor daily NSE was recorded for gauges 120112a and 120106b. A relatively poor calibration was recorded for the smallest catchment 120102a; here poor volume and monthly NSE were recorded. The Cape catchment had only one extra gauge upstream from the end of valley gauge. Here all calibration statistics were met. In the Belyando Suttor, poor calibration was recorded apart from gauge 120305a. The Bowen catchment was the worst performed catchment in terms of meeting few of the calibration criteria.

Time series plots of gauged sub-basins of Sellheim, Suttor and Cape show an under prediction of peak flow at the daily time scale, however the fit at a monthly and yearly scale showed good agreement with observed data (Appendix C) (Figure 26). Error was reasonably well scattered as discharge increased (Figure 10) and regression shows a good fit in terms of total volume, with larger relative scatter associated with smaller discharges (Figure 11).

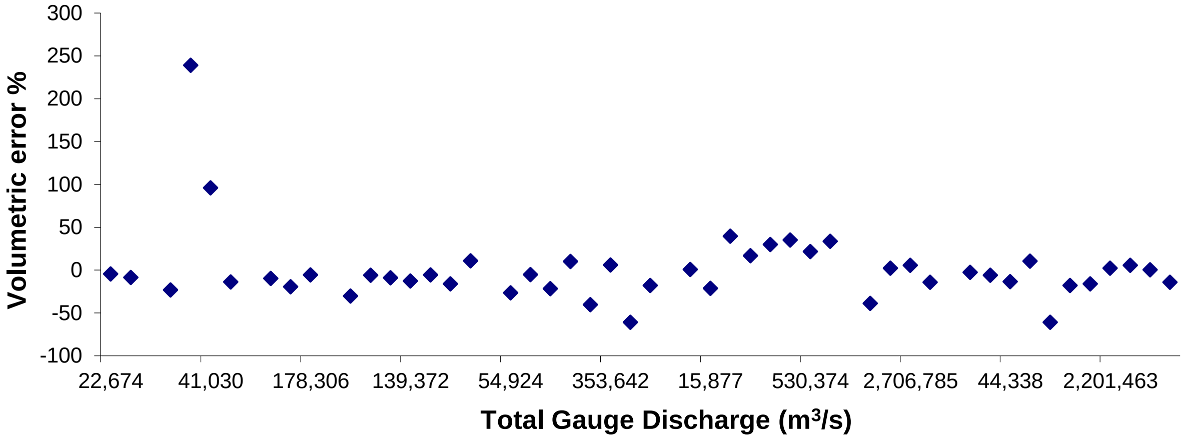

Figure 10 Burdekin region PEST calibration; volumetric error (%) vs total gauge volume (m^3/s)

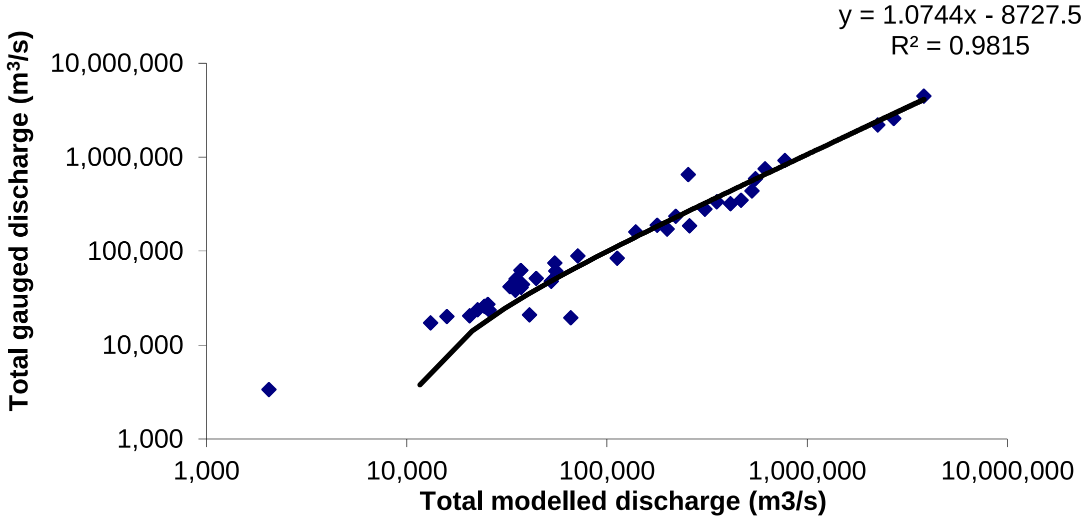

Figure 11 Burdekin region total gauged vs modelled volumes (m^3/s)

Annual comparisons for wet and dry periods are selected to ensure the model is representing the extreme climate periods adequately. The model run period from 1986–2009 captured both wet and dry periods across the Burdekin region. Figure 12 shows the gauged and modelled flow volumes for (a) the average annual flow during the period, (b) the water year with the most discharge and (c) a low flow year. Modelled average annual flow volumes in general match the observed. In addition wet years such as the 1990 water year, match observed given the uncertainties in gauged flow during these high flow events. However, in the dry years considerable differences between observed and modelled flows are apparent, as outlined in the 1991 water year.

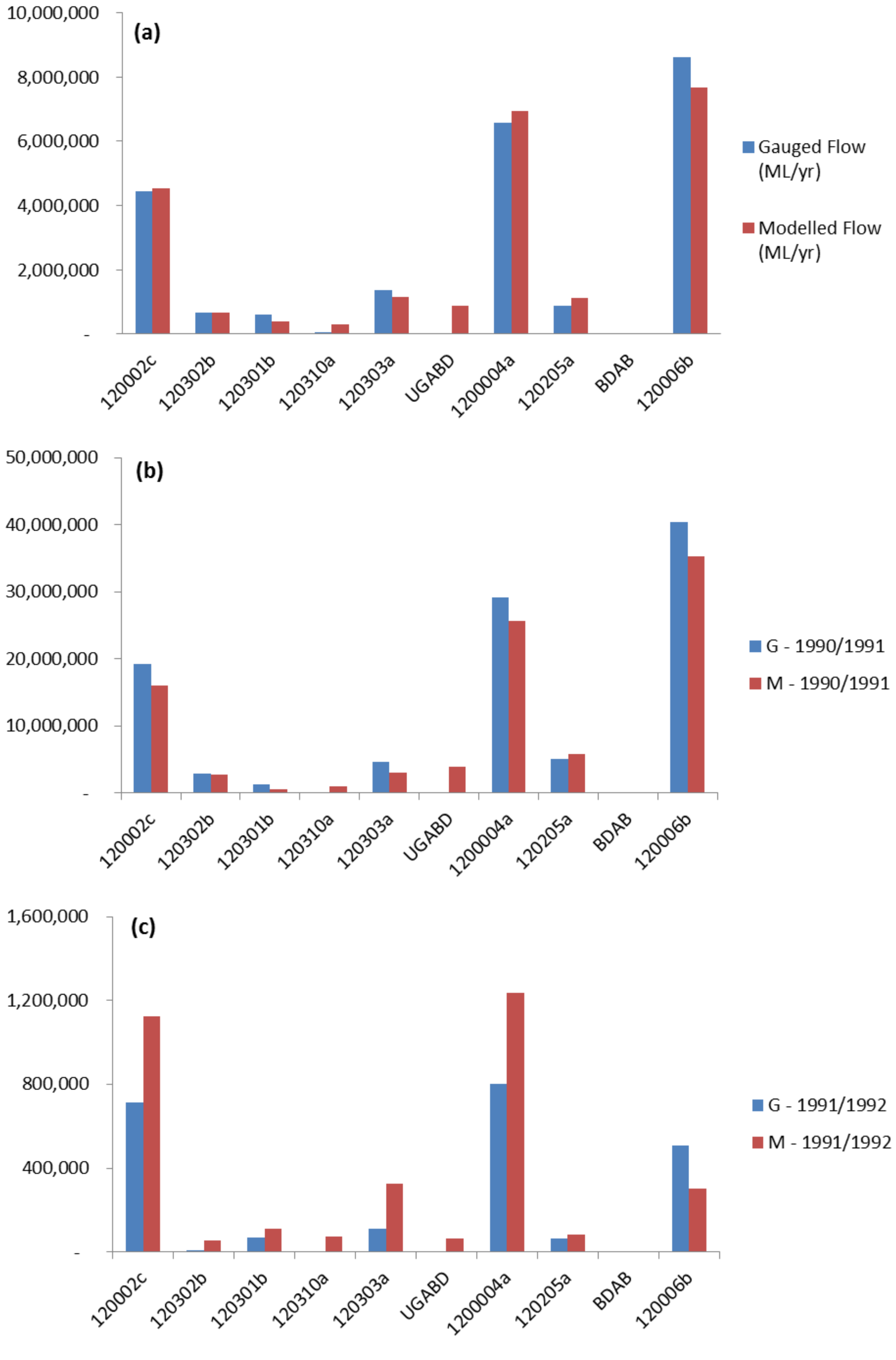

Figure 12 Gauged and modelled flow (ML) for key Burdekin Catchment sites. (a) Average annual discharge (1986–2008), (b) 1990/1991 water year (wettest year) (c) 1991/1992 water year (driest year)

4.1.2 Regional discharge comparison

The modelled average annual flow for the Burdekin region was ~12,000,000 ML/yr or 19% of the total GBR average annual flow (Figure 13). The Wet Tropics has the largest average annual flow for the modelled period compared to the five other GBR regions. The next largest flow was from the Cape York region (18,000,000 ML/yr), which is roughly double the area of the Wet Tropics region.

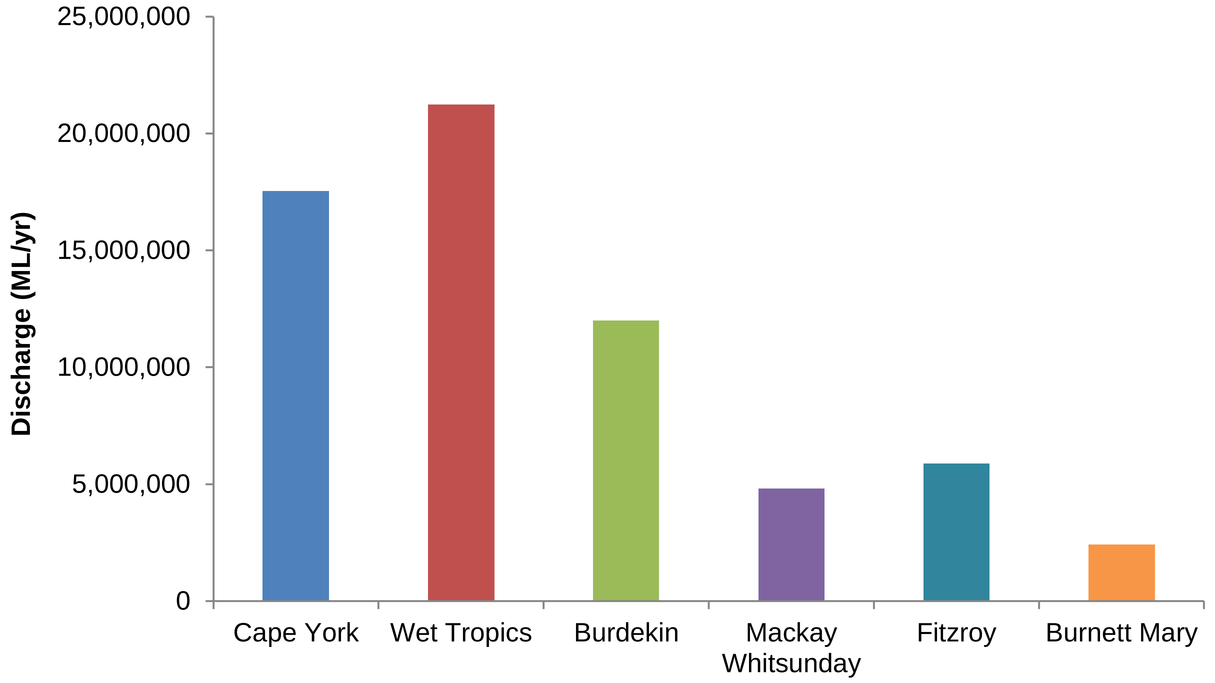

Figure 13 Annual average modelled discharge for GBR regions (1986–2009)

4.1.3 Burdekin region flow characteristics

The annual modelled regional flow is ~12,000,000 ML/yr, with the Burdekin basin contributing 9,000,000 ML/yr (~74% of total for the region). Of the coastal catchments, the Haughton contributes 1,000,000 ML/yr, Don 850,000 ML/yr, Black 620,000 ML/yr and Ross 570,000 ML/yr. Four years contribute ~50% of the total flow, 1990, 1999, 2007 and 2008. The 1990 water year is the largest contributing ~20% of the total discharges (Figure 14).

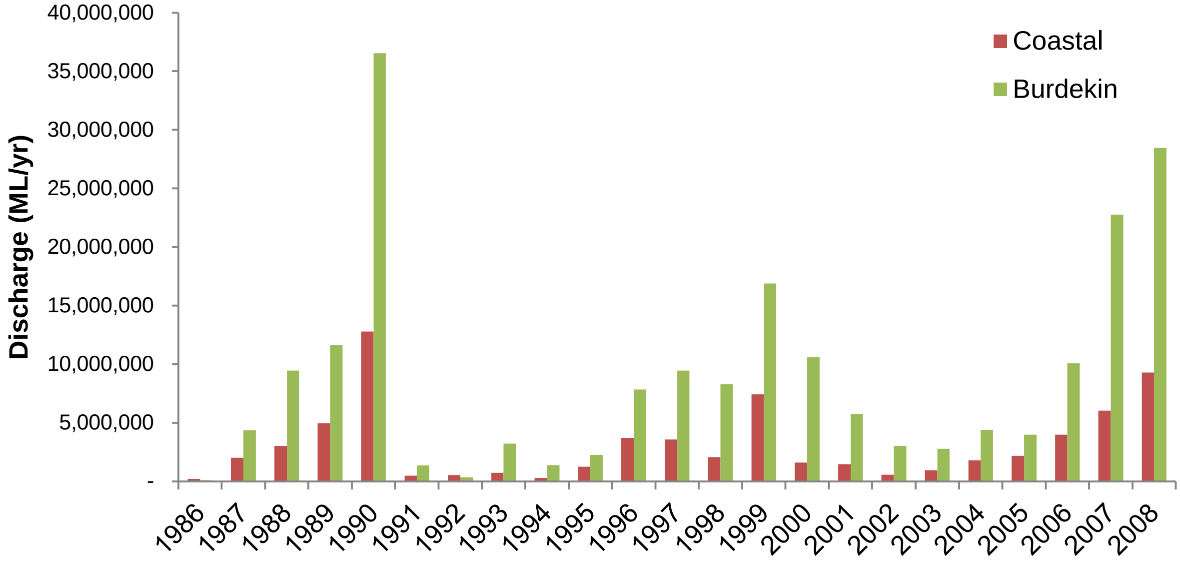

Figure 14 Annual modelled flow for the Burdekin and Coastal Basins (1986–2009)

4.2 Modelled loads

4.2.1 Total baseline load

The Burdekin and Wet Tropics NRM regions were the two highest contributors for nine of the ten constituents modelled. The Burdekin region had the greatest constituent total loads for TSS, PN, TP, DIP, and PP. Table 16 presents the total constituent load for all regions. Table 17 presents this data as a percent contribution across the GBR. The Burdekin region generated 3,976 kt/yr of TSS or 47% of the total GBR export load. The TN export load from the Burdekin region was 10,110 t/yr or 28% of total GBR export. It is estimated that 10,532 t/yr of DIN is exported from the GBR region; with the Burdekin region generating 25% of total GBR export or 2,647 t/yr.

The Burdekin region was the third highest contributor of DON at 22%. PN contributed 36% of the total export to the GBR. The majority of the Burdekin region TN export load was from dissolved N (~57% of TN), the remaining ~43% from PN. For phosphorus, the Burdekin region contributed 35% of the TP load, 29% of the DIP load, 25% of the DOP load and 37% of the PP load to the total GBR load. The majority of the Burdekin region TP export load was from PP (77% of TP), the remaining 23% from dissolved P. The GBR PSII herbicide export load was 16,740 kg/yr, with the Burdekin Region load 2,091 kg/yr (12% of GBR total export) and was considerably lower than the Wet Tropics (highest contributor).

Table 16 Total baseline constituent loads for the six GBR contributing regions

NRM region	Area (km^2)	TSS (kt/yr)	TN (t/yr)	DIN (t/yr)	DON (t/yr)	PN (t/yr)	TP (t/yr)	DIP (t/yr)	DOP (t/yr)	PP (t/yr)	PSIIs (kg/yr)
Cape York	42,988	429	5,173	492	3,652	1,030	531	98	195	238	3
Wet Tropics	21,722	1,219	12,151	4,437	3,870	3,844	1,656	228	130	1,297	8,596
Burdekin	140,671	3,976	10,110	2,647	3,185	4,278	2,184	341	153	1,690	2,091
Mackay-Whitsunday	8,992	511	2,819	1,129	950	739	439	132	35	271	3,944
Fitzroy	155,740	1,948	4,244	1,272	1,790	1,181	1,093	278	56	759	579
Burnett Mary	53,021	462	2,202	554	873	775	392	78	35	278	1,528
GBR total	**423,134**	**8,545**	**36,699**	**10,532**	**14,320**	**11,847**	**6,294**	**1,155**	**606**	**4,532**	**16,740**

Table 17 Area, flow and regional contribution as a per cent of the GBR total baseline loads for all constituents

NRM region	Area	Flow	TSS	TN	DIN	DON	PN	TP	DIP	DOP	PP	PSIIs
	% of GBR total											
Cape York	10.2	27.3	5.0	14.1	4.7	25.5	8.7	8.4	8.5	32.3	5.2	0.0
Wet Tropics	5.1	33.1	14.3	33.1	42.1	27.0	32.4	26.3	19.8	21.5	28.6	51.4
Burdekin	33.2	18.7	46.5	27.5	25.1	22.2	36.1	34.7	29.5	25.3	37.3	12.5
Mackay-Whitsunday	2.1	8.0	6.0	7.7	10.7	6.6	6.2	7.0	11.4	5.8	6.0	23.6
Fitzroy	36.8	9.1	22.8	11.6	12.1	12.5	10.0	17.4	24.0	9.3	16.7	3.5
Burnett Mary	12.5	3.8	5.4	6.0	5.3	6.1	6.5	6.2	6.8	5.8	6.1	9.1
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Within the Burdekin region, the Burdekin basin was the greatest contributor for all constituents, except PSII herbicides (Table 18). This is not surprising given that the Burdekin has by far the greatest area and the Haughton basin contains the largest area of sugarcane and has the greatest contribution of PSII herbicides.

