Reef Water Quality Protection Plan 2013

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

Wet Tropics 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 Wet Tropics (WT) NRM region modelled load reductions resulting from improved management practices for sediment, nutrients and herbicides. The report outlines the progress made towards Reef Plan 2009 water quality targets from the baseline year 2008–2009 for four reporting periods: 2008–2010, 2010–2011, 2011–2012 and 2012–2013 (Report Cards 2010–2013).

The WT is one of six NRM regions adjacent to the GBR and is approximately 5% (21,722 km^2) of the total GBR catchment area (423,134 km^2). Land use is characterised by nature conservation (including forestry) occupying 51% and grazing (including dairy) covering 33% of the total area, with intensive agriculture covering 10% of the WT area. The region is comprised of eight drainage basins: Daintree, Mossman, Barron, Mulgrave-Russell, Johnstone, Tully, Murray and the Herbert. Previous studies have highlighted that the WT is a high risk to reef ecosystems due to herbicides and dissolved inorganic nitrogen (DIN) runoff from agriculture, particularly sugarcane.

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, 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 sugarcane and grazing. 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 resulting from improved grazing management practices. An Event Mean Concentration (EMC) approach was used to calculate loads for 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-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 discharges. 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 17 of the 21 gauges (80%) having monthly NSE values >0.8 and 90% of modelled flow at gauges had total runoff volumes within 20% of observed flows. Most were under predicting. The Wet Tropics average annual modelled flow (1986–2009) was 21 million ML, which accounts for 33% of the total GBR average annual flow. Of the six GBR regions, the WT had the highest runoff per unit area.

The modelled WT total baseline load for total suspended sediment (TSS) was 1,219 kt/yr and was 14% of the GBR export load (Table 1). The largest contributor of the TSS load was the Herbert Basin (38%) and there was a 3-fold increase from predevelopment loads. The WT total nitrogen (TN) load was 12,151 t/yr or 33% of the GBR export load and there was a 2-fold increase in TN from predevelopment loads. WT DIN was 37% (4,437 t/yr) of the WT TN load and the WT DIN load was 42% of the GBR DIN load. The highest WT contributor of DIN was the Johnstone Basin (31% of the total WT load). The WT total phosphorus (TP) load was 1,656 t/yr or 26% of GBR load and there was a 3-fold increase in TP from predevelopment loads. Particulate phosphorus (PP) accounted for the majority of the WT TP load (78%) and the WT PP load was 29% of the GBR PP load. The highest contributor of PP was the Johnstone Basin (35% of the WT load). The photosystem-II (PSII) inhibiting herbicides total load was 8,596 kg/yr or 51% of the GBR export load. The highest WT contributor of PSIIs was the Herbert Basin (28% of the total WT load), followed by the Johnstone Basin at (22% of the total WT load).

By land use, grazing (including dairy) was the biggest source of TSS at 247 kt/yr or 32% of the total export load, followed by sugarcane at 29% of the total load. Sugarcane and nature conservation contributed the largest total baseline TN loads, 33% and 28% respectively with sugarcane the greatest contributor of DIN (41% of the total DIN load). For TP, sugarcane and grazing were the highest contributors, 30% and 27% respectively of the total load. PP was similar with sugarcane contributing 33% and grazing 31% of the total load. Sugarcane generated the biggest proportion of PSII herbicides, 96% of the total load, with the remaining 4% from cropping.

Bananas contributed a small portion to the total TSS export load, but exhibited the largest per unit area of TSS to export, 1.8 t/ha/yr, followed by sugarcane, 1.2 t/ha/yr and horticulture, 1.1 t/ha/yr.

Similar per unit area relationships for bananas and sugarcane were seen for TN (25 kg/ha/yr and 22 kg/ha/yr) and for TP (3.1 kg/ha/yr and 2.7 kg/ha/yr). Sugarcane exported 46 g/ha/yr of PSII herbicides, followed by cropping at 23 g/ha/yr.

Table 1 Summary of Wet Tropics total baseline load, contribution to the GBR and load reduction due to improved management practice adoption (2008–2013)

	TSS (kt/yr)	TN (t/yr)	DIN (t/yr)	DON (t/yr)	PN (t/yr)	TP (t/yr)	DIP (t/yr)	DOP (t/yr)	PP (t/yr)	PSIIs (kg/yr)
Total baseline load	1,219	12,151	4,437	3,870	3,844	1,656	228	130	1,297	8,596
Anthropogenic baseline load	773	6,365	2,023	2,035	2,307	1,013	90	27	896	8,596
Load reduction (2008–2013) (%)	12.5	8.0	12.7	N/A*	11.1	18.7	9.1*	7.6*	20.0	25.9

*DON was not modelled for management changes

Across the GBR for Report Card 2013 management improvements, TSS export loads were reduced by 11%, TN and TP by 10% and 13% respectively. The PSII herbicide export load had the greatest reduction of all constituents at 28%. The modelling showed that 'very good' progress was made towards reaching the 2020 target of a 20% reduction in fine sediment load from the GBR. However, the target of a 50% reduction by 2013 as outlined in Reef Plan 2009 for nutrients and herbicides has not been met. The timeline for meeting this target has been revised in Reef Plan 2013, and Report Card 2014 and beyond will report against this. For Report Card 2013, there has been a total WT reduction in TSS and DIN loads of 13% each and PSII herbicides at 26%. The TSS reduction was mostly due to riparian fencing in grazing and improvements in sugarcane such as controlled traffic farming and a cowpea cover crop in the fallow. For DIN and PSIIs the reduction was solely due to improvements in sugarcane. The nutrient improvements in sugarcane were primarily a result of improved management practice adoption using the 'Six Easy Steps' nutrient management program and for PSIIs, the improvement was mostly due to the reduction of residual herbicides for knockdown herbicides.

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 simulated streamflow volumes that showed good agreement with gauging station data, particularly at long-term average annual and yearly time-steps. At shorter time scales (weeks to days) the model tended to underestimate peak discharge and overestimate low flow. This resulted in an under prediction in modelled flows (total volume difference). Future work will explore the potential to recalibrate the model with greater emphasis on simulating high flows. Overall, the current hydrological model performs very well for sites with good historical flow records. These results suggested that reasonable confidence could be given to modelled flow results for streams and catchments in the Wet Tropics region where no gauged flow data exists.

In general, the modelled average annual loads of constituents are lower than most previous modelled estimates for the WT region. This is due to the different approaches used to derive the loads between studies and in this study, improvements made to constituent generation and transport modelling methodologies and utilising the most recent data sets. Long-term loads generated using a Flow Range Concentration Estimator (FRCE) method were calculated for five WT gauges and the average annual loads generated by Source Catchments were within the likely range of FRCE values. Modelled values compared to FRCE values at a monthly time-step, for TSS, TN, DIN, TP and DIP (dissolved inorganic phosphorus) at the five gauges, were mostly ranked in the best category of 'very good'. Modelled loads and loads estimated from the GBR Catchment Loads Monitoring Program (GBRCLMP) are also generally in close agreement. Average modelled constituent loads for TSS, TN, DIN, TP and DIP were within ±60% of GBRCLMP loads for the 2006–2010 period. Most modelled loads were lower than load estimates from measured data. This is most likely due to the under prediction in hydrology.

Major recommendations for enhanced model prediction include:

- Recalibration of the hydrological model to better simulate maximum discharge
- Paddock scale modelling of bananas using the paddock model HowLeaky
- Improved spatial allocation of specific management practice information and an updated ABCD management framework
- Incorporation of seasonal rather than annual dry season cover data inputs for hillslope erosion prediction
- Improved gully and streambank erosion input data
- Better representation of sediment sources from land uses modelled using EMCs

The current modelling framework is flexible, innovative and is 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:

- Natural Resource Management groups, governments and other agencies now have a new modelling tool to assess various climate and management change scenarios on a consistent platform for the entire GBR catchment.
- Methods have been developed to implement and calibrate an underlying hydrological model that produced reliable flow simulations for gauged sites and increased confidence in modelled flows for ungauged sites.
- Daily time-step capabilities and high resolution source catchment areas allowed for modelled flow volumes and loads of constituents to be reported at catchment scales 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
ASRIS	Australian Soils Resource Information System
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 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 (where freshwater streams or rivers join into an estuary or the sea
ERS	Environment and Resource Sciences
FPC	Foliage Projected Cover
FRCE	Flow Range Concentration Estimator – a modified Beale ratio method used to calculate average annual loads from monitored data.
FU	Functional unit
GBR	Great Barrier Reef
GBRCMLP	Great Barrier Reef Catchment Loads Monitoring Program (supersedes GBRI5)
HowLeaky	Water balance and crop growth model based on PERFECT
HRU	Hydrological response unit

NLWRA	National Land and Water Resources Audit
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
P2R	Paddock to Reef Integrated Monitoring, Modelling and Reporting Program
PET	Potential Evapotranspiration
PSII herbicides	Photosystem-II (PSII) inhibiting herbicides – ametryn, atrazine, diuron, hexazinone and tebuthiuron
QLUMP	Queensland Land use Mapping Project
Quickflow	Overland runoff exiting the land surface (entering the stream)
Reef Rescue	An ongoing and key component of Caring for our Country. Reef Rescue represents a coordinated approach to environmental management in Australia and is the single largest commitment ever made to address the threats of declining water quality and climate change to the Great Barrier Reef World Heritage Area.
Report Cards 2010–2013	Annual reporting approach communicating outputs of Reef Plan/Paddock to Reef (P2R) Program
RUSLE	Revised Universal Soil Loss Equation
SedNet	Catchment model that constructs sediment and nutrient (phosphorus and nitrogen) budgets for regional scale river networks (3,000–1,000,000 km^2) to identify patterns in the material fluxes
Six Easy Steps program	Integrated sugarcane nutrient management tool that enables the adoption of best practice nutrient management on-farm. The Six Easy Steps program forms part of the nutrient management initiative involving BSES limited, CSR Ltd and the Queensland Department of Environment and Resource Management (DERM). It is supported by CANEGROWERS and receives funding from Sugar Research and Development corporation (SRDC), Queensland Primary Industries and Fisheries (PI&F) and the Australian Department of the Environment, Water, Heritage and the Arts.
Slowflow	Subsurface seepage and low energy overland flow otherwise known as baseflow. The seepage could be related to ground water interaction, but this is not an explicit design assumption in the GBR modelling
STM	Short-term Modelling project
WT	Wet Tropics

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/ha/yr	tonnes per hectare per year
µg/L	micrograms per litre

Full list of Technical Reports in this series

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

McCloskey, G.L., Ellis, R., Waters, D.K., Carroll, C. (2014) *Modelling reductions of pollutant loads due to improved management practices in the Great Barrier Reef catchments – Cape York NRM Region, Technical Report, Volume 2,* Queensland Department of Natural Resources and Mines. Cairns, 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 spatially and temporally variable cover over the 23 year modelling period, rather than a single static cover factor for a particular land use.
- Representation of identifiable hillslope, gully and streambank erosion processes, with the ability to also incorporate 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.
- The predevelopment land use scenario includes all storages, weirs and water extractions represented in the current model, with no change to the current hydrology. Hence, a change to water quality represented in the model is due solely to a change in land management practice.
- Paddock model runs used to populate the catchment models represent ‘typical’ management practices and do not reflect the actual array of management practices being used within the GBR catchments.
- Application rates of herbicides used to populate the paddock models were derived through consultation with relevant industry groups and stakeholders.
- Practice adoption areas represented in the model are applied at the spatial scale of the data supplied by regional bodies, which currently is not spatially explicit for all areas. Where it is not spatially explicit, estimates of A, B, C and D areas (where A is cutting edge and D is unacceptable) are averaged across catchment areas. Depending on the availability of useful investment data, there may be instances where a load reduction is reported for a particular region or subcatchment that in reality has had no investment in land management improvement. Future programs aim to capture and report spatially explicit management change data.
- Water quality improvements from the baseline for the horticulture, dairy, banana and cotton industries are currently not modelled due to a lack of management practice data and/or limited experimental data on which to base load reductions. Banana areas are defined in the WT model, but management changes are not provided. Dissolved inorganic nitrogen (DIN) reductions are not being modelled in the cropping system, as there is no DIN model available currently in HowLeaky.

- For land uses that require spatially variable data inputs for pollutant generation models (USLE based estimates of hillslope erosion and SedNet-style gully erosion), data pre-processing captures the relevant spatially variable characteristics using the specific 'footprint' of each land use within each subcatchment. 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 slowflow (baseflow) and 'dry weather concentrations' (DWC) of constituents. However, these loads are not subject to management effects.
- Deposition of fine sediment and particulate nutrients is modelled on floodplains and in storages. No attempt to include in-stream deposition/re-entrainment of fine sediment and particulate nutrients has been undertaken at this point.
- It is important to note these are modelled average annual pollutant load reductions not measured loads and are based on practice adoption data provided by regional NRM groups and industry. Results from this modelling project are therefore indicative of the likely (theoretical) effects of investment in changed land management practices for a given scenario rather than a measured (empirical) reduction in load.

1 Introduction

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

Over the past 150 years, Great Barrier Reef (GBR) basins 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 2013a). A set of water quality and management practice targets are outlined for basins 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 basin 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 basin can be highly variable from year to year because of these factors. Therefore, the P2R Program used modelling validated against monitoring data to report on progress towards Reef Plan 2009 targets.

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

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

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

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

The water quality targets were set for the whole GBR and there are six contributing NRM regions: Cape York, Wet Tropics, Burdekin, Mackay Whitsunday, Fitzroy and Burnett Mary. This document outlines the Wet Tropics (WT) NRM catchment modelling methodology and results used to report on the constituent loads entering the GBR for the total baseline, predevelopment, anthropogenic baseline (total baseline minus predevelopment) and post adoption of improved practices from the eight regional basins: Daintree, Mossman, Barron, Mulgrave-Russell, Johnstone, Tully, Murray and Herbert.

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 basins. 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, Cogle, Carroll & Sherman 2006, McKergow et al. 2005a, McKergow et al. 2005b). 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. From that study, the WT estimated total suspended sediment (TSS) load was 1,400 kt/yr, total nitrogen (TN) load was 16,000 t/yr, total phosphorus (TP) load was 2,000 t/yr; representing a respective 4.7, 3.6 and 4-fold increase in constituent loads from predevelopment conditions (Kroon et al. 2012). The estimated total photosystem-II (PSII) inhibiting herbicides load was 12,000 kg/yr, with no increase factor since predevelopment conditions, as herbicides are not a naturally occurring compound (Kroon et al. 2012).

When considering the modelling approach required for the P2R Program, there was no ‘off the shelf’ modelling framework that could meet all of the modelling requirements. SedNet alone could not provide the finer resolution time-step 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 the integration of the best available data sources and landscape process understanding into the catchment model. Purpose built routines were developed that enabled representations of processes such as; the effects of temporally and spatially variable ground cover on soil erosion, the aggregation of deterministic crop model outputs to be directly imported into the catchment model and the incorporation of SedNet gully and streambank erosion algorithms (Ellis & Searle 2014).

1.3 Wet Tropics 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 and 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) and Event Mean Concentration (EMC) 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 were all incorporated into the WT model. Model validation was done using water quality monitoring information from the WT region. The small coastal catchments were also included into the WT model to ensure the total area contributing loads to the GBR were captured in the model. For a broad GBR overview of the modelling approach, refer to Waters & 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 Wet Tropics (WT) NRM region has an approximate catchment area of 21,722 km^2 and is approximately 5% of the total GBR catchment area (423,134 km^2). There are eight Australian Water Resources Council basins that comprise the WT region (ANRA 2002). From north to south they are Daintree, Mossman, Barron, Mulgrave-Russell, Johnstone, Tully, Murray and Herbert (Figure 1). The WT NRM region includes 91% of the Wet Tropics of Queensland World Heritage Area and is part of the Great Barrier Reef World Heritage Area and Great Barrier Reef Marine Park. The Herbert Basin covers the largest area in the region (45% of the total area), with the Daintree, Barron, Mulgrave-Russell and Johnstone basins all having similar areas (9-11% of the total area) (Table 2).

Table 2 WT basins and modelled area

Basin name	Area (km^2)	Area (%)
Daintree	2,107	10
Mossman	479	2
Barron	2,189	10
Mulgrave-Russell	1,979	9
Johnstone	2,326	11
Tully	1,685	8
Murray	1,115	5
Herbert	9,842	45
Total	**21,722**	**100**

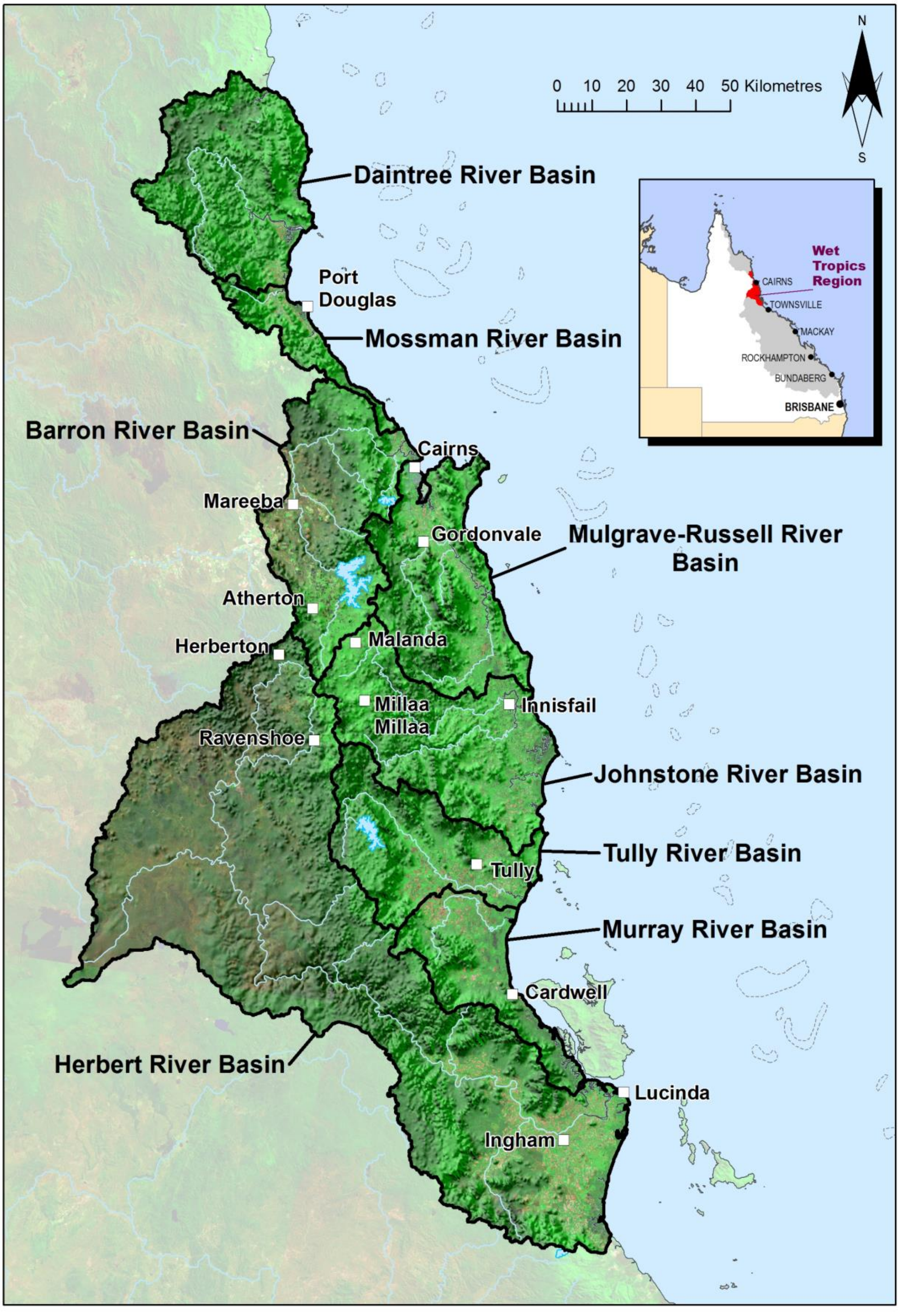

Figure 1 Wet Tropics NRM region and eight reporting basins

2.1 Climate

The WT NRM region has two distinct climatic seasons (wet and dry), with the majority of rainfall falling in the wet season (December to March). Rainfall is dominated by major events such as rain depressions, monsoons and cyclones. Rainfall for the WT NRM region averages 1,580 mm, with an approximate range of 500–4,500 mm (Figure 2). There is a strong rainfall gradient westwards from the coast, partly due to orographic effects of the coastal mountain ranges, with average annual rainfall of approximately 3,000 mm on the coastal fringe declining to 500 mm at the western edge of the WT NRM region. The wettest meteorological station in Australia is located on Mt Bellenden Ker (in the Mulgrave-Russell Basin) and receives an average annual rainfall of 8,000 mm (Queensland Government 2011). Both the Herbert and Barron basins have significant inland areas of relatively low rainfall (<1000 mm per annum), as well as wetter coastal fringes.

Temperatures are fairly uniform throughout the year in the region, typically ranging from a minimum of 22˚C on the coast down to 10˚ inland and maximums from 29˚ to 31˚C. Average coastal humidity reaches 78% in summer but often rises into the high nineties. The tablelands and uplands are cooler, with mean daily temperatures of between 17˚C to 28˚C in summer and 9˚C and 22˚C in winter. Further west temperatures increase to between 21˚C and 35˚C in summer and 10˚C and 29˚C in winter (McDonald & Weston 2004).

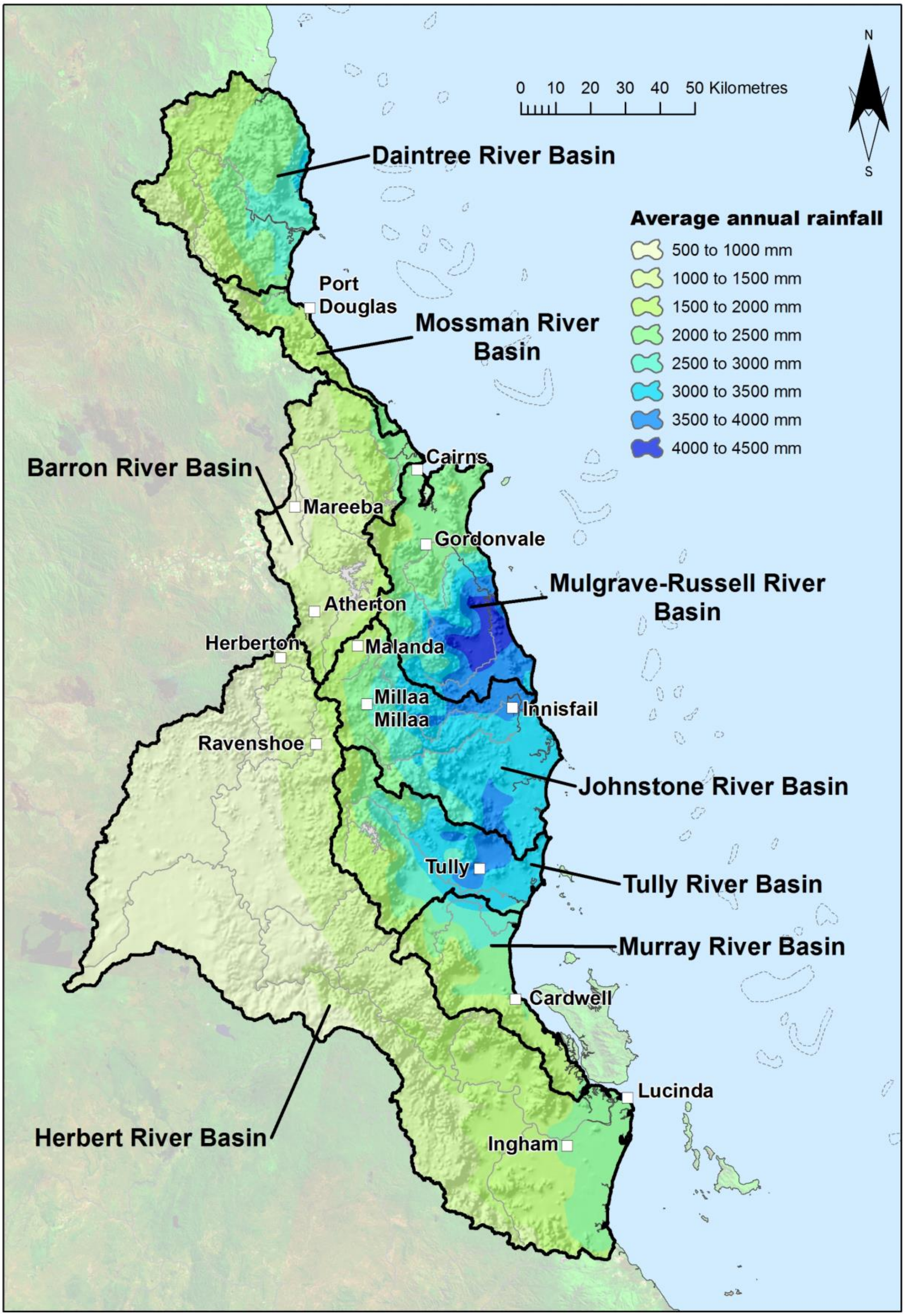

Figure 2 Spatial distribution of WT average annual rainfall

2.2 Hydrology

The WT NRM region is characterised by high relief mountains located close to the coast resulting in a narrow coastal plain (McDonald & Weston 2004). These features, combined with high rainfall results in rivers with large discharges and high streamflow velocities (DEH & DNR 1999). For the majority of WT basins, more than half of the rainfall leaves as runoff from the soil surface, mostly during the large wet season events. Rainfall throughout the year and ground water input result in perennial flows in the largest WT NRM rivers. In the smaller catchments such as the Tully, several flood events (of varying size) usually occur within a wet season. The time between rainfall and runoff is short in the Tully as large storms can occur over the whole basin and the distance from headwaters to the coast is small (Furnas 2003). In contrast, the larger drier catchment such as the Herbert, most runoff occurs as a single wet season flood, but a major flood may not occur every year (Furnas 2003).

2.3 Geomorphology, geology and soils

The WT NRM region covers the Peninsula and Burdekin Provinces of the Eastern uplands division (McDonald & Weston 2004). One of the defining features of the WT NRM region is the mountainous belt that runs close to the coast resulting in a very narrow coastal floodplain. Tablelands and ranges are located in the west on the Great Escarpment and these areas contain large outcrops of basalt. The geology of the mountainous regions consists mostly of granite with some acid volcanic and metamorphic rocks. The presence of the more erodible metamorphics has resulted in deep incised valleys and has accentuated the topographic relief (McDonald & Weston 2004). Quaternary marine deposits, coastal dunes, alluvial plains and piedmont fans occur in the coastal floodplain (Goosem, Morgan & Kemp 1999). The three dominant soil types found in the WT NRM region are dermosols (including non-sodic chromosols/kurosols/kandosols), ferrosols and rudosols/tenosols. Dermosols are the most widespread soils in the region and occur mostly in the humid coastal area, forming on a wide range of geologies and terrain and are commonly quite fertile. Kandosols generally have low fertility and are susceptible to erosion and are, mostly located in the upper Herbert River catchment. Ferrosols are the 'red soils' of the Atherton tablelands with exceptional physical properties that make them prized for agriculture, particularly sugarcane, dairying and horticulture. Rudosols and tenosols soils occur in the upper Herbert on many types of parent material, with quartz-rich sandstones and siliceous volcanic rock the most common and are used mainly for grazing.

2.4 Land use

The most recent land use dataset from the Queensland Land Use Mapping Project (QLUMP) was used to define land use, which was mapped using 2009 imagery (DSITIA 2012a). Land use in the WT NRM region is dominated by nature conservation and plantation forestry (51% of WT area), followed by grazing (33% of WT area) and intensive agricultural industries (sugarcane, horticulture, bananas and cropping) (10% of WT area) of which, sugarcane was the dominant crop (8% of WT area) (DSITIA 2012a) (Figure 3 and Table 3). Grazing is the major land use in the western part of the region, where the climate is generally drier, but only a minor part of the coastal lowlands land use composition. In coastal areas, the main crops are sugarcane and bananas. Nature conservation is generally restricted to the mountainous regions. At the GBR scale, the WT had the highest proportion of sugarcane at 33% of the total GBR sugarcane area, followed by the Mackay Whitsunday area at 31% and the Burdekin at 20%. The WT region had the second highest proportion of horticulture (including bananas) at 32%, with the Burnett Mary region at 39%. Grazing and cropping (not sugarcane) in the WT only accounted for 2% and 1% respectively of the total GBR area. Land use area by basin is presented in Table 39 (Appendix E).

Between 1999 and 2009, there were some changes to land use in the WT NRM region. The area of land use change, (relative to the change in intensity at the Australian Collaborative Land Use and Management Program, Secondary Level) was ~129,000 ha or 6% of WT NRM region (DSITIA 2012c). Of the total change, 70% went from more intense to less intense and the remaining 30% went to more intense from less intense. Almost 50% of the total change in land use area went from minimal use and management resource protection, into protected areas such as National Parks and protected area estates. The next biggest change (13%) was a shift into production and plantation forestry from a mixture of beef grazing native vegetation and sugarcane (DSITIA 2012c).

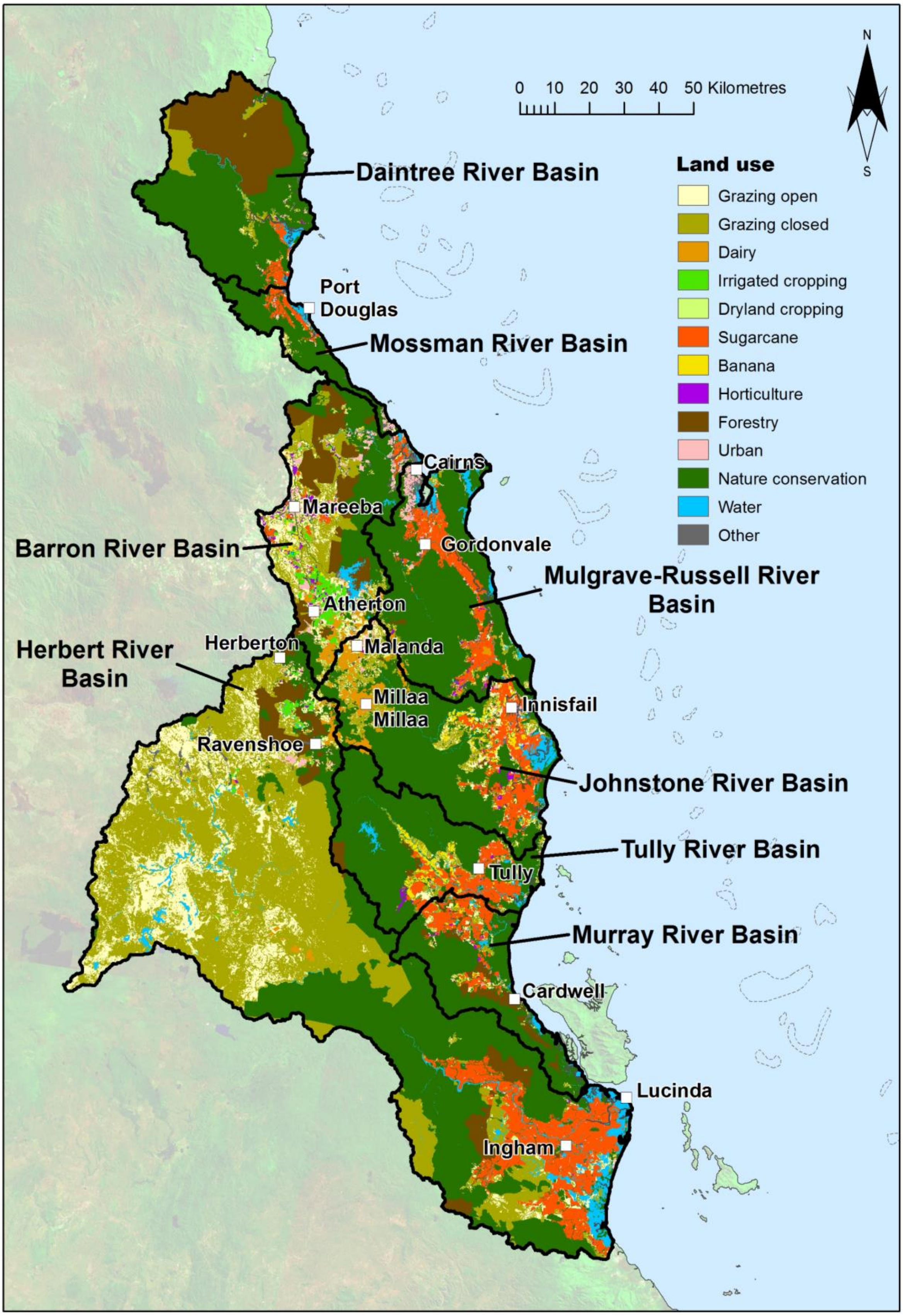

Figure 3 Wet Tropics NRM region land use classification

Table 3 Wet Tropics NRM region land use area

Land use	Area (km^2)	Area (%)
Bananas	156	0.7
Dairy	300	1.4
Dryland cropping	8	<0.05
Forestry	1,643	7.5
Horticulture	88	0.4
Irrigated cropping	142	0.7
Nature conservation	9,468	43.5
Grazing (closed)	5,120	23.6
Grazing (open)	1,830	8.4
Other	142	0.7
Sugarcane	1,797	8.3
Urban	314	1.4
Water	714	3.3

2.5 Water quality issues

The inner-shelf and mid-shelf reefs of the WT NRM region are exposed regularly (one to three times per year) to a mixture of land sourced nutrients, herbicides and sediments (Devlin & Schaffelke 2009). Fertilised agricultural areas are hotspots for nutrient and herbicide loss, with sediment fluxes less of a concern due to high vegetation cover maintained in the region throughout the year (Brodie et al. 2013). In the wet season, the WT can produce flood plumes that extend far into the GBR lagoon. The inshore area has high exposure to DIN and PSII herbicides (Devlin et al. 2012).

The relative risk of reef pollutants to the GBR from agricultural land uses was recently assessed by Waterhouse et al. (2012). They classified the WT NRM region as a high risk for PSII herbicides and DIN. Herbicides and anthropogenic DIN are mainly sourced from the dominant land use of sugarcane followed by bananas. The remaining pollutants derived from the WT such as DON, DIP, DOP, particulate nutrients and TSS are considered a minor risk to the GBR.

Sugarcane (1,797 km^2) and bananas (156 km^2) are the major intensive crops grown in the region with high concentrations and loads of N reported from both crops in streams and groundwater in the Johnstone and Tully basins (Armour, Hateley & Pitt 2009, Hunter & Walton 2008, Rasiah, Armour & Cogle 2005, Rasiah et al. 2010, Thorburn et al. 2003). Most DIN (primarily nitrate) found in streams that drain cropping areas is considered to come from fertiliser, with 90% of DIN attributed to this source in the Tully and Murray basins (Armour, Hateley & Pitt 2007, Mitchell et al. 2006). The herbicides that are currently monitored in freshwater systems include those PSII herbicides that are mostly used in sugarcane land use. A recent review of herbicides loads across the GBR ranked the WT as contributing the highest load of PSII herbicides out of the six GBR regions (Kroon et al. 2012). The extensive grazing areas across the GBR also contribute to the pollutant load to the reef, in particular suspended sediment, but are of less concern in the WT NRM region.

An emerging water quality issue is the number of newer herbicides that are being used in agricultural industries that are either not yet monitored, as the analysis methodology has not yet been established, or they are appearing in the monitoring data and need to be considered for modelling. The ecotoxicology of these products is usually poorly understood. Rapid coastal development is another potential issue. Interestingly, there has been a shift in land use over the last 10 years from generally more intense to less intense. The two main changes have been the protection of existing minimal use and managed resource protection into protected areas and a shift into forestry from grazing and sugarcane (DSITIA 2012c). However, some of the forestry has failed and there has been a shift back into sugarcane (J Brodie, 2014, pers. comm.).

Water Quality Improvement Plans (WQIPs) are a part of the 2013 Reef Plan. They are designed to identify the main issues affecting waterways and the marine environment from land-based activities and to identify and prioritise management actions that will halt or reverse the trend of declining water quality within an NRM region. WQIPs have been developed for three individual catchments; Daintree, Barron and Tully and Terrain NRM are working towards a Wet Tropics WQIP. In addition, an urban water management plan is also being developed. Scenarios from this study are being used to inform the Wet Tropics WQIP. For more information about Terrain and WQIPs see http://www.terrain.org.au/Projects/Water-Quality-Improvement-Plan.

3 Methods

The Wet Tropics model was built within the Source Catchments modelling framework. Source Catchments is a water quantity and quality modelling framework that has been developed by eWater Ltd. This framework allows users to simulate how catchment and climate variables (such as rainfall, land use, management practice and vegetation) affect runoff and constituents, by integrating a range of models, data and knowledge. Source Catchments supersedes the E2 and WaterCAST modelling frameworks (eWater Ltd 2012). Model input data is provided in Appendix E. A summary of the GBR Source Catchments modelling is 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 4). Subcatchments are the basic spatial unit in Source Catchments. A subcatchment is further delineated into 'functional units' (FUs) based on common hydrologic response or land use (eWater Ltd 2013). In the case of the GBR Source Catchments framework, FUs were defined as land use categories.

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

- Runoff generation
- Constituent generation

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

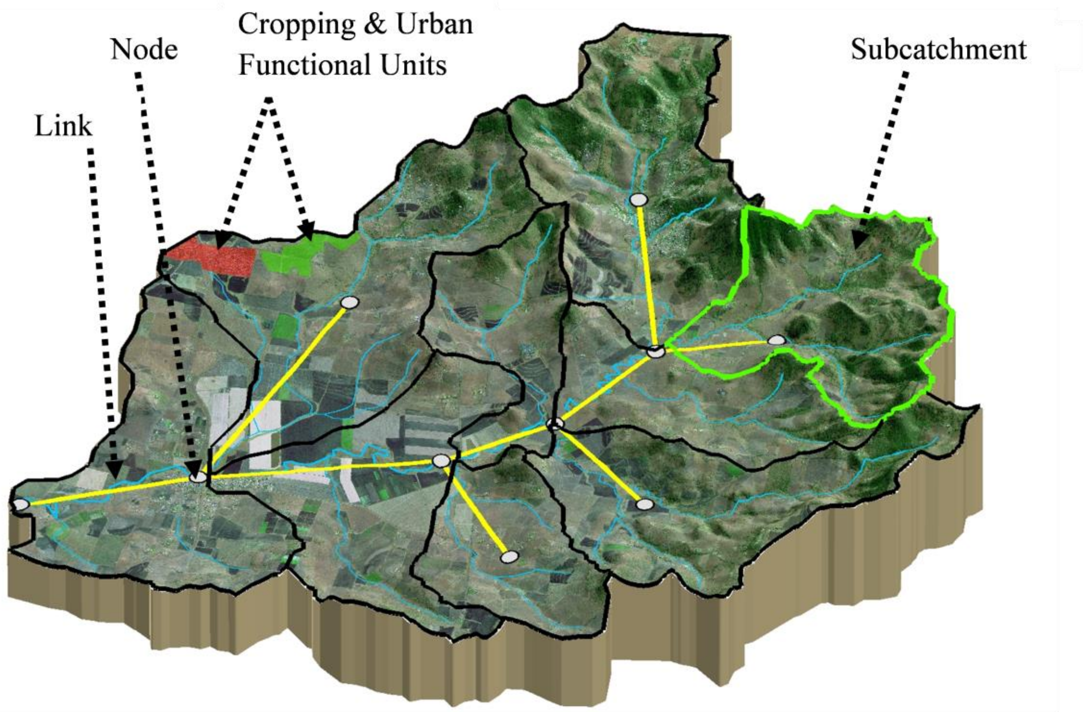

Figure 4 Example of a functional unit and node-link network generated in Source Catchments. These components represent the subcatchment and stream network

3.1.1 Land use functional units

The original detailed QLUMP (DSITIA 2012a) categories were reclassified into 13 major land uses (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 grazing was defined with Foliage Projected Cover (FPC), of >= 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 hydrology calibration and to utilise separate C-factor relationships for these grazing systems (see section 3.3.1). Banana growing areas were separated from horticulture land use for the Wet Tropics NRM region using the same imagery used to create the 2009 land use mapping. This was undertaken to enable the load contribution for bananas to be identified separately from the remaining horticultural industries given their high contribution per unit area. The area of sugarcane supplied by industry (GHD 2010) differed from the 2009 QLUMP sugarcane area. This was taken into account and is described in the sugarcane constituent generation section 3.3.2. Any given land use within a subcatchment is aggregated and represented as a single entity in the model hence is not represented spatially within a subcatchment. Customisation of the modelling software and specific data pre-processing techniques has provided a way to capture the effects of spatial distribution of land uses within each subcatchment.

3.1.2 Subcatchment generation

The Wet Tropics Source Catchments model encompasses eight drainage basins (Figure 1 and Table 2). These basins were delineated into smaller subcatchments using a Digital Elevation Model (DEM). A 100 metre, hydrologically enforced DEM and 30 km^2 drainage threshold was used to identify the major stream network and contributing subcatchments. In this process, some flat coastal areas were not captured. In order to rectify this, the flat coastal areas not captured were manually added to the DEM derived subcatchment layer in a GIS environment, based on visual assessment of imagery. The final subcatchment map was then re-imported into Source Catchments. A total of 450 subcatchments (including 33 manually defined low-relief coastal catchments) were generated with an average subcatchment area of 48 km^2 (Figure 5). The addition of these flat coastal areas, some of which were not included in previous catchment models, will improve the overall load estimates to the end-of-system (EOS). An arbitrary node was created in the ocean as an ‘outlet’ node to enable the aggregation of loads for the entire region for reporting purposes. The selection of the most appropriate stream threshold value for subcatchment 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 and available computing resources (Wilkinson, Henderson & Chen 2004).

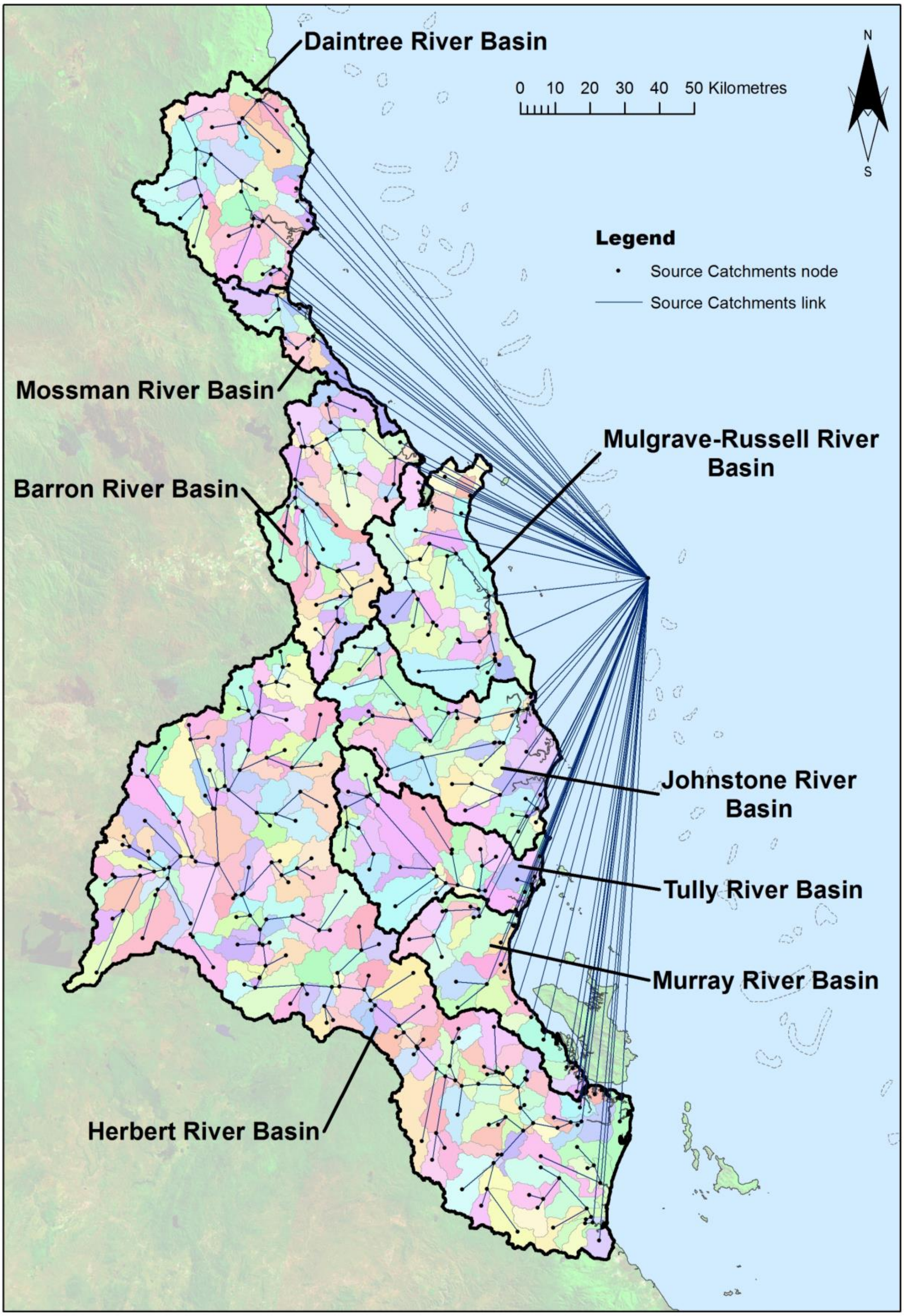

Figure 5 WT subcatchment, node and link network

3.1.3 Runoff generation

Six rainfall-runoff (RR) models were available within Source Catchments. A comparison of the six models concluded that there is little difference between these six models for broad scale application (Vaze et al. 2011). SIMHYD is a catchment scale conceptual RR model that estimates daily streamflow from daily rainfall and areal potential evapotranspiration (PET) data (eWater Ltd 2013). The SIMHYD RR 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 et al. 2009).

