Reef Water Quality Protection Plan 2013

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

Cape York NRM region

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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 Cape York (CY) 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).

CY is one of six NRM regions adjacent to the GBR. It is approximately 10% (43,000 km^2) of the GBR catchment area (423,122 km^2), and is characterised by grazing and nature conservation land uses. The region is comprised of seven drainage basins: Jacky Jacky, Olive-Pascoe, Lockhart, Stewart, Normanby, Jeannie and Endeavour. CY is considered a low risk to the health of the GBR for all constituents in recent literature.

The eWater Ltd Source Catchments modelling framework was used to calculate 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 and 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 benchmarked against the anthropogenic baseline load (2008–2009 land use and management). Improved management practices from 2008–2013 were modelled for four Report Cards covering management changes in grazing only (grazing only in CY, although sugarcane and cropping investments were considered in other NRM regions). 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 static climate period was used (1986–2009) for all scenarios. The 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 estimates, 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 nature conservation and the remaining minor land use areas.

Source Catchments was coupled to an independent Parameter EStimation Tool (PEST) to perform hydrology calibrations. A multi-part 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 Coefficient of Efficiency (NSE) and difference in total gauging station streamflow volumes. The NSE 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 15 of the 18 gauges (83%) having monthly NSE values >0.8, and 17 gauges (94%) had total runoff volumes within 20% of observed flows. The average annual modelled flow (1986–2009) from the CY region was 18 million ML, which accounts for 27% of the total GBR average annual flow.

Modelled outputs for the total baseline scenario indicate that approximately 429 kt/yr of total suspended sediment (TSS) load is exported to the GBR from the CY NRM region. The estimated regional TSS load is 1.7 times higher than the predevelopment load. Dissolved organic nitrogen (DON) (3,652 t/yr) accounts for the majority of the total nitrogen (TN) load (5,173 t/yr). TN loads are estimated to be only 1.1-times the predevelopment load. Particulate phosphorus (PP) (238 kt/yr) is the greatest contributor to total phosphorus (TP) load (531 t/yr), but only a minor contributor to the overall GBR load. TP load has increased 1.5-times from the predevelopment load. The Normanby Basin contributes the highest loads of all CY basins. Improved practice adoption have been minimal in CY with an 8.6% decline in TSS load, a 6% decline in TN and 7.4% decline in TP anthropogenic loads as a result of improved management practice adoption. Table 1 provides a summary of the total baseline CY load, the contribution of CY loads to the total GBR load and the percentage load reduction due to Report Card 2013 management improvements.

Three main approaches were used to validate the GBR Source Catchments modelling. Comparison to previous best estimates, a long-term comparison (1986–2009) against available measured data and thirdly a short-term comparison (2006–2010) against the Queensland Government catchment loads monitoring program estimates (GBRCLMP).

The modelled average annual loads of constituents are lower than previous best estimates for CY. The differences in estimates are due to the different approaches used to derive the loads between studies, and improvements made to constituent generation and transport modelling methodologies and updated spatial data sets, which in turn are improving load estimates. Modelled loads are much closer to loads estimated from measured data. For the long-term comparison, all average annual modelled loads were within the likely range of loads calculated by Joo et al. (2014). At a monthly time-step, the modelling results are rated as ‘very good’ for TSS and TN and ‘good’ for TP using the Moriasi et al. (2007) ratings for assessing model performance.

For the short-term comparison, modelled loads were in close agreement with the GBRCLMP estimates. All average annual modelled constituent loads were within ±40% of GBRCLMP loads for the 2006–2010 validation periods. TSS loads were 8% higher than GBRCLMP, TN 6% lower than GBRCLMP and TP 38% higher.

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

	TSS (kt/yr)	**TN (t/yr)**	**PN (t/yr)**	**DIN (t/yr)**	**DON (t/yr)**	**TP (t/yr)**	**PP (t/yr)**	**DIP (t/yr)**	**DOP (t/yr)**	**PSIIs (kg/yr)**
Total baseline load	429	5,173	1,030	492	3,652	531	238	98	195	2.6
Anthropogenic baseline load	180	264	191	5	67	518	113	22	43	3
Load reduction (2008–2013) (%)	8.6	6.0	8.3	NA	NA	7.4	11.6	NA	NA	NA

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

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 scales. 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 recalibrate the model with greater emphasis on simulating high flows. However, the current hydrological model performs very well for sites with good historical flow records. These results suggest that reasonable confidence can be given to modelled flow results for streams and catchments in the CY region where no flow data exists.

Recommendations for enhanced model performance include improving gully and streambank erosion input data layers, moving from annual to seasonal ground cover data inputs to improve inter-annual variability in hillslope erosion rates and recalibration of the hydrological model to better simulate high flows.

The current modelling framework is flexible, innovative and fit for purpose. It is a substantial improvement on previous GBR load modelling applications, with a consistent methodology adopted across all NRM regions. 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:

- NRM 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 ungauged sites
- Daily time-step capabilities and high resolution catchment areas allow for modelled flow volumes and loads of constituents to be reported at a catchment scale for periods ranging from events over a few days, to wet seasons and years.

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Acronyms

Acronym	Description
ANNEX	Annual Network Nutrient Export—SedNet module speciates dissolved nutrients into organic and inorganic forms
CY	Cape York
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—a Source Catchments 'plug-in' developed by DNRM/DSITIA, which provides a suite of constituent generation and in-stream processing models that simulate the processes represented in the SedNet and ANNEX catchment scale water quality model at a finer temporal resolution than the original average annual SedNet model
DSITIA	Department of Science, Information Technology, Innovation and the Arts
DWC	Dry weather concentration—a fixed constituent concentration to base or slowflow 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 quickflow generated from a functional unit to calculate total constituent load
EOS	End-of-system
ERS	Environment 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
GBRCLMP	Great Barrier Reef Catchment Event Monitoring Program (supersedes GBRI5)
HowLeaky	Water balance and crop growth model based on PERFECT
NRM	Natural Resource Management
NRW	Natural Resources and Water (previously incorporated into 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
PSII herbicides	Photosystem II herbicides—ametryn, atrazine, diuron, hexazinone and tebuthiuron
Report Cards 2010–2013	Annual reporting approach communicating outputs of Reef Plan/Paddock to Reef (P2R) Program
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
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
STM	Short-term modelling project

Units

Units	Description
g/ml	grams per millilitre
kg/ha	kilograms per hectare
kg/ha/yr	kilograms per hectare per year
kt/yr	kilotonnes 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//yr	tonnes per year
t/ha/yr	tonnes per hectare per year
µg/L	micrograms per litre

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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, Queensland (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).

Dougall, C., McCloskey, G.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 – Fitzroy NRM region, Technical Report, Volume 6,* Queensland Department of Natural Resources and Mines, Rockhampton, Queensland (ISBN: 978-0-7345-0444-9).

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:

- 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
- Incorporation of hillslope, gully and streambank erosion processes, with the ability to also use EMC/DWC approaches
- Inclusion of small, coastal catchments not previously modelled
- Integration of monitoring and modelling, and using the modelling outputs to inform the monitoring program
- 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
- 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 grains 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 land use within each sub-catchment. These characteristics are then used to provide a single representation of aggregated pollutant generation per land use in each sub-catchment.
- 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, 'A' herbicide practices) rather than individual practices. The potential to overstate the water quality benefits of 'A' herbicide or 'A' nutrient practice, by also assigning benefits from the adoption of 'A' 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 changes reflected in the models 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 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, it was updated in 2009 (Reef Plan 2009), and again 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 2013). 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 using 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 modelling validated against monitoring data to report on the 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 of the GBR and there are six contributing NRM regions: Cape York, Wet Tropics, Burdekin, Mackay Whitsunday, Fitzroy, and Burnett Mary. This document outlines the Cape York (CY) regional 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 load) and post adoption of improved practices from the seven regional basins: Jacky Jacky, Olive-Pascoe, Lockhart, Stewart, Normanby, Jeannie and Endeavour that make up the CY 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 runoff (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, McKergow et al. 2005a, McKergow et al. 2005b, Cogle, Carroll & Sherman 2006). Most recently, Kroon et al. (2012) used collated modelling and monitoring information (Brodie et al. 2009), along with recent monitoring data and the linear regression estimator (LRE) tool to estimate natural and total catchment loads. In Kroon et al. (2012) in the CY region, the estimated total suspended sediment (TSS) load was 2,388 kt/yr, the total phosphorus (TP) load was 1,516 t/yr and the total nitrogen (TN) load was 14,338 t/yr; representing a respective 5.4-, 4.0- and 4.8-fold increase in constituent loads from predevelopment conditions. Herbicide load estimates were not reported in Kroon et al. (2012) for CY, due to the lack of an industry that uses a significant amount of herbicides, and no monitoring (or other) data.

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 set out in this project. 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 us to integrate 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 Cape York modelling approach

A consistent modelling approach was used across all regions to enable direct comparisons of export loads. A standardised 23 year static 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, as well as floodplain deposition (Wilkinson et al. 2010). 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), with an Event Mean Concentration/Dry Weather Concentration (EMC/DWC) approach used to generate loads for nature conservation and the remaining 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 Australian Soil Resource Information System (ASRIS) soils information (Brough, Claridge & Grundy 2006) were all incorporated into the CY model. Model validation was done using water quality information from the CY region. The small coastal catchments were also included into the CY catchment model to ensure the total area contributing loads to the GBR were captured in the model. For a broad overview of the GBR modelling approach refer to Waters and Carroll (2012).

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

The Cape York (CY) NRM region has an approximate area of 43,000 km^2, and is drained by seven Australian Water Resources Council basins (ANRA 2002) (Figure 1). It covers the northern most tip of Australia, is sparsely populated and is characterised by savannah rangelands. CY is approximately 10% of the total Great Barrier Reef (GBR) modelled area (423,134 km^2).

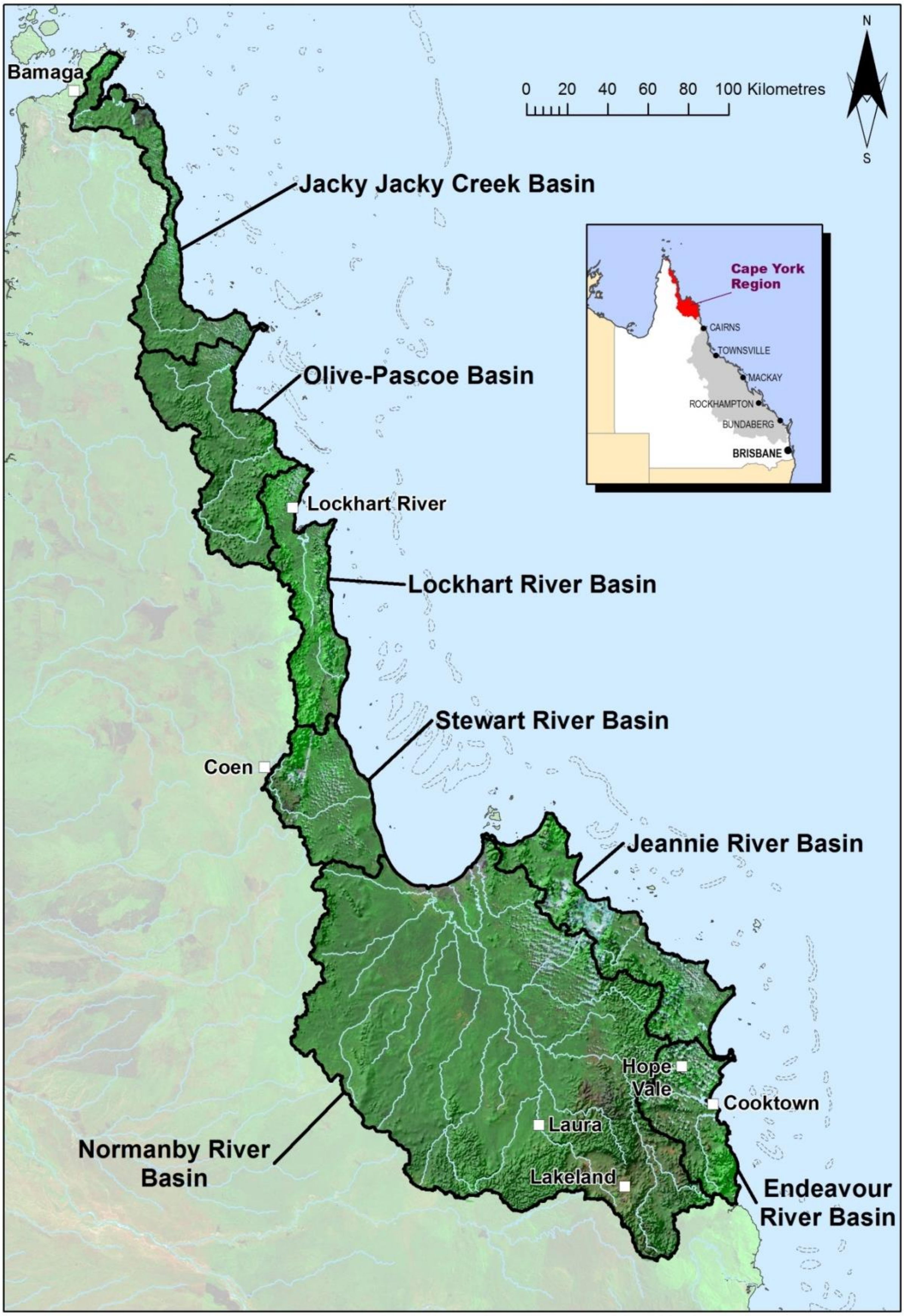

Figure 1 CY NRM region and seven reporting basins

The Normanby Basin is the largest of the reporting basins in the CY NRM region, covering 57% of the total CY area (Table 2). The remaining basins range from 5% to 10% of the CY total area.

Table 2 CY basins and modelled area

Basin name	Area (km^2)	% of total area
Jacky Jacky	2,963	7
Olive-Pascoe	4,180	10
Lockhart	2,883	7
Stewart	2,743	6
Normanby	24,399	57
Jeannie	3,638	8
Endeavour	2,182	5
Total	**42,988**	**100**

2.1 Climate

The CY NRM region experiences a typically tropical climate with a distinct wet and dry season. Average annual rainfall ranges from over 2,000 mm in northern CY to 800 mm in south-western areas (Figure 2); however totals can be highly variable from year to year. Dry season rainfall can occur, and is associated with moist south-easterly trade winds being uplifted over the coast (Tropical Savannas CRC 2011). Maximum temperature at Lockhart River ranges from an average of 27°C in July to 32°C in December, while minimum temperature ranges from 19°C in August to 24°C in January.

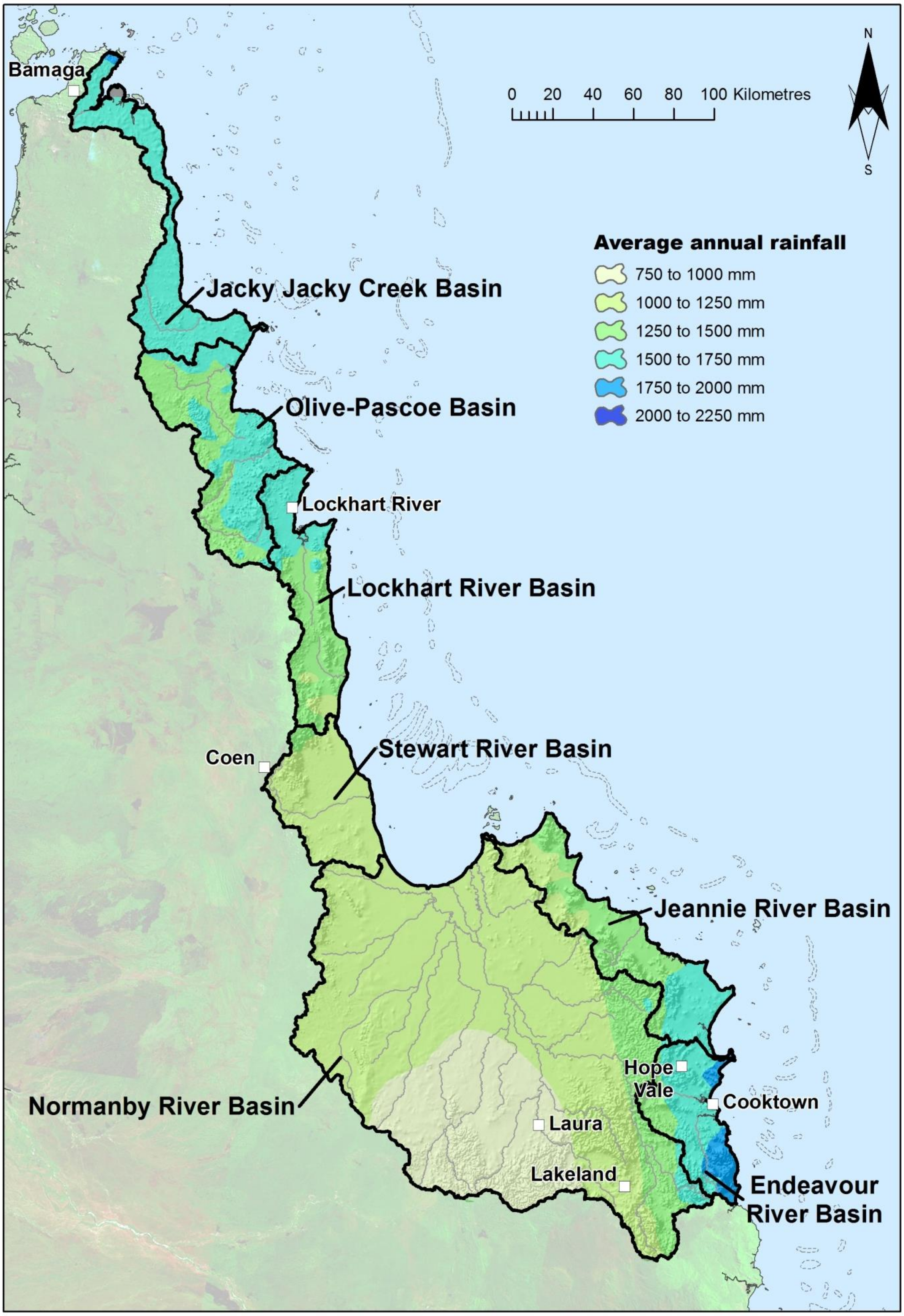

Figure 2 Spatial distribution of CY average annual rainfall

2.2 Hydrology

Cape York experiences highly seasonal rainfall, and as such, a seasonal pattern in flow. A distinct wet season occurs during November to April, with peak river flows typically occurring during the same period. Low flows are recorded during the dry season (May to October), with flow ceasing altogether at some gauging stations. During the dry season, many of the rivers have disconnected waterholes, although some may be connected by minimal subsurface flow. During the wet season, much of the region is flooded, with these flood waters feeding extensive wetlands and alluvial and marine plains, particularly in the Normanby Basin (Howley 2010).

Figure 3 demonstrates the seasonal nature of flow of rivers in the CY region. While there is a considerable difference in catchment area (Normanby 12,930 km^2 vs Pascoe 1,313 km^2) and flow between the two, the main point of interest is that there is typically greater dry season flow in the Pascoe River (10% of annual flow) compared to the Normanby (3% of annual flow). Generally, the Normanby, Endeavour, Stewart and Jeannie basins have a similar pattern of flow with little dry season flow between July and November, while the Olive-Pascoe, Jacky Jacky and Lockhart are similar with more continuous annual flows. Further to this, the CY region can be described as two separate regions, with the savannah dominated landscapes of southern CY, and the rainforest type environments of northern CY.

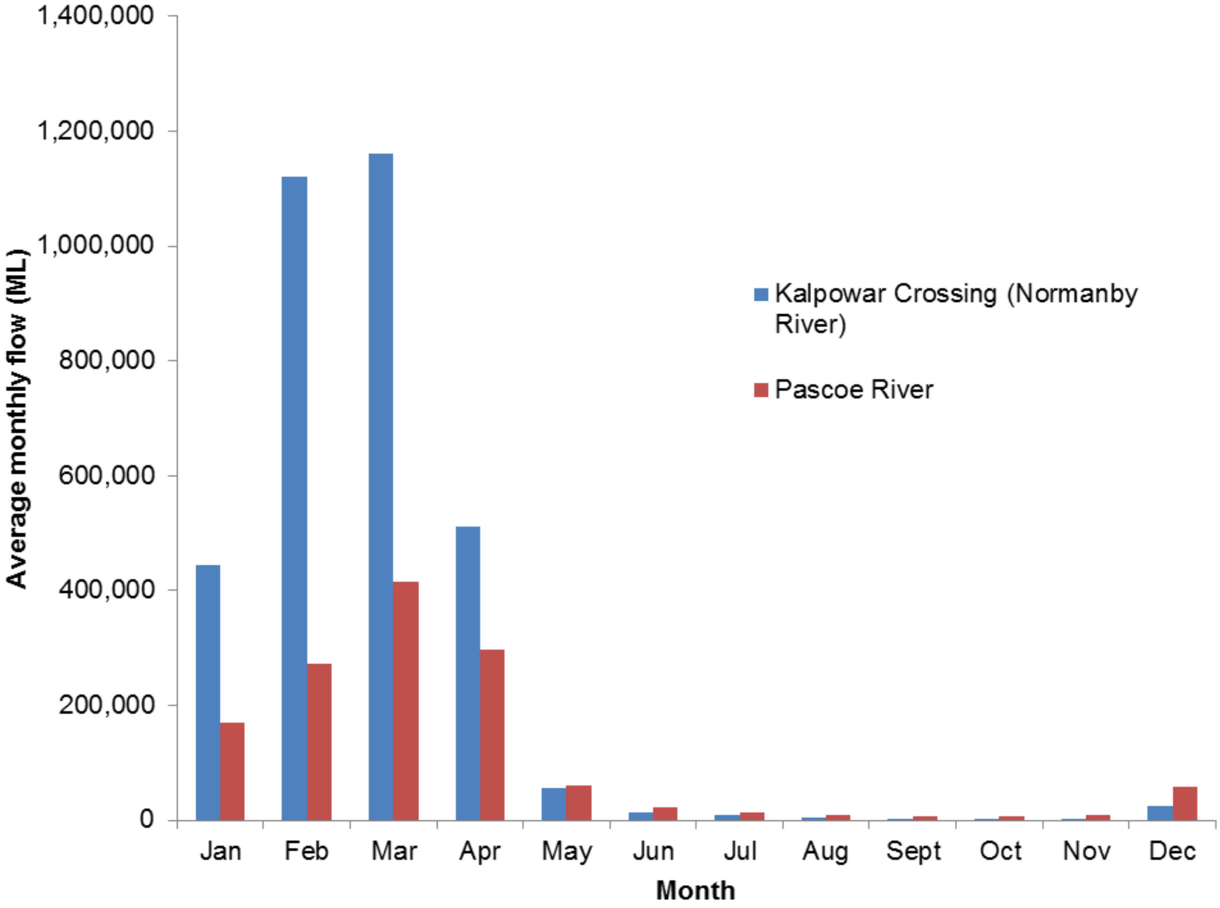

Figure 3 Average monthly flows at Normanby River – Kalpowar Crossing gauging station (105107A) and Pascoe River (102102A)

2.3 Geomorphology, geology and soils

The geology of CY is dominated by part of the Great Dividing Range, made up of Precambrian and Palaeozoic rocks. As the range hugs the eastern coast line, most rivers on the CY Peninsula drain from east to west, while the rivers draining to the east (the rivers of interest in this project) are typically short, with small catchment areas (ANRA 2002). Many of the rivers in CY have developed alluvial fans in the lower reaches, such as the Normanby River (draining to the GBR), and the Mitchell River (draining to the Gulf of Carpentaria). There are several geological features of note in CY, including the large areas of dune fields along the eastern coast around Shellburne Bay and the Cape Bedford – Cape Flattery regions; the limestone karsts around Palmerston in the south of CY; and the black granite boulders in the Black Mountain National Park (near Cooktown) and also at Cape Melville (ANRA 2002). The soils of CY are lateritic, weathered and nutrient poor, and generally unproductive. The predominant soil types include yellow earths, red earths, podsols, lithosols, earthy sands and yellow brown clays. There are areas along the western and south-western coast that consist of saline clay plains, siliceous sands, and sand and shell beach ridges with grey clays (Sattler & Williams 1999).

2.4 Land use

Grazing and nature conservation are the primary land uses in CY; combined, they total 98% of the area. Cattle were introduced to CY around 1865, and stocking rates are low compared to other savanna regions. The area is considered only marginally productive, due to limited infrastructure, poor soil fertility and the remoteness of the region (Tropical Savannas CRC, 2011).

Clearing for agricultural production is relatively new to CY and exists in small pockets particularly around the Lakeland area, in the southern CY NRM region, and around Cooktown. Cropping in this region includes maize, sorghum and coffee. In the past, peanuts have also been produced, and there may be small areas of grass seed crops in existence. Bananas, mangoes and passionfruit are also in production in this region. These crops occupy a very small area, and are represented as irrigated or dryland cropping, and horticulture crops in the model. CY land use categories used in the model are provided in Figure 4, while the area of each land use is outlined in Table 3.

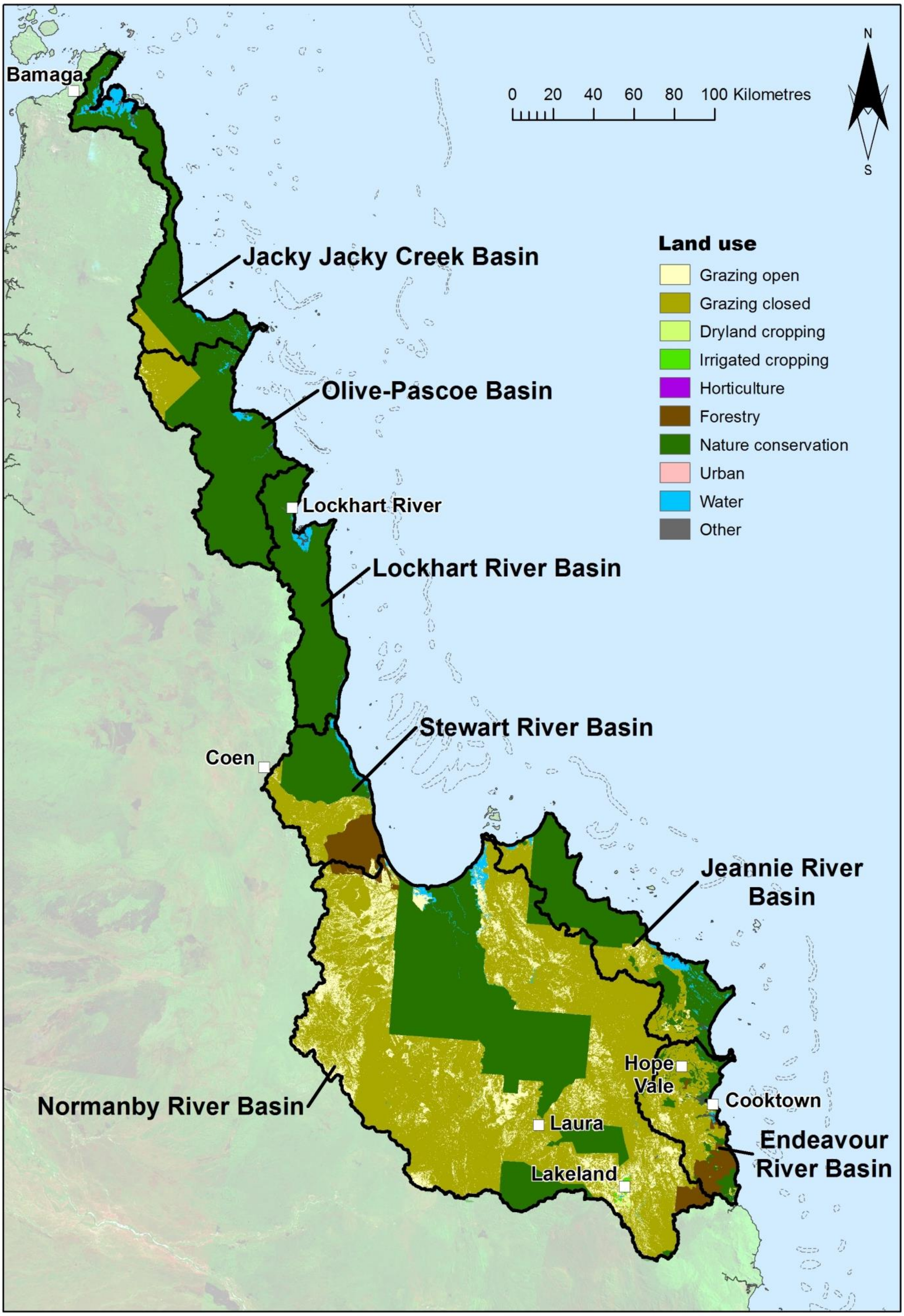

Figure 4 CY NRM region land use classification

Table 3 CY NRM region land use area

Land use	Area (km^2)	% of area
Nature conservation	19,126	45
Grazing (closed)	18,041	42
Grazing (open)	3,459	8
Forestry	1,191	3
Water	904	2
Urban	8	<1
Horticulture	0 (0.45)	<1
Irrigated cropping	31	<1
Other (e.g. mining)	10	<1
Dryland cropping	20	<1

2.5 Water quality issues

Howley (2010) cites water quality and quantity protection as the number one priority for regional stakeholders in the Laura-Normanby catchment, in the southern CY NRM region. The main threats to water quality in the region are: accelerated erosion from cattle grazing and road works; impacts of feral animals in the riparian zone; contamination of surface and/or groundwater as a result of agricultural practices in the Lakeland area; and small-scale mining operations and groundwater extraction for irrigation purposes (Howley 2010). A water quality sampling program as part of the above research concludes that while there may be pulses of some nutrients during, or after, heavy rains, there appears to be little impact from agricultural runoff in the Lakeland area (Howley 2010). It should be noted there was little data available as part of this research with which to validate the CY Source Catchments model.

Generally, very little water quality data is available for the CY region. However, the former Department of Environment and Resource Management (DERM, now Department of Science, Information Technology, Innovation and the Arts (DSITIA)) commenced an event water quality monitoring program (GBRCLMP) in 2005 across all GBR regions, including CY (Joo et al. 2012). As a result of this monitoring, water quality data is now available for the Normanby Basin from 2005–present at the Kalpowar Crossing gauging station (105107A). The Normanby River at Kalpowar Crossing gauge (105107A) gauges 54% of the basin. This was the key data set used for the model validation process. The estimated mean annual TSS load at the Kalpowar Crossing gauge (based on 2006–2010 monitoring) was 137 kt/yr, TN is 1,237 t/yr and for TP 127 t/yr.