Table 18 Contribution of Burdekin basins to the total baseline Burdekin region load

Basin	TSS (%)	TP (%)	PP (%)	DIP (%)	DOP (%)	TN (%)	PN (%)	DIN (%)	DON (%)	PSIIs (%)
Black River	3	3	3	4	4	4	4	3	5	1
Ross River	3	4	2	10	9	5	3	8	5	0
Haughton River	7	12	9	22	15	14	7	29	11	65
Burdekin River	80	73	77	59	66	69	75	54	73	30
Don River	8	8	9	5	6	8	10	5	6	4
Regional total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

4.2.2 Total baseline load-sources and sinks

The Burdekin region predicted mean annual input of fine sediment to the stream network is shown in Table 19. Sub-surface or channel erosion, in this instance is defined as bank and gully erosion. Sub-surface erosion contributes the highest regional erosion source comprising (57%) of the fine sediment input with hillslope erosion 43% and undefined <1%. EMC models (diffuse dissolved) are small suppliers, due to the area occupied by their parent land use (urban and horticulture). Hillslope erosion is the dominant source in the steeper Coastal Basins while in the Burdekin Basin, channel erosion is the dominant source.

At the Burdekin region scale, open grazing supplies the most fine sediment (3,139 kt/yr or 35% of total), followed by grazing forested (2,392 kt/yr or 27% of total). Conservation land use is a major source of supply in the Black and Ross basins. The Don basin has similar proportions to the Burdekin basin with grazing dominating supply, whereas in the Haughton, sugar and grazing are the dominant sources.

In terms of the sediment supplied to streams at the Burdekin region scale, not all sediment is exported to the end-of-system. Of the sediment supplied from catchments; 55% is deposited or removed, with 30% in reservoir deposition, 21% from floodplain deposition and 3% removed via extraction. Within the Burdekin basin the Burdekin Falls Dam traps 34% of total sediment supplied to the basin. The Eungella and Paluma Dams trap a negligible amount of the entire budget due to low levels of supply. At the Burdekin region scale, diffuse dissolved nitrogen is the dominant source of DIN supplied to stream network comprising (94%) of the DIN input (Table 19), with point sources (STP's) supplying 6%. In terms of land use supply at the Burdekin region scale, grazing supplies the most DIN (1,201 t/yr or 44% of total), followed by Sugarcane (952 t/yr or 35% of total).

Diffuse dissolved is the dominant source comprising (100%) of the PSII input. At the Burdekin region scale, sugarcane supplies the most PSII (2,171 kg/yr or 89% of total), followed by dryland cropping (120 kg/yr or 5% of total). This is to be expected due to the dominance of these two land uses in terms of PSII application. In terms of PSII supplied to streams not all PSII is exported to the end-of-system. Of the PSII supplied from catchments; 14% is decayed in stream.

Table 19 Burdekin region fine sediment (TSS), DIN, PSIIs source sink

Process	TSS (kt/y)	TSS (%)	DIN (t/y)	DIN (%)	PSII (kg/y)	PSIIs (%)
Sources	**8,880**	**100**	**2,705**		**2,428**	**-**
Hillslope	3,792	43	-	-	-	-
Gully	2,784	31	-	-	-	-
Streambank	2,293	26	-	-	-	-
Point Source	-	-	162	6	-	-
Diffuse Dissolved	-	-	2,543	94	2,428	100
Undefined	11	0				
SINKS	**4,905**	**100**	**60**	**100**	**338**	**100**
Extraction	271	6	46	78	2	1
Flood Plain Deposition	1,890	39	-	-	-	-
Reservoir Deposition	2,743	56	-	-	-	-
Reservoir Decay	-	-	-	-	-	-
Residual Link Storage	0	0	13	22	0	0
Stream Decay	-	-	-	-	335	99
Stream Deposition	-	-	-	-	-	-
EXPORT	**3,976**		**2,645**		**2,091**	

4.2.3 Anthropogenic baseline and predevelopment loads

The anthropogenic baseline load is calculated by subtracting the predevelopment load from the total baseline load. The TSS anthropogenic baseline load was 2,525 kt/yr or 64% of the total baseline load with the remaining 36% attributed to the predevelopment load. The Burdekin region contributes 45% of the total GBR TSS anthropogenic load. When the anthropogenic component is expressed as a percentage of the total baseline load, within the Burdekin region, all Basins except the Black and the Ross had values greater than >50% (Figure 15). The constituents and their Basin source within the Burdekin region are shown in Appendix E (Table 38).

Within the Burdekin region the Burdekin basin generated the highest baseline fine sediment load at 2,146 kt/yr (85% of Burdekin region load), followed by the Don at 171 t/yr (7%) and Haughton with 185 kt/yr (6%) (Figure 15). The Burdekin basin also provides the highest anthropogenic DIN contribution to Burdekin region at 860 t/y (45%), followed by the Haughton with 701 t/y (37%). The Haughton catchment contributes the majority of the PSII load with 1,353 kg/y (65%).

The total baseline nitrogen load exported from the Burdekin region is estimated at 10,110 t/yr, of which 5,816 t/yr or 58% is anthropogenic load. The Burdekin region contributes 35% GBR anthropogenic baseline load. Of the TN baseline load, DIN contributed 36% of the GBR total 33% of the DON load and 35% of the PN load

The total phosphorus load exported from the Burdekin region is an estimated 2,184 t/yr, of which 1,293 t/yr or 59% is estimated to be the anthropogenic load and makes up 36% of the GBR total anthropogenic loads. Of the TP baseline load, PP contributed 34% of the GBR baseline. The Burdekin region was the highest contributor for TP and PP baseline loads.

By land use sugarcane had the highest anthropogenic DIN load contributing 48% of the anthropogenic load. For TSS load, grazing and streambank erosion supplied the majority of the anthropogenic load.

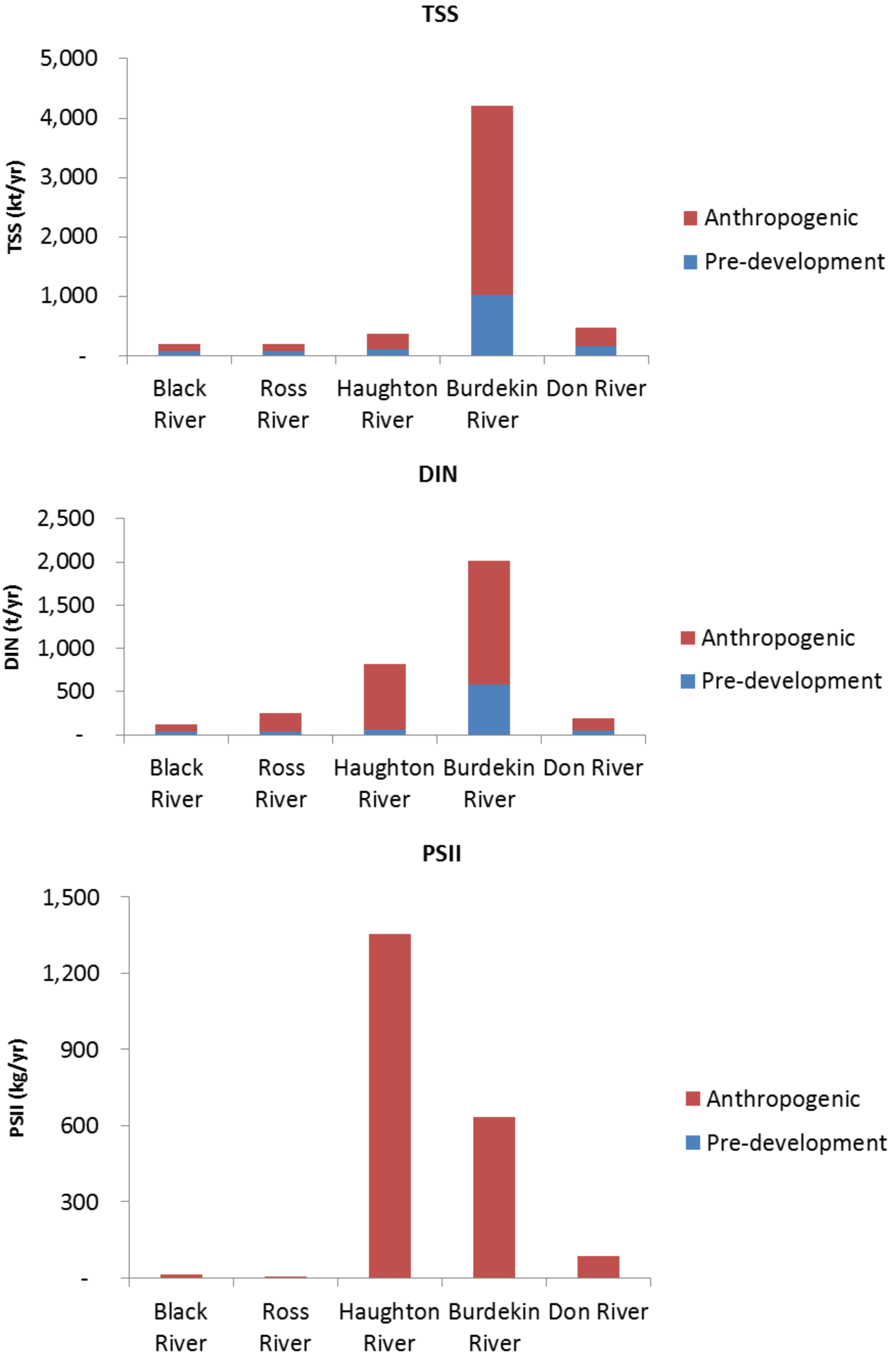

Figure 15 Burdekin region basins; showing total baseline load, (anthropogenic baseline plus predevelopment) for main reef WQ pollutants of concern

4.3 Constituent load validation

There were a range of water quality datasets against which the Burdekin region Source Catchments modelling results could be compared or validated. The four sources are 1) the previous best estimates from Report Card 1 (LRE and SedNet) (Kroon et al. 2012), 2) the long-term loads report (1986–2009) using the FRCE and LRE methods (Joo et al. 2014), 3) GBRCLMP 2006-10 monitoring program established by the Queensland State Government (Turner et al. 2012, Joo et al. 2012) and 4) other validation data sets which included sediment tracing and the Burdekin Falls Dam dataset outlined in the methods.

4.3.1 Previous estimates

A comparison was made between RC1 load estimates (Kroon et al. 2012) (Table 22) and the Source Catchments modelled loads for TSS, DIN and PSII (Figure 16). Here the estimates for the Black, Ross, Haughton and Don are based on prior average annual SedNet modelling. While in the Burdekin basin, estimates are derived from long-term monitored water quality data and have been calculated using a loads regression estimator (LRE) (Kuhnert et al. 2012)

When the Source Catchments modelled TSS loads are compared against (Kroon et al. 2012) the Black, Ross and Don Basins show modelled loads at the higher end of these estimates. In contrast, the Burdekin basin fine sediment load is ~21% lower than (Kroon et al. 2012). In the Haughton the estimate ~13% less than Kroon et al. (2012).

Comparing the Source Catchments modelled DIN load against (Kroon et al. 2012) the Black, Ross, Haughton and Don Basins show higher modelled loads. In contrast, in the Burdekin the DIN load is ~20% less than the LRE estimate.

When compared against Kroon et al. (2012) the PSII Source Catchments modelled load across the Basins are considerably less, with the exception being the Ross Basin. In contrast the loads are greater than Lewis et al. (2011), with the exception being the Don.

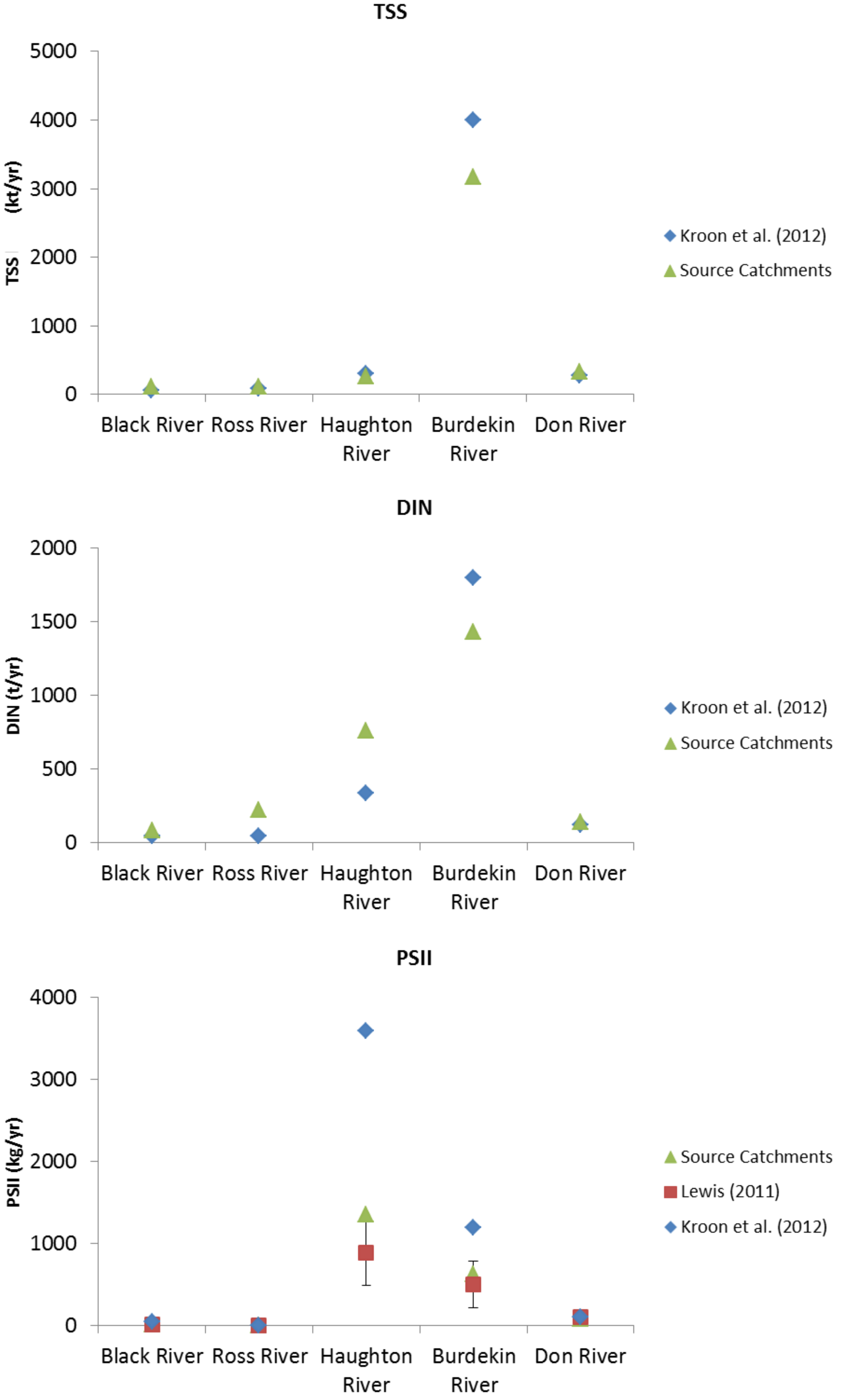

Figure 16 Burdekin region basins; Total baseline load estimates for main reef WQ pollutants of concern

4.3.2 Long-term FRCE and LRE loads (1986–2009)

Estimates of catchment loads were calculated by Joo et al. (2014) (Figure 17) using all available measured water quality data for the Burdekin Basin. The average annual modelled loads for the Burdekin are in relatively close agreement with the estimated loads for the same period with % differences ranging from 30% for TSS to -39% for TP. All modelled annual loads apart from DIP are within the likely upper and lower ranges estimated by Joo et al. (2014).

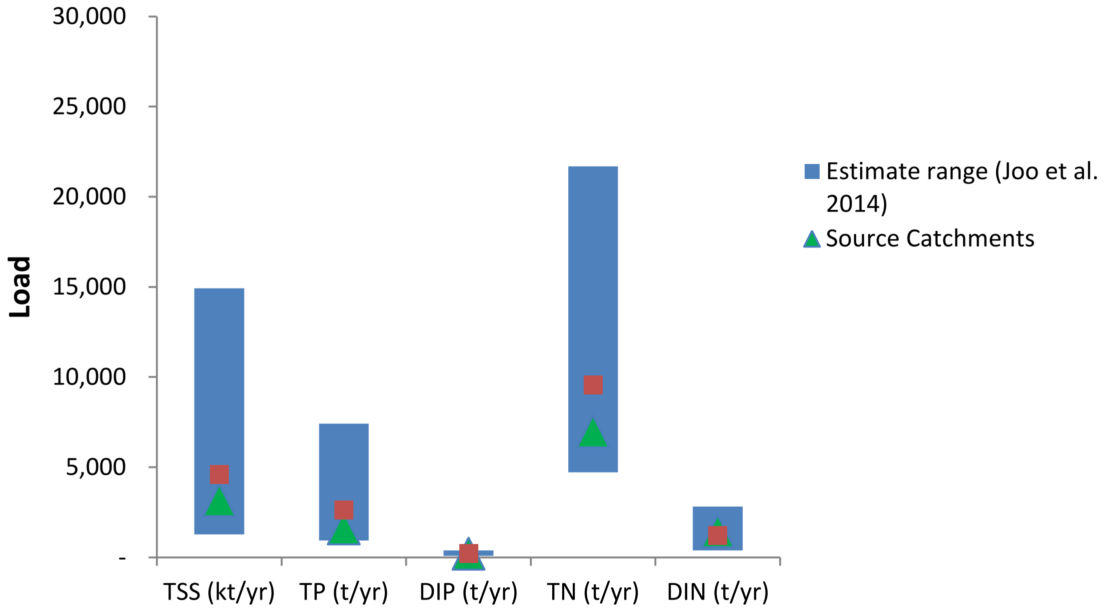

Figure 17 Comparison between modelled loads and loads estimated by Joo et al. (2014) for the Burdekin between 1986 and 2009 (modelling period)

Model performance for the Burdekin basin was also assessed against Joo et al. (2014) at the monthly time-step using the performance criteria recommended by (Moriasi et al. 2007) and outlined in Table 14. Model performance was rated as "good" to "satisfactory" for TSS, TN and TP at a monthly time-step for the 23 year modelling period (Table 20).