Each FU possesses a unique instance of the SIMHYD RR model and constituent generation models (Chiew & Scanlon 2002). Typically, a RR 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, extractions and subcatchment outlets. Links connect nodes and represent streams or storages. A range of models can be applied to links to route or process water and constituents throughout the network (eWater Ltd 2013).

3.1.4 Constituent generation

In the GBR Source Catchments framework, there is the ability to link to external models and/or add your own component models as specific ‘plug-ins’ to customise for particular modelling objectives. This capability was extensively used to incorporate the most appropriate constituent generation models across the GBR (Figure 6). SedNet modelling functionality was 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.

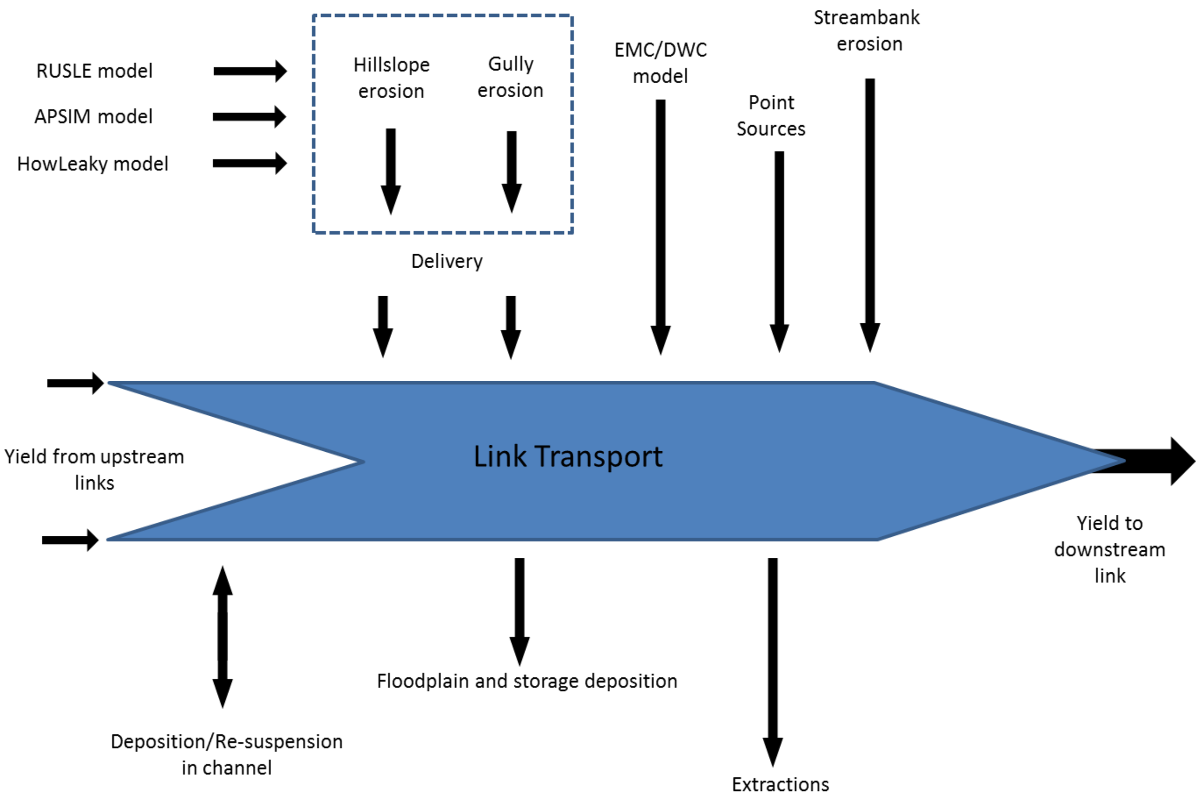

Figure 6 Conceptual diagram of GBR Source Catchments model

The APSIM (Agricultural Production Systems Simulator) model was chosen for modelling sugarcane, particularly for DIN in runoff (Keating et al. 2003). 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.

3.1.5 Climate simulation period

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

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

3.2 Hydrology

Hydrology calibration is a major aspect of constituent load modelling, given that constituent generation is driven by rainfall and runoff. Thus, it was imperative that the hydrology calibration process was rigorous and achieved the best possible results. The calibration process was developed building on previous calibration work in the GBR (Ellis et al. 2009). The SIMHYD RR model was selected as the preferred model. The rationale for selecting SIMHYD is outlined in section 3.1.3. Quickflow (runoff) and slowflow (subsurface seepage and low energy overland flow otherwise known as baseflow) 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 or link models.

3.2.1 PEST calibration

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

A three-part objective function was employed, using log transformed daily flows, monthly flow volumes and flow exceedance curves to achieve an optimum calibration. The monthly flow volume component ensures that modelled volumes match measured volumes over long periods, the exceedance values ensure the flow volumes are proportioned well into slowflow and quickflow 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 WT gauges used in the calibration process. Performance was assessed for the calibration period 1/1/1970–31/3/2010. Most gauges had the complete 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 adequate)
- Monthly NSE (>0.8 adequate)
- Percentage volume difference (±20% adequate)

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 one indicate perfect alignment between simulated and observed values (Chiew & McMahon 1993). The PEST setup, operation and linkage with Source Catchments can be found in Appendix B. Flow duration curves for each of the calibration gauges aided in visually assessing the calibration performance. A selection of flow duration curves is shown in Figure 42 (a–d) and Figure 43 (e–h) (Appendix D).

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. In the Wet Tropics region, 102 gauging stations were initially identified as suitable for PEST calibration, which was reduced to a reasonable number to allow hydrology calibration within the required time period. A subset of 21 gauging stations were identified as suitable for PEST calibration, this was based on the following criteria:

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

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

3.2.3 Rainfall-runoff model parameterisation approach

The SIMHYD RR 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 one (assuming nil impervious areas of significance), therefore making the impervious threshold parameter redundant and fixed. Default SIMHYD and Laurenson flow parameters were used as the starting values. The final set of SIMHYD and Laurenson flow routing parameters used to generate runoff can be found in Table 28 (Appendix C), along with SIMHYD starting parameters and parameter range, Table 27 (Appendix C).

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 (Table 26, Appendix B). 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 (Thornton et al. 2007, Yee Yet & Silburn 2003). Flow routing models were also grouped according to the same regions. FUs, links and nodes continued to operate as discrete units within the Source Catchments structure.

Each gauging station included in the calibration represented its own region and modelled subcatchments were therefore divided into 21 regions. Regions were based on the contributing area to a gauge. Nested gauge (gauged upstream or downstream by other gauges) regions excluded 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). Regionalisation was only implemented via the template and instruction files that PEST assessed. This method of parsimony implies uniformity within, but not between, calibration regions.

After calibration, the 21 parameter sets were applied to the 21 regions (Figure 7) which included the ungauged areas. Ungauged catchments comprised 28% of Wet Tropics NRM area. These are shaded grey in Figure 9 (see section 4.1.1). There are a few gauging stations located within the grey shaded area and were not included during the calibration. For the purposes of the modelling, this area is deemed ungauged.

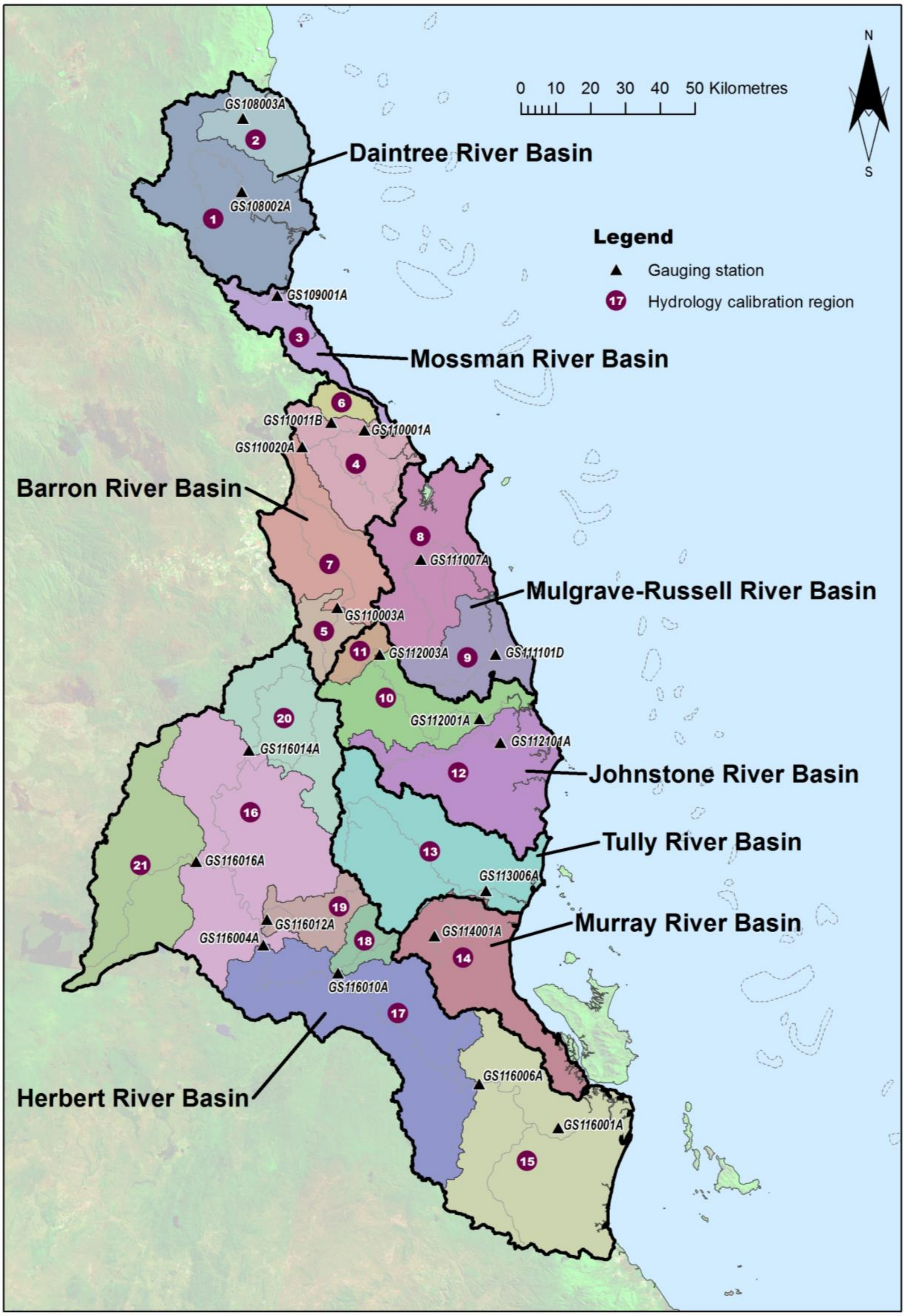

Figure 7 Hydrology calibration regions for Wet Tropics

3.3 Constituent modelling

The key water quality constituents modelled are outlined in Reef Plan and shown in Table 4. Total suspended sediment (TSS) was based on the international particle size fraction classification and is restricted to the <20 µm fraction (National Committee on Soil and Terrain 2009). Fine sediment (<16 µm) is the fraction most likely to reach the Great Barrier Reef lagoon (Scientific Consensus statement, Brodie et al. 2013). The choice of a <20 µm to determine the fine sediment fraction is also consistent with previous SedNet modelling studies, which used a clay percentage layer from the ASRIS database based on the international particle size fraction classification, to calculate particulate nutrient (PN and PP) loads. Moreover, Packett et al. (2009) found that for the in-stream sediment sampled for some subcatchments, and at the Fitzroy River outlet, >95% of the TSS was very fine sediment (<20 µm). With regard to herbicides, Reef Plan focuses on the reduction in loads of herbicides considered 'priority'; atrazine, ametryn, diuron, hexazinone and tebuthiuron. These are Photosystem-II (PSII) inhibiting herbicides, which are applied for residual herbicide control; collectively they are referred to as PSIIs. They are considered priority pollutants due to their extensive use and frequent detection in GBR waterways and in the GBR lagoon (Lewis et al. 2009, Shaw et al. 2010, Smith et al. 2012).

The catchment models were set up to include tebuthiuron as one of the five PSIIs, however due to the availability of application data it was only modelled in the Fitzroy and the Burnett Mary basins. Ametryn was considered but not reported in WT, as it was not part of a typical application profile. The Mackay Whitsunday region was the only area where ametryn was reported as being commonly applied and was modelled along with atrazine. The herbicide application scenarios also include the knockdown herbicides paraquat, glyphosate and 2,4-D, as well as the alternative residual herbicide, metolachlor although they were not required for reporting. It should be noted that many alternative herbicides are in use in the GBR catchment and have not been represented in the current modelling. The focus on reducing the use of the priority 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	
Ametryn, atrazine, diuron, hexazinone, tebuthiuron	

The most appropriate paddock scale model outputs were used to generate data for Source Catchments. These were APSIM for sugarcane, with the HowLeaky model for pesticides and phosphorus, HowLeaky for cropping, RUSLE for grazing and EMC/DWC models for the remainder. A detailed summary of the models used for individual constituents for sugarcane, cropping and grazing is shown in Table 5. In addition, SedNet functionality was incorporated to model the contribution of gully and streambank erosion and floodplain deposition processes. A detailed description of the models used at the FU and link scale can be found in Ellis and Searle (2014) and Shaw & Silburn (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 DERM/DSITIA specifically for this project. The plug-in provided a suite of constituent generation and in-stream processing models that simulated 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 had a variety of data analysis, parameterisation and reporting tools. These tools are an important addition, as the complexity of a Source Catchments model (both spatially and temporally) representing SedNet processes across many landscapes makes it difficult to adequately populate and communicate in a traditional water quality modelling sense. The following sections describe the Source Catchments Dynamic SedNet model configuration. The description includes:

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

3.3.1 Grazing constituent generation

Rainfall and ground cover are two dominant factors affecting hillslope runoff and erosion in the GBR. Previous studies reported that gully erosion is also a significant source of sediment to the GBR (Dougall et al. 2009, Wilkinson et al. 2005, Wilkinson et al. in press). 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, 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 (Lu et al. 2001, Renard et al. 1997, Renard & Ferreira 1993) (Equation 1). This modified version is based on the Revised Universal Soil Loss Equation and is referred to as the RUSLE in this document (Lu et al. 2001, Renard & Ferreira 1993). The RUSLE model was chosen due to its proven ability to provide reasonable estimates of hillslope erosion worldwide, including various GBR SedNet models, the ability to apply the model across a large spatial extent and at the same time incorporate detailed spatial and temporal data layers including cover and rainfall components. The model is:

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

where

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

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

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

L = Slope length (static value)

S = Slope steepness (static value)

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

P = Practice management factor (static value)

In the GBR Source Catchments framework, a daily time-step, spatially variable RUSLE was used to generate hillslope sediment predictions in grazing areas. The spatial data inputs were assessed at a fine resolution, with results accumulated up to a single representation of the particular grazing instance within each subcatchment. The spatial and global parameter values applied for WT model are shown in Table 29, Table 31 and Table 32 (Appendix E).

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

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

Slope steepness factor (S) was calculated by methods outlined in Lu et al. (2003). The slope values for these calculations are derived from the SRTM 1-second DEM (Farr et al. 2007), reprojected and resampled to 30 m. The use of a shuttle DEM has been found to miscalculate slopes on floodplain areas or areas of low relief. The slope map produced from the 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 DEM's, covering floodplains in the Fitzroy region.

Slope length factor (L) was set to one 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-step 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 ensured that extended wet and dry periods were reflected in hillslope erosion processes. This was 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 improve erosion estimates when data is available, as it will better represent inter-annual variability in RUSLE predictions. Ground cover was estimated using BGI (Scarth et al. 2006) (version CI2). This product was 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 has currently only been considered to be accurate in areas where the FPC (Goulevitch et al. 2002) is <20%. To deal with this, the GCI was classified into 'no tree' areas (FPC <20%) and 'tree' areas (FPC >20%) (Equation 2). The 2009 FPC coverage was used to represent the 'tree' coverage, for all years.

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

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

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

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

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

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 proportion located in the ASRIS layers (the best data source available to generate this layer at the GBR scale). The clay and silt fraction proportion was 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 (Brodie et al. 2003, Hateley 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% sediment delivery ratio (Wilkinson, Henderson & Chen 2004, Hateley et al. 2006). However, in some regions the SDR was increased so that the generated fine sediment load better matched monitored data. The SDR for this region can be found in Table 29, Appendix E. The equation takes the form:

TSS load (kg/day) = RUSLE sediment load (kg/day) * (silt prop + clay prop) * SDR (4)

This estimated the TSS load, which reaches the stream.

Nutrient generation models

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

Hillslope particulate nutrient load (kg/ha) = RUSLE sediment load (kg/day) * clay (prop) * Surface nutrient concentration (kg/kg) * Enrichment factor * Nutrient delivery ratio (NDR) (5)

This estimated the total suspended nutrient load, which reaches the stream. The surface soil nutrient layers were from the Queensland ASRIS database.

For the dissolved nutrient load, an EMC/DWC value (mg/L) was multiplied by the quickflow and slowflow output (Table 31, Appendix E). These models are described in Ellis and Searle (2014) and replicate the original SedNet approach to dissolved and particulate nutrient generation modified to a daily basis. Enrichment ratios and load conversion factors are outlined in Table 33 and Table 34 (Appendix E). Three rasters are required as inputs to these models, two nutrient rasters (surface nitrogen and phosphorus), as well as a surface clay (%) raster.

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 are 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 (static concentration x runoff) model was used, based on measured in-stream data from the Fitzroy catchment 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 (2008). Tebuthiuron was not been detected by the GBR Catchment Loads Monitoring Program (GBRCLMP) in the Wet Tropics for 2009–2010 or 2010–2011 season and was therefore not modelled in the WT.

3.3.1.2 Gully – sediment and nutrient generation models

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

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 was converted to an 'eroded' soil mass. This eroded mass was then distributed over the model run period as a function of runoff (Equation 6). The gully average annual sediment supply (AASS) was calculated by:

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

where:

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

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

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

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

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

To derive a daily gully erosion load, the long-term average annual gully erosion load is multiplied by the ratio of daily runoff to annual runoff to apportion a daily gully load. Spatial raster inputs and parameter global values are shown in Table 30, Appendix E.

The National Land and Water Resources Audit (NLWRA) gully density layer was used as the input raster (km/km^2) for gully density in WT (NLWRA 2001). Much of the Australian research on gully erosion has occurred in south-eastern Australia and measurements of gully cross sectional area suggest a value of 10–23 m^2 would be appropriate in SedNet modelling (Hughes & Croke 2011, Prosser & Winchester 1996, Rustomji et al. 2010). Recent research from northern Australia indicates that a value of 5 m^2 is more appropriate (Hughes & Croke 2011) and this has been applied in the WT model. The soil bulk density (g/cm^3) and B-horizon clay plus silt (%) rasters were both created from the Queensland ASRIS dataset. The year of disturbance can either be input as a raster or as a uniform value. In the WT model, a uniform value of 1870 was applied. This value was chosen as it coincided with a large increase in domestic livestock numbers within the Burdekin catchment (Lewis et al. 2007). The inference here is that major gully expansion started during this time.

Similar to the hillslope nutrient generation, gully nutrients were derived as a function of the gully particulate 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 were two nutrient rasters (subsurface nitrogen and phosphorus) and a subsurface clay raster (%).

3.3.2 Sugarcane constituent generation

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

3.3.2.1 Hillslope - sediment, nutrient and herbicide generation

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

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

DIN loads modelled by APSIM were imported directly as supplied (under the procedure for runoff analysis above). Herbicide and phosphorus loads were modelled using HowLeaky functions based on the outputs of the APSIM model of sugarcane systems for water balance and crop growth. The HowLeaky herbicide and phosphorus models are described for dryland and irrigated cropping below. DON was an EMC model. Further details on the APSIM and HowLeaky models and the parameters used to define simulations of sugarcane are provided in Table 33 and Table 34 (Appendix E) and in Shaw & Silburn (2014).

There were differences between the industry supplied sugarcane areas (hectares) (129,745 ha) (GHD 2010) and the QLUMP derived sugarcane area (179,669 ha) used for the modelling. This indicated that the QLUMP data was most likely representing more area than the industry recognises as actually growing sugarcane at any given time, due to consideration of crop rotations, headlands, infrastructure and other factors. Comparison with industry supplied estimates of sugarcane area indicated that the QLUMP over estimate may be in the order of 25%, and an area correction factor was applied to the APSIM pollutant loads accordingly.

The Dry Weather Concentration (DWC) for DIN was increased to 1.5 mg/L in the wettest basins and reduced from 1.5 to 0.19 mg/L for the drier Barron and Herbert basins. In addition, the DIN nutrient delivery ratio (NDR) was reduced from 100% to 50% in the Barron Basin. This was necessary to better match water quality loads derived from measured estimates.

3.3.2.2 Gully – sediment and nutrient generation

Gully modelling for sugarcane used the same methodology as for grazing lands (3.3.1.2). Similarly, to the grazing areas, the total subcatchment contribution for sugarcane FUs combined the hillslope and gully loads. Gully nutrients were derived as a function of the gully particulate sediment load, the subsurface clay (%) and the subsurface soil nutrient concentrations. Sugarcane drains were not incorporated into the modelling due to a lack of data.

3.3.3 Cropping constituent generation

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

3.3.3.1 Hillslope sediment, nutrient and herbicide generation

Daily time series loads of fine sediment, phosphorus and herbicides in runoff were supplied from HowLeaky model runs for the dryland and irrigated cropping FUs (Shaw & Silburn 2014). Simulations of a range of typical cropping systems in the WT 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, RUSLE K, L and S and a cover-sediment concentration relationship derived by Freebairn & Wockner (1986). This generalised equation applies anywhere where the cover-sediment concentration relationship holds. In addition, the Freebairn and Wockner equation was 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. A large percentage of cropping ferrosols in the WT are on topography between 1% and 6% and up to 8% on red ferrosols (Shepherd & MacNish 1989). Slope was therefore capped to a maximum of 8% to avoid overestimation of loads. This 8% maximum slope was also confirmed with expert agronomists in the sugarcane and banana industries (D Calcino and S Lindsay, 2012, pers. comm.).

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 Source Catchments. 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. DIN and DON were modelled using an EMC. Further details on the HowLeaky model and the parameters used to define simulations of cropping and sugarcane are provided in Shaw & Silburn (2014).

3.3.3.2 Gully sediment and nutrient generation

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

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

The remaining land uses: forestry, nature conservation, urban, ‘other’, horticulture, dairy and bananas, had Event Mean Concentration/Dry Weather Concentration (EMC/DWC) models applied (Equation 7). In comparison to grazing, cropping and sugarcane areas, these land uses had a small relative contribution to region loads, except for nature conservation for some constituents. In the absence of specific models for these land uses, EMC/DWC models were applied estimating the daily load, where:

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

Where quickflow represents the storm runoff component of daily runoff, the remainder was attributed to slowflow. Where 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 estimates from previous studies (Bartley et al. 2012, Rohde et al. 2008, Waters & Packett 2007).

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 20^{th} percentile of daily flows (Table 35, Appendix E). 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 studies. The estimation of soil erosion especially from steep rainforest areas with RUSLE has overestimated sediment loss (Armour, Hateley & Pitt 2009, Hateley et al. 2005). 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 identified. Currently 68% of the WT 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/DWC approach assume that the EMC/DWC derived load incorporates both hillslope and gully contributions. To derive an estimate for the total hillslope and gully contribution for this report, the EMC/DWC 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/DWC derived source. The EMC/DWC derived source for dissolved nutrients was added to diffuse dissolved source load to simplify the results.

3.3.5 Subcatchment models

3.3.5.1 Point sources

Sewage Treatment Plants (STPs) were deemed a significant point source contribution to nutrient loads exported to the GBR. The larger STPs with an arbitrary criterion of a minimum 10,000 equivalent person's (EP) capacity were included (Table 6). STP details and data were provided by DERM's (formerly Environment Protection Agency) Point Source Database (PSD). All STPs located in the WT that were modelled are maintained by the Cairns City Council.

Table 6 Sewage treatment plants >10,000 equivalent persons

STP	Discharge point	Catchment	Lat	Long	EP
Marlin Coast	Avondale Creek	Barron River	-16.8286	145.7081	10,000–50,000
Northern	Barron River		-16.8714	145.7429	50,000–100,000
Southern	Smith's Creek (Trinity Inlet)	Mulgrave-Russell River	-16.9547	145.7541	50,000–100,000
Edmonton	Trinity Inlet		-16.9911	145.7622	10,000–50,000

The Source Catchments model required average annual loads (kg/yr) of DIN, DOP, DIP and DOP. However, the majority of the nutrient data in the PSD database was reported as TN, TP and Ammonia (as N-NH3). Twelve STPs from Queensland with recorded concentrations of DIN, DON, DIP, DOP, TN and TP were used to calculate the mean percentage of each constituent to the total. Of the 12 STPs, eight were tertiary and four were secondary treatment plants. No differentiation was made between tertiary and secondary treatment plants, as there was a 10% difference in N speciation and 4% difference in P speciation. Moreover, STP sources only accounted for a small fraction of the total nutrient budget. Out of the 12 STP plants, 550 samples were used to calculate N speciation mean percentages and 469 samples used to calculate P speciation, see Table 7 for percentages. Data pairs were discarded where the speciation concentration added together was greater than the TN or TP concentration. The fixed percentages were applied to 2010 TN and TP concentration data from each STP to derive the speciation. Annual loads (kg/yr) were then calculated by multiplying the average annual flow (2007–2010) from each STP by the average 2010 daily concentration of DIN, DON, DIP and DOP. To reflect the recent upgrades to STPs in the region only the 2010 nutrient concentrations were used.

Table 7 TN, TP speciation ratios

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

3.3.6 In–stream models

The in-stream processes represented in the model are streambank erosion, decay, channel deposition and 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 transport was not able to be represented adequately, and was therefore deemed to be 'trapped' at the point of entry into the stream network, with no export reported.

3.3.6.1 Streambank erosion

The *SedNet Stream Fine Sediment model* calculates a mean annual rate of fine streambank erosion (t/yr) as a function of riparian vegetation extent, streambank erodibility and retreat rate. The mean annual streambank erosion was disaggregated as a function of the daily flow. For a full description of the method refer to Ellis & Searle (2014) also see Table 36 (Appendix E) for parameter values. The *SedNet Stream Particulate Nutrient* model calculates the particulate N and P contribution from streambanks by taking the mean annual rate of soil erosion (t/yr) from the stream network multiplied by the ASRIS subsurface soil N and P concentrations.

3.3.6.2 In-stream deposition, decay and remobilisation

The implemented in-stream model allows both the deposition and remobilisation of fine and coarse sediment. However, with limited data available to validate this component at the time of model development, remobilisation and in-stream deposition was not included in any of the GBR models. The assumption was made that all coarse sediment deposits in the main stream with no remobilisation occurring. Hughes et al. (2010) note that in-channel benches are an important store of large volumes of sediment in the Fitzroy catchment, however these benches are predominantly comprised of sand. A small fraction of fine sediment may be trapped in these coarse (bedload) deposits, however the time scale for fine sediment movement is much shorter and thus this fraction is ignored in the bedload budget (Wilkinson, Henderson & 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 & 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 WT model. Monitoring data suggests that dissolved nutrient concentrations showed little reduction from source to the catchment outlet therefore no decay model was applied. However further research is required to improve our understanding of in-stream decay process for dissolved nutrients.

Herbicides were decayed in-stream using a first order exponential decay function (Ellis & Searle 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, 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 Table 37 (Appendix E).

3.3.6.3 Floodplain (deposition)

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

3.3.6.4 Node models

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

Extraction, Inflows and loss node models

To simulate the removal of water from storages and/or rivers, daily extraction estimates for a river reach were incorporated at relevant nodes. The data was obtained from previous Integrated Quantity and Quality Models (IQQM). Time series data was obtained from the Barron IQQM report (Department of Natural Resources and Mines 2001, Water Studies PTY LTD 1998) and the draft Tully IQQM report (DSITIA 2013a). At the time of model development only two IQQM models were available. Demands for water include town water supply, irrigators, hydroelectric power generation and unregulated users. An extraction node model was placed at the node immediately downstream of storages to represent demands taken directly from the storage. Five river extraction node models were implemented in the Barron catchment at the following gauging station sites: Picnic Crossing (110003A), Mareeba (110002A), Bilwon (110020A), Myola (110001A) and Freshwater (110104A). Multiple types of extractions were aggregated and allocated at the appropriate downstream node. In all cases, the extraction and inflows were extended to match the model simulation period (1986–2009). The time series were extended by taking the median monthly extraction or inflow value from the available IQQM estimates for Barron and Tully basins and disaggregating to daily values. IQQM flow data (extractions) for the Barron was extended from 1995–2009 and for the Tully storage releases (inflow model) were available 1976–1989, so data was extended back to 1970 and extended to 2009. Four loss models were included in the Barron Basin to account for channel losses as done by the IQQM model. An inflow model was incorporated to simulate the return water from the Tully River from the Kareeya Hydroelectric power station.

3.3.6.5 Storage models

Storages (dams and weirs) with a capacity >10,000 ML (Table 8) were incorporated into the model at links. Only storages of significant capacity were incorporated as it was impractical to include all storages into the model and it was assumed the smaller storages would have minimal impact on the overall water balance and pollutant transport dynamics. Storage locations, dimensions and flow statistics were used to simulate the storage dynamics on a daily basis. Tinaroo Falls Dam is located near Atherton and the Copperloade Dam is located closer to Cairns, both in the Barron River catchment (Figure 1). Koombooloomba Dam is located in the headwaters of the Tully River catchment.

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

Storage	Catchment	Construction Date	Capacity (ML)
Tinaroo Falls Dam	Barron	1958	436,500
Copperlode Dam	Barron	1976	44,500
Koombooloomba Dam	Tully	1961	200,700

Trapping of fine sediment and particulate nutrients in storages was simulated by the *SedNet Storage Lewis model* and the *SedNet Storage Particulate Nutrient Deposition* model, respectively. Here fine sediment and particulate nutrient was captured using a 'trapping' algorithm based on daily storage capacity, length and discharge rate. The implemented trapping algorithm is a daily modification of the Churchill fine sediment trapping equation (Churchill 1948). Lewis et al. (2013) reviewed and tested an annual weighted version of this equation against measured data for the Burdekin Falls dam and storages in the USA, in general, predictive capability improved with use of daily data. Dissolved constituents are decayed in storages using the *SedNet Storage Dissolved Constituent Loss* model, which applies a first order decay. Storage details are presented in Table 38 (Appendix E).

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 (Equation 8, 9 and Figure 8).

$$\text{Anthropogenic baseline load} = \text{total baseline load} - \text{predevelopment load} \qquad (8)$$

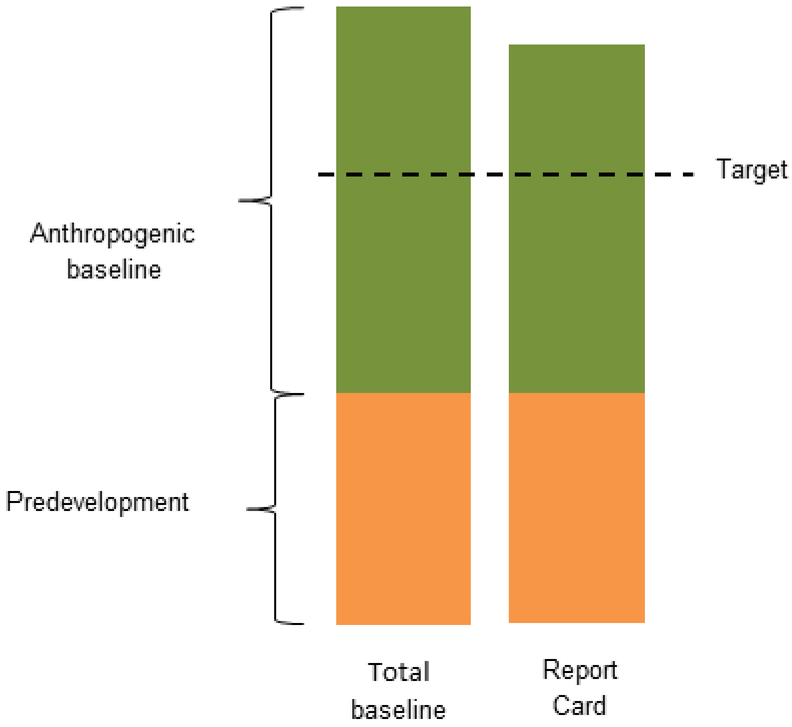

Figure 8 Example of how modelling results will be reported to demonstrate the estimated long-term load reduction resulting from adoption of improved management practices for Report Cards 2010– 2013 against the target

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

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

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

Report Cards, measuring progress towards Reef Plan's goals and targets, are produced annually as part of the P2R Program. The first Report Card was released in August 2011 (Kroon et al. 2010). Report Cards 2010–2013 represent management changes based on a yearly period, usually financial year to financial year. The total and anthropogenic baseline load was based on land use and management status at the start of the July 2008. All scenarios were run using the same modelling period 1986–2009 (23 years), see Table 9 for details of the total and anthropogenic baseline scenarios and Report Card scenarios. Note that Report Card 2010 includes two years of management change. Report Card 2011 and beyond represent cumulative change each year.

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

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

3.4.1 Modelling baseline management practice and practice change

State and Australian government funds (Reef Rescue Program) were made available under Reef Plan to the six regional NRM groups and industry bodies to co-fund landholder implementation of improved land management practices. The typical practices that were funded under the Reef Rescue Program for grazing included 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 attributed (subject to review) 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 inter-related practice changes are often required to complete the transition to a new management system. For a summary of typical management practice changes attracting co-investment, refer to Table 40 (Appendix E) (K McCosker, 2014, pers. comm.).

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

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

B – Best management practice, generally recommended by industry

C – Code of practice or common practices

D – Unacceptable practices that normally have both production and environmental inefficiencies.

The proportion of each industry was established in A, B, C or D condition. The area of A,B,C or D was then reflected in the total baseline model. The proportion of area of A,B,C or D then changed each year between 2008 and 2013 based on adoption of improved practices. Management practice change was based on farmers using Reef Rescue funding for an improved management practice or voluntarily improved management without applying for funding. Management changes were captured in a database by Terrain NRM and changes provided to the paddock models, which was then fed into the Source Catchments model. For more information on the ABCD framework and associated management practices see the Reef Plan website: www.reefplan.qld.gov.au.

The total baseline load was modelled using 2009 land use and land management practices. The most recent Queensland land use mapping program (QLUMP) map was used to define the spatial location of the major land uses in the region (DSITIA 2012b). Land use categories in QLUMP were amalgamated to represent broader land use classes including: nature conservation, forestry, grazing (open and closed), sugarcane, bananas, cropping, horticulture and dairying (Table 3).

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

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

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

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

For sugarcane, the majority of the baseline nutrient management was B practice (45%), for soil and herbicide C practice (75%) and (48%) respectively (Table 11).

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

Management system	Period	A	B	C	D
		(%)			
Nutrient	Baseline	2.2	44.3	28.5	25.0
	2008-2010	3.0	55.6	32.6	8.7
	2008-2011	4.9	63.7	23.0	8.4
	2008-2012	5.4	65.3	21.2	8.1
	2008-2013	9.6	69.7	14.2	6.6
Herbicide	Baseline	1.2	7.3	48.1	43.5
	2008-2010	1.2	12.9	42.4	43.5
	2008-2011	1.3	20.0	35.2	43.5
	2008-2012	2.4	24.6	30.4	42.5
	2008-2013	4.1	37.9	19.3	38.8
Soil	Baseline	0.1	11.1	75.4	13.4
	2008-2010	1.1	20.1	65.4	13.4
	2008-2011	1.5	30.0	55.4	13.1
	2008-2012	5.7	33.8	47.3	13.1
	2008-2013	13.0	38.0	36.6	12.4

3.4.1.2 Grazing

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

The GRASs Production model (GRASP) provided scaling factors for adjusting RUSLE C-factors where management practice changes occur (McKeon et al. 1990). 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 (i.e. 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 on 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 basin specified.

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

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

Management system	Period	A	B	C	D
		(%)			
Soil	Baseline	0.0	69.7	28.3	2.0
	2008-2010	1.5	68.9	27.7	1.9
	2008-2011	2.5	68.7	26.9	1.9
	2008-2012	2.7	68.7	26.6	1.9
	2008-2013	2.7	68.7	26.6	1.9

Riparian fencing

Improved grazing management (in particular cover management) can have both a 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 hillslopes can reduce runoff rates and volumes from upstream contributing areas to a gully or stream. This process was represented in the model by implementing relative reductions in rates of erosion per management class, as described by Thorburn & Wilkinson (2012), Table 13.

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

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

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

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

Indirect effects have been applied for WT for Report Cards 2011–2013 only and riparian fencing data to represent direct effects was only provided to the modelling team for WT for Report Card 2012 and beyond. For assessing the direct effect of riparian fencing, where investment in riparian fencing were identifiable, the riparian vegetation percentage for the stream was increased linearly with respect to the proportion of the stream now excluded from stock. For Report Card 2012, the length of riparian fencing was 27 km, and in Report Card 2013, it was 63 km, a total of 90 km over the two Report Cards.

Additional scenarios

Additional scenarios were run for inclusion in the Wet Tropics WQIP that represented either a single management class or a combination of management classes. The definitions of each scenario are presented in Table 14. These additional model runs were developed just for DIN and PSIIs for sugarcane land use. The updated baseline model (Report Cards 2012–2013) was used for these additional model runs. The reductions in the DIN and PSII anthropogenic baseline loads for these additional scenarios are compared with Report Card 2013 reductions and are presented in the results.

Table 14 Additional scenarios and definitions

Scenario	Definition
All A	100% A
All B	All B except, except properties already in A in the baseline
All C	All C except, except properties already in D in the baseline
All D	100% D
Fifty % AB	50% A, 50% B

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
- A 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 9 the predevelopment scenario was run from 1986 to 2009.

3.5 Constituent load 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). 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). A range of other measured datasets at smaller time scales were also included, see section 3.5.4. It is important to note that the catchment model load outputs were compared or 'validated' against loads estimated from measure data as opposed to the common calibration approach whereby model parameters are adjusted to fit the measured data. No formal calibration approach was used, however minor adjustments were made to better align with estimates derived from measured data.

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

Kroon et al. (2012) reported current, pre-European and anthropogenic loads from the 35 reef basins (in six NRM regions), using published and available loads data. The best estimates for WT basins for the 'current' loads (except PSII herbicides) were either based on SedNet modelling (Hateley et al. 2006) or loads generated from the Loads Regression Estimator (LRE) (Kroon et al. 2012). Basins that had existing water quality data such as Barron, Johnstone, Tully and Herbert had LRE loads to represent the current condition. The LRE methodology was used to estimate annual pollutant loads with uncertainties for each water year where GBR catchment monitoring data was collected by using a four step process outlined in Wang, Kuhnert & Henderson (2011). The remaining basins had load estimates available from previous SedNet modelling (Hateley et al. 2006). The pre-European loads described were from (McKergow et al. 2005a, McKergow et al. 2005b) except for TSS in the Herbert where (Bartley et al. 2003) was used. Both of these studies also used the SedNet model, but with different input data sets and parameters to SedNet modelling by Hateley et al. (2006). The PSII herbicide basin load estimates reported in Kroon et al. (2012) were derived from Brodie, Mitchell & Waterhouse (2009) and for the Mulgrave-Russell Basin from Shaw et al. (2010). Lewis et al. (2011) had also estimated PSII herbicide loads and was included in the PSII herbicide section. The difference between the Kroon et al. (2012) current and pre-European load provided an estimate of the 'anthropogenic' load. The anthropogenic loads could not be compared due to differences in modelling periods and methodologies and is outlined in the discussion. The Kroon et al. (2012) loads are presented in Table 25 (Appendix A). It should be noted that any comparisons made with these loads 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 a range of EOS gauging stations across the GBR. The standard approaches were examined including averaging, developing a concentration to flow relationship (regression) and/or the Beale Ratio (Joo et al. 2014, Marsh & Waters 2009, Richards 1999). It is acknowledged that these can result in large errors in the load estimates especially when extrapolating far beyond the sampled flow ranges due to a lack of representative data (Joo et al. 2014, Marsh & Waters 2009). Joo et al. (2014) has applied a Flow Range Concentration Estimator (FRCE) method (a modified Beale ratio method) to provide estimates of annual loads. The mean modelled loads were compared with the likely upper (95th percentile concentration) and likely lower (5th percentile concentration) FRCE range and mean FRCE loads for all modelled 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, percent bias (PBIAS) and the ratio of the root mean square error to the standard deviation of validation data (RSR). Model evaluation performance ratings were established for each recommended statistic, and are presented in Table 15. Modelled monthly loads were also assessed against these ratings. The statistical evaluation technique was tested on

TSS, TN, DIN, TP and DIP.

Table 15 General performance ratings for recommended statistics for a monthly time-step (Moriasi et al. 2007)

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

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

In 2006, the Queensland Government commenced a GBR Catchment Loads Monitoring Program (GBRCLMP) designed to measure sediment and nutrient loads entering the GBR lagoon (Joo et al. 2012). The water quality monitoring focussed at the EOS of ten priority rivers; Normanby, Barron, Johnstone, Tully, Herbert, Burdekin, O'Connell, Pioneer, Fitzroy, Burnett and 13 major sub-basins. Water sampling of herbicides commenced in 2009–2010 in eight GBR catchments and three subcatchments (Smith et al. 2012). Five priority PSII herbicides commonly detected from GBR catchments are: 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. 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 the WT, the modelled loads for the Barron, Nth and Sth Johnstone, Tully and Herbert EOS are compared with the GBRCLMP estimates for 2006 to 2010 for all modelled constituents except herbicides (Joo et al. 2012, Turner et al. 2012).

The Herbert GBRCLMP data is only based on the years 2006–2007 and 2009–2010. For 2007–2009, the load data is unreliable due to number of samples collected (n=3) and timing of sample collection (ambient). Source Catchments comparisons were therefore made by averaging the 2006–2007 and 2009–2010 years.

3.5.4 Other datasets

In addition to the three validation approaches discussed, two additional data sets were used as part of the model validation. A long-term sampling program was conducted in the Tully River by the Australian Institute of Marine Science (AIMS) in conjunction with the Tully office of the Bureau of Experiment Stations (BSES) (Mitchell et al. 2007). This long-term dataset was also compared to the Source Catchments loads over the same period (1988–2000). The AIMS loads were taken from Table 20 in Mitchell et al. (2007) and the average annual load adjusted to the mean annual flow was used. DON and TN were not included, as there were analyses issues with DON during the sampling period (J Brodie, 2012, pers. comm.). The AIMS TSS load at the Herbert EOS gauge (1995–2000) was also compared to Source Catchments for the same time period.

At a smaller time scale, a comparison was also made with event loads calculated during cyclone Sadie for the Herbert River from 30/4/1994 to 5/2/1994 (Mitchell, Bramley & Johnson 1997) to the Source Catchments loads for the same time period. The flow weighted estimate by interpolation was taken from Table 1 in Mitchell, Bramley & Johnson (1997).