In Kroon et al (2012) estimates of average annual pollutant loads for CY are provided, based largely on previous modelling work. This data is provided in Appendix A, Table 23, and it presents the natural and anthropogenic loads from each of the seven basins in the CY NRM region. These estimates suggest that 2,388 kt/yr of suspended sediment is exported to the GBR from the CY region. Of this, 1,944 kt/yr (81%) is from anthropogenic sources. It is also reported that 1,093 kt/yr of suspended sediment is exported from the Normanby Basin, which is significantly higher than average annual load estimates from the monitored samples. It should be noted that the Kroon et al. (2012) values are indicative only, as the data from which the loads are calculated are sporadic, and no time period over which loads are determined is provided.

The findings discussed above highlight the variability in the measured and modelled load estimates for the CY region. This reinforces the need for continued long-term monitoring of catchment loads to reduce the uncertainty in monitored and modelled load estimates for the CY region. There is currently a draft Water Quality Management Plan for the Normanby catchment, which will aim to identify and propose management actions for improving or maintaining water quality in the catchment.

3 Methods

The Cape York model was built within the Source Catchments modelling framework. Source Catchments is a water quality and quantity 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). Model input data sets are provided in Appendix E and 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 hydrological 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.

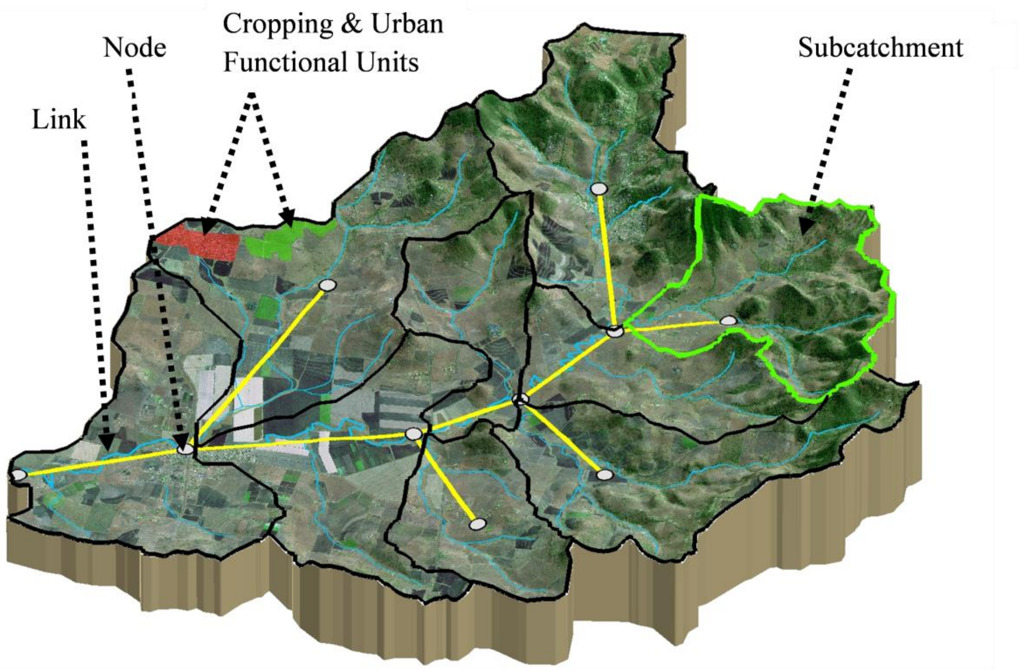

Figure 5 Example of a functional unit (FU) and node-link network generated in Source Catchments. These components represent the subcatchment and stream network

3.1.1 Land use functional units

In the CY region, the most recent land use mapping from the Queensland Land Use Mapping Project (QLUMP) (DSITIA 2012) was used to define the FUs, which were mapped using 1999 imagery. The original detailed QLUMP categories were reclassified into 10 alternative land uses/FUs (Figure 4, Table 3). 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 were those areas with a Foliage Projected Cover (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 (HRUs) 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 CY Source Catchments framework encompasses the NRM region with seven drainage basins (Figure 4). The Normanby Basin is the largest of the reporting basins in the CY NRM region, covering 57% of the total CY area, while the remaining basins range from 5–10% of the total area (Table 3).

These basins are delineated into smaller subcatchments using a Digital Elevation Model (DEM). A 100 metre, hydrologically enforced DEM and a 50 km^2 drainage threshold were 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 by Source Catchments were added manually to the DEM derived subcatchment layer in a GIS environment, using visual assessment of aerial photography. The final subcatchment map was then re-imported into Source Catchments. A total of 546 subcatchments were generated, with an average subcatchment area of 78 km^2 (Figure 6). Out of the 546 subcatchments, 51 coastal catchments were added manually; the inclusion of these flat coastal areas 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 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.

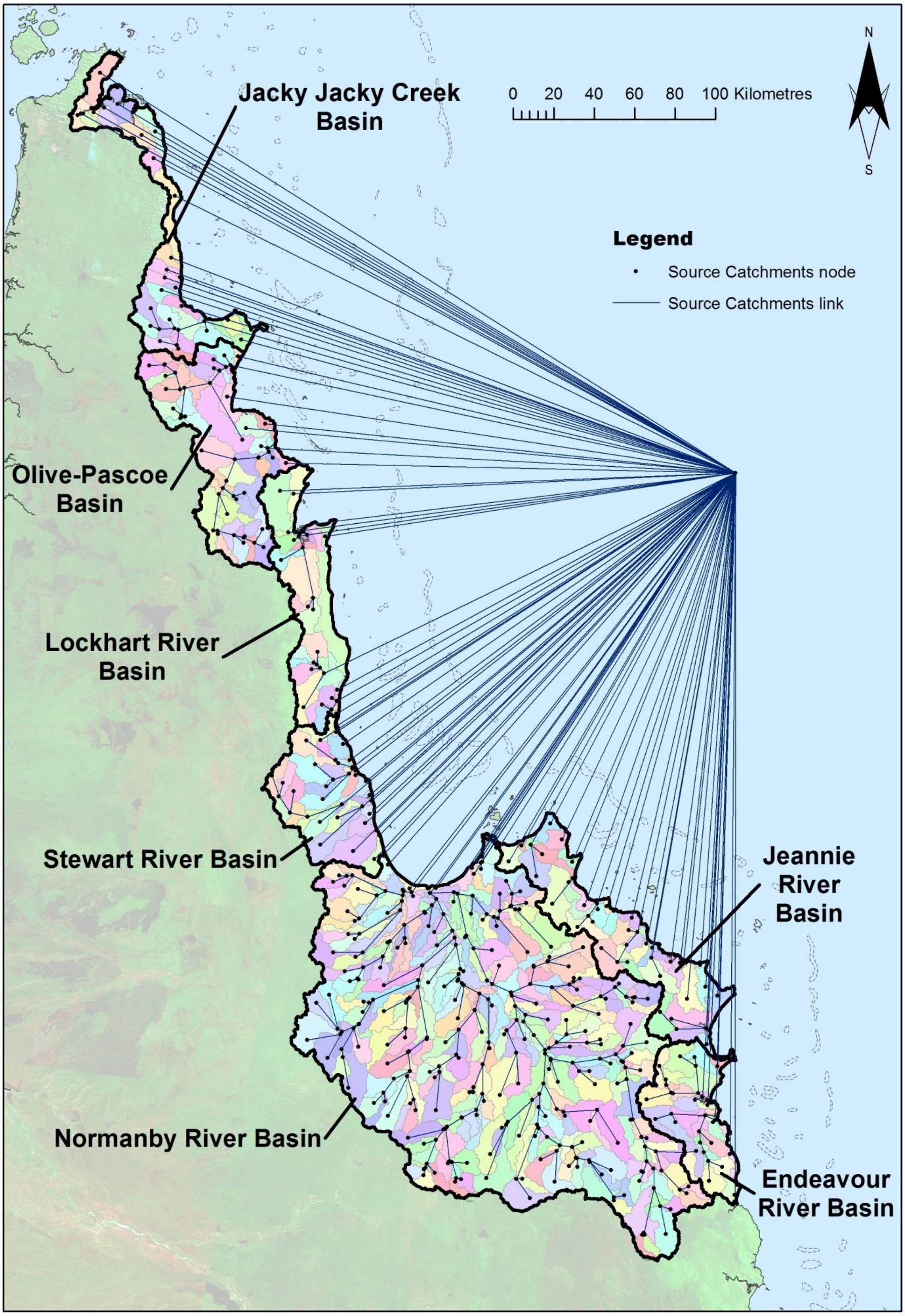

Figure 6 CY subcatchment, node and link network

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, Peel & Western 2002) and in particular for a large catchment in the GBR (Ellis, Doherty & Searle 2009). An investigation of the performance of a number of other models available in Source Catchments was undertaken (Zhang, Waters & Ellis 2013) following the release of 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, Peel & Western 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 the particular modelling objectives. This capability has been extensively used to incorporate the most appropriate constituent generation models across the GBR (Figure 7). SedNet 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 subannual resolution will yield results that are difficult to reconcile with observed events or data.

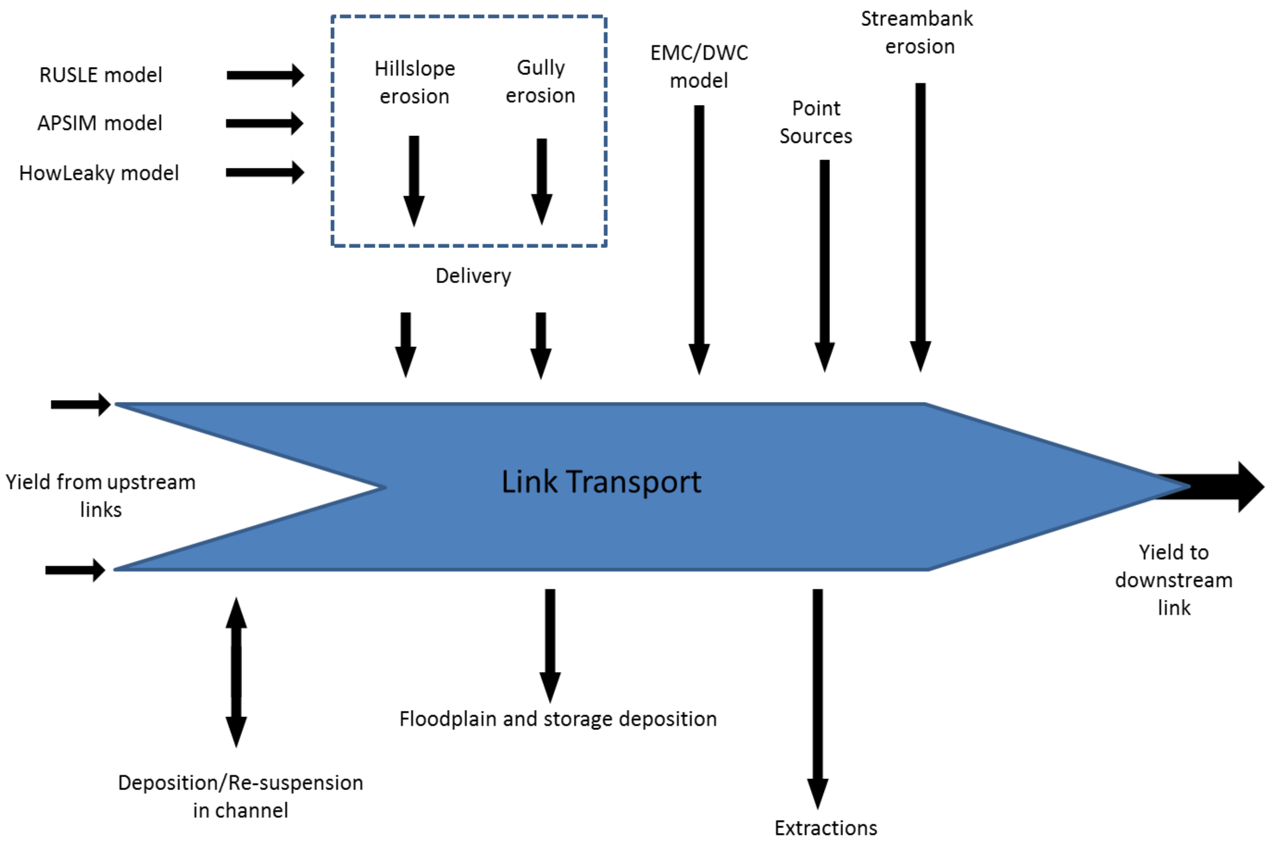

Figure 7 Conceptual diagram of GBR Source Catchments model

The APSIM (Agricultural Production Systems Simulator) model was chosen for modelling sugarcane (Keating et al. 2003), particularly for dissolved inorganic nitrogen (DIN) in runoff. The HowLeaky model, with some enhancements, was used to model herbicides and phosphorus in sugarcane and all constituents for 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 subannual (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 subannual 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 Resources and Mines (DNRM) Silo Data Drill database (Queensland Government 2011). The data drill accesses grids of data derived by interpolating 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 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, Doherty & Searle 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 'slowflow' (or baseflow; subsurface 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. No node models have been applied in the CY model, as there are no storages, extractions, inflows or losses.

3.2.1 PEST calibration

Hydrology calibration was undertaken using PEST, a model-independent parameter estimation tool (Doherty 2009). Parameter optimisation incorporated both the SIMHYD rainfall-runoff parameters and 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 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 18 CY gauges used in the calibration process. Performance was assessed for the calibration period 1/1/1970–31/3/2010. About half of the gauges had the full flow record for the entire calibration period.

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 within ± 20%.

Values for NSE can range from 1 to negative infinity (-∞). 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). Detail on the actual PEST setup, operation and linkage with Source Catchments can be found in Appendix B. Flow duration curves for each of the calibration gauges can be found in Appendix D, Figure 27 through Figure 44, which aided in visually assessing the calibration performance.

3.2.2 Stream gauge selection for calibration

Flow data were extracted from DNRM's Hydstra Surface Water Database to provide the 'observed' flow values for calibration. Eighteen gauging stations were identified as suitable for PEST calibration in CY, based on the following criteria:

- Located on the modelled stream network
- Had a minimum of five years of flow record (post 1970) with data suitable corresponding minimum quality codes.

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

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 routing parameters were used as the starting values. The final set of calibrated SIMHYD and Laurenson flow routing parameters used to generate runoff can be found in Appendix C, Table 26, along with the 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 C, Table 24). These broad groupings were selected from previous research in central 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; Thornton et al. 2007). 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. Regionalisation was only implemented via the template and instruction files that PEST considered. This method of parsimony implies uniformity within, but not between, calibration regions.

Each gauging station included in the calibration represented its own region and modelled subcatchments were therefore divided into 18 regions (Figure 8). 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; Zhang & Chiew 2009). Following the calibration, the 18 parameter sets were applied to the 18 regions (Figure 8) which included ungauged areas. Ungauged catchments comprised 62% of CY modelled area and are shaded grey in Figure 10.

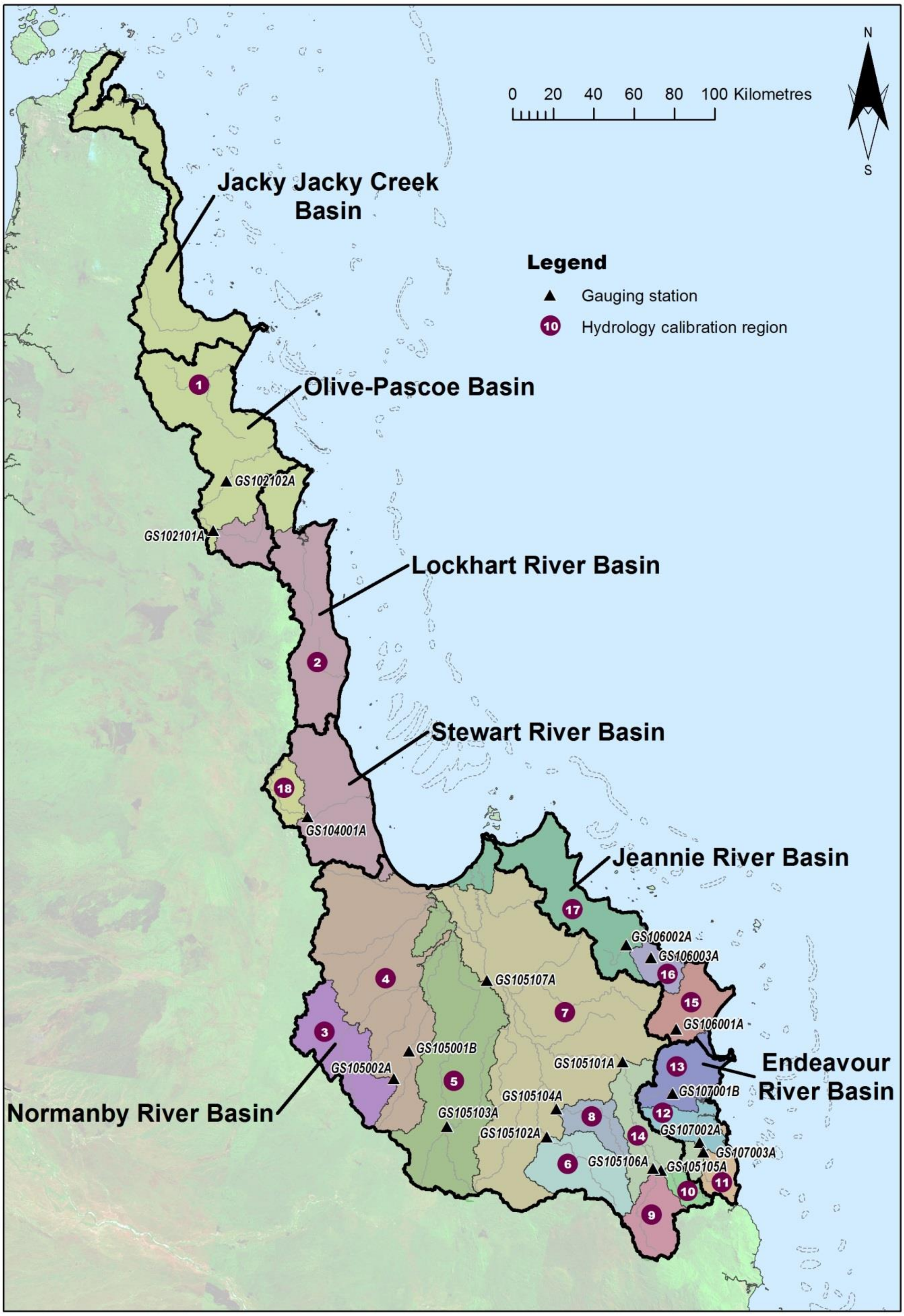

Figure 8 Hydrology calibration regions for CY

3.3 Constituent modelling

The key water quality constituents modelled, are outlined in Reef Plan and shown in Table 4. 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 sub-catchments, and at the Fitzroy basin outlet, >95% of the total suspended sediment (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 Burnett Mary regions. 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 4 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	
atrazine, ametryn, 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 herbicides 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 5. In addition, SedNet functionality has also been 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 Shaw et al. (2014 and Ellis & Searle (2014).

Table 5 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 DNRM/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 catchment scale water quality model (that is, gully and 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, is very 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
- Data requirements of each of the component models
- Methodologies 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 impacting 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. in press, Wilkinson et al. 2005, Dougall et al. 2009). 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. Dynamic SedNet incorporates daily rainfall, and spatially and temporally variable cover to generate erosion.

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 & Ferreira 1993, Renard et al. 1997, Lu et al. 2001). This modified version is based on the Revised Universal Soil Loss Equation, and is referred to as the RUSLE in this document (Renard & Ferreira 1993, Lu et al. 2001). 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.hr.day) (generated as a daily value)

K = Soil erodibility (t.ha.hr/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 in the CY model are shown in Appendix E, Table 27.

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 specifically for CY, to account for rock fragments on the soil surface (Loch & Rosewell 1992) and was available from Report Cards 2011–2013 model runs (it was not available for Report Card 2010 model runs, where an erodibility layer based on ASRIS data was used). (Biggs & Philip 1995) reported significant rock cover across CY which was not accounted for in the ASRIS K factor developed for Report Card 2010. Rock cover will reduce hillslope erosion. The detailed methodology is described further in Appendix E, 'A rock cover factor for Cape York GBR RUSLE modelling'.

Slope steepness factor (S) was calculated by methods outlined in Lu et al. (2003). The slope values for these calculations are derived from the 1 second shuttle DEM (Farr et al. 2007). The use of shuttle DEMs has been found to miscalculate slopes on floodplain areas or areas of low relief. The slope map produced from the 1 second shuttle 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 DEMs covering floodplains in the Fitzroy region.

Slope 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 management 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 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%). The 2009 FPC coverage was used to represent the ‘tree’ coverage, for all years.

‘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). 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 provided 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 an 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 fraction 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 (Wilkinson, Anderson and Chen, 2004; Hateley et al 2009). 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 SDR for this region can be found in Table 27. The equation takes the form: (eq 4):

$$\text{Total suspended sediment load (kg/day)} = \text{RUSLE sediment load (kg/day)} * (\text{silt} + \text{clay}_{\text{(prop)}}) * \text{SDR} \quad (4)$$

This estimates the total suspended sediment (TSS) load, which reaches the stream (see Appendix E for data inputs in the CY model).

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). This algorithm assumes that all nutrients in the soil are attached to the clay fraction where:

$$\text{Hillslope particulate nutrient load (kg/day)} = \text{RUSLE sediment load (kg/day)} * \text{Clay}_{\text{(prop)}} * \text{Surface nutrient concentration (kg/kg)} * \text{Enrichment factor} * \text{Nutrient delivery ratio (NDR)} \quad (5)$$

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 slowflow output (Table 30). These models are described in more detail 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 E. Three rasters are required as inputs to these models, two nutrient rasters (surface nitrogen and phosphorus), as well as surface clay (proportion) raster. The surface soil nutrient layers were extracted from the QLD 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 repeated 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 total baseline load is generated in the model. No data has been provided to model changes in its application beyond the baseline year. Tebuthiuron has not been detected by the GBR catchment loads monitoring program in CY and was therefore not modelled.

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 across the GBR (Hateley et al. 2005, McKergow et al. 2005b, Dougall et al. 2009).

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. The gully average annual sediment supply (AASS) is given 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 FU (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 E, Table 29. The National Land and Water Resources Audit (NLWRA) gully density layer was used as the input raster (km/km^2) for gully density in CY. 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 (Prosser & Winchester 1996, Hughes et al. 2001). Recent research from northern Australia indicates that a value of 5 m^2 is more appropriate (Hughes & Croke 2011) and this has been applied in the CY model. The soil bulk density (g/cm^3) and B-horizon clay plus silt (%) rasters were both created from the QLD ASRIS dataset. The year of disturbance can either be input as a raster or as a uniform value. In the CY model, a uniform value of 1870 was applied as this coincides with the introduction of livestock to the region.

As per hillslope nutrient generation, gully nutrients were derived as a function of the gully fine sediment load. Subsurface nutrient concentrations are multiplied by the gully sediment load to provide an estimate of the gully nutrient contribution and the subsurface clay (%). Raster inputs to these models are two nutrient rasters (subsurface nitrogen and phosphorus), as well as a subsurface clay (%) raster.

3.3.2 Cropping constituent generation

In the GBR Source Catchments framework the component model referred to as the Cropping Sediment (Sheet & Gully) model combines 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), as calculated by HowLeaky (Rattray et al. 2004, Robinson et al. 2010) are combined with the daily gully erosion estimate as outlined above.

3.3.2.1 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 CY were run in the HowLeaky model to represent unique combinations of soil groups, climate and land management.

Runoff was modelled in HowLeaky using a modified version of the Curve Number approach (Littleboy et al. 1989, Shaw & Silburn 2014). Soils in the GBR catchment were grouped according to hydrologic function and assigned a curve number parameter to represent the rainfall versus runoff response for average antecedent moisture conditions and for bare and untilled soil. This curve number was modified within the 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 derived by Freebairn and Wockner (1986). This generalised equation applies anywhere where the cover-sediment concentration relationship holds. In addition, the Freebairn and Wockner equation has been tested and calibrated for 14 sites in Queensland, predominantly in the GBR, for a detailed summary of the results refer to http://www.howleaky.net/index.php/library/supersites.

For each of the unique combinations of soil and climate, an average slope value was derived from the intersected 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 PP was modelled as a function of sediment concentration in runoff and the soil P status (Robinson et al. 2010). 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, Edwards & Shand 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 et al. 2011), 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).

3.3.2.2 Gully sediment and nutrient generation

Gully constituent generation used the same methodology as for grazing lands. Refer to section 3.3.1.2 above. Similarly to the grazing areas, the total subcatchment contribution for cropping FUs combines the hillslope and gully loads. Gully nutrients are derived as a function of the gully particulate sediment load, the subsurface clay (%) and the soil nutrient concentrations.

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

The remaining land uses: forestry, nature conservation, urban, other and horticulture had Event Mean Concentration/Dry Weather Concentration (EMC/DWC) models applied. In the absence of specific models for these land uses, EMC/DWC models were applied to give an estimate of the daily load, where:

$$\text{Daily load (kg)} = (\text{EMC (mg/L)} \times \text{quickflow runoff (ML)}) + (\text{DWC (mg/L)} \times \text{base/slowflow runoff (ML)}) \qquad (7)$$

Where quickflow runoff represents the storm runoff component of daily runoff, the remainder is attributed to base (or slow) flow. 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 (Waters & Packett 2007, Rohde et al. 2008, Bartley et al. 2012). An EMC value for a constituent was calculated directly from the load and flow data for the entire period when reliable long-term monitoring data was available.

DWCs were calculated from data collected during low flow periods (reflecting baseflow). Where there was insufficient data available a value of 50% of the applied EMC was used for the DWC. Low flow periods were defined as the lowest 20th percentile of daily flows; see Appendix E, Table 33 for values used in this model. It is important to highlight that the EMC/DWC applied in this model represented the in-stream generation rates. Hence the assumption is that any physical processes such as hillslope and gully erosion and/or deposition are reflected in the EMC/DWC value.

We chose an EMC/DWC model for nature conservation due to problems with the application of the RUSLE style model in previous modelling efforts. The estimation of soil erosion especially from steep rainforest areas with RUSLE has overestimated sediment loss (Hateley et al. 2005, Armour, Hateley & Pitt 2009). Here we used EMC/DWC values from locally derived monitoring (data from a site draining rainforest). However a limitation of the current EMC/DWC approach is that erosion processes such as gully and hillslope erosion cannot be separated. Currently 50% of the CY area was modelled using the EMC/DWC model and future modelling work will address this issue with the aim to separate out hillslope and gully erosion processes where EMC/DWC models are applied.

To simplify the identification of sources and sinks, any sediment generation models that use an EMC approach assume that the EMC derived load incorporates both hillslope and gully contributions. To derive an estimate for the total hillslope and gully contribution, the EMC derived load was split by taking the percentage of hillslope and gully sources estimated for the remainder of the region and applying the same proportion to the EMC derived source. The EMC derived source for dissolved nutrients was added to diffuse dissolved source load to simplify the results.

3.3.4 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.

3.3.4.1 Streambank erosion

The SedNet Stream Fine Sediment Model calculates a mean annual rate of fine sediment 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 et al. (2013) also see Appendix E, Table 34 for parameter values. The SedNet Stream Particulate Nutrient Model calculates 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 subsurface soil N and P concentrations.

3.3.4.2 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 & Searle (2014). The in-stream decay of dissolved nutrients was not implemented in the CY 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 processes for dissolved nutrients.

Herbicides were decayed in-stream using a first order exponential decay function (Ellis & Searle 2014). 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 B 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 (B Packett, 2012, pers. comm.). Where values were not available in the PPDB 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 E, Table 35.

3.3.4.3 Floodplain (deposition)

Floodplain trapping or deposition occurs during overbank flows. When floodwater rises above river 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 (Prosser et al. 2001b, Wilkinson et al. 2010, Ellis & Searle 2014).

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.

3.3.4.4 Node models

Nodes represent points in a stream network where links are joined. Catchment processes or behaviour can also be represented at nodes. In the GBR Source Catchments model, irrigation extractions, STP inflows, and losses from channels were represented at nodes. For the description of these models refer to eWater Ltd (2013). No node models have been applied in the CY model, as there are no extractions, inflows or loss models and are therefore not described in this report.

3.4 Progress towards Reef Plan 2009 targets

Water quality targets were set under Reef Plan 2009 in relation to the anthropogenic baseline load; that is, the estimated increase in human induced constituent loads from predevelopment conditions (Figure 9).

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

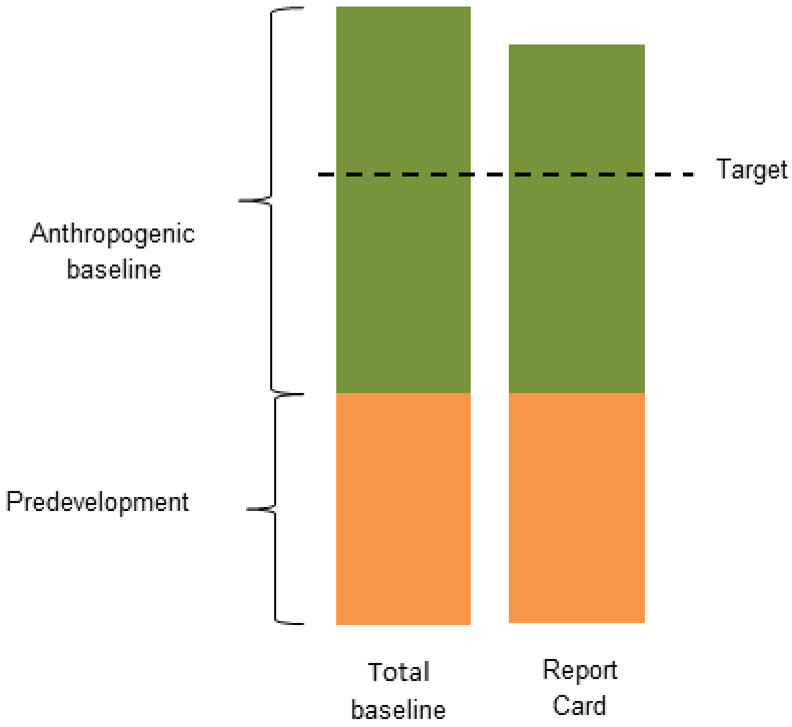

Figure 9 Example of how modelling results will be reported to demonstrate the estimated long-term load reduction resulting from adoption of improved management practices for Report Card 2010–Report Card 2013 against the target

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

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

The progress made towards meeting 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. 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 6 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 6 Total and anthropogenic baseline and Report Card model run details

Scenario	Reporting period	Land use	Model run period
Total and anthropogenic baseline	2008–2009	1999	1986–2009
Report Card 2010	2008–2010	1999	1986–2009
Report Card 2011	2008–2011	1999	1986–2009
Report Card 2012	2008–2012	1999	1986–2009
Report Card 2013	2008–2013	1999	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 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 offsite 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 interrelated 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 Appendix E, Table 36.