Table 20 Burdekin basin general performance ratings when compared to (Joo et al. 2014) for recommended statistics for a monthly time-step (from Moriasi et al. 2007)

Performance rating	NSE		RSR		PBIAS	
	Value	Result	Value	Result	Value	Result
TSS	0.64	Satisfactory	0.60	Good	31.06	Satisfactory
TN	0.65	Good	0.59	Satisfactory	26.96	Good
TP	0.53	Satisfactory	0.69	Satisfactory	38.55	Good

At the annual time-step, load estimates for annual fine sediment loads (Burdekin River at Clare) are shown in Figure 18 (a,b,c). The load estimates of Kuhnert et al. (2012) and Joo et al. (2014), show substantial variations for some water years, in particular 1990 and 2008 and this highlights some of the uncertainty in calculating and comparing annual loads. As such, and not knowing which load is more valid in a particular year, the two estimates have been combined into a "Kuhnert_Joo" average load comparison dataset (Figure 18c). Here a water year is defined as 01/07/1986 – 30/06/1987.

To aid analyses and interpretation, water years have been classified by the size of the TSS load generated. For this exercise we have classed years as "Large" when load is >10,000 kt/y, "Midsized" (1,000 – 10,000 kt/y) and "Small" (<1,000 kt/y).

Water years defined as "Large" by load, total three years and comprise 54% of the fine sediment load. Individually the years defined as large are represented by the 1990 year contributing 22%, followed by 2007 (17%) and 2008 (15%). "Midsized" years total 11 and export ~42% of the load while "Small" years total 9 and export only ~4% of the total load.

The model loads track reasonably well, when compared against Kuhnert et al (2012) (Figure 18) with an NSE of ~0.71. However, predictive capability drops against (Joo et al. 2014) with an NSE value of ~0.66, but is slightly higher when compared against the Joo_Kuhnert average (NS ~0.72)

By classification, the "Large" years are ~40% lower than the Joo_Kuhnert estimate, while the "Midsized" years are approximately ~16% lower, in contrast years defined as "Small" are well over predicted.

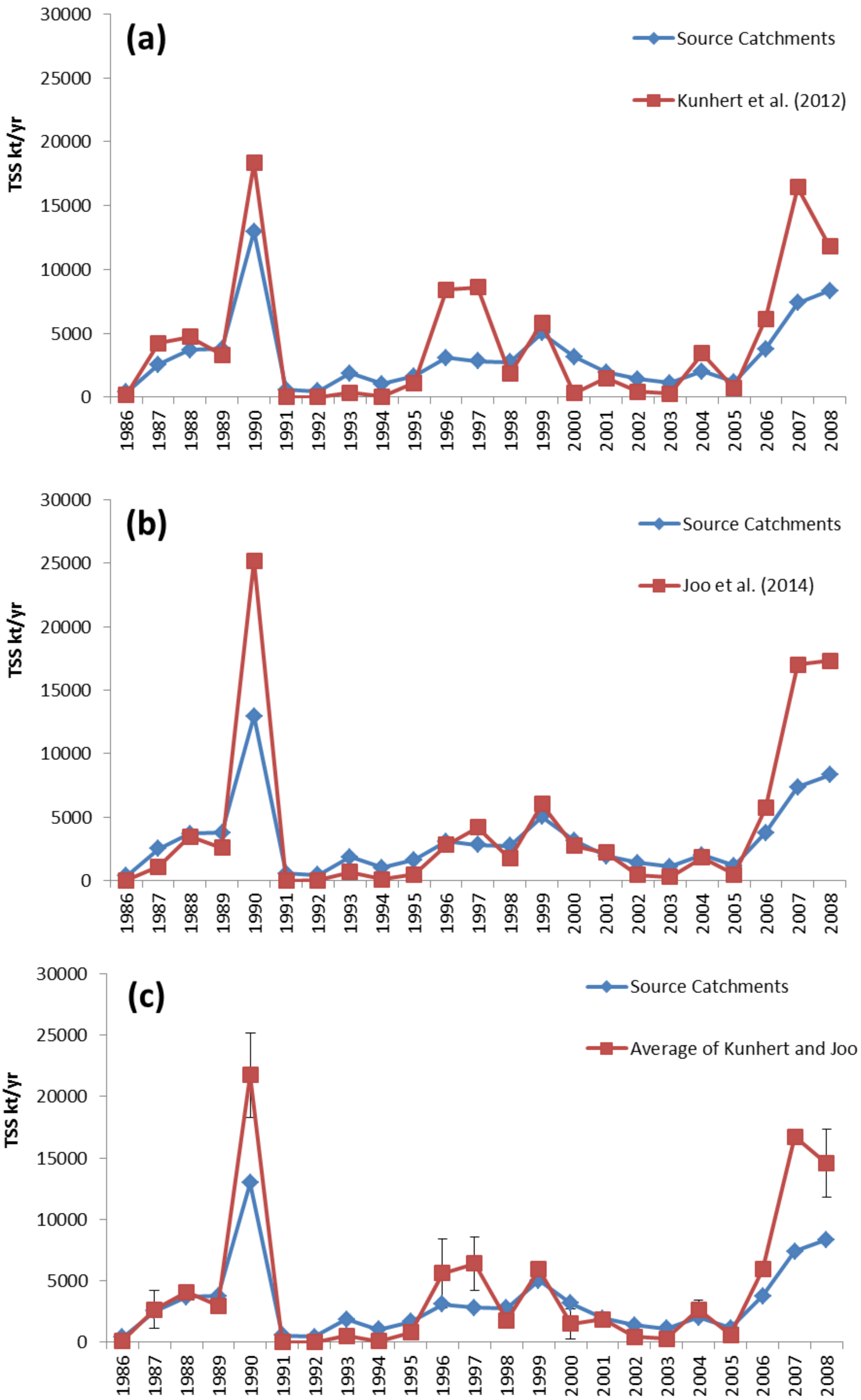

Figure 18 (a) Yearly comparisons of Kuhnert et al. (2012) and Source Catchments TSS loads at 120006b (Burdekin river at Clare) (b) Yearly comparisons of Joo et al. (2014) and Source Catchments (c) The average of Kuhnert et al. (2012) and Joo et al. (2014) vs Source Catchments loads, Note error bars show high and low estimate for that year (either Kuhnert or Joo)

4.3.3 GBR Catchment Loads Monitoring Program (GBRCLMP) – (2006 to 2010)

Whilst the modelled period used for reporting ceased 30th June 2009, to accommodate short-term validation the model was extended by one year to incorporate the most recent GBRCLMP loads data for the 2009/10 wet season. A comparison was made between the mean GBRCLMP discharge and loads (averaged over four years, 2006-2010) and the Source Catchments modelled loads for the same locations and the same time period (Figure 19).

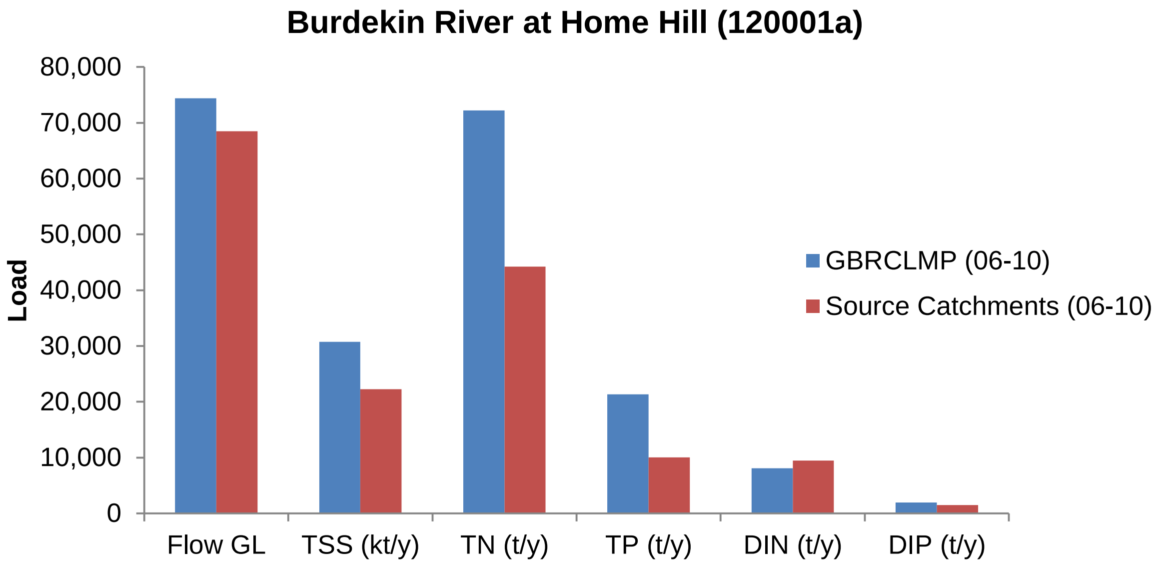

Figure 19 Comparison between modelled and GBRCLMP loads for the period 2006-2010 for the Burdekin River at Home Hill (120001a)

Modelled flow is within 10% of the gauged flow for the period. Modelled constituent loads for fine sediment, TN, TP and FRP are between 25% and 50%) of GBRCLMP loads. The DIN load is ~20% higher than the GBRCLMP estimate.

4.3.4 Burdekin Falls Dam (2005-2009) dataset

Comparisons between the modelled sediment trapping and the estimates of (Lewis et al. 2013) for the Burdekin Falls Dam are shown in Figure 20.

The average annual (2005-2009) model estimate of the inflow and outflow of fine sediment compares well for the study period (Figure 20.a). On an annualised basis, the model predicts 16% less fine sediment inflow and 20% less outflow than (Lewis et al. 2013) estimates. This equates to an annualised trapping percentage of 68% for the model and 66% for (Lewis et al. 2013).

At the annual time step, the trapping efficiency fits within the Lewis error bars, matching the yearly trend (Figure 20b). The 2006 and 2007 values are higher than Lewis, while the 2008 and 2009 years are much lower.

For the total modelling period (1986–2009) the annualised trapping is 74%; varying from a low of 54% in the 1990 water year to a high of 100% in 1986 (Figure 20c). For the water years defined as “Large”, by load (total three years), an average trapping rate of 59% was modelled. “Mid-sized” events total eleven water years and have an average trapping rate of 77%, while in years defined as “Small” the trapping increases further to 88%. Annual dam outflow is reasonably well correlated to trapping (r^2 = 0.8).

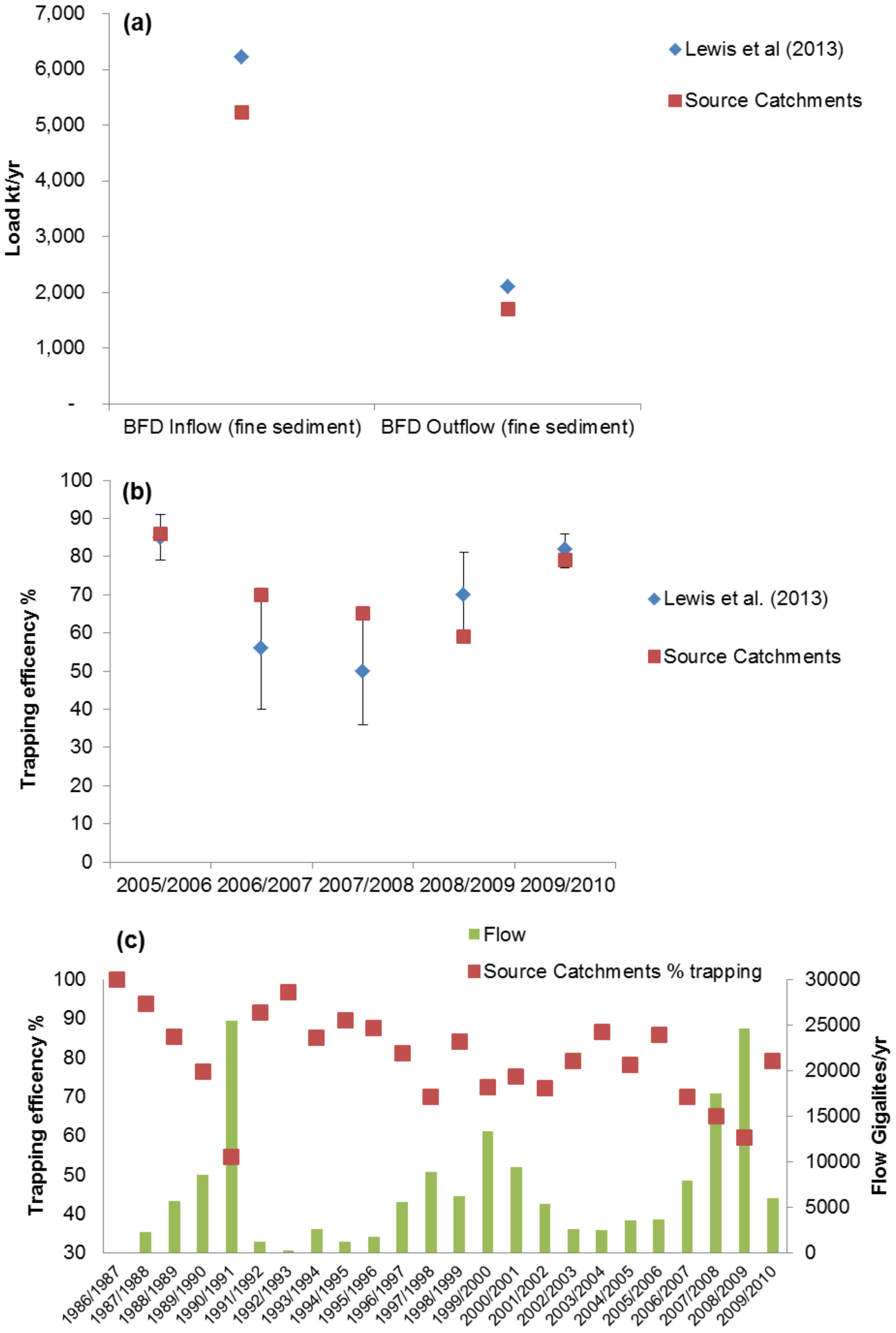

Figure 20 (a) Comparison of Source Catchments and Lewis et al. (2013) average annual fine sediment load (05-09 water years) estimated to enter and exit the Burdekin Falls Dam (b) Lewis et al. (2013) estimated Burdekin Falls Dam trapping by water year (c) Gauged BFD outflow and Source Catchments (%) sediment trapped

4.3.5 Source and Sinks

For a series of events at various locations the sediment tracing work of (Wilkinson et al. 2013) predicts that ~80% of fine sediment is sourced from sub-surface soil and the most likely source is gullies; however channel (bank) and hillslope rilling may also contribute (Table 21). In contrast, the Source Catchments model predicts a greater proportion of hillslope erosion, however this is less than the SedNet modelling of Kinsey-Henderson et al. (2007).

Table 21 Results showing surface soil tracing and contribution of hillslope predicted using a SedNet Model (Kinsey-Henderson et al. 2007) and Source Catchments. Table modified from Wilkinson et al. (2013)

River sediment sampling location	Catchment area (ha)	MRE[a] (%)	Surface soil contribution (tracing)% [b]	Hillslope erosion contribution (SedNet)%	Hillslope erosion contribution (Source Catchments) (%)
Little Bowen River	147,000	11	13 (+5-5)	89	59
Broken River	219,000	16	65 (+14-14)	83	81
Bowen River downstream of Broken confluence	366,000	6	29 (+-9)	85	80
Bowen River at Myuna	704,000	7	19 (+6-7)	80	65
Bowen River at Hotel	765,000	14	17 (+6-%)	76	
Upper Burdekin River	3,480,000		~20 [c]	53	37
Weany Creek	1400		~40[c]	84	
Keelbottom Creek	117,000	5	13 (+2-2)	86	62
Thornton Creek	8,400	3	20 (+3-3)	86	

[a] Mean Relative Error
[b] Upper and lower 95% confidence intervals, respectively
[c] Estimated by linear mixing of mean ^{137}Cs and $^{210}Pb_{xs}$ activities.

4.4 Progress towards Reef Plan 2009 targets

Across the GBR region, modelled average annual pollutant loads entering the reef from 2008-2013 have been reduced as a result of the adoption of improved land management practices (Figure 22). Progress towards the Reef Plan TSS target was rated as very good with the estimated average annual sediment load leaving the GBR basins reduced by 11% over the five years to June 2013 (Appendix E). Progress towards the TN target was rated very poor with the estimated average annual load reduction 10%. The highest TN reduction occurred in the MW NRM region at 17% (302t/yr).TN load reductions were achieved through a combination of managing dissolved nitrogen (mostly DIN) from sugarcane and PN from grazing areas. The GBR DIN load reduction was 16% (‘poor’ progress), with the Burnett Mary Region having the highest reduction (31%).

The GBR TP average annual load reduction was 13%. Reductions were predominately achieved through improved grazing management and sugarcane practices with the Burdekin and Wet Tropics NRM regions accounted for over 75% of the reductions. A large proportion of TP was associated with PP, with a GBR reduction of 14% from the anthropogenic baseline load. The largest load reduction across the GBR was for PSII herbicides. The average annual PSII herbicide load leaving the GBR catchments reduced by 28%. Over 84% of the reduction occurred in the sugarcane areas of Wet Tropics and Mackay Whitsunday NRM Regions.