EMC values for TSS, DIN and PSII herbicides were also compared to Source Catchments at the Tully EOS site (Department of Natural Resources and Mines 2012).

4 Results

This section is separated into hydrology and modelled loads. For hydrology, the results of the calibration process will be presented, as well as a general summary of the hydrology of the GBR regions. The modelled loads section includes the results of the total baseline, the anthropogenic baseline and predevelopment loads. The validation of the WT results is then presented using load estimates from measured data and previous catchment modelled data. This concentrates mainly on DIN and PSII herbicides that have been identified as high risk in the Wet Tropics region, to the GBR (Waterhouse et al. 2012). The remaining constituents will be summarised, but in less detail. Progress towards Reef Plan 2009 targets is reported against the 2009 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 WT loads, refer to Appendices F–J and for a broad GBR summary of the results, refer to Waters et al. (2014).

4.1 Hydrology

4.1.1 Calibration performance

Model performance was assessed for the 21 WT gauges used in the calibration process for the period 1/1/1970–31/3/2010. Most gauges had the complete flow record for the 39 year calibration period. The calibration results for 21 gauges with varying catchment areas (100–9,000 km^2) are presented in Table 16. 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. A ‘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 criteria are shaded red. 17 of 21 gauges (81%) met all three criteria. Twenty gauges or 95% of gauges had monthly NSE values >0.8. Ninety per cent of gauges met the volumetric difference criteria. Most modelled gauge data (86%) under predicted the total runoff volume. Whilst the statistics indicate the overall fit was sufficient for long-term predictions, close inspection of the hydrograph shape and timing suggests that the daily simulated runoff is often poorly matched to observed flows.

Table 16 Wet Tropics hydrology calibration (1970–2010)

Gauge	Gauge name	Catchment area (km^2)	Years of record^	Daily NSE	Monthly NSE	Total volume difference (%)
108002A	Daintree River at Bairds (EOS)	911	39	0.54	0.89	-6%
108003A	Bloomfield River at China camp	264	39	0.58	0.72	-31%
109001A	Mossman River at Mossman (EOS)	106	39	0.62	0.83	-24%
110001A-D	Barron River at Myola (EOS)	1,945	39	0.71	0.95	-9%
110003A	Barron River at Picnic Crossing	228	39	0.64	0.90	-20%
110011B	Flaggy Creek at Recorder	150	39	0.58	0.87	0%
110020A	Barron River at Bilwon	1,258	39	0.47	0.87	-10%
111007A	Mulgrave River at the Fisheries (EOS)	520	37	0.70	0.87	7%
111101A-D	Russell River at Buckland's (EOS)	315	39	0.77	0.88	-20%
112001A*	North Johnstone River at Tung Oil (EOS)	936	39	0.84	0.95	-9%
112003A	North Johnstone River at Glen Allyn	165	39	0.76	0.95	-6%
112101A-B	South Johnstone River at Upstream Central Mill (EOS)	401	39	0.61	0.96	-6%
113006A	Tully River at Euramo (EOS)	1,450	37	0.81	0.94	-7%
114001A	Murray River at Upper Murray (EOS)	156	38	0.66	0.86	-13%
116001A-D	Herbert River at Ingham (EOS)	8,581	39	0.70	0.94	-10%
116004A-C	Herbert River at Glen Eagle	5,236	39	0.79	0.95	-1%
116006A	Herbert River at Abergowrie College	7,440	39	0.76	0.95	-4%
116010A	Blencoe Creek at Blencoe Falls	226	39	0.65	0.92	-8%
116012A	Cameron Creek at 8.7 km	360	39	0.45	0.80	-19%
116014A	Wild River at Silver Valley	591	39	0.73	0.95	-1%
116016A	Rudd Creek at Gunnawarra	1,450	38	0.63	0.85	0%

Green = 3 criteria met, Orange = 2 criteria met and Red = 1 criteria met. NSE (Nash Sutcliffe coefficient of Efficiency).

* The flow from 112004A was added onto flow from 112001A.

^ Years of record = number of years of flow data that was within the hydrology calibration period (1970–2009).

(EOS) – end-of-system. It refers to the furthest downstream gauge on a stream or river.

The smaller calibration regions tended to have the biggest differences in per cent volume. These data are presented spatially in Figure 9, where grey areas represent ungauged regions.

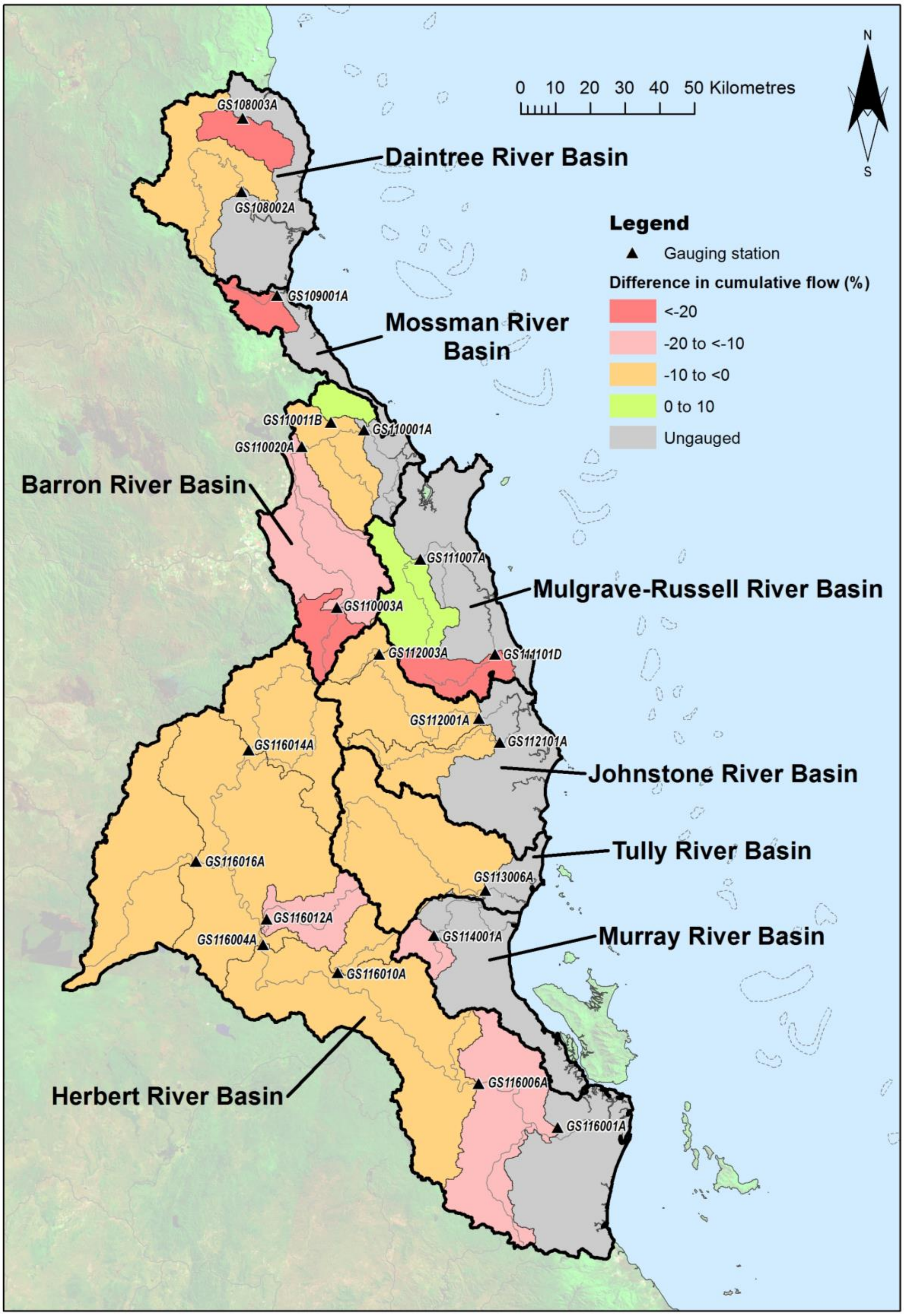

Figure 9 Percentage volume difference for WT calibration regions

The per cent difference between measured and modelled runoff volumes (1970–2009) are shown in Figure 10. As measured annual runoff volume increases, the per cent difference between measured and modelled runoff volume decreases. Therefore, the greatest differences in volumes were for the smaller calibration regions (Figure 9).

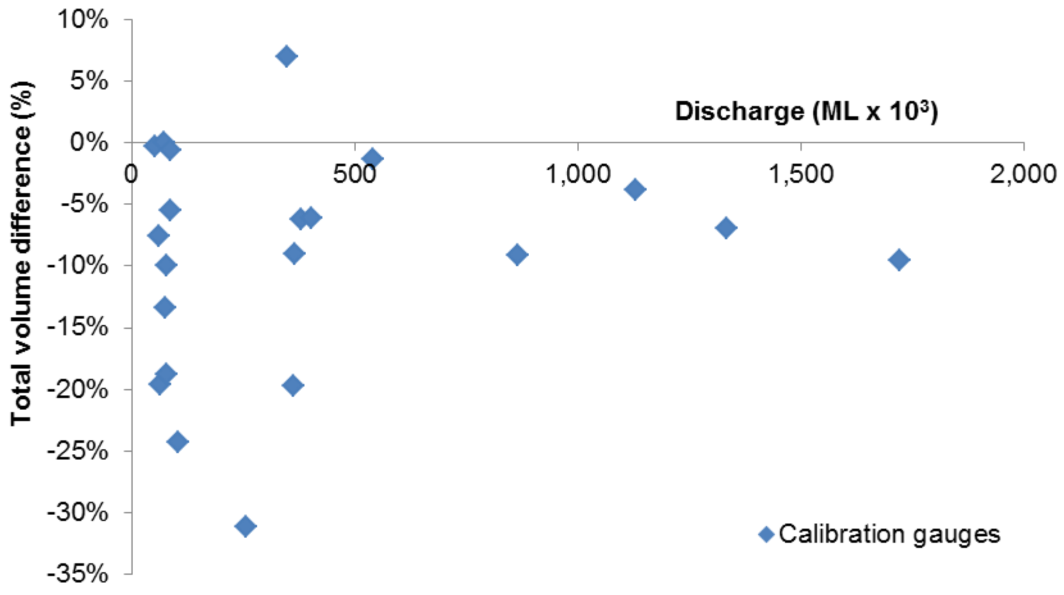

Figure 10 Per cent difference between measured and modelled runoff volume for calibration period (1970–2009)

Annual comparisons for wet and dry periods were selected to ensure the model adequately represented the extremes. An example is the measured and modelled annual flow volumes for the three wettest and three driest years at the EOS gauge at Tully (113006A) (Figure 11). The modelled simulation period (1986–2009) captured two out of the three highest flows for the period over which measured flow was available (1973–2009). The simulation period also captured the driest years 1991–1992 and 2002–2003. The average per cent volume difference for the three wettest years was -10% and for the three driest was +19%.

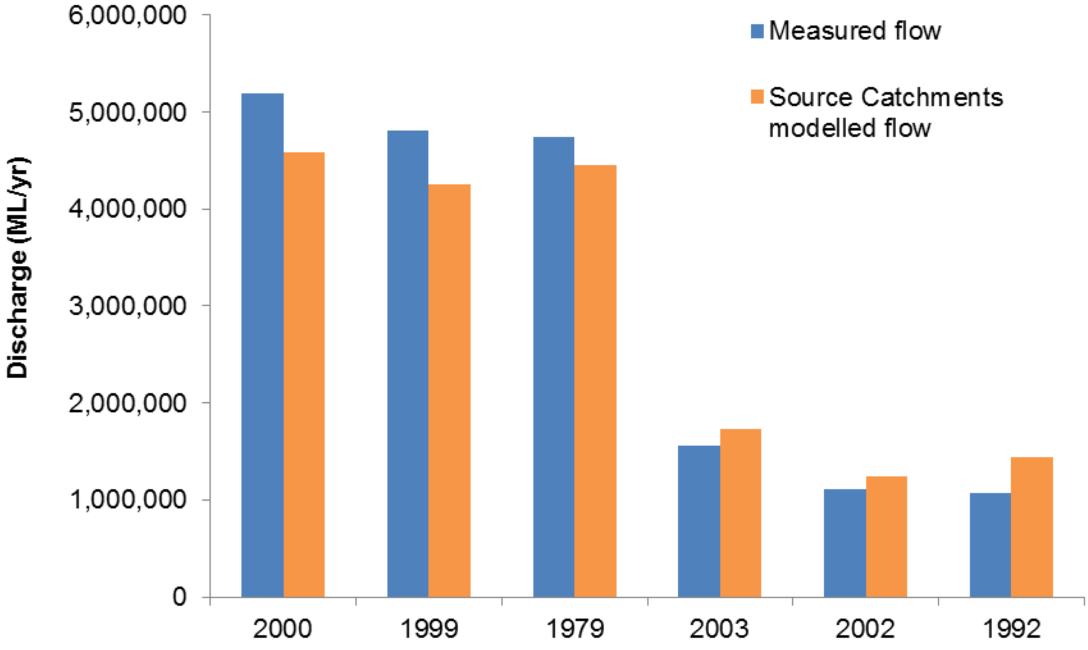

Figure 11 Annual measured and modelled discharge (ML/yr) for Tully River at Euramo (1973–2009) for the three wettest and three driest years

4.1.2 Regional discharge comparison

The modelled average annual flow for the WT was 21,000,000 ML/yr or 33% of the total GBR average annual flow (Figure 12). The WT had the largest average annual flow for the modelled period compared to the five other GBR regions. The next largest flow was from the Cape York region (18,000,000 ML/yr), which is roughly double the area of the WT.

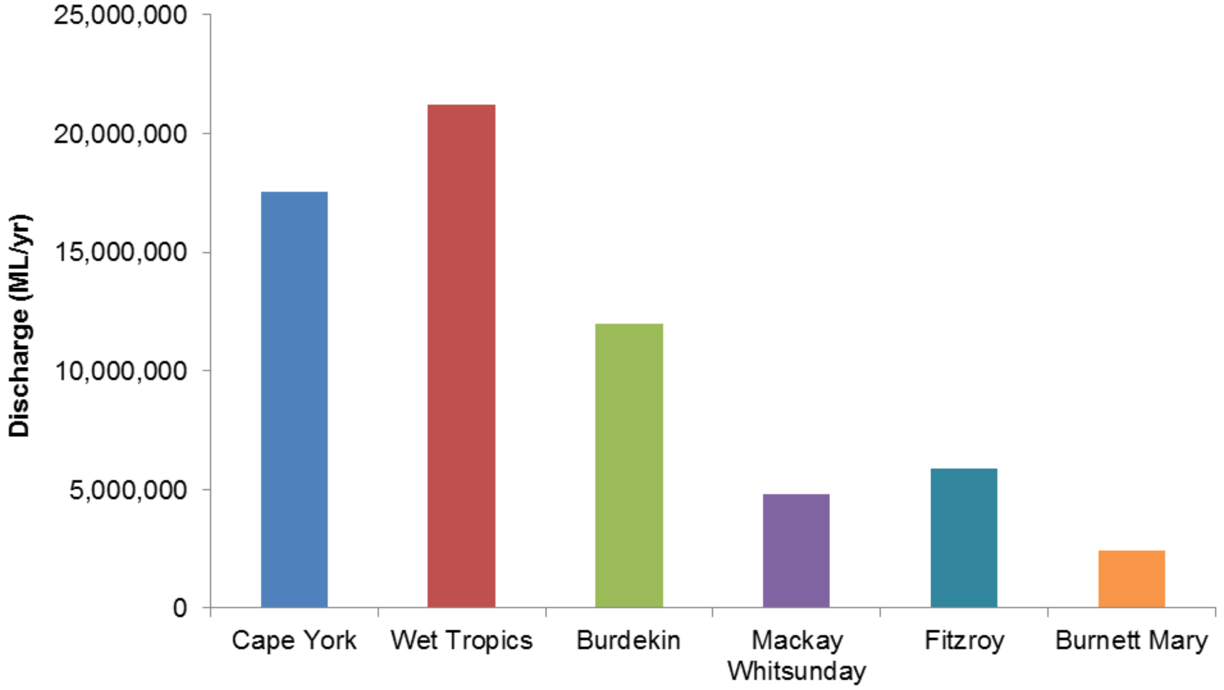

Figure 12 Average annual modelled discharge (ML/yr) for GBR regions (1986–2009)

The Johnstone Basin had the highest average annual flow (4,560,000 ML/yr) from the WT (1986–2009), followed by the Herbert Basin (4,300,000 ML/yr) then the Mulgrave-Russell Basin (3,700,000 ML/yr) (Figure 13).

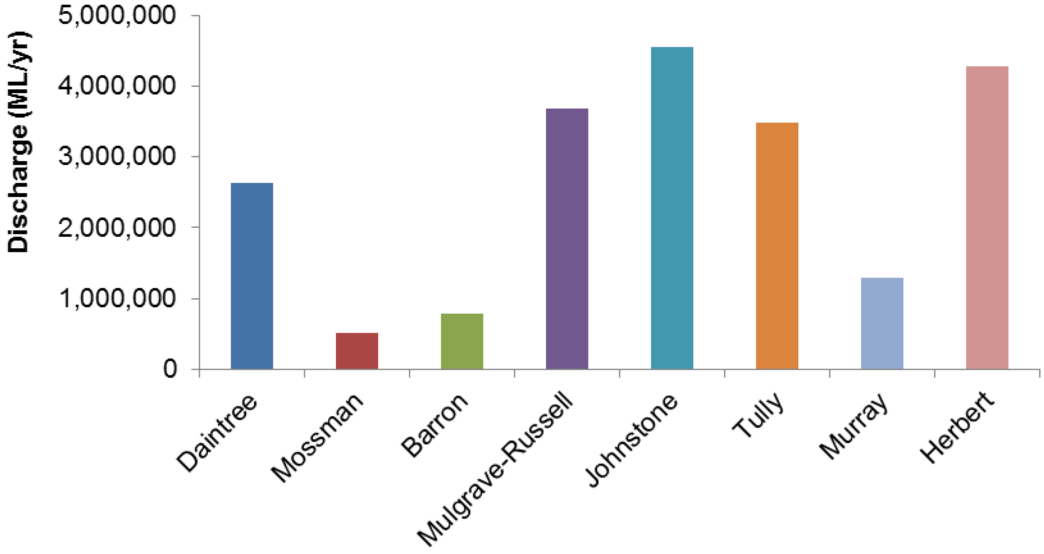

Figure 13 Average annual discharge (ML/yr) for WT basins (1986–2009)

The average annual rainfall, runoff (area weighted) and per cent runoff for the model period (1986–2009) for each basin is shown in Table 17. The Tully, Johnstone and Mulgrave-Russell were the three highest runoff basins, all producing approximately ~2000 mm runoff per year. All basins had >50% of rainfall going to runoff, except the Barron and Herbert, with the Tully having ~70% of its rainfall going to runoff.

Table 17 Average annual rainfall, runoff and runoff (%) for WT basins (1986–2009)

Basin	Average annual rainfall (mm)	Average annual runoff (mm)	Runoff (%)
Daintree	2,212	1,253	57
Mossman	1,747	1,060	61
Barron	1,361	495	36
Mulgrave-Russell	3,135	1,862	59
Johnstone	3,115	1,960	63
Tully	2,773	1,867	67
Murray	2,104	1,157	55
Herbert	1,180	434	37
Wet Tropics	2,203	1,261	54

4.2 Modelled loads

The Wet Tropics and Burdekin NRM regions were the two highest contributors for nine of the ten constituents modelled. The WT region had the greatest constituent total loads for TN, DIN, DON and PSII herbicides. The total baseline loads for all NRM regions is presented in Table 18 and the contribution as a per cent of the total GBR load is presented in Table 19. The WT generated 1,219 kt/yr of TSS or 14% of the total GBR export load. The TN export load from the WT was 12,151 t/yr or 33% of total TN GBR export load. It is estimated that 10,532 t/yr of DIN is exported from the GBR region; with the WT generating 42% of total DIN GBR export (4,437 t/yr). The WT region was also the highest contributor of DON at 27% of the total DON GBR export load. The WT contributed 32% of the total GBR PN export load. The majority of the WT TN export load was from dissolved N (68% of TN), with the remaining 32% from PN. For phosphorus, the WT contributed 26% of the GBR TP load, 20% of the GBR DIP load, 22% of the GBR DOP load and 29% of the GBR PP load. The majority of the WT TP export load was from PP (78% of TP), with the remaining 22% from dissolved P. The GBR PSII herbicide export load was 16,740 kg/yr, of this the WT total load was 8,596 kg/yr (51% of GBR total export) and was considerably higher than Mackay Whitsunday (second highest contributor). The WT export load for the knockdown herbicides was 760 kg/yr and the alternative residual herbicide was 230 kg/yr.

Table 18 Total baseline loads for the GBR regions

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

Table 19 Area, flow and regional contribution as a percentage of the GBR total for all constituents

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

Within the WT NRM region, the Johnstone and Herbert basins were the highest contributors for all constituents (Table 20). The Herbert and Johnstone basins contributed 60% of the TSS WT load, with the majority of the load from the Herbert Basin (38%). The Johnstone Basin contributed the largest proportion of TN at 26%, followed by the Herbert at 23% and Mulgrave-Russell and Tully ~14% each. The Johnstone Basin contributed the highest total DIN load at 31%, followed by the Herbert Basin at 18% and the Tully and Mulgrave-Russell basins at 16% each. The Herbert Basin contributed the highest DON proportion at 24% followed by the Daintree and Johnstone at 18% each. The Johnstone Basin contributed 30% of the PN load, followed by the Herbert at 27%.

The Johnstone Basin contributed 32% of the TP load and 35% of the PP load. Both the Johnstone and Herbert basins contributed similar amounts of DIP and DOP, ~22% each. The Herbert Basin contributed 28% of the total PSII herbicide load followed by the Johnstone Basin at 22% and ~16% each for Tully and Mulgrave-Russell basins. Loads for scenarios are presented in Table 41 (Appendix F).

Table 20 Contribution from WT basins to the total WT baseline load

Basin	TSS (kt/yr)	TN (t/yr)	DIN (t/yr)	DON (t/yr)	PN (t/yr)	TP (t/yr)	DIP (t/yr)	DOP (t/yr)	PP (t/yr)	PSIIs (kg/yr)
Daintree	62	1,353	387	685	282	95	24	15	57	235
Mossman	14	235	107	69	59	22	5	3	14	150
Barron	92	464	90	192	182	85	12	6	67	269
Mulgrave-Russell	168	1,804	695	549	559	238	41	22	175	1,482
Johnstone	265	3,204	1,360	700	1,144	530	49	29	453	1,861
Tully	110	1,566	702	443	421	160	33	17	110	1,359
Murray	43	731	288	283	159	71	17	9	46	862
Herbert	463	2,794	807	948	1,038	454	47	30	377	2,378
Wet Tropics	**1,219**	**12,151**	**4,437**	**3,870**	**3,844**	**1,656**	**228**	**130**	**1,297**	**8,596**

4.2.1 Anthropogenic baseline and predevelopment loads

The anthropogenic baseline load was calculated by subtracting the predevelopment load from the total baseline load. The TSS anthropogenic baseline load was 773 kt/yr or 63% of the total baseline load with the remaining 37% attributed to the predevelopment load. For TSS, all basins except the Daintree and Mossman basins were dominated (>50%) by the anthropogenic baseline load compared to the total baseline load (Figure 14). Loads are also presented in tabular form, see Table 41 (Appendix F).

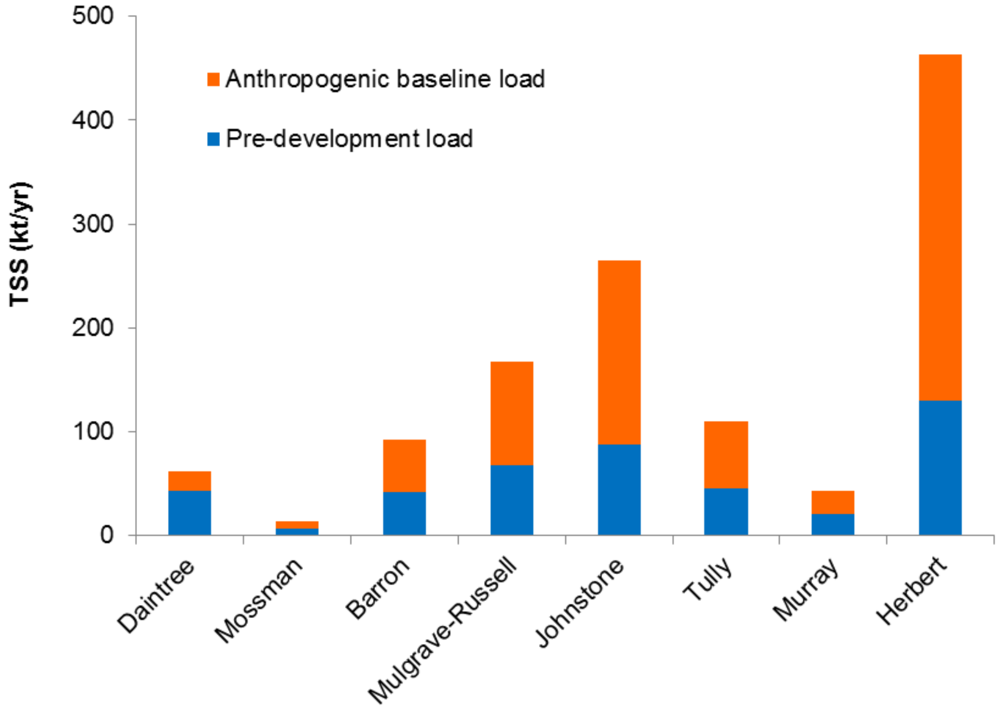

Figure 14 TSS (kt/yr) loads for WT basins, highlighting the predevelopment and anthropogenic baseline contributions

The anthropogenic baseline contribution of TN was 6,365 t/yr or 52% of the total baseline load. The anthropogenic baseline DIN load was 2,023 t/yr or 46% of the total baseline load, with the remaining 2,414 t/yr or 54% attributed to the predevelopment load. The Johnstone had the highest proportion of the DIN anthropogenic baseline load to the total load at 63% and along with the Tully (51%) were the only two basins to be dominated by the anthropogenic load (>50% of total load) (Figure 15). Predevelopment DIN proportions to the total load were highest in the Daintree (84%), followed by Herbert (66%) and Mulgrave-Russell (63%) basins.

The anthropogenic baseline load of TP was 1,013 t/yr or 61% of the total baseline load. Most of the WT DOP and DIP total baseline loads were attributed to the predevelopment load, 27 t/yr or 79% and 90 t/yr or 61% respectively. The highest anthropogenic baseline loads compared to the total baseline load are from PSII herbicides (100%), PP at 69% followed by TSS at 63% then PN at 60%.

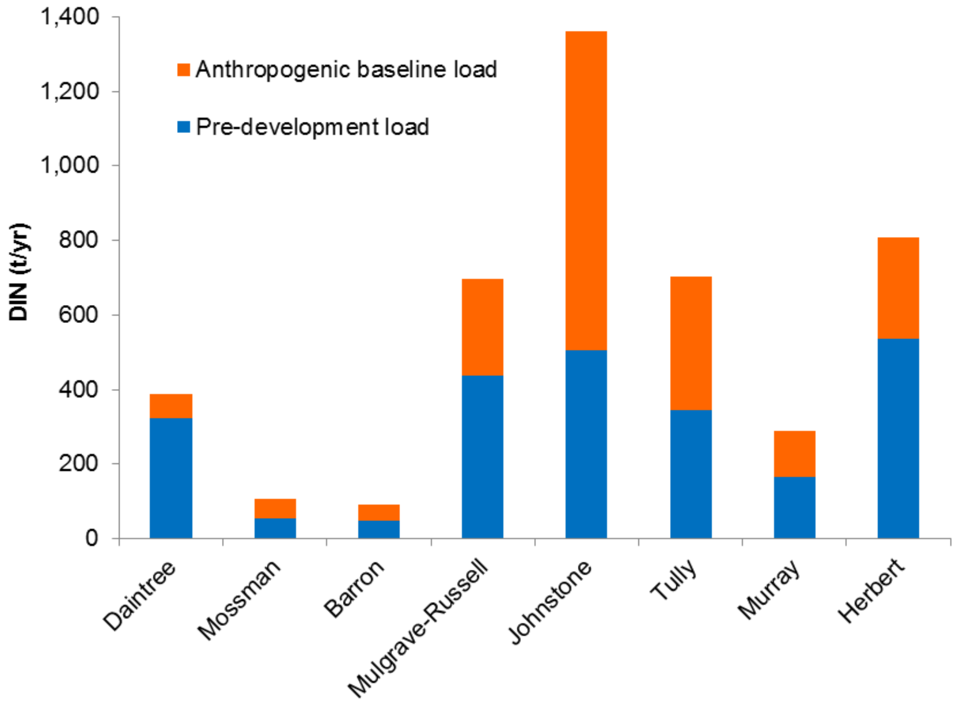

Figure 15 DIN (t/yr) loads for WT basins highlighting the predevelopment and anthropogenic baseline contributions

4.3 Constituent load validation

There were a range of water quality datasets against which the Wet Tropics Source Catchments modelling results can be compared, or validated. The three key sources are the previous best estimates from (Kroon et al. 2012) (LRE and SedNet), the long-term loads report (1986–2009) using the FRCE method (Joo et al. 2014) and the GBRCLMP monitoring program established by the Queensland State Government (2006–2010) (Joo et al. 2012, Turner et al. 2012). Other validation included the long-term AIMS loads at Tully and Herbert EOS sites, event loads during cyclone Sadie in 1994 at Herbert EOS (Mitchell, Bramley & Johnson 1997) and a comparison of measured versus modelled EMCs at Tully EOS (Department of Natural Resources and Mines 2012).

4.3.1 Previous estimates – Kroon et al. (2012)

A comparison was made between Kroon et al. (2012) load estimates and the Source Catchments modelled loads for TSS, DIN and PSII herbicides. The Source Catchments baseline load for TSS was generally lower than Kroon et al. (2012) current load (average -13%), apart from Tully, Murray and Herbert (Figure 16). Kroon et al. (2012) consisted of a range of data sources to derive catchment load estimates. The difference in Source Catchments and Kroon et al. (2012) load estimates were generally smaller where the LRE method was used to calculate a load compared to SedNet derived loads. The range of differences for LRE was (range -17 to 22%) (Barron, Johnstone, Tully and Herbert) compared to SedNet derived loads (range -65% to 6%) (Daintree, Mossman, Mulgrave-Russell and Murray). The differences in load estimates are due to methodology and are outlined in the discussion.

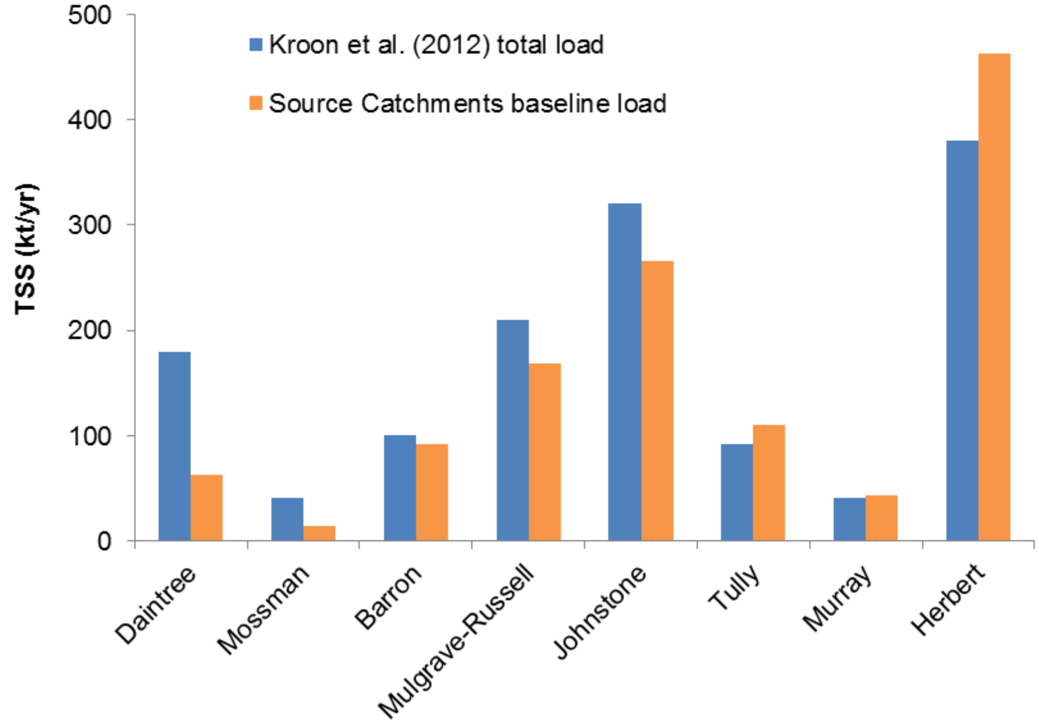

Figure 16 TSS (kt/yr) load comparison for Kroon et al. (2012) and Source Catchments modelled estimate for WT basins

The Source Catchments baseline load for DIN for the WT was lower than the Kroon et al. (2012) total load (average -37%) and by basin all Source Catchments loads were lower apart from the Barron (80% higher) (Figure 17). The per cent difference between Kroon et al. (2012) and Source Catchments by basin were generally less where the LRE method was used compared to the SedNet derived estimates. The per cent difference between Source Catchments and LRE was -38% to -16% and Source Catchments and SedNet was -59% to -14%.

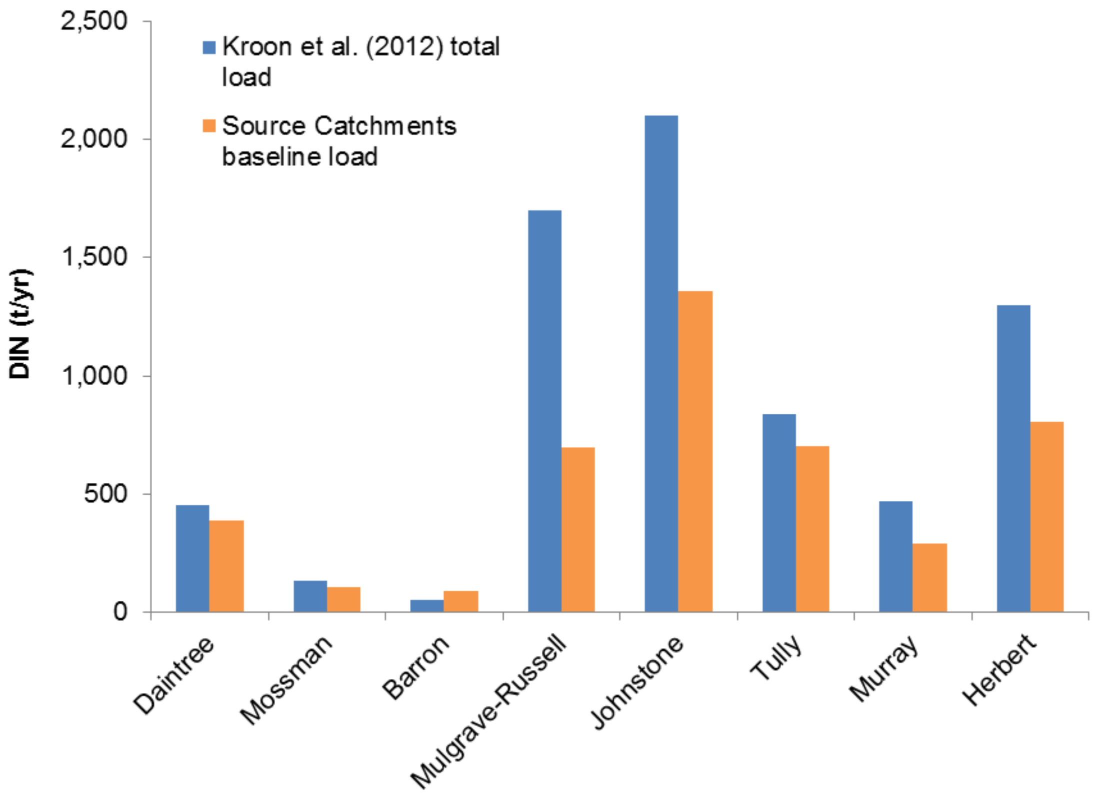

Figure 17 DIN (t/yr) load comparison for Kroon et al. (2012) and Source Catchments modelled estimate for WT basins

For PSII herbicides, the Source Catchments load estimate (8,596 kg/yr) was 28% lower than Kroon et al. (2012) (12,000 kg/yr). However, the differences by basin ranged from -61% to +418%. Another recent study estimated PSII herbicide loads from the Wet Tropics of 4,551 kg/yr (±2667 kg/yr) (Lewis et al. 2011). The PSII plot of the Kroon et al. (2012) current load, Lewis et al. (2011) load and the Source Catchments total baseline load by basin is shown in Figure 18. Error bars from (Lewis et al. 2011) has also been included. Both the Kroon et al. (2012) loads and the Source Catchments modelled estimates are higher than Lewis et al. (2011) loads for all basins. There were no consistent differences between Source Catchments and Kroon et al. (2012) for the calculated loads.

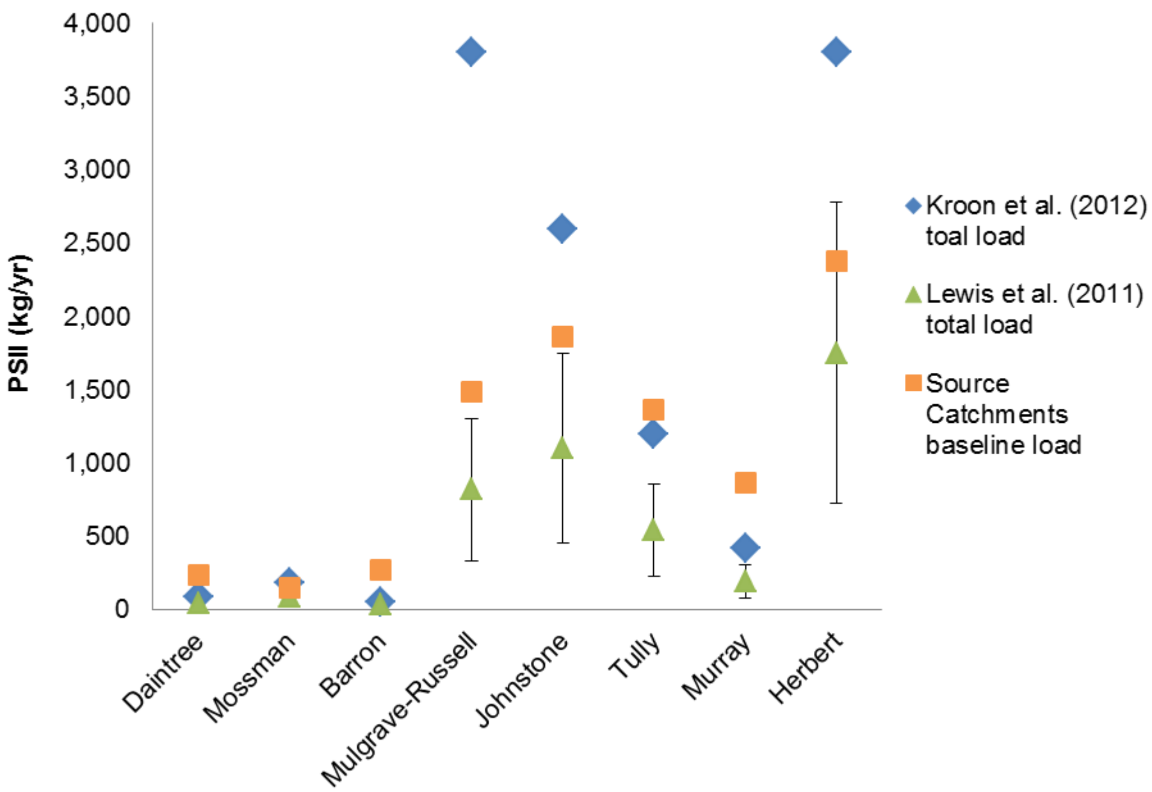

Figure 18 PSII (kg/yr) load comparison for Kroon et al. (2012), Lewis et al. (2011) and Source Catchments by basins

A further comparison was made between the Kroon et al. (2012) predevelopment loads to the Source Catchments predevelopment loads. The Source Catchments predevelopment load for TSS was higher than Kroon et al. (2012) predevelopment load (48% higher). The comparison for DIN was similar to TSS, where the Source Catchments predevelopment load estimate was much higher at 119% increase to the Kroon et al. (2012) estimate.

4.3.2 Long-term FRCE loads (1986–2009)

Long-term and annual load estimates derived from water quality data were calculated using the Flow Range Concentration Estimator (FRCE) for five EOS gauges in the Wet Tropics (Joo et al. 2012). All modelled constituent loads fell within the likely range, except for PN in the Barron Basin. For TSS, all modelled loads were within ±48% of FRCE values (Figure 19).

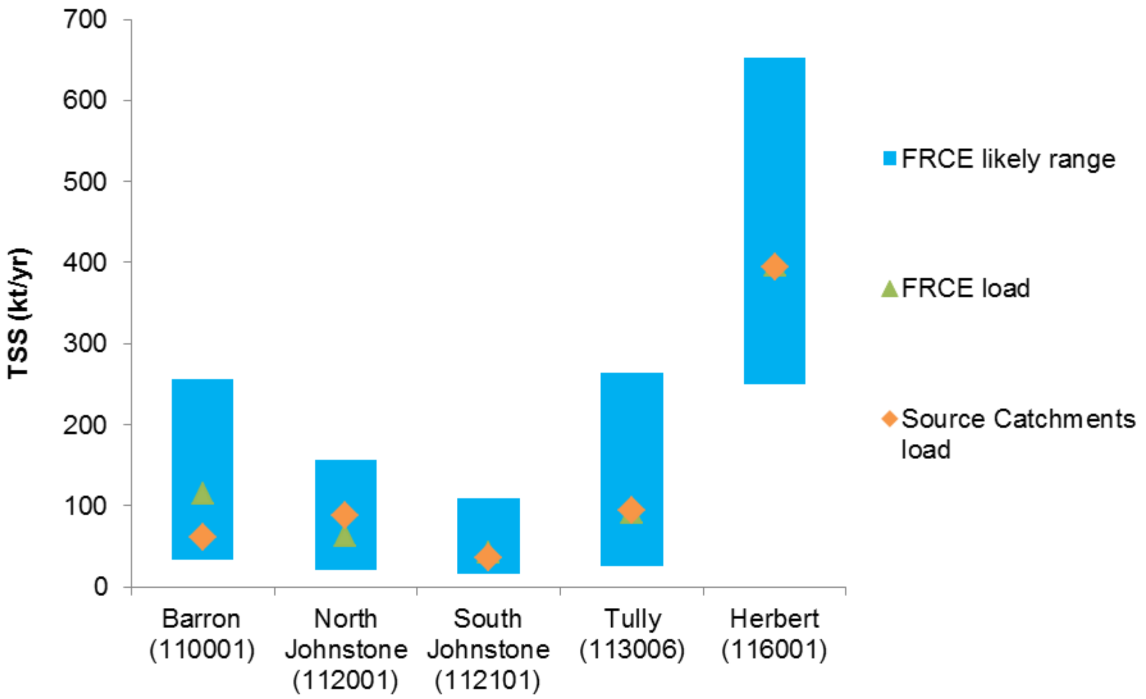

Figure 19 TSS (kt/yr) comparison between modelled and FRCE loads (observed data) for the period 1986–2009 for five EOS gauges

For TN and DIN, all modelled loads were ±38% and ±15% respectively of the FRCE values (Figure 20 and Figure 21). For DON, all modelled loads were within ±26% of the FRCE load. For PN, all sites were within ±57%, however the modelled load for the Barron was below the likely lower range (Figure 46 and Figure 47, Appendix G).