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 the 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 1999 land use and 2008–2009 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 2012). Land use categories in QLUMP were amalgamated to represent broader land use classes including: nature conservation, forestry, grazing (open and closed), cropping and horticulture (Figure 4).

Grazing was the only major industry where investment occurred in the CY, and there was 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 (Queensland Government 2013).

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 CY region, baseline and management change data was provided at a river basin scale, and only for the Normanby Basin. The thresholds and progress towards target definitions are provided in Table 7.

Table 7 Pollutant load definitions of the status/progress towards the Reef Plan 2009 water quality 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 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 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 randomly 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 across the GBR, the majority of the baseline management practice was in B class, Table 8 provides the area (%) of the ABCD framework for the baseline and Report Cards 2010–2013.

Table 8 Summary of the baseline management and management changes for grazing (% area) for the CY baseline and Report Cards 2010-2013

Management class	Period	A	B	C	D
		(%)			
Soil	Baseline	0	8	56	36
	2008-2010	0	12	54	34
	2008-2011	0	20	47	33
	2008-2012	0	20	49	31
	2008-2013	0	21	49	30

Riparian fencing

Improved grazing management (in particular cover management) can have both direct and indirect effects on gully and streambank erosion rates. The direct effects of riparian fencing are a result of increased cover on the actual stream or gully. Indirect effects of improved grazing management or increasing cover on hillslope 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 9).

Table 9 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 CY for Report Cards 2011–2013 only, and riparian fencing data to represent the direct effects, was only provided to the modelling team for CY for Report Cards 2012–2013. For assessing the direct effect of riparian fencing, where investments of 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 refers to the period prior to European settlement; hence the anthropogenic baseline load is the period since European settlement. The assumptions made to represent predevelopment conditions were:

- Ground cover was increased to 95% in grazing (open and closed) areas
- With the exception of grazing, all land uses had a nature conservation EMC/DWC applied
- An FPC was created to represent 100% riparian cover
- Gully cross-section area was reduced from 5 m^2 to 0.5 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 6, the predevelopment model was run from 1986 to 2009.

3.5 Constituent load model validation

Three main approaches were used to validate the GBR Source Catchments modelling. Firstly, a comparison was made with the previous best estimates in 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 (Joo et al. 2012,Turner et al. 2012).

It is important to note that the catchment model outputs are compared or 'validated' against measured loads as opposed to the common calibration approach whereby model parameters are adjusted to fit the measured data.

3.5.1 Previous best estimates – Kroon et al. (2012)

Kroon et al. (2012) estimated current, pre-European and anthropogenic loads from the 35 reef catchments (in six NRM regions), using published and available loads data. The best estimates for CY catchments for the 'current' loads were based on SedNet modelling by McKergow et al. (2004). The difference between the Kroon et al. (2012) current and pre-European load provided an estimate of the 'anthropogenic' load. Anthropogenic loads could not be compared due to differences in modelling periods and methodologies. This is further outlined in the discussion. The RC1 loads are presented in Appendix A, Table 23. It should be noted that any comparisons made with Kroon et al. (2012) 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 loads (1986–2009)

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 all end of system gauging stations. The standard approaches were examined including averaging, developing a concentration to flow relationship (regression), and/or the Beale Ratio (Richards 1999, Marsh & Waters 2009, Joo et al. 2014). 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 lack of representative data (Marsh & Waters 2009, Joo et al. 2014). 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 (95^{th} percentile concentration) and likely lower range (5^{th} percentile concentrations) and FRCE load for all constituents (except herbicides) across 23 water years (1/7/1986 to 31/6/2009).

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: NSE, per cent 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 10. Modelled monthly loads were also assessed against these ratings.

Table 10 General 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 Load Monitoring Program – GBRCMLP (2006–2010)

In 2006 the Queensland Government commenced a water quality monitoring program designed to measure sediment and nutrient loads entering the GBR lagoon (Joo et al. 2012). The water quality monitoring focussed on 10 EOS 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). Five priority PSII herbicides that are commonly detected from GBR catchments: diuron, atrazine, hexazinone, ametryn and tebuthiuron are tested for. Organochlorine and organophosphate insecticides (e.g. endosulfan, chlorpyriphos) as well as fungicides are also tested for in laboratory analysis. Herbicides are not sampled in the current GBRCLMP for CY, but are highlighted for inclusion in future sampling regimes. 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). For model validation in CY, catchment modelled loads are compared with the one catchment monitoring site for the 2006 to 2010 period at the Kalpowar Crossing gauge.

4 Results

This section is separated into hydrology and modelled loads. In the hydrology section, the results of the calibration process will be presented, as well as a general summary of the hydrology of the GBR regions. The modelled loads section includes the results of the total baseline, anthropogenic baseline and predevelopment loads. The validation of the CY Source Catchments modelled data is then presented using load estimates from measured and previous modelled data. Progress towards targets due to investment is reported against the anthropogenic baseline for Report Card 2013. A summary of the total baseline load by land use and land use by basin is also reported, as well as a mass balance summary of the sources and sinks by constituent. For a full list of the Cape York region loads for Report Cards 2010–2013 refer Appendix F–I, Table 40 through Table 42.

4.1 Hydrology

4.1.1 Calibration performance

Model performance was assessed for the 18 CY gauges used in the calibration process. Performance was assessed for the calibration period 1970–2010. The results for the three performance criteria: daily NSE (>0.5), monthly NSE (>0.8) and total modelled volume difference ±20% of observed volume are listed. Sixteen of the 18 gauges met all three criteria, one gauge met two of the criteria and one gauge met only one of the criteria (Table 11). The 'traffic light' colour scheme shows those gauges that met all three criteria as green, gauges that met two of three criteria as orange and the gauges that met only one criterion are shaded red. The total volume difference is also represented spatially, with grey areas indicating ungauged catchments (Figure 10).

Monthly NSE values >0.8 suggest a good result for modelling runoff for catchment studies (Chiew & McMahon 1993). Fifteen gauges or 83% of gauges had monthly NSE values >0.8. Ninety per cent of gauges met the volumetric difference criteria. Most modelled gauge data (72%) under-predicted the total runoff volume. Whilst the statistics indicate the overall fit was sufficient for average annual, yearly, even monthly flow predictions, close inspection of the hydrograph shape and timing suggests that daily simulated runoff is often poorly matched to observed flows.

Table 11 Cape York hydrology calibration (1970–2010)

Gauge	Gauge name	Catchment area (km^2)	Years of record	Daily NSE	Monthly NSE	Total volume difference (%)
102102	Pascoe River at Garraway Creek	1,313	39	0.61	0.81	-13
102101	Pascoe River at Fall Creek	651	39	0.52	0.80	-17.5
105002	Jungle Creek at Kalinga	306	18	0.66	0.87	-2
105001	Hann River at Sandy Creek	984	1	0.68	0.90	-2.7
105103	Kennedy River at Fairlight	1,083	18	0.50	0.90	-7.8
105102	Laura River at Coalseam Creek	1,316	39	0.45	0.85	-2.7
105107	Normanby River at Kalpowar Crossing	12,934	4	0.57	0.66	25.4
105104	Deighton River at Deighton	590	18	0.52	0.75	-1.6
105106	West Normanby at Mount Sellheim	839	19	0.62	0.90	8.3
105105	East Normanby River at Mulligan Highway	297	4	0.57	0.85	-0.1
107003	Annan River at Beesbike	247	39	0.70	0.93	-3.2
107002	Annan River at Mount Simon	373	21	0.67	0.86	-17.6
107001	Endeavour River at Flaggy	337	39	0.50	0.84	-0.4
105101	Normanby River at Battle Camp	2,302	39	0.60	0.78	5.9
106001	McIvor River at Elderslie	175	18	0.50	0.81	0.9
106003	Starcke River at Causeway	192	18	0.61	0.86	-5.7
106002	Jeannie River at Wakooka Road	323	18	0.57	0.86	3.3
104001	Stewart River at Telegraph Road	470	39	0.61	0.88	-5.9

Flow duration curves for each gauge used in the calibration process are included in Appendix D (Figure 27 to Figure 44).

The top three performing gauges all had a volumetric flow difference of <1%, while also meeting the daily and monthly NSE criteria. The catchment area of each of these gauges was less than

350 km^2. Two of these three gauges had flow records for the entire calibration period, while the other extended for 18 years.

Gauging station 105107A at Kalpowar Crossing had the poorest performance, with a volumetric flow difference of +25%, and a monthly NSE of 0.66. This gauging station has the largest contributing area gauging over half of the Normanby Basin (54% gauged area, 46% ungauged). It is important to note however, that this gauge has the shortest record of all gauges in CY, being installed in 2005. This is the only gauging station in CY to have monitored water quality data collected, and it also represents the catchment with the greatest change in land use from the natural condition.

In Figure 11 the modelled versus measured loads are compared, and a 1:1 line also shown. The gauges with the lowest discharge have the smallest volumetric error when compared with the modelled flows, as is evidenced by their proximity to the 1:1 line. The gauge with the greatest deviation from the measured volume is also the gauge with the shortest recording period, and the greatest gauging area (105107A).

The three wettest and driest years were also compared to modelled flows for the Battle Camp Creek gauging station in the Normanby Basin. This gauging station was selected as it had observed data for the full modelling period (1986–2009), and it had the second largest catchment area behind the Kalpowar Crossing gauging station (105107A). At the annual time-step the model is matching well at low flows, with variable results for high flows (Figure 12). For the three wettest years at Battle Camp Creek gauge, total flow volumes were within 1% of measured flows, while the driest years are within 100%, although this number is skewed by the small volumes and the 200% volume difference in 1983. It has been identified as a priority for model improvement to recalibrate the hydrology such that high flows are better matched, as the bulk of constituents are transported during these events.

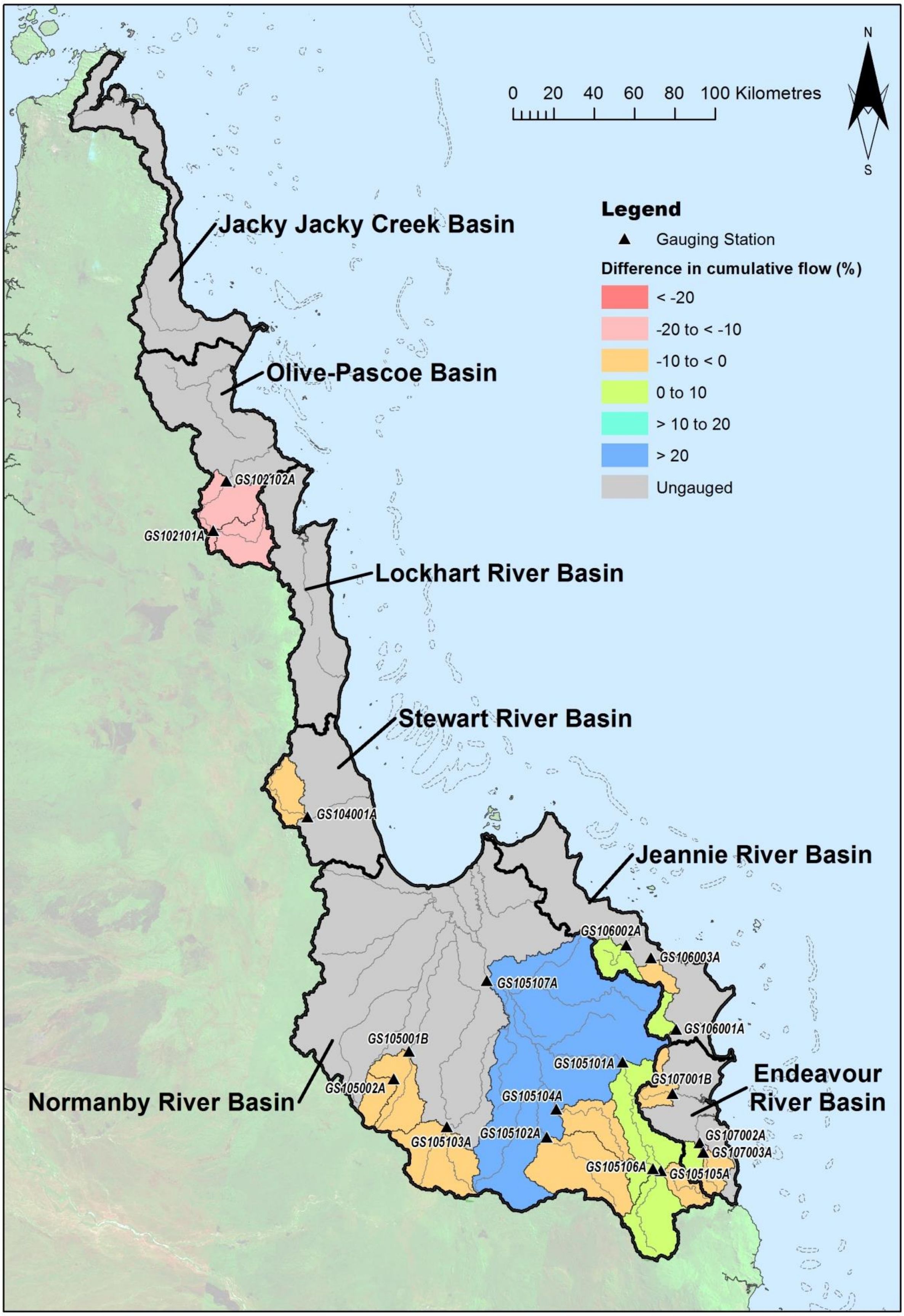

Figure 10 Percentage volume difference for CY calibration regions

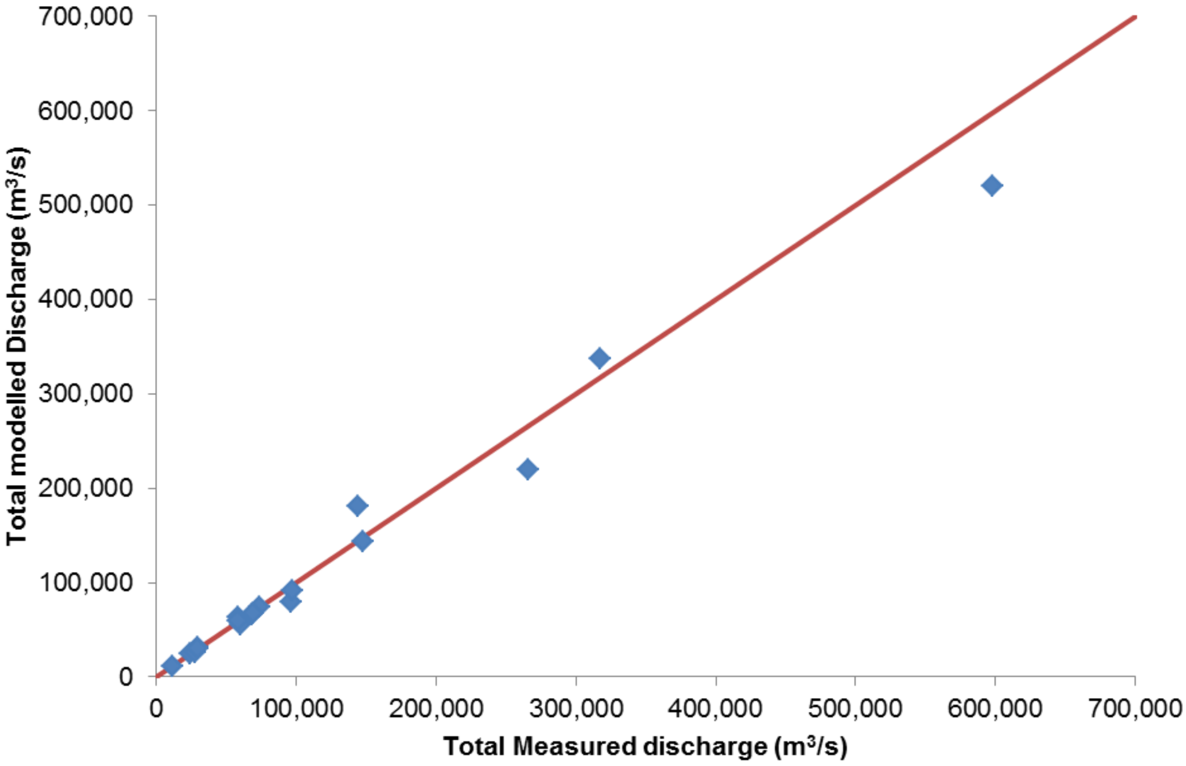

Figure 11 Modelled versus measured average annual flow for the calibration period at all gauges; red line indicates a 1:1 match

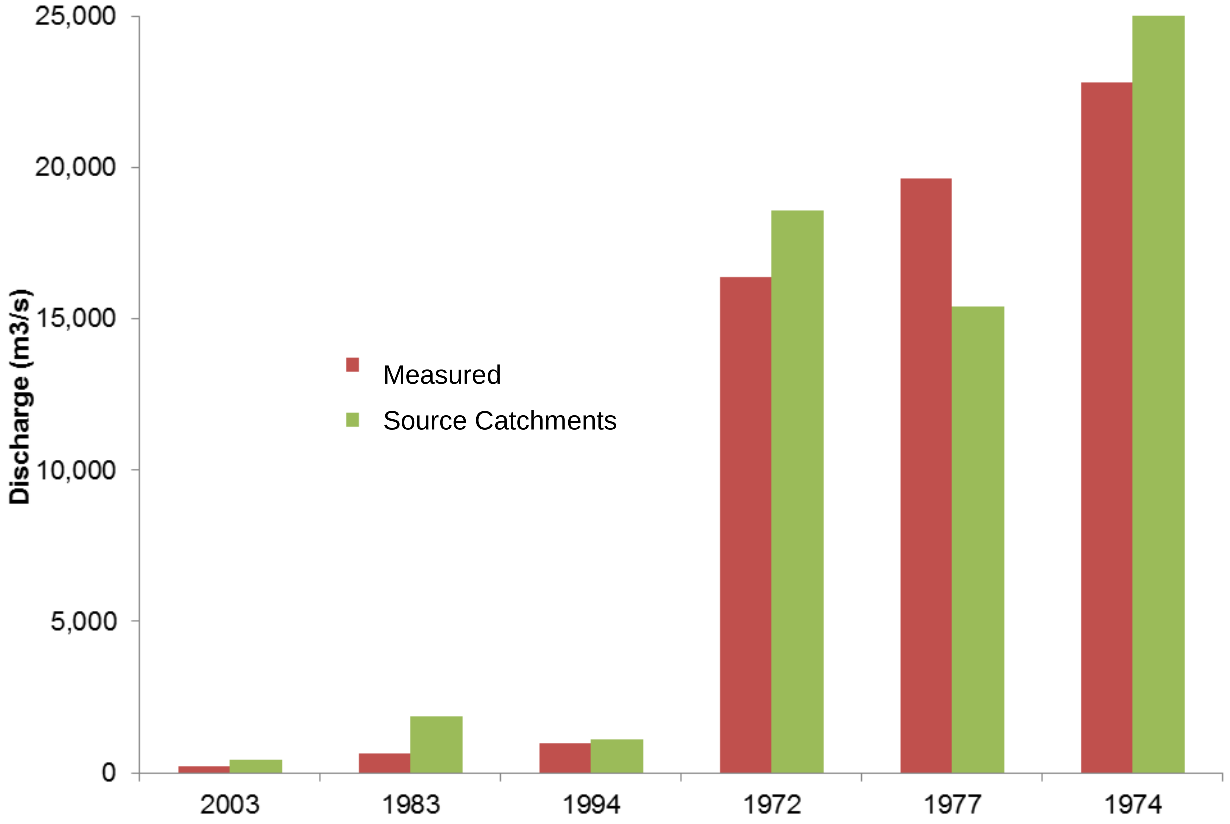

Figure 12 Measured and modelled flow for the three driest and wettest (calendar) years at Battle Camp Creek Gauge (105101) in the Normanby Basin

4.1.2 Regional discharge comparison

The modelled average annual flow (1986–2009) for the Cape York NRM region was 18,000,000 ML/yr (Figure 13), which is 27% of the total modelled GBR average annual flow. CY has the second highest average annual flow and double the area of the Wet Tropics region, which has the greatest average annual flow (21,000,000 ML/yr).

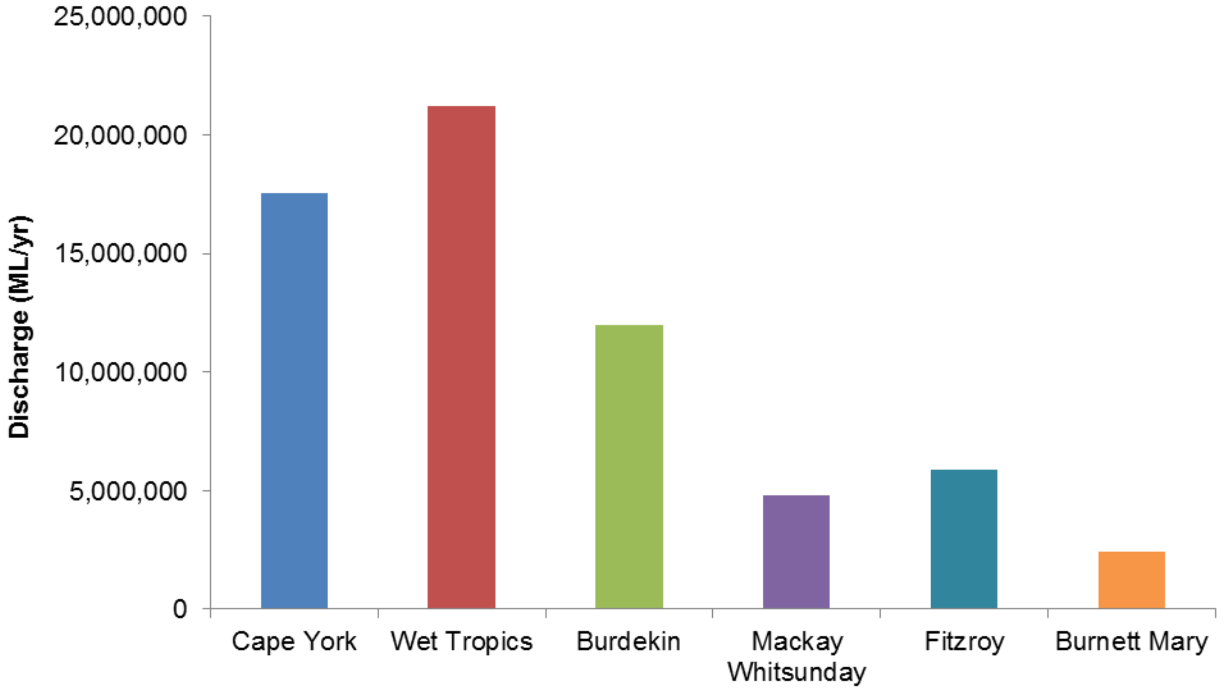

Figure 13 Average annual modelled discharge for the GBR (1986–2009)

For the CY region, the Normanby Basin has the highest modelled average annual flow (4,700,000 ML/yr), followed by the Olive-Pascoe (3,600,000 ML/yr) and Jacky Jacky (2,800,000 ML/yr) basins (Figure 14). In terms of runoff per unit area, the Normanby has the lowest (192 mm), while the Jacky Jacky and Olive-Pascoe basins have the highest runoff (955 mm and 855 mm, respectively) (Table 12). The per cent of rainfall that becomes runoff ranges from 18% in the Normanby to 56% in the wetter Jacky Jacky Basin.

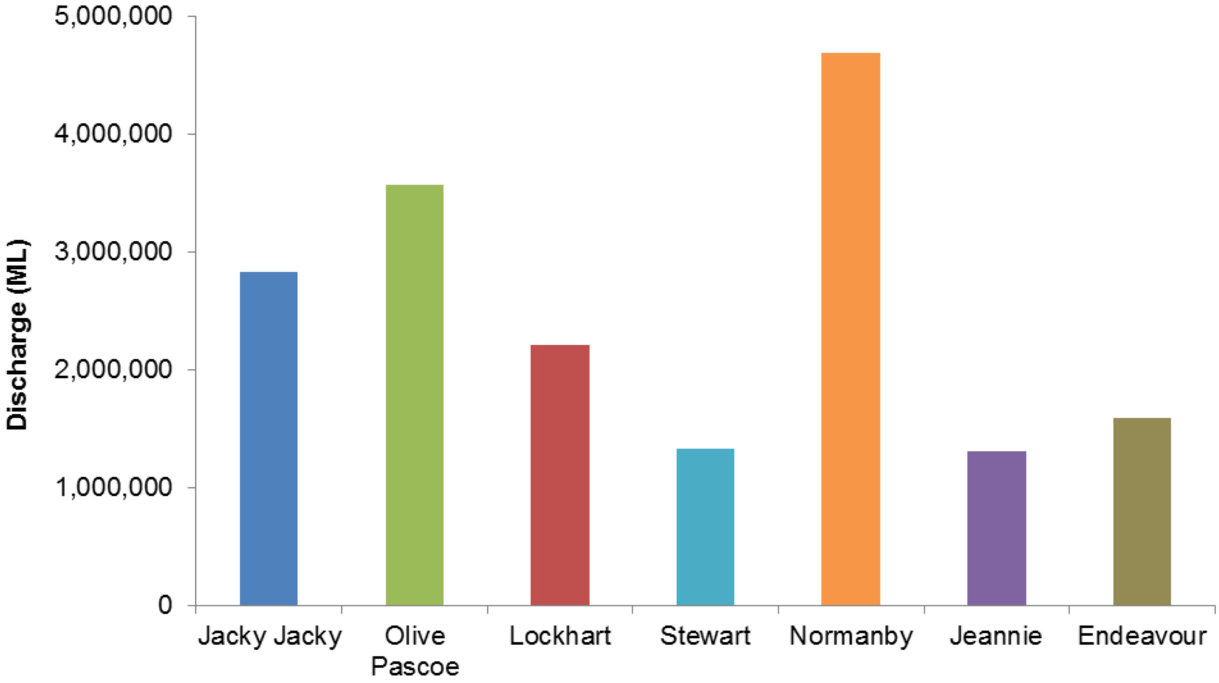

Figure 14 Average annual discharge for the CY basins (1986–2009)

Table 12 Average annual rainfall, runoff and runoff (%) for CY basins (1986–2009)

Basin	Average annual rainfall (mm)	Average annual runoff (mm)	Runoff (%)
Jacky Jacky	1,707	955	56
Olive-Pascoe	1,650	855	52
Lockhart	1,614	768	48
Stewart	1,208	483	40
Normanby	1,050	192	18
Jeannie	1,281	360	28
Endeavour	1,694	728	43

4.2 Modelled loads

It is estimated that 8,545 kt/yr of fine sediment is exported from the six GBR NRM regions, of this 2,931 kt/yr is predevelopment load, and therefore 5,614 kt/yr is the anthropogenic baseline load across the GBR. In Table 13 the total constituent baseline load for all regions is presented, while in Table 14 this data is presented as a per cent contribution.

The Burdekin region is the greatest contributor for most constituents excluding PSII herbicides, for which the Wet Tropics is the largest source. The Burdekin is the largest contributor due to the size of the region and the large flows, as well as the predominant soil types, prevalence of gullies and terrain. Grazing is the predominant land use in the Burdekin. With regard to PSII herbicides, the Wet Tropics has the greatest load (8,596 kg/yr) which is a function of land use, especially the large areas of sugarcane and other irrigated crops within the region, such as bananas, as well as the close proximity of these land uses to the coast. The Wet Tropics supplies 51.4% of the total PSII export from the GBR catchments, and is considerably higher than the second greatest contributor, the Mackay Whitsunday region, with 3,944 kg/yr (23.6% of GBR total).

Table 13 Total baseline loads for the GBR region

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)	PSII (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**

Cape York contributes 5% of the total baseline TSS load being exported to the GBR. CY was one of the three lowest contributors, along with the Burnett Mary at 5% and Mackay Whitsunday at 6%. Generally, CY was among the lowest contributor for all constituents, except for DOP where CY was the highest contributor, and DON, both of which is likely a function of the large area of nature conservation and grazing lands, as well as a large contribution of naturally occurring DON in the Normanby (Turner et al. 2012). While CY does have the highest per cent contribution to DOP load, when converted to a concentration, DOP (mg/L) for CY was the third lowest.

Table 14 Area, flow and regional contribution as a percentage of the GBR total baseline load

NRM region	Area	Flow	TSS	TN	DIN	DON	PN	TP	DIP	DOP	PP	PSII
	% 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 CY region, the Normanby River Basin was the greatest contributor for all constituents, and the only source of PSII herbicides (Table 15). This is not surprising given that the Normanby has the greatest area (57% of region total CY region), and therefore has the greatest areas of grazing (open and closed) and nature conservation land uses. In addition, all of the irrigated and dryland cropping land are located in the upper Normanby Basin, with horticulture occurring only in the Jeannie and Endeavour basins.

Table 15 Contribution from CY basins to the total CY baseline load

Basin	TSS (kt/yr)	TN (t/yr)	PN (t/yr)	DIN (t/yr)	DON (t/yr)	TP (t/yr)	PP (t/yr)	DIP (t/yr)	DOP (t/yr)	PSII (kg/yr)
Jacky Jacky	44	721	171	73	477	58	22	12	24	0.0
Olive-Pascoe	60	1,012	227	102	683	83	31	17	35	0.0
Lockhart	39	575	147	59	369	46	18	9	18	0.0
Stewart	29	395	83	36	276	40	17	8	15	0.0
Normanby	188	1,559	224	139	1,196	205	105	34	67	2.6
Jeannie	27	359	75	34	250	35	16	6	13	0.0
Endeavour	42	553	104	48	400	63	29	11	23	0.0
Cape York	**429**	**5,173**	**1,030**	**492**	**3,652**	**531**	**238**	**98**	**195**	**2.6**

4.2.1 Anthropogenic baseline and predevelopment loads

The anthropogenic baseline load is calculated by subtracting the predevelopment load from the total baseline load. In Figure 15, below, the predevelopment and anthropogenic baseline load for fine sediment for each of the major basins in CY is presented. This graph makes two things abundantly clear: firstly, that the Normanby Basin is by far the largest contributor of TSS load being exported from CY, and secondly, that other than the Normanby and Endeavour rivers, most other basins are largely undisturbed, with very little anthropogenic contribution (any anthropogenic contribution is due to pockets of open grazing in each of these basins).