Within the Burdekin region for Report Card 2013 there has been “very good progress” for fine sediment and moderate to poor progress for the other constituents in relation to the Reef Plan 2009 targets (Figure 22). The PSII load reduction was 13% with the reductions attributed to investment in Sugarcane. Sugarcane herbicide management showed an 11% shift in area from the C to A management system, which includes practices relating to the selection of herbicide products with a reduction in the reliance on residual herbicides for weed control.

There was also “poor progress” towards reducing the DIN load (~14%). There was a net decrease in area of 1.2% out of the D nutrient management system and a net reduction of ~37% of the area from C management system, with ~29% movement into B and ~9% move into A. Most system changes were step wise, so for example C to B, but in some cases, there was a two-step system change from C to A. The biggest increase in area of a management system was into B, where improved nutrient management strategies, simulated in APSIM, based on specific practices (Table 37) outlined under the sugarcane industries ‘Six Easy Steps’ nutrient management program.

The TSS load reduction was the highest out of all the constituents at 16% with the reductions attributed to investment in grazing. For PN and PP, there were reductions of 14% and 15% change respectively. Most of the change was attributed to grazing for both constituents and was associated with improved grazing management increasing cover and riparian fencing projects (Table 37). It is worth noting that the greatest reductions were achieved following the first year of the program between Report Card 2010 and Report Card 2011 (Figure 22).

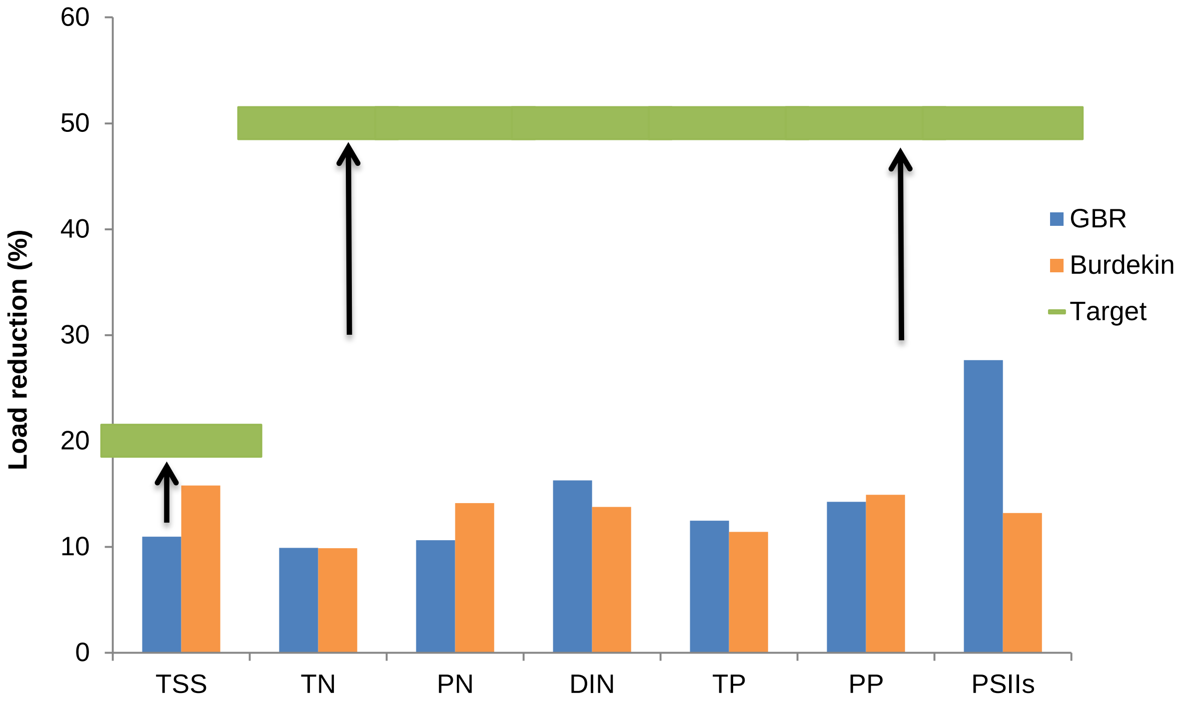

Figure 21 GBR and Burdekin region modelled load reductions for Report Card 2013

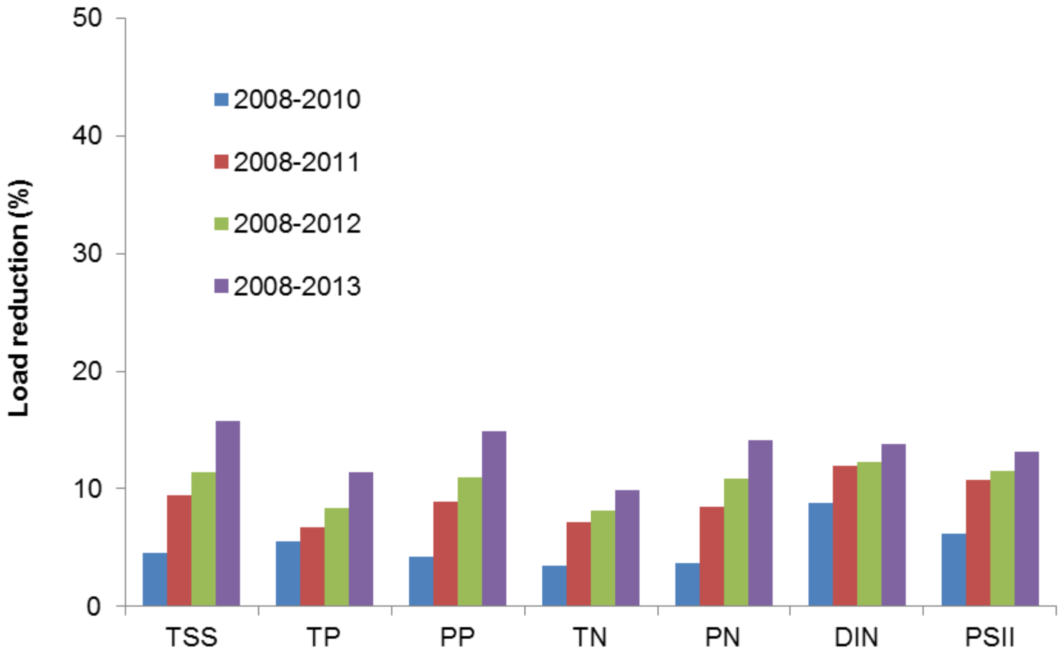

Figure 22 Burdekin region constituent reductions for individual reporting periods

5 Discussion

In the Paddock to Reef program a consistent approach was applied using the Source Catchments modelling framework to generate predevelopment, total loads and subsequent anthropogenic baseline loads for key constituent for the 35 reef catchments (including small coastal catchments), for the six NRM regions. In addition SedNet/ANNEX modelling functionality was incorporated to provide estimates on the contribution of gully and streambank erosion, along with improved: hydrology, spatial and temporal resolution of remotely sensed ground cover, riparian vegetative cover, soils information, representation of land management practices, and water quality data to validate model outputs. These collective enhancements have resulted in a comprehensive improvement in modelling constituent loads and reporting on changes of loads discharging from GBR catchments.

5.1 Hydrology Modelling

The addition of finer spatial and temporal representation of hydrology in this model in comparison to previous modelling approaches has been a critical enhancement of the catchment modelling undertaken. The more detailed hydrology modelling allowed investigation into the source of flow within catchments and the relative contributions between catchments. It also allows extrapolation when there is missing data within ungauged areas, particularly for small coastal catchments.

The hydrology modelling calibration for the Burdekin and Coastal basins produced very good agreement with gauged flow data, particularly for monthly and annual flows.

The majority of gauges met the monthly and daily Nash Sutcliffe Coefficient of Efficiency (NSE) (>0.8 and >0.5 respectively) and 62% of gauges were within the total volume criteria of ±20%. Moriasi et al. (2007) in a global review of hydrology model performance rated NSE values >0.75 as "very good". All key coastal and Burdekin catchment sites had a Monthly NSE >0.75, except the Belyando River at Gregory Development Road, highlighting the very good monthly hydrology calibration for the region.

The hydrology modelling showed good agreement to measured flow volumes particularly at the larger spatial scales. The Coastal basins that met the NSE performance criteria were the Black, Haughton and Don (Table 25). Whereas, the Ross catchment had two flow gauges that did not meet the performance criteria. The Ross catchment is particularly complex, including the township of Townsville. The calibration of this area could be improved through better representation of dam releases, extractions and urban runoff.

The Upper Burdekin catchment calibrated well, with catchments above 1,500 km^2 meeting all three performance criteria. For catchments under 1,500 km^2; monthly NSE were met, with only the two smallest catchments not meeting the volume criteria. Likewise, hydrology calibration of smaller catchments within the Belyando Suttor and Bowen were generally poor, with likely under performance due to a combination of relatively small discharges, low rain gauge density and possible gauging station flow rating issues related to overbank flow estimates and the regions extensive floodplains. Given the Bowen catchment generates and exports a large proportion of the regions sediment budget, future modelling will aim to improve the calibration and hydrological performance of this catchment.

Whilst the calibration performance is adequate, it is proposed that hydrology for all of the GBR catchment models will be re-calibrated, particularly to better estimate/capture major flow events that transport a large proportion of the sediment loads to the GBR lagoon. The SIMHYD Rainfall-Runoff (RR) model used in this project may be reconsidered for consistency with a change to the Sacramento RR model, used in the Integrated Quantity Quality Model (IQQM) for water planning purposes by Queensland government. In addition, a recent comparison of three hydrology models (Zhang, Waters & Ellis 2013) found the Sacramento RR model performed better than the SIMHYD and GR4J models in two selected GBR catchments. While the current hydrology calibration provides good estimates of annual and long-term average annual flows, the current objective functions will generally result in under-estimation of high flows, and over-estimation of low (base) flows. Future hydrology modelling will revisit the objective functions used in the calibration, and reconsidered the weighting of each objective function (weighted equally in this project), particularly increasing the weighting of high flows (i.e. calibrating to high flows). Given large flows generate and discharge most of the sediment and nutrient loads to the GBR lagoon.

5.2 Constituent Loads

Catchment modelling is an ideal tool to investigate constituent budgets and the potential impact of changes in land management practices on the exported load to the GBR lagoon. It also follows that the better a catchment model performs spatially and temporally the greater the confidence there is in prioritising areas for improved land management actions.

In the Burdekin basin, there have been numerous short-term projects that have collected water quality data (Bainbridge et al. 2007, 2008, Lewis et al. 2011). An advantage of the Source Catchments modelling framework running at a daily time-step is its capacity to make use of this disparate water quality data, taken at different times and at different locations, to assess the performance and validation of the modelled loads.

5.2.1 Validation

In addition to the range of other data sets mentioned above, the performance of GBR Source Catchments loads for the Burdekin basin were validated against three additional sources of data that used measured flow and water quality data to estimate loads. Firstly, a comparison was made with a linear regression estimation of loads determined by Kuhnert et al. (2012) for the 23 year modelling period. Secondly, modelled loads were compared with Joo et al. (2014) loads where estimates were determined through a correlation between available measured water quality data and discharge to produce an annual and average annual load for the 23 year model period. Thirdly, a comparison was made with a short period of catchment monitoring data for 2006 to 2010 and compared to the equivalent 4 year modelled loads. Annual Source Catchments modelled TSS loads for the Burdekin basin showed good agreement with both Kuhnert et al. (2012) and (Joo et al. 2014) load estimates, with respective Nash Sutcliffe E values of ~0.71 and ~0.66. The results are similar to a study on an earlier version of the model (Wilkinson et al. 2014).

At the Burdekin basin scale model performance was assessed against a set of performance criteria recommended by (Moriasi et al. 2007). Model performance was rated as “good” to “satisfactory” for TSS, TN and TP at a monthly time-step for the 23 year modelling period. At the annual time-step Source Catchments estimated loads exported from the Burdekin were on average lower in the large flow years of 1990, 2007 and 2008. These 3 years exported 50% of the total load over the 23 year period, so it is critical that improved load estimates are achieved for larger flow years. Areas that require further analysis to improve model performance would be to further investigate sediment generation rates from the major erosion processes of hillslope, gully and streambank, the sediment trapping efficiency of the Burdekin Falls dam in high flows, and floodplain deposition rates within the catchment. Misrepresentation of any of these processes could lead to lower estimates in export of loads from the Burdekin basin.

The Burdekin Falls dam is in the lower reaches of the Burdekin basin and traps a significant amount of sediment (Lewis et al. 2013). The Source Catchments modelling has shown that the sediment trapping efficiency can range from 100% when there are low inflows to the dam, and reduce to 50% when there are large discharges over the dam wall, with an average of ~2,700 kt/yr trapped by the dam during the modelling period. The modelled trapping efficiency shows good agreement with estimates of Lewis et al. (2013); nevertheless, further exploration is warranted as new datasets become available, given its importance in the overall constituent export budget.

It is important to note that the modelled loads are only indicative of actual measured loads. The measured water quality data represents a particular set of land use and land management condition at a particular period in time. It does not reflect the annual and seasonal variations within the landscape and catchment represented by the catchment modelled loads. Therefore model validation aims to demonstrate that the models are achieving a reasonable approximation of the loads derived from measured water quality data. Validation therefore, is more appropriate at an average annual to annual timescale and any comparisons made at smaller time-steps should be treated cautiously and be considered to have a higher degree of uncertainty.

Across the validation datasets, the trend is an under prediction in modelled loads compared to load estimates derived directly from measured data, although the results are within likely error bounds. Encouragingly at the monthly time-step model performance was rated as “good” to “satisfactory” for the Burdekin basin scale. Overall, the Burdekin region Source Catchments loads performed well when compared to a range of measured data.

5.2.2 Anthropogenic loads

Reef Plan water quality targets look to reduce the anthropogenic baseline load The modelling suggests that 64%, 59% and 58% of the total TSS, TP and TN Burdekin region load is anthropogenic, and is approximately 3-fold greater than the predevelopment loads. For the whole of GBR, a 4 -10 fold increase in sediment loads has been estimated, (Lewis et al. 2007) shows such an increase is correlated with livestock numbers.

The increase in loads from the Burdekin Source Catchments modelling is smaller than previous estimates which ranged from 5-8 fold increase in TSS, TP, TN loads from predevelopment conditions (Kroon et al. 2012). A major reason for these differences is in how the groundcover and hence C factor was determined. McKergow et al. (2005a) used a low constant groundcover for the current condition scenario and a high cover value (95%) for predevelopment. Whereas, in Source Catchments a spatially and temporally variable Bare Ground Index (BGI) for the current condition which had an average cover of ~75%, with an assumption that predevelopment groundcover was 90%. The smaller difference between predevelopment and current groundcover resulted in smaller increases in anthropogenic loads than previously reported. However, both Source Catchments and McKergow et al. (2005a) estimated anthropogenic sediment loads show similar relative contribution, and generation patterns, with the Bowen, BDAB and the Upper Burdekin catchments the main contributors of sediment from the region to the GBR lagoon.

The anthropogenic load defines the potential room for improvement in land management across GBR Catchments and hence more relevant targets. An important consideration in the design of the predevelopment scenario is the inclusion or exclusion of existing dams and reservoirs. The Source Catchments modelling, similar to previous GBR modelling, retained dams, reservoirs and extractions for the predevelopment modelled scenario. This provides a more realistic estimate of anthropogenic loads, and hence achievable water quality targets set against current land management conditions, without the added complications of removing dams and storages. However, it is planned to explore the impact on predevelopment loads when dams, storages and extractions are removed.

5.2.3 Contribution by land use and sources

In the Burdekin Dry Tropics region, it is estimated the Burdekin basin exports ~80% of the TSS total load with the remaining ~20% being exported from the Coastal basins, which is similar to previous estimates (Kroon et al. 2012, Kroon et al. 2010). The Burdekin basin also contributes the highest loads for, PN, TP, DIP, DOP and PP. Both the modelling and monitoring reveal the Bowen, BDAB and the Upper Burdekin sub catchments are the main sources of sediment within the Burdekin region. This is supported by a variety of studies (eg. Dougall & Carroll 2013), including a recent Burdekin basin assessment of event based sediment sources to the GBR (Bartley et al. 2013).

In the Burdekin region, grazing is an important industry occupying 90% of the area and contributing the major proportion of the sediment load from the region. It is estimated open grazing contributes the largest source of fine sediment (35%), followed by grazing forested (27%), with the majority coming from the Burdekin basin. In terms of the sediment supplied to streams not all sediment is exported to the end-of-system. Of the sediment supplied from catchments; 55% is deposited or removed within the catchments, with 31% deposited in reservoirs, 21% on floodplains and 3% removed via water extraction. The Burdekin Falls Dam itself traps 43% of total sediment supply. However, Turner et al. (2013) has shown that the sediment loads discharged from the Burdekin basin has a greater percentage of clays (less than four micrometres), hence contributing proportionally more fine particles to the Great Barrier Reef lagoon. It has been found that large flood plumes from the Burdekin basin can reach far north of the Burdekin River mouth (Devlin et al. 2012). In a recent risk assessment Waterhouse et al. (2012) identified sediment loads discharged from the Burdekin produce a medium to high risk to the reef. This highlights the need for on-going investment and improvement in grazing management practices in the Burdekin region to reduce the associated risk to the reef.

The risk assessment also ranked the Burdekin region as a medium-high risk for herbicide and dissolved inorganic nitrogen. The major PSII herbicides found in receiving waters are atrazine, ametryn, hexazinone and diuron (Kroon et al. 2012, Davis et al. 2012, Davis et al. 2011). Sugarcane is the major source of herbicides in the region and the Haughton basin with the largest proportion of sugarcane contributed the largest proportion of PSII's. The sugarcane industry also produces 48% of the anthropogenic DIN output from the region, and this is associated with fertiliser use in the region. There is great scope for improved management of both PSII herbicides and fertiliser use in the Burdekin region to meet Reef Plan water quality targets.