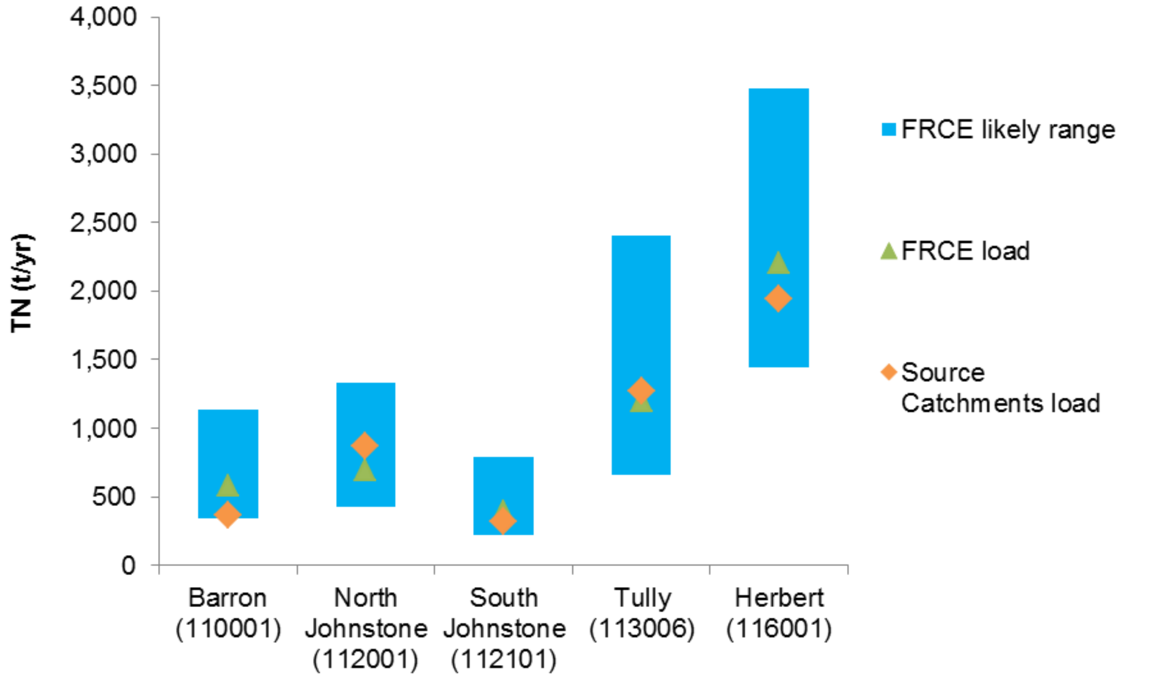

Figure 20 TN (t/yr) comparison between modelled and FRCE loads (observed data) for the period 1986–2009 for five EOS gauges

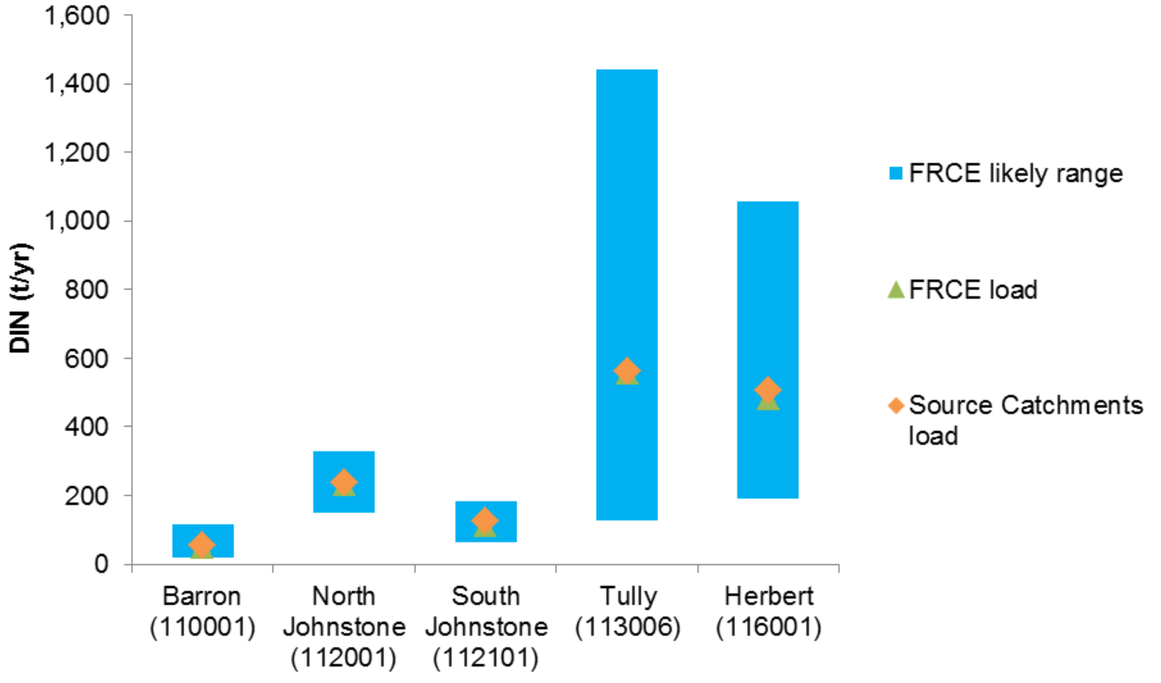

Figure 21 DIN (t/yr) comparison between modelled and FRCE loads (observed data) for the period 1986–2009 for five EOS gauges

For TP and DIP, all modelled loads were ±56% and ±73% respectively of the FRCE values (Figure 22 and Figure 23). For DOP, all modelled loads were under predicting compared to the FRCE estimate, with an average of -43% (Figure 48, Appendix G). The average difference between modelled and the FRCE value for PP was ±62% (Figure 49, Appendix G).

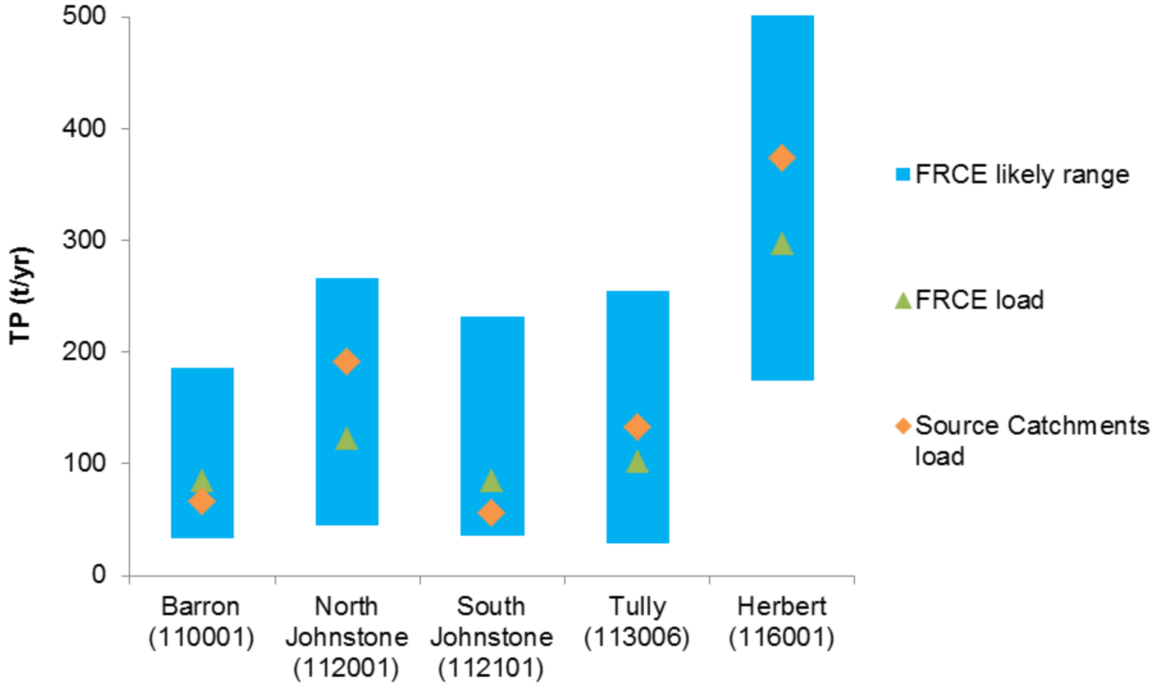

Figure 22 TP (t/yr) comparison between modelled and FRCE loads (observed data) for the period 1986–2009 for five EOS gauges

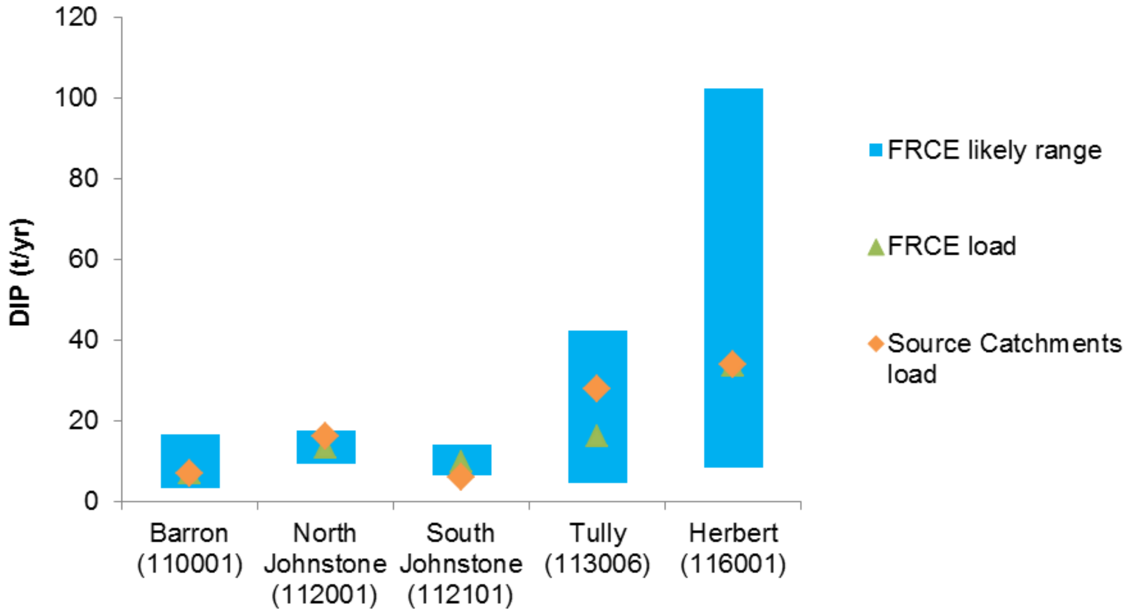

Figure 23 DIP (t/yr) comparison between modelled and FRCE loads (observed data) for the period 1986–2009 for five EOS gauges

Using the per cent error performance rating of Moriasi et al. (2007) the modelling at a monthly time-step rated as mostly 'very good' for all constituents (Table 21). Of the 75 statistical values (NSE, RSR and PBIAS), 63% of values were classed as 'very good'. The Herbert was the best performing site out of the five sites, mostly all 'very good' except for PBIAS for TP, which was ranked as 'good'. Of the five constituents, DIN had the best ranking, 13 of 15 statistics ranking 'very good'.

Table 21 Performance statistics based on three evaluation guidelines the monthly time-step (Moriasi et al. 2007)

Gauging station	Constituent	NSE		RSR		PBIAS	
		Value	Result	Value	Result	Value	Result
Barron 110001A-D	TSS	0.60	Satisfactory	0.64	Satisfactory	-47.6	Satisfactory
	TN	0.69	Good	0.56	Good	-37.7	Good
	DIN	0.61	Satisfactory	0.62	Satisfactory	14.8	Very good
	TP	0.78	Very good	0.47	Very good	-21.6	Very good
	DIP	0.89	Very good	0.33	Very good	1.4	Very good
Nth Johnstone 112001A/ 112004A	TSS	0.66	Good	0.58	Good	41.0	Satisfactory
	TN	0.84	Very good	0.40	Very good	25.5	Good
	DIN	0.91	Very good	0.29	Very good	2.9	Very good
	TP	0.64	Satisfactory	0.60	Good	55.4	Satisfactory
	DIP	0.82	Very good	0.43	Very good	18.4	Very good
Sth Johnstone 112101A	TSS	0.56	Satisfactory	0.67	Satisfactory	-14.7	Very good
	TN	0.63	Satisfactory	0.61	Satisfactory	-20.1	Very good
	DIN	0.93	Very good	0.26	Very good	11.3	Very good
	TP	0.50	Satisfactory	0.71	Unsatisfactory	-33.9	Good
	DIP	0.81	Very good	0.44	Very good	-34.2	Good
Tully 113006A	TSS	0.88	Very good	0.34	Very good	3.5	Very good
	TN	0.93	Very good	0.27	Very good	6.1	Very good
	DIN	0.92	Very good	0.29	Very good	1.2	Very good
	TP	0.79	Very good	0.46	Very good	30.9	Good
	DIP	0.33	Unsatisfactory	0.82	Unsatisfactory	73.8	Unsatisfactory
Herbert 116001A-D	TSS	0.87	Very good	0.37	Very good	-0.3	Very good
	TN	0.87	Very good	0.36	Very good	-11.8	Very good
	DIN	0.90	Very good	0.32	Very good	5.6	Very good
	TP	0.89	Very good	0.33	Very good	26.0	Good
	DIP	0.95	Very good	0.23	Very good	1.6	Very good

4.3.3 FRCE annual load comparison

The annual Source Catchments modelled loads for DIN at North Johnstone River at Tung Oil (112001A) were plotted with the FRCE annual loads (Joo et al. 2012) (Figure 24). The range of per cent difference from modelled to FRCE load was -19% to 107%. Generally, the Source Catchments loads over predicted in the drier years and under predicted in the wet years, in line with the hydrology results.

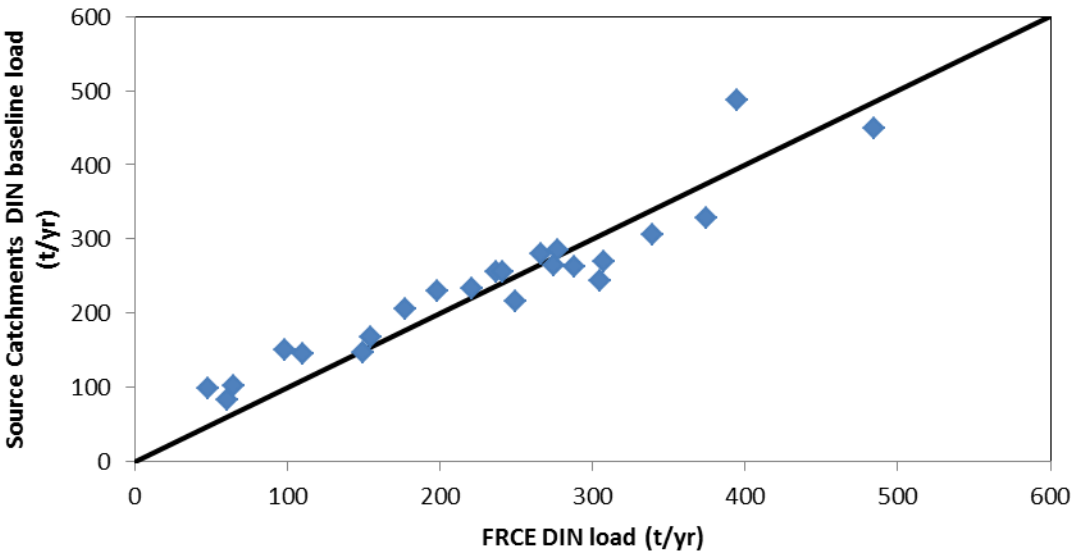

Figure 24 DIN (t/yr) comparison between Source Catchments annual modelled and FRCE (2013) loads (observed data) for the period 1986–2009 at North Johnstone River (112001A)

4.3.4 GBR Catchment Loads Monitoring Program – (2006 to 2010)

Whilst the modelled period used for reporting ceased on 30 June 2009, for short-term validation purposes, the model was extended by one year to incorporate the GBRCLMP loads data for the 2009–2010 wet season (Turner et al. 2012). A comparison was made between the mean GBRCLMP loads (averaged over four years, 2006–2010) and the Source Catchments modelled loads for the same time period. For TSS, all modelled loads were within ±50% except for the Barron (-58%) and all modelled loads were under predicted for this time period, except the Herbert (+12%) (Figure 25). Three of the five modelled loads were ±12% of the GBRCLMP load.

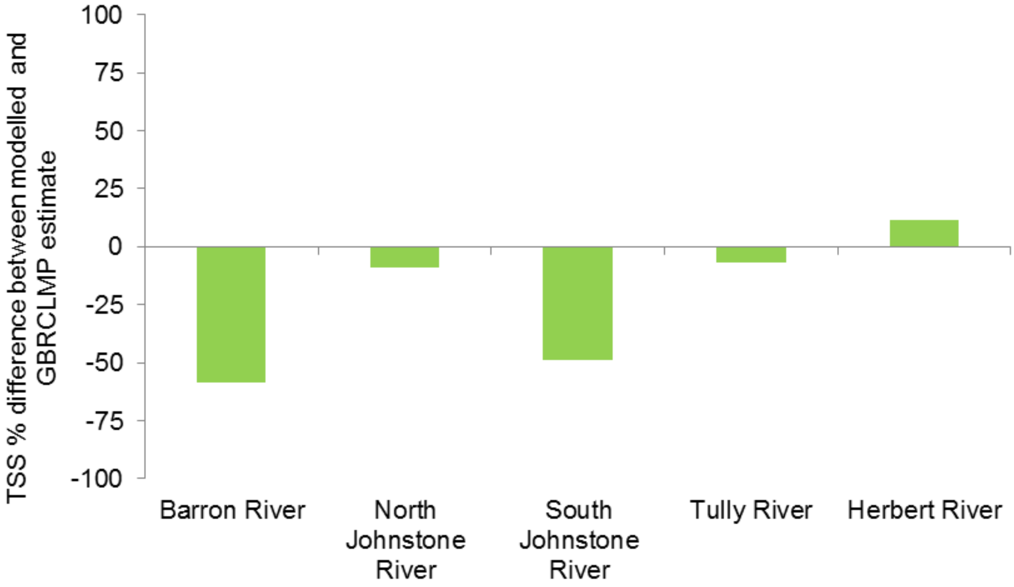

Figure 25 TSS difference (%) between modelled and GBRCLMP estimate from measured data for the period 2006–2010 for five EOS gauges

For TN, all modelled loads except the Barron (-51%), were ± 50% of the GBRCMLP load (Figure 50, Appendix G). For DIN, all modelled loads were within ± 50%, with the wetter basins under predicting and the drier basins over predicting (Figure 26). For DON, all modelled loads were within ± 50% of the GBRCMLP load (Figure 51, Appendix G). For PN, three of the five modelled loads fell within ± 50%, all modelled loads under predicted for this time period (Figure 52, Appendix G).

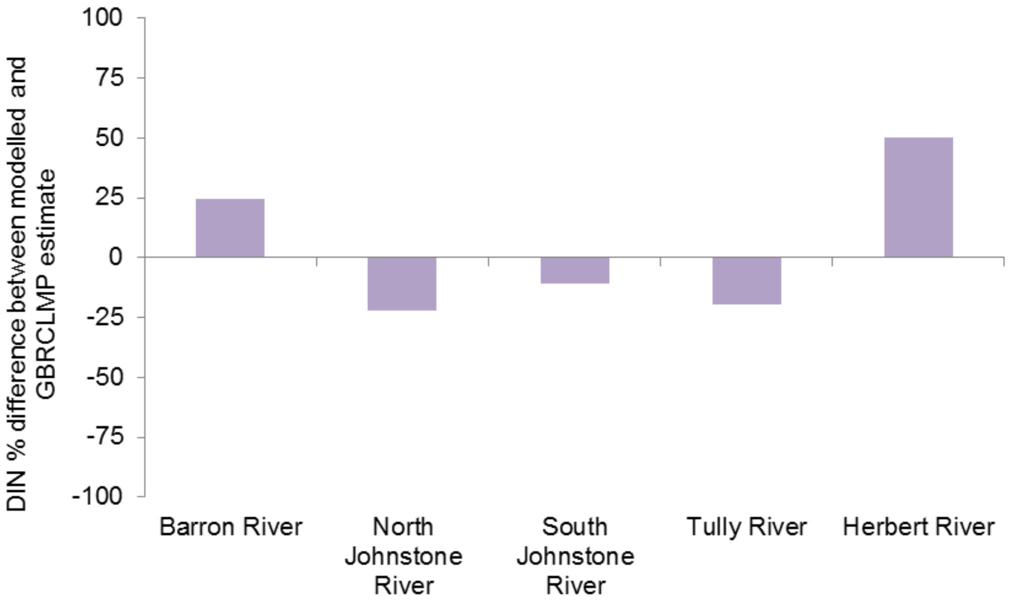

Figure 26 DIN difference (%) between modelled and GBRCLMP estimate from measured data for the period 2006–2010 for five EOS gauges

For TP, all modelled loads except Sth Johnstone (-60%) were within ±50% and all modelled loads were under predicting, mostly due to DOP and PP (Figure 53, Appendix G). For DIP, all modelled loads were within ± 50%, with three sites within ±10% and most modelled loads were under predicting compared to the GBRCMLP load (Figure 27). For DOP and PP, all modelled loads were under predicting compared to the GBRCMLP load, except PP for Herbert (+2%) (Figure 54 and Figure 55, Appendix G).

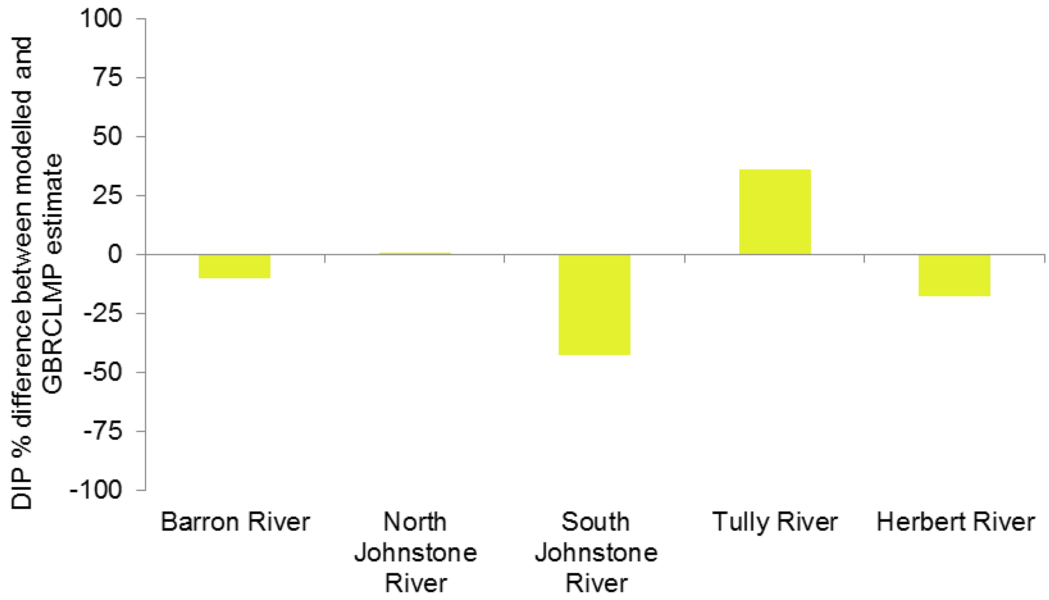

Figure 27 DIP difference (%) between modelled and GBRCLMP estimate from measured data for the period 2006–2010 for five EOS gauges

4.3.5 AIMS load estimates (1988–2000)

The AIMS load estimates (1988–2000) (adjusted to mean flow) for seven constituents at the EOS gauge at Tully were compared to the Source Catchments loads for the same period (1988–2000). All modelled loads were ±50% of the AIMS load estimates except for DIP (+100%), see Figure 28. Flow difference was +2%.

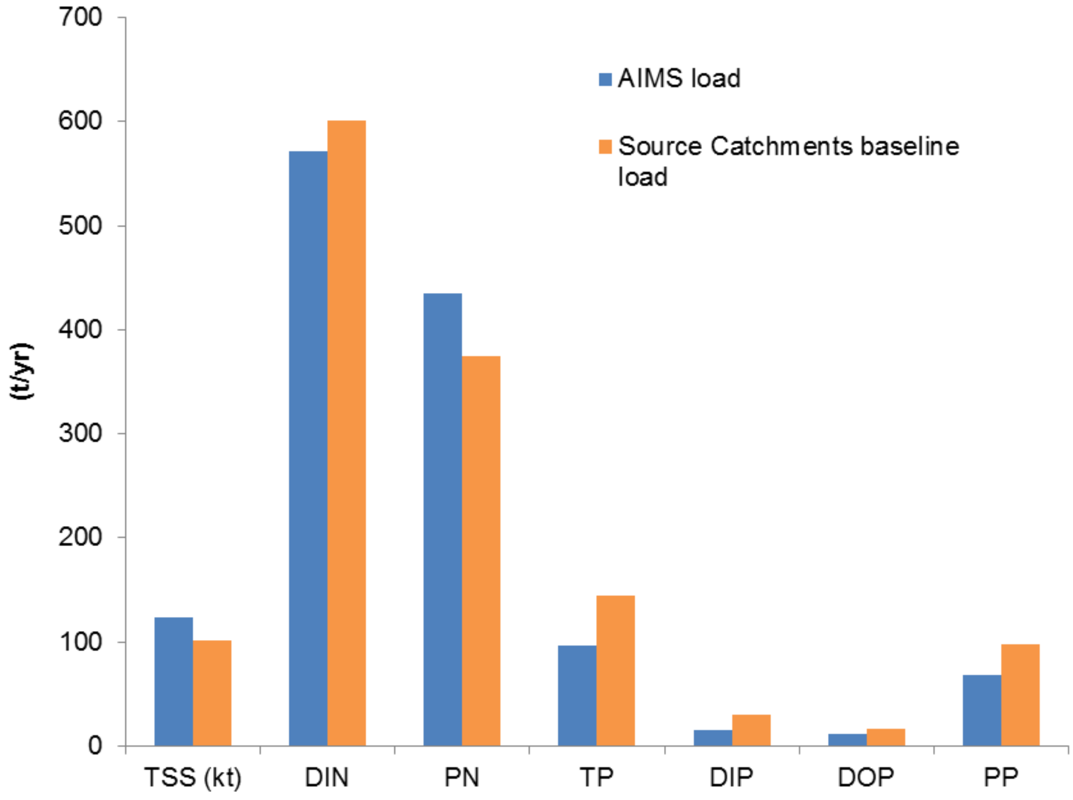

Figure 28 Comparison between modelled and AIMS observed loads for the period 1988–2000 for the Tully gauge at Euramo

AIMS in conjunction BSES also had a long-term suspended sediment monitoring program established in the Herbert River catchment during 1995–2000 (Furnas 2003). The measured average TSS load estimate of 540 kt/yr at the Herbert River at Ingham compared well with the TSS modelled estimate for the same time period of 551 kt/yr.

4.3.6 AIMS event load estimates (1994)

At a finer time scale, a comparison was made with event loads whereby event loads are defined here as any significant runoff event less than one month in duration to the Source Catchments loads for the same time period (Table 22). Samples were taken during cyclone Sadie in the Herbert River from 30/1/1994–5/2/1994 (Mitchell, Bramley & Johnson 1997).

There was generally good agreement between the Source Catchments loads and the event loads, considering that the model was not designed to report at the event scale, with all constituents within ±69% of the event load (Mitchell, Bramley & Johnson 1997). Seven of the nine modelled constituent loads were ±50% of the event load.

Table 22 Modelled loads and estimates of event loads during cyclone Sadie (30/1/1994–5/2/1994)

	TSS	TN	DIN	DON	PN	TP	DIP	DOP	PP
	(kt)		(t)						
AIMS event load	101	595	153	132	309	65	9	4	52
Source Catchments modelled load	104	482	126	188	168	105	11	6	88

4.3.7 Concentration data

For the EOS Tully site (Euramo gauge 113006A) which had the longest water quality monitoring record in the WT, the average long-term monitored DIN concentration of 0.2 mg/L (AIMS and DNRM 1987–present) matched well with the average modelled concentration of 0.19 mg/L (1986–2009). In addition, the average long-term monitored TSS concentration of 32 mg/L (AIMS and DNRM 1987–present) matched well with the long-term modelled (1986–2009) concentration of TSS 31 mg/L at Tully. In the larger and drier Herbert Basin, the long-term modelled TSS concentration (1986–2009) of 128 mg/L, was higher than the long-term monitored concentration of 70 mg/L (AIMS and DRNM, 1983–2008, n=269).

There was limited monitoring data for PSII herbicides at EOS gauges up to the end of the validation period (2009–2010) for a detailed comparison. The longest continuous grab sample data set was taken at the Tully EOS gauge from 10/1/2010–3/4/2010 (n=32). The average measured concentration of PSII herbicides (atrazine, diuron, hexazinone) was 0.31 µg/L. The average modelled concentration for the same herbicides and time period was 0.34 µg/L, which was 10% higher than the measured concentration.

4.4 Contribution by land use

By land use, grazing (including dairy) was the biggest source of TSS when compared to the other land uses at 247 kt/yr or 32% of the total export load (Figure 29). Sugarcane was the next biggest source and contributed approximately 29% of the TSS export load at 219 kt/yr, followed by nature conservation at 178 kt/yr or 23% of the total export load (Table 42, Appendix F). Although streambank erosion is not a land use (nor attributable to any specific land use in the modelling structure), this type of erosion accounted for 452 kt/yr of the total export TSS load, which is almost double that of grazing. Hillslope and gully erosion are separated in some land use categories and TSS loads by erosion type are outlined in section 4.5.

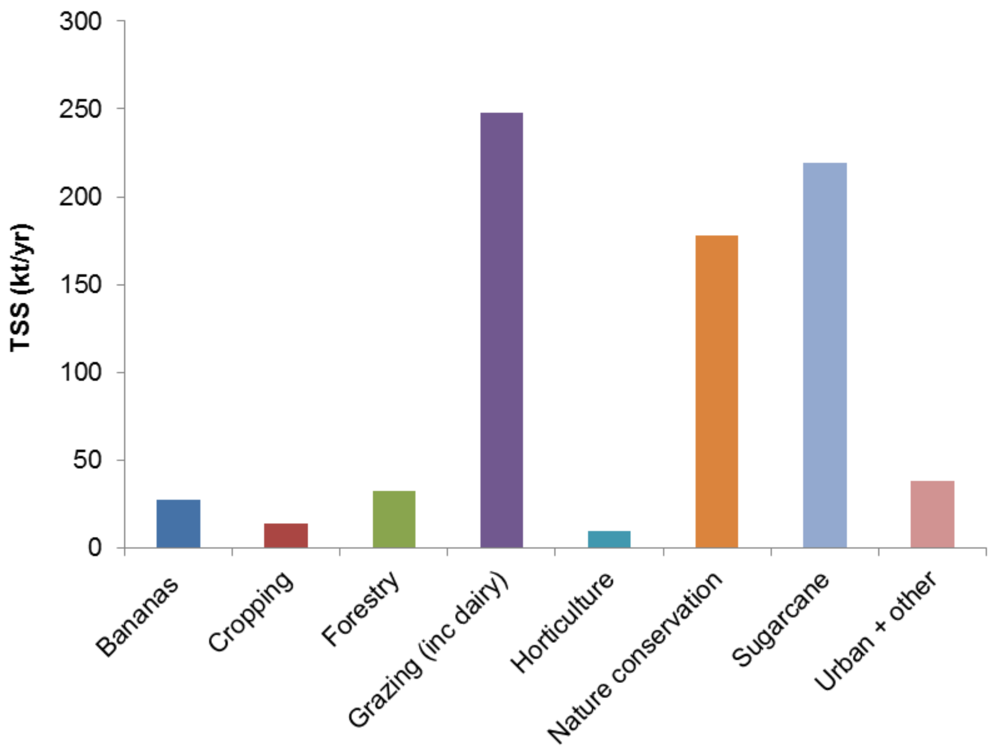

Figure 29 TSS (kt/yr) contribution to export by land use

Sugarcane had the highest proportion of the total DIN export load at 41% (1,828 t/yr) followed by nature conservation 1,411 t/yr or 32% (Figure 30). Sugarcane contributed the highest PSII herbicide export load, contributing 96% with the remaining 4% from cropping.

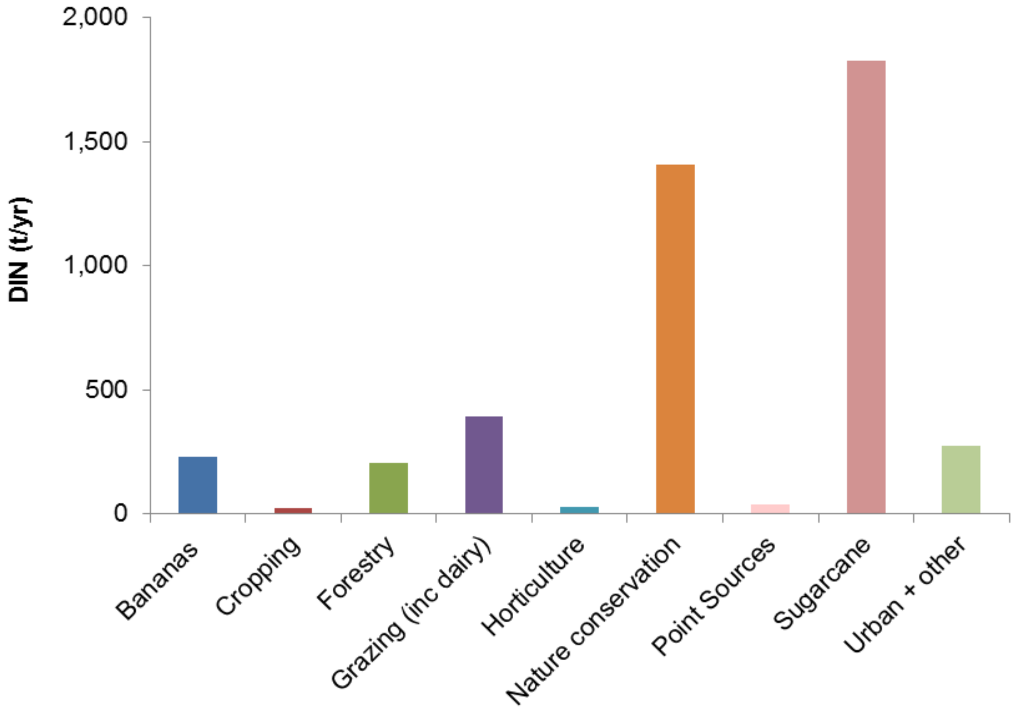

Figure 30 DIN (t/yr) contribution to export by land use and point sources

The DIN load contribution to export for sugarcane, bananas, cropping and horticulture by basin is shown in Figure 31. Five hotspot basins for sugarcane, they are; Mulgrave-Russell (225 t/yr), Johnstone (755 t/yr), Tully (316 t/yr), Murray (134 t/yr) and the Herbert (326 t/yr). Sugarcane occurs in the Barron Basin however, the DIN export load is small at 4 t/yr. Two hotspot basins for bananas are the Johnstone (122 t/yr) and the Tully (88 t/yr) (no banana occurs in the Daintree, Mossman or Herbert basins). Compared to sugarcane, cropping and horticulture produced very small export loads. Loads are tabulated in Table 43 (Appendix F).

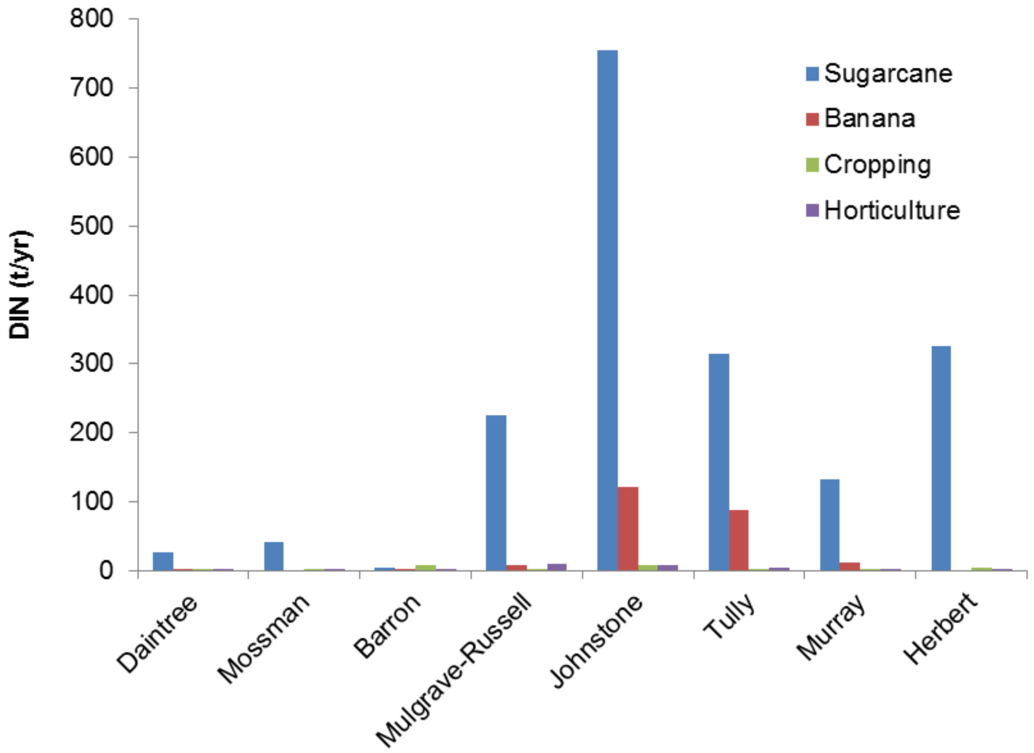

Figure 31 DIN (t/yr) contribution to export for sugarcane, banana, cropping and horticulture by basin

The sugarcane DIN results were spilt geographically based location of the EOS gauge in each basin. The area of sugarcane (%) and DIN load (%) above and below each EOS gauge is presented in Table 23. The area and DIN load below the EOS gauge also included small coastal subcatchments (shaded grey in Figure 9, see section 4.1.1). A total of 75% of the sugarcane DIN load was generated in the ungauged area and by basin, the per cent of DIN load varies from the lowest in the Tully at 26% to 100% in the Daintree. The per cent of sugarcane area and per cent of sugarcane DIN load for each catchment are similar. The slightly higher sugarcane DIN load versus area of sugarcane in the ungauged section is most likely due to slightly higher rainfall and runoff in these areas compared to sugarcane found upstream of the EOS gauges.

Table 23 Sugarcane area (%) and the sugarcane DIN load (%) above or below the EOS gauge for each basin

Basin	Sugarcane area Above EOS gauge (%)	Sugarcane DIN load Above EOS gauge (%)	Sugarcane area Below EOS* gauge (%)	Sugarcane DIN load Below EOS* gauge (%)
Daintree	0	0	100	100
Mossman	46	43	54	57
Barron	64	56	36	44
Mulgrave-Russell	16	22	84	78
Johnstone	8	6	92	94
Tully	74	74	26	26
Murray	1	1	99	99
Herbert	36	32	64	68
Wet Tropics	**30**	**25**	**70**	**75**

*Also includes small coastal subcatchments north or south of each EOS gauge

4.4.1 Land use contribution per unit area to export

On a land use by area basis, bananas contributed to export the highest areal rate of TSS at 1.8 t/ha/yr, followed by sugarcane at 1.2 t/ha/yr then horticulture at 1.1 t/ha/yr (Figure 32). For TN, bananas had the highest areal load at 25 kg/ha/yr, followed by sugarcane at 22 kg/ha/yr and urban/other at 12 kg/ha/yr**.** Bananas generated the highest areal load for DIN at 15 kg/ha/yr, followed by sugarcane at 10 kg/ha/yr and urban/other at 6 kg/ha/yr (Figure 33 and Table 44, Appendix F, for all land use areal loads).

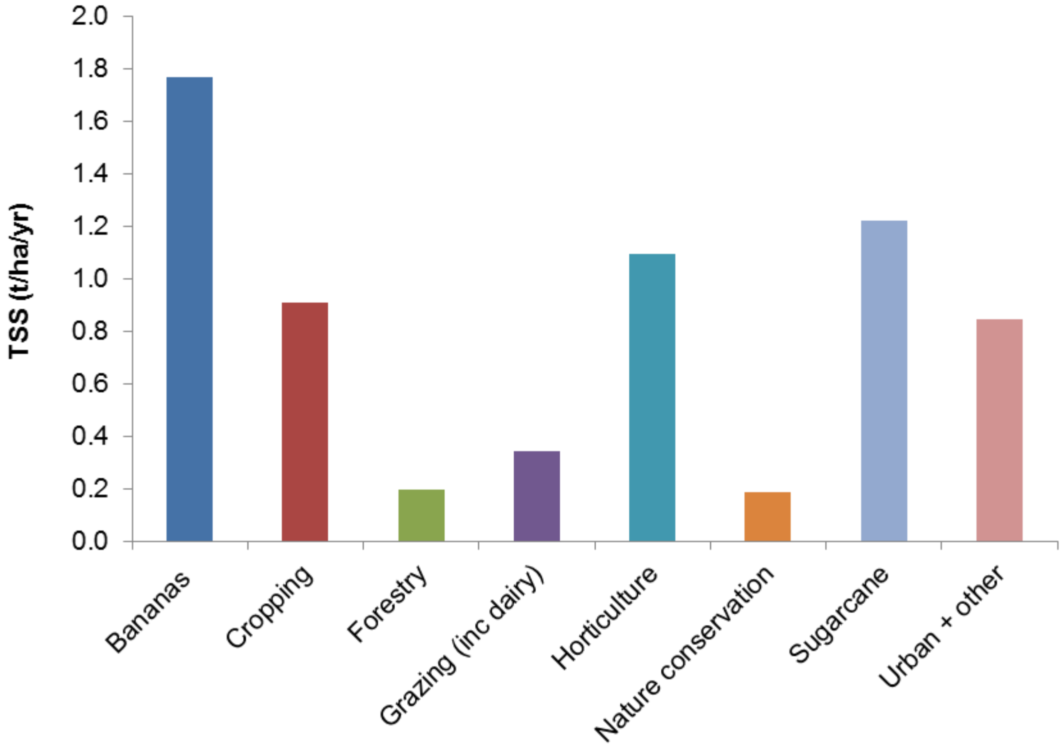

Figure 32 TSS (t/ha/yr) areal contribution to export by land use

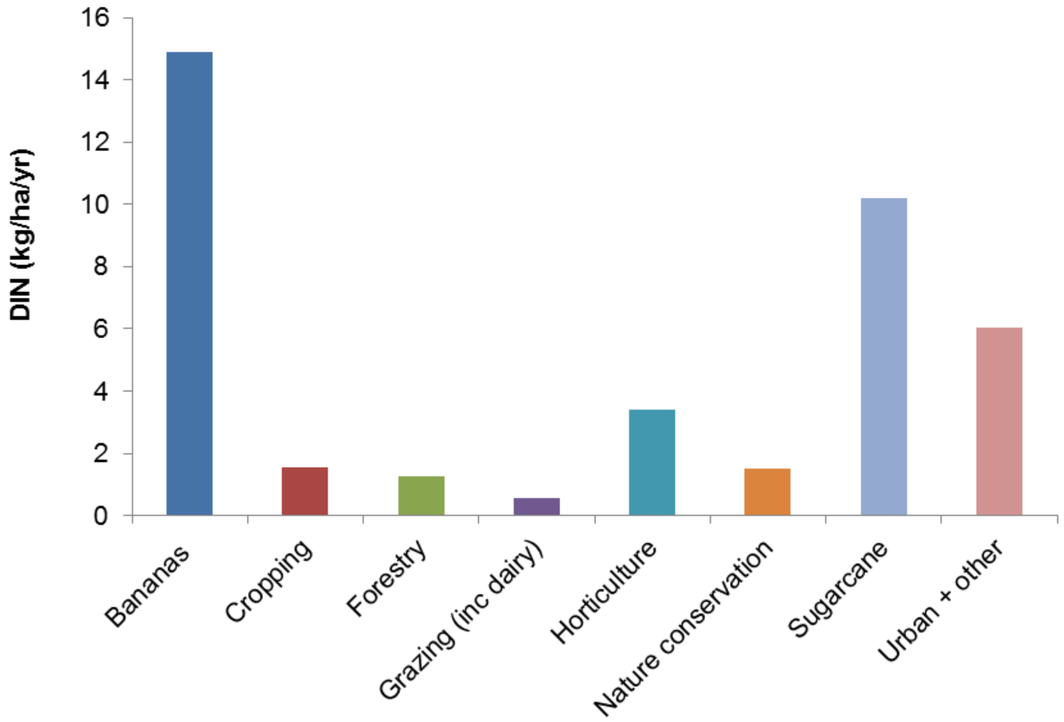

Figure 33 DIN (kg/ha/yr) areal contribution to export by land use

Across the WT NRM region, bananas and sugarcane had the highest areal rates for DIN. However, by basin, there was a range of values for DIN (Figure 34). The range of DIN for bananas was 2 kg/ha/yr in the Barron Basin to 24 kg/ha/yr in the Mulgrave-Russell Basin. For sugarcane, the range was 1 kg/ha/yr in the Barron to 27 kg/ha/yr in the Johnstone Basin. For cropping, the range was from 1 kg/ha/yr in the Barron and Herbert basins to 13 kg/ha/yr in the Daintree and Tully basins. For horticulture, the range was again from 1 kg/ha/yr in the Barron and Herbert basins to 9 kg/ha/yr in the Mulgrave-Russell Basin (Table 45, Appendix F).