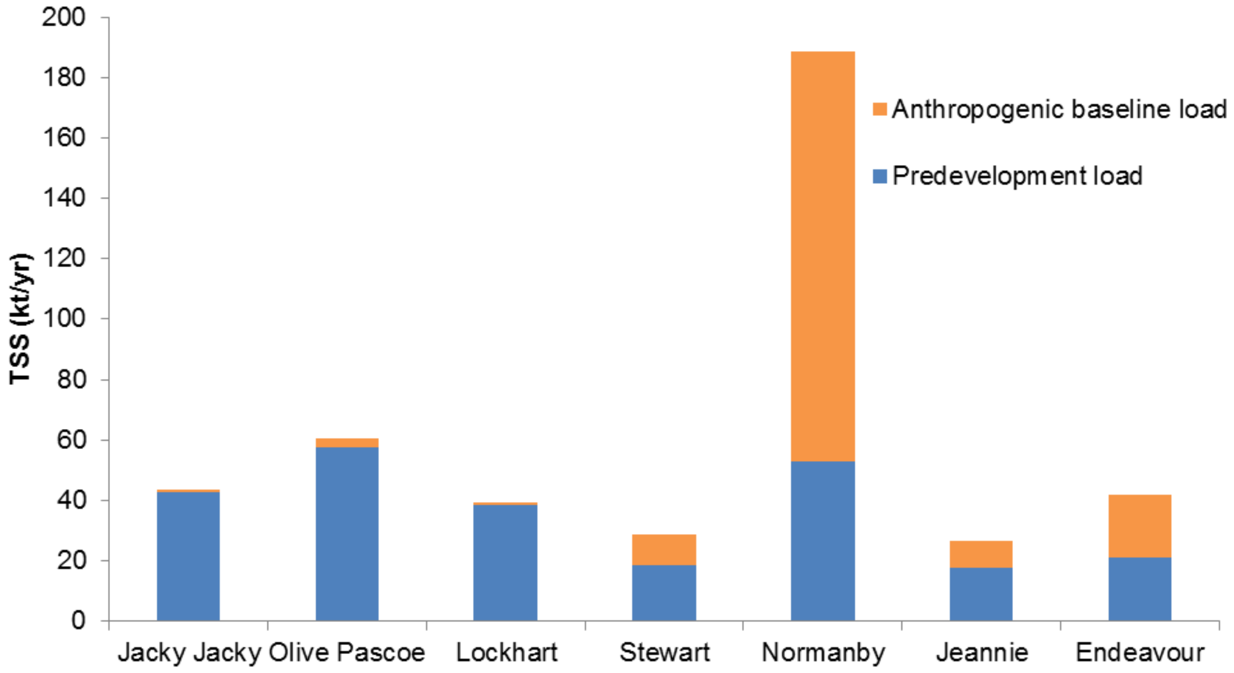

Figure 15 TSS (kt/yr) loads for the CY basins, highlighting the predevelopment and anthropogenic baseline contributions

The Normanby Basin contributes 75% of the CY regional anthropogenic baseline TSS load, and has increased 4-fold from predevelopment conditions. The Endeavour Basin contributes 12% to the regional anthropogenic baseline load, while the remaining regions combined contribute 13%. Open and closed grazing are the dominant land uses in the Endeavour Basin, although there is a large area of forestry, and also a small area of urban land use, encompassing Cooktown shire. This deviation from natural conditions is the cause of a 2-fold increase in TSS load in the Endeavour Basin.

In relation to the anthropogenic baseline contributions to total nitrogen (TN) load, five of the seven basins have negligible change in TN load from the predevelopment conditions (Figure 16). There are small anthropogenic increases in the Normanby and Endeavour basins (both increased by 1.2-times). The source of this increase, in both basins, is particulate nitrogen (PN). The particulate nutrients are attached to fine sediments generated from the gully, hillslope and streambank sources. The Normanby and Endeavour basins had an increase in TSS load from natural condition, therefore it is expected that both PN and PP will also increase. As was the case for the TN load, TP has increased in the Normanby and Endeavour basins due to the associated rise in

PP with an increase in TSS load (Figure 17). The Jeannie and Stewart basins have also had small increases in TN and TP loads, due to particulate nutrients, in line with increases in TSS load. The change in these basins is not as great as those in the Normanby and Endeavour.

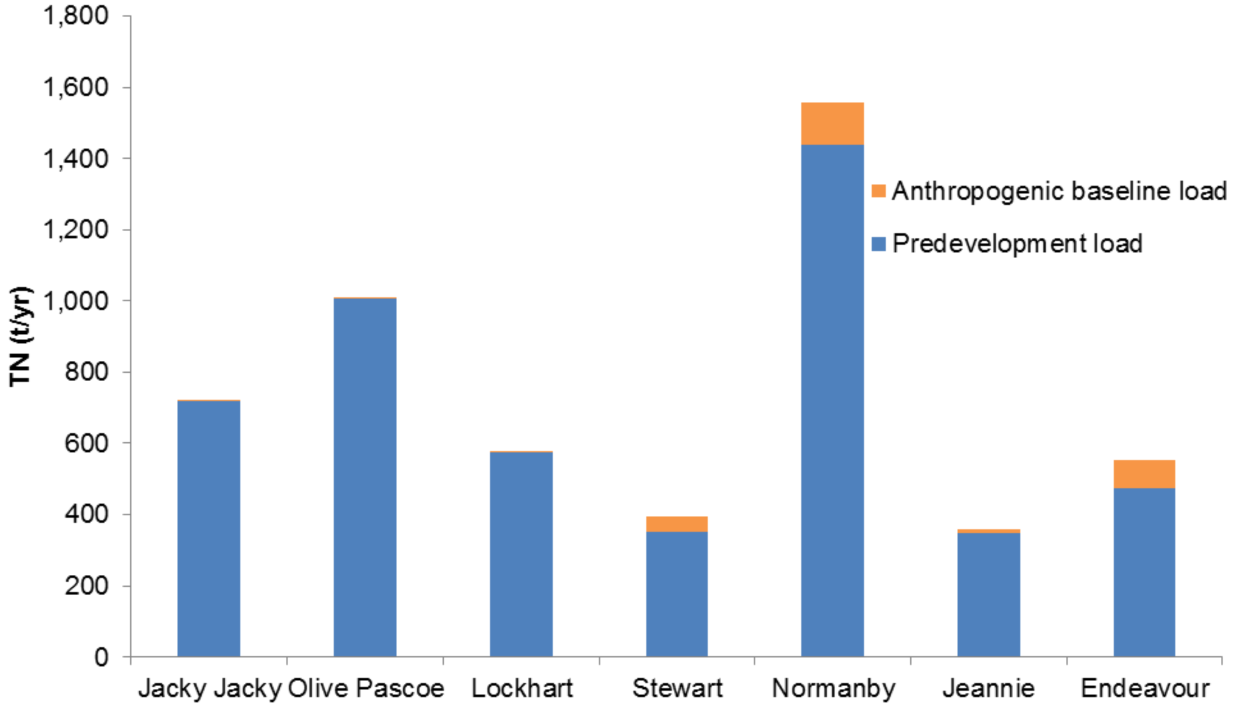

Figure 16 TN loads (t/yr) for the CY basins; highlighting the natural and anthropogenic baseline contributions

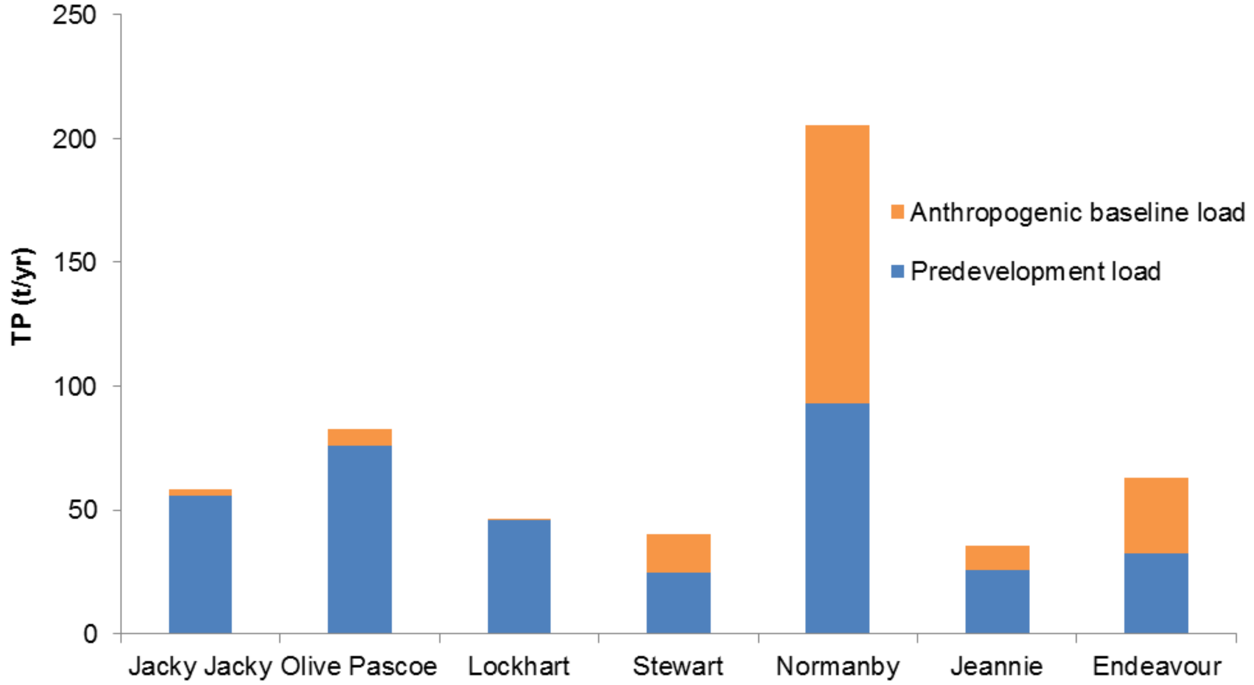

Figure 17 TP load (t/yr) for the CY basins; highlighting the natural and anthropogenic baseline contributions

Comparing the ratio of total nutrients to the particulate and dissolved fractions (Table 16) indicates that dissolved organic nitrogen (DON) is the greatest component of the CY TN load, and this is due to the large area of relatively undisturbed catchment in CY and the large amount of naturally occurring DON (Turner et al. 2012). Particulate nutrients erode attached to the soil, hence the ratio of PN directly relates to the concentration of N in the soil and the amount of soil eroded. Dissolved inorganic nitrogen (DIN) is elevated in other GBR catchments due to its application as fertiliser in agricultural systems, especially sugarcane and bananas. As these specific land uses are absent in CY, and other horticulture/cropping land uses are minimal, DIN is a very low contributor to the TN load. Dissolved organic phosphorus (DOP) and particulate phosphorus (PP) comprise 37% and 45% of the TP total baseline load respectively. The high DOP load is again the product of the large area of relatively undisturbed catchment and therefore high organic nutrient inputs. Phosphorus binds very effectively to fine material, hence the ratio of PP to TP is higher than PN to TN. Dissolved inorganic phosphorus (DIP) does occur naturally, however like DIN, is applied as fertiliser, and as such it is the lowest contributor to the TP load. The nutrient ratios to the total load are presented in Table 16.

Table 16 Modelled nutrient ratios to total (%)

DIN:TN	DON:TN	PN:TN	DIP:TP	DOP:TP	PP:TP
10	70	20	18	37	45

Herbicides are modelled for the cropping land uses, and as such only a very small load is reported from CY, all generated in the Normanby Basin. The herbicide load is derived entirely from diuron with an average annual load exported of 2.6 kg/yr.

4.3 Constituent load validation

At the time of model development and report writing, there were limited sources against which the CY Source Catchments modelling results can be compared, or validated. The three key sources are the Kroon et al. (2012), the catchment load estimates (1986–2009) calculated by Joo et al. (2014) and the GBRCLMP 2006–2010 monitoring program established by the Queensland state government (Joo et al. 2012, Turner et al. 2012). Future model runs will be validated against any new water quality data, as it becomes available.

4.3.1 Previous estimates – Kroon et al. (2012)

Kroon et al. (2012) estimated baseline loads from the 35 reef catchments (in six NRM regions), using the most recent published and available loads data. The best previous estimates for CY are typically those provided in McKergow et al. (2005 a, b) which is based on SedNet modelling of the region. There is low confidence in these numbers given that the loads are based entirely on modelling and no monitoring data (Kroon et al. 2010, Kroon et al. 2012). The two outputs are presented in Figure 18.

The CY regional export reported in RC1 is 2,388 kt/yr, made up of 444 kt/yr natural load and 1,944 kt/yr baseline load. These numbers are significantly higher than those generated in this study, that is 429 kt/yr, 249 kt/yr and 180 kt/yr respectively. The Source Catchments model outputs for all constituents are considerably lower than the Kroon et al. (2012) estimates; loads for TSS, TN and TP are 3- to 6-times higher than the Source Catchments loads.

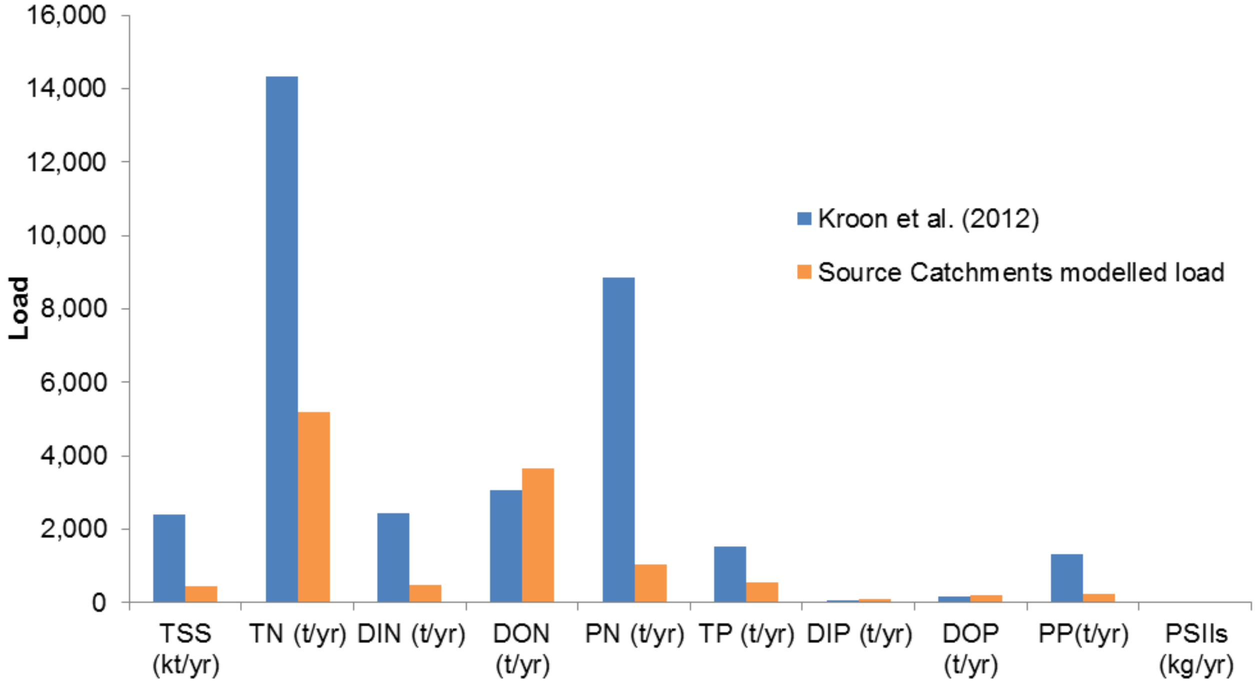

Figure 18 Kroon et al. (2012) and Source Catchments total baseline load comparison

4.3.2 Long-term FRCE loads (1986–2009)

The Source Catchments and FRCE average annual loads for all constituents are presented in Table 17. With the exception of PN, the Source Catchments modelled loads are all within ± 40% of the average annual FRCE (Joo et al. 2014) loads. Annual loads are also compared between the two sources (Figure 19). Sixty-one per cent of the annual TSS modelled loads fall within the FRCE load likely range limits. For nitrogen, 91% of TN modelled loads fall within the FRCE load likely range limits, with all years falling within the range for DIN, and only one year is outside of the likely range for both PN and DON. 61% of the annual TP modelled loads fall within the FRCE load likely range limits, with all years for DIP and DOP falling within the range, and 70% of years for PP falling within the range. In Figure 19 the FRCE generated likely range of each constituent (average annual) is presented, and as discussed, the Source Catchments modelled constituent load always falls within this range. Thus, while the PN per cent difference between the FRCE average annual load and the Source Catchments annual load is high, most years are within the likely range of values as calculated by Joo et al. (2014).

Table 17 FRCE mean and Source Catchments mean modelled constituent loads for the Kalpowar Crossing gauging station (1986–2009)

	TSS	TN	PN	DIN	DON	TP	PP	DIP	DOP
FRCE estimate	86	1,010	298	80	611	126	79	20	45
Source Catchments	110	799	136	68	594	130	80	17	33
% difference	22	-26	-119	-18	-3	2	1	-17	-37

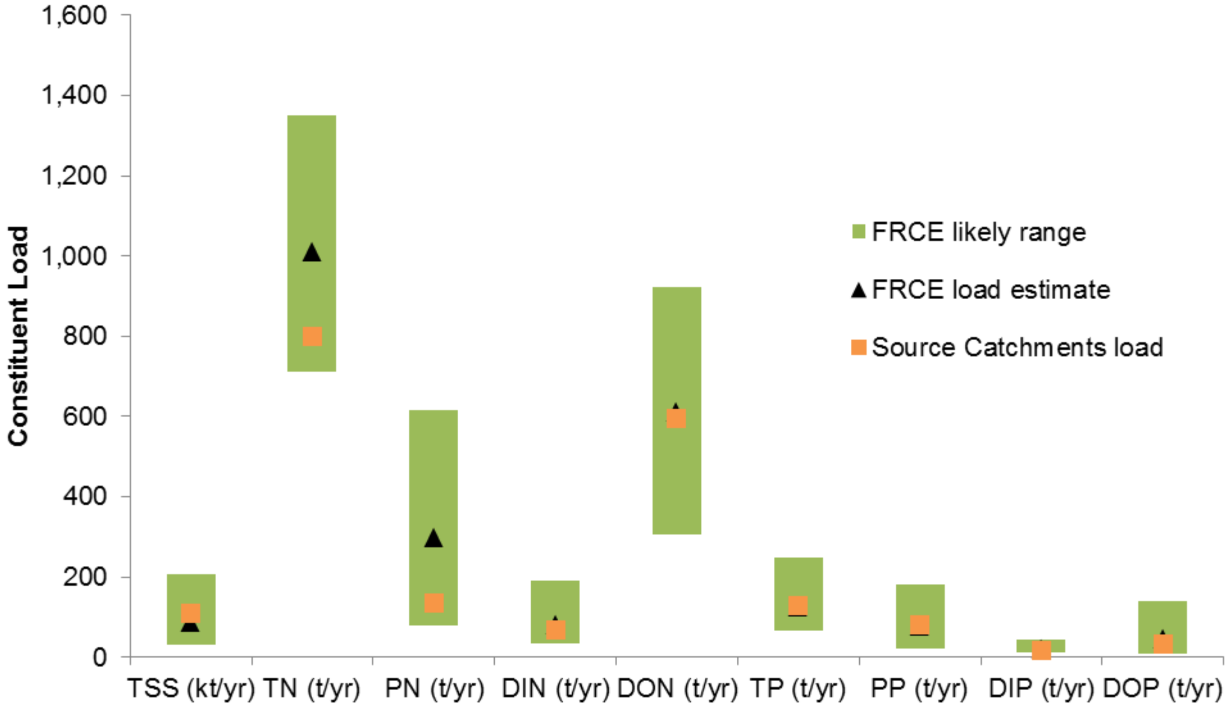

Figure 19 Source Catchments modelled average annual constituent loads, compared to the FRCE average annual constituent load and the FRCE load likely range for 1986–2009 at the Kalpowar Crossing gauge

The Source Catchments TSS loads match well with the FRCE calculated loads, where 61% of years fall within the minimum and maximum expected range of the FRCE loads (Figure 20). Typically, the Source Catchments load is higher than the FRCE mean load. There are several years however where the Source Catchments mean is above the maximum range, generally occurring during low flow years. An obvious outlier occurs in 1988, where there is a significant difference between the FRCE and Source Catchments generated load, despite using the same, modelled hydrology. The only event sampled in 1988 was a small event, where the TSS concentration was low at 10 mg/L. The product of the low flow and low concentration resulted in a very small load. While the FRCE calculated loads are an additional source of data against which to validate the Source Catchments model, some results should be interpreted with caution. As the example for 1988 indicates, if only a small number of samples have been taken, and only at low flow/small events, then the loads generated can be much lower than those produced by the

Source Catchments model. As the hydrology was consistent for both FRCE and the model the difference in load can only be attributed to the low number of samples collected and the timing of sample collection on the hydrograph resulting in a lower than expected load estimate compared to other years. Importantly, the loads calculated at high flows match well, which is likely due to the availability of a high frequency of sampling data for load estimation.

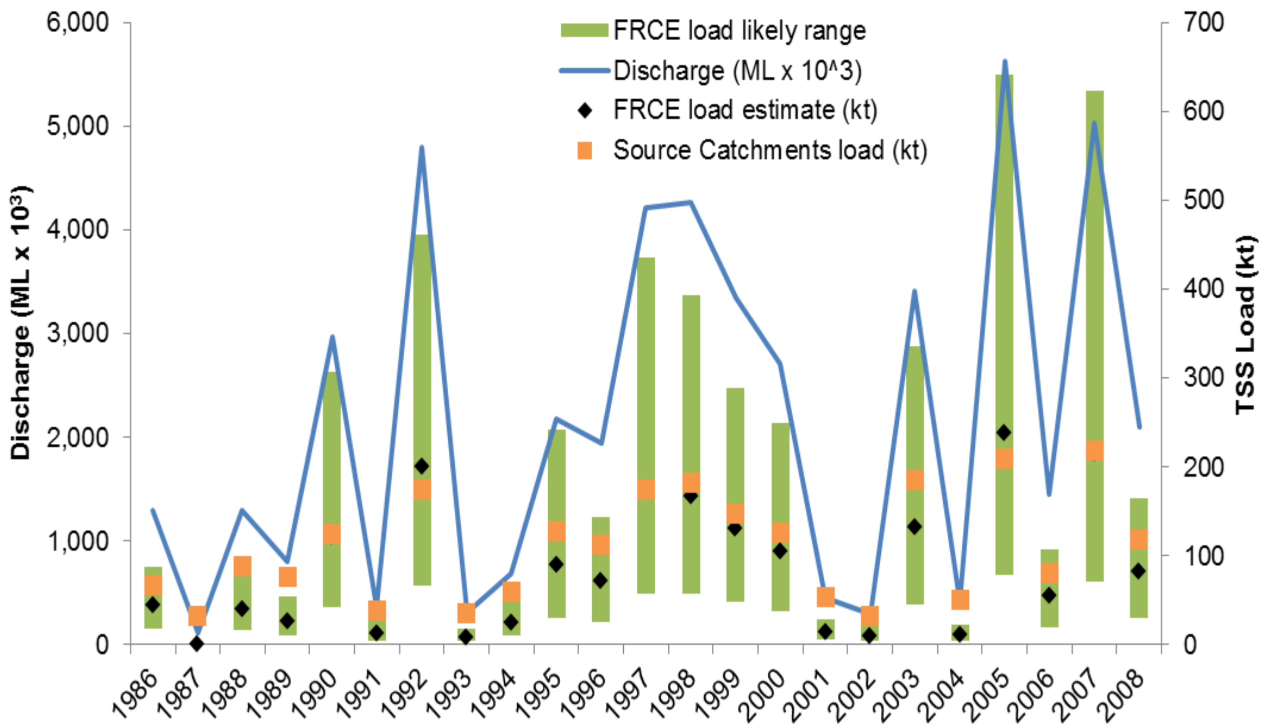

Figure 20 Annual fine sediment loads, expected loads range and flow for Source Catchments and the FRCE estimated loads (Joo et al. 2014)

The model was further tested at the monthly time-step using performance statistics based on three evaluation guidelines in Moriasi et al. (2007). TSS, TN and TP load comparisons all had good to very good ratings (Table 18), for each performance statistic outlined in Table 10.

Table 18 Performance statistics for TSS, TN and TP load comparisons to FRCE estimates based on three evaluation guidelines in Moriasi et al. (2007) at the monthly time-step

	NSE		RSR		PBIAS	
	Value	Result	Value	Result	Value	Result
TSS	0.88	Very good	0.35	Very good	-27.69	Good
TN	0.92	Very good	0.28	Very good	20.93	Very good
TP	0.88	Very good	0.35	Very good	-2.49	Very good

4.3.3 GBR Catchment Load Monitoring Program (2006–2010)

While the model period (for reporting) ceased in 2009, the model was extended by one year to incorporate the GBRCLMP loads data for the 2009–2010 wet season (Joo et al. 2012, Turner et al. 2012). A comparison was made between the mean GBRCLMP loads (averaged over four years, 2006–2010) and the modelled load for the same location and the same time period (Figure 21). The modelled constituent loads at the Kalpowar Crossing gauging station were within ± 40% of the observed loads. Modelled flow was within ±25% of observed flow for the four year monitoring period. Across the four year monitoring period, the model is over-predicting loads for two-thirds of the constituents, although the modelled loads for the four year period fall within the error bounds of the observed data. The greatest difference was for PN where the model was under-predicting by 40% and the smallest difference for DON at -1.5%.

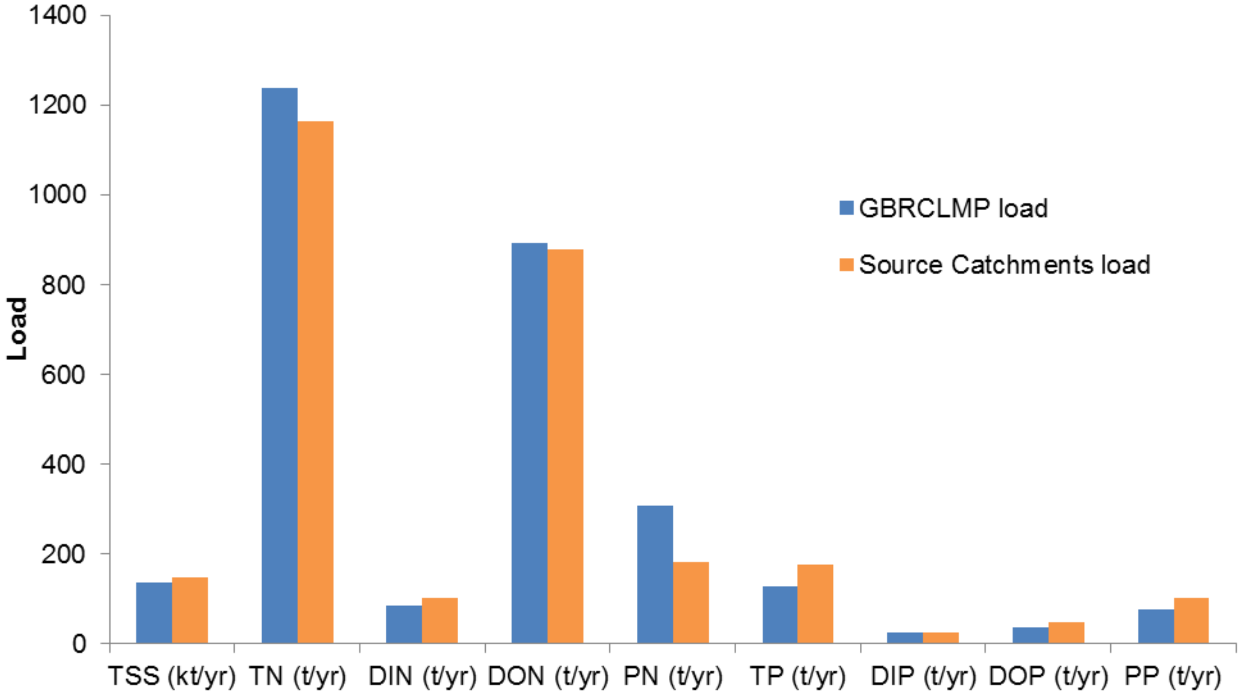

Figure 21 Comparison between average Source Catchments modelled and GBRCLMP loads for the period 2006–2010 for the Normanby River at Kalpowar Crossing (105107A)

4.4 Contribution by land use

Nature conservation and grazing (open and closed) account for (45% and 51% of CY area respectively) and contribute 81% of the total baseline load for CY (Figure 22). Forestry is the only other significant contributor of TSS load. TN and TP loads exported, show a similar contribution by land use to fine sediment load. Comparing the TSS load contribution per unit area (t/ha/yr) for the whole of CY (Table 19) indicate that cropping land uses (horticulture, irrigated and dryland cropping) have the highest TSS yield, while the non-intensive land uses (nature conservation, open and closed grazing) had the lowest land use yields. Similar patterns in yield by land use were observed for TN and TP loads.