It is critical the relative contribution of erosion from different sources are identified so that that regional bodies effectively direct investments towards the most cost effective on-ground management actions to reduce the export of loads to the reef lagoon. At the NRM region scale, subsurface erosion, (gully erosion-31% and streambank-26%) are the dominant erosion sources, with hillslope erosion (43%) still a large contribution. At the Burdekin basin scale, gully and streambank erosion are the two dominant sources of sediment, while the Coastal basins have a higher proportion of hillslope erosion. It should be noted that the delineation of erosion process across the GBR has been complicated by erosion source definition (Bartley et al. 2013), as opposed to erosion process definition as defined by recent sediment tracing (Wilkinson et al. 2013, Hancock et al. 2013, Bartley et al. 2013). This work identifies scalded land as a high contributor to the sediment budget. The different conclusions have led to some uncertainty and this is discussed in further detail in the future work section. Nonetheless, given the link between all three erosion sources all sources of sediment need to be considered if reduction's in TSS loads are to be achieved.

Furthermore, it is acknowledged that the presence of gullies in sugarcane would be non-existent or minimal. Of the total sediment supplied from sugarcane, only a small percentage of the total load was attributed to gully erosion. This is most likely due to a mismatch in mapping between gully and land use mapping. Gullies in sugarcane will be turned off in next round of modelling.

The GBR Source Catchments modelling is the most consistent estimate yet produced across the entire GBR catchments, with an improved ability to consider a range of land management scenarios through the ensemble of paddock models and incorporation of SedNet functionality. In order to address the impacts on ecosystem health there is increasing expectations for improved daily-time step load estimates for receiving water models. Encouragingly in some instances at shorter time-steps, such as years to weeks, the model has performed well compared to the estimates from measured data. Although it is preferable to used measured data where possible to inform catchment generation rates, the Source Catchments model provides insights for periods when there is a lack of water quality data, and also provides the ability to explore catchment behaviour at multiple scales. The total baseline estimated loads provide a measure of the flux of stream pollutants delivered to the streams, wetlands and the GBR and this information can be used in the assessment of water quality impacts on ecosystem health. Similarly, the data can be used to assess the required progress towards inshore water quality targets (Kroon 2012).

5.3 Progress towards Reef Plan 2009 targets

At the GBR scale, average annual TSS, TN and TP were reduced by 11%, 10% and 13% respectively, following five years of the adoption of improved land management practices.

In the Burdekin region, there has been good progress towards meeting the reef fine sediment targets. However, progress was rated as poor for the other constituents. The PSII herbicide reduction of ~13% was a result of improved practices in sugarcane. The reduction came from a ~11% change in area from C to A management practices and a shift in the reliance from residual to knockdown herbicides for weed control.

There was poor progress made towards the DIN load reduction target of 50%. Whilst there were some significant shifts out of D class to C class management practices the results suggest that alternative management option for reducing DIN, particularly in cane, may need to be explored if the Reef Plan 2013 targets are to be achieved.

In grazing improved pasture and riparian management reduced TSS by ~16%, and PN and PP by ~14% and ~15%. This is promising progress towards Reef Plan water quality targets, however modelling management change is complex and requires additional research to support the models and improve our understanding of the effects of improved riparian management in particular on water quality response in grazing areas.

5.4 Future work

A number of studies (Lewis et al. 2013, Dougall & Carroll 2013) illustrate the importance of the Burdekin falls dam (BFD) in regulating sediment transport sourced from the sub catchments located above the dam. When floodwaters enter the dam, much of the sediment transport energy is dissipated and sediment is deposited and trapped within the dam. Previous SedNet catchment modelling calculated a greater trapping efficiency from the BFD (~80%) (Kinsey-Henderson 2007). In contrast, the Source Catchments model has implemented a reservoir trapping equation derived from sediment trapping research work in the BFD (Lewis et al. 2013) and we calculate an average annual trapping efficiency of 70% for the modelling period (1986–2009). Though, the rate varies by event and year and analysis shows, annual trapping dropping to as low as 50%, for the 1990 water year. Although the BFD traps considerable sediment, its efficacy drops with increasing discharge, also finer particle sizes have lower trapping efficiencies (Lewis et al. 2013) and it's this finer material that travels well into the GBR lagoon during large events (Bainbridge et al. 2012). Thus sediment sourced from above the dam, when sampled at Burdekin EOV is enriched in the finer particle size classes. For better targeting we recommend further investigation into event source identification for years that produce large inshore plumes (Dougall & Carroll 2013, Bainbridge et al. 2012). In addition, given the large loads delivered to the BFD small changes in trapping efficiency can have substantial impacts on modelled EOV loads. Given BFD trapping uncertainties (Lewis et al. 2013) confidence in targeting may be improved with further studies into BFD trapping.

The Burdekin Source Catchments model provides the opportunity to assess pollutant transport and process across various timescales. In terms of annual delivery, the Burdekin basin at (EOV) has 95% of its load delivered in 14 of the 23 assessment years with ~50% of the load delivered in the three water years (1990, 2007, 2008). This is important as it shows the temporal variability of sediment delivery, while also giving insight into the type of events that are exporting the majority of the sediment to the GBR; this highlights the importance of modelling these key water years in the future.

There is also additional scope to improve the modelling of sediment sources and sinks. Gully, streambank and hillslope are the key sediment supply sources, while areas of loss are floodplain, reservoir deposition and extractions. In terms of loss the Burdekin basin TSS modelled budget indicates substantial sediment loss in the BFD and on the catchment's floodplains. While there have been some studies on the trapping efficiency of the BFD with modelling shown to match these rates. The measurements made on the lower floodplain of the Burdekin river are scarce but indicate low sediment deposition rates (Alexander, Fielding & Pocock 1999).

The Burdekin Source Catchments model tended to under predict both gully and hillslope erosion. Even when gully cross sectional area was doubled from 5 m^2 to 10 m^2 and hillslope delivery ratio was increased from 10% to 50% (equating to a 20% delivery in ratio when clay is not considered, thus an approximate doubling of the default 10% in earlier SedNet modelling) there was still a likely 20% under estimate in sediment export. It was decided not to increase the parameters further, given parameters should be kept within a realistic uncertainty range (Arnold et al. 2012). Notably these results suggest that the spatial inputs for the gully and hillslope models are underestimating. However, preliminary analysis showed a good correlation between observed gullies and the 1:100k drainage mapping. Thus it appears possible to populate a new gully model with measured density data and this should lead to a better representation of linear gully erosion features in the catchment, allowing further parameter constrain and in turn improved modelling.

Gully and hillslope erosion processes are indelibly linked and both need to be considered and understood if reduction in fine sediment loads are to be achieved. A model comparison against sediment tracing data, shows a greater proportion of modelled surface erosion than the (Wilkinson et al. 2013) sediment tracing study (Table 21). However, there is some uncertainty associated with the tracing work as the fall out radionuclides concentrations could not distinguish between rills and gullies (Wilkinson et al. 2013). The lack of discrimination between rill and gullies lead to the investigation of (Hancock et al. 2013) who found that up to 50% of eroded material may be derived from rilled areas. What is unresolved more broadly across the region is the amount eroding from within the gully or from rilled hillslopes and this may have implications for management.

Elements contributing to the underestimation of supply from hillslope and gully erosion were briefly investigated. Principally it was found that the RUSLE erosion grid may not be simulating cover at a high enough spatial resolution. A study located at Weany Creek in the Burdekin (Bartley et al. 2010) identified that 97% of the hillslope sediment budget came from 3% of the area. These areas are located mainly on the lower slopes and have low ground cover, are scalded in nature, and are within close proximity to gullies and drainage lines and provide a large proportion of the total runoff (Bartley et al. 2010). Importantly, the lower slope scalded areas have a high proportion of woody shrubs (Bartley et al. 2010) and it has been noted that BGI may over estimate in these areas (Dougall et al. 2009). Hence the RUSLE catchment modelling is not representing these very low and persistent scalded areas due to the resolution of the BGI as seen in Figure 23; in addition to the use of a global hillslope delivery ratio. It has been identified that the high sediment generation sub catchments are the Bowen, BDAB and upper Burdekin and it is in these catchments that future detailed analysis of spatial layers should be undertaken.

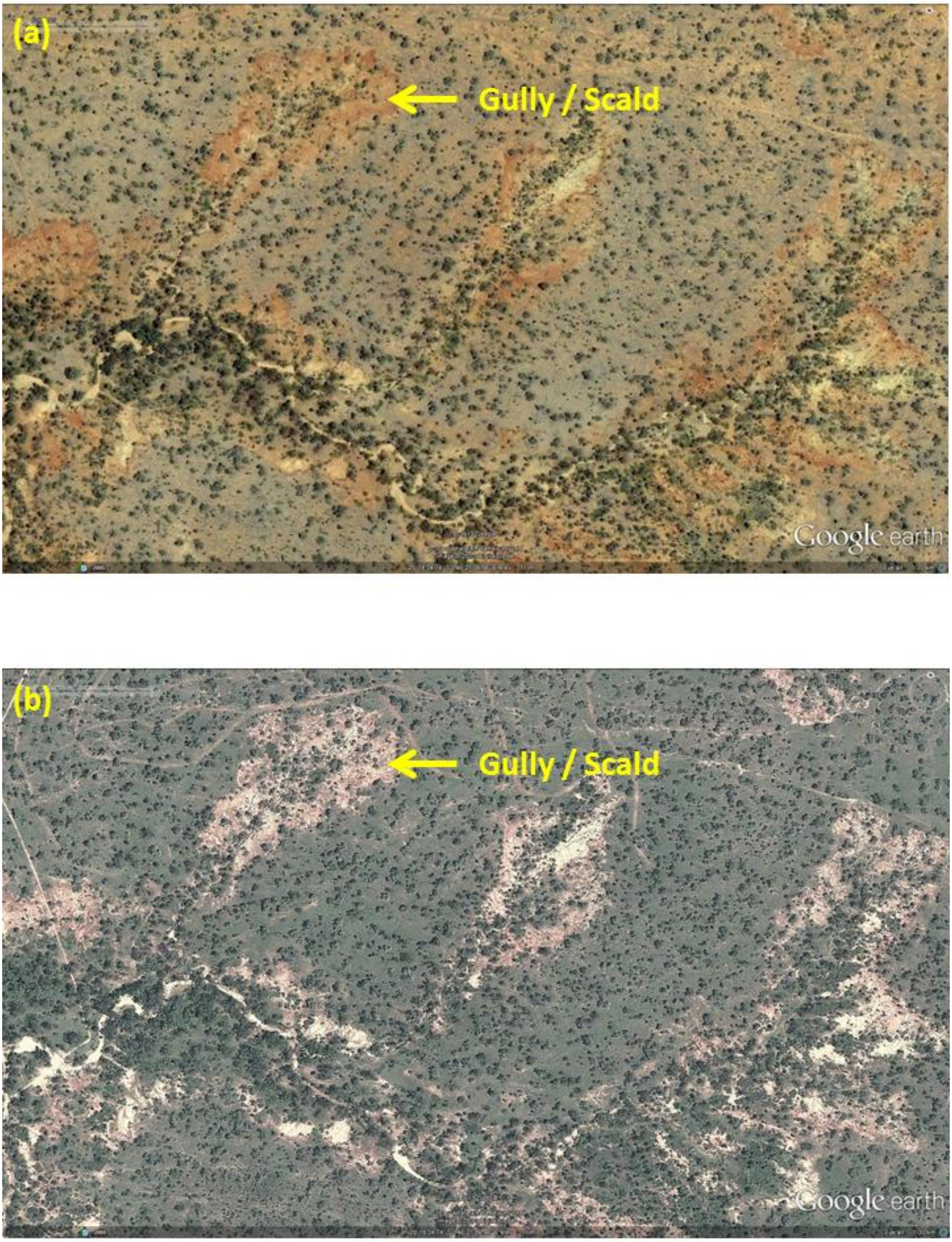

Figure 23 Lack of cover response on Gully / Scald complex, despite good wet seasons (a) After a series of Drought years (2005) (b) and following consecutive good wet seasons (2012)

6 Conclusion

The catchment scale water quality modelling as described in this report is one of multiple lines of evidence used to report on progress towards Reef Plan 2009 targets. Improved land management practices (Report Cards 2010–2013) have resulted in a reduction in sediment load to the GBR from the six NRM regions of ~11%. Similarly, total nitrogen and total phosphorus have declined by ~10% and ~12% respectively. Herbicide loads have been reduced by ~28%. The reduction in sediment and nutrient load is positive progress towards meeting the Reef Plan 2013 targets. Specifically in the Burdekin, PSII herbicide reduction was ~13% with the reductions attributed to investment in sugarcane. There was a 14% reduction in the DIN load, again from investments in sugarcane areas.

The results from this project are somewhat lower than previous estimates for sediment and nutrient loads from the Burdekin region. This can be attributed to the input datasets of ground cover and gully density; gully density was not high enough in key locations within the catchment to match generation rates. Over the course of the Paddock to Reef program more empirical data has become available, for example improved k-factors, and it is likely that the modelled outputs from all regions will change as a result of monitoring and modelling feedback.

The Paddock to Reef Program, as a whole, is designed to be an adaptive process, where monitoring and modelling outputs will both inform reef targets and also identify where our current conceptual understanding and knowledge needs to be strengthened (Waters & Carroll 2012). Developing, parameterising and running the catchment model described in this technical report, and accompanying reports, was a considerable challenge. However, what has been developed is a platform for future modelling, and with improvements in technology, data inputs and model concepts, greater confidence in the outputs will be achieved.

There are numerous successes of the GBR wide modelling project. Firstly, this project has developed the first temporally and spatially variable water quantity and quality model for Burdekin region. Also, the use of a consistent methodology across whole of GBR enables the direct comparison of loads across regions. Furthermore, due to the flexible nature of the Source Catchments framework, there is now the ability to temporally differentiate erosion processes (hillslope, gully and streambank), as opposed to traditional EMC approaches. The benefit of this approach is to enable targeted investment in the most appropriate areas. Finally, a highly collaborative approach in model development and application has been a very positive outcome of this project. A particular advantage of this is the integration of monitoring and modelling, and using modelling outputs to inform the monitoring program. Overall, the project can be considered to be a significant improvement on past models built for the GBR catchments; however there will always be scope for improvement. It follows that the better the modelling performs spatially and temporally the greater the confidence and possible sophistication in targeted management actions.

A process has been identified, and is in place, to improve the model as a whole. This includes the re-calibration of the model hydrology to better match high flows; sourcing and/or developing improved gully mapping (gully density layers) for the Burdekin, Fitzroy and Cape York regions in particular; investigating hillslope erosion rates as compared to recent paddock scale research; and, incorporation of seasonal cover. The greatest priority is to continue on-ground research and water quality monitoring. This data is the key information against which the catchment scale models can be calibrated, and validated. These changes will provide an enhanced GBR Source Catchments total baseline load and load reductions for Reef Plan 2013.

It should be noted, that due to the proposed model enhancements, the outcomes for the Reef Plan 2013 reporting period should not be directly related to the outcomes reported in Reef Plan 2009.

Overall, the catchment scale water quality modelling has been successful, and the aim of reporting progress towards Reef Plan 2009 targets has been achieved. The results show that land managers are on track towards meeting the overall sediment, nutrient and herbicide reduction targets revised for Reef Plan 2013.

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Appendix A – Previous estimates of pollutant loads

Table 22 Pre-European (natural), current and anthropogenic loads for the Burdekin NRM region taken from Kroon et al. (2012)

Basin Name	TSS (kt/yr)			TN (t/yr)			DIN (t/yr)			DON (t/yr)			PN (t/yr)		
	Pre-European	Current	Anthropogenic	Pre-European	Current	Anthropogenic	Pre-European	Current	Anthropogenic	Pre-European	Current	Anthropogenic	Pre-European	Current	Anthropogenic
Black	30	64	34	77	1,500	1,400	26	45	19	43	1,100	1,100	8	300	290
Ross	20	80	60	39	690	650	16	50	34	17	280	260	6	350	340
Haughton	29	300	270	91	1,700	1,600	42	340	300	42	120	78	7	1,200	1,200
Burdekin	480	4,000	3,500	2,200	8,600	6,400	980	1,800	820	1,000	1,800	800	170	5,500	5,300
Don	39	280	240	75	1,100	1,000	33	120	87	33	110	77	9	890	880
Burdekin region	**600**	**4,700**	**4,100**	**2,500**	**14,000**	**11,500**	**1,100**	**2,400**	**1,300**	**1,100**	**3,400**	**2,300**	**200**	**8,200**	**8,000**

Basin Name	TP (t/yr)			DIP (t/yr)			DOP (t/yr)			PP (t/yr)			PSII (kg/yr)		
	Pre-European	Current	Anthropogenic	Pre-European	Current	Anthropogenic	Pre-European	Current	Anthropogenic	Pre-European	Current	Anthropogenic	Pre-European	Current	Anthropogenic
Black	11	75	64	1	7	6	4	3	-1	6	65	59	0	44	44
Ross	5	140	140	0	15	15	2	61	59	3	62	59	0	1	1
Haughton	12	280	270	2	12	10	4	7	3	6	260	250	0	3,600	3,600
Burdekin	280	1,800	1,500	16	240	220	100	74	-26	170	1,500	1,300	0	1,200	1,200
Don	10	240	230	1	12	11	3	6	3	6	220	210	0	110	110
Burdekin region	**320**	**2,500**	**2,200**	**20**	**290**	**260**	**110**	**150**	**40**	**190**	**2,100**	**1,900**	**0**	**5,000**	**5,000**

TSS = Total suspended sediment, DIN = dissolved inorganic nitrogen, DON = dissolved organic nitrogen, PN = particulate nitrogen, TN= total nitrogen, DIP = dissolved inorganic phosphorus, DOP = dissolved organic phosphorus, PP = particulate phosphorus, TP = total phosphorus, PSII = herbicides, taken from Kroon et al. 2012.