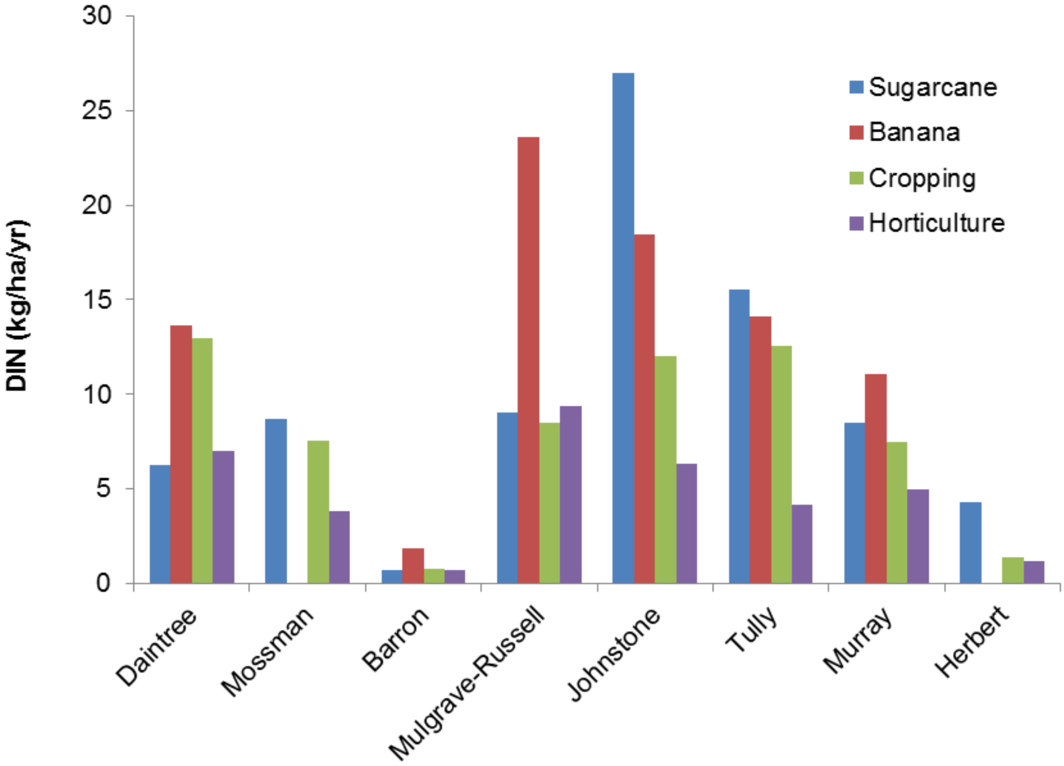

Figure 34 DIN (kg/ha/yr) export by basin for sugarcane, banana, cropping and horticulture land use

For TP, bananas had the highest areal load at 3.1 kg/ha/yr, followed by sugarcane at 2.7 kg/ha/yr and horticulture at 1.6 kg/ha/yr. Sugarcane had the highest export areal load for PP at 2.4 kg/ha/yr, followed by bananas at 1.5 kg/ha/yr. Sugarcane had the highest export areal rate of 46 g/ha/yr for PSII herbicides, followed by cropping at 23 g/ha/yr. There was a range of values for PSII herbicides for sugarcane by basin, see Figure 35. The range of PSII herbicides for sugarcane was 16 g/ha/yr in the Barron Basin to 67 g/ha/yr in the Tully Basin (Table 46, Appendix F).

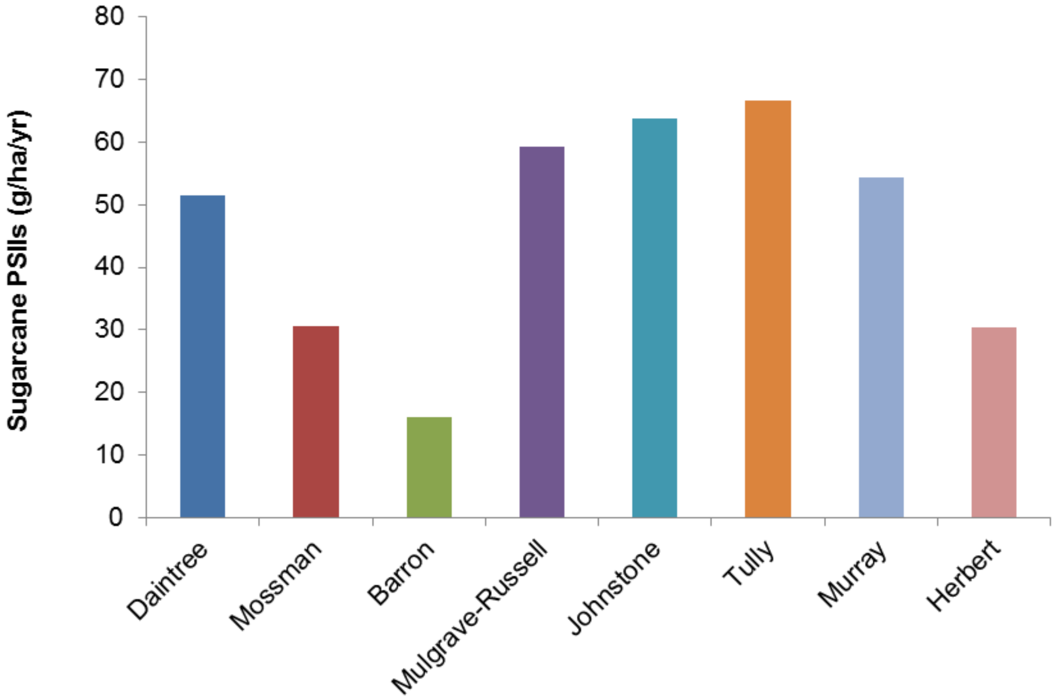

Figure 35 PSII herbicides (g/ha/yr) export by basin for sugarcane land use

4.5 Sources and sinks

The greatest sources of TSS in the WT were from hillslope 59% and streambanks 37%, with contribution from gullies the remaining 4%. The sources, sinks and resultant export of each constituent are presented in Table 24. Only 3% of TSS is lost to deposition, with 97% of the TSS being exported to EOS. Storage deposition was the main process by which TSS and particulate nutrient constituent losses occurred. The majority of the dissolved nutrient supply (99%) was from diffuse dissolved land uses, with the remaining 1% from point sources (sewage treatment plants). Dissolved nutrient loss was only 2% of total supply, mostly due to storage decay. The modelled PSII herbicide supplied to the stream was 10,014 kg/yr, with 86% of supply exported to EOS (8,596 kg/yr). Of the remaining 14% lost, the majority of the loss was from in-stream decay.

Table 24 WT sources and sinks

	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)
SOURCE	**1,253**	**12,467**	**4,499**	**3,971**	**3,997**	**1,715**	**234**	**134**	**1,347**	**10,014**
Hillslope	737	3,722			3,722	1,108			1,108	
Gully	54	63			63	12			12	
Streambank	462	212			212	227			227	
Point source		48	38	10		9	7	2		
Diffuse dissolved		8,422	4,461	3,961		359	227	132		10,014
SINK (loss)	**34**	**316**	**62**	**101**	**153**	**60**	**6**	**4**	**50**	**1,418**
Storage decay		139	54	85		8	5	3		224
Extraction	4	43	8	16	19	6	1	1	4	2
Floodplain deposition	5	11			11	5			5	
Storage deposition	25	123			123	41			41	
Stream decay										1,192
EXPORT	**1,219**	**12,151**	**4,437**	**3,870**	**3,844**	**1,655**	**228**	**130**	**1,297**	**8,596**

4.6 Progress towards Reef Plan 2009 targets

Across the GBR region, modelled average annual pollutant loads entering the reef from 2008–2013 have been reduced as a result of the adoption of improved land management practices (Table 10 and section 1.1). Progress towards the Reef Plan TSS target was rated as very good with the estimated average annual sediment load leaving the GBR basins reduced by 11% over the five years to June 2013 (Figure 36 and Table 47, Appendix F). Progress towards the TN target was rated very poor with the estimated average annual load reduction 10%. The highest TN reduction occurred in the MW NRM region at 17% (302 t/yr).TN load reductions were achieved through a combination of managing dissolved nitrogen (mostly DIN) from sugarcane and PN from grazing areas. The GBR DIN load reduction was 16% (‘poor’ progress), with the Burnett Mary region having the highest reduction (31%).

The GBR wide estimated average annual TP load reduction of 13% was rated as poor progress. This reduction was predominately due to improved grazing management practices. The Wet Tropics and Mackay Whitsunday NRM regions had 19% and 14% reductions respectively. Over 80% of the TP reduction was related to reductions in particulate phosphorus. The largest water quality load reduction across the GBR was for PSII herbicides. The average annual PSII herbicide load leaving the GBR basins reduced by 28% (rated as 'moderate' progress) for Report Card 2013 (2008–2013). Over 80% of the reduction in the PSII load occurred in the sugarcane areas of Wet Tropics and Mackay Whitsunday NRM regions.

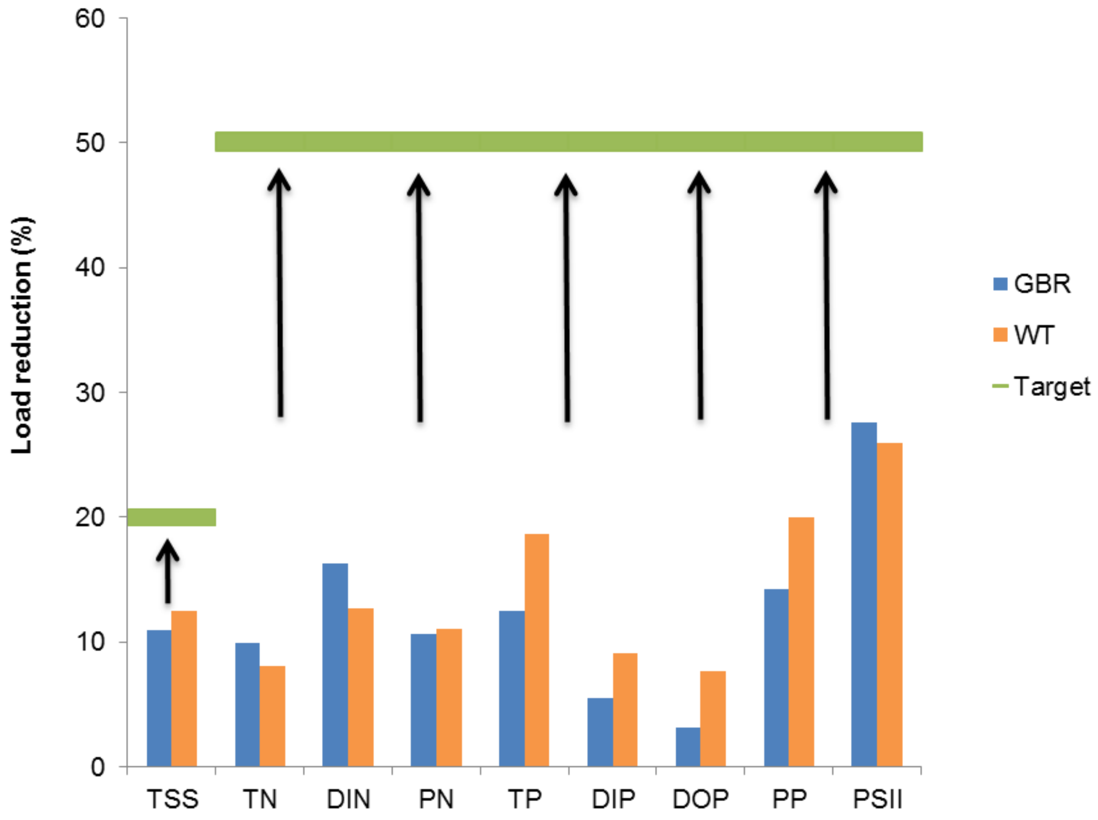

Figure 36 GBR and WT modelled load reductions (%) for Report Card 2013

WT NRM region load reductions are outlined in Table 47, Appendix F. WT TSS load reduction was rated as very good, with the estimated annual average sediment load reduced by 13% over the five years to June 2013. Of the 13%, the major reduction was from investment in improved streambank management (50% of the reduction) mostly riparian fencing, followed by sugarcane soil management at 43%. The remaining 7% reduction was a result of a reduction in hillslope and gully erosion. Improved management of gullies and streams was incorporated into the model for Report Cards 2011–2013 once the data became available from regional NRM groups.

Of the 43% reduction in TSS load attributed to sugarcane, the majority was due to improvements in hillslope erosion management. For soil management in sugarcane, a total of 1% of the area moved out of D class management systems and 39% of the area moved out of the C class management system while there was a net increase of 27% into B and a net increase of 13% into A class management. These system changes were attributed to a shift from conventional tillage with bare fallows to controlled traffic often with a cowpea cover crop in the fallow. The majority of management practice change in sugarcane was due to Reef Rescue investment (97% of the total reduction). The remaining 3% was due to other programs and investments.

For soil management in grazing, <1% of the area moved out of the D management system, 1.7%

of the area moved out of the C management system and 1% of the area moved out of the B management system while there was a net increase of 2.7% into A. Of the total WT grazing area, 6% of grazing land use underwent change. Grazing can be spilt further into Reef Rescue and other government and industry programs, including extension services. The majority of the reduction in TSS in the grazing load came from Reef Rescue investments, approximately 97% across the reporting periods, with the remaining from other programs and investments.

There was ‘poor’ progress made towards reducing the WT DIN anthropogenic baseline load. Management practice adoption in sugarcane resulted in a 13% reduction in the DIN load. The major change was a net decrease in the area of land under D class management of 18%. There was a 14% shift out of the C management systems and a net increase in area of 25% into B and 7% move into A class management. Most system changes were stepwise, so for example C to B, in some cases, there was a two-step system change from D to B. The biggest increase in area of a management system change was into B practices, attributed to the adoption of the ‘Six Easy Steps’ nutrient management program for sugarcane. No information was available on practice change for DON and therefore was not modelled. For sugarcane, there were differences in the total hectares of change between nutrients, soil and herbicides for the four reporting periods. For nutrients, 52% of the total sugarcane area underwent change (a shift into a better management class), 43% for soil and 35% for herbicides. There was a difference in the total hectares of sugarcane change between each basin. Of the total hectares of change, 46% of the changed occurred in the Herbert Basin, followed by the Tully/Murray at 23%, 16% in the Russell-Mulgrave, 8% in the Johnstone, 5% in the Daintree/Mossman region and 2% in the upper Barron.

For DIP and DOP, there was a reduction in load of 9% and 8% respectively from the anthropogenic baseline load (‘very poor’ progress). Reductions in the load of phosphorus were modelled as a response to changes in management practices that reduce runoff from a paddock. Some of these changes would have occurred in Report Card 2010, however, the methodology to account for these improvements was only implemented in the modelling for Report Card 2011.

For PN and PP there were reductions of 11% (‘very poor’ progress) and 20% (‘poor’ progress) respectively. Most of the change (>89%) was attributed to sugarcane for both constituents and was associated with improved soil management. Grazing improvements accounted for 9% of total change for PN and 11% of total change for PP. Of the grazing PN and PP improvements, the majority of the reduction in the grazing load came from Reef Rescue investments at 96% of the total reduction with the remaining from other programs and investments.

The PSII herbicide reduction was the highest out of all constituents at 26% (‘moderate’ progress) with the reductions attributed to investment in sugarcane. There was a net decrease in area of 5% out of the D management system, 29% out of the C management system and there was a net increase in area of 30.6% into B and a 3% move into A. Most of the change was into B management system, including practices relating to the selection of non-residual herbicides moving to knockdowns for weed control. Part of the large reduction for PSIIs from the baseline was also due to the move into ‘A’ class management, which mostly occurred for the reporting period (2012–2013). Sugarcane herbicide improvements were mostly from Reef Rescue investments (91% of the total reduction), with the remaining 9% from other programs and investments. Reef Rescue accounted for 100% of the total reductions for Report Cards 2010–2012.

Each Report Card presents the cumulative improvement (percent reduction and per cent change) from the previous period. Different load reductions were seen between Report Cards (Figure 37). The biggest reduction across all Report Cards occurred between 2012 and 2013 reporting period for TSS, TN, PN, TP, PP and PSIIs. The greatest load reduction for DIN occurred between the 2010 and 2011 reporting periods.

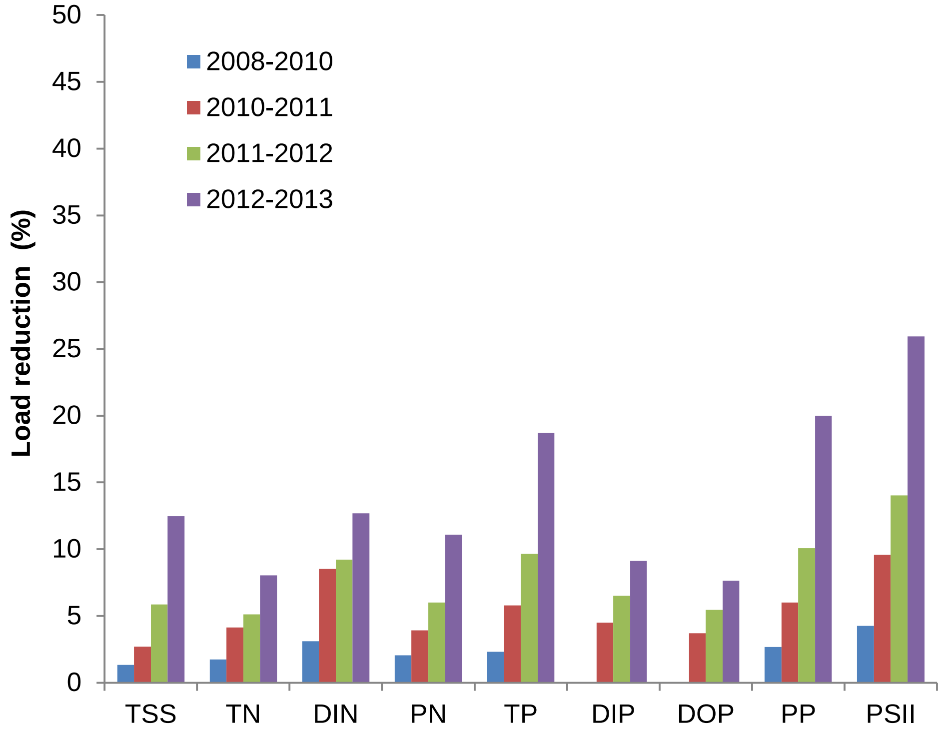

Figure 37 WT constituent reductions (%) for individual reporting periods

Additional scenarios were run that modelled an ‘All A’ class management scenario through to an ‘All D’ class management scenario for DIN and PSIIs for sugarcane. Results from Report Card 2013 were included to demonstrate how progress related to the other hypothetical scenarios. Under an ‘All A’ management scenario, DIN loads were expected to be reduced by 28% from the anthropogenic baseline (Figure 38). A reduction of up to 95% is possible under an ‘All A’ scenario for PSIIs (Figure 39). The larger jump from the anthropogenic baseline to an ‘All B’ scenario for PSIIs compared to DIN reflects the larger proportion of the area of cane in C and D class management at the baseline year compared the nutrient management practices whereby a larger area of cane was in C and B class for nutrient management at the baseline year resulting in less room for improvement.

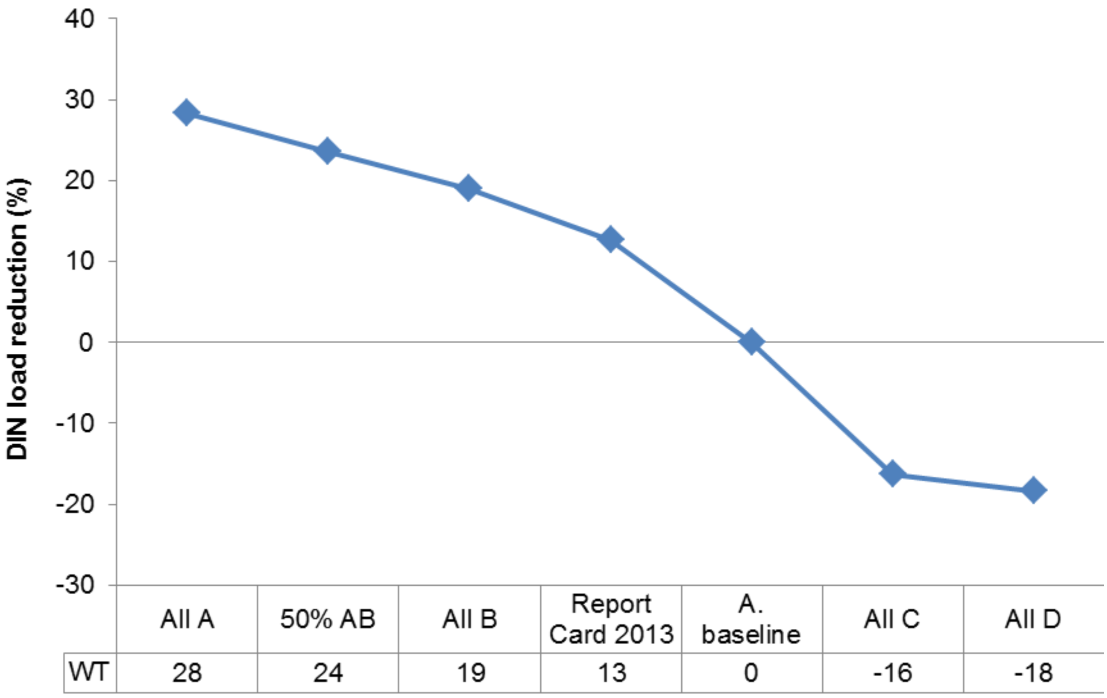

Figure 38 DIN load reductions (%) from additional scenarios

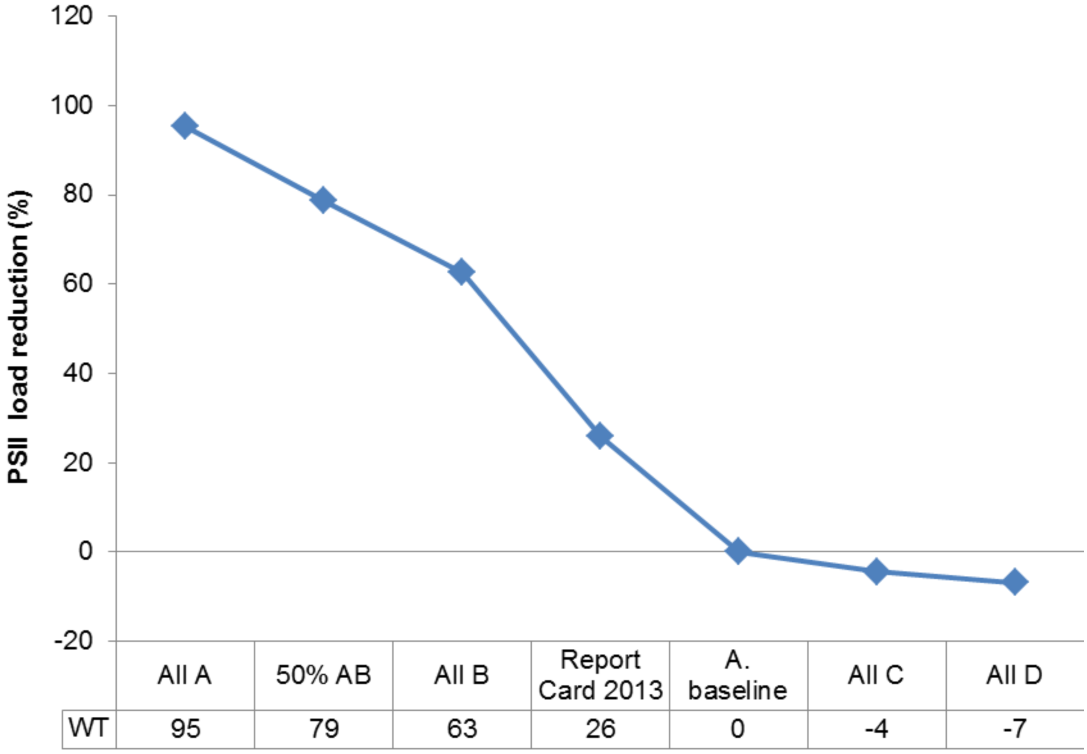

Figure 39 PSII load reductions (%) from additional scenarios

5 Discussion

Catchment modelling has quantified the effects of improved agricultural land management practices adoption on water quality, primarily as a result of government investment. The results are assessed against the Reef Plan water quality targets and the associated focus on EOS water quality. The use of a consistent modelling platform (Source Catchments) and methodology across all GBR regions, enables the direct comparison of outputs from each region, as well as from each scenario (total baseline, anthropogenic baseline, predevelopment and management change loads). This study is an updated estimate of the pollutant loads from those in Kroon et al. (2012) due to use of the most recent point and spatial data sets. It is the first GBR-wide catchment modelling since 2005 that separated the predevelopment or natural component from total baseline loads (McKergow et al. 2005a, McKergow et al. 2005b). One of the main improvements since Kroon et al. (2012) was the use of the same modelling platform across the GBR and the inclusion of coastal catchments below the EOS gauging station to enable the prediction of a total exported load to the GBR. Previous estimates were either not able to model those coastal subcatchments, or used a scaling approach to account for runoff and loads generated from these areas.

Other improvements included the increase in temporal and spatial resolution of input datasets and the ability to apply a specific model to each functional unit within the Source Catchments modelling framework. A daily time-step model, rather than the traditional long-term average annual model, has allowed the investigation of flows and constituent loads at a range of time-steps. This was not possible with previous models. In addition, the availability of event monitoring data collected at a high temporal frequency has enabled model validation down to an event time-step in some instances. The ability to 'plug-in' the most appropriate paddock scale model outputs and combine this with models simulating landscape processes such as gully and bank erosion and floodplain deposition into a single framework was invaluable. Other advantages of the current modelling approach include a high level of transparency (that is, repeatability) and high flexibility in analysing the model outputs at a range of scales and time-steps. The high level of validation undertaken in this study was not possible in previous modelling studies due to the availability of data (or lack thereof). There is a high degree of confidence in the model outputs from this research because of the extensive validation of hydrology and constituent loads. An overall discussion of the GBR results can be found in Waters et al. (2014).

5.1 Hydrology

There was generally good agreement between the simulated streamflow volumes from the underlying hydrological model and the gauging station data, particularly at long-term average annual and annual time-steps. The majority of the modelled flows used in the calibration met the 'goodness of fit' for three objective functions. Most gauges met the monthly and daily NSE (>0.8 and >0.5 respectively) and most modelled flows were within the total volume criteria of ±20%. NSE values >0.8 are a good result for modelling catchment runoff (Chiew & McMahon 1993). The modelled flows for streams and catchments in the Wet Tropics region where no flow data exists are considered a good estimate of flows because of the good agreement between modelled and measured flow data in gauged streams.

The smaller calibration regions had poorer calibration results than the larger downstream calibration regions. These smaller areas tend to have flows that are 'flashy' (rapid increase/decrease in streamflow), which often makes accurate rating curves difficult to obtain. For example, in the Tully Basin, the gauging station at Tully River Euramo (1,450 km^2) has 92% of recorded peaks (DSITIA 2013a). Recorded peaks are the highest stream gauging measurements as a percentage of the highest recorded flow (estimated from height record), the higher the percentage, so does the likelihood of more reliable medium and high flow records (DSITIA 2013a). In contrast, the gauging stations with a catchment area <276 km^2, recorded only an average 17% (n=6) of peaks. The exception is the Tully River at Koombooloomba (164 km^2) where 98% of peaks were recorded as a requirement for dam operation. The lack of rainfall stations in these smaller, upland areas, combined with steep rainfall gradients may also add to the calibration error in these areas, compared with the larger downstream catchments.

On an annual time-step across the region, the modelled annual flows typically agreed well with the annual observed flows. Peak flows were generally under-predicted in wetter years, but the smaller flows were over-predicted in the drier years. For the three wettest years, the modelled peaks were within the same order of magnitude as the measured peaks. Inspection of the hydrograph shape and timing suggests that the daily simulated runoff is often poorly matched to observed flows. At this scale (weeks to days), the model tends to underestimate peak discharge and overestimate low or baseflow.

Uncertainty in the SILO rainfall grids was one main reason for the general under-prediction of flows (DSITIA 2013f). This uncertainty resulted from a low density of rainfall gauges, particularly in steep terrain where there are large rainfall gradients and variable lengths of rainfall station records. Both are common in the WT (DSITIA 2013f). Recent calibrations undertaken by DSITIA hydrologists using the Sacramento RR model for input into the Integrated Quantity and Quality Model (IQQM), found that mean annual 50 year isohyets were generally more reliable in reflecting mean annual rainfall variation than the SILO data. To correct the SILO data, they scaled it using the 50 year mean annual isohyets. All Sacramento calibration regions (46 in total) had positive scaling factors for Mossman, Mulgrave-Russell Johnstone, Tully-Murray and Hebert basins (DSITIA 2013a, DSITIA 2013e, DSITIA 2013d, DSITIA 2013c, DSITIA 2013b). The average scaling factor was 28%. The Mossman Basin had the highest average scaling factor of 54%. This is most likely the main reason why the modelled flow at the only Mossman gauge had a total volume difference of -24%. Of the 21 gauges used in the SIMHYD calibration, the Mossman gauge has the second largest total volume difference.

Recent work has reported that five out of the eight WT basins had >10% of annual flow potentially by-passing or under-read by each EOS gauge (Wallace, Karim & Wilkinson 2012). Therefore, the constituent loads calculated by the model for the Herbert, Mossman, Tully, Mulgrave-Russell and Murray basins could be considered a minimum load because of possible under-estimation of the flows.

The movement of sediment, nutrients and herbicides is largely controlled by the volume, intensity and distribution of rainfall (Furnas 2003). The WT is unique compared to the other GBR regions as it has the highest annual flow volume with 33% of the flow to the GBR from only 5% of the GBR contributing land area. Moreover, runoff is greater than 50% of rainfall for most of the WT basins. Other factors such as topography, soils and vegetation greatly influence the amount of rainfall moving as runoff (Furnas 2003). The time from rainfall to runoff to discharge is short in the WT compared to the larger basins such as the Fitzroy and Burdekin. This results in limited loss of dissolved nutrients and herbicides by in-stream or floodplain processes before being transported into the GBR lagoon in floods. Streams flow all year round in the major Wet Tropics rivers due to intermittent falls and groundwater inputs. For example, there is less difference in annual discharge in the Tully River than in the highly seasonal Burdekin River, primarily due to more constant discharge in the Tully River (Furnas 2003). Future work will concentrate on improving the calibration and is further discussed in section 5.5.

5.2 Modelled constituent loads and validation

This discussion focusses primarily on DIN and PSII herbicides, as DON is considered to have low and variable bioavailability in the marine environment (Seitzinger, Sanders & Styles 2002). TN is discussed in the context of speciated N. Fine sediments are generally not a priority constituent in the WT but as the WT was the third highest contributor and thus the results are examined. Particulate nutrients are associated with sediments, so are not discussed. Phosphorus is briefly considered but because primary production in the GBR is thought to be nitrogen limited, the emphasis is placed on N rather than P (Furnas et al. 2005).

The Wet Tropics NRM region had the highest proportion of the current GBR loads of TN, dissolved N and PSII herbicides. Of the remaining constituents, the WT was either the second or third highest contributor. It is clear that the WT is an important contributor of all modelled constituents, all of which were generated from 5% of the GBR contributing area. The WT and Mackay Whitsunday region had a high relative risk for DIN and PSII herbicides in a recent risk rating of the priority contaminants in the GBR basins (Waterhouse et al. 2012).

The Herbert and Johnstone basins contributed the largest loads for all constituents. Three factors are common across these two basins. They are the largest of the WT basins in area, with the largest areas of intensive agriculture (sugarcane, cropping, bananas and horticulture) and they generate the highest average annual flows. For DIN and PSII herbicides, the four highest contributors are the Herbert, Johnstone, Mulgrave-Russell and Tully. These results agree with Kroon et al. (2012) and the recent GBR risk assessment (Waterhouse et al. 2012). The order of relative contribution of PSII herbicides and DIN from these four basins varies with each study and reasons for variation include different methodologies and land use mapping. Hotspot catchments in terms of areal rates for TSS, DIN and PSII herbicides are also discussed under each constituent heading in conjunction with the total loads.

The modelled loads are generally lower than most previous modelled estimates for the WT NRM region and are considered an improvement on the Kroon et al. (2012) estimates. This is due to improvements in constituent generation and transport methodologies. Direct comparisons between the current modelled loads and Kroon et al. (2012) estimates were limited due to the Kroon et al. (2012) estimates being derived from a range of sources and therefore methodologies. In some cases, the Kroon et al. (2012) current or total load was lower than the predevelopment load, which created a negative anthropogenic load. For example, the DON anthropogenic load for the Johnstone Basin was an unrealistic -230 t/yr (Kroon et al. 2012). This highlights the importance of using one modelling platform when estimating and comparing different types of loads.

Generally, the modelled loads matched well with a range of measured data, including loads from stream monitoring, concentration and tracing data at various time scales. The model was designed to produce outputs at the long-term average annual scale and the current calibration objective was to ensure predictions matched the long-term loads estimated from measured data. At shorter time-steps, such as years to weeks, the model also performed fairly well compared to the estimates from measured data. The differences between modelled and 'measured' loads are within the likely error bounds of the observed data, as measured data has its own sources of error. Across the validation datasets, the modelled loads were mostly an under-prediction compared to loads estimated from measured data, primarily due to the under-prediction in flow. The main constituents are discussed separately below.

Catchment modelling depends heavily on catchment monitoring for both the validation of the calculated loads and as another crucial line of evidence in the understanding of in-stream condition and delivery to the GBR. However, the loads estimated at the EOS gauges are most, but not all, of the load delivered to the GBR. Loads estimated from water quality monitoring are limited to the location of the most downstream gauging station, whereas catchment modelling is able to report the entire load delivered to the GBR. The ungauged modelled area, either directly downstream of the EOS gauging station or the small coastal subcatchments, is 28% of the WT NRM region. Land use in the ungauged area (~6000 km^2) is dominated by nature conservation (52%) and sugarcane (21%). As much as 70% of the sugarcane is grown downstream of the EOS gauge or in small coastal subcatchments. More than 90% of the sugarcane area in the Johnstone, Murray and Daintree basins is grown below the EOS gauge or in small coastal subcatchments. The remainder of the catchments had >50% of sugarcane in the ungauged area, except for the Tully (26%) and Barron (36%), where most sugarcane is grown upstream of the EOS gauging station. This clearly highlights the importance of catchment modelling and the interrelationship between modelling and monitoring. Catchment modelling is essential and is able to report the complete picture of loads delivered to the GBR, where loads estimated from water quality monitoring cannot. In turn, catchment monitoring is critical for validation of catchment modelling.

5.2.1 TSS

The TSS load from the Herbert Basin was 38% of the WT load. Grazing areas were typically the major source of the TSS load and large tracts of grazing land are located in this basin. Ground cover is a key driver of sediment loss (Silburn et al. 2012) and is on average lower in the drier parts of the Herbert Basin than in other parts of the WT region. For example, in 2009, the average ground cover from the BGI for grazing land use ranged from 75% in the Herbert Basin to 82% in the Mulgrave-Russell Basin. A large component of the TSS load exported from the Herbert and Johnstone basins is from the anthropogenic baseline component (~70%). This suggests that these catchments are a priority for future sediment reduction.

The highest average areal rates across the WT NRM region for TSS was from bananas (1.8 t/ha/yr) followed by sugarcane (1.2 t/ha/yr). A recent paddock scale monitoring trial in bananas and sugarcane in the Johnstone Basin measured sediment losses of 0.9–11 t/ha/yr for a C class banana site (bare inter-rows) (Armour et al. 2013a), which matches well with the modelled estimate. Limited samples were collected at the sugarcane site and annual runoff loads could not be calculated (Armour et al. 2013a). The most recent comprehensive study on soil loss from sugarcane was from the Victoria Plains site in the Mackay region (Rohde, Bush & Agnew 2011). The average annual soil loss in that study was 2 t/ha/yr, which also matches well with the modelling results (Rohde, Bush & Agnew 2011).

The source of sediment can only be estimated for grazing, cropping and sugarcane, which occupy 40% of the WT, because of the sediment generation models used for each land use. The other land use classes had an EMC/DWC model applied, which does not discriminate between hillslope and gully sources. However, the EMC derived load can be partitioned into sources based on the surface to subsurface ratio from the loads generated by non-EMC land uses. This partitioning method is a coarse estimation. In the Herbert Basin, 36% of the area was modelled using the EMC approach and this has been apportioned based on the surface to subsurface ratio for the remaining 64% of the catchment. The proportions of surface (hillslope) versus subsurface (gully and streambank) erosion generated by the model agreed with recent sediment tracing work done in the Herbert using fallout plutonium (Tims et al. 2010). The modelled results for the Herbert Basin showed that subsurface erosion (streambank + gully) contributed 58% of the sediment exported, while surface erosion contributed 42%. Surface erosion was the dominant process in natural forested areas (Tims et al. 2010). However, when the entire WT NRM region is considered, surface erosion becomes more dominant at 59% and the remaining 41% for subsurface erosion. In terms of investment for sediment reduction, it is important to interrogate the data at the finest scale possible, as it has been demonstrated that the proportion of sources change depending on the scale at which the data is interpreted. Future improvements in the model will allow the calculation of hillslope/gully erosion from areas such as forests, where an EMC model is currently applied. In addition, improvements to gully mapping and a finer scale network definition will likely increase the proportion of subsurface erosion at the WT scale. It is acknowledged that the presence of gullies in sugarcane would be non-existent or minimal. Of the total sediment supplied from sugarcane, only 1% of the total load was attributed to gully erosion. This is most likely due to a mismatch in gully and land use mapping. Gully erosion contribution in future modelling will be set to zero if thorough analysis reveals that none of the sugarcane area, as represented in the QLUMP input data set, has no significant gullies.

There was a general increase in the WT predevelopment TSS load and a general decrease in the total WT TSS load compared to Kroon et al. (2012). Important changes from previous modelling studies using SedNet have been the use of annual cover estimates to predict hillslope erosion and the use of EMC/DWC rather than RUSLE to model sediment loss from forests. For TSS, the main difference in predevelopment methodologies was the use of RUSLE model in Kroon et al. (2012) and the combination of the EMC/DWC model and the RUSLE model (grazing only) used in Source Catchments. In previous SedNet studies, a low ground cover value was used in the current condition scenario (equates to ~60% cover) and then a comparatively high cover value (95%) was used in the predevelopment scenario (McKergow et al. 2005b). In Source Catchments, an annual BGI with an average cover of 82% was used for the baseline load calculation and the predevelopment scenario had a constant 95% groundcover, so the difference between the two was not as marked as that in McKergow et al. (2005b). For the EMC land uses, the median TSS EMC value for nature conservation was 20 mg/L (average 26 mg/L). This value was taken from Tully Gorge gauging station (113015A) (n = 187, 2007–2010). It is acknowledged that this value could be too high to apply as a constant to the WT NRM region compared to water quality measurements from other forest sites. For example, Bartley et al. (2012) describes a median value 10 mg/L (mean 26 mg/L) from an extensive review of water quality measurements across mostly eastern Australia (n = 17). For this study, the areal rate for TSS from nature conservation was 0.19 t/ha/yr and in Kroon et al. (2012) it was 0.16 t/ha/yr. Other SedNet studies reported 0.8 t/ha/yr (Hateley et al. 2005) and 0.3 t/ha/yr (Armour, Hateley & Pitt 2009), with the former value being regarded as too high. Gullies were not modelled for the predevelopment scenario in Kroon et al. (2012) whereas they were modelled in Source Catchments, which is another reason why these predevelopment loads are higher than Kroon et al. (2012). Research from northern Australia suggests that gullies pre-date the introduction of cattle (McCloskey 2010).

EOS TSS modelled loads for the five sites in the Wet Tropics matched well to the measured loads across a range of temporal scales. Most modelled loads were within ±50% of the load estimated from measured data. Generally the modelled loads compared better with the long-term loads from measured data (Joo et al. 2014), compared to the shorter time-steps, such as the four year GBRCLMP dataset (Joo et al. 2012, Turner et al. 2012). However, the modelled TSS loads at a monthly time-step at the five EOS sites were ranked as 'satisfactory' to 'very good'. The modelled loads were generally closer in agreement with loads calculated from stream measurements than from other modelled loads. Modelled loads were generally lower than the loads estimated from measured data except for the Herbert Basin, where the modelled loads and concentrations were generally higher than the measured data. In this basin, further investigation in the input parameters and the balance of erosion between land uses is needed. Sediment loss is likely to have stabilised or declined over last 10 years in the WT, mostly due to improved sugarcane practices, particularly green sugarcane trash blanketing and perhaps improvements made in grazing management (Waterhouse et al. 2012). However, time lags and natural variability can mask trends in constituent loads (Bainbridge et al. 2009).

5.2.2 DIN

DIN export load from the WT was the highest across the GBR NRM regions, delivering 44% of the total GBR load from 5% of the total GBR area. A large proportion of the WT load was from the Johnstone Basin. Approximately half of the DIN load came from cropping, of which most came from sugarcane (86%). The high DIN load from sugarcane was the result of location, management and climate. Crops receive relatively high rates of N fertiliser and production is mostly close to the coast in high rainfall and runoff areas, which enables efficient delivery of nitrate-N. In terms of management practice for nutrients in sugarcane (at Report Card 2013 or at June 2013) 21% land holders were either in the C or D category, an indication that future improvements can be made. Other factors that are important for the transport of DIN include, high slopes, impermeable soil types and whether a large storage such as a dam is located downstream of the land use. It has been shown that storages such as the Tinaroo Falls Dam, located in the western part of the Barron Basin, trap nutrients and sediments (Cogle et al. 2000).

Bananas had the highest export areal rates for TN (25 kg/ha/yr), followed by sugarcane (22 kg/ha/yr), most of which was attributed to DIN (60% of TN in bananas and 46% of TN in sugarcane). Bananas have a much higher rate of N fertiliser application, typically 340 N kg/ha/yr for a B class practice (ratoon), compared to sugarcane at ~130 N kg/ha/yr also for a B class practice (Armour et al. 2013a). Recent paddock scale monitoring of bananas in the Wet Tropics reported TN surface runoff values of 3–60 kg/ha/yr from a C class site, most of this was in the particulate form (82–91%) (Armour et al. 2013a). Similarly for the sugarcane monitoring trial, particulate N was the dominant form of TN exported in surface runoff from a B and C class site, with TN in surface runoff 2–9 kg/ha/yr (Armour et al. 2013a). PN accounted for approximately 30% of the TN export rates for both bananas and sugarcane. These monitoring results differ from the modelling and the N budget will be reviewed for the next round of modelling.

An EMC/DWC model was used to model constituent loads from bananas. One of the limitations of this model is that a constant EMC/DWC value was applied to runoff. An important improvement would be to model bananas with the paddock scale model HowLeaky, so that features such as management practice, slope, soil type and herbicides could also be included. Cropping and horticulture contributed relatively low export loads of DIN. This was mainly due to the generally lower rates of fertiliser application and production further away from the coast.

Modelled total loads for DIN are similar to those of Kroon et al. (2012). There was a general increase in the WT predevelopment load and a general decrease in the total WT load compared to

Kroon et al. (2012). For DIN predevelopment and baseline loads from nature conservation, the same method (EMC/DWC model) was used for Kroon et al. (2012) and this study. The DIN EMC used in Kroon et al. (2012) was 0.04 mg/L and in this study the value was 0.16 mg/L. Whilst the value is four times higher than Kroon et al. (2012), a recent review of water quality data reported a median value of 0.1 mg/L (n=49), with a mean of 0.2 mg/L (Bartley et al. 2012). It is acknowledged that the EMC values for DIN may be too high when compared to other measured EMC concentrations from forests. Future modelling should improve the DIN supply from each of the land uses in line with measured data. This will also improve the predevelopment and anthropogenic proportion of DIN, similar to that of TSS. This is likely to increase the anthropogenic DIN in the next iteration of the modelling.