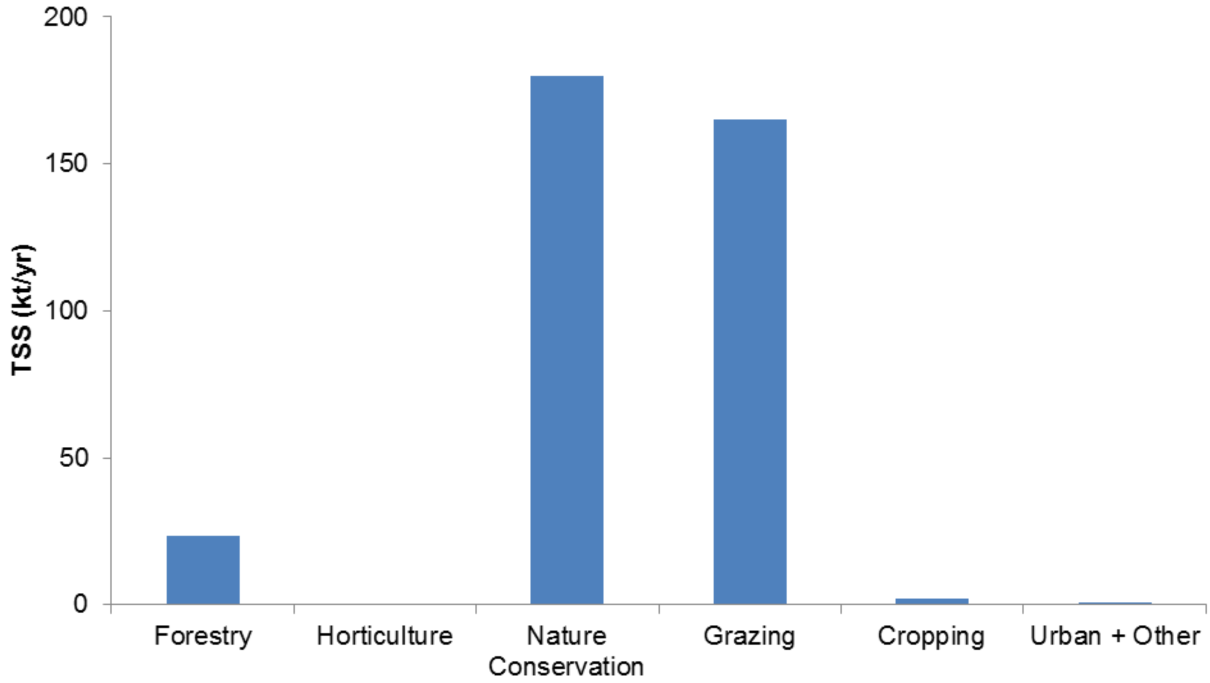

Figure 22 Contribution to fine sediment export by land use for the CY region

Table 19 Fine sediment contribution rates by land use (t/ha/yr) for CY

Land use	Contribution rate (t/ha/yr)
Grazing	0.1
Nature conservation	0.1
Cropping	0.42
Horticulture	0.43
Other + Urban	0.31
Forestry	0.2

4.5 Sources and sinks

Of the total modelled fine sediment generated (442 kt/yr that is supplied to the stream) in the CY NRM region (Table 20), 97% (428 kt/yr) is exported to the GBR lagoon, with the remaining 3% (14 kt/yr) deposited on the floodplain. No in-stream deposition of fine sediment was modelled due to a lack of supporting data to quantify the deposition component at the time of model development. With an improved understanding of the process, and a better mathematical representation in the model, in-stream deposition can be enabled in future model runs as it has been identified as a significant contribution to the overall sediment budget in the Normanby Basin (Brooks et al. 2013).

For both TN and TP, 99% of the loads supplied to the stream network are exported. Particulate nutrients follow the same pattern as TSS, whereby 97% are exported, while 100% of dissolved nutrients are exported. The greatest sources of fine sediment in CY are from hillslope and gully sources, the former contributing 65% of the total load, and the latter 21% (Table 20).

Table 20 CY sources and sinks

	TSS (kt/yr)	TN (t/yr)	DIN (t/yr)	DON (t/yr)	PN (t/yr)	TP (t/yr)	DOP (t/yr)	DIP (t/yr)	PP (t/yr)
SOURCE	**443**	**5,194**	**492**	**3,652**	**1,050**	**537**	**195**	**98**	**244**
Hillslope	290	1,128			1,019	183			226
Gully	94	15			22	12			9
Streambank	59	8			9	8			8
Diffuse dissolved	0	4,144	492	3,652	0	293	195	98	0
SINK	**14**	**24**	**0**	**0**	**20**	**5**	**0**	**0**	**6**
Residual link storage	0	1	0	0	0	0	0	0	0
Floodplain deposition	14	23	0	0	23	5	0	0	5
EXPORT	**429**	**5,173**	**492**	**3,652**	**1,030**	**531**	**195**	**98**	**238**

4.6 Progress towards Reef Plan 2009 targets

There has been moderate progress towards meeting the reef targets following 2008–2013 adoption of improved land management practices. This period covers Report Card 2010 through to Report Card 2013, noting that each report card is cumulative. The modelling results suggest there was an 11% reduction in average annual anthropogenic TSS load leaving all GBR catchments from 2008–2013, which is rated as ‘good’ progress (Table 7) with the greatest reduction from grazing areas. In the case of total nitrogen, progress was rated as ‘very poor’, with the average annual anthropogenic load reduced by 10%, with the greatest reduction from the Burdekin and Wet Tropics NRM regions. The average annual PSII herbicide load was reduced by 28%, which is rated as ‘moderate’, with 70% of the reduction from the Wet Tropics and Mackay Whitsunday regions. Improved herbicide management practices in the sugarcane industry contributed to the large reduction.

The per cent reduction in constituents due to investment in improved management practices each year is presented in Figure 23. Fine sediment loads in CY were reduced by 8.6% from the anthropogenic baseline load. This is regarded as ‘very good’ progress (Table 7). Grazing related TSS load changes were modelled as an increase in cover levels on hillslopes and improvements in cover both adjacent to and in gully and streambanks (section 0) where riparian investment data is provided. Data was provided on the extent of riparian fencing for Report Cards 2012–2013 and incorporated into the model runs. The addition of the riparian investment data has resulted in the larger reductions than previous years between Report Cards 2012–2013 (Figure 24).

There has been a 6% reduction in TN and 8.3% in PN. TP has decreased by 7.4% and PP by 11.6%. The results are rated as 'very poor' progress (Table 7). Management change data in CY was only available in the grazing land use area, and only in the Normanby Basin. No information was available on practice change for DIN, DON, DIP and DOP; therefore they are not reported on. Similarly, as no information on management practice was available for the cropping land uses, no reduction in herbicide load was reported.

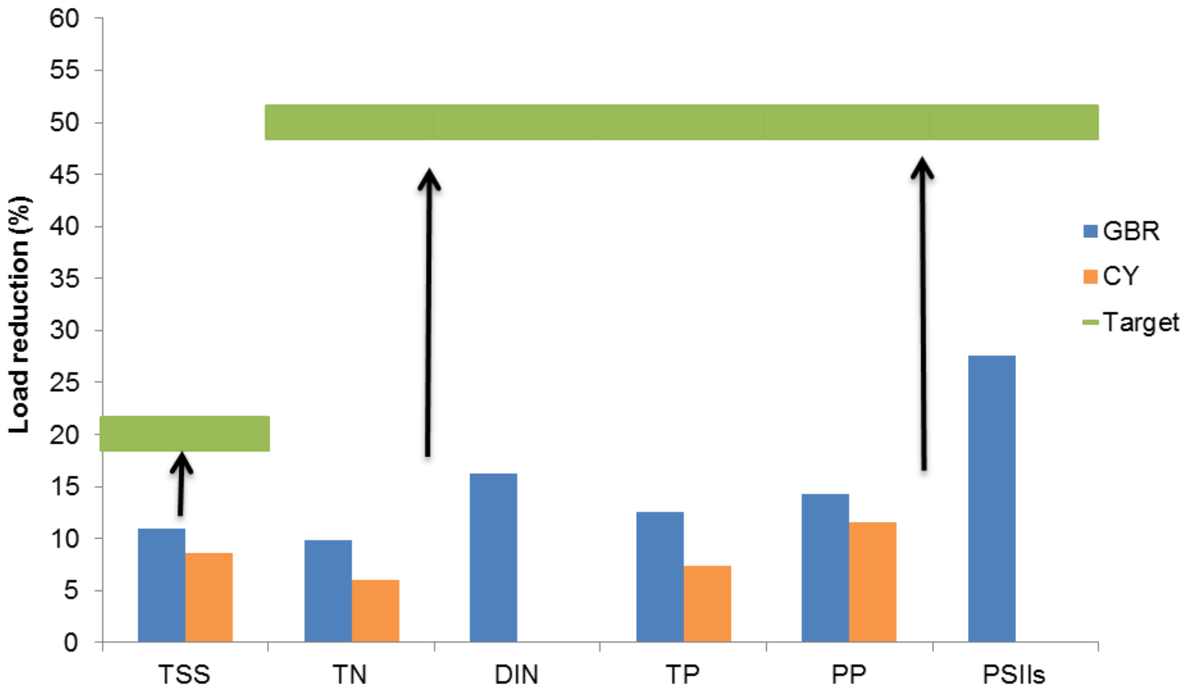

Figure 23 CY and GBR per cent reduction in key constituent loads from Report Card 2013 management practice changes and anthropogenic load reduction targets

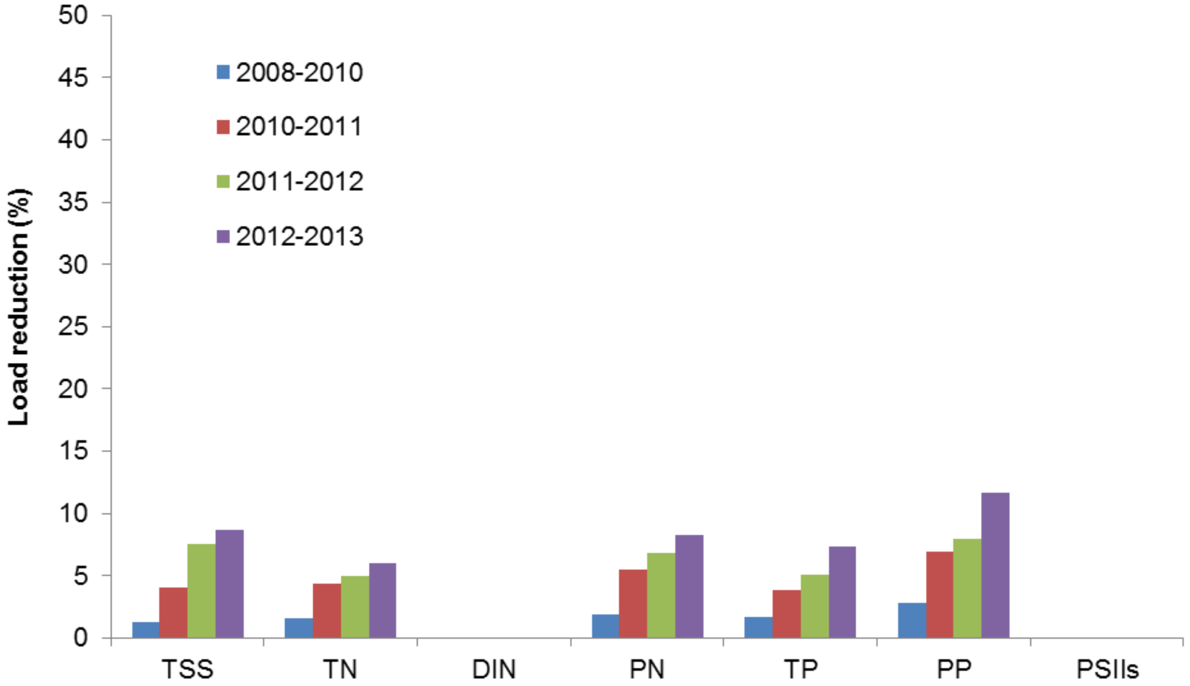

Figure 24 CY constituent reductions (%) for individual reporting periods

5 Discussion

The modelled estimates of the total, anthropogenic baseline and natural loads of sediment and nutrients exported to the GBR from Cape York can be considered a significant improvement on past estimates due to the use of a consistent modelling framework, and improved representation of land management practices. Constituent loads are considerably lower than previously reported estimates largely due to improved model input data, as well as the modelling framework having the ability to apply the most appropriate model to each land use and incorporating the various (hillslope, gully and streambank) sediment erosion processes. In addition, there is an increasing length of record of water quality data, particularly for the Normanby Basin, that will continue to be used to validate and improve the Source Catchments model load predictions. A discussion of the model hydrology, constituent loads and the progress towards 2009 targets follows. An overall discussion of the GBR results can be found in Waters et al. (2014).

5.1 Hydrology

An improved spatial and temporal representation of hydrology has been a critical enhancement of the catchment modelling undertaken. Overall, the CY hydrology calibration was very good for the three performance criteria: daily NSE (>0.5), monthly NSE (>0.8) and total modelled volume difference ± 20% of observed volume. Sixteen of the 18 gauges met all three criteria, one gauge met two of the criteria, and one gauge met only one of the criteria. Out of the 18 flow gauges, 17 had monthly NSE values >0.75 which can be regarded as an extremely good calibration result given Moriasi et al. (2007) in a global review of hydrology calibrations rated NSE values >0.75 as 'very good' performance. The gauges that met all three criteria had either a small catchment area or a long gauging record, with the per cent flow difference between the measured and modelled data <8%. However, only half of the 18 flow gauges had a monitored flow record for the entire calibration period (1970–2010).

The Kalpowar Crossing flow gauge (105107A) in the Normanby Basin has the largest catchment area and the shortest gauging record (commencing late 2005); it also has the greatest volumetric flow difference between measured and modelled data. This is an important gauge given it is located where the most consistent water quality dataset has been collected in CY, providing a critical validation dataset for Source Catchments loads. The model over-predicts flow at the Kalpowar Crossing gauge, and examination of aerial photography and comprehensive DNRM hydrography experience (V Manley, G Herbert, pers. comm.) provide an explanation for this over-prediction of flow. Immediately upstream of the Kalpowar Crossing gauge is an area of numerous small tributaries and an extensive wetland area (comprising part of the Marina Plains – Lakefield Aggregation, a wetland classified under the Directory of Important Wetlands in Australia). During the wet season this area is regularly inundated, and flow effectively ponds (with sediments also likely dropping out and depositing on this surface). Flow is most likely returned back into the main channel system from the floodplain area, with a proportion of the flow retained in the wetland, plus evapotranspiration and infiltration losses before flow returns to the main channel. It is unlikely there is extensive water loss to groundwater due to the geology of the region and low infiltration rates on these soils. Much of the Normanby River falls within the Laura Basin group, which is characterised by the Gilbert River Formation (sandstone) overlain by the Rolling Downs Formation, which is itself characterised by fine materials (silt and clay) (Jell 2013). It is unlikely that significant flow diverts around the Kalpowar Crossing gauge; since gauging of flows began in 2005 only 12 days of flow have occurred above the 9 m flood level (V Manley, pers. comm.) highlighting that very little flow escapes the main channel of the Normanby River (at the gauge). This is contrary to the assumption of Wallace, Karim and Wilkinson (2012) who determined that approximately 43% of annual flow is potentially either bypassed or under-read by the gauge; however the authors did recognise there was much uncertainty in their flood level estimates.

To independently check the Wallace, Karim and Wilkinson (2012) assumption we used the latest rating table to convert stream water level to discharge, with 148,000 ML/day the amount of water in the channel prior to flow going over bank. The current observed average annual flow at Kalpowar Crossing gauge is 2,884,145 ML, hence a 43% annual flow bypass is equivalent to an additional 1,240,182 ML, which over 12 days is an additional 70% of the 9 m flood level discharge per day. From these estimates flow would go over-bank upstream of the gauging station, but it would likely still be contained within the Normanby Basin, and not diverted into the adjacent North Kennedy and Kennedy rivers. It is possible that in very large events some flow would enter these systems, but it is more likely that detention of runoff on the floodplain results in a slow re-entry to the Normanby channel. An investigation of flow during individual events was also undertaken to determine the relative contribution from upstream catchments. Kalpowar Crossing gauging station has a catchment area of 12,934 km^2, 28% of this area is made up of the contributing areas of the Battle Camp gauging station (105101A Normanby River) (18%) and the Laura River gauging station at Coalseam Creek (105102A) (10%). Between 20–50% of the total flow at the downstream gauge, 105107A is generated from the areas draining to gauges 105101A and 105102A (G Orr, pers. comm.). This is consistent with the rainfall distribution patterns for these areas. Therefore, the analyses of individual events and examination of the landscape (especially the geology and topography), in conjunction with local DNRM hydrographical expert knowledge challenges the idea that up to 43% of annual flow is bypassing the gauge.

Nevertheless, the model is over-predicting flow by 25% at the Kalpowar Crossing gauge, and the short flow record of just seven years could be an additional reason for the over prediction. When calibrating flow, errors in estimates of long-term runoff reduce with calibration data of 10 or more years (Boughton 2007). While the hydrology calibration provides a good estimate of flow, particularly at the annual and long-term average annual scales, the current objective functions will generally result in under-estimation of high flows and over-estimation of low (base) flows. Future work will modify the current objective functions used in the calibration to apply greater weighting to high flows. Improving high flow calibration is important given that the majority of the sediment and nutrient loads are generated during high flows. Finally, greater consideration should be paid to the starting parameters used in the hydrology calibration. The rainfall-runoff and flow routing parameters were started at their default value; it would be pertinent in any future calibration process to utilise local knowledge and expert opinion in setting these starting parameters, regardless of which rainfall-runoff model is used. This ensures the relative differences in catchment attributes are reflected to some degree in the model starting parameters.

In addition, an alternative rainfall-runoff model, Sacramento, will be considered for consistency given the model is used in the Integrated Quantity Quality Model (IQQM) used for water planning purposes by the Queensland government. Recent research has shown that the Sacramento model performed better than SIMHYD model in a number of the GBR catchments used in the study (Zhang, Waters & Ellis 2013). Unlike SIMHYD, the Sacramento model is also better able to account for losses from the system (e.g. groundwater), which is of particular benefit in the wetter GBR catchments.

5.2 Modelled Loads

5.2.1 Anthropogenic loads

Reef Plan 2009 water quality targets look to reduce the anthropogenic baseline load, which is the load contribution caused by human induced development and management practice activities. Therefore, the anthropogenic load is determined by the difference between the total baseline load and predevelopment load. The Normanby Basin contributes 75% of the anthropogenic baseline TSS for the CY region, with the Endeavour Basin contributing 12%.

Source Catchments modelling suggests the TSS, TN and TP anthropogenic loads have increased by 2-fold, 1.1-fold, and 1.5-fold respectively from predevelopment loads in the region. The estimated increase in loads is much smaller than previously reported (McKergow et al. 2005b, Kroon et al. 2010) where estimated increases were 5.4, 4.0 and 4.0-fold for TSS, TN and TP. The reasons for these differences include the use of a spatially and temporally variable BGI used to generate the C-factor in the RUSLE. McKergow et al. (2005a) used a generic low ground cover value for their current condition scenario, and then used a static and comparatively high value (95%) for the predevelopment scenario. In the Source Catchments modelling framework, an annual BGI was used for the current condition scenario, which had an average cover of 86%, and a predevelopment groundcover of 95%, leading to a smaller increase in anthropogenic baseline loads than previously reported.

Likewise, the total fine sediment export for Cape York of 429 kt/yr is considerably lower than for previous reported estimates due to:

- Improved input datasets in the current project (for example, temporal and spatially variable cover estimates to represent grazing by using BGI scenes)
- The ability to apply the most appropriate models to each land use (as opposed to an all EMC or RUSLE approach)
- The availability of recent monitoring data with which the model can be validated against, as well as using this monitoring data to derive input parameters such as EMC/DWC values.

5.2.2 Validation

The only gauge where water quality samples are consistently monitored in the Cape York region is at the Kalpowar Crossing gauge in the Normanby Basin. The location of the flow gauge results in 54% of the Normanby Basin being sampled, and 46% ungauged. The Source Catchments modelling for the total Normanby Basin estimates 61% of the fine sediment is generated from above the Kalpowar Crossing gauge, while the remaining 39% is from below the gauge catchment area. The Source Catchments model is showing good agreement with the four year catchment monitoring period, with the average sediment concentration similar between Source Catchments and the catchment monitoring, 51 mg/L and 45 mg/L respectively at Kalpowar Crossing. The 23 year averaged modelled sediment concentration is 76 mg/L, hence well within the range of the derived monitored loads and concentration. When looking at the Normanby Basin at the end-of-system (EOS) for the 23 year modelled period, the average concentration is 40 mg/L, which is substantially lower than that estimated by Brooks et al. (2013) and Brodie et al. (2003), 297 mg/L and 233 mg/L respectively. Brooks et al. (2013) and Brodie et al. (2003) derived sediment concentrations are more in line with the EOS concentrations reported for more developed Burdekin, Fitzroy and Burnett basins. GBR catchment monitoring particle size distribution cluster analysis (Turner et al. 2013) groups the Normanby with the Burdekin River and also the Burnett River for the 2010–2011 monitoring year; however, further analysis of this type is required before conclusions are drawn.

Although the model shows good agreement with the monitoring derived loads for the four year monitoring period, it is imperative that water quality monitoring is continued so that: more seasonal variability is captured, ongoing validation is conducted, and improved estimates of loads determined.

An additional enhancement to the RUSLE K-factor (soil erodibility) was undertaken between the production of Report Card 2010 and Report Card 2011 to bring constituent load estimates closer in line with GBR catchment monitored loads. The enhanced K-factor in Report Cards 2011–2013 considers the impact of rock fragments on the soil layer on reducing the soil erodibility (see section 3.3.1.1). The enhanced K-factor resulted in a reduction in the per cent difference between the Source Catchments and the four year GBR catchment monitoring loads (Table 21), with similar improved comparison for TP and TN load estimates likely due to a corresponding decrease in particulate nutrient supply. DIN and DIP remained unchanged. The Source Catchments modelling has a continuous improvement approach and further improvements of key input data is planned in further model enhancements.

Table 21 Percentage difference in constituent loads between Source Catchments and GBRCLMP measured results for Report Card 2010 and Report Card 2011 (following inclusion of rock cover) at the Kalpowar Crossing gauge

	TSS	TN	DIN	DON	PN	TP	DIP	DOP	PP
Report Card 2010	45	4	20	-2	18	24	4	37	24
Report Card 2011	7	-0.3	20	-2	-17	12	4	37	-10

5.2.3 Contribution by land use and sediment sources

The modelled loads per unit area are typically lower than previous reported estimates for CY, particularly for grazing, for example 0.07 t/ha/yr, compared to 0.56 t/ha/yr (Brodie et al. 2003) for the Normanby Basin. In previous modelling Brodie et al. (2003) used a static C-factor of 0.03 for ‘grazing with good cover’ (from the Endeavour River north), which equates to a cover percentage of around 60%. The spatially and temporally variable BGI average cover is 86%, resulting in a much lower sediment generation for the current model. Brooks et al. (2013) notes that past modelling has used late dry season C-factors, while the average C-factors across the wet season are significantly lower (higher cover), and therefore using the dry season C-factor may result in the over-prediction of hillslope erosion. While the rates derived by Source Catchments are lower than those of Brodie et al. (2003), the ‘ranking’ or the spread of values between the basins in CY for grazing are similar. For example, this report is similar to Brodie et al. (2003) where the Endeavour and Jeannie basins have the highest grazing unit area loads contribution. Likewise, the contribution from nature conservation (or forest/savanna) is the same in this project to Brodie et al. (2003) at 0.09 t/ha/yr. Modelled estimates of TSS load for dryland and irrigated cropping are calculated through the HowLeaky model, and both land uses occur only in the Normanby Basin.

These estimates are a significant improvement on past estimates as they have been generated through a specific cropping model, rather than by a simple static EMC approach.

The CY Source Catchments modelling indicates that 66% of fine sediment is sourced from hillslope erosion, 21% from gullies and 13% from streambank erosion (where the EMC derived load is apportioned based on the grazing land ratio of hillslope to gully erosion). Early modelling in northern Australia indicated that hillslope erosion was the major source of sediment (Brodie et al. 2003). More recent studies suggest that subsurface erosion, especially gully erosion, is in fact the dominant source in many northern Australian catchments (Caitcheon et al. 2012, Wilkinson et al. in press). The current Source Catchments model framework does not specifically account for alluvial gullies which have been identified as the major source of sediment in a number of northern Australian rivers, including in the Mitchell catchment, Queensland (Brooks et al. 2009, Shellberg 2011) and in the Victoria River, Northern Territory (McCloskey 2010). Ongoing research highlights that this is also likely to be true for the Normanby Basin (Brooks et al. 2013). Therefore, sediment supply from this source is likely to be accounted for in hillslope figures, as alluvial gullies typically occur on flat surfaces and are not identified in gully density mapping. Therefore, gully sources could be underestimated, and hillslope sources overestimated.

The Source Catchments modelling for the Normanby estimates hillslope erosion contributes 54% of the sediment source, with equal contributions from gully and streambanks (Table 22). In terms of contribution to export, hillslope erosion contributes 66% of the total load, gullies 21% and 13% contribution from streambanks. Previous estimates are highly variable for the Normanby Basin, with Brodie et al. (2003) estimating up to 90% hillslope erosion. Recent empirically based model estimates (Brooks et al. 2013) believe this is a gross over-estimation, suggesting the hillslope erosion contribution to be as little as 1% of the sediment supply. The Source Catchments model results lie in between the two estimates of Brodie et al. (2003) and Brooks et al. (2013). In terms of modelled sediment losses, the model estimates that 5% of sediment generated is stored within the system due to floodplain deposition. It should be noted that the in-stream deposition functionality was not applied in the current model. Brodie et al. (2003) suggests 62% of sediment source is exported at the end of system, with 37% stored, while Brooks et al. (2013) suggest that 45% is exported, 55% stored. Based on recent findings by Brooks et al. (2013) in-stream deposition processes must be considered in future model development. Correctly representing the major sediment sources is a key component of modelling, as the outputs may directly influence management decisions. Identifying the sediment sources physically (through on-ground assessment, high resolution aerial imagery or sediment tracing, for example) is imperative to improve model predictions.

Table 22 Summary table showing sediment sources and sinks for the Normanby Basin. Per cent breakdown of sediment source is shown in the green highlighted cells

	Brodie (2003)		Source Catchments		Brooks (2013)	
	kt/yr	**%**	**kt/yr**	**%**	**kt/yr**	**%**
SOURCES	1,758	100	199	100	3,086	100
Hillslope	1,567	89	108	54	16	0.5
Gully*	173	10	45	23	1,148	37
Streambank**	18	1	46	23	1,922	62.5
SINKS	664	38	11	5	1,694	55
EXPORT	1,094	62	188	95	1,392	45

* Gully sources include alluvial and colluvial gullies

** Streambank erosion includes main channel bank erosion and secondary channel erosion

The gully density map available at the time of Source Catchments model development was that generated by the National Land and Water Resources Audit (NLWRA 2001). It is recognised that this mapping has a poor predictive performance in Queensland (NLWRA 2001, Rustomji et al. 2010), and is a likely source of inaccuracy in the model. Brooks et al. (2013) have derived an improved gully density map that has been created for the Normanby Basin based on manual interpretation of Google Earth imagery. It is hoped that this map can be incorporated into future Source Catchments modelling such that estimates of gully erosion can be improved.

5.3 Progress towards Reef Plan 2009 targets

Across the GBR, anthropogenic TSS loads have been reduced by 11%, TN and TP by 10% and 12.5% 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 (Reef Plan 2013) 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.

In Cape York, model predictions suggest that long-term TSS, TN and TP loads have been reduced by 8.6%, 6% and 7.4% respectively due to improved land management practices. Minimal herbicide use occurs in CY, and as such no reduction in PSII herbicides occurred. All of the changes in CY are due to investment in grazing management practices; primarily a result of a large shift of graziers from C to B management classes, and a smaller shift from D to C. There remain a third of graziers utilising D class practices, hence there is still scope for further improvement in (particularly) fine sediment load reductions. It should be noted that the spatial scale at which the model should be interpreted is the river basin scale. This is mainly due to the application of non-spatial management practice data for the baseline, Report Cards 2010–2013 management years. Obtaining spatially explicit management practice data would greatly improve the ability to represent change. At the start of the Paddock to Reef program it was determined that any major model enhancements would only take place at the commencement of Reef Plan 2013, hence every four years. Only relatively minor enhancements or corrections to the Source Catchments model took place within the Reef Plan 2009 reporting period, with these changes and their relative impacts being outlined in Appendices G to I. This allowed some relative yearly comparison within the Reef Plan 2009 reporting period to be undertaken. However, it is more pertinent to consider the cumulative load reductions at the end of the Reef Plan 2009 reporting period (Report Card 2013) rather than considering the specific individual year reductions.

As with all numerical modelling projects used to simulate natural systems, model outputs would be enhanced by improving input data and model processes. As part of the P2R program's continual improvement process major modelling enhancement will take place for Reef Plan 2013; including recalibration of the hydrology model to improve high flow prediction, the use of the Sacramento hydrology model to align with other Queensland Government water planning modelling; incorporation of seasonal rather than annual dry season cover; improved spatial allocation of specific management practice information and an updated ABCD management framework. These changes will provide an enhanced GBR Source Catchments total baseline load and load reductions to that for Reef Plan 2009. Consequently, the outcomes for the Reef Plan 2013 reporting period should not be directly related to the outcomes reported in Reef Plan 2009. The current modelling framework is flexible, innovative and fit for purpose. It is a substantial improvement on previous GBR load modelling applications utilising a consistent methodology across all NRM regions. The model has proven to be an appropriate tool for assessing load reductions due to on-ground land management change.

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. Investment in improved land management practices between 2008 2013 has 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 9.9% and 12.5% respectively. Pesticide loads have been reduced by 14.6%. The reduction in sediment, nutrient and pesticide loads is positive progress towards meeting the Reef Plan 2013 targets. Specifically in Cape York, anthropogenic sediment loads were reduced by 8.6%, TN by 6% and TP by 7.4%.

The results from this project are lower than previous estimates for sediment and nutrient loads from CY. Reasons for the lower estimates include: improved input layers (in particular spatial and temporal cover layers), the ability to apply the most appropriate model to each land use as opposed to a single EMC/DWC or RUSLE approach as applied in previous models. The availability of recent event monitoring data to validate models against is a major improvement. Over the course of the Paddock to Reef program more empirical data has become available, for example an improved k-factor, 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. These changes will provide an enhanced GBR Source Catchments total baseline load and load reductions to that used for Reef Plan 2009. 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.

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 models across the entire GBR including CY. The use of a consistent methodology across whole of GBR enables the direct comparison of loads across regions. Due to the flexible nature of the Source Catchments framework, there is now the ability to 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 true integration of monitoring and modelling, and using modelling outputs to inform the monitoring program. It follows that the better the modelling performs spatially and temporally the greater the confidence and possible sophistication in targeted management actions

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 sediment, nutrient and herbicide reduction targets for Reef Plan 2013.

7 References

ANRA 2002*, User guide: Australian Natural Resources Atlas*, URL: http://nrmonline.nrm.gov.au/downloads/mql:2479/PDF, viewed 28 May 2011.

Armour, JD, Hateley, LR, Pitt, GL 2009, Catchment modelling of sediment, nitrogen and phosphorus nutrient loads with SedNet/ANNEX in the Tully-Murray Basin, *Marine and Freshwater Research* 60 (11), 1091–96.

Bartley, R, Speirs, WJ, Ellis, TW, Waters, DK 2012, A review of sediment and nutrient concentration data from Australia for use in catchment water quality models, *Marine Pollution Bulletin* 65 (4–9), 101–16.