Appendix B – PEST calibration approach

The process of coupling PEST and Source Catchments is presented in Figure 24. Initially, a model is built in the Source Catchments Graphical User Interface (GUI), which is then run in the E2CommandLine utility. E2CommandLine enables rapid model run times, when compared to running the model within the GUI. TSPROC is a time series processor utility that processes the model output, created by running the model in E2CommandLine, and then prepares an input file for PEST. PEST processes the TSPROC output and creates new parameter sets. The process then returns to running the model in E2CommandLine, with the new parameter set.

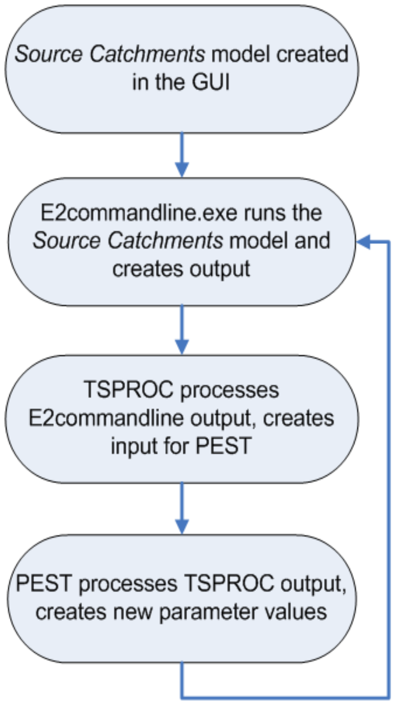

Figure 24 PEST-Source Catchments Interaction (Stewart 2011)

A detailed description of the PEST set up and operation can be found in (Doherty 2005). PEST operates largely via batch and instructional text files. The project team created a number of project specific tools to automate the compilation of these files, where possible. The TSPROC.exe (Time Series Processor) utility was also used to create the files used by PEST (the PEST control file), to manipulate the modelled time series, and present the statistics to PEST for assessment (Stewart 2011). More information on TSPROC can be found in (Doherty 2005). A three-part objective function was employed, using daily discharge, monthly volumes and exceedance times. All three objective functions were weighted equally. Regularisation was added prior to running PEST. This ensures numerical stability, by introducing extra information such as preferred parameter values, resulting from parameter non-uniqueness. Parameter non-uniqueness occurs when there is insufficient observation data to estimate unique values for all model parameters, and is an issue in large models, such as those in the GBR (Stewart 2011).

The PEST Super Parameter Definition (SVD-assist) was used to derive initial parameter sets and calibration results based on the initial regions. The main benefit of using SVD-assist is the number of model runs required per optimisation iteration. SVD-assist does not need to equal or exceed the number of parameters being estimated. 150 super parameters were defined from the possible 874 parameters. The SVD-assist calibration was stopped once phi started to level out (Iteration 4). Due to IT limitations as stated above, the number of calibration regions was then reduced.. Given the size of the Burdekin region model, Parallel PEST was used to enable multiple computers (and processors) to undertake model runs at the same time. The programs used, and process of running Parallel PEST is demonstrated in Figure 25.

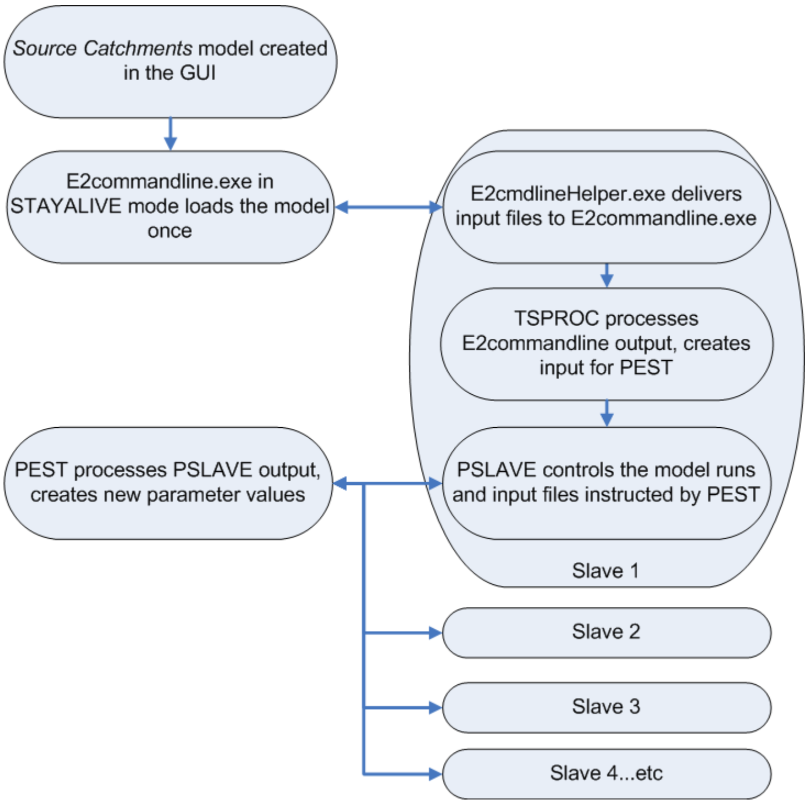

Figure 25 PEST operation (Stewart 2011)

Appendix C – SIMHYD model structure, parameters for calibration and performance

The re-classification of the full set of land uses into three Hydrological Response Units (HRUs) is presented in Table 23. Default SIMHYD and Laurenson parameters were used as the starting values for the calibration process, and these are identified in Table 24. The calibrated parameter values for three hydrological response units (HRUs) in 21 regions are provided in Table 26.

Table 23 Reclassification of FU's for hydrology calibration

Functional Unit (FU)	HRU
Nature conservation	Forest
Grazing forested	Forest
Grazing open	Grazing
Forestry	Forest
Water	Not considered
Urban	Grazing
Horticulture	Agriculture
Irrigated cropping	Agriculture
Other	Grazing
Dryland cropping	Agriculture
Sugarcane	Agriculture

Table 24 PEST Start, Lower and Upper boundary Parameters for SIMHYD and Laurenson models

Model	Parameter	Starting	Lower	Upper
SIMHYD	Rainfall Interception Store Capacity (RISC)	2.25	0.5	5
SIMHYD	Soil Moisture Storage Capacity (SMSC)	240	20	500
SIMHYD	Infiltration Shape (INFS)	5	1.00E-08	10
SIMHYD	Infiltration Coefficient (INFC)	190	20	400
SIMHYD	Interflow Coefficient (INTE)	0.5	1.00E-8	1
SIMHYD	Recharge Coefficient (RECH)	0.5	1.00E-8	1
SIMHYD	Baseflow Coefficient (BASE)	0.1485	3.00E-03	0.3
SIMHYD	Impervious Threshold (fixed at 1)	1		
SIMHYD	Pervious Fraction (fixed at 1)	1		
Laurenson	Routing Constant (k)	2.25	1.0	4.86+05
Laurenson	Exponent (m)	240	0.6	2

Table 25 Model Performance; Burdekin region hydrology calibration. red = criteria not met, Green = Criteria met, Blue = Gauge used in calibration. See hydrology results for a detailed description of model performance criteria

Catchment	Gauge Name	Gauge	Upstream Area (km^2)	Daily NS	Monthly NS	Percentage volume difference
Black	Bluewater Creek at Bluewater	117003A	86	0.70	0.90	-5
Black	Black River at Bruce Highway	117002A	256	0.35	0.83	-9
Ross	Alligator Creek at Allendale	118106A	69	0.72	0.85	-23
Ross	Bohle River at Hervey Range Road	118003A	143	-2.80	-11.18	239
Ross	Bohle River at Mount Bohle	118001B	183	-2.13	-10.29	96
Ross	Ross River at Ross River Dam Headwater	118104A	747	0.63	0.85	-14
Haughton	Major Creek at Damsite	119006A	468	0.67	0.94	-10
Haughton	Haughton River at Mount Piccaninny	119005A	1,133	0.75	0.93	-19
Haughton	Haughton River at Powerline	119003A	1,773	0.44	0.90	-6
Don	Elliot River at Guthalungra	121002A	273	0.66	0.87	-3
Don	Euri Creek at Koonandah	121004A	429	0.71	0.83	-6
Don	Don River at Ida Creek	121001A	604	0.31	0.71	-14
Don	Don River at Reeves	121003A	1,016	0.76	0.88	11
Upper Burdekin	Keelbottom Creek at Keelbottom	120102A	193	0.54	0.77	-30
Upper Burdekin	Fanning River at Fanning River	120120A	490	0.67	0.85	-26
Upper Burdekin	Star River at Laroona	120112A	1,212	0.40	0.89	-6
Upper Burdekin	Basalt River at Bluff Downs	120106B	1,301	0.26	0.91	-9
Upper Burdekin	Burdekin River at Lake Lucy Dam Site	120121A	2,216	0.71	0.93	-13
Upper Burdekin	Burdekin River at Blue Range	120107B	10,528	0.60	0.93	-6
Upper Burdekin	Burdekin River at Mount Fullstop	120110A	17,299	0.61	0.91	-16
Upper Burdekin	Burdekin River at Gainsford	120122A	26,316	0.81	0.99	11
Upper Burdekin	Burdekin River at Sellheim	120002C	36,260	0.73	0.97	2

Cape	Cape River at Pentland	120307A	775	0.64	0.81	-5
Cape	Cape River at Taemas	120302B	16,074	0.65	0.88	6
Belyando and Suttor	Native Companion Creek at Violet Grove	120305A	4,065	0.39	0.87	10
Belyando and Suttor	Suttor River at Eaglefield	120304A	1,915	0.08	0.73	-22
Belyando and Suttor	Mistake Creek at Twin Hills	120309A	8,048	0.51	0.64	-40
Belyando and Suttor	Belyando River at Gregory Development Rd.	120301B	35,411	0.52	0.67	-61
Belyando and Suttor	Suttor River at St Anns	120303A	50,291	0.64	0.78	-18
Bowen	Broken River at Eungella Dam T/W	120215A	150	0.70	0.68	1
Bowen	Pelican Creek at Kerale	120220A	528	0.62	0.90	-21
Bowen	Broken River at Urannah	120207A	1,103	0.46	0.46	40
Bowen	Broken River at Mt. Sugarloaf	120214A	2,269	0.57	0.75	17
Bowen	Bowen River at Pump Station	120299A	4,199	0.52	0.75	30
Bowen	Bowen River at Jacks Creek	120209B	4,305	0.45	0.77	35
Bowen	Bowen River at Myuna	120205A	7,104	0.35	0.88	22
Bowen	Bowen River at Red Hill Creek	120219A	8,280	0.11	0.74	33

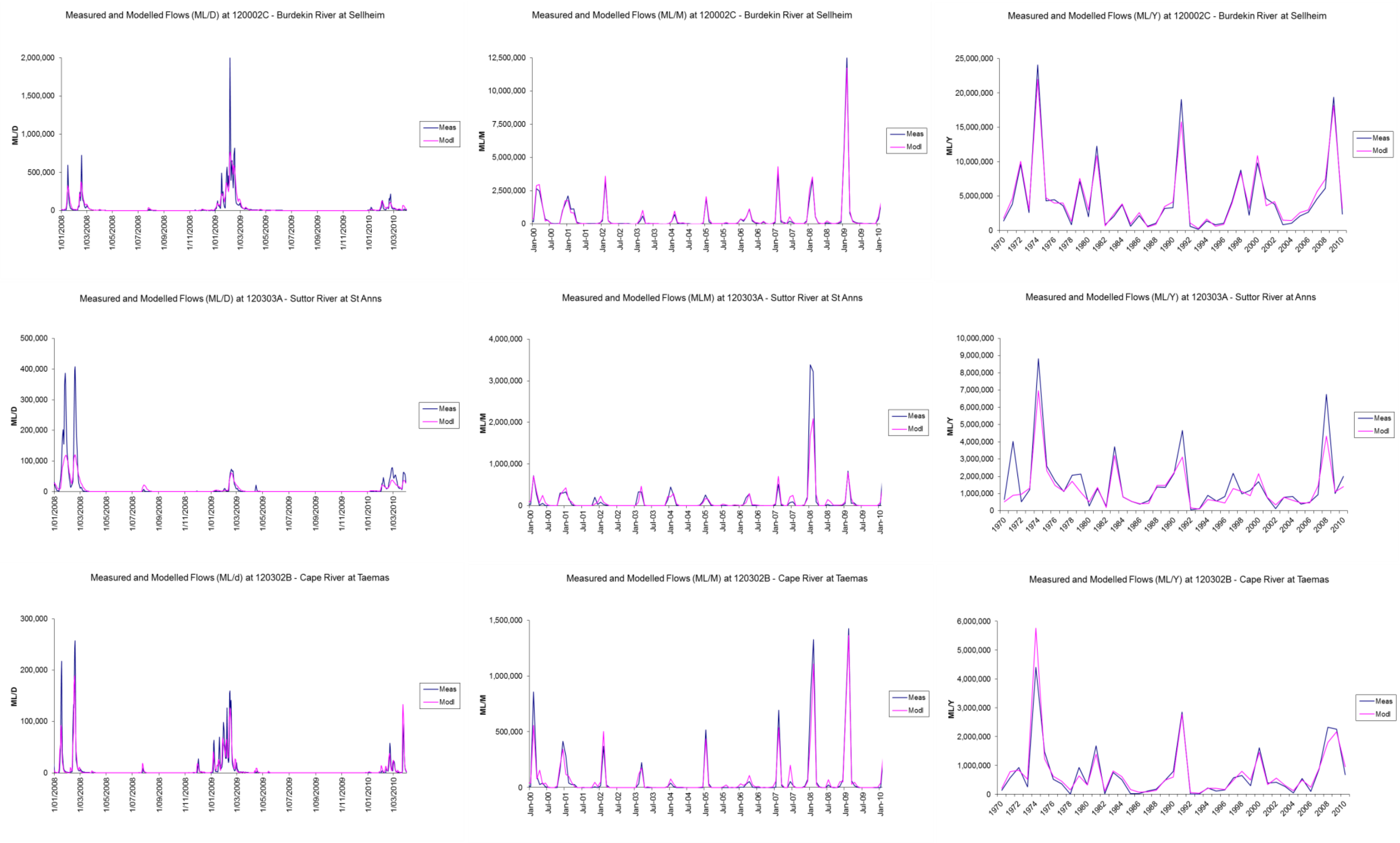

Figure 26 Examples of temporal sub-basin hydrographs day, month and year

Table 26 Calibrated SIMHYD and Laurenson parameter values for three HRU's across 37 regions

Region	FU	% Area of Region	SIMHYD Parameters							Laurenson Parameters	
			base	infi	infs	inte	rech	risc	smsc	k	m
117002	ag	0.43	0.160	210.490	4.991	0.497	0.487	2.960	259.720	14497	1.554
	fo	61.37	0.300	385.389	0.923	0.157	0.017	5.000	368.656		
	gz	37.46	0.300	270.071	2.548	0.277	0.107	5.000	326.057		
117003	ag	0.10	0.150	210.097	4.977	0.504	0.497	2.752	263.519	143616	0.967
	fo	88.38	0.096	262.796	3.218	0.744	0.338	5.000	373.272		
	gz	11.47	0.138	218.722	4.743	0.524	0.477	5.000	267.754		
119005	ag	0.01	0.151	209.794	5.005	0.500	0.500	2.749	259.760	15175	1.107
	fo	36.62	0.300	192.446	3.528	0.139	0.087	5.000	213.775		
	gz	63.35	0.300	281.856	3.567	0.200	0.082	5.000	355.292		
119006	ag	3.22	0.164	211.253	5.112	0.474	0.437	3.705	250.243	21542	1.215
	fo	37.09	0.300	212.474	3.842	0.158	0.057	5.000	198.994		
	gz	59.62	0.300	341.394	5.613	0.489	0.122	5.000	328.835		
119101	ag	13.55	0.115	138.748	10.000	0.327	0.294	3.115	500.000	56705	0.895
	fo	25.05	0.074	269.088	3.812	0.291	0.327	2.424	500.000		
	gz	61.01	0.033	303.878	3.306	0.093	0.150	3.304	500.000		
120002	ag	0.07	0.151	209.740	5.014	0.497	0.497	2.760	260.733	259200	0.300
	fo	29.87	0.151	294.215	2.561	0.805	0.971	5.000	500.000		
	gz	69.34	0.123	195.055	8.679	0.595	0.742	4.818	500.000		
120005	ag	0.00	0.152	210.000	5.000	0.500	0.500	2.750	260.000	20853	1.255
	fo	22.35	0.276	283.352	2.690	0.214	0.417	5.000	500.000		
	gz	76.91	0.300	250.780	2.157	0.070	0.032	5.000	393.527		
120106	ag	0.00	0.152	210.000	5.000	0.500	0.500	2.750	260.000	25499	0.622
	fo	17.83	0.121	174.711	4.552	0.258	0.203	5.000	288.021		
	gz	81.31	0.063	143.849	2.473	0.035	0.015	5.000	414.286		
120107	ag	0.01	0.152	210.046	4.998	0.500	0.500	2.758	260.462	36	0.300
	fo	42.33	0.092	323.202	1.363	0.273	0.105	5.000	500.000		
	gz	57.17	0.073	252.305	2.783	0.324	0.067	5.000	500.000		