There was generally good agreement with the DIN modelled loads and estimates from measured data at a range of time-steps. The modelled DIN loads at a monthly time-step were overall ranked the best compared to the other four constituents. This demonstrates that the model is performing acceptably for DIN. The DIN loads (both measured and modelled) from the Barron Basin were significantly lower than all other catchments, even though the catchment is highly modified (only 29% of the catchment is natural forest). The long-term median measured concentration of DIN is also significantly lower at the EOS site compared to the other EOS sites. For example, the median concentration at Barron River at Myola (EOS) was 0.06 mg/L (n=312,1995–2009), compared to the median values at the North and South Johnstone Rivers and Tully River of 0.17 mg/L (North and South Johnstone River, n = 343, 1994–2009), (Tully River, n= 619, 1994–2009). A combination of factors contributes to the low DIN loads in the Barron. A large proportion of the cropping land in the Barron catchment drains into Tinaroo Falls Dam, which is a sink for nutrients and sediments (Cogle et al. 2000). The generally drier climate would also reduce the runoff and associated constituents. In addition, the average annual discharge more than doubles between Mareeba and Myola (~40 km), helping to dilute the concentration of nitrate (Mitchell et al. 2006). The doubling of discharge is from increased rainfall, return irrigation water from the Mareeba Dimbulah irrigation scheme and groundwater inputs from the basalt region (downstream of the dam). Moreover, the diverse range of crops (potatoes, peanuts, corn, tree crops, coffee etc.) and associated fertiliser regimes in the upper Barron combined with very little monitored data is another possible factor in the export of DIN. One of the limitations in the HowLeaky modelling for cropping (dryland and irrigated) was the use of one crop, maize (corn) to represent all cropping. The DIN EMC/DWC concentrations for cropping and grazing in the Barron may be too high and these values will be reviewed in the next round of modelling.

The ability to calculate loads from the entire WT contributing area is a major advantage of the modelling. Loads estimated from monitoring data at gauging stations are only a partial estimate of the constituents being delivered to the GBR. As much as 75% of the sugarcane DIN load was generated in the ungauged area. The per cent of sugarcane area and per cent of sugarcane DIN load for each catchment are similar. The slightly higher sugarcane DIN load versus area of sugarcane in the ungauged section is due most likely to slightly higher rainfall and runoff in these areas compared to sugarcane found upstream of the EOS gauge. Two gauging stations in the Mulgrave-Russell Basin were recently installed in October 2013, one each in the lower sections of the Mulgrave and Russell Rivers. The purpose of the two additional gauging stations is to capture water quality information, as there is little historical water quality data collected from this basin and to capture a larger catchment area, especially sugarcane land use draining into the Mulgrave and Russell Rivers. The two existing EOS gauging stations (GS111007a and GS111101D, Figure 7) operating prior to these two new stations only captured 42% of the Mulgrave-Russell Basin or 16%

of the sugarcane area. The two new gauging stations now capture 68% of the basin and ~72% of the sugarcane area; this will improve modelled predictions of constituents in future model builds in the GBR.

The recent scientific consensus statement reported that there is an increasing link between intensive agricultural production and elevated levels of contaminants such as nitrogen, phosphorus and herbicide residues in groundwater (Brodie et al. 2013). Losses of nutrients are of a particular concern in crops where high amounts of fertilisers are applied combined with large amounts of rainfall, such as sugarcane and banana growing areas of the Wet Tropics. A recent review revealed that median groundwater nitrate concentrations significantly exceed the Australian water quality guidelines for surface waters in areas of the Wet Tropics, lower Burdekin and Mackay Whitsunday GBR regions (Hunter 2012). Of the three areas, the Wet Tropics had the highest proportion of groundwater discharge to surface water bodies compared to coastal or submarine discharge, with mean annual total groundwater discharge generally <10% of mean annual streamflow. Several studies have reported elevated stream nitrate levels from groundwater discharge in sugarcane growing and banana areas of the Johnstone Basin (Hunter & Walton 2008, Armour et al. 2013b, Rasiah et al. 2003, Walton & Hunter 2009). Currently, the Source Catchments framework does not model subsurface drainage of constituents, particularly nitrate, from sugarcane or bananas to surface streams and rivers from ephemeral aquifers. This is seen as a major priority for future improvements to the catchment modelling. High concentrations of nitrate are sometimes seen on the tail end of an event and it is likely that is it from subsurface or groundwater discharge (Brodie & Mitchell 2005). It is also thought that the EOS surface water gauging station sites do not account for the majority of groundwater inflows (as they generally occur further downstream) (Hunter 2012). Therefore, the EOS loads could be considered a minimum load being exported to the GBR lagoon.

5.2.3 PSII herbicides

The WT NRM region exported 56% of the total PSII herbicide contribution to GBR. Most of the load was derived from sugarcane in the Tully, Johnstone, Mulgrave-Russell and Murray basins. These basins had similar rates of PSII herbicides exported per hectare. In addition to the land use and climatic factors that contribute to the hotspot areas for DIN in the WT, herbicides are decayed in-stream. Herbicides from cropping areas situated closest to the coast have less opportunity for decay. For management of herbicides practice (at Report card 2013 or at June 2013), the majority of sugarcane area had either C or D class management (58%), a clear indication that there could be improvements made. The modelled WT PSII herbicide load (8,596 kg/yr) is between the Kroon et al. (2012) estimate (12,000 kg/yr) and that of Lewis et al. (2011) (4,551 kg/yr). It has been suggested that the lower of the two estimates is more accurate due to the development of regionally specific runoff coefficients for individual herbicides (Lewis et al. 2011) as opposed to a collective PSII herbicide GBR runoff coefficient that represented all sugarcane (Brodie, Mitchell & Waterhouse 2009).

Diuron is the most common pesticide found in the Wet Tropics and is predominantly applied to sugarcane, with lesser amounts applied in cropping areas. The herbicide application profile developed for the Wet Tropics modelling was based on scenarios considered 'typical' for the region. The profiles represented applications of priority PSII herbicides as well as metolachlor, 2,4-D, glyphosate and paraquat. Diuron was modelled as the primary residual herbicide for sugarcane, while atrazine was modelled as the residual herbicide applied in the dryland and irrigated land use (represented as maize). In reality, there is a wider range of herbicide products in use than reflected in these typical scenarios and so modelled loads will not match that of every producer. Further, the choice of herbicide products included in the typical scenarios has an effect on the loads modelled for the WT due to differences in physical/chemical properties.

The most comprehensive measured dataset to compare to the modelled data was collected in the Tully River at the EOS site (Department of Natural Resources and Mines 2012). It was limited by the number of samples and timing of collection, so average concentrations rather than annual measured loads were calculated. The average modelled PSII herbicide concentration was ~10% higher than the measured concentration (for the same time period). These results are encouraging and model parameters will be refined as more local data becomes available.

Brodie et al. (2012) reported that the estimate of 12,000 kg/yr of herbicides exported to GBR from the WT NRM region was likely to be an underestimate of total herbicide losses due to the wide range of herbicides available for use that are currently either not modelled or not analysed in water quality data. By comparison, the use of typical herbicide application scenarios for all cropping areas is likely to result in an overestimate of the load of the PSII herbicides, which are included in the modelling. This requires further analysis for inclusion into future modelling. In conjunction with the P2R Program, a preliminary survey of seven groundwater bores within the Tully-Murray and Johnstone basins confirmed the presence of nine herbicides and one insecticide (Masters et al. 2013). Previous monitoring in the Johnstone Basin in 1995–1996 only detected the PSII herbicide atrazine in four bores. No other PSII herbicides were detected in the 16 bores surveyed (Hunter 2012, Hunter et al. 2001). This adds further weight to incorporating subsurface drainage into the catchment modelling.

5.2.4 Other constituents

The WT had the second highest TP load of the GBR contributing regions, mostly from PP. Phosphorus is also considered to be a limiting factor in plankton and algal growth, but not as significant as nitrogen (Schaffelke 2001). Phosphorus records obtained from a 60 year coral core record off shore from the Tully Basin suggested that phosphorus levels have increased 8 fold between 1949 and 2008 (Mallela, Lewis & Croke 2013). The majority of fertiliser phosphorus is attached to soils particles so that most phosphorus export occurs when soil erosion is highest (Furnas 2003).

The greatest differences between modelled loads and estimates derived from measured data were for DIP but there was not a consistent pattern in the differences. The DIP concentration data used in the long-term estimate from measured data had excellent flow coverage at the South Johnstone and Tully, good coverage in the Barron, North Johnstone and moderate coverage in the Herbert (Joo et al. 2014). The modelled Tully DIP results were classed as unsatisfactory for all three performance statistics on a monthly time-step. The modelled loads were consistently higher than the FRCE loads, but at a long-term scale, the DIP load was within the likely upper and lower range. Further investigation into the DIP modelled loads is warranted.

5.2.5 Changes to the baseline model

At the start of the P2R 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

H to J. This allowed some relative yearly comparisons 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.

Most baseline model changes from Report Card 2010 to Report Card 2013 resulted in little change of the overall WT baseline loads (<2% for most constituents except PSII herbicides and PP). These changes improved the agreement between the modelled loads and validation data. The main improvements were the inclusion into the APSIM model of representative climates and soils of sugarcane areas in the Wet Tropics. Report Card 2010 estimates were based on just one climate (Tully) and only four soil types found in the Tully Basin. To compensate for the gross over-estimation of runoff (Report Card 2010) in the drier basins (compared to the Tully climate) and a slight underestimation in the wetter basins, a variable delivery ratio (DR) was used for DIN and PSII herbicides based on differences in runoff between each basin to the Tully Basin. The differences in the baseline loads between Report Card 2010 and Report Card 2011 for DIN (-0.2%) and PSII herbicides (-16%) demonstrated that the variable DR used in Report Card 2010 was an appropriate methodology. PP water quality monitoring loads were only made available after Report Card 2010. The PP enrichment ratio was changed from 4 to 5 and the particulate DR was increased from 15% to 20% for sugarcane cropping and grazing. This change resulted in a better match between PP modelled loads and PP loads derived from measured data.

5.3 Progress towards Reef Plan 2009 targets

The Reef Water Quality Protection Plan outlines a clear set of water quality and management practice targets. The catchment modelling has been one of multiple lines of evidence to report on progress towards these targets. Across the GBR TSS has been reduced by 11%, TN and TP by 10% and 12.5% respectively. The PSII herbicide load had the greatest reduction of all constituents at 28%. The WT was responsible for 48% of the GBR PSII load reduction. The modelling showed that very good progress has been made towards reaching the 2020 target of a 20% reduction in sediment load from the GBR. However, the target of a 50% reduction by 2013 as outlined in Reef Plan 2009 for nutrients and herbicides has not been met. The timeline for meeting this target has been revised in Reef Plan 2013, and Report Card 6 and beyond will report against this.

There was ‘very poor’ to ‘very good’ progress towards targets for all modelled constituents in the WT NRM region for both sugarcane and grazing for Report Card 2013. Most of the change for nutrients and herbicides was attributed to improvements in sugarcane management from a higher proportion of B practice (‘Six Easy Steps’ program). Most of the TSS reduction was due to riparian fencing. Overall, for all constituents most of the load reductions were attributed to investments through the Reef Rescue program. Part of the large reduction in the PSII load was the shift into A practice. For ‘A’ practice, a typical PSII application would only be atrazine and only applied in the plant phase. This is quite different from B practice, where a combination of atrazine, diuron and hexazinone is applied in the plant and ratoon phases (Shaw & Silburn 2014).

An average of 43% of sugarcane land use (different areas for soil, nutrients and herbicides) and 6% of grazing land use underwent a shift in management class compared to the baseline management class. These per cent values are likely to be an overestimate as it was assumed that areas of change did not overlap between Report Cards. In reality, the same parcel of land could have changed more than once over the five years of investment, but due to the non-spatial representation of management data, this could not be represented. At the end of the Report Card

2013 reporting period, the per cent area of WT grazing in C or D soil management was 29%. For sugarcane with either C or D management practice for soil was 49%, nutrients 21% and herbicide 58%. Consequently, there is still much scope for improvement in terms of area of land use to undergo improvements in management practice.

Additional scenarios for DIN and PSIIs were run to determine if targets could be met, by shifting for example to an 'All A' practice adoption. Modelling suggests that the PSII target could be met under an 'All B' management scenario, whilst the 50% DIN reduction target may not be met under an 'All A' management scenario. Alternative management strategies should be considered if the targets are to be achieved. It has been suggested that the required reduction in DIN export will be achieved by reducing the total amount of nitrogen applied to crops, rather than changing management of current application regimes (Thorburn & Wilkinson 2012).

One of the limitations of the modelling was that management changes only affected the load derived from the quickflow (event flow) component of the total flow. This limitation only affected the magnitude of modelled reductions of dissolved nutrients such as DIN, because fine sediment and PSIIs have a very small slowflow load or no slowflow load in the current model structure. For sugarcane and grazing, the proportion of slowflow was approximately 41% of the total modelled flow. In order to make modelled export loads of DIN more equitable with validation data, the WT region had a significant proportion of DIN slowflow load, which resulted in that portion of the load remaining unchanged in all scenarios. Under current modelling concepts, investment in management improvement only effects quickflow constituent loads. This is due to the lack of scientific knowledge to confidently represent the interaction of groundwater with streams, and the associated DIN transfer that may (or may not) occur. As our model structure improves and more data becomes available regarding this, the representation will be made.

This is the first time that on-ground changes at the paddock scale have been simulated and the potential benefit to water quality at the EOS realised in the GBR region, highlighting the power of modelling. The effect of climate has been effectively reduced by using the same climatic period of 1986–2009 and this has allowed the direct impact of changed management on water quality change to be assessed.

The establishment and validation of the model platform now allows regional NRM groups to make use of the modelling outputs to target specific basins for investment. However, one of the limitations with the management practice data is the spatial assignment of this data within basins. The proportions of each management practice system for the baseline, Report Card 2010–Report Card 2013 in the WT were provided at the basin scale. Therefore, the assignment of the management data *within* each basin was done randomly. The spatial scale at which the model should be interpreted is the basin scale. However, we acknowledge that NRM groups will be interested in finer scale modelled outputs and they should consider this when interpreting results at a finer scale. An analysis was done for Terrain NRM, identifying the main reasons why loads differ between and within basins for selected constituents, see Appendix K. A future improvement would be to include finer scale management practice data.

While the total baseline loads differ from previous estimates, the only change in the anthropogenic baseline model is the inclusion of data for changes in management. Therefore, regardless of the current accuracy of modelled constituent loads (within reason), the modelled reduction in loads due to management change will remain relatively consistent for higher or lower annual load estimates. In summary, when model outputs are compared to previous estimates (in general) and recent monitoring data (in particular), there is a reasonable degree of confidence in the relative percentage reduction in loads calculated from the provided management change data.

5.4 Prioritisation of on-ground works

This modelling framework and its outputs will allow NRM groups to make better decisions about where investment should occur to achieve the greatest load reductions for the least cost. Combinations of landscape and management practices that have a high risk of constituent generation and transport and thus warrant priority include:

- high rainfall and a high proportion of runoff
- intensive agriculture situated closest to the coast
- land uses that use high amounts of fertilisers and herbicides
- steeper slopes
- management practices in the C and D categories

These factors agree with the recent risk assessment in the WT as a part of the GBR assessment (Waterhouse et al. 2012). In addition, we highlight rainfall and runoff, slope and management practice as additional key factors to consider. Overall, the sediment generation and delivery was low compared to the larger drier basins such as the Burdekin and Fitzroy resulting in a lower priority for improved sediment management in the WT NRM region. However, when particulate forms of N and P are important, as highlighted in the recent banana paddock monitoring, then improved sediment management will reduce particulate N and P loss.

This work has focussed on terrestrial constituent runoff to the reef at the GBR scale. However, there are localised water quality threats within the WT that may be affecting freshwater ecosystems. These can also be assessed by this modelling framework so that the localised water quality issues may be addressed. It is recommended that the prioritisation of on-ground works be done at the basin scale, for further information see Appendix K.

5.5 Future work

As with all numerical modelling projects used to simulate natural systems, model outputs would be enhanced by improving input data and model processes and as part of the P2R Program's continual improvement process, major modelling enhancement will take place for Reef Plan 2013. Future work for all of the GBR catchment models will include recalibration of the hydrology, particularly to better simulate flow characteristics. The SIMHYD RR model used in this project will be replaced with the Sacramento RR model. This would align the GBR Source Catchments models with the IQQM models used in DNRM water planning studies. Furthermore, recent research has shown that the Sacramento model performs better than the SIMHYD and GR4J models in some GBR basins (Zhang, Waters & Ellis 2013). This is due to 22 parameters controlling the runoff characteristics within the Sacramento model compared to nine in SIMHYD.

The Sacramento model is better able to account for losses in the system (e.g. groundwater), which is particularly useful in the wetter GBR basins. Another improvement would be to refine the objective function used in the calibration, which was predetermined based on the previous successful calibration for the GBR basins. Much of the sediment and nutrient loads are delivered during high flows, so it is important to model all event characteristics as accurately as possible. This, in addition to improvement in rainfall data, will improve the hydrology calibration. While the hydrology calibration as it stands is fit for purpose and 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. Finally, the starting parameters used in the hydrology calibration will be re-assessed. The default SIMHYD and Laurenson flow routing parameters were used, but future calibration processes should use local knowledge and expert opinion to set these starting parameters, regardless of which RR model is used. This will help ensure that the calibration-derived parameter set will generate flows that are comparable with the monitored data. Recommendations for additional improved model prediction include:

- Paddock scale modelling of bananas using the paddock model HowLeaky
- Increased combinations of ABCD soil, nutrient and herbicide scenarios in the paddock modelling
- Improved spatial allocation of specific management practice information and an updated ABCD management framework
- Incorporation of seasonal rather than annual dry season cover for hillslope erosion prediction
- A review of crop rotation and herbicide application in the cropping paddock modelling
- Incorporation of locally derived dissipations rates for herbicides in the paddock modelling and to represent in-stream decay
- Improved gully and streambank erosion input data
- Better representation of sediment sources from land uses modelled using EMCs/DWCs

These changes will provide enhanced GBR Source Catchments total baseline loads 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 is appropriate for assessing load reductions due to on-ground land management change.

The continuation of on-ground research and water quality monitoring is integral to improving the Source Catchments model outputs (through model validation) as well as corroborating the progress towards the water quality targets. The selection of monitoring sites in the Mulgrave-Russell Basin is an important improvement as it is the only 'hotspot' basin without long-term water quality monitoring data.

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

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

6 Conclusion

The loads calculated for the Wet Tropics as part of the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program are an improvement on previous estimates of modelled loads for the region. Overall, the current implementation of a modified Source Catchments model is performing well as a tool for estimating load reductions due to on-ground investment and changes in catchment management. 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 from 2008–2013 has resulted in a reduction in TSS load to the GBR from the six NRM regions of 11%. Similarly, GBR TN and TP loads have declined by 10% and 13% respectively. PSII herbicide loads have been reduced by 28%. In the WT, TSS was reduced by 13%, TN reduced by 8% and TP by 19%. The biggest reduction in the Wet Tropics thus far has been for PSII herbicide use with a reduction of 26%. The modelling showed that 'good' progress has been made towards reaching the 2020 target of a 20% reduction in sediment load from the GBR. However, the target of a 50% reduction by 2013 as outlined in Reef Plan 2009 for nutrients and herbicides has not been met. The timeline for meeting this target has been revised in Reef Plan 2013, and Report Card 6 and beyond will report against this.

Modelled outputs for the baseline load indicate that approximately 1,219 kt/yr of TSS was exported to the GBR from the WT NRM region. The estimated regional TSS load is a 2.7 x increase from predevelopment loads. DIN (4,437 t/yr) accounted for the majority of the TN load (12,151 t/yr) and the WT was the highest contributor of DIN across the six GBR NRM regions. TN loads were estimated to be 2.1 times the predevelopment load. PP (1,297 kt/yr) was the greatest contributor to TP load (1,656 t/yr) and second highest contributor to the GBR load after the Burdekin. TP has increased 2.6 times from the predevelopment load. The Johnstone and Herbert basins were the greatest contributors for all constituents.

The results from this project are somewhat lower than previous estimates for sediment and nutrient loads from the WT. 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 monitoring data to validate models against is a major improvement. Modelled values compared to FRCE values at a monthly time-step, for TSS, TN, DIN, TP and DIP at five EOS gauging stations, were mostly ranked in the best category of 'very good' (Moriasi et al. 2007). Over the course of the P2R Program more empirical data has become available and it is likely that the modelled outputs from all regions will continue to improve as a result of new input information and water quality monitoring data.

The P2R Program, as a whole, is designed to be an adaptive process, where monitoring and modelling outputs will both inform reef targets and also identify where our current conceptual understanding and knowledge needs to be strengthened (Waters & Carroll 2012). Developing, parameterising and running the catchment model described in this technical report and accompanying reports, was a considerable challenge. However, what has been developed is a platform for future modelling and with improvements in technology, data inputs and model concepts, greater confidence in the outputs will be achieved.

There are numerous successes of the GBR wide modelling project. Firstly, progress towards the water targets has been quantified. This project has also developed the first temporally and spatially variable water quantity and quality model for WT. In addition, the use of a consistent methodology across whole of GBR enables the direct comparison of loads across regions. Furthermore, due to the flexible nature of the Source Catchments framework, there is now the ability to 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. Overall, the project can be considered a significant improvement on past models built for the GBR catchments; however, there will always be scope for improvement. It follows that the better the modelling performs spatially and temporally, the greater the confidence and possible sophistication in targeted management actions.

A process has been identified to improve the model as a whole. Major improvements in the Wet Tropics model that can be made include the recalibration of the model hydrology; inclusion of subsurface drainage information particularly in sugarcane and bananas; estimating erosion processes for the entire WT region and better parameterisation of nature conservation constituents (leading to improved estimates of predevelopment and anthropogenic loads). 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. The greatest priority is to continue on-ground research and water quality monitoring. This data is the key information against which the catchment scale models can be validated.

Overall, the catchment scale water quality modelling has been successful and the aim of reporting progress towards Reef Plan targets has been achieved. However, improvement to the model can and will be made in the future. The results show that land managers are on track towards meeting the overall sediment, nutrient and herbicide reduction targets revised for Reef Plan 2013.

7 References

Agriculture & Environment Research Unit (AERU) 2006–2013, The Pesticide Properties Database (PPDB), University of Hertfordshire, UK.

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

Armour, JD, Davis, A, Masters, B, Mortimore, C & Whitten, M 2013a, Paddock Scale Water Quality Monitoring of Sugarcane and Banana Management Practices: Final Technical Report 2010-2013 Wet Seasons, Wet Tropics Region, Queensland Department of Natural Resources and Mines, Centre for Tropical Water & Aquatic Ecosystem Research and Queensland Department of Agriculture, Fisheries and Forestry for Terrain Natural Resource Management, Australia, Mareeba.

Armour, JD, Nelson, PN, Daniells, JW, Rasiah, V & Inman-Bamber, NG 2013b, 'Nitrogen leaching from the root zone of sugarcane and bananas in the humid tropics of Australia', Agriculture, Ecosystems and Environment, vol. 180, pp. 68-78.

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, vol. 60, no. 11, pp. 1091-1096.

Armour, JD, Hateley, LR & Pitt, GL 2007, Improved SedNet and ANNEX modelling of the Tully-Murray catchment. A report prepared for the Tully Water Quality Improvement Plan, Department of Natural Resources and Water, Mareeba, QLD.

Bainbridge, ZT, Brodie, JE, Lewis, SE, Waterhouse, J & Wilkinson, SN 2009, "Utilising catchment modelling as a tool for monitoring Reef Rescue outcomes in the Great Barrier Reef catchment area", 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation: Interfacing Modelling and Simulation with Mathematical and Computational Sciences, eds. R.S. Anderssen, R.D. Braddock & L.T.H. Newham, Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics, Cairns, July, pp. 3301.

Bartley, R, Henderson, A, Prosser, IP, Hughes, AO, McKergow, LA, Lu, H, Brodie, J, Bainbridge, Z & Roth, CH 2003, Patterns of erosion and sediment and nutrient transport in the Herbert River catchment, Queensland, CSIRO Land and Water, Atherton.

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, vol. 6, no. 3-4, pp. 317-329.

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.

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.

Brodie, JE, Mitchell, A & Waterhouse, J 2009, Regional Assessment of the Relative Risk of the Impacts of Broad-Scale Agriculture on the Great Barrier Reef and Priorities for Investment under the Reef Protection Package, Stage 2 Report, ACTFR Technical Report 09/30, Australian Centre for Tropical Freshwater Research, Townsville.

Brodie, JE & Mitchell, AW 2005, 'Nutrients in Australian tropical rivers: Changes with agricultural development and implications for receiving environments', Marine and Freshwater Research, vol. 56, no. 3, pp. 279-302.

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.

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.

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, vol. 65, no. (4-9), pp. 136-149.

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, vol. 48, no. 4, pp. 703-710.

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, eds VP Singh & DK Frevert . Water Resources Publication, Littleton, Colorado, pp. 335–67.

Chiew, FHS & McMahon, TA 1993, 'Assessing the adequacy of catchment streamflow yield estimates', Australian Journal of Soil Research, vol. 31, no. (5), pp. 665-680.

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, eds. A. Zerger & R.M. Argent, Modelling and Simulation Society of Australia and New Zealand, Melbourne, December 2005, pp. 2883-89.

Churchill, MA 1948, "Discussion of paper by L. C. Gottschalk "Analyses and use of reservoir sedimentation data''", Federal Inter-agency Sedimentation Conference Proceedings, U.S. Geological Survey, Denver, Colorado, April, pp. 139–140.

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.

Cogle, AL, Langford, P, Kistle, S, Ryan, T, McDougall, A, Russell, D & Best, E 2000, Natural resources of the Barron river catchment 2. Water quality, land use & land management interactions, Department of Natural Resources, Mareeba.

DEH & DNR 1999, Testing the Waters: A Report on the Quality of Queensland Waters, Department of Environment and Heritage and Department of Natural Resources, Brisbane.

Department of Natural Resources and Mines 2012, September-last update, Water Monitoring Data

Portal [Homepage of State of Queensland], [Online]. Available: http://watermonitoring.derm.qld.gov.au/host.htm [2013, May, 3].

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 Natural Resources and Mines 2001, Barron water resource plan, Surface Water Assessment Group, Brisbane.

Department of the Premier and Cabinet 2013a, 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. www.reefplan.qld.gov.au.

Department of the Premier and Cabinet 2013b, 23rd July-last update, Reef Water Quality Protection Plan, Great Barrier Reef Second Report Card 2010 [Homepage of Reef Water Quality Protection Plan Secretariat, the State of Queensland], [Online]. Available: http://www.reefplan.qld.gov.au/measuring-success/report-cards/second-report-card.aspx [2013, July, 30].

Department of the Premier and Cabinet 2009, Reef Water Quality Protection Plan, 2009, For the Great Barrier Reef World Heritage Area and adjacent catchments, The State of Queensland and the Commonwealth of Australia. www.reefplan.qld.gov.au.

Devlin, M & Schaffelke, B 2009, 'Spatial extent of riverine flood plumes and exposure of marine ecosystems in the Tully coastal region, Great Barrier Reef', Marine and Freshwater Research, vol. 60, no. 11, pp. 1109-1122.

Devlin, MJ, McKinna, LW, Álvarez-Romero, JG, Petus, C, Abott, B, Harkness, P & Brodie, J 2012, 'Mapping the pollutants in surface riverine flood plume waters in the Great Barrier Reef, Australia', Marine pollution bulletin, vol. 65, no. 4-9, pp. 224-235.

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 2013a, Wet Tropics Water Resource Plan - Calibration of Sacramento and IQQM Models for the Tully and Murray River Basins, Queensland Department of Science, Information Technology, Innovation and the Arts, Brisbane.

DSITIA 2013b, Wet Tropics Water Resource Plan - Calibration of Sacramento and IQQM Models for the Herbert River Basin, Queensland Department of Science, Information Technology, Innovation and the Arts, Brisbane.

DSITIA 2013c, Wet Tropics Water Resource Plan - Calibration of Sacramento and IQQM Models for the Johnstone River Basin, Queensland Department of Science, Information Technology, Innovation and the Arts, Brisbane.

DSITIA 2013d, Wet Tropics Water Resource Plan - Calibration of Sacramento and IQQM Models for the Mossman River Basin, Queensland Department of Science, Information Technology, Innovation and the Arts, Brisbane.

DSITIA 2013e, Wet Tropics Water Resource Plan - Calibration of Sacramento and IQQM Models for the Russell-Mulgrave River Basin, Queensland Department of Science, Information Technology, Innovation and the Arts, Brisbane.

DSITIA 2013f, Wet Tropics Water Resource Plan - Summary Report on Rainfall Investigation, Queensland Department of Science, Information Technology, Innovation and the Arts, Brisbane.

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

DSITIA 2012b, Land use summary 1999–2009: Burdekin NRM region, Queensland Department of Science, Information Technology, Innovation and the Arts, Brisbane.

DSITIA 2012c, Land use summary 1999–2009: Wet Tropics NRM region, Queensland Department of Science, Information Technology, Innovation and the Arts, Brisbane.

Ellis, R, & Searle, RD 2014, Dynamic SedNet Component Model Reference Guide, Queensland Department of Science, Information Technology, Innovation and the Arts, Bundaberg, QLD.

Ellis, R, Doherty, J, Searle, R & Moodie, KB 2009, "Applying PEST (Parameter ESTimation) to improve parameter estimation and uncertainty analysis in WaterCAST models", 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation: Interfacing Modelling and Simulation with Mathematical and Computational Sciences, eds. R.S. Anderssen, R.D. Braddock & L.T.H. Newham, Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics, Cairns, July.

eWater Ltd 2013, Source Scientific Reference Guide (v 3.5.0), eWater Ltd, Canberra.

eWater Ltd 2012, Source Catchments Product Information URL: 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, vol. 45, no. 2.

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

Furnas, M, Mitchell, A, Skuza, M & Brodie, J 2005, 'In the other 90%: Phytoplankton responses to enhanced nutrient availability in the Great Barrier Reef Lagoon', Marine pollution bulletin, vol. 51, no. 1-4, pp. 253-265.

Furnas, MJ 2003, Catchment and corals: terrestrial runoff to the Great Barrier Reef, Australian Institute of Marine Science, Townsville.

GHD 2010, Canegrowers report for sugar cane land management practices baseline study GBR-wide report, GHD, Brisbane.

Goosem, S, Morgan, G & Kemp, JE 1999, "Wet Tropics, in The Conservation Status of Queensland's Bioregional Ecosystems" in The Conservation Status of Queensland's Bioregional Ecosystems, eds. P. Sattler & R. Williams, Environmental Protection Agency, Queensland Government, Brisbane, pp. 7/1-7/73.

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", MODSIM 2005 International Congress on Modelling and Simulation, eds. A. Zerger & R.M. Argent, Modelling and Simulation Society of Australia and New Zealand, Melbourne, December, pp. 290.

Hateley, L, Armour, J, Pitt, G, Sherman, BS, Read, A, Chen, Y, Brodie, J & Cogle, AL 2006, Sediment and nutrient modelling in the Wet Tropics NRM region. Volume 2. In: The use of SedNet and ANNEX models to guide GBR catchment sediment and nutrient target setting Ed A.L. Cogle, C. Carroll and B.S. Sherman. QNRM06138, Department of Natural Resources Mines and Water, Brisbane.

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, vol. 62, no. 8, pp. 962-973.

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, vol. 114, no. 3, pp. 338-347.

Hunter, HM 2012, Nutrients and herbicides in the groundwater flows to the great Barrier Reef lagoon; processes, fluxes and links to on-farm management, DERM, Brisbane.

Hunter, HM & Walton, RS 2008, 'Land-use effects on fluxes of suspended sediment, nitrogen and phosphorus from a river catchment of the Great Barrier Reef, Australia', Journal of Hydrology, vol. 356, no. 1-2, pp. 131-146.

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 Catchment model validation, Department of Science, Information Technology, Innovation, and the Arts, Queensland Government (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, vol. 65, no. 4-9, pp. 150-166.

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, vol. 18, no. 3-4, pp. 267-288.

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, vol. 65, no. 4-9, pp. 167-181.

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, Bainbridge, ZT, Kuhnert, PM, Sherman, BS, Henderson, B, Dougall, C, Cooper, M & Brodie, JE 2013, 'Calculating sediment trapping efficiencies for reservoirs in tropical settings: A case study from the Burdekin Falls Dam, NE Australia', Water Resources Research, vol.

49, pp. 1017.

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, vol. 157, no. 8-9, pp. 2470-2484.

Lewis, SE, Shields, GA, Kamber, BS & Lough, JM 2007, 'A multi-trace element coral record of land-use changes in the Burdekin River catchment, NE Australia', Palaeogeography, Palaeoclimatology, Palaeoecology, vol. 246, no. 2-4, pp. 471-487.

Lewis, SE, Smith, R, Brodie, JE, Bainbridge, ZT, Davis, AM & Turner, R 2011, "Using monitoring data to model herbicides exported to the Great Barrier Reef, Australia", MODSIM 2011 - 19th International Congress on Modelling and Simulation - Sustaining Our Future: Understanding and Living with Uncertainty, eds. F. Chan, D. Marinova & R.S. Anderssen, Modelling and Simulation Society of Australia and New Zealand, Perth, December, pp. 2051.

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, vol. 30, no. 2, pp. 233-248.

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, vol. 41, no. 6, pp. 1037-1062.

Mallela, J, Lewis, SE & Croke, B 2013, 'Coral Skeletons Provide Historical Evidence of Phosphorus Runoff on the Great Barrier Reef', PLoS ONE, vol. 8, no. 9.

Marsh, N & Waters, D 2009, "Comparison of load estimation methods and their associated error", 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation: Interfacing Modelling and Simulation with Mathematical and Computational Sciences, eds. R.S. Anderssen, R.D. Braddock & L.T.H. Newham, 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.

McDonald, G & Weston, N 2004, Sustaining the Wet Tropics: A Regional Plan for Natural Resource Management Volume 1: Background to the Plan, Rainforest Corporate Research Centre and Far North Queensland Natural Resource Management Ltd, Cairns.

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, vol. 17, no. (4-5), pp. 355-372.

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, vol. 51, no. 1-4, pp. 186-199.

McKergow, LA, Prosser, IP, Hughes, AO & Brodie, J 2005b, 'Sources of sediment to the Great Barrier Reef World Heritage Area', Marine pollution bulletin, vol. 51, no. 1-4, pp. 200-211.

Mitchell, A, Brodie, J, Lewis, S, Devlin, M, Bainbridge, Z, Bulsink, D & Furnas, M 2006, Water Quality Issues in the Barron WQIP Area, Australian Centre for Tropical Freshwater Research, Townsville.

Mitchell, AW, Bramley, RGV & Johnson, AKL 1997, 'Export of nutrients and suspended sediment during a cyclone-mediated flood event in the Herbert River Catchment, Australia', Marine and Freshwater Research, vol. 48, no. 1, pp. 79-88.

Mitchell, AW, Reghenzani, JR, Furnas, M, De'ath, G, Brodie, J & Lewis, S 2007, Nutrients and suspended sediments in the Tully River: Spatial and temporal trends, Australian Centre for Tropical Freshwater Research, Townsville, QLD.

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, vol. 50, no. 3, pp. 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", Downstream Effects of Land Use Change, eds. H.M. Hunter, A.G. Eyles & G.E. Rayment, Department of Natural Resources, Rockhampton, 26th-28th 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, vol. 58, no. 7, pp. 976-986.

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, vol. 52, no. 1, pp. 81-99.

Prosser, IP & Winchester, SJ 1996, 'History and processes of gully initiation and development in eastern Australia', Zeitschrift fur Geomorphologie, Supplementband, vol. 105, pp. 91-109.

Queensland Government 2011, SILO Climate Data [Homepage of Queensland Government], [Online]. Available: www.longpaddock.qld.gov.au [2012, 02/22].

Rasiah, V, Armour, JD & Cogle, AL 2005, 'Assessment of variables controlling nitrate dynamics in groundwater: Is it a threat to surface aquatic ecosystems?', Marine pollution bulletin, vol. 51, no. 1-4, pp. 60-69.

Rasiah, V, Armour, JD, Cogle, AL & Florentine, SK 2010, 'Nitrate import-export dynamics in groundwater interacting with surface-water in a wet-tropical environment', Australian Journal of Soil Research, vol. 48, no. 4, pp. 361-370.

Rasiah, V, Armour, JD, Menzies, NW, Heiner, DH, Donn, MJ & Mahendrarajah, S 2003, 'Nitrate retention under sugarcane in wet tropical Queensland deep soil profiles', Australian Journal of Soil Research, vol. 41, no. 6, pp. 1145-1161.

Rattray, DJ, Freebairn, DM, McClymont, D, Silburn, DM, Owens, JS & Robinson, JB 2004, "HOWLEAKY? - The journey to demystifying 'simple' technology", Conserving Soil and Water for Society: Sharing Solutions, The 13th International Soil Conservation Organisation Conference, eds. S.R. Raine, A.J.W. Biggs, N.W. Menzies, D.M. Freebairn & P.E. Tolmie, ISCO, Brisbane, July.

Renard, KG & Ferreira, VA 1993, 'RUSLE model description and database sensitivity', Journal of environmental quality, vol. 22, no. 3, pp. 458-466.

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, vol. 48, no. 1, pp. 58-68.

Rohde, K, Bush, A & Agnew, J 2011, Paddock to Sub-catchment Scale Water Quality Monitoring of Sugarcane Management Practices. Interim Report 2010/11 Wet Season, Mackay Whitsunday Region, Department of Environment and Resource Management, Queensland Government for Reef Catchments (Mackay Whitsunday Isaac) Limited, Australia, Mackay.

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.

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: Proc. of the 13th Australasian Remote Sensing *and Photogrammetry* Conference, Earth observation: from science to solutions, Spatial Sciences Institute (Australia), Canberra, 21st-24th November.

Schaffelke, B 2001, 'Surface alkaline phosphatase activities of macroalgae on coral reefs of the central Great Barrier Reef, Australia', Coral Reefs, vol. 19, no. 4, pp. 310-317.

Seitzinger, SP, Sanders, RW & Styles, R 2002, 'Bioavailability of DON from natural and anthropogenic sources to estuarine plankton', Limnology and Oceanography, vol. 47, no. 2, pp. 353-366.

Shaw, M, Silburn, DM, Thornton, CM, Robinson, B & McClymont, D 2011, "Modelling pesticide runoff from paddocks in the Great Barrier Reef with HowLeaky", MODSIM 2011 - 19th International Congress on Modelling and Simulation - Sustaining Our Future: Understanding and Living with Uncertainty, eds. F. Chan, D. Marinova & R.S. Anderssen, 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, vol. 60, no. 1, pp. 113-122.

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.

Shepherd, RN & MacNish, SE 1989, Land management field manual Atherton/Mareeba district, Queensland Department of Primary Industries QE89002, Brisbane.

Silburn, DM, Wilkinson, SN, Whish, G, Thornton, CM, Stokes, CJ, Star, M, O'Reagain, PJ, Hawdon, AA, Henderson, A & Dougall, C 2012, Paddock to Reef Synthesis of Management Practice Effectiveness in Grazing (GBR-wide): knowledge to date, Queensland Department of Natural Resources and Mines (unpublished report), Toowoomba.

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, vol. 65, no. 4-9, pp. 117-127.

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", MODSIM 2011 - 19th International Congress on Modelling and Simulation - Sustaining Our Future: Understanding and Living with Uncertainty, eds. F Chan, D Marinova & RS Anderssen, 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, Biggs, JS, Weier, KL & Keating, BA 2003, 'Nitrate in groundwaters of intensive agricultural areas in coastal Northeastern Australia', Agriculture, Ecosystems and Environment, vol. 94, no. 1, pp. 49-58.

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.

Tims, SG, Everett, SE, Fifield, LK, Hancock, GJ & Bartley, R 2010, 'Plutonium as a tracer of soil and sediment movement in the Herbert River, Australia', Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms, vol. 268, no. 7-8, pp. 1150-1154.

Turner, R, Huggins, R, Wallace, R, Smith, R, Vardy, S & Warne, MSJ 2012, Sediment, Nutrient and Pesticide Loads: Great Barrier Reef Catchment Loads Monitoring 2009-10, 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", MODSIM 2011 - 19th International Congress on Modelling and Simulation - Sustaining Our Future: Understanding and Living with Uncertainty, eds. F Chan, D Marinova & RS Anderssen, 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, vol. 65, no. 4–9, pp. 194-202.

Walton, RS & Hunter, HM 2009, 'Isolating the water quality responses of multiple land uses from stream monitoring data through model calibration', Journal of Hydrology, vol. 378, no. 1-2, pp. 29-45.

Wang, Y-, Kuhnert, P & Henderson, B 2011, 'Load estimation with uncertainties from opportunistic sampling data - A semiparametric approach', Journal of Hydrology, vol. 396, no. 1-2, pp. 148-157.

Water Studies PTY LTD 1998, Barron basin hydrology water allocation and management plan: Volume 1, Prepared for Department of Natural Resources, Brisbane.

Waterhouse, J, Brodie, J, Lewis, S & Mitchell, A 2012, 'Quantifying the sources of pollutants in the Great Barrier Reef catchments and the relative risk to reef ecosystems', Marine pollution bulletin, vol. 65, no. 4-9, pp. 394-406.

Waters, DK, Carroll, C, Ellis, R, Hateley, LR, McCloskey, GL, Packett, R, Dougall, C & Fentie, B 2014, *Modelling reductions of pollutant loads due to improved management practices in the Great Barrier Reef Catchments – Whole of GBR, Technical Report, Volume 1*, Queensland Department of Natural Resources and Mines, Brisbane.

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", Proceedings of the 5th Australian Stream Management Conference. Australian Rivers: Making a Difference, eds. A.L. Wilson, R.L. Dehaan, R.J. Watts, K.J. Page, K.H. Bowmer & A. Curtis, Charles Sturt University, Thurgoona, NSW, 21st-25th May.

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, pp. 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, vol. 36, no. 1, pp. 143-165.

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

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, eds. R.S. Anderssen, R.D. braddock & L.T.H. Newham, Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics, Cairns, July.

Appendix A - Previous estimates of pollutant loads

Table 25 Pre-European (natural), current and anthropogenic loads for the Wet Tropics NRM basins, taken from Kroon et al. 2012

Basin	TSS (kt/yr)			TN (t/yr)			DIN (t/yr)			DON (t/yr)			PN (t/yr)		
	Pre-European	Current	Anthropogenic	Pre-European	Current	Anthropogenic	Pre-European	Current	Anthropogenic	Pre-European	Current	Anthropogenic	Pre-European	Current	Anthropogenic
Daintree	45	180	140	570	1,800	1,200	120	450	330	430	370	60	22	980	960
Mossman	7	41	34	67	470	400	17	130	110	46	48	2	4	290	290
Barron	25	100*	75	220	700*	480	59	50*	9	150	440*	290	13	440*	430
Mulgrave-Russell	41	210	170	760	3,900	3,100	170	1,700	1,500	570	620	50	23	1,500	1,500
Johnstone	41	320*	280	1,100	3,800*	2,700	240	2,100*	1,900	830	600*	230	26	2,200*	2,200
Tully	24	92*	68	710	1,400*	690	170	840*	670	520	470*	50	14	380*	370
Murray	9	41	32	230	920	690	72	470	400	160	200	40	4	250	250
Herbert	110	380*	270	750	2,600*	1,900	260	1,300*	1,000	440	740*	300	47	930*	880
Wet Tropics	**300**	**1,400**	**1,100**	**4,400**	**16,000**	**11,000**	**1,100**	**7,000**	**5,900**	**3,200**	**3,500**	**340**	**150**	**7,000**	**6,900**

Basin	TP (t/yr)			DIP (t/yr)			DOP (t/yr)			PP (t/yr)			PSIIs (kg/yr)		
	Pre-European	Current	Anthropogenic	Pre-European	Current	Anthropogenic	Pre-European	Current	Anthropogenic	Pre-European	Current	Anthropogenic	Pre-European	Current	Anthropogenic
Daintree	63	280	220	9	31	22	29	20	9	25	220	200	0	84	84
Mossman	7	72	65	1	5	4	3	3	0	3	64	61	0	180	180
Barron	26	76*	50	3	10*	7	11	54*	43	12	77*	65	0	52	52
Mulgrave-Russell	84	680	600	14	60	46	38	74	36	32	540	510	0	3,800	3,800
Johnstone	120	500*	380	26	46*	20	56	64*	8	38	550*	510	0	2,600	2,600
Tully	78	110*	32	17	21*	4	36	27*	9	25	67*	42	0	1,200	1,200
Murray	28	86	58	8	19	11	12	12	0	8	55	47	0	420	420
Herbert	93	240*	150	10	32*	22	36	56*	20	47	180*	130	0	3,800	3,800
Wet Tropics	**500**	**2,000**	**1,600**	**90**	**220**	**130**	**220**	**310**	**90**	**190**	**1,800**	**1,600**	**0**	**12,000**	**12,000**

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

*Indicates current load estimates derived from monitoring data

Appendix B – PEST calibration approach

The process of coupling PEST and Source Catchments is presented in Figure 40. 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.