Belperio, AP 1979, The combined use of wash load and bed material load rating curves for the calculation of total load: An example from the Burdekin River, Australia, *Catena* 6 (3–4), 317–29.

Biggs, AJW, Philip, SR 1995, *Soils of Cape York Peninsula,* Queensland Department of Primary Industries, Brisbane.

Biggs, JS, Thorburn, PJ 2012, *Paddock to Reef integrated monitoring, modelling and reporting program, Paddock scale modelling technical report—Simulating sugarcane management systems for improving water quality leaving farms in the Bundaberg, Burdekin, Mackay and Tully regions, Australia*, Department of Natural Resources and Mines, Brisbane.

Boughton, WC 2007, Effect of data length on rainfall–runoff modelling, *Environmental Modelling & Software* 22 (3), 406–13.

Brodie, J, McKergow, LA, Prosser, IP, Furnas, M, Hughes, AO, Hunter, H 2003, *Sources of sediment and nutrient exports to the Great Barrier Reef World Heritage Area*, Australian Centre for Tropical Freshwater Research, James Cook University, Townsville.

Brodie, J, Waterhouse, J, Lewis, S, Bainbridge, Z, Johnson, J 2009, *Current loads of priority pollutants discharged from Great Barrier Reef Catchments to the Great Barrier Reef*, ACTFR Report 09/02, Townsville.

Brodie, J, Waterhouse, J, Schaffelke, B, Kroon, F, Thorburn, P, Rolfe, J, Johnson, J, Fabricius, K, Lewis, S, Devlin, M, Warne, M, McKenzie, L 2013, *2013 Scientific consensus statement, Land use impacts on Great Barrier Reef water quality and ecosystem condition*, Reef Water Quality Protection Plan Secretariat, Brisbane.

Brooks, A, Spencer, J, Olley, J, Pietsch, T, Borombovits, D, Curwen, G, Shellberg, J, Howley, C, Gleeson, A, Simon, A, Bankhead, N, Klimetz, D, Eslami-Endargoli, L, Bourgeault, A 2013, *An empirically-based sediment budget for the Normanby Basin: sediment sources, sinks, and drivers on the Cape York Savannah*, Australian Rivers Institute, Griffith University.

Brooks, AP, Shellberg, JG, Knight, J, Spencer, J 2009, Alluvial gully erosion: an example from the Mitchell fluvial megafan, Queensland, Australia, *Earth Surface Processes and Landforms* 34 (14), 1951–69.

Brough, DM, Claridge, J, Grundy, MJ 2006, *Soil and landscape attributes: a report on the creation of a soil and landscape information system for Queensland*, Department of Natural Resources, Mines & Water, Brisbane.

Caitcheon, GG, Olley, JM, Pantus, F, Hancock, G, Leslie, C 2012, The dominant erosion processes supplying fine sediment to three major rivers in tropical Australia, the Daly (NT), Mitchell (Qld) and Flinders (Qld) rivers, *Geomorphology* 151–52, 188–95.

Carroll, C, Waters, D, Vardy, S, Silburn, DM, Attard, S, Thorburn, PJ, Davis, AM, Halpin, N, Schmidt, M, Wilson, B, Clark, A 2012, A paddock to reef monitoring and modelling framework for the Great Barrier Reef: paddock and catchment component, *Marine Pollution Bulletin* 65 (4–9), 136–49.

Chapman, PJ, Edwards, AC, Shand, CA 1997, The phosphorus composition of soil solutions and soil leachates: influence of soil:solution ratio, *European Journal of Soil Science* 48 (4), 703–10.

Chiew, FHS, McMahon, TA 1993, Assessing the adequacy of catchment streamflow yield estimates, *Australian Journal of Soil Research* 31 (5), 665–80.

Chiew, FHS, Peel, MC, Western, AW 2002, 'Application and testing of the simple rainfall-runoff model SIMHYD' in *Mathematical models of small watershed hydrology and applications*, VP Singh & DK Frevert (eds), Water Resources Publication, Littleton, Colorado, pp. 335–67.

Chiew, FHS, Siriwardena, L 2005, 'Estimation of SIMHYD parameter values for application in ungauged catchments' in *MODSIM 2005 International Congress on Modelling and Simulation: Advances and Applications for Management and Decision Making*, A Zerger & RM Argent (eds), Modelling and Simulation Society of Australia and New Zealand, Melbourne, December 2005, pp. 2883–89.

Cogle, AL, Carroll, C, Sherman, BS 2006, *The use of SedNet and ANNEX models to guide GBR catchment sediment and nutrient target setting*, Department of Natural Resources, Mines and Water, Brisbane.

Department of Natural Resources and Mines 2003, *Land cover change in Queensland 1999–2001: a Statewide Landcover and Trees Study (SLATS) report*, Department of Natural Resources and Mines, Brisbane.

Department of the Premier and Cabinet 2009, *Reef Water Quality Protection Plan 2009. For the Great Barrier Reef World Heritage Area and adjacent catchments*, Reef Water Quality Protection Plan Secretariat, Brisbane. URL: www.reefplan.qld.gov.au.

Department of the Premier and Cabinet 2013, *Reef Water Quality Protection Plan 2013. Securing the health and resilience of the Great Barrier Reef World Heritage Area and adjacent catchments*, Reef Water Quality Protection Plan Secretariat, Brisbane. Available www.reefplan.qld.gov.au.

Doherty, J 2005, *PEST: Model-Independent Parameter Estimation, User manual,* (5th edition), Watermark Numerical Computing, Brisbane.

Dougall, C, Carroll, C, Herring, M, Trevithick, R, Neilsen, S, Burger, P 2009, *Enhanced sediment and nutrient modelling and target setting in the Fitzroy Basin*, Department of Environment and Resource Management, Emerald, Queensland.

Drewry, J, Higham, W, Mitchell, C 2008, *Water quality improvement plan: final report for Mackay Whitsunday region*, Mackay Whitsunday Natural Resource Management Group, Mackay, Australia.

DSITIA 2012, *Land use summary 1999–2009: Great Barrier Reef catchments*, Queensland Department of Science, Information Technology, Innovation and the Arts, Brisbane.

Ellis, R and Searle, RD 2014, *Dynamic SedNet component model reference guide*, Queensland Department of Science, Information Technology, Innovation and the Arts, Bundaberg, Queensland.

Ellis, R, Doherty, J, Searle, RD, Moodie, K 2009, 'Applying PEST (Parameter ESTimation) to improve parameter estimation and uncertainty analysis in WaterCAST models', in *18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation, Interfacing modelling and simulation with mathematical and computational sciences*, RS Anderssen, RD Braddock & LTH Newham (eds), Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics, Cairns, July 2009.

Ellis, R, Searle, R 2013, 'An integrated water quality modelling framework for reporting on Great Barrier Reef catchments', in *MODSIM2013 20th International Congress on Modelling and Simulation*, J Piantadosi, RS Anderssen & J Boland (eds), Modelling and Simulation Society of Australia and New Zealand, Adelaide, South Australia, December 2013.

eWater Ltd 2013, *Source scientific reference guide (v3.5.0)*, eWater Ltd, Canberra.

eWater Ltd 2012, *Source Catchments product information*, URL: http://www.ewater.com.au/products/ewater-source/for-catchments/, viewed May 2011.

Farr, TG, Rosen, PA, Caro, E, Crippen, R, Duren, R, Hensley, S, Kobrick, M, Paller, M, Rodriguez, E, Roth, L, Seal, D, Shaffer, S, Shimada, J, Umland, J, Werner, M, Oskin, M, Burbank, D Alsdorf, DE 2007, The shuttle radar topography mission, *Reviews of Geophysics* 45 (2).

Freebairn, DM, Wockner, G 1986, 'A study of soil erosion on Vertisols of the eastern Darling Downs, Queensland. I. Effect of surface conditions on soil movement within contour bay catchments', *Australian Journal of Soil Research*, vol. 24, no. 2, pp.135–158.

Goulevitch, BM, Danaher, TJ, Stewart, AJ, Harris, DP, Lawrence, LJ 2002, 'Mapping woody vegetation cover over the state of Queensland using Landsat TM and ETM+ imagery', in *Proceedings of the 11th Australasian Remote Sensing and Photogrammetry Conference, Images to information*, Remote Sensing and Photogrammetry Association of Australasia, Brisbane, 2–6 September 2002.

Hateley, L, Armour, A, Pitt, G, Cogle, L 2005, 'Use of SedNet model to establish sediment export targets for catchments of the Wet Tropics draining to the Great Barrier Reef', in *MODSIM 2005 International Congress on Modelling and Simulation*, A Zerger & RM Argent (eds), Modelling and Simulation Society of Australia and New Zealand, Melbourne, December, pp. 290.

Howley, C 2010, *Results of the Laura-Normanby River water quality monitoring project: an assessment of ambient water quality and water quality impacts, June 2006–June 2010*, CYMAG Environmental Inc, Cooktown, Queensland.

Hughes, AO, Croke, JC, Pietsch, TJ, Olley JM 2010, Changes in the rates of floodplain and in-channel bench accretion in response to catchment disturbance, central Queensland, Australia, Geomorphology 114 (3), 338–47.

Hughes, AO, Croke, JC 2011, Validation of a spatially distributed erosion and sediment yield model (SedNet) with empirically derived data from a catchment adjacent to the Great Barrier Reef Lagoon, *Marine and Freshwater Research* 62 (8), 962–73.

Hughes, AO, Prosser, IP, Stevenson, J, Scott, A, Lu, H, Gallant, J, Moran, CJ 2001, *Gully density prediction for the intensive landuse zone of Australia*, CSIRO Land and Water, Canberra.

Jell, PA (ed) 2013, *Geology of Queensland*, Geological Survey of Queensland.

Joo, M, McNeil, V, Carroll, C, Waters, D, Choy, S 2014, *Sediment and nutrient load estimates for major Great Barrier Reef catchments (1987–2009) for Source Catchments model validation*, Department of Science, Information Technology, Innovation and the Arts, (unpublished report), Brisbane.

Joo, M, Raymond, MAA, McNeil, VH, Huggins, R, Turner, RDR, Choy, S 2012, Estimates of sediment and nutrient loads in 10 major catchments draining to the Great Barrier Reef during 2006–2009, *Marine Pollution Bulletin* 65 (4–9), 150–66.

Keating, BA, Carberry, PS, Hammer, GL, Probert, ME, Robertson, MJ, Holzworth, D, Huth, NI, Hargreaves, JNG, Meinke, H, Hochman, Z, McLean, G, Verburg, K, Snow, V, Dimes, JP, Silburn, M, Wang, E, Brown, S, Bristow, KL, Asseng, S, Chapman, S, McCown, RL, Freebairn, DM, Smith, CJ 2003, An overview of APSIM, a model designed for farming systems simulation, *European Journal of Agronomy* 18 (3–4), 267–88.

Kinsey-Henderson, AE, Sherman, B, Bartley, R 2007, *Improved SedNet modelling of grazing lands in the Burdekin Catchment. Report for Burdekin Dry Tropics NRM*, CSIRO Land and Water Science Report 63/07, Townsville.

Kroon, F, Kunhert, K, Henderson, A, Turner, R, Huggins, R, Wilkinson, S, Abbott, B, Brodie, J, Joo, M 2010, Baseline pollutant loads to the Great Barrier Reef, CSIRO: Water for a Healthy Country Flagship report series ISSN: 1835-095X. 41 pp.

Kroon, FJ, Kuhnert, PM, Henderson, BL, Wilkinson, SN, Kinsey-Henderson, A, Abbott, B, Brodie, JE, Turner, RDR 2012, River loads of suspended solids, nitrogen, phosphorus and herbicides delivered to the Great Barrier Reef lagoon, *Marine Pollution Bulletin* 65 (4–9), 167–81.

Laurenson, EM, Mein, RG 1997, *RORB Version 4, runoff routing program—user manual*, Department of Civil Engineering, Monash University/Montech Pty Ltd, Melbourne.

Lewis, SE, Brodie, JE, Bainbridge, ZT, Rohde, KW, Davis, AM, Masters, BL, Maughan, M, Devlin, MJ, Mueller, JF, Schaffelke, B 2009, Herbicides: a new threat to the Great Barrier Reef, *Environmental Pollution* 157 (8–9), 2470–84.

Littleboy, M, Silburn, MD, Freebairn, DM, Woodruff, DR, Hammer, GL 1989, *PERFECT: a computer simulation model of Productivity Erosion Runoff Functions to Evaluate Conservation Techniques*, Soil Conservation Research and Agriculture Branch, Queensland Department of Primary Industries, Brisbane.

Loch, RJ, Rosewell, CJ 1992, Laboratory methods for measurement of soil erodibilities (K factors) for the Universal Soil Loss Equation, *Australian Journal of Soil Research* 30 (2), 233–48.

Lu, H, Gallant, J, Prosser, IP, Moran, CJ, Priestley, G 2001, *Prediction of sheet and rill erosion over the Australian continent, incorporating monthly soil loss distribution*, CSIRO Land and Water, Canberra.

Lu, H, Prosser, IP, Moran, CJ, Gallant, JC, Priestley, G, Stevenson, JG 2003, Predicting sheetwash and rill erosion over the Australian continent, *Australian Journal of Soil Research* 41 (6), 1037–62.

Marsh, N, Waters, D 2009, 'Comparison of load estimation methods and their associated error', in *18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation, Interfacing modelling and simulation with mathematical and computational sciences*, RS Anderssen, RD Braddock & LTH Newham (eds), Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics, Cairns, July, pp. 3322.

McCloskey, GL 2010, *Riparian erosion morphology, processes and causes along the Victoria River, Northern Territory, Australia*, PhD thesis, Charles Darwin University.

McKeon, G, Day, K, Howden, S, Mott, J, Orr, D, Scattini, W, Weston, E 1990, Northern Australian savannas: management for pastoral production, *Journal of Biogeography* 17 (4–5), 355–72.

McKergow, LA, Prosser, IP, Hughes, AO, Brodie, J 2005a, Regional scale nutrient modelling: exports to the Great Barrier Reef World Heritage Area, *Marine Pollution Bulletin* 51 (1–4), 186–99.

McKergow, LA, Prosser, IP, Hughes, AO, Brodie, J 2005b, Sources of sediment to the Great Barrier Reef World Heritage Area, *Marine Pollution Bulletin*, 51 (1–4), 200–11.

Moriasi, DN, Arnold, JG, Van Liew, MW, Bingner, RL, Harmel, RD, Veith, TL 2007, Model evaluation guidelines for systematic quantification of accuracy in watershed simulations, *Transactions of the ASABE* 50 (3), 885–900.

Moss, AJ, Rayment, GE, Reilly, N, Best, EK 1992, *A preliminary assessment of sediment and nutrient exports from Queensland coastal catchments*, Queensland Department of Environment and Heritage, Brisbane.

National Committee on Soil and Terrain 2009, *Australian Soil and Land Survey Field Handbook,* (3rd edition), CSIRO Publishing, Collingwood, Victoria.

Neil, DT, Yu, B 1996, 'Fluvial sediment yield to the Great Barrier Reef lagoon: spatial patterns and the effect of land use', in *Downstream effects of land use change*, HM Hunter, AG Eyles & GE Rayment (eds), Department of Natural Resources, Rockhampton, 26–28 April, pp. 281–286.

NLWRA 2001, *National Land & Water Resources Audit—Australian agriculture assessment*, CSIRO Land & Water Australia, Canberra.

Packett, R, Dougall, C, Rohde, K, Noble, R 2009, Agricultural lands are hot-spots for annual runoff polluting the southern Great Barrier Reef lagoon, *Marine Pollution Bulletin* 58 (7), 976–86.

Post, DA, Waterhouse, J, Grundy, M, Cook, F 2007, *The past, present and future of sediment and nutrient modelling in GBR catchments*, CSIRO: Water for a Healthy Country National Research Flagship.

PPDB 2009, *The pesticide properties database* (PPDB) developed by the Agriculture & Environment Research Unit (AERU), University of Hertfordshire, funded by UK national sources and the EU-Funded FOOTPRINT project (FP6-SSP-022704).

Prosser, IP, Rustomji, P, Young, WJ, Moran, CJ, Hughes, A 2001a, *Constructing river basin sediment budgets for the National Land and Water Resources Audit*, CSIRO Land and Water, Canberra.

Prosser, IP, Rutherfurd, ID, Olley, JM, Young, WJ, Wallbrink, PJ, Moran, CJ 2001b, Large-scale patterns of erosion and sediment transport in river networks, with examples from Australia, *Marine and Freshwater Research* 52 (1), 81–99.

Prosser, IP, Winchester, SJ 1996, History and processes of gully initiation and development in eastern Australia, *Zeitschrift fur Geomorphologie, Supplementband* 105, 91–109.

Queensland Government 2011, *SILO Climate Data*, URL: http://www.longpaddock.qld.gov.au/silo/, viewed 22 Feb 2012.

Queensland Government 2013*, Great Barrier Reef Second Report Card 2010, Reef Water Quality Protection Plan,* URL: http://www.reefplan.qld.gov.au/measuring-success/report-cards/second-report-card.aspx, viewed 30 July 2013.

Rattray, DJ, Freebairn, DM, McClymont, D, Silburn, DM, Owens, JS, Robinson, JB 2004, ‘HOWLEAKY? The journey to demystifying 'simple' technology’, in *Conserving soil and water for society: sharing solutions, The 13th International Soil Conservation Organisation Conference*, SR Raine, AJW Biggs, NW Menzies, DM Freebairn & PE Tolmie (eds), ISCO, Brisbane, July.

Renard, KG, Ferreira, VA 1993, RUSLE model description and database sensitivity, *Journal of Environmental Quality* 22 (3), 458–66.

Renard, KG, Foster, GA, Weiss, DK, McCool, DK, Yoder, DC 1997, *Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE)*, United States Department of Agriculture, Agriculture handbook no 73, 404 pp.

Richards, RP 1999, *Estimation of pollutant loads in rivers and streams: a guidance document for NPS programs. Prepared under grant X998397-01-0*, Environmental Protection Agency, USA.

Robinson, JB, Silburn, DM, Rattray, D, Freebairn, DM, Biggs, A, McClymont, D, Christodoulou, N 2010, Modelling shows that the high rates of deep drainage in parts of the Goondoola Basin in semi-arid Queensland can be reduced with changes to the farming systems, *Australian Journal of Soil Research* 48 (1), 58–68.

Rohde, K, Masters, B, Fries, N, Noble, R, Carroll, C 2008, *Fresh and marine water quality in the Mackay Whitsunday region 2004/05 to 2006/07*, Queensland Department of Natural Resources and Water for the Mackay Whitsunday Natural Resource Management Group, Australia.

Rosewell, CJ 1993, *SOILOSS A program to assist in the selection of management practices to reduce erosion, Technical handbook no 11*, (2nd edition), Soil Conservation Service, NSW.

Rustomji, P, Shellberg, J, Brooks, A, Spencer, J, Caitcheon, G 2010, *A catchment sediment and nutrient budget for the Mitchell River, Queensland, A report to the Tropical Rivers and Coastal Knowledge (TRaCK) Research Program*, CSIRO: Water for a Healthy Country National Research Flagship.

Sattler, P, Williams, R 1999, *The conservation status of Queensland's bioregional ecosystems,* Queensland. Environmental Protection Agency, Brisbane.

Scarth, P, Byrne, M, Danaher, T, Henry, B, Hassett, R, Carter, J, Timmers, P 2006, ‘State of the paddock: monitoring condition and trend in groundcover across Queensland’, in *Proceedings of the 13th Australasian Remote Sensing and Photogrammetry Conference, Earth* *observation: from science to solutions*, Spatial Sciences Institute (Australia), Canberra, 21–24 November 2006.

Shaw, M, Silburn, DM, Thornton, CM, Robinson, B, McClymont, D 2011, 'Modelling pesticide runoff from paddocks in the Great Barrier Reef with HowLeaky', in *MODSIM2011 19th International Congress on Modelling and Simulation, Sustaining our future: understanding and living with uncertainty*, F Chan, D Marinova & RS Anderssen (eds), Modelling and Simulation Society of Australia and New Zealand, Perth, December, pp. 2057.

Shaw, M, Furnas, MJ, Fabricius, K, Haynes, D, Carter, S, Eaglesham, G, Mueller, JF 2010, Monitoring pesticides in the Great Barrier Reef, *Marine Pollution Bulletin* 60 (1), 113–22.

Shaw, M & Silburn, DM 2014, Paddock to Reef Integrated Monitoring, Modelling and Reporting Program, Paddock Scale Modelling Technical Report, Queensland Department of Natural Resources and Mines, Brisbane.

Shellberg, JG 2011, *Alluvial gully erosion rates and processes across the Mitchell River fluvial megafan in northern Queensland, Australia*, PhD thesis, Griffith University, Australia.

Smith, R, Middlebrook, R, Turner, R, Huggins, R, Vardy, S, Warne, M 2012, Large-scale pesticide monitoring across Great Barrier Reef catchments—Paddock to Reef integrated monitoring, modelling and reporting program, *Marine Pollution Bulletin* 65 (4–9), 117–27.

Smith, R, Turner, R, Vardy, S, Warne, M 2011, 'Using a convolution integral model for assessing pesticide dissipation time at the end of catchments in the Great Barrier Reef Australia', in *MODSIM2011 19th International Congress on Modelling and Simulation, Sustaining our future: understanding and living with uncertainty*, F Chan, D Marinova & RS Anderssen (eds), Modelling and Simulation Society of Australia and New Zealand, Perth, December, pp. 2064.

Stewart, J 2011, *Great Barrier Reef Catchment modelling: parameter sensitivity and uncertainty analysis and hydrologic model parameterisation methodology.* Prepared for the Queensland Department of Environment and Resource Management, BMT WBM Pty Ltd, Leichardt, NSW, Australia.

Thorburn, PJ, Wilkinson, SN 2012, Conceptual frameworks for estimating the water quality benefits of improved agricultural management practices in large catchments, *Agriculture, Ecosystems and Environment* 180, 1–3.

Thornton, CM, Cowie, BA, Freebairn, DM, Playford CL, 2007, The Brigalow Catchment study:II Clearing brigalow (Acacia harpophylla) for cropping or pasture increases in runoff, *Australian Journal of Soil Research* 45 (7), 496–511.

Tropical Savannas CRC 2011*, Savanna Explorer—North Australian information resource*, URL: www.savanna.org.au, viewed May 2011.

Turner, R, Huggins, R, Smith, R, Warne, MSJ 2013, *Total suspended solids, nutrient and pesticide loads (2010–2011) for rivers that discharge to the Great Barrier Reef. Great Barrier Reef Catchment Loads Monitoring 2010–2011*, Department of Science, Information Technology, Innovation and the Arts, Brisbane.

Turner, R, Huggins, R, Wallace, R, Smith, R, Vardy, S, Warne, MSJ 2012, *Sediment, nutrient and pesticide loads: Great Barrier Reef Catchment loads monitoring 2009–2010*, Department of Science, Information Technology, Innovation and the Arts, Brisbane.

Vaze, J, Perraud, J-, Teng, J, Chiew, F, Wang, B 2011, 'Estimating regional model parameters using spatial land cover information—Implications for predictions in ungauged basins', in *MODSIM2011 19th International Congress on Modelling and Simulation, Sustaining our future: understanding and living with uncertainty*, F Chan, D Marinova & RS Anderssen (eds), Modelling and Simulation Society of Australia and New Zealand, Perth, December, pp. 3433.

Wallace, J, Karim, F, Wilkinson, S 2012, Assessing the potential underestimation of sediment and nutrient loads to the Great Barrier Reef lagoon during floods, *Marine Pollution Bulletin* 65 (4–9), 194–202.

Waters, D, Carroll, C 2012, *Great Barrier Reef Paddock and Catchment Modelling Approach and Quality Assurance Framework*, Department of Natural Resources and Mines, Queensland.

Waters, D, Packett, R 2007, 'Sediment and nutrient generation rates for Queensland rural catchments—an event monitoring program to improve water quality modelling', in *Proceedings of the 5th Australian stream management conference, Australian rivers: making a difference*, AL Wilson, RL Dehaan, RJ Watts, KJ Page, KH Bowmer & A Curtis (eds), Charles Sturt University, Thurgoona NSW, 21–25 May 2007.

Wilkinson, S, Cook, F, Bartley, R, Henderson, A, Searle, R, Ellis, T, Jordan, P, Miller, A 2010, *Specification for sediment, nutrient and pesticide generation and transport modules in source catchments*, eWater Cooperative Research Centre, Canberra.

Wilkinson, S, Henderson, A, Chen, Y 2004, *SedNet User Guide. Client report for the Cooperative Research Centre for Catchment Hydrology*, CSIRO Land and Water, Canberra.

Wilkinson, SN, Hancock, GJ, Bartley, R, Hawdon, AA, Keen, RJ in press, Using sediment tracing to assess processes and spatial patterns of erosion in grazed rangelands, Burdekin River Basin, Australia, *Agriculture, Ecosystems and Environment*.

Wilkinson, SN, Olley, JM, Prosser, IP, Read, AM 2005, Targeting erosion control in large river systems using spatially distributed sediment budgets, *IAHS-AISH Publication*, no. 299, 56–64.

Yee Yet, J, Silburn, DM 2003, *Deep drainage estimates under a range of land uses in the QMDB using water balance modelling*, Queensland Department of Natural Resources and Mines, Toowoomba, Queensland QNRM03021.

Young, WJ, Prosser, IP, Hughes, AO 2001, *Modelling nutrient loads in large-scale river networks for the National Land and Water Resources Audit*, CSIRO, Canberra.

Yu, B 1998, Rainfall erosivity and its estimation for Australia's tropics, *Australian Journal of Soil Research* 36 (1), 143–65.

Zhang, YQ, Chiew, FHS 2009, 'Evaluation of regionalisation methods for predicting runoff in ungauged catchments in southeast Australia', *18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation, Interfacing modelling and simulation with mathematical and computational sciences*, RS Anderssen, RD Braddock & LTH Newham (eds), Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics, Cairns, July.

Zhang, X, Waters, D, Ellis, R 2013, 'Evaluation of Simhyd, Sacramento and GR4J rainfall runoff models in two contrasting Great Barrier Reef catchments', in *MODSIM2013 20th International Conference on Modelling and Simulation*, J Piantadosi, RS Anderssen & J Boland (eds), Modelling and Simulation Society of Australia and New Zealand, Adelaide, South Australia, December 2013.

Appendix A – Previous estimates of pollutant loads

Table 23 Kroon et al. (2012) natural (predevelopment), baseline and total pollutant loads for the Cape York NRM regions

Basin name	TSS (kt/yr)			DIN (t/yr)			DON (t/yr)			PN (t/yr)			TN (t/yr)		
	Pre-European	Anthropogenic	Current	Pre-European	Anthropogenic	Current	Pre-European	Anthropogenic	Current	Pre-European	Anthropogenic	Current	Pre-European	Anthropogenic	Current
Jacky Jacky	17	79	96	133	125	258	149	162	311	10	562	572	292	849	1,141
Olive-Pascoe	57	275	332	236	246	482	268	340	608	27	1,402	1,429	531	1,988	2,519
Lockhart	28	123	151	85	82	167	167	86	253	8	364	372	260	532	792
Stewart	22	86	108	69	68	137	85	81	166	7	277	284	161	426	587
Normanby	184	939	1,093	517	432	949	544	631	1,175	85	4,459	4,544	1,146	5,522	6,668
Jeannie	66	171	237	122	82	204	140	79	219	23	788	811	285	949	1,234
Endeavour	70	301	371	119	100	219	186	139	325	18	835	853	323	1,074	1,397
Cape York	**444**	**1,944**	**2,388**	**1,281**	**1,135**	**2,416**	**1,539**	**1,518**	**3,057**	**178**	**8,687**	**8,865**	**2,998**	**11,340**	**14,338**

Basin name	DIP (kt/yr)			DOP (t/yr)			PP (t/yr)			TP (t/yr)			PSIIs (kg/yr)		
	Pre-European	Anthropogenic	Current	Pre-European	Anthropogenic	Current	Pre-European	Anthropogenic	Current	Pre-European	Anthropogenic	Current	Pre-European	Anthropogenic	Current
Jacky Jacky	12	0	12	14	2	16	14	57	71	40	59	99	0	0	0
Olive-Pascoe	10	0	10	25	5	30	38	201	239	73	206	279	0	0	0
Lockhart	5	1	6	13	1	14	14	73	87	32	75	107	0	0	0
Stewart	3	0	3	8	0	8	10	43	53	21	43	64	0	0	0
Normanby	10	3	13	53	8	61	72	525	597	135	536	671	0	0	0
Jeannie	5	1	6	13	1	14	19	78	97	37	80	117	0	0	0
Endeavour	3	1	4	16	2	18	23	134	157	42	137	179	0	0	0
Cape York	**48**	**6**	**54**	**142**	**19**	**161**	**190**	**1,111**	**1,301**	**380**	**1,136**	**1,516**	**0**	**0**	**0**

TSS = total suspended solids, 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.

Appendix B – PEST calibration approach

The process of coupling PEST and Source Catchments is presented in Figure 25. 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.

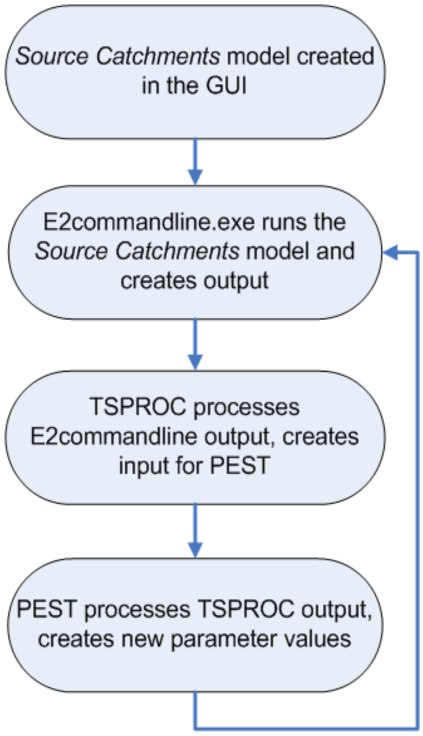

Figure 25 PEST – Source Catchments Interaction (Stewart 2011)

A detailed description of PEST set up and operation can be found in (Doherty 2009). 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 2009). 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 SVD-assist Super Parameter Definition was used to derive initial parameter sets and calibration results. 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. Of a possible 874 parameters, 150 super parameters were defined. The SVD-assist calibration was stopped once phi started to level out (Iteration 4). PEST was instructed to use E2CommandLine to perform the model runs. Given the size of the regional models, 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 26.