120110	ag	0.00	0.152	210.000	5.000	0.500	0.500	2.750	260.000	21117	0.300
	fo	33.21	0.151	164.501	4.218	0.352	0.233	3.659	500.000		
	gz	66.50	0.121	221.505	0.723	0.169	0.106	5.000	500.000		
120111	ag	0.03	0.151	210.070	4.994	0.501	0.500	2.742	261.699	259200	0.300
	fo	32.65	0.048	400.000	0.510	0.526	0.171	2.969	500.000		
	gz	66.86	0.005	400.000	0.729	0.866	0.125	0.858	500.000		
120112	ag	0.00	0.152	210.000	5.000	0.500	0.500	2.750	260.000	10411	1.342
	fo	92.50	0.152	189.554	4.738	0.326	0.060	5.000	323.540		
	gz	5.94	0.157	165.941	8.013	0.459	0.432	3.310	203.796		
120121	ag	0.00	0.152	210.000	5.000	0.500	0.500	2.750	260.000	114869	0.738
	fo	77.59	0.164	243.975	2.092	0.254	0.092	5.000	220.498		
	gz	21.33	0.114	229.255	4.572	0.115	0.106	5.000	381.582		
120122	ag	0.04	0.151	209.755	5.021	0.499	0.499	2.751	259.343	28435	0.870
	fo	31.02	0.174	287.072	2.733	0.666	0.218	5.000	500.000		
	gz	68.01	0.263	121.956	10.000	0.132	0.184	5.000	336.521		
120205	ag	0.13	0.152	208.783	5.055	0.502	0.500	2.741	257.619	991	0.300
	fo	19.69	0.166	387.405	2.121	0.417	0.365	4.090	426.230		
	gz	79.61	0.289	400.000	2.462	0.378	0.176	5.000	442.952		
120207	ag	1.14	0.112	230.379	3.721	0.510	0.609	1.217	500.000	77728	0.300
	fo	84.42	0.035	400.000	0.338	0.031	0.057	0.500	500.000		
	gz	13.84	0.211	235.639	1.522	0.261	0.179	1.305	500.000		
120209	ag	0.00	0.152	210.000	5.000	0.500	0.500	2.750	260.000	732	0.300
	fo	23.11	0.174	200.713	5.320	0.441	0.347	3.206	250.719		
	gz	75.40	0.228	196.056	5.126	0.331	0.165	3.921	296.496		
120210	ag	0.06	0.152	210.057	4.998	0.497	0.497	2.786	259.759	2217	
	fo	45.26	0.300	156.468	3.875	0.055	0.026	5.000	221.823		
	gz	54.53	0.300	201.358	2.482	0.132	0.062	5.000	500.000		1.140
120212	ag	0.00	0.152	210.000	5.000	0.500	0.500	2.750	260.000	11008	1.595
	fo	49.33	0.300	273.778	0.334	0.060	0.020	5.000	500.000		
	gz	50.67	0.300	311.130	0.255	0.070	0.024	5.000	500.000		
120213	ag	0.00	0.152	210.000	5.000	0.500	0.500	2.750	260.000		

	fo	78.47	0.300	400.000	0.107	0.026	0.005	5.000	500.000	23594	1.483
	gz	21.53	0.204	279.670	1.228	0.247	0.189	5.000	500.000		
120214	ag	0.00	0.152	210.000	5.000	0.500	0.500	2.750	260.000	50425	0.573
	fo	44.85	0.141	230.272	2.971	0.393	0.309	3.484	434.956		
	gz	53.19	0.147	241.128	2.627	0.416	0.299	3.435	479.437		
120215	ag	1.58	0.144	280.177	3.641	0.342	0.492	3.247	452.582		
	fo	78.11	0.050	400.000	1.738	0.298	0.425	1.697	500.000		
	gz	13.97	0.081	281.312	2.528	0.294	0.377	2.740	500.000		
120219	ag	0.04	0.152	209.963	5.000	0.500	0.500	2.749	259.945	39923	0.300
	fo	10.59	0.152	200.250	5.394	0.493	0.486	2.841	254.212		
	gz	89.09	0.158	131.560	10.000	0.430	0.389	3.784	204.609		
120220	ag	0.11	0.153	210.716	4.976	0.500	0.497	2.783	259.811	4766	0.903
	fo	22.36	0.300	400.000	2.167	0.300	0.102	5.000	135.582		
	gz	77.49	0.300	400.000	0.427	0.308	0.012	5.000	188.571		
120301	ag	0.00	0.152	210.000	5.000	0.500	0.500	2.750	260.000	42575	0.920
	fo	25.35	0.168	211.225	1.806	0.227	0.205	5.000	235.952		
	gz	74.58	0.207	400.000	0.353	0.043	0.028	5.000	500.000		
120302	ag	0.01	0.151	209.984	4.993	0.499	0.499	2.754	260.163	6307	1.132
	fo	25.01	0.300	217.788	1.413	0.248	0.221	5.000	344.989		
	gz	74.41	0.300	154.714	1.043	0.190	0.096	5.000	283.326		
120303	ag	0.09	0.151	209.897	5.013	0.500	0.500	2.753	259.843	95446	0.913
	fo	18.73	0.157	189.436	6.480	0.452	0.439	3.303	240.655		
	gz	80.88	0.172	149.357	10.000	0.299	0.273	5.000	224.118		
120304	ag	0.25	0.155	211.737	4.966	0.501	0.498	2.824	263.080	8106	1.589
	fo	18.79	0.300	296.063	2.663	0.350	0.239	5.000	245.702		
	gz	80.69	0.300	400.000	1.494	0.088	0.018	5.000	192.255		
120305	ag	0.00	0.152	210.000	5.000	0.500	0.500	2.750	260.000	3946	1.576
	fo	29.06	0.300	192.465	1.880	0.125	0.107	5.000	445.262		
	gz	70.91	0.300	155.707	2.142	0.021	0.013	5.000	244.800		
120306	ag	0.00	0.152	210.000	5.000	0.500	0.500	2.750	260.000		
	fo	31.22	0.300	135.773	2.011	0.158	0.078	5.000	500.000		

	gz	68.73	0.300	400.000	0.729	0.049	0.011	5.000	392.214	4708	1.386
120308	ag	0.00	0.152	210.000	5.000	0.500	0.500	2.750	260.000	5515	1.648
	fo	55.37	0.300	162.930	1.534	0.233	0.020	5.000	267.294		
	gz	44.41	0.300	161.808	2.352	0.250	0.039	5.000	244.855		
120309	ag	2.77	0.166	201.475	5.022	0.434	0.420	3.210	256.963	35917	1.075
	fo	18.23	0.185	318.968	2.299	0.304	0.284	5.000	350.493		
	gz	78.75	0.300	235.323	1.812	0.050	0.049	5.000	500.000		
120310	ag	12.72	0.126	223.932	2.407	0.314	0.375	5.000	344.154	15697	1.099
	fo	11.27	0.137	125.199	10.000	0.365	0.407	4.670	260.815		
	gz	75.85	0.300	208.373	1.496	0.125	0.099	5.000	500.000		
121001	ag	0.00	0.152	210.000	5.000	0.500	0.500	2.750	260.000	16810	1.165
	fo	59.42	0.069	315.432	0.424	0.039	0.017	5.000	364.454		
	gz	39.30	0.129	365.188	0.952	0.164	0.085	5.000	419.145		
121002	ag	0.11	0.153	210.031	5.001	0.499	0.495	2.810	259.261	4717	0.430
	fo	37.48	0.300	270.498	2.246	0.256	0.044	5.000	270.134		
	gz	61.18	0.300	287.999	1.574	0.150	0.008	5.000	206.922		
121003	ag	2.24	0.155	203.735	5.109	0.498	0.487	2.842	251.327	6910	1.073
	fo	21.28	0.180	175.753	4.380	0.438	0.356	5.000	241.137		
	gz	75.43	0.282	110.671	3.110	0.321	0.156	5.000	202.068		
121004	ag	9.07	0.203	198.845	10.000	0.495	0.397	4.491	179.796	10589	1.343
	fo	28.76	0.300	184.876	10.000	0.413	0.181	5.000	102.949		
	gz	60.86	0.300	178.912	10.000	0.425	0.072	5.000	28.146		
1	ag	0.10	0.150	210.097	4.977	0.504	0.497	2.752	263.519	143616	0.967
	fo	88.38	0.096	262.796	3.218	0.744	0.338	5.000	373.272		
	gz	11.47	0.138	218.722	4.743	0.524	0.477	5.000	267.754		
2	ag	3.22	0.164	211.253	5.112	0.474	0.437	3.705	250.243	21542	1.215
	fo	37.09	0.300	212.474	3.842	0.158	0.057	5.000	198.994		
	gz	59.62	0.300	341.394	5.613	0.489	0.122	5.000	328.835		
4	ag	0.11	0.153	210.031	5.001	0.499	0.495	2.810	259.261	4717	0.430
	fo	37.48	0.300	270.498	2.246	0.256	0.044	5.000	270.134		
	gz	61.18	0.300	287.999	1.574	0.150	0.008	5.000	206.922		

5	ag	0.00	0.152	210.000	5.000	0.500	0.500	2.750	260.000	20853	1.255
	fo	22.35	0.276	283.352	2.690	0.214	0.417	5.000	500.000		
	gz	76.91	0.300	250.780	2.157	0.070	0.032	5.000	393.527		
6	ag	0.09	0.151	209.897	5.013	0.500	0.500	2.753	259.843	95446	0.913
	fo	18.73	0.157	189.436	6.480	0.452	0.439	3.303	240.655		
	gz	80.88	0.172	149.357	10.000	0.299	0.273	5.000	224.118		

Appendix D – Dynamic SedNet global parameters and data requirements

Spatial projection

Spatial data was projected in the DNRM Albers Equal-Area Projection. It is a conic projection commonly used for calculating area. Albers uses two standard parallels between which distortion is minimised and these are set using the latitudes at 1/5 & 4/5 of the full Y extent of the area of interest. These are the Standard Parallel 1 and Standard Parallel 2 below.

- Central Meridian = 146.0000000
- Standard Parallel 1 = -13.1666666
- Standard Parallel 2 = -25.8333333
- Latitude of Origin = 0.0000000

Grazing constituent generation

Hillslope erosion

Table 27 Hillslope erosion parameters

Characteristic	Value
TSS HSDR value (%)	50
Coarse sediment HSDR value (%)	0
Maximum quick flow concentration (mg/L)	10,000
DWC (mg/L)	0

Gully erosion

Table 28 Gully erosion model input-spatial data and global parameters

Input parameters	Value
Daily runoff power factor	1.4
Gully model type	DERM
TSS delivery ratio value (%)	100
Coarse sediment delivery ratio value (%)	0
Gully cross sectional area (m^2)	10
Average gully activity factor	1
Management practice factor	Variable
Default gully start year	1900
Gully full maturity year	2010
Density raster year	2001

Nutrients (hillslope, gully and streambank)

The ANNEX (Annual Nutrient Export) model estimates particulate and dissolved nutrient loads. Particulate nutrients are generated via hillslope, gully and streambank erosion, while dissolved nutrients are generated via point sources (for example, sewerage treatment plants), or diffuse runoff from other land uses or from inorganic diffuse sources such as fertilised cropping lands (Cogle, Carroll & Sherman 2006).

Six rasters are required as inputs to the Nutrients parameteriser, four nutrient rasters (surface and sub-surface nitrogen and phosphorus), as well as surface and sub-surface clay (%). All of the nutrient data was derived from the ASRIS database, and 'no data values' were adjusted to the median value for that particular catchment. A 'land use based concentrations' table is also required (see Table 29), which provides data on EMC/DWC values for each of the functional units.

Table 29 Dissolved nutrient concentrations for nutrient generation models (mg/L)

Functional Unit	DIN EMC	DIN DWC	DON EMC	DON DWC	DIP EMC	DIP DWC	DOP EMC	DOP DWC	PN EMC	PN DWC	PP EMC	PP DWC
Sugarcane	APSIM	0.6	0.6	0	APSIM+HL		APSIM+HL		Function of sediment	0	Function of sediment	0
Cropping	0.5	0.5	0.37	0.37	HL	0	HL	0		0		0
Grazing	0.128	0.128	0.25	0.25	0.02	0.02	0.025	0.025		0		0

(HL) HowLeaky

Enrichment and delivery ratios are required for nitrogen and phosphorus. The input parameter values used in Burdekin region are found in Table 30.

Table 30 Particulate nutrient generation parameter values

	Phosphorus	Nitrogen
Enrichment ratio	2	1.2
Hillslope delivery ratio	50	100
Gully delivery ratio	100	100

Sugarcane and cropping constituent generation

HowLeaky is a point model which was run externally to Source Catchments to model cropping practices. A unique HowLeaky simulation was run for each combination of soil group, slope and climate which was defined through a spatial intersection. A DERM Tools plugin linked the spatial intersection with databases of parameters to build HowLeaky simulations which could then be batch processed. The intersect shape file also contained information on clay percentage (derived from the ASRIS database) which was used to affect the delivery of fine sediment from the paddock to the stream. Time series files for each of the spatial and management combinations within each subcatchment were accumulated using spatial weighting to generate a single daily load per subcatchment. These time series files were then used as the input for the HowLeaky parameteriser in Source Catchments.

HowLeaky modelling was applied to cropping FUs, which in the Burdekin include: irrigated cropping and dryland cropping. HowLeaky time series files were prepared by the Paddock Modelling team and were used as an input to the HowLeaky parameteriser in Source Catchments. HowLeaky was applied to four constituents: sediment, dissolved phosphorus, particulate nutrients and herbicides. See the HowLeaky input parameters for the Burdekin region model are shown in Table 31 and Table 32.

Table 31 Cropping nutrient input parameters

Parameter	Constituent	Value
Conversion Factor	DOP	0.2
	DIP	0.8
Delivery ratio (%)	Dissolved nutrients	90
	Dissolved herbicides	90
	Particulates, TSS and particulate herbicides	20
Maximum slope (%)	TSS and particulates	8
Use Creams enrichment	P	False
Particulate enrichment	P	N.A
Particulate enrichment	Nitrogen	1.2
Gully DR (%)	N and P	100

Table 32 Cropping sediment (hillslope) input parameters

Parameter	Value
Clay (%)	36
Hillslope DR (%)	20
Maximum slope (%)	8
FU actually growing sugarcane (%)	90
Gully delivery ratio (%)	100
TSS DWC (mg/L)	0

EMC/DWC

Table 33 EMC/DWC values (mg/L)

Constituent	Urban		Horticulture	
	EMC	DWC	EMC	DWC
TSS	80	40	78	39
PN	0.48	0.24	0.45	0.225
DIN	0.16	0.08	0.74	0.74
DON	0.261	0.15	0.251	0.251
PP	0.04	0.02	0.15	0.075
DIP	0.01	0.005	0.014	0.001
DOP	0.02	0.01	0.02	0.01

In-stream models

Streambank erosion

The *SedNet Stream Fine Sediment* model calculates a mean annual rate of fine streambank erosion in (t/yr) and there are several raster data layers and parameter values that populate this model. The same DEM used to generate subcatchments is used to generate the stream network. A value used to determine the 'ephemeral streams upslope area threshold' is also required, and is equal to the value used to create the subcatchment map, which in Burdekin region was 50 km^2. Floodplain area and extent was used to calculate a floodplain factor (potential for bank erosion) and for deposition (loss). The floodplain input layer was determined by using the Queensland Herbarium pre-clearing vegetation data and extracting the land zone 3 (alluvium) codes. The Queensland 2007 Foliage Projective Cover (FPC) layer was used to represent the proportion of riparian vegetation. Riparian vegetation was clipped out using the buffered 100 m stream network raster. A value of 12% was used for the FPC threshold for riparian vegetation. A 20% canopy cover is equivalent to 12% riparian veg cover and this threshold discriminates between woody and non-woody veg and we assumed that the non-woody FPC cover (below 12%) is not effective in reducing streambank erosion (Department of Natural Resources and Mines 2003).

Streambank soil erodibility accounts for exposure of rocks resulting in only a percentage of the length of the streambank being erodible material, decaying to zero when floodplain width is zero. The steps below were followed to create a spatially variable streambank soil erodibility layer with its value increasing linearly from 0% to 100% as floodplain width increases from zero to a cut-off value. It is assumed that once floodplain width exceeds the cut-off value, the streambank will be completely erodible (i.e. streambank erodibility = 100%). The cut-off value used was 100 m.

$$\text{Streambank soil erodibility (\%)} = \text{MIN}(100, 100/\text{cut-off}*\text{FPW}) \quad (10)$$

Where: FPW is floodplain width (m) and cut-off is the cut-off floodplain width (m).

Surface clay and silt values taken from the ASRIS database were added together to create the clay and silt percentage layer. 'No data' values were changed to the median value. Using the raster data layers described above, *SedNet Stream Fine Sediment* model calculates eight raster data sets that are used in the parameterisation process. The calculated rasters are: slope (%), flow direction, contributing area (similar to flow accumulation in a GIS environment), ephemeral streams, stream order, stream confluences, main channel, and stream buffers.