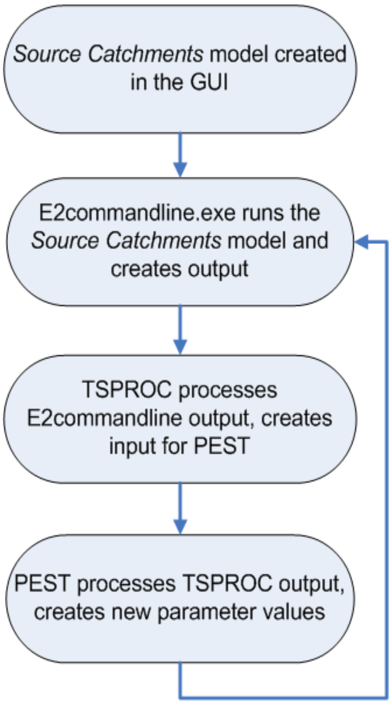

Figure 40 PEST - Source Catchments Interaction (Stewart 2011)

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

The PEST Super Parameter Definition (SVD-assist) was used to derive initial parameter sets and calibration results based on the initial 38 regions. The main benefit of using SVD-assist is the number of model runs required per optimisation iteration. SVD-assist does not need to equal or exceed the number of parameters being estimated. Of a possible 874 parameters, 150 super parameters were defined. The SVD-assist calibration was stopped once phi started to level out (Iteration 4). Due to IT limitations, the number of calibration regions was then reduced to 21. A full PEST run using all estimable parameters was then employed. Iteration 4 parameters were used as the starting values for the full 21 region PEST run. PEST was instructed to use E2commandline to perform the model runs. Given the size of the WT model, Parallel PEST was used to enable multiple computers (and processors) to undertake model runs at the same time. The programs used and process of running Parallel PEST is demonstrated in Figure 41.

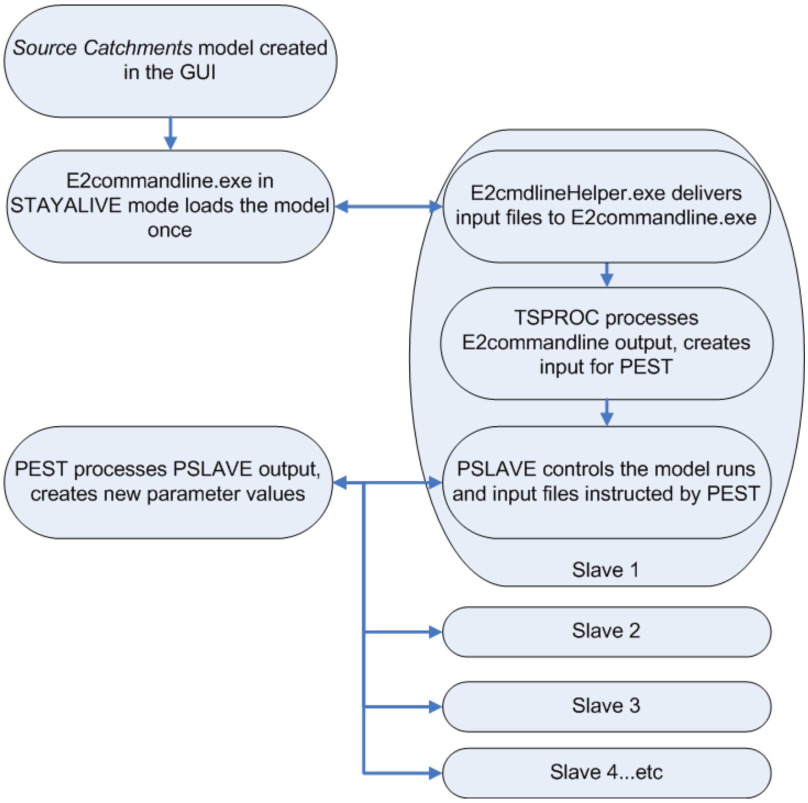

Figure 41 PEST operation (Stewart 2011)

Appendix C - SIMHYD model structure and parameters for calibration

The re-classification of land uses (FUs) into three HRUs is presented in Table 26. Default SIMHYD and Laurenson parameters were used as the starting values for the calibration process and these are identified in Table 27. The calibrated parameter values for three HRUs in 21 regions are provided in Table 28.

Table 26 Reclassification of land use (FUs) for hydrology calibration

Land use (FU)	HRU
Nature conservation	Forest
Grazing (closed)	Forest
Grazing (open)	Grazing
Forestry	Forest
Water	Not considered
Urban	Grazing
Horticulture	Agriculture
Irrigated cropping	Agriculture
Other	Grazing
Dryland cropping	Agriculture
Banana	Agriculture
Dairy	Grazing
Sugarcane	Agriculture

Table 27 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)	0.15	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

Table 28 Calibrated SIMHYD and Laurenson parameter values for three HRUs across 21 WT calibration regions

Forest	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
BASE	0.02	0.02	0.01	0.13	0.09	0.02	0.03	0.02	0.03	0.02	0.04	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.10	0.13
INFC	400	285	400	174	163	243	171	234	400	400	400	400	400	400	400	400	400.00	400	400	400	185
INFS	6.85	2.53	2.88	1.50	0.37	3.86	2.89	1.57	2.95	3.96	1.91	3.64	0.26	5.76	10	6.71	10	10	10	6.83	2.30
INTE	0.20	0.32	0.09	0.59	0.54	0.04	0.20	0.07	0.11	0.11	0.04	0.22	0.61	0.32	0.17	0.03	0.04	0.14	0.07	0.02	0.07
RECH	1	1	1	0.35	0.53	0.57	1	0.29	0.95	1	1	1	1	1	1	0.60	0.82	1	0.99	0.98	0.27
RISC	0.50	0.50	0.50	2.84	1.02	5.00	0.85	1.54	0.50	0.50	0.50	0.50	0.50	0.50	0.50	5.00	0.50	0.50	5.00	5.00	4.54
SMSC	750	20	20	750	551	296	137	750	22	255	23	377	20	298	665	328	583	704	344	451	199
Grazing																					
BASE	0.15	0.15	0.11	0.29	0.30	0.18	0.16	0.16	0.13	0.05	0.01	0.10	0.07	0.14	0.14	0.17	0.14	0.07	0.07	0.04	0.06
INFC	190	189	136	287	142	204	327	225	162	400	400	226	369	183	193	400	218	400	310	400	225
INFS	5.03	5.07	9.11	2.34	0.78	4.75	1.78	3.53	6.96	0.81	3.84	4.71	2.95	5.96	5.42	0.93	8.73	1.74	4.01	10	2.22
INTE	0.50	0.50	0.54	0.37	0.99	0.42	0.41	0.37	0.57	0.38	0.05	0.53	0.59	0.51	0.48	0.04	0.31	0.12	0.29	0.04	0.30
RECH	0.50	0.51	1.00	0.67	0.32	0.55	1	0.47	0.65	1	1	1	1	0.66	0.54	0.09	0.36	1	1	0.06	0.01
RISC	2.24	2.21	1.25	2.15	0.74	2.56	0.54	2.47	1.53	0.50	0.50	0.88	1.07	1.50	2.24	5.00	2.80	1.14	5.00	4.10	5.00
SMSC	239	238	159	311	750	208	583	230	184	22	282	178	360	203	233	258	171	109	90	234	750
Agriculture																					
BASE	0.15	0.15	0.07	0.21	0.13	n/a	0.18	0.15	0.05	0.09	0.08	0.06	0.04	0.14	0.08	0.15	0.14	n/a	n/a	0.30	n/a
INFC	190	190	400	227	313	n/a	153	212	277	309	400	400	400	179	296	195	221	n/a	n/a	400	n/a
INFS	5	5	2.52	3.33	1.12	n/a	10	3.92	3.29	2.64	2.69	1.45	5.55	6.46	2.65	4.91	4.21	n/a	n/a	1.59	n/a
INTE	0.50	0.50	1	0.48	0.64	n/a	0.48	0.43	1	1	0.34	0.30	0.11	0.51	0.34	0.44	0.36	n/a	n/a	0.26	n/a
RECH	0.50	0.50	1	0.50	0.07	n/a	0.23	0.47	1	1	1	1	1	1	1	0.44	0.50	n/a	n/a	0.40	n/a
RISC	2.25	2.25	0.50	3.32	1.69	n/a	0.81	2.45	0.50	0.50	1.59	0.50	0.50	1.18	0.88	2.82	2.87	n/a	n/a	5	n/a
SMSC	240	240	20	297	750	n/a	750	249	102	118	307	323	463	191	180	263	239	n/a	n/a	508	n/a
Laurenson flow routing																					
k	682	722	348	327	464	1,473	354	397	716	1,710	334	905	989	881	1078	2,420	13,466	1,519	2,858	647	748
m	1.79	2.00	1.79	1.34	2.00	1.77	0.72	1.61	1.96	1.46	1.65	1.91	1.70	2.00	1.41	1.24	0.94	1.92	1.80	1.83	1.84

(*NA indicates that these values were not applicable in a region due to the lack of that FU/HRU)

Appendix D – PEST calibration results

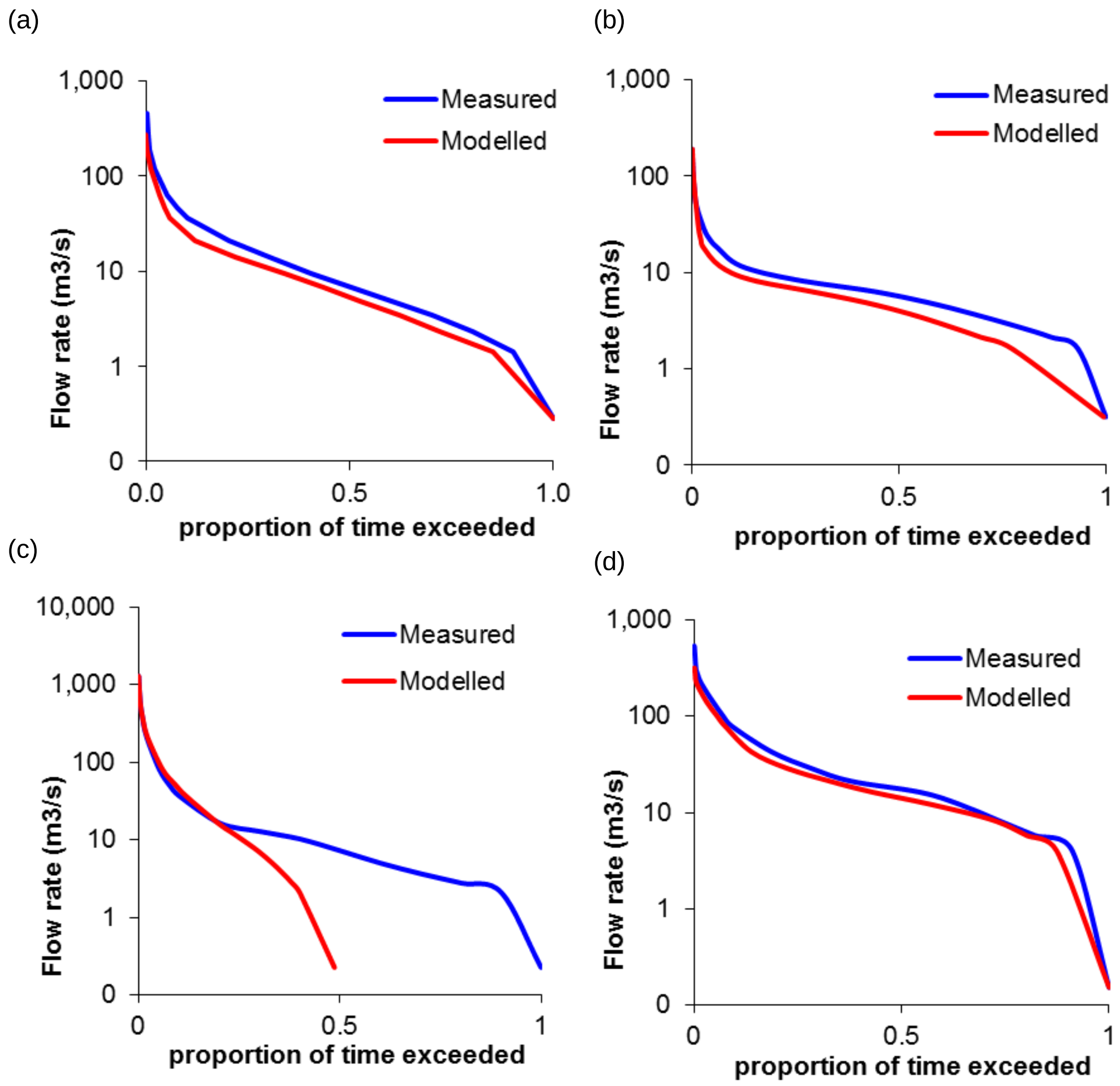

Figure 42 Flow duration curves of (a) 108003A, (b) 109001A, (c) 110001A-D and (d) 111101A-D

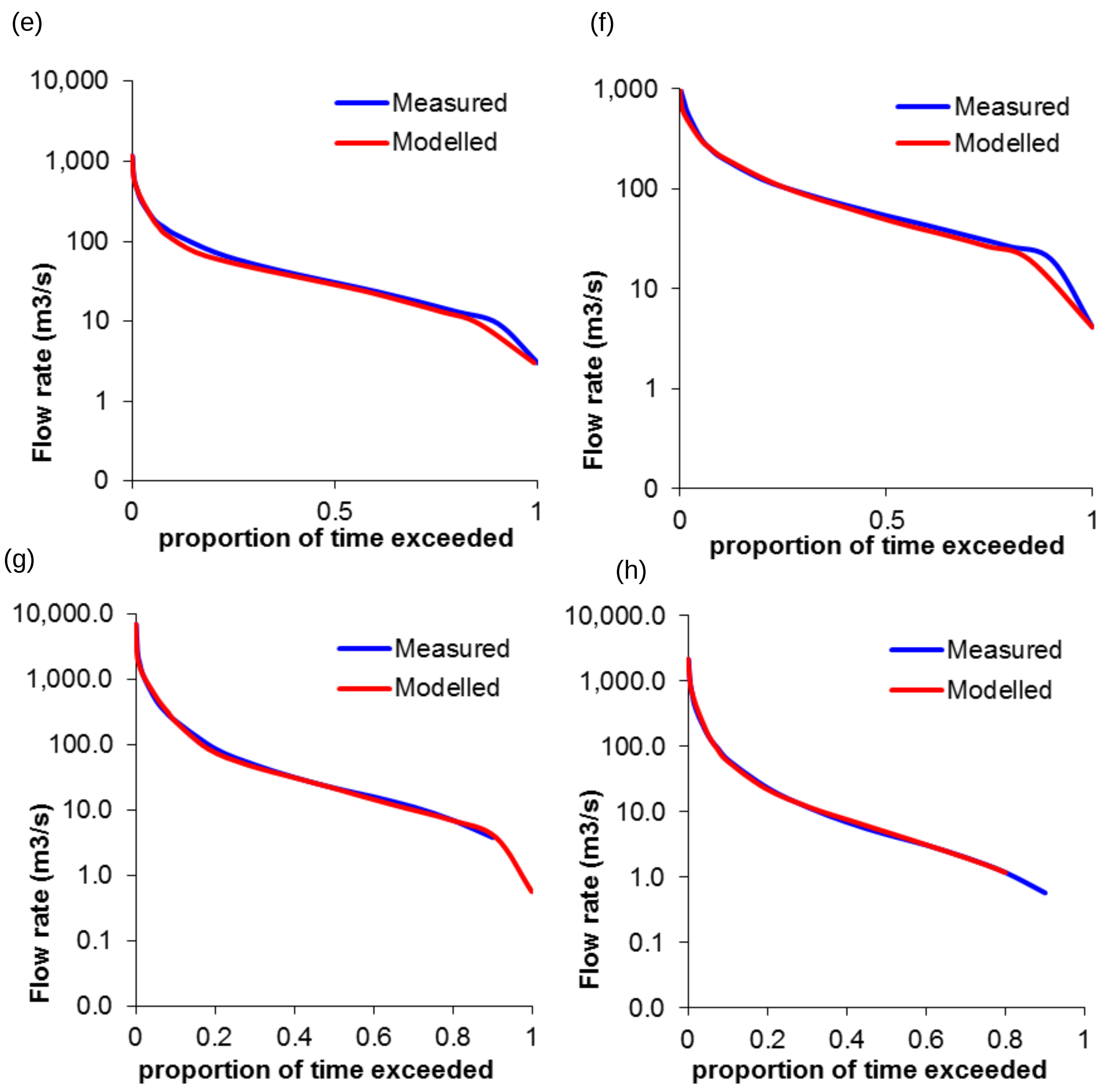

Figure 43 Flow duration curves of (e) 112001A/112004A, (f) 113006A, (g) 116001A-D and (h) 116004A-C

Appendix E – Dynamic SedNet global parameters and data requirements

Spatial projection

Spatial data was projected in the DNRM Albers Equal-Area projection. It is a conic projection commonly used for calculating area. Albers uses two standard parallels between which distortion is minimised and these are set using the latitudes at 1/5 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 29 Hillslope erosion parameters

Parameter	Value
TSS delivery ratio (DR) (%)	20
Coarse sediment DR (%)	0
Maximum quickflow concentration (mg/L)	10,000
DWC (mg/L)	15

Gully erosion

Table 30 Gully erosion parameters

Parameter	Value
Daily runoff power factor	1.4
Gully model type	DERM
TSS (fine sediment) DR (%)	100
Coarse sediment DR (%)	0
Gully cross sectional area (m^2)	5
Average gully activity factor	1
Management practice factor	variable
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), or diffuse runoff from other land uses or from inorganic diffuse sources such as fertilised cropping lands (Cogle, Carroll & Sherman 2006).

Six rasters are required as inputs, 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 database and 'no data values' were adjusted to the median value for that particular basin. A 'land use based concentrations' table was also required (see Table 31 and Table 35), which provides data on EMC/DWC values for each of the functional units.

Table 31 Dissolved nutrient concentrations for nutrient generation models (mg/L)

Land use	DIN EMC	DIN DWC	DON EMC	DON DWC	DIP EMC	DIP DWC	DOP EMC	DOP DWC	PN EMC	PN DWC	PP EMC	PP DWC
	(mg/L)											
Sugarcane	APSIM	1.5	0.5	0.3	APSIM+HL	N/A	APSIM+HL	N/A	Function of sediment	0.3	Function of sediment	0.015
Cropping	0.75	0.375	0.5	0.25	HL	0.007	HL	0.014		0.25		0.026
Grazing	0.16	0.08	0.3	0.15	0.013	0.0065	0.015	0.0075		0.48		0.021

(HL) HowLeaky

Nutrient enrichment and delivery ratios (NDR) are required for nitrogen and phosphorus. The input parameter values used in WT are found in Table 32.

Table 32 Particulate nutrient generation parameter values

Parameter	Phosphorus	Nitrogen
Enrichment ratio	5	3
Hillslope DR (%)	20	20
Gully DR (%)	100	100

Sugarcane and cropping constituent generation

HowLeaky is a point model, which was run externally to Source Catchments to model cropping practices. A unique HowLeaky simulation was run for each combination of soil group, slope and climate that was defined through a spatial intersection. A DERM tools plugin linked the spatial intersection with databases of parameters to build HowLeaky simulations that 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, which in WT 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. The HowLeaky input parameters for the WT model are shown in Table 33 and Table 34.

Table 33 Sugarcane and cropping nutrient input parameters

Parameter	Constituent	Value
Conversion factor	DOP	0.2
	DIP	0.8
Hillslope DR (%)	Dissolved nutrients	100
	Dissolved herbicides	90
	Particulates, sediment and particulate herbicides	20
Maximum slope (%)	sediment and particulates	8
Use Creams enrichment	Phosphorus	false
Particulate enrichment	Phosphorus	5
Particulate enrichment	Nitrogen	3
Gully DR (%)	Nitrogen and phosphorus	100

Table 34 Sugarcane and cropping sediment (hillslope and gully) input parameters

Parameter	Value
Clay (%)	40.6
Hillslope DR (%)	20
Maximum slope (%)	8
FU actually growing sugarcane (%)	75
Gully DR (%)	100
TSS DWC (mg/L)	72

EMC/DWC

A ‘land use based concentrations’ table is also required (Table 35), which provides data on EMC/DWC values for each of the functional units that was used an EMC/DWC model.

Table 35 EMC/DWC values (mg/L)

Land use	DIN EMC	DIN DWC	DON EMC	DON DWC	DOP EMC	DOP DWC	DIP EMC	DIP DWC	PN EMC	PN DWC	PP EMC	PP DWC	TSS EMC	TSS DWC
	(mg/L)													
Banana	1.02	0.51	0.21	0.105	0.03	0.015	0.08	0.04	0.5	0.25	0.1	0.05	120	60
Horticulture	0.41	0.205	0.21	0.105	0.03	0.015	0.048	0.024	0.5	0.25	0.1	0.05	120	60
Dairy	0.188	0.094	0.119	0.06	0.017	0.009	0.015	0.0075	0.48	0.24	0.04	0.02	150	75
Forestry	0.2	0.1	0.723	0.362	0.007	0.003	0.012	0.006	0.15	0.075	0.02	0.01	30	15
Nature conservation	0.16	0.08	0.119	0.06	0.007	0.003	0.009	0.0045	0.1	0.05	0.02	0.01	20	10
Urban	0.757	0.379	0.27	0.135	0.014	0.007	0.043	0.022	0.48	0.24	0.04	0.02	105	35
Other	0.757	0.379	0.27	0.135	0.014	0.007	0.043	0.022	0.48	0.24	0.04	0.02	105	35

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 subcatchments was 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 WT was 30 km^2. Floodplain area and extent was used to calculate a floodplain factor (potential for bank erosion) and for deposition (loss). The floodplain input layer was determined by using the Queensland Herbarium pre-clearing vegetation data and extracting the land zone 3 (alluvium) codes. The Queensland 2007 foliage 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. This threshold discriminates between woody and non-woody veg and it was assumed that the non-woody FPC cover (below 12%) is not effective in reducing streambank erosion (Department of Natural Resources and Mines 2003).

Streambank soil erodibility accounted for exposure of rocks resulting in only a percentage of the length of the streambank being erodible material, decaying to zero when floodplain width is zero. The steps below were followed to create a spatially variable streambank soil erodibility layer with its value increasing linearly from 0% to 100% as floodplain width increases from zero to a cut-off value (Equation 10). It was 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.

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

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

Surface clay and silt values taken from the ASRIS database were added together to create the clay and silt percentage layer. 'No data' values were changed to the median value, which in WT was 65%. Using the raster data layers described above, *SedNet Stream Fine Sediment model* calculates eight raster data sets that are used in the parameterisation process. The calculated rasters are: slope (%), flow direction, contributing area (similar to flow accumulation in a GIS environment), ephemeral streams, stream order, stream confluences, main channel and stream buffers.

Variable bank height and width functions were incorporated in the model to replace the default Dynamic SedNet fixed streambank height and width values. Bank height and width parameters were developed from local gauging station cross section data (DNRM Hydstra database). Regression relationships were determined from 22 data points of channel width and upstream catchment area (Figure 44), and channel height and upstream catchment area (Figure 45) from the WT region. 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 DNRM hydrographers. The equation was sourced from Wilkinson, Henderson & Chen (2004) (Equation 11) where:

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

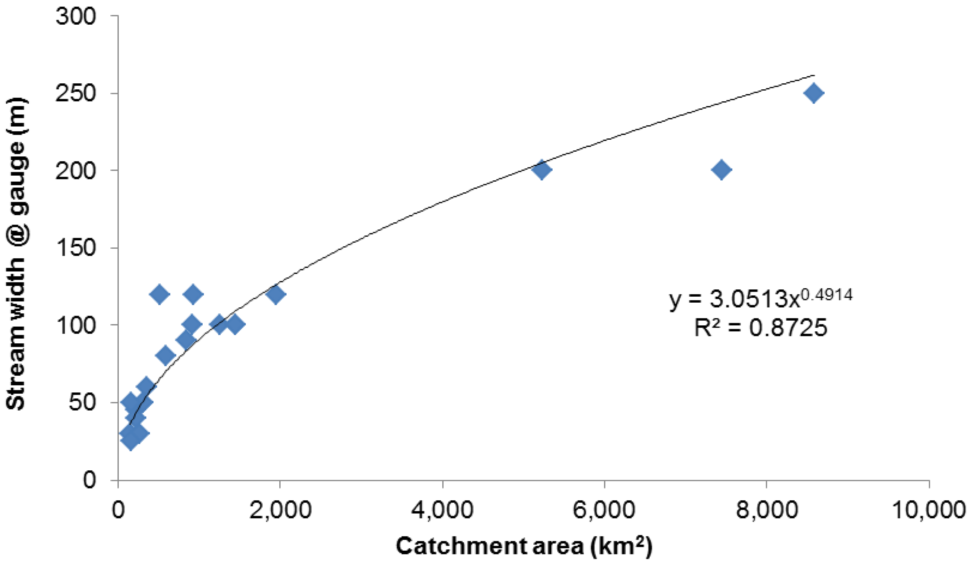

Figure 44 Catchment area and stream width used to determine streambank width parameters

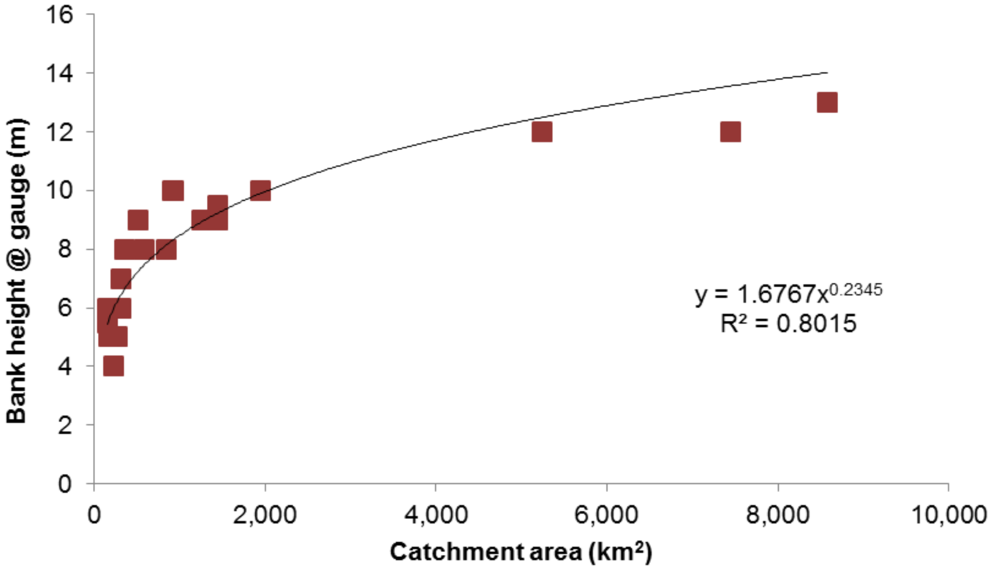

Figure 45 Catchment area and bank height used to determine streambank height parameters

A series of global input parameters are also required for the *SedNet Stream Fine Sediment model* to run. These were determined on a region-by-region basis, using the available literature, or default values identified in Wilkinson, Henderson & Chen (2004). The parameter values for WT are presented in Table 36.

Table 36 Streambank erosion parameters

Input parameters	Value
Bank Height Method: SedNet Variable – Node Based	
Proportion for TSS deposition	0
Catchment area exponent	0.2345
Catchment area coefficient	1.6767
Link Width Method: SedNet Variable – Node Based	
Minimum width (m)	10
Maximum width (m)	250
SedNet area exponent	0.4914
SedNet area coefficient	3.0513
SedNet slope exponent	0
Link Slope Method: Main Channel	
Minimum link slope	0.000001
Stream Attributes	
Bank full recurrence interval (years)	4
Stream buffer width (m)	100
Maximum vegetation effectiveness (%)	95
Sediment dry bulk density (t/m^3)	1.5
Sediment settling velocity (m/sec)	0.0007
Sediment settling velocity for remobilisation (m/sec)	0.1
Bank erosion coefficient	0.00002
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
Bank erosion management factor	variable

Herbicide half-lives

Table 37 Herbicide half-lives

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

Storage details

Table 38 Storage details and Lewis trapping parameters for WT

Storage	Storage details			Lewis trapping parameters						
	Full supply level (m)	Initial storage level (m)	Dead storage (m)	Length of storage (m)	Subtractor parameter	Multiplier parameter	Length/ discharge factor	Length/ discharge power	Capacity = Max geometry	Use outflow
Tinaroo Falls Dam	670.42	670.42	638.44	447	100	800	3.28	-0.2	False	False
Copperlode Dam	399.359	399.359	383.599	728	100	800	3.28	-0.2	False	False
Koombooloomba Dam	740.359	740.359	715.034	8645	100	800	3.28	-0.2	False	False

Land use area by basin

Table 39 Land use area (km^2) and per cent of total land use area by basin

Land use	Units	Daintree	Mossman	Barron	Mulgrave-Russell	Johnstone	Tully	Murray	Herbert	Total
Bananas	(km^2)	0.3	-	14	4	66	62	10	-	156
	(%)	0.2	-	9	2	42	40	6	-	100
Cropping	(km^2)	1	0.2	109	1	6	0.3	0.4	32	150
	(%)	0.7	0.1	73	0.4	4	0.2	0.2	22	100
Forestry	(km^2)	677	0.7	397	7	9	41	108	404	1,643
	(%)	41	0.04	24	0.4	0.5	2	7	25	100
Grazing (including dairy)	(km^2)	148	17	735	105	530	85	69	5,561	7,250
	(%)	2	0.2	10	1.4	7	1.2	1.0	77	100
Horticulture	(km^2)	2	1	43	11	13	8	6	4	88
	(%)	3	1	49	12	15	9	7	5	100
Nature conservation	(km^2)	1,175	363	632	1,429	1,275	1,219	712	2,661	9,468
	(%)	12	4	7	15	13	13	8	28	100
Sugarcane	(km^2)	44	48	56	249	280	203	158	759	1,797
	(%)	2	3	3	14	16	11	9	42	100
Urban/other	(km^2)	18	29	145	90	62	20	12	81	456
	(%)	4	6	32	20	14	4	3	18	100
Water	(km^2)	40	21	58	83	85	47	40	340	714
	(%)	6	3	8	12	12	7	6	48	100
Total	**(km^2)**	**2,107**	**479**	**2,189**	**1,979**	**2,326**	**1,685**	**1,115**	**9,842**	**21,722**

Management practice information

Table 40 Examples of improved management practices targeted through Reef Plan (including Reef Rescue) investments

Note: this list is not comprehensive (K McCosker pers.comm. 2014)

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

Modelled loads

Table 41 Modelled loads by basin for all scenarios

TSS (kt/yr)	Predevelopment load	Total baseline load	Increase factor	Anthropogenic baseline load	Report card 2013 load	Load reduction (%)
Daintree Basin	44	62	1.4	19	61	5.4
Mossman Basin	7	14	2.0	7	14	9.9
Barron Basin	42	92	2.2	50	82	19.79
Mulgrave-Russell Basin	67	168	2.5	101	150	17.9
Johnstone Basin	88	265	3.0	178	236	16.5
Tully Basin	46	110	2.4	64	104	9.0
Murray Basin	21	43	2.1	22	40	13.3
Herbert Basin	130	463	3.6	333	434	8.6
Wet Tropics	**445**	**1,219**	**2.7**	**773**	**1,122**	**12.5**
TN (t/yr)	**Predevelopment load**	**Total baseline load**	**Increase factor**	**Anthropogenic baseline load**	**Report card 2013 load**	**Load reduction (%)**
Daintree Basin	760	1,353	1.8	594	1,343	1.8
Mossman Basin	130	235	1.8	105	226	8.5
Barron Basin	182	464	2.5	281	454	3.3
Mulgrave-Russell Basin	1,040	1,804	1.7	764	1,722	10.8
Johnstone Basin	1,224	3,204	2.6	1,981	3,029	8.8
Tully Basin	810	1,566	1.9	756	1,529	4.9
Murray Basin	387	731	1.9	344	706	7.3
Herbert Basin	1,253	2,794	2.2	1,540	2,630	10.6
Wet Tropics	**5,786**	**12,151**	**2.1**	**6,365**	**11,639**	**8.0**
DIN (t/yr)	**Predevelopment load**	**Total baseline load**	**Increase factor**	**Anthropogenic baseline load**	**Report card 2013 load**	**Load reduction (%)**
Daintree Basin	323	387	1.2	64	379	11.8
Mossman Basin	55	107	1.9	52	101	12.4

Barron Basin	47	90	1.9	43	89	2.0
Mulgrave-Russell Basin	438	695	1.6	258	652	16.9
Johnstone Basin	506	1,360	2.7	854	1,304	6.5
Tully Basin	344	702	2.0	358	686	4.3
Murray Basin	166	288	1.7	122	273	12.1
Herbert Basin	535	807	1.5	272	695	41.2
Wet Tropics	**2,414**	**4,437**	**1.8**	**2,023**	**4,180**	**12.7**
DON (t/yr)	**Predevelopment load**	**Total baseline load**	**Increase factor**	**Anthropogenic baseline load**	**Report card 2013 load**	**Load reduction (%)**
Daintree Basin	241	685	2.8	444	685	N/A*
Mossman Basin	41	69	1.7	28	69	N/A*
Barron Basin	70	192	2.8	122	192	N/A*
Mulgrave-Russell Basin	327	549	1.7	223	549	N/A*
Johnstone Basin	378	700	1.9	323	700	N/A*
Tully Basin	256	443	1.7	186	443	N/A*
Murray Basin	124	283	2.3	160	283	N/A*
Herbert Basin	399	948	2.4	549	948	N/A*
Wet Tropics	**1,835**	**3,870**	**2.1**	**2,035**	**3,870**	**N/A***
PN (t/yr)	**Predevelopment load**	**Total baseline load**	**Increase factor**	**Anthropogenic baseline load**	**Report card 2013 load**	**Load reduction (%)**
Daintree Basin	195	282	1.4	86	279	3.7
Mossman Basin	34	59	1.7	25	56	10.2
Barron Basin	66	182	2.7	116	173	7.3
Mulgrave-Russell Basin	276	559	2.0	284	521	13.6
Johnstone Basin	340	1,144	3.4	804	1,025	14.8
Tully Basin	210	421	2.0	211	400	10.3
Murray Basin	97	159	1.6	62	149	16.4
Herbert Basin	319	1,038	3.3	719	987	7.2
Wet Tropics	**1,537**	**3,844**	**2.5**	**2,307**	**3,589**	**11.1**

TP (t/yr)	Predevelopment load	Total baseline load	Increase factor	Anthropogenic baseline load	Report card 2013 load	Load reduction (%)
Daintree Basin	73	95	1.3	22	92	13.7
Mossman Basin	12	22	1.7	9	19	25.8
Barron Basin	33	85	2.6	53	77	15.0
Mulgrave-Russell Basin	108	238	2.2	129	213	19.0
Johnstone Basin	153	530	3.5	377	428	27.3
Tully Basin	77	160	2.1	83	146	16.5
Murray Basin	36	71	2.0	35	63	23.4
Herbert Basin	150	454	3.0	304	427	8.8
Wet Tropics	**643**	**1,656**	**2.6**	**1,013**	**1,466**	**18.7**
DIP (t/yr)	**Predevelopment load**	**Total baseline load**	**Increase factor**	**Anthropogenic baseline load**	**Report Card 2013 load**	**Load reduction (%)**
Daintree Basin	18	24	1.3	6	23	9.9
Mossman Basin	3	5	1.7	2	5	19.6
Barron Basin	5	12	2.4	7	12	0.5
Mulgrave-Russell Basin	25	41	1.7	16	40	6.9
Johnstone Basin	28	49	1.7	21	47	9.8
Tully Basin	19	33	1.7	13	32	8.4
Murray Basin	9	17	1.9	8	16	15.0
Herbert Basin	30	47	1.6	17	45	10.2
Wet Tropics	**138**	**228**	**1.7**	**90**	**220**	**9.1**
DOP (t/yr)	**Predevelopment load**	**Total baseline load**	**Increase factor**	**Anthropogenic baseline load**	**Report Card 2013 load**	**Load reduction (%)**
Daintree Basin	14	15	1.1	1	15	11.6
Mossman Basin	2	3	1.1	0	2	33.2
Barron Basin	4	6	1.6	2	6	0.4
Mulgrave-Russell Basin	18	22	1.2	4	22	7.8
Johnstone Basin	21	29	1.4	8	28	6.5

Tully Basin	14	17	1.2	3	17	9.6
Murray Basin	7	9	1.2	1	8	20.7
Herbert Basin	23	30	1.3	7	30	6.0
Wet Tropics	**103**	**130**	**1.3**	**27**	**128**	**7.6**
PP (t/yr)	**Predevelopment load**	**Total baseline load**	**Increase factor**	**Anthropogenic baseline load**	**Report Card 2013 load**	**Load reduction (%)**
Daintree Basin	41	57	1.4	16	54	15.3
Mossman Basin	7	14	2.0	7	12	27.3
Barron Basin	23	67	2.8	43	59	18.3
Mulgrave-Russell Basin	65	175	2.7	110	152	21.1
Johnstone Basin	104	453	4.4	349	352	28.7
Tully Basin	44	110	2.5	66	98	18.5
Murray Basin	20	46	2.3	26	39	26.1
Herbert Basin	97	377	3.9	280	353	8.8
Wet Tropics	**401**	**1,297**	**3.2**	**896**	**1,118**	**20.0**
PSIIs (kg/yr)	**Predevelopment load**	**Total baseline load**	**Increase factor**	**Anthropogenic baseline load**	**Report Card 2013 load**	**Load reduction (%)**
Daintree Basin		235		235	192	18.5
Mossman Basin		150		150	119	20.9
Barron Basin		269		269	239	11.1
Mulgrave-Russell Basin		1,482		1,482	1,114	24.8
Johnstone Basin		1,861		1,861	1,264	32.1
Tully Basin		1,359		1,359	1,000	26.4
Murray Basin		862		862	590	31.6
Herbert Basin		2,378		2,378	1,850	22.2
Wet Tropics		**8,596**		**8,596**	**6,367**	**25.9**

*DON was not modelled for management changes

Land use contribution to export

Table 42 Land use contribution to export loads

Land use	TSS		TN		DIN		DON		PN		TP		DIP		DOP		PP		PSII	
	(kt/yr)	% of total	(t/yr)	% of total	(t/yr)	% of total	(t/yr)	% of total	(t/yr)	% of total	(t/yr)	% of total	(t/yr)	% of total	(t/yr)	% of total	(t/yr)	% of total	(kg/yr)	% of total
Bananas	28	4	396	3	233	5	48	1	115	3	48	3	18	8	7	5	23	2		
Cropping	14	2	97	1	23	1	21	1	53	1	16	1	2	1	1	1	13	1	351	4
Forestry	32	4	1,153	10	207	5	784	20	162	4	42	3	13	6	7	6	22	2		
Grazing (including dairy)	247	32	2,252	19	392	9	697	18	1,163	32	467	33	37	16	33	26	396	37		
Horticulture	10	1	87	1	30	1	17	0	40	1	14	1	4	2	2	2	8	1		
Nature conservation	178	23	3,366	28	1,411	32	1,065	28	890	24	318	22	80	35	60	46	178	16		
Point sources					38	1	10	0		0			7	3	2	1				
Sugarcane	219	29	3,980	33	1,828	41	1,123	29	1,029	28	486	34	50	22	12	10	424	39	8,245	96
Urban/other	39	5	566	5	275	6	105	3	186	5	38	3	17	7	5	4	16	1		
Wet Tropics	**766**	**100**	**11,897**	**100**	**4,437**	**100**	**3,870**	**100**	**3,638**	**100**	**1,429**	**100**	**228**	**100**	**130**	**100**	**1,079**	**100**	**8,596**	**100**

Table 43 DIN (t/yr) contribution to export loads by basin for banana, sugarcane, cropping and horticulture

Basin	DIN (t/yr)			
	Banana	Sugarcane	Cropping	Horticulture
Daintree	0	27	1.3	1.7
Mossman		42	0.1	0.2
Barron	3	4	8.7	2.9
Mulgrave-Russell	9	225	0.4	10
Johnstone	122	755	7.6	8.1
Tully	88	316	0.4	3.5
Murray	11	134	0.3	3.0
Herbert		326	4.6	0.5
Wet Tropics	**233**	**1,828**	**23**	**30**

Land use areal contribution to export

Table 44 Land use areal contribution to export

Land use	TSS	TN	DIN	DON	PN	TP	DIP	DOP	PP	PSII
	(t/ha/yr)	(kg/ha/yr)								(g/ha/yr)
Bananas	1.8	25.3	14.9	3.1	7.4	3.1	1.2	0.4	1.5	
Cropping	0.9	6.5	1.6	1.4	3.5	1.1	0.2	0.1	0.9	23
Forestry	0.2	7.0	1.3	4.8	1.0	0.3	0.1	0.04	0.1	
Grazing (including dairy)	0.3	3.1	0.5	1.0	1.6	0.6	0.1	0.05	0.5	
Horticulture	1.1	9.9	3.4	1.9	4.5	1.6	0.4	0.3	0.9	
Nature conservation	0.2	3.6	1.5	1.1	0.9	0.3	0.1	0.1	0.2	
Sugarcane	1.2	22.2	10.2	6.3	5.7	2.7	0.3	0.1	2.4	46
Urban/other	0.8	12.4	6.0	2.3	4.1	0.8	0.4	0.1	0.3	
Wet Tropics	**0.4**	**5.7**	**2.1**	**1.8**	**1.7**	**0.7**	**0.1**	**0.1**	**0.5**	**44**

Table 45 DIN (kg/ha/yr) areal contribution to export by basin for banana, sugarcane, cropping and horticulture

Basin	DIN (kg/ha/yr)			
	Banana	Sugarcane	Cropping	Horticulture
Daintree	14	6	13	7
Mossman	N/A	9	7.6	3.8
Barron	2	1	0.8	0.7
Mulgrave-Russell	24	9	8.5	9.4
Johnstone	18	27	12	6.3
Tully	14	16	12.5	4.2
Murray	11	8	7.5	4.9
Herbert	N/A	4	1.4	1.2
Wet Tropics	**15**	**10**	**1.6**	**3.4**

Table 46 PSIIs (g/ha/yr) areal contribution to export by basin for sugarcane and cropping

Basin	PSIIs (g/ha/yr)	
	Sugarcane	Cropping
Daintree	51	111
Mossman	31	121
Barron	16	16
Mulgrave-Russell	59	98
Johnstone	64	114
Tully	67	217
Murray	54	134
Herbert	30	21
Wet Tropics	**46**	**23**

Progress towards Reef Plan 2009 targets

Table 47 Report Card 2013 GBR load reduction (%) and WT load reduction (%)

Constituent	GBR load reduction (%)	WT load reduction (%)
TSS	11.0	12.5
TN	9.9	8.0
DIN	16.3	12.7
DON	2.2	N/A*
PN	10.6	11.1
TP	12.5	18.7
DIP	5.5	9.1
DOP	3.1	7.6
PP	14.3	20.0
PSIIs	27.6	25.9

*DON was not modelled for management changes

Appendix G - Additional validation

Long-term FRCE loads (1986–2009)