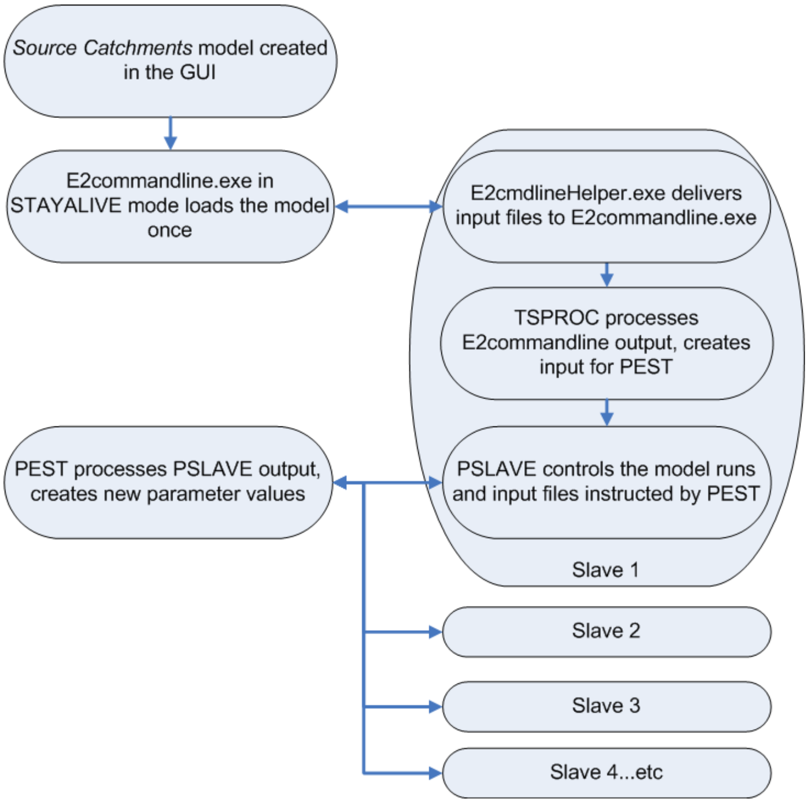

Figure 26 PEST operation (Stewart 2011)

Appendix C – SIMHYD model structure and parameters for calibration

The reclassification of the full set of land uses into three HRUs is presented in Table 24. Default SIMHYD and Laurenson parameters were used as the starting values for the calibration process, and these are identified in Table 25. The calibrated parameter values for three HRUs in 18 regions are provided in Table 26.

Table 24 Reclassification of FUs for hydrology calibration

Land use (FU)	HRU
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

Table 25 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	864,000
Laurenson	Exponent (m)	240	0.6	2

* It should be noted that the upper value of the SMSC range was increased in CY beyond the recommended range due to the inability to remove water from a particular area during the calibration process. This is further explained in the discussion section of this document. The upper value was increased from 500 to 750.

Table 26 Calibrated SIMHYD and Laurenson parameter values for three HRUs across 18 CY regions

Forest	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
BASE	0.01	0.03	0.01	0.09	0.04	0.09	0.30	0.20	0.13	0.04	0.02	0.10	0.04	0.09	0.02	0.04	0.10	0.07
INFC	272	400	400	400	400	161	191	286	287	95	400	171	136	177	140	303	156	309
INFS	10.00	8.84	2.95	3.84	4.79	3.41	3.90	2.13	3.62	1.42	7.26	10.00	1.69	2.01	3.06	6.02	2.04	3.93
INTE	0.40	0.06	0.35	0.11	0.22	0.07	0.00	0.08	0.02	0.10	0.73	1.00	0.50	0.05	0.47	0.26	0.35	0.02
RECH	0.76	1.00	0.16	0.13	0.14	0.06	0.00	0.03	0.02	0.13	1.00	0.65	0.20	0.06	0.27	0.49	0.04	0.28
RISC	0.50	5.00	2.10	5.00	5.00	4.69	2.62	5.00	5.00	5.00	0.50	1.28	5.00	5.00	2.60	5.00	5.00	5.00
SMSC	750	432	750	493	378	397	408	471	417	697	615	98	723	750	731	395	345	267
Grazing																		
BASE	0.01	0.01	0.00	0.00	0.02	0.02	0.05	0.02	0.04	0.05	0.01	0.01	0.02	0.05	0.00	0.01	0.01	0.01
INFC	72	72	176	141	251	280	102	196	104	400	89	63	400	187	400	35	138	169
INFS	10.00	10.00	1.47	3.90	7.00	7.30	3.72	6.86	3.59	4.13	10.00	10.00	0.31	4.34	0.90	2.69	6.14	10.00
INTE	0.02	0.02	0.02	0.02	0.02	0.01	0.00	0.01	0.01	0.03	0.02	0.02	0.04	0.02	0.02	0.02	0.02	0.01
RECH	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00
RISC	0.50	0.50	0.50	0.54	0.50	0.82	0.50	0.75	1.60	0.54	0.50	0.50	0.50	0.63	0.55	0.50	0.52	0.50
SMSC	328	328	228	417	221	267	312	257	166	295	335	287	670	266	423	750	406	750
Agriculture																		
BASE	NA	NA	NA	NA	NA	0.17	NA	NA	NA	NA	0.15	0.15	0.15	0.14	0.15	NA	NA	NA
INFC	NA	NA	NA	NA	NA	257	NA	NA	NA	NA	190	190	190	192	190	NA	NA	NA
INFS	NA	NA	NA	NA	NA	5.04	NA	NA	NA	NA	5.00	5.00	5.00	4.96	5.00	NA	NA	NA
INTE	NA	NA	NA	NA	NA	0.42	NA	NA	NA	NA	0.50	0.50	0.50	0.52	0.50	NA	NA	NA
RECH	NA	NA	NA	NA	NA	0.38	NA	NA	NA	NA	0.50	0.50	0.50	0.56	0.50	NA	NA	NA
RISC	NA	NA	NA	NA	NA	5.00	NA	NA	NA	NA	2.25	2.25	2.25	1.91	2.25	NA	NA	NA
SMSC	NA	NA	NA	NA	NA	184	NA	NA	NA	NA	240	240	240	222	240	NA	NA	NA
Laurenson flow routing																		
k	486,000	125,059	311,457	91,089	58,657	25,372	168,369	35,038	6,5194	97,508	310,197	144,947	118,255	29,479	205,297	313,339	52,296	106,838
m	0.67	0.87	0.84	0.86	1.08	0.87	0.83	1.03	0.87	1.15	0.72	0.86	1.04	1.05	1.03	0.94	1.02	0.99

Appendix D – PEST calibration results

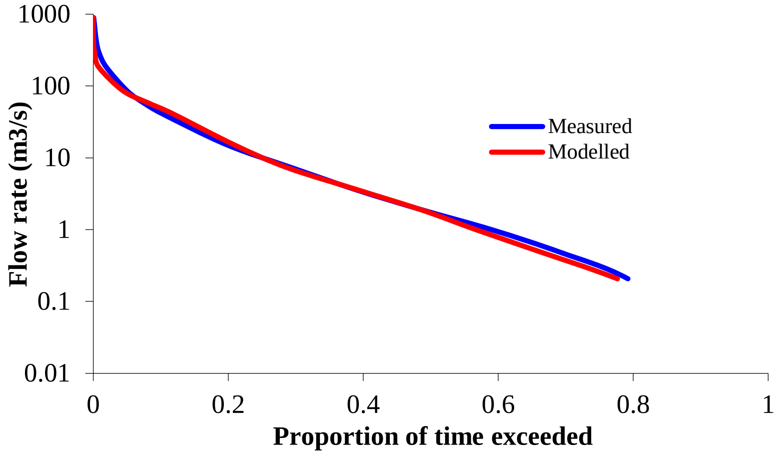

Figure 27 Flow duration curve 102101

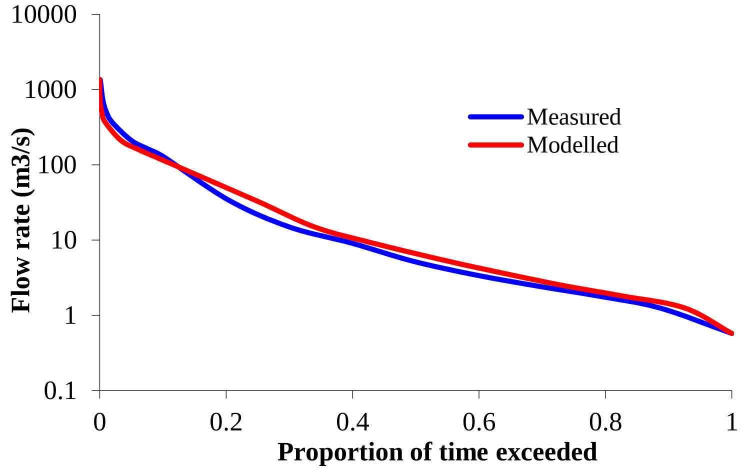

Figure 28 Flow duration curve 102102

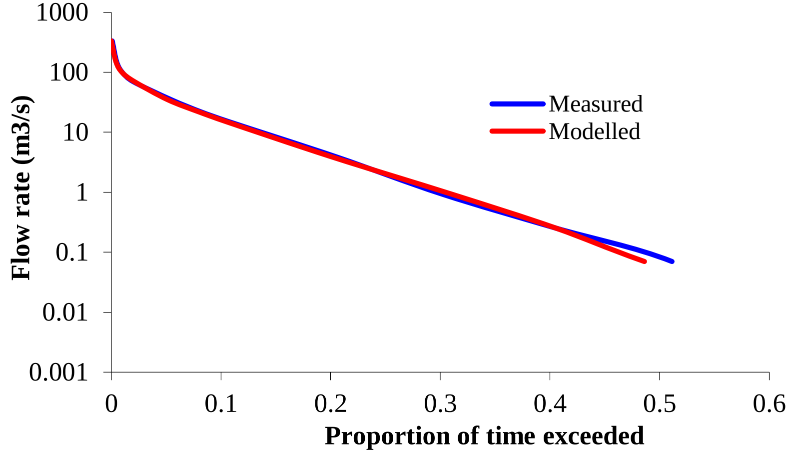

Figure 29 Flow duration curve 104001

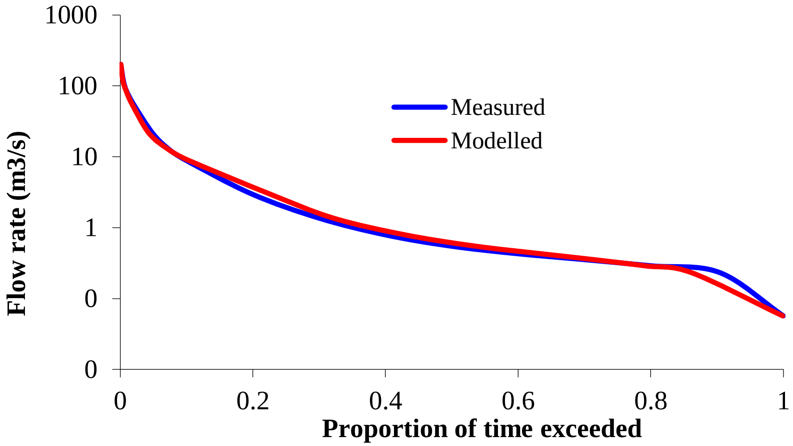

Figure 30 Flow duration curve 105001

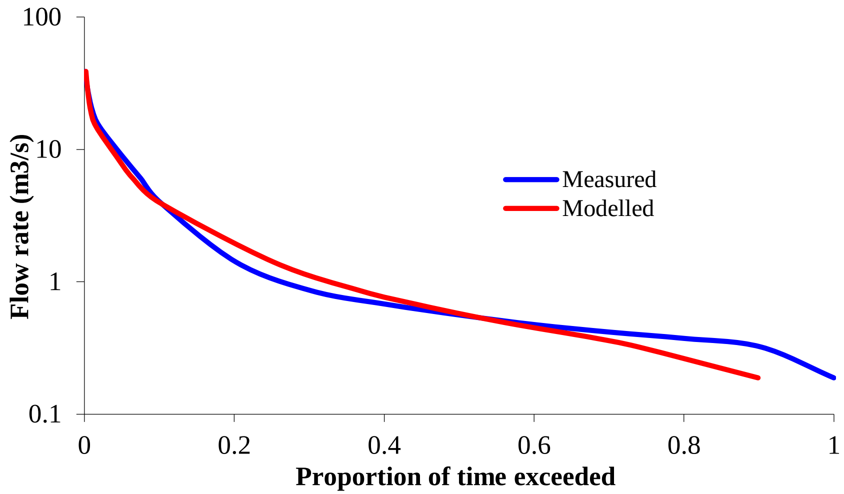

Figure 31 Flow duration curve 105002

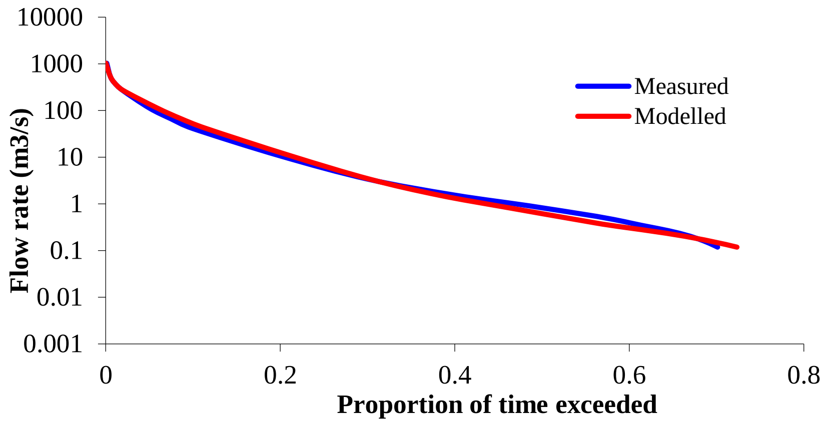

Figure 32 Flow duration curve 105101

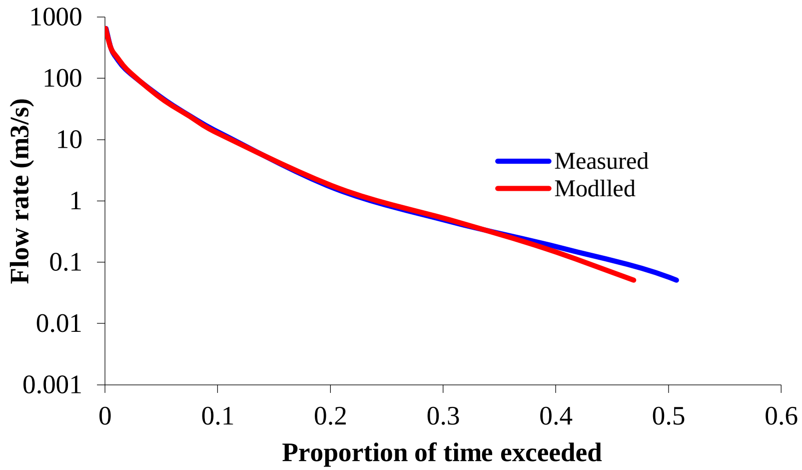

Figure 33 Flow duration curve 105102

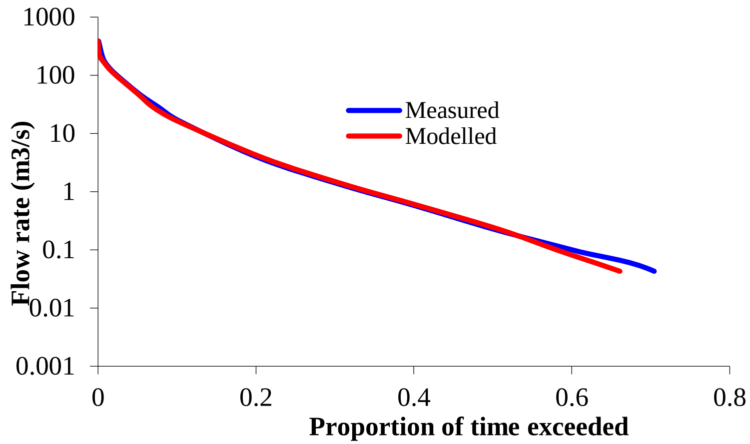

Figure 34 Flow duration curve 105103

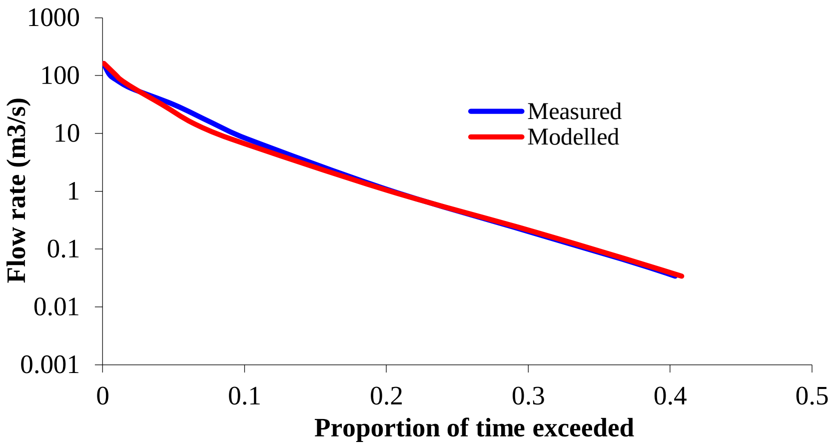

Figure 35 Flow duration curve 105104

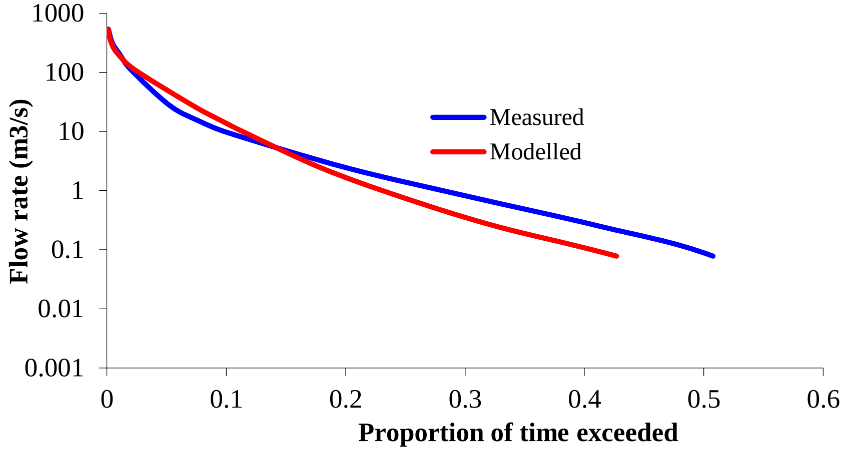

Figure 37 Flow duration curve 105106

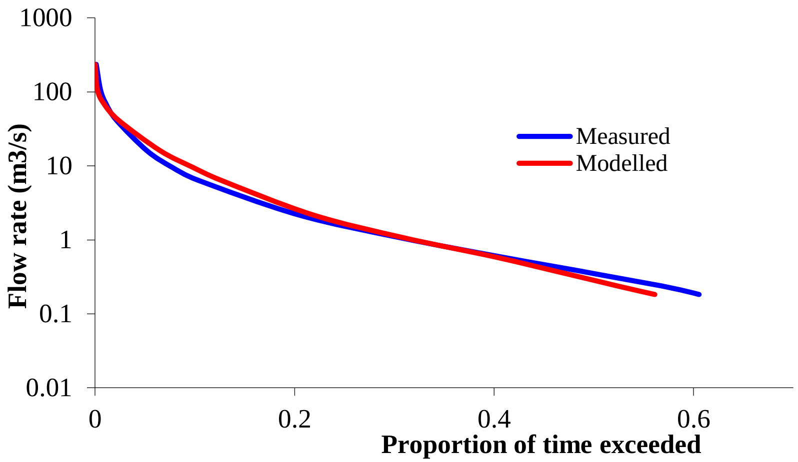

Figure 36 Flow duration curve 105105

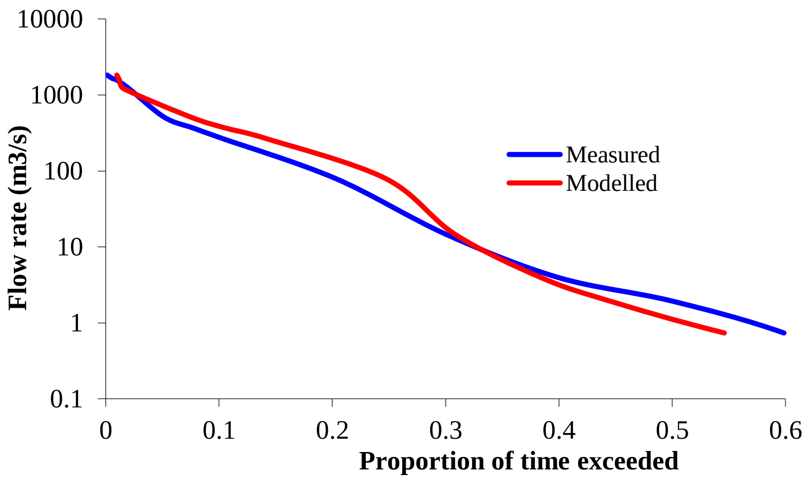

Figure 38 Flow duration curve 105107

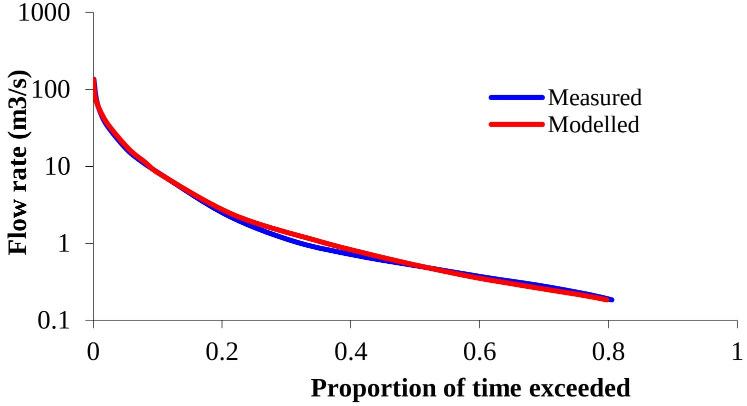

Figure 39 Flow duration curve 106001

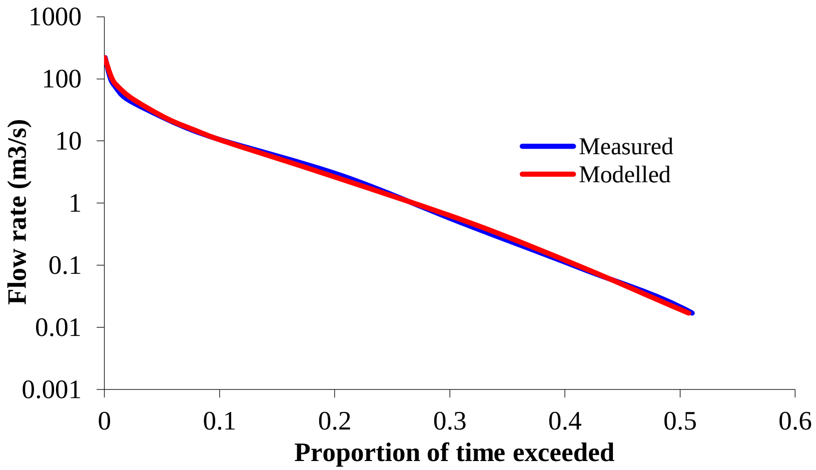

Figure 40 Flow duration curve 106002

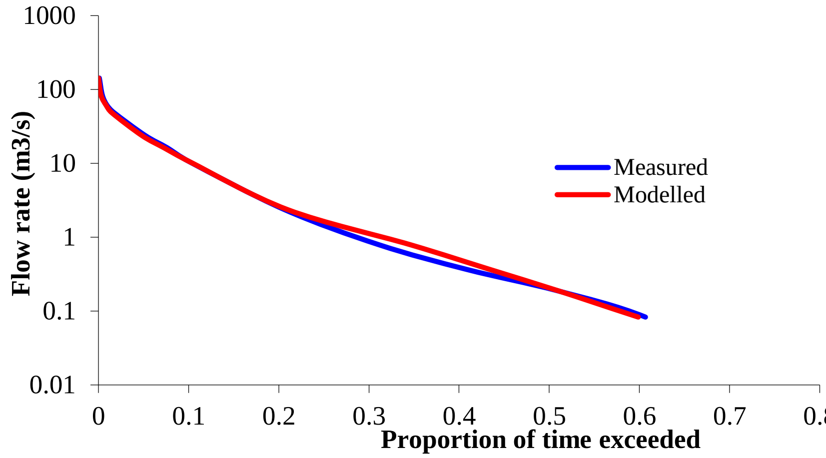

Figure 41 Flow duration curve 106003

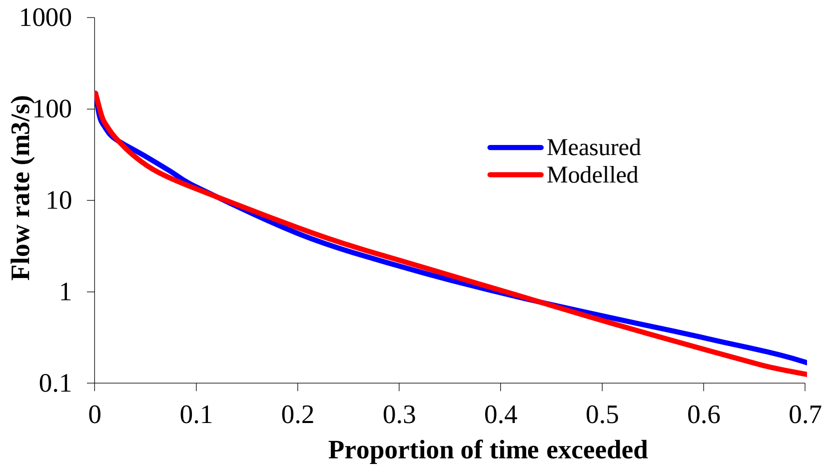

Figure 42 Flow duration curve 107001

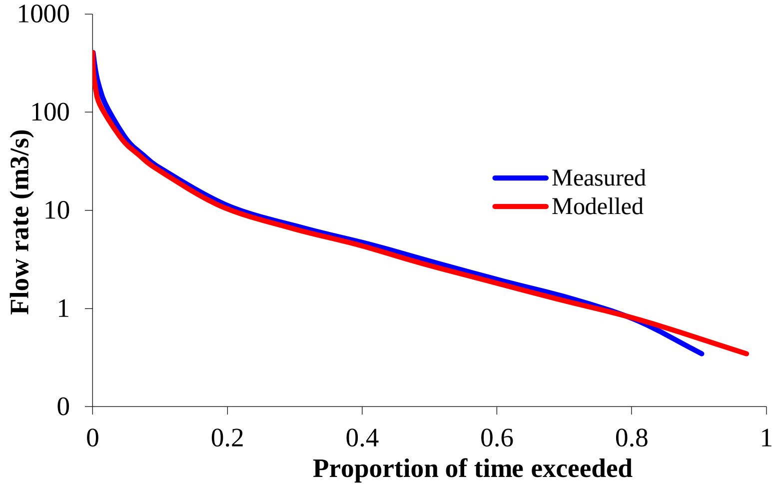

Figure 43 Flow duration curve 107002

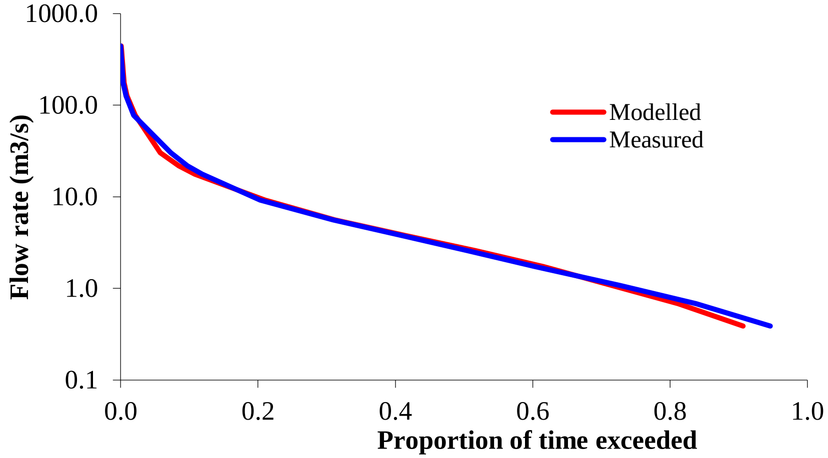

Figure 44 Flow duration curve 107003

Appendix E – Dynamic SedNet global parameters and data requirements

Spatial projection

All 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 and 4/5 of the full Y extent of the area of interest. These are the Standard Parallel 1 and Standard Parallel 2 below, where:

- 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

Parameter	Value
Fine sediment HSDR value (%)	10
Coarse sediment HSDR value (%)	0
Maximum quickflow concentration (mg/L)	10,000
DWC (mg/L)	10

A rock cover factor for Cape York GBR RUSLE modelling

Tessa Chamberlain, Mark Silburn and Andrew Biggs, February 2013

Rock fragments resting on the soil surface, or partly incorporated into the surface soil, affect erosion directly by shielding the soil surface from detachment and intercepting splashed sediment, in a similar way to vegetative surface cover (Poesen, Torri & Bunti 1994). They also affect erosion indirectly by impacting on hydrological processes such as rainfall interception, rock flow (runoff on the rock surface), infiltration, overland flow and evaporation (Poesen & Lavee 1994).

At the hillslope scale (encompassing both rill and interrill erosion processes, approximately 10^1–10^4 m^2), numerous studies have found an exponential decay relationship between surface rock cover and erosion rate (see Poesen, Torri & Bunti 1994 Table 1). This relationship has the same form as for the effect of vegetative surface cover. The general form of the equation is:

$$Rf = e^{-b.Rc}$$

where

b = exponent representing the effectiveness of rock cover in reducing erosion

Rc = per cent rock cover

Rf = 'rock factor'; relative rill and inter-rill sediment yield due to effect of surface rock cover (ranging from 0–1)

The exponent *b* varies between individual studies, and it is likely different between cultivated and rangeland soils. Poesen, Torri & Bunti (1994), reviewing numerous studies, proposed a universal *b* value of 0.04. However, most datasets they used were derived from studies on cultivated soils, and in the GBR project we are implementing the rock cover factor in grazing areas only. Two studies in rangelands in the US (Simanton et al. 1984 and Box 1981) returned *b* values of 0.049 and 0.053 respectively. We are not clear as to the optimal *b* value to use for the GBR rock cover factor, and so have decided in this first implementation to use the 'default' RUSLE *b* value of 0.035 (which is generally used to calculate C-factor for vegetative surface cover).