Variable bank height and width functions were incorporated in the model to replace the default Dynamic SedNet fixed stream bank height and width values. Bank height and width parameters were developed from local gauging station data. Regression relationships were determined between point observations of channel width and upstream catchment area (Figure 27) and channel height and upstream catchment area (Figure 28). The equation was sourced from Wilkinson, Henderson & Chen (2004) where:

$$(\text{Coefficient}) * (\text{Area, km}^2) \wedge (\text{Area exponent}) \qquad (11)$$

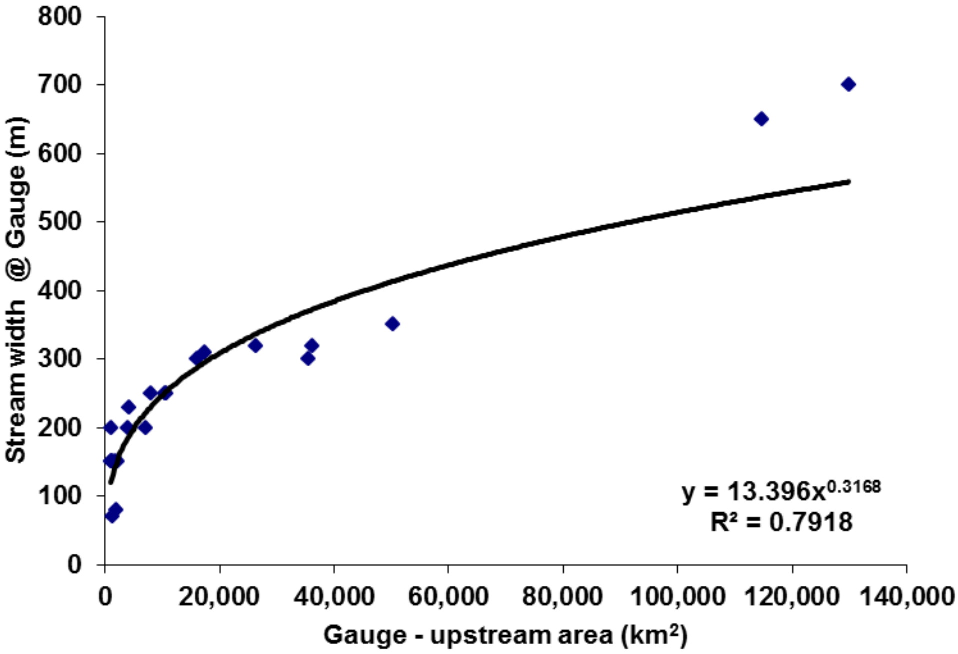

Figure 27 Catchment area vs. bank width used to determine streambank erosion parameters

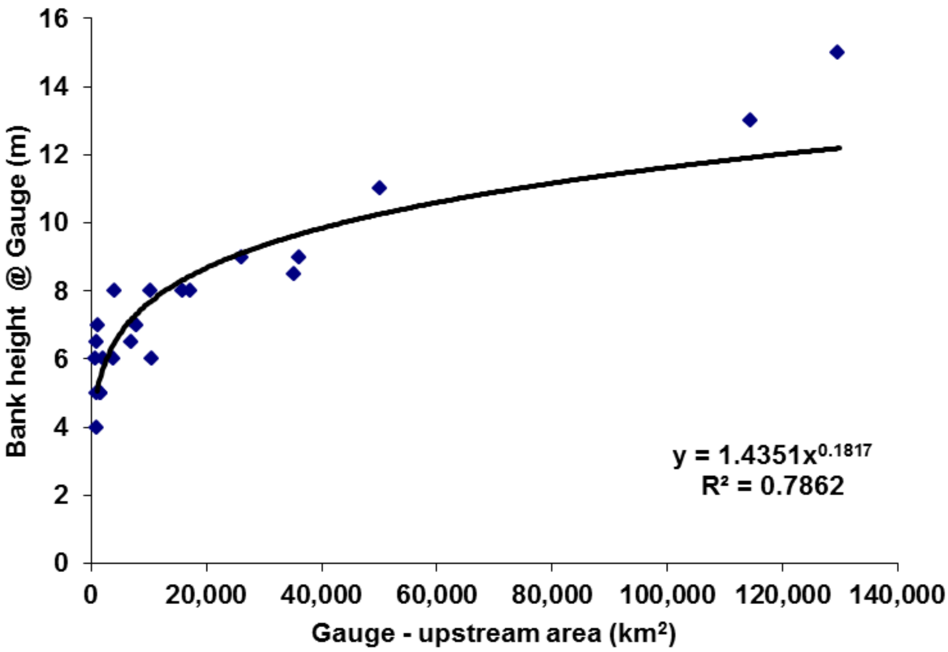

Figure 28 Catchment area vs. bank height used to determine streambank parameters

A series of global input parameters are also required for the *SedNet Stream Fine Sediment* model to run. These were determined on a region by region basis, using the available literature, or default values identified in Wilkinson, Henderson & Chen (2004). The parameter values for Burdekin Region are presented in Table 34.

Table 34 Dynamic SedNet stream parameteriser values for Burdekin region

Input Parameters	Value
Bank Height Method: SedNet Variable – Node Based	
Proportion for TSS deposition	0
Catchment area exponent	0.1817
Catchment area coefficient	1.4351
Link Width Method: SedNet Variable – Node Based	
Minimum width (m)	1
Maximum width (m)	1000
SedNet area exponent	0.3168
SedNet area coefficient	13.396
SedNet slope exponent	0
Link Slope Method: Main Channel	
Minimum Link Slope	0.000001
Stream Attributes	
Bank full recurrence interval (years)	2.5
Stream buffer width (m)	100
Maximum vegetation effectiveness (%)	95
Sediment dry bulk density (t/m^3)	1.5
Sediment settling velocity (m/sec)	0.000001
Sediment settling velocity for remobilisation (m/sec)	0.1
Bank erosion coefficient	0.00008
Manning's N coefficient	0.04
FPC threshold for streambank vegetation (%)	12
Initial proportion of fine bed store (%)	0
Daily flow power factor	1.4

Herbicide half lives

Table 35 Herbicide half-lives

Herbicide	Half-life value (seconds)	Days
Atrazine	432,000	5
Diuron	760,320	8.8
Hexazinone	760,320	8.8
Metalochlor	777,600	9
Tebuthiuron	2,592,000	30
2,4-D	2,505,600	29
Paraquat	864,000	10
Glyphosate	216,000	2.5

Storage details

Table 36 Storage details and Lewis trapping parameters for Burdekin Region

Storage	Storage details			Lewis trapping parameters						
	Full supply level (m)	Initial storage level (m)	Dead storage (m)	Length of storage (m)	Subtractor parameter	Multiplier parameter	Length/ discharge factor	Length/ discharge power	Capacity = Max geometry	Use outflow
Paluma Dam	100	95	89.03	1,000	100	800	3.28	-0.2	False	False
Ross River Dam	38.55	30	19.1	4,000	100	800	3.28	-0.2	False	False
Clare Weir	20.54	20	13.68	N.A	N.A	N.A	N.A	N.A	N.A	N.A
Burdekin Falls Dam	154	100,000 (ML)	118.4	25,000	100	800	3.28	-0.2		
Eungella Dam	562.7	530	525	4,500	100	800	3.28	-0.2		

Management practice information

Table 37 Examples of improved management practices targeted through Reef Plan (including Reef Rescue) investments (McCosker pers.comm. 2014). Note: the list is not comprehensive.

Targets for management change	What is involved
Grazing	
Land type fencing	New fencing that delineates significantly different land types, where practical. This enables land types of varying quality (and vulnerability) to be managed differently.
Gully remediation	Often involves fencing to exclude stock from gullied area and from portion of the catchment above it. May also involve engineering works to rehabilitate degraded areas (e.g. re-battering gully sidewalls, installation of check dams to slow runoff and capture sediment).
Erosion prevention	Capacity building to acquire skills around appropriate construction and maintenance of roads, firebreaks and other linear features with high risk of initiating erosion. Often also involves co-investment for works, such as installing whoa-boys on roads/firebreaks and constructing stable stream crossings.
Riparian or frontage country fencing	Enables management of vulnerable areas – the ability to control grazing pressure. Usually requires investment in off stream watering points.
Off stream watering points	Installation of pumps, pipelines, tanks and troughs to allow stock to water away from natural streams. Enables careful management of vulnerable streambanks and also allows grazing pressure to be evenly distributed in large paddocks.
Capacity Building – Grazing Land Management	Extension/training/consultancy to acquire improved skills in managing pastures (and livestock management that changes as a result). Critical in terms of achieving more even grazing pressure and reducing incidences of sustained low ground cover.
Voluntary Land Management Agreement	An agreement a grazier enters into with an NRM organisation which usually includes payments for achieving improved resource condition targets, e.g. areas of degraded land rehabilitated, achievement of a certain level of pasture cover at the end of the dry season.
Sugarcane	
Subsurface application of fertilisers	Changing from dropping fertiliser on the soil surface, to incorporating 10-15cm below the surface with non-aggressive narrow tillage equipment
Controlled traffic farming	Major farming system change. Changes required to achieve CTF include altering wheelbases on all farm machinery, wider row widths, re-tooling all implements to operate on wider row widths, use of GPS guidance

Nutrient management planning	Capacity building to improve skills in determining appropriate fertiliser rates
Recycling pits	Structure to capture irrigation runoff water on-farm. Also includes sufficient pumping capacity to allow timely reuse of this water, maintaining the pit at low storage level
Shielded/directed sprayers	Equipment that allows more targeted herbicide application. Critical in increasing the use of knockdown herbicides in preference to residual herbicides.
Reduced and/or zonal tillage	New or modified equipment that either reduces the frequency and aggressiveness of tillage and/or tills only a certain area of the paddock (e.g. only the portion of the row that is to be planted).
High-clearance boomsprays	Important in extending the usage window for knockdown herbicides (i.e. longer period of in-crop use)
Sediment traps	Structures that slow runoff transport sufficiently to allow retention of sediments
Variable rate fertiliser application equipment	Equipment that enables greater control of fertiliser rate (kg/ha) within blocks or between blocks
Zero tillage planting equipment	Planting equipment for sugarcane and/or fallow crops that reduce or negate the need for tillage to prepare a seedbed.
Laser levelling	Associated with improvements in farm drainage and runoff control and with achieving improved irrigation efficiency.
Irrigation scheduling tools	Equipment and capacity building to optimise irrigation efficiency. Matching water applications to crop demand minimises potential for excess water to transport pollutants such as nutrients and pesticides.

Appendix E – Report Card 2013 modelling results

Table 38 Constituent loads for natural, total, anthropogenic and Report Card 2013 change model runs for the Burdekin NRM region

TSS (kt/yr)	Predevelopment	Total baseline	Increase factor	Anthropogenic baseline	Report Card 2013	Load reduction (%)
Black	82	107	1.3	25	106	5
Ross	84	110	1.3	26	109	5
Haughton	104	261	2.5	157	251	6
Burdekin	1,027	3,173	3.1	2,146	2,813	17
Don	153	325	2.1	171	298	16
Total region	**1,451**	**3,976**	**2.7**	**2,525**	**3,577**	**16**
TN (t/yr)	**Predevelopment**	**Total baseline**	**Increase factor**	**Anthropogenic baseline**	**Report Card 2013**	**Load reduction (%)**
Black	256	413	1.6	157	410	2
Ross	185	540	2.9	356	539	0
Haughton	294	1,398	4.7	1,104	1,204	18
Burdekin	3,191	6,979	2.2	3,788	6,654	9
Don	368	779	2.1	411	729	12
Total region	**4,294**	**10,110**	**2.4**	**5,816**	**9,536**	**10**
DIN (t/yr)	**Predevelopment**	**Total baseline**	**Increase factor**	**Anthropogenic baseline**	**Report Card 2013**	**Load reduction (%)**
Black	37	86	2.3	48	84	4
Ross	31	224	7.2	193	224	0
Haughton	61	762	12.5	701	578	26
Burdekin	576	1,436	2.5	860	1,367	8
Don	49	139	2.8	90	134	6
Total region	**755**	**2,647**	**3.5**	**1,893**	**2,387**	**14**
DON (t/yr)	**Predevelopment**	**Total baseline**	**Increase factor**	**Anthropogenic baseline**	**Report Card 2013**	**Load reduction (%)**
Black	73	151	2.1	78	151	0
Ross	61	174	2.9	113	174	0
Haughton	120	343	2.8	222	343	0
Burdekin	1,133	2,319	2.0	1,186	2,319	0
Don	97	199	2.1	102	199	0
Total region	**1,484**	**3,185**	**2.1**	**1,701**	**3,185**	**0**
PN (t/yr)	**Predevelopment**	**Total baseline**	**Increase factor**	**Anthropogenic baseline**	**Report Card 2013**	**Load reduction (%)**
Black	146	177	1.2	31	176	3

Ross	93	142	1.5	49	141	2
Haughton	113	294	2.6	181	283	6
Burdekin	1,482	3,224	2.2	1,742	2,968	15
Don	222	441	2.0	219	397	20
Total region	**2,056**	**4,278**	**2.1**	**2,222**	**3,964**	**14**
TP (t/yr)	**Predevelopment**	**Total baseline**	**Increase factor**	**Anthropogenic baseline**	**Report Card 2013**	**Load reduction (%)**
Black	53	69	1.3	16	69	2
Ross	31	81	2.6	50	81	1
Haughton	62	256	4.1	194	249	4
Burdekin	658	1,603	2.4	945	1,477	13
Don	86	174	2.0	88	160	16
Total region	**891**	**2,184**	**2.5**	**1,293**	**2,036**	**11**
DIP (t/yr)	**Predevelopment**	**Total baseline**	**Increase factor**	**Anthropogenic baseline**	**Report Card 2013**	**Load reduction (%)**
Black	6	12	1.9	6	12	1
Ross	5	35	6.7	30	35	0
Haughton	10	74	7.2	64	74	0
Burdekin	97	201	2.1	105	201	0
Don	8	18	2.2	10	18	0
Total region	**127**	**341**	**2.7**	**214**	**341**	**0**
DOP (t/yr)	**Predevelopment**	**Total baseline**	**Increase factor**	**Anthropogenic baseline**	**Report Card 2013**	**Load reduction (%)**
Black	3	7	2.1	4	7	0
Ross	3	13	4.9	10	13	0
Haughton	5	23	4.4	18	23	0
Burdekin	49	101	2.1	52	101	0
Don	4	9	2.2	5	9	0
Total region	**65**	**153**	**2.4**	**89**	**153**	**0**
PP (t/yr)	**Predevelopment**	**Total baseline**	**Increase factor**	**Anthropogenic baseline**	**Report Card 2013**	**Load reduction (%)**
Black	43	50	1.2	7	50	4
Ross	23	33	1.4	10	33	3
Haughton	47	159	3.4	113	153	6
Burdekin	512	1,300	2.5	788	1,174	16
Don	73	146	2.0	73	132	19
Total region	**699**	**1,690**	**2.4**	**990**	**1,542**	**15**
PSII (kg/yr)	**Predevelopment**	**Total baseline**	**Increase factor**	**Anthropogenic baseline**	**Report Card 2013**	**Load reduction (%)**
Black		13		13	10	21

Ross		6		6	6	0
Haughton		1,353		1,353	1,163	14
Burdekin		632		632	555	12
Don		85		85	80	6
Total region		**2,090**		**2,090**	**1,814**	**13**

Appendix F – Report Card 2010 notes and results

The four model scenario results for the Burdekin are presented in Table 39. Notes on Report Card 2010 model runs regarding methodology are provided below:

- Methodology in Source Catchments was made available for Report Card 2011that allowed dissolved P loads to change with management practice, changes that influenced runoff in APSIM. In Report Card 2010, no management effect was incorporated for dissolved phosphorus and hence no reductions in DIP and DOP loads due to improved management.

Table 39 Report Card 2010 predevelopment, baseline and management change results. Note, these are different to Report Cards 2012–2013 total baseline loads which are the loads that should be cited when referencing this work

	TSS (kt/yr)	TN (t/yr)	DIN (t/yr)	DON (t/yr)	PN (t/yr)	TP (t/yr)	DIP (t/yr)	DOP (t/yr)	PP (t/yr)	PSIIs (kg/yr)
Predevelopment load	1,297	4,116	755	1,484	1,877	825	127	65	634	0
Total baseline load	4,104	9,678	2,352	3,036	4,289	2,141	310	146	1,686	2,219
Anthropogenic baseline load	2,087	5,562	1,598	1,552	2,412	1,315	183	81	1,051	2,219
Report Card 2010 load	4,043	9,331	2,119	3,036	4,176	2,106	310	146	1,651	1,994
Load reduction (%)	2.2	6.2	14.6	NA	4.7	2.6	NA	NA	3.3	10.1

NA – management changes were not modelled for DON, DOP and DIP

Appendix G – Report Card 2011 notes and results

The four model scenario results for the Burdekin are presented in Table 40. Notes on Report Card 2011model runs regarding methodology are provided below:

- For Report Card 2011for sugarcane, slightly different baseline management proportions were used compared to the Report Cards 2012–2013 baseline management proportions. This slight shifting in baseline management proportions was necessary to accommodate reported management changes. For each Report Card, the modellers receive additional information on investments by regional bodies. The assumption has to be that if the investment funded a change from C to B management, the 'from' category existed in our baseline year. In reality, it may be that this investment was a follow up to an earlier improvement on the same piece of land; however, this information was not provided to the modellers. Therefore, for each report card the baseline distribution was reallocated to ensure that reported changes could be represented.

Table 40 Report Card 2011 predevelopment, baseline and management change results. Note, these are different to Report Cards 2012–2013 total baseline loads which are the loads that should be cited when referencing this work

	TSS (kt/yr)	TN (t/yr)	DIN (t/yr)	DON (t/yr)	PN (t/yr)	TP (t/yr)	DIP (t/yr)	DOP (t/yr)	PP (t/yr)	PSIIs (kg/yr)
Predevelopment load	1,297	4,116	755	1,484	1,877	825	127	65	634	0
Total baseline load	3,962	10,068	2,621	3,183	4,264	2,119	365	160	1,594	2,117
Anthropogenic baseline load	2,665	5,953	1,866	1,699	2,387	2,038	239	95	960	2,117
Report Card 2011load	3,705	9,589	2,350	3,183	4,056	2,028	365	159	1,503	1,758
Load reduction (%)	9.7	8.1	14.5	NA	8.7	7	NA	NA	9.5	17

NA – management change was not modelled for DON, DIP or DOP.

Appendix H – Report Card 2012 notes and results

The four model scenario results for the Burdekin are presented in Table 41. Some changes were made to the Burdekin model between the production of Report Card 2011and Report Card 2012:

- Inflow used in as the input to the storage trapping model in Report Cards 2012–2013instead of outflow which was used in Report Card 2011and Report Card 2010.
- Actual storage capacity was used in Report Cards 2012–2013instead of the maximum storage volume in the storage rating curve in Report Card 2011and Report Card 2010. This change is significant where there are many storages and the maximum storage volumes in the rating curves are greater than the actual storage capacities.

Table 41 Report Card 2012 predevelopment, baseline and management change results. Note, these are different to Report Cards 2012–2013 total baseline loads which are the loads that should be cited when referencing this work

	TSS (kt/yr)	TN (t/yr)	DIN (t/yr)	DON (t/yr)	PN (t/yr)	TP (t/yr)	DIP (t/yr)	DOP (t/yr)	PP (t/yr)	PSIIs (kg/yr)
Predevelopment load	1,451	4,294	755	1,484	2,056	891	127	65	699	0
Total baseline load	3,976	10,110	2,647	3,185	4,278	2,184	341	153	1,690	2,091
Anthropogenic baseline load	2,525	5,816	1,893	1,701	2,222	1,293	214	89	990	2,091
Report Card 2012 load	3,688	9,636	2,415	3,185	4,035	2,075	341	153	1,581	1,849
Load reduction (%)	11.4	8.2	12.3	NA	10.9	8.4	NA	NA	10.9	11.5

NA – management change was not modelled for DON, DIP or DOP.