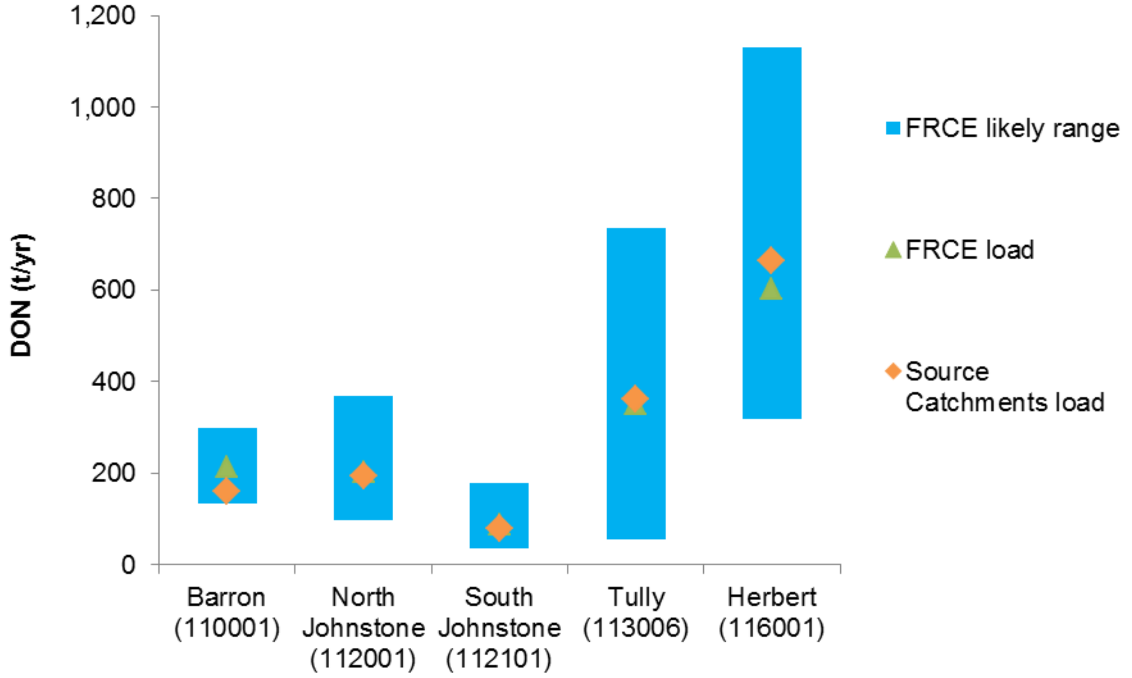

Figure 46 DON (t/yr) comparison between modelled and FRCE loads (observed data) for the period 1986–2009 for five EOS gauges

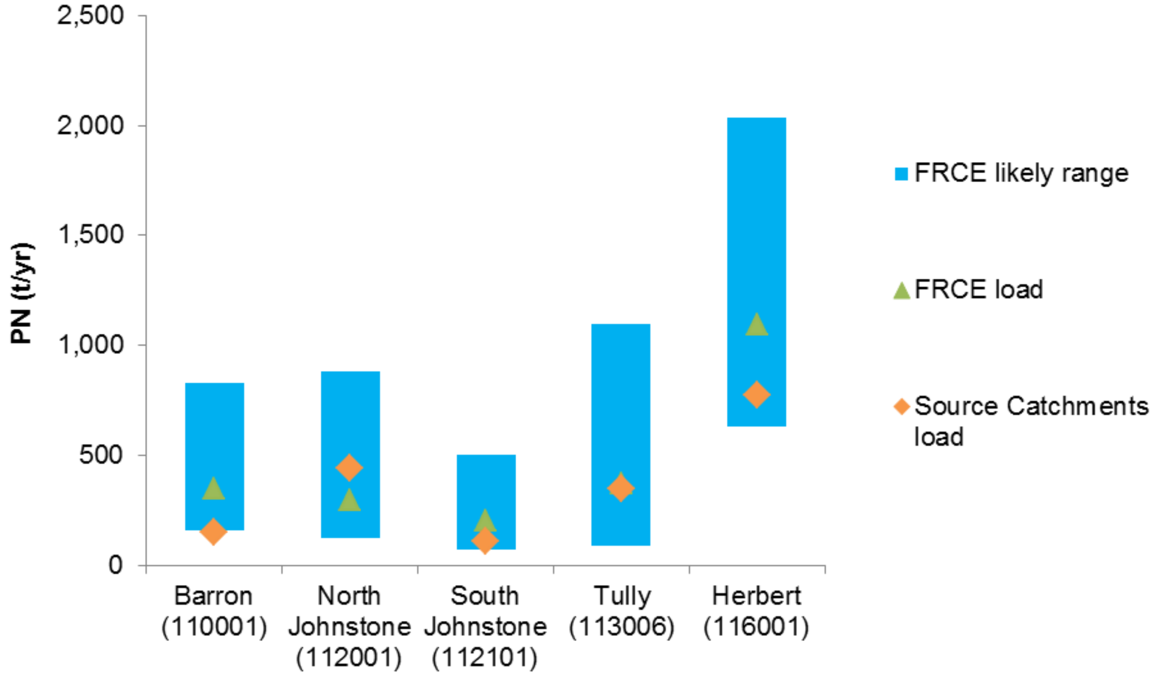

Figure 47 PN (t/yr) comparison between modelled and FRCE loads (observed data) for the period 1986–2009 for five EOS gauges

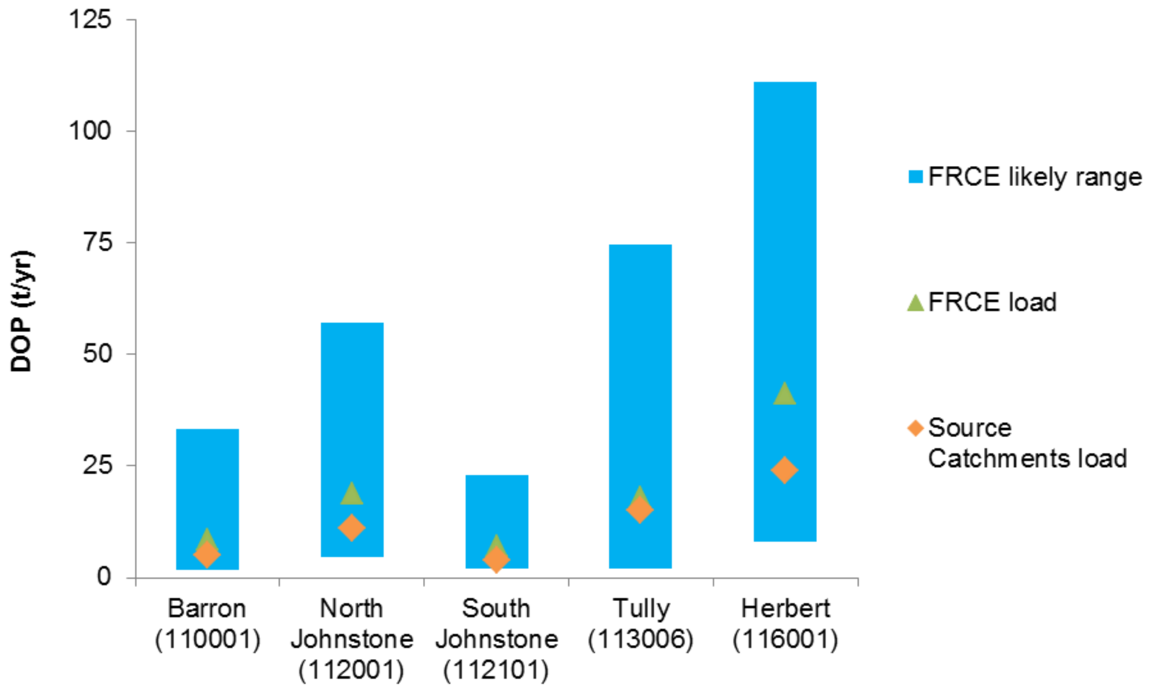

Figure 48 DOP (t/yr) comparison between modelled and FRCE loads (observed data) for the period 1986–2009 for five EOS gauges

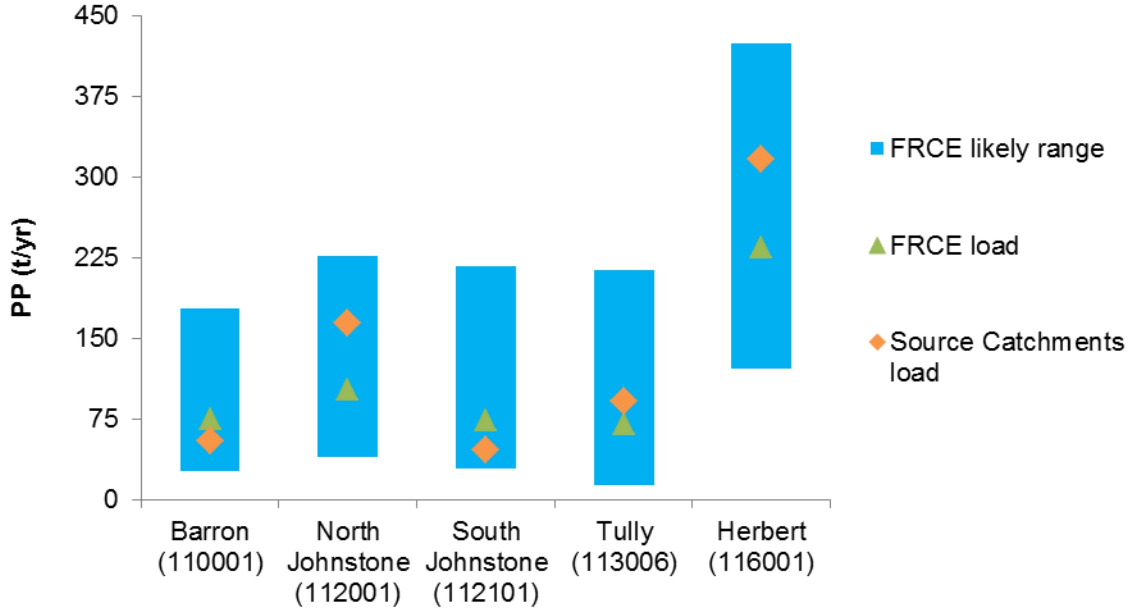

Figure 49 PP (t/yr) comparison between modelled and FRCE loads (observed data) for the period 1986–2009 for five EOS gauges

GBRCLMP validation (2006–2010)

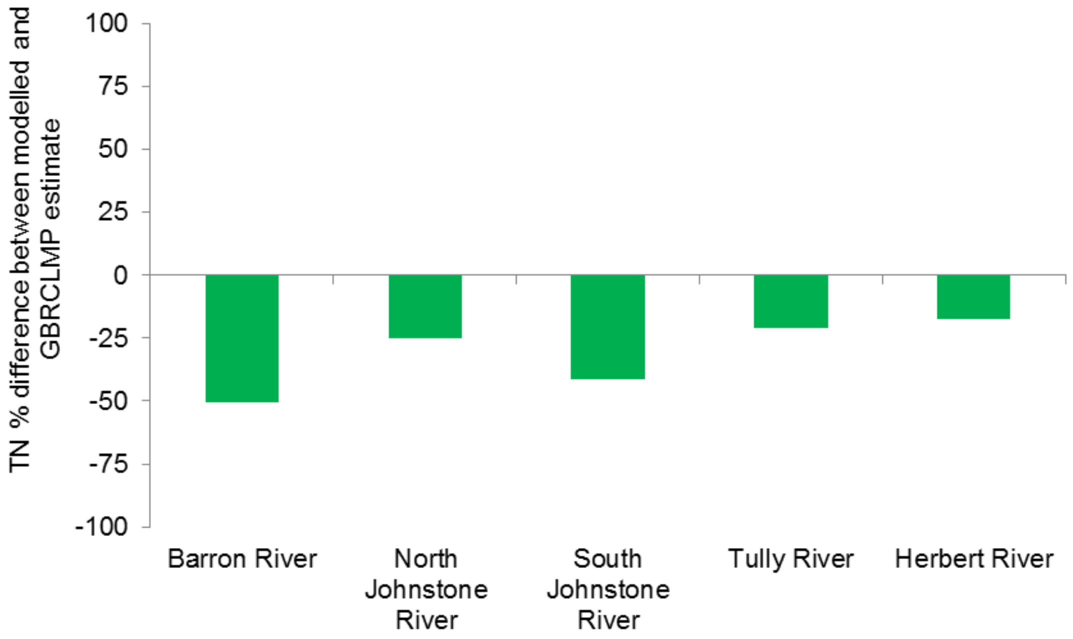

Figure 50 TN difference (%) between modelled and GBRCLMP estimate from measured data for the period 2006–2010 for five EOS gauges

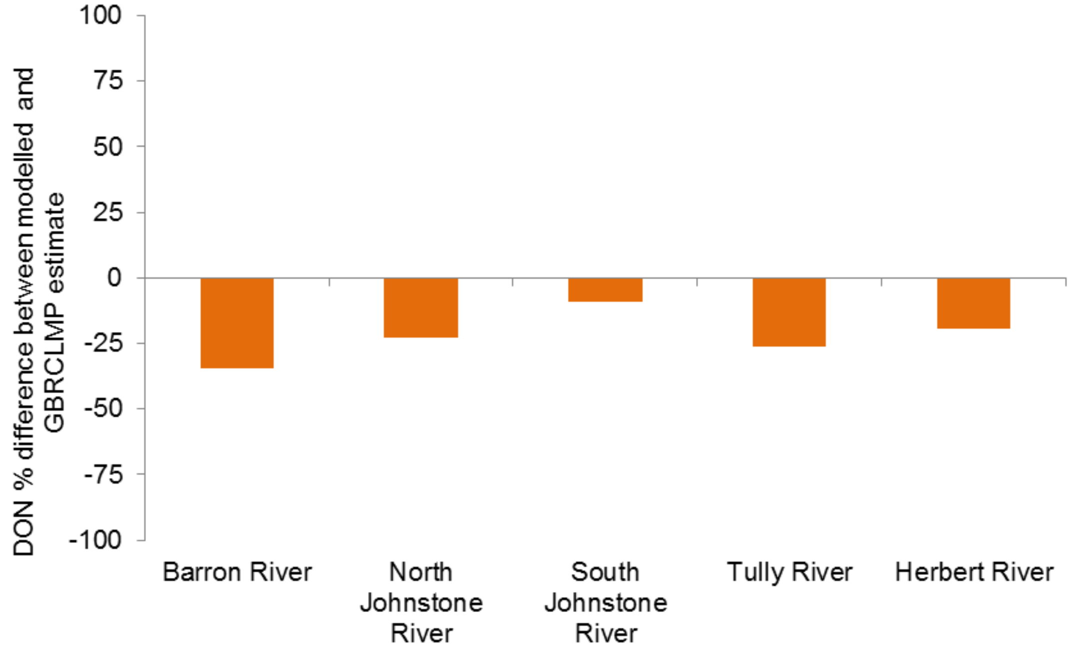

Figure 51 DON difference (%) between modelled and GBRCLMP estimate from measured data for the period 2006–2010 for five EOS gauges

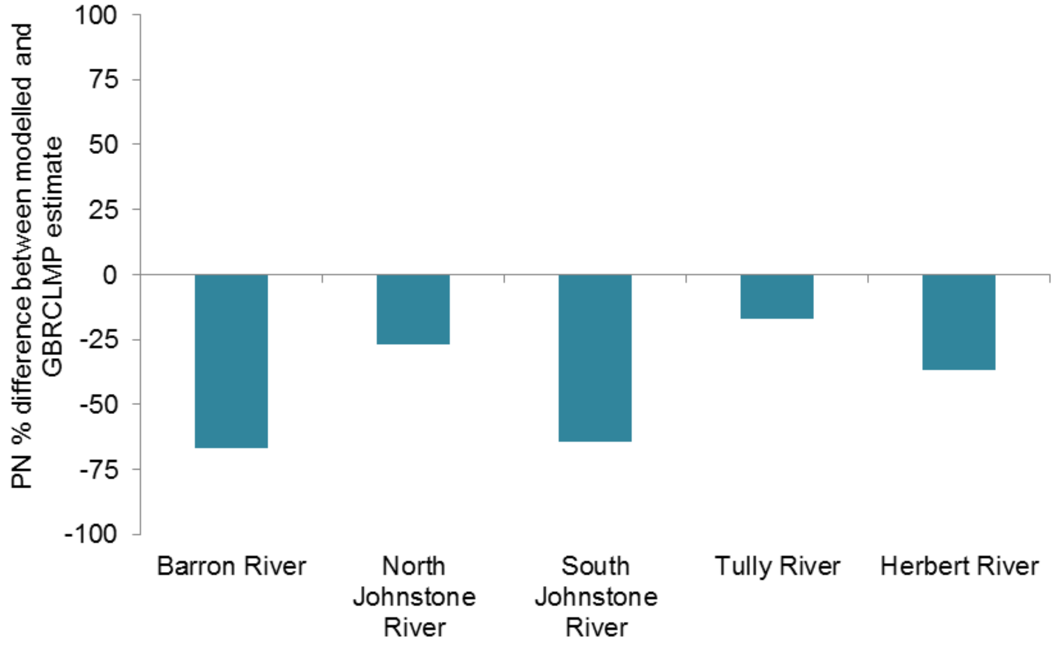

Figure 52 PN difference (%) between modelled and GBRCLMP estimate from measured data for the period 2006–2010 for five EOS gauges

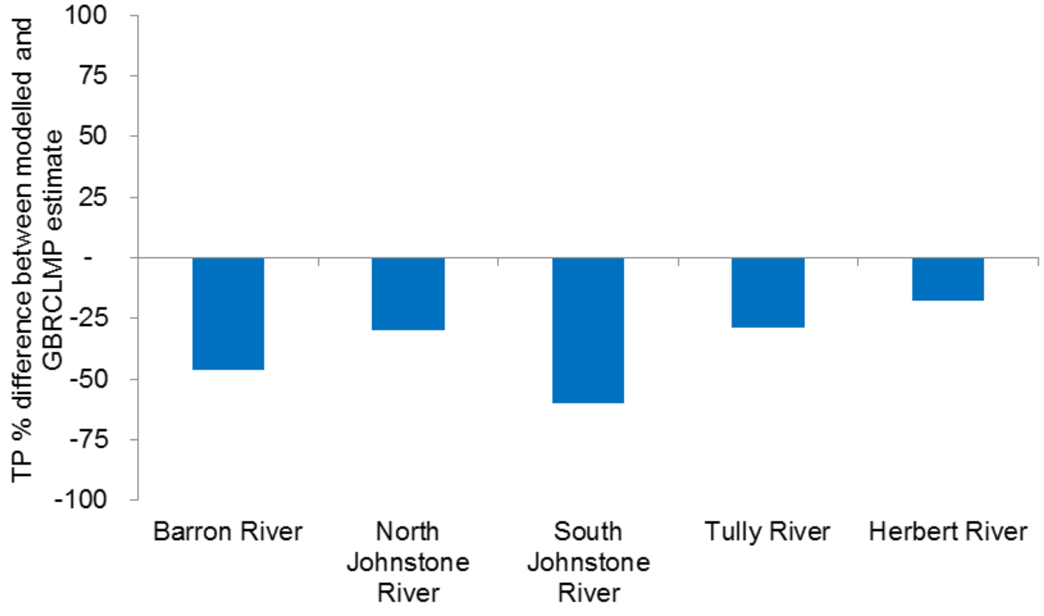

Figure 53 TP difference (%) between modelled and GBRCLMP estimate from measured data for the period 2006–2010 for five EOS gauges

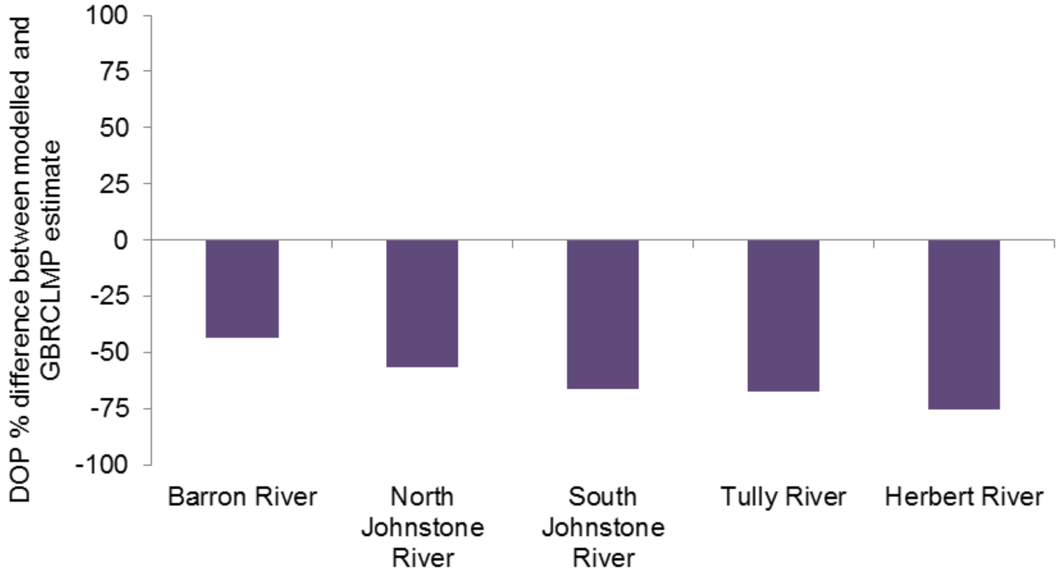

Figure 54 DOP difference (%) between modelled and GBRCLMP estimate from measured data for the period 2006–2010 for five EOS gauges

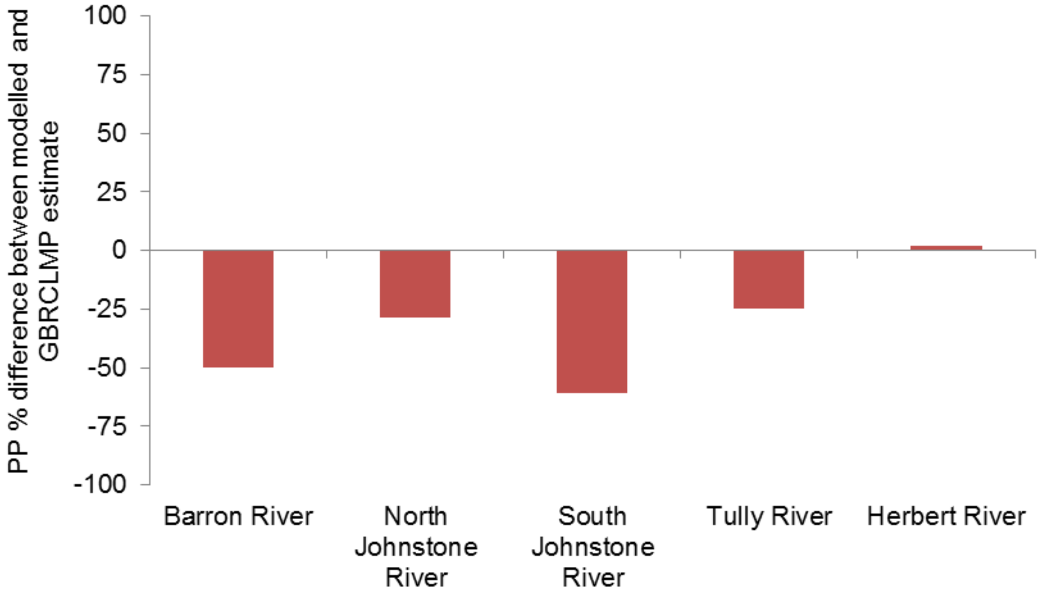

Figure 55 PP difference (%) between modelled and GBRCLMP estimate from measured data for the period 2006–2010

Appendix H – Report Card 2010 notes and results

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

- For Report Card 2010 the APSIM model runs for the WT consisted of one climate representation (Tully) and four soil types, assumed to be representative of the entire sugarcane area represented in the WT model. This resulted in a gross over estimation of runoff in the drier basins such as the Barron and Herbert and a slight under estimation of runoff in the Johnstone and Mulgrave-Russell basins. DIN and PSII herbicides loads were generated from the runoff derived from the APSIM model. To compensate for the runoff differences, a variable DR was used based on the runoff differences between the average runoff from Tully sugarcane and the average runoff form the other sugarcane basins. In addition, to better match the modelled DIN load for the Barron with loads estimated from measured data, the DR for DIN was further reduced by 50% (12.5%). Average runoff for each basin and variable DR applied based on runoff differences, is presented in Table 48.
- Methodology in Source Catchments was made available for Report Card 2011 that allowed dissolved P loads to change with management practice (changes that influenced runoff in APSIM). In Report Card 2010, no management effect was incorporated for dissolved phosphorus and hence no reductions in DIP and DOP loads due to improved management.
- DOP DWC was changed from 0.008 in Report Card 2010 to 0.02 in Report Card 2011.

Table 48 Variable delivery ratios for DIN and PSII herbicides in sugarcane, based on runoff comparisons, used in Report Card 2010

Basin	Average runoff (mm) (1986–2009)	% of Tully average runoff	DIN DR (%)	Herbicide DR (%)
Daintree	39,989	82	82	72
Mossman	31,019	64	64	54
Barron	12,113	25	12.5	15
Mulgrave-Russell	52,178	107	100	90
Johnstone	59,386	122	100	90
Tully	48,741	100	100	90
Murray	33,757	69	69	59
Herbert	21,814	45	45	35

- The DIN DWC for the Herbert Basin was reduced from 0.75 mg/L in Report Card 2010 to 0.19 mg/L in Report Card 2011. This was to better match modelled DIN EOS loads in the Herbert to the loads estimated from measured data.
- The indirect effects of grazing management on gullies and streambanks were 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.
- The hillslope DR for TSS and particulates was increased from 15% in Report Card 2010 to 20% in Report Card 2011 for grazing, cropping and sugarcane.
- The PP enrichment ratio for sugarcane and cropping was increased from 4 in Report Card 2010 to 5 in Report Card 2011and beyond.
- Finally, between Report Card 2010 and Report Card 2011model runs, the HowLeaky output timeseries for cropping land uses were also updated. The main difference between the runs was that the Report Card 2011 HowLeaky runs reverted to using the curve number function algorithm, from the CREAMS modelling method, for estimating runoff and as such reduced the erosion/runoff potential. In addition, the DOP DWC was increased from 0.007 mg/L in Report Card 2010 to 0.014 mg/L in Report Card 2011. PP DWC was also increased from 0.013 mg/L in Report Card 2010 to 0.026 mg/L in Report Card 2011.
- The constituent loads for each scenario as part of Report Card 2010 are presented for reference (Table 49). It is recommended that the Report Card 2013 values are cited/used when referencing Source Catchments loads. Most model changes resulted in little overall load change at the WT scale, generally -2% different from Report Card 2010 to Report Card 2011. The biggest change was for PSII herbicides, reflecting the move from one climate to many climates representative of the WT NRM region.

Table 49 Report Card 2010 predevelopment, total baseline and load reductions due to investment. Note, these are different to Report Card 2013 loads which are the loads that should be cited when referencing this work

Wet Tropics	TSS (kt/yr)	TN (t/yr)	DIN (t/yr)	DON (t/yr)	PN (t/yr)	TP (t/yr)	DIP (t/yr)	DOP (t/yr)	PP (t/yr)	PSIIs (kg/yr)
Predevelopment load	445	5,786	2,414	1,835	1,537	643	138	103	401	0
Total baseline load	1,228	12,222	4,437	3,870	3,915	1,513	232	131	1,150	10,229
Anthropogenic baseline load	782	6,436	2,023	2,035	2,378	870	94	28	749	10,229
Report Card 2010	1,217	12,111	4,375	N/A	3,866	1,493	N/A	N/A	1,130	9,795
Load reduction (%)	1.3	1.7	3.1	N/A	2.0	2.3	N/A	N/A	2.7	4.2

Appendix I – Report Card 2011 notes and results

The total baseline load values changed between Report Card 2011 and Report Card 2012 – Report Card 2013. The reasons for this were:

- For Report Card 2011 for sugarcane, slightly different baseline management proportions were used compared to the Report Card 2012 – Report Card 2013 baseline management proportions. This slight shifting in baseline management proportions (Report Card 2012 and Report Card 2013) was necessary to accommodate reported management changes. For each Report Card the modellers received additional information on investments by regional bodies. The assumption has to be that if the investment funded a change from C to B management, the 'from' category existed in our baseline year. In reality, it may be that this investment was a follow up to an earlier improvement on the same piece of land; however, this information was not provided to the modellers. Therefore, for each report card the baseline distribution was reallocated to ensure that reported changes could be represented.
- Data on riparian fencing that was implemented in the model as direct effects on streambank erosion was only made available for Report Card 2012 – Report Card 2013.
- Inflow was used as a component of the storage trapping model for Report Card 2012 and Report Card 2013, instead of outflow (used in Report Card 2011 and Report Card 2010).
- Actual storage capacity used in Report Card 2012 and Report Card 2013 instead of the max storage volume in the storage rating curve in Report Card 2011 and Report Card 2010. This change is significant where there were many storages and the max storage volumes in the rating curves are much greater than the actual storage capacities (this extrapolation sometimes occurs to ensure that no foreseeable climate fluctuation will create storage height/volume relationships that are mathematically unstable).
- The constituent loads for each scenario as part of Report Card 2011 are presented for reference (Table 50). It is recommended that the Report Card 2013 values are cited/used when referencing Source Catchments loads. Most model changes resulted in little overall load change at the WT scale.

Table 50 Report Card 2011 predevelopment, total baseline and load reductions due to investment

Note, these are different to Report Card 2013 loads which are the loads that should be cited when referencing this work

Wet Tropics	TSS (kt/yr)	TN (t/yr)	DIN (t/yr)	DON (t/yr)	PN (t/yr)	TP (t/yr)	DIP (t/yr)	DOP (t/yr)	PP (t/yr)	PSIIs (kg/yr)
Predevelopment load	445	5,786	2,414	1,835	1,537	643	138	103	401	0
Total baseline load	1,219	12,141	4,426	3,870	3,846	1,657	229	130	1,298	8,596
Anthropogenic baseline load	774	6,356	2,012	2,035	2,309	1,014	90	27	897	8,596
Report Card 2011 load	1,199	11,879	4,254	N/A	3,755	1,599	224	129	1,244	7,774
Load reduction (%)	2.7	4.1	8.5	N/A	3.9	5.8	4.5	3.7	6.0	9.6

Appendix J – Report Card 2012 notes and results

- The Report Card 2012 and Report Card 2013 total baseline loads are the same. No changes were made to the baseline model between Report Card 2012 and Report Card 2013.
- The summary of Report Card 2012 results are presented in Table 51.

Table 51 Report Card 2012 predevelopment, total baseline and load reductions due to investment

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

Wet Tropics	TSS (kt/yr)	TN (t/yr)	DIN (t/yr)	DON (t/yr)	PN (t/yr)	TP (t/yr)	DIP (t/yr)	DOP (t/yr)	PP (t/yr)	PSIIs (kg/yr)
Predevelopment load	445	5,786	2,414	1,835	1,537	643	138	103	401	0
Total baseline load	1,219	12,151	4,437	3,870	3,844	1,656	228	130	1,297	8,596
Anthropogenic baseline load	773	6,365	2,023	2,035	2,307	1,013	90	27	896	8,596
Report Card 2012 load	1,173	11,826	4,251	N/A	3,706	1,558	223	129	1,207	7,391
Load reduction (%)	5.9	5.1	9.2	N/A	6.0	9.6	6.5	5.4	10.1	14.0

Appendix K – Hotspot analysis of TSS, DIN and PSII herbicides by basin and by subcatchments for Terrain NRM

The Source Catchments modelling framework has been applied in the Wet Tropics region to predict loads of sediment, nutrients, and herbicides entering the GBR lagoon. The modelling framework incorporates functionality to enable reporting of the contribution of individual land uses and processes (e.g. gully erosion) within those land uses, to end of catchment pollutant loads.

A basin and subcatchment analysis was conducted to identify the areas within the WT region that contribute disproportionately (hotspots) to the loads of TSS, DIN and PSIIs. This was done by examining pollutant export on a per hectare basis with a focus on sugarcane and grazing land uses. The analysis also identified the factors that contributed to high pollutant export from these hotspots. The main factors that were considered were;

- Land use
- Rainfall/runoff
- Soil type distribution
- Slope
- The proportion of farmers in either A,B,C or D level management practices
- Gully and streambank erosion

Many of the factors that contributed to differences in per hectare loads of pollutants were applied in the modelling at a finer spatial scale than the modelling subcatchments. However, it is recommended that hotspots be identified at a spatial scale consistent with the information on management practice distribution. In the WT region, management practice distributions were provided at a basin scale (e.g. Barron Basin) up to and including Report Card 2013. Results from the baseline year (2008) were used in the hotspot analysis presented here.

Gully and streambank erosion is not presented at subcatchment scale due to broad scale of input data and brief comments will be made at the basin scale. Should detailed contribution from gully and streambank erosion be required, local data on gully density and stream bank migration rates would be required.

Basin analysis

TSS

By basin, the range of TSS areal rates for land use (excluding streambank erosion) was 0.2 t/ha/yr in the Barron and Herbert basins to 0.9 t/ha/yr in the Johnstone Basin (Table 52). The majority of the land use TSS load in the Johnstone Basin came from intensive agriculture (sugarcane, cropping, bananas and other horticulture) at 46% of total Johnstone TSS land use load. Grazing (including dairy) contributed 31% of the total Johnstone TSS load, followed by nature conservation at 18% of the total Johnstone TSS load. The majority of the Johnstone intensive agriculture load was from hillslope erosion. The Herbert Basin had the highest gully erosion rate at 0.02 t/ha/yr, followed by the Barron and Johnstone each at

~0.01 t/ha/yr. Grazing, sugarcane and cropping were the only land uses modelled for gully erosion. The majority of the total WT gully erosion was from grazing. Streambank erosion accounted for 37% of the WT TSS supplied. The majority of the bank erosion was from the Herbert Basin at 53% of the exported streambank erosion, followed by the Johnstone and Russell-Mulgrave basins at ~14% each. The Mulgrave-Russell Basin had the highest streambank TSS areal load at 0.26 t/m/yr.

Table 52 TSS loads and areal loads for land uses and processes

Basin	Area (km^2)	Land use TSS load (t/yr)	Land use TSS areal load (t/ha/yr)	Gully TSS load (t/yr)	Gully TSS areal load (t/ha/yr)	Stream bank TSS load (t/yr)	Stream bank TSS areal load (t/m/yr)
Daintree	2,107	60,457	0.3	20	0	3,401	0.01
Mossman	479	12,718	0.3	9	0	1,791	0.04
Barron	2,189	43,010	0.2	2,402	0.011	49,855	0.14
Mulgrave-Russell	1,979	110,820	0.6	297	0.002	59,286	0.26
Johnstone	2,326	202,515	0.9	1,992	0.010	66,472	0.17
Tully	1,685	89,553	0.5	459	0.003	21,855	0.09
Murray	1,115	35,599	0.3	315	0.003	8,663	0.07
Herbert	9,842	225,038	0.2	23,650	0.024	240,981	0.16
Total	**21,722**	**779,710**	**0.4**	**29,145**	**0.013**	**452,305**	**0.14**

The grazing export rate for TSS ranged from 0.2 t/ha/yr in the Murray and Herbert basins to 1.8 t/ha/yr in the Mulgrave-Russell Basin, with an overall WT grazing export TSS rate of 0.3 t/ha/yr (Table 53). The sugarcane hillslope export rate for TSS ranged from 0.3 t/ha/yr in the Barron Basin to 2.5 t/ha/yr in the Johnstone Basin, with an overall WT hillslope export TSS rate of 1.2 t/ha/yr (Table 53). In the baseline year, the majority of sugarcane land was managed at a C level or below in all basins other than the Barron and the Herbert. As the Barron and Herbert basins overall have the lowest runoff and a higher percentage of sugarcane area in A and B soil management, these two basins have the lowest TSS export rates, along with the Daintree and Mossman basins. While the Daintree and Mossman basins had higher runoff and slopes than in the Herbert, the contribution from gully erosion in the Herbert meant that the overall sugarcane TSS export rates from the Herbert were similar to the Daintree and Mossman regions (Table 52).

DIN

The Johnstone Basin had the highest sugarcane DIN export rate at 27 kg/ha/yr (Table 53). In the baseline year, the Johnstone Basin had one of the highest proportions of area in C and D class management for nutrient management (73%), with an average N fertiliser application of rate of 145 kg/ha/yr. The Mossman and Daintree basins also had a high proportion of the sugarcane area under C and D level management (74%). However, the proportion in D management (~18.5%) was much lower than in the Johnstone Basin (~35%) and the average N application rate was 142 kg/ha/yr. This difference in the areas under D class management practices, combined with lower runoff in these basins and slightly lower application rate meant that the overall export rate of DIN from the Mossman and Daintree basins was much lower than from the Johnstone.

The Mulgrave-Russell and Tully basins had similar runoff to the Johnstone Basin. However, both the Mulgrave-Russell and Tully basins had a lower proportion of area in C and D nutrient management which resulted in lower sugarcane DIN export rates of 9 and 16 kg/ha/yr respectively.

The lowest DIN export rates were from the Barron (1 kg/ha/yr) and the Herbert (4 kg/ha/yr). Both basins have similar runoff and sugarcane area in C and D management. The dry weather concentration (DWC) was modelled as 0.19 mg/L in these basins rather than the 1.5 mg/L applied in the other Wet Tropics basins. This value was set to better match measured water quality data at each EOS gauge. In addition, the DIN dissolved delivery ratio for the Barron Basin was reduced from 100% to 50% to reflect the lower RR ratio in this drier basin and to better match water quality data. The DWC also made a significant contribution to the DIN export rates modelled (Table 53) as well as the proportion of the slowflow (baseflow) to the total flow. For sugarcane, slowflow contributed 41% of the total flow, with the remaining from quickflow (event flow or runoff). The DWC concentrations and delivery ratios will be reconsidered in the next model build particularly in the areas below the EOS gauge in these two basins.

PSII herbicides

The highest PSII export rate was from the Tully Basin at 67 g/ha/yr (Table 53). The Tully had a slightly higher export rate than the Johnstone (64 g/ha/yr) which was attributed to the higher runoff volume in the Tully. Both of these basins had 100% of sugarcane managed at a C and D level. Export of PSIIs was slightly lower again from the Mulgrave-Russell (59 g/ha/yr) which was primarily due to slightly lower runoff and less area under C and D management. The same delivery ratio for PSII herbicides was applied to paddock export loads to stream. This was set as 90% for the dissolved fraction in all of the basins.

Table 53 Basin comparison of sugarcane parameters and results and grazing results

Basin	Average annual runoff (mm)	Average N application rate (kg/ha/yr)	Sugarcane DIN export rate (kg/ha/yr)	Sugarcane DIN DWC concentration (mg/L)	Sugarcane DIN Dissolved delivery ratio (%)	Sugarcane area in C and D nutrient management (%)	Sugarcane PSIIs export rate (g/ha/yr)	Sugarcane area in C and D herbicide management (%)	Average sugarcane slope (%)	Sugarcane TSS (hillslope) export rate (t/ha/yr)	Grazing TSS export rate (t/ha/yr)	Sugarcane area in C and D soil management (%)
Daintree	1,253	142	6	1.5	100	74	51	96	3.0	0.6	0.6	100
Mossman	1,074	142	9	1.5	100	74	31	96	4.0	0.7	0.6	100
Barron	363	128	1	0.19	50	53	16	31	2.0	0.3	0.3	75
Mulgrave-Russell	1,858	128	9	1.5	100	39	59	93	3.0	1.5	1.8	>99
Johnstone	1,961	145	27	1.5	100	73	64	100	2.8	2.5	1.2	96
Tully	2,072	134	16	1.5	100	38	67	100	1.0	1.7	0.6	>99
Murray	1,167	134	8	1.5	100	38	54	100	1.1	0.9	0.2	>99
Herbert	434	141	4	0.19	100	58	30	87	1.1	0.7	0.2	78
WT average		**137**	**10**				**46**		**1.9**	**1.2**	**0.3**	

Subcatchment analysis

TSS

Grazing and sugarcane were the two dominant land uses that contributed the highest exports of TSS per hectare. The ten highest contributing subcatchments in terms of TSS export rates are shown in Table 54. For the subcatchments that were ranked in the top ten in terms of TSS export, rates ranged from 1.7–3.1 t/ha/yr. When the export of TSS was considered only from the dominant land use within a subcatchment, the rates varied from 1.6–3 t/ha/yr in sugarcane and 2–4.9 t/ha/yr in grazing lands.

DIN

Areal export rates for the top ten contributing subcatchments for DIN ranged from 13–23 kg/ha/yr (Table 55). The highest export rates of DIN by subcatchment were located in the Johnstone basin. The proportion of each subcatchment that had intensive agriculture was the main factor behind the differences in DIN areal export rates for the Johnstone basin. Subcatchments 147, 149 and 150 are all located in the Silkwood/El Arish region, share common subcatchment boundaries, have similar runoff volumes, but have different DIN export rates, 14 kg/ha/yr for SC147 and SC149 and 23 kg/ha/yr for SC150. Intensive agriculture comprised 75% of the area of SC150 compared to 44% in SC147 and 38% in SC149.

The export rate of DIN from sugarcane for the top ten subcatchments ranged from 16–32 kg/ha/yr. The differences in areal rates were influenced by the average DIN application rate, which was a function of the management classes assigned. Of the three basins that were represented in the top ten DIN contributing subcatchments, the Johnstone had the highest average sugarcane N application rate at 145 kg/ha/yr, which resulted in the highest sugarcane DIN loads by area (28–32 kg/ha/yr). Differences were also due to the soil types mapped (Figure 56) and the amount and timing of runoff (Figure 57). For example, within the Johnstone Basin the subcatchment with the highest sugarcane DIN areal load (kg/ha/yr) was SC149 where the APSIM soil types mapped were the brown chromosol (40%) and the brown dermosol (60%). By comparison, the subcatchment with the lowest sugarcane DIN areal load (kg/ha/yr) (of the top 10) was SC395 where 60% of the soil was mapped as a ferrosol and only 10% as the brown chromosol. The loss of DIN was modelled as almost half from the ferrosol compared to the brown chromosol for an equivalent application scenario, which contributed to the higher rate of DIN export from SC147.

The average DIN export rate per hectare from land uses other than sugarcane in the top ten subcatchments was 17 kg/ha/yr for bananas, 12 kg/ha/yr from cropping and 7 kg/ha/yr from horticulture.

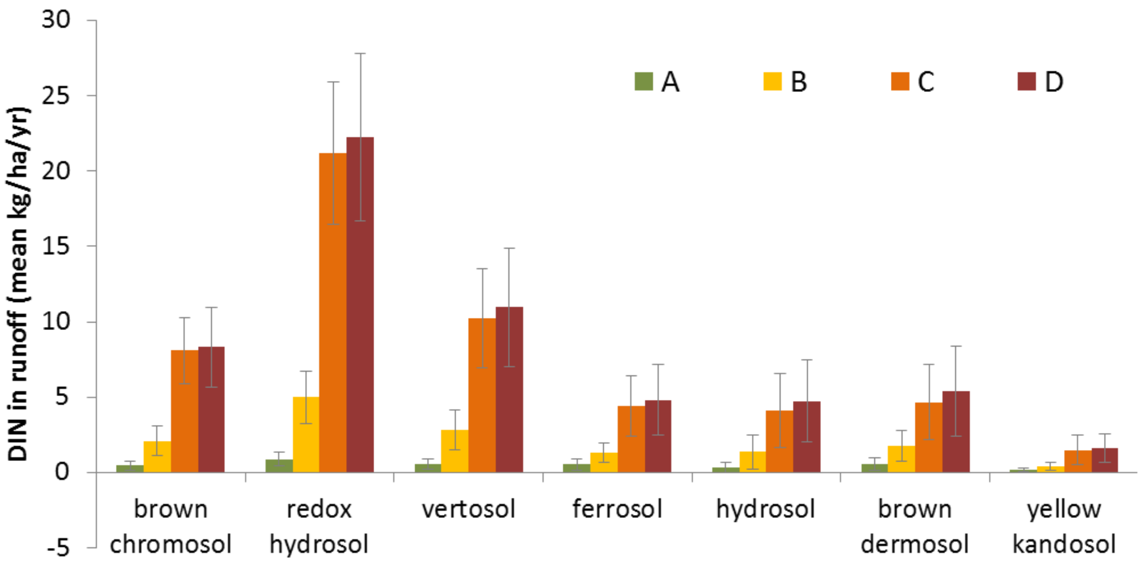

Figure 56 Loss of DIN in runoff (mean kg/ha/yr) from sugarcane for each of the soil types modelled in APSIM