Vegetative surface cover may overlie rock fragments on the soil surface. If the two cover types can be measured together to give one overall cover value (e.g. Simanton et al. 1984), a single C-factor can be calculated which accounts for the effect both cover types simultaneously. Conversely, if the cover types are measured independently, and they overlap, adjustments must be made to cover estimates to avoid 'double accounting' and overestimation of the cover effect.

For the Cape York GBR catchments, soils are mapped at 1:250 000 scale in the Cape York Peninsula Land Use Study (CYPLUS) survey (Biggs & Philip 1995). Surface coarse fragments, that is, particles coarser than 2 mm resting on the soil surface, are characterised for each soil profile class (SPC) in the survey. Attributes used in this analysis are per cent abundance and frequency of occurrence. Abundance is recorded as a range, such as 2–10% (National Committee on Soil and Terrain 2009). The sizes of coarse fragments are also recorded, but this is not used directly in the analysis as the abundance category represents the total surface area covered by coarse fragments regardless of size. Size of coarse fragments does have an effect on the nature of the hydrologic and erosion response at the interrill scale (Poesen, Torri & Bunti 1994), but effects of coarse fragment size have not been quantified at the hillslope scale and are not considered here.

Any surface coarse fragments described with a frequency of 'occasionally present' were excluded from analysis, as they have a patchy distribution and are not considered typical of a particular SPC.

Figure 45 shows the distribution of surface coarse fragment abundance (ignoring those 'occasionally present') for the CYPLUS survey.

The ranges described for abundance were converted into discrete values for the model by taking the midpoint of each category (Table 28). The exponential equation with a *b* value of 0.035 ($Rf = e^{-0.035.Rc}$) was applied to these values, resulting in a coarse fragment factor which is mapped out in Figure 46.

Table 28 Surface coarse fragment abundance categories, midpoint values and corresponding Rf values

Category	Range	Midpoint	Rf
None	0	0	1
Very few	<2%	1	0.97
Few	2–10%	6	0.81
Common	10–20%	15	0.59
Many	20–50%	35	0.29
Abundant	50–90%	70	0.07
Very abundant	>90%	95	0.04

The surface coarse fragment data are measured independently of the ground cover data used in the GBR catchment models (which are sourced from Landsat imagery). Therefore, it is possible we are overestimating cover if vegetation and rocks overlap. However, local knowledge of the Cape York region indicates that areas with rock cover (at least for fragments of cobble size or larger) are likely to be devoid of vegetation. Figure 47 shows the size of coarse fragments mapped in the CYPLUS survey.

References

Biggs, AJW, Philip, SR 1995, *Soils of Cape York Peninsula*, Queensland Department of Primary Industries, Land Resources Bulletin QV95001.

Box, JE Jnr 1981, The effects of surface slaty fragments on soil erosion by water. *Soil Science Society of America Journal* 45, 111–16.

National Committee on Soil and Terrain 2009, *Australian Soil and Land Survey Field Handbook*, (3rd edition), CSIRO Publishing, Melbourne.

Poesen, J, Lavee, H 1994, Rock fragments in top soils: significance and processes, *Catena* 23 (1), 1–28.

Poesen, J, Torri, D, Bunte, K 1994, Effect of rock fragments on soil erosion by water at different spatial scales: a review, *Catena* 23 (1), 141–66.

Simanton, JR, Rawitz, E, Shirley, ED 1984, ‘Chapter 7—Effects of rock fragments on erosion of semiarid rangeland soils’, in *Erosion and productivity of soils containing rock fragments*, JD Nichols, PL Brown & WJ Grant (eds), Soil Science Society of America Special Publication 13.

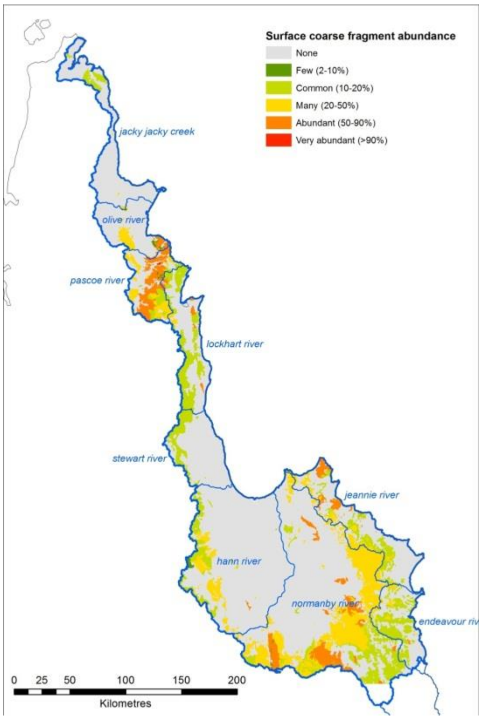

Figure 45 Surface coarse fragment abundance for the CYPLUS soil survey

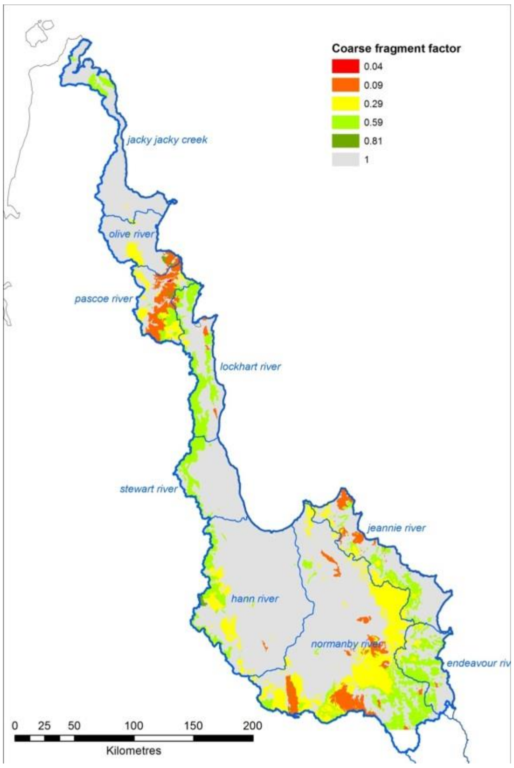

Figure 46 Surface coarse fragment factor (Rf) for the Cape York GBR catchments

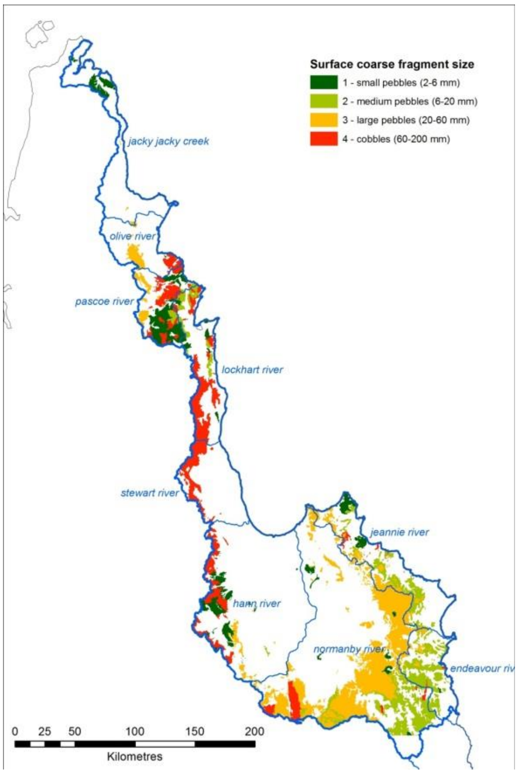

Figure 47 Surface coarse fragment size for the CYPLUS soil survey

Gully erosion

Table 29 Gully erosion model parameters

Parameter	Value
Fine sediment HDR value	100
Coarse sediment HDR value	0
Average gully activity factor	1
Management practice factor	variable
Daily runoff power factor	1.4
Raster processing cell size	250
Gully cross sectional area	5
Default gully start year	1870
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), diffuse runoff from other land uses or from inorganic 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 subsurface nitrogen and phosphorus), as well as surface and subsurface clay (%). All of the nutrient data was derived from the ASRIS dataset, and 'no data values' were adjusted to the median value for that particular catchment. Enrichment and delivery ratios (DR) are required for each of nitrogen and phosphorus. The input parameter values used in Cape York are found in Table 30.

Table 30 Nutrient generation parameter values

Parameter	Phosphorus	Nitrogen
Enrichment ratio	5	3
Hillslope delivery ratio	10	10
Gully delivery ratio	100	100

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 plug-in 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 CY 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 CY model are shown in Table 31, Table 32 and Table 33.

Table 31 Cropping nutrient input parameters

Parameter	Constituent	Value
Conversion factor	DOP	0.2
	DIP	0.8
Dry weather concentration	DOP	0.015
	DIP	0.0075
Delivery ratio	Dissolved nutrients	100%
	Dissolved herbicides	90%
	Particulates, fine sediment and particulate herbicides	10%
Maximum slope		8%
Use Creams enrichment	Phosphorus	False
Particulate enrichment	Phosphorus	NA
Particulate enrichment	Nitrogen	5
Gully DR (%)	N and P	100%

Table 32 Cropping sediment (hillslope and gully) input parameters

Parameter	Value
Clay %	26.38
Hillslope DR (%)	10%
Maximum slope	8%
Gully delivery ratio	100%
TSS DWC	30 mg/L

Other land uses

A ‘Land use based concentrations’ table is also required (see Table 33), which provides data on EMC/DWC values for each of the functional units.

Table 33 Land use based concentrations (mg/L) (EMC/DWC)

FU	TSS EMC	TSS DWC	PN EMC	PN DWC	DIN EMC	DIN DWC	DON EMC	DON DWC	PP EMC	PP DWC	DOP EMC	DOP DWC	DIP EMC	DIP DWC
Nature conservation	20	10	0.08	0.04	0.032	0.016	0.2	0.1	0.01	0.005	0.01	0.005	0.005	0.0025
Other	40	20	0.15	0.075	0.04	0.02	0.3	0.15	0.035	0.0175	0.02	0.01	0.01	0.005
Horticulture	60	30	0.225	0.1125	0.06	0.03	0.45	0.225	0.0525	0.02625	0.03	0.015	0.015	0.0075
Urban	40	20	0.15	0.075	0.04	0.02	0.3	0.15	0.035	0.0175	0.02	0.01	0.01	0.005
Forestry	40	20	0.15	0.075	0.04	0.02	0.3	0.15	0.035	0.0175	0.02	0.01	0.01	0.005
Water	20	10	0.075	0.0375	0.02	0.01	0.15	0.075	0.0175	0.00875	0.01	0.005	0.005	0.0025

In-stream models

Streambank erosion

The SedNet Stream Fine Sediment Model calculates a mean annual rate of fine streambank erosion (t/yr) and there are several raster data layers and parameter values that populate this model. The same DEM used to generate subcatchment 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 CY was 50 km^2. Floodplain area and extent was used to calculate a floodplain factor (potential for streambank erosion) and for deposition (loss). The floodplain input later was determined by using the Queensland Herbarium pre-clearing vegetation data and extracting the land zone 3 (alluvium) codes. The Queensland 2007 foliage projected 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 vegetation cover and this threshold discriminates between woody and non-woody vegetation, and we assumed that 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 may be 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.

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

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 data set were added together to create this layer. 'No data' values were changed to the median value, which in Cape York is 15. Using the raster data layers described above, the 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.

A series of global input parameters are also required for the stream parameteriser 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 CY are presented in Table 34.

Table 34 Dynamic SedNet stream parameteriser values for Cape York

Input parameters	Value
Bank height method: SedNet variable – Node based	
Proportion for fine sediment deposition	0
Catchment area exponent	0.1935
Catchment area coefficient	1.6549
Link width method: SedNet variable – Node based	
Minimum width	5
Maximum width	500
SedNet area exponent	0.3237
SedNet area coefficient	5.3067
SedNet slope exponent	0
Link slope method: Main channel	
Minimum link slope	0.000001
Stream attributes	
Bank full recurrence interval (years)	2
Stream buffer width (m)	100
Maximum vegetation effectiveness (%)	95
Sediment dry bulk density (t/m^3)	1.5
Sediment settling velocity (m/sec)	0.00007
Sediment settling velocity for remobilisation (m/sec)	0.1
Bank erosion coefficient	0.0004
Manning’s N coefficient	0.04
FPC threshold for streambank vegetation (%)	12
Initial proportion of fine bed store	0.00001
Daily flow power factor	1.4

Figure 48 and Figure 49, below, show how the bank height and link width exponent and coefficient values were calculated. The catchment area, channel height and width data were taken from cross-sections of each of the gauging stations in CY. In some instances, the cross-section data may have been adjusted, due to the age of these profiles and the dynamic nature of channel morphology, based on local knowledge such as that from the DERM hydrographers.

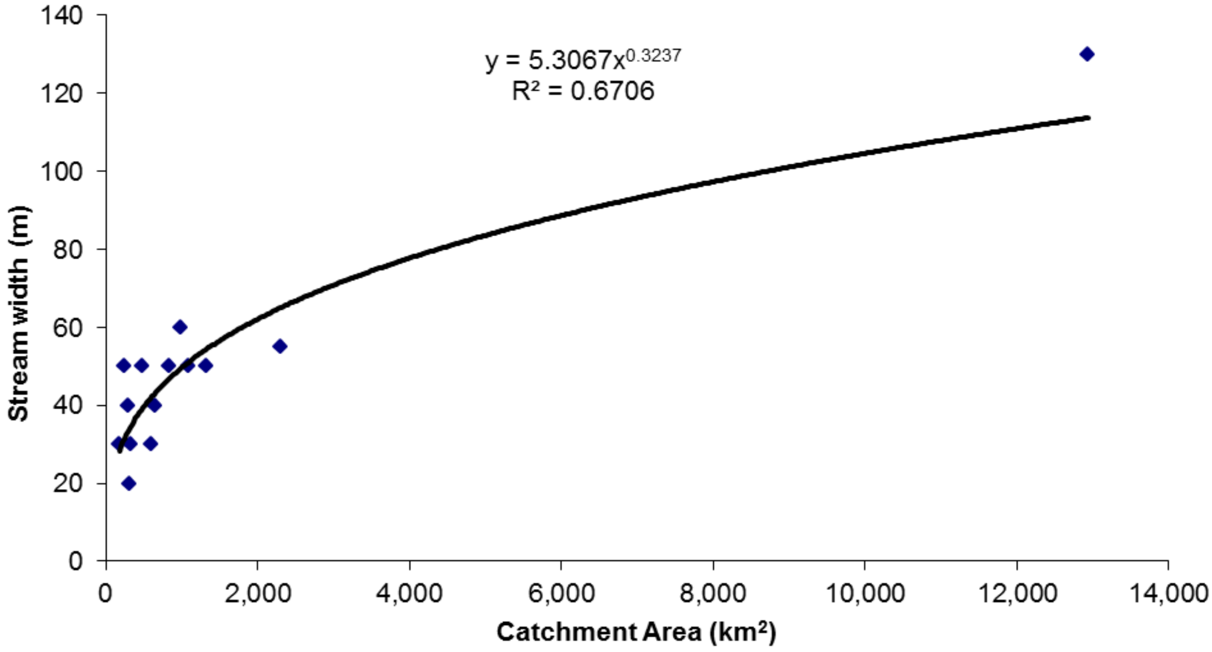

Figure 48 Catchment area vs stream width used to determine streambank erosion parameters

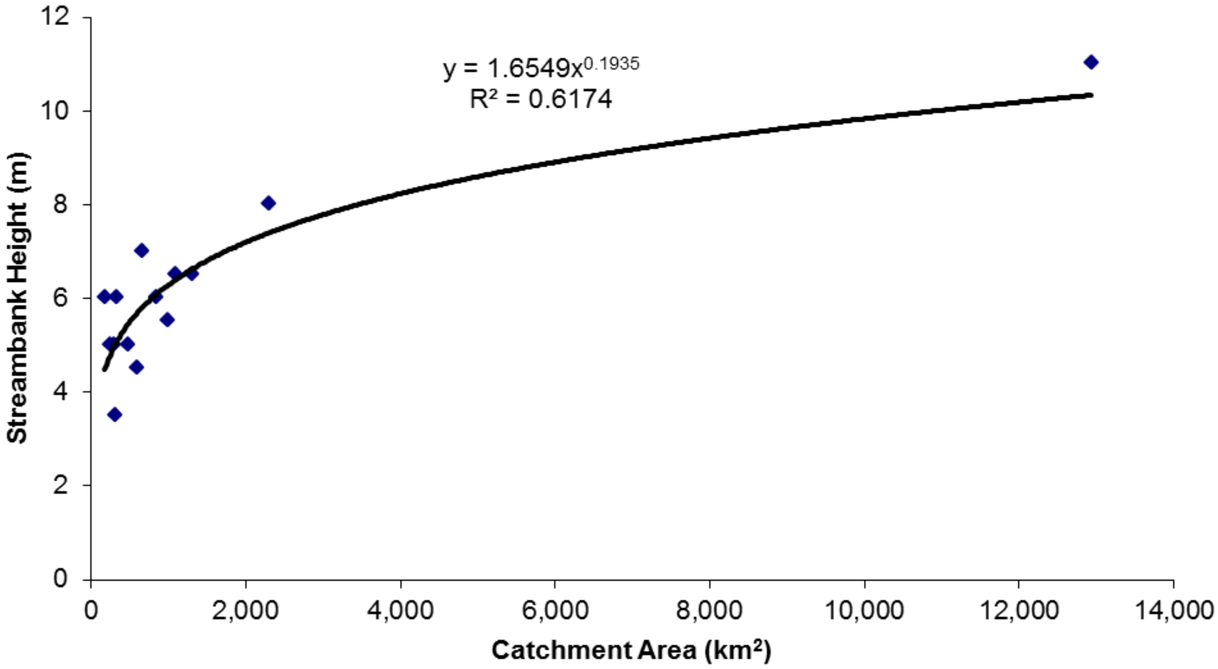

Figure 49 Catchment area vs streambank height used to determine streambank parameters

Herbicide half-lives

Table 35 Herbicide half-lives (seconds)

Herbicide	Half-life (seconds)
Metolachlor	777,600
Atrazine	432,000
Diuron	760,320
Hexazinone	760,320
Tebuthiuron	2,592,000

Management practice information

Table 36 Examples of improved management practices targeted through Reef Plan (including Reef Rescue) investments.

Note, this list is not comprehensive (K McCosker, pers. comm.)

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 10–15 cm below the surface with non-aggressive narrow tillage equipment.
Controlled traffic farming (CTF)	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 F – Report Card 2013 modelling results

Table 37 Constituent loads for natural, total, anthropogenic and Report Card 2013 change model runs for the CY NRM region

Total fine sediment (kt/yr)						
	Predevelopment	**Total baseline**	**Increase factor**	**Anthropogenic baseline**	**Report Card 2013 load**	**Load reduction (%)**
Jacky Jacky	43	44	1	1	44	0.0
Olive-Pascoe	58	60	1	3	60	0.0
Lockhart	38	39	1	1	39	0.0
Stewart	19	29	2	10	29	0.0
Normanby	53	188	4	135	173	11.5
Jeannie	18	27	1	9	27	0.0
Endeavour	21	42	2	21	42	0.0
Total	**249**	**429**	**2**	**180**	**413**	**8.6**
Total phosphorus (t/yr)						
	Predevelopment	**Total baseline**	**Increase factor**	**Anthropogenic baseline**	**Report Card 2013 load**	**Load reduction (%)**
Jacky Jacky	56	58	1.0	3	58	0.0
Olive-Pascoe	76	83	1.1	6	83	0.0
Lockhart	46	46	1.0	0	46	0.0
Stewart	25	40	1.6	15	40	0.0
Normanby	93	205	2.2	89	192	11.6
Jeannie	26	35	1.4	8	35	0.0
Endeavour	33	63	1.9	27	63	0.0
Total	**353**	**531**	**1.5**	**147**	**518**	**7.4**
Particulate phosphorus (t/yr)						

	Predevelopment	Total baseline	Increase factor	Anthropogenic baseline	Report Card 2013 load	Load reduction (%)
Jacky Jacky	21	22	1.0	1	22	0.0
Olive-Pascoe	28	31	1.1	3	31	0.0
Lockhart	18	18	1.0	0	18	0.0
Stewart	8	17	2.0	9	17	0.0
Normanby	28	105	3.7	76	91	17.1
Jeannie	10	16	1.6	6	16	0.0
Endeavour	11	29	2.6	18	29	0.0
Total	**125**	**238**	**1.9**	**113**	**225**	**11.6**
Dissolved inorganic phosphorus (t/yr)						
	Predevelopment	**Total baseline**	**Increase factor**	**Anthropogenic baseline**	**Report Card 2013 load**	**Load reduction (%)**
Jacky Jacky	11	12	1.0	1		
Olive-Pascoe	16	17	1.1	1		
Lockhart	9	9	1.0	0		
Stewart	5	8	1.4	2		
Normanby	22	34	1.6	12		
Jeannie	5	6	1.2	1		
Endeavour	7	11	1.6	4		
Total	**76**	**98**	**1.3**	**22**		
Dissolved organic phosphorus (t/yr)						
	Predevelopment	**Total baseline**	**Increase factor**	**Anthropogenic baseline**	**Report Card 2013 load**	**Load reduction (%)**
Jacky Jacky	23	24	1.1	1		

Olive-Pascoe	32	35	1.1	3		
Lockhart	18	18	1.0	0		
Stewart	11	15	1.4	5		
Normanby	43	67	1.6	24		
Jeannie	11	13	1.2	2		
Endeavour	14	23	1.6	8		
Total	**152**	**195**	**1.3**	**43**		
Total nitrogen (t/yr)						
	Predevelopment	**Total baseline**	**Increase factor**	**Anthropogenic baseline**	**Report Card 2013 load**	**Load reduction (%)**
Jacky Jacky	719	721	1.0	2	721	0.0
Olive-Pascoe	1006	1,012	1.0	5	1,012	0.0
Lockhart	575	575	1.0	0	575	0.0
Stewart	351	395	1.1	44	395	0.0
Normanby	1438	1,559	1.1	121	1,543	13.0
Jeannie	346	359	1.0	13	359	0.0
Endeavour	475	553	1.2	78	553	0.0
Total	**4,910**	**5,173**	**1.1**	**264**	**5,158**	**6.0**
Particulate nitrogen (t/yr)						
	Predevelopment	**Total baseline**	**Increase factor**	**Anthropogenic baseline**	**Report Card 2013 load**	**Load reduction (%)**
Jacky Jacky	169	171	1.0	2	171	0.0
Olive-Pascoe	222	227	1.0	5	227	0.0
Lockhart	146.73	146.81	1.0	0.08	147	0.0
Stewart	61	83	1.3	21	83	0.0

Normanby	118	224	1.9	106	208	14.9
Jeannie	62	75	1.2	12	75	0.0
Endeavour	60	104	1.7	44	104	0.0
Total	**838**	**1,030**	**1.2**	**191**	**1,014**	**8.3**
Dissolved inorganic nitrogen (t/yr)						
	Predevelopment	**Total baseline**	**Increase factor**	**Anthropogenic baseline**	**Report Card 2013 load**	**Load reduction (%)**
Jacky Jacky	73	73	1.0	0		
Olive-Pascoe	102	102	1.0	0		
Lockhart	59	59	1.0	0		
Stewart	35	36	1.0	2		
Normanby	138	139	1.0	1		
Jeannie	34	34	1.0	0		
Endeavour	46	48	1.1	3		
Total	**487**	**492**	**1.0**	**5**		
Dissolved organic nitrogen (t/yr)						
	Predevelopment	**Total baseline**	**Increase factor**	**Anthropogenic baseline**	**Report Card 2013 load**	**Load reduction (%)**
Jacky Jacky	477	4767	1.0	0		
Olive-Pascoe	683	6823	1.0	0		
Lockhart	369	369	1.0	0		
Stewart	255	276	1.1	21		
Normanby	1182	1196	1.0	14		
Jeannie	250	250	1.0	0		
Endeavour	369	400	1.1	31		

Total	**3,585**	**3,652**	**1.0**	**67**		
PSII herbicides (kg/yr)						
	Predevelopment	**Total baseline**	**Increase factor**	**Anthropogenic baseline**	**Report Card 2013 load**	**Load reduction (%)**
Jacky Jacky	0	0	0	0		
Olive-Pascoe	0	0	0	0		
Lockhart	0	0	0	0		
Stewart	0	0	0	0		
Normanby	0	2.6	0	2.6		
Jeannie	0	0	0	0		
Endeavour	0	0	0	0		
Total	**0**	**2.6**	**0**	**2.6**		

Table 38 Export land use loads (t/yr) for Cape York

	TSS	TN	DIN	DON	PN	TP	DOP	DIP	PP
Dryland cropping	999	8	0	3	5	1	0	0	1
Forestry	23,649	294	24	181	89	39	12	6	21
Grazing closed	133,540	1,660	137	1,288	235	162	69	34	59
Grazing open	31,598	439	36	342	61	52	23	11	18
Horticulture	19	0	0	0	0	0	0	0	0
Irrigated cropping	1,157	10	1	4	5	1	0	0	1
Nature conservation	180,106	2,844	293	1,830	721	227	91	46	90
Other	249	3	0	2	1	0	0	0	0
Urban	319	4	0	2	1	1	0	0	0

Table 39 Export land use by area rate (kg/ha/yr) for Cape York

	TSS (t/ha/yr)	TN	DIN	DON	PN	TP	DOP	DIP	PP
Dryland cropping	43	4.1	0.2	1.3	2.7	0.7	0.0	0.1	0.6
Forestry	1,028	2.5	0.2	1.5	0.7	0.3	0.1	0.1	0.2
Grazing closed	5,806	0.9	0.1	0.7	0.1	0.1	0.0	0.0	0.0
Grazing open	1,374	1.3	0.1	1.0	0.2	0.2	0.1	0.0	0.1
Horticulture	1	5.4	0.4	3.4	1.6	0.7	0.2	0.1	0.4
Irrigated cropping	50	3.3	0.2	1.4	1.7	0.5	0.0	0.1	0.4
Nature conservation	7,831	1.5	0.2	1.0	0.4	0.1	0.0	0.0	0.0
Other	11	3.0	0.2	1.8	0.9	0.4	0.1	0.1	0.2
Urban	14	4.7	0.4	2.9	1.4	0.6	0.2	0.1	0.3

Appendix G – Report Card 2010 notes and results

The total baseline load figures changed since the production of Report Card 2010. The reasons for this are:

- In Report Card 2010, a standard ASRIS k-factor layer was used. A k-factor specifically developed for CY was used in Report Cards 2011–2013.
- The indirect effects of grazing management on gullies and streambanks are not considered in Report Card 2010.

In Table 40 below the constituent loads for each scenario as part of Report Card 2010 are presented for reference. It is recommended that the Report Cards 2012–2013 total baseline values are used when referencing on Source Catchments loads.

Table 40 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)**
Predevelopment load	265	4,964	487	3,585	892	352	76	152	124
Total baseline load	495	5,412	492	3,652	1,269	526	98	195	232
Anthropogenic baseline load	229	449	5	67	376	174	22	43	108
Report Card 2010 load	492	5,405	492	3,652	1,262	523	98	195	229
Load reduction (%)	1.3	1.6	0	0	1.9	1.7	0	0	2.8

Appendix H – Report Card 2011 notes and results

The total baseline load figures changed between Report Card 2010 and Report Card 2011. The reasons for this are:

- In Report Card 2010, a standard ASRIS k-factor layer was used. The layer developed for Report Card 2011 accounts for rock fragments on the soil surface and as such, reduces the amount of erosion occurring, and therefore reduces the fine sediment load (and in conjunction the particulate nutrient load)
- The indirect effects of grazing management on gullies and streambanks are also considered in Report Card 2011. This takes effect with regard to the gully management factor, and the streambank erosion coefficient, as described in the Methods section of this report. This data was not available for Report Card 2010
- Between Report Card 2010 and Report Card 2011 model runs, the HowLeaky output time series for cropping land uses were also updated. The main difference between the runs was that the Report Card 2011 HowLeaky runs reverted to the curve number function algorithm from the old CREAMS modelling, and as such reduced the erosion/runoff potential
- The predevelopment load also changed between Report Card 2010 and Report Card 2011 due solely to the inclusion of the improved k-factor layer in Report Card 2011 model runs.

In Table 41 the Report Card 2011 predevelopment, baseline and management change loads are presented for reference. It is recommended that the Report Cards 2012–2013 baseline values are used when referencing this work, and not the values in the table below, due to the improvements to the model described above.

Table 41 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)
Predevelopment load	249	4,931	487	3,585	860	345	76	152	117
Total baseline load	428	5,272	492	3,652	1,128	492	98	195	198
Anthropogenic baseline load	179	340	5	67	268	147	22	43	82
Report Card 2011 load	421	5,257	492	3,652	1,113	486	98	43	192
Load reduction (%)	4	4.3	0	0	5.5	3.8	0	0	6.9

Appendix I – Report Card 2012 notes and results

The total baseline load figures changed between Report Card 2011and Report Cards 2012–2013. The reasons for this are:

- A change to the N and P particulate enrichment ratios to bring them in line with other GBR NRM regions (P to 5, N to 3). This had the effect of increasing the particulate P load between Report Card 2011 and Report Card 2012, and decreasing the particulate N load between Report Card 2011 and Report Card 2012
- Data became available between Report Card 2011 and Report Cards 2012–2013 regarding investment in riparian fencing (direct effect on streambank erosion). This impacted the load reductions in Report Card 2012 and Report Card 2013, as this data was not available for Report Card 2010 and Report Card 2011.

The predevelopment scenario was also updated during the Report Card 2012 modelling period to reflect the changes described to the particulate nutrient enrichment ratios described above. This had the effect of changing the anthropogenic baseline load for PP and PN for Report Card 2012 and Report Card 2013.

Table 42 Report Card 2012 predevelopment, baseline and management change results

Note, these are the same as the total baseline loads presented in the results of this report

	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)
Predevelopment	249	4,910	487	3,585	838	353	76	152	125
Total baseline load	429	5,173	492	3,652	1,030	531	98	195	238
Anthropogenic baseline load	180	264	5	67	191	178	22	43	113
Report Card 2012 load	415	5,160	492	3,652	1,017	522	98	195	229
Load reduction (%)	7.5	4.9	0	0	6.8	5	0	0	7.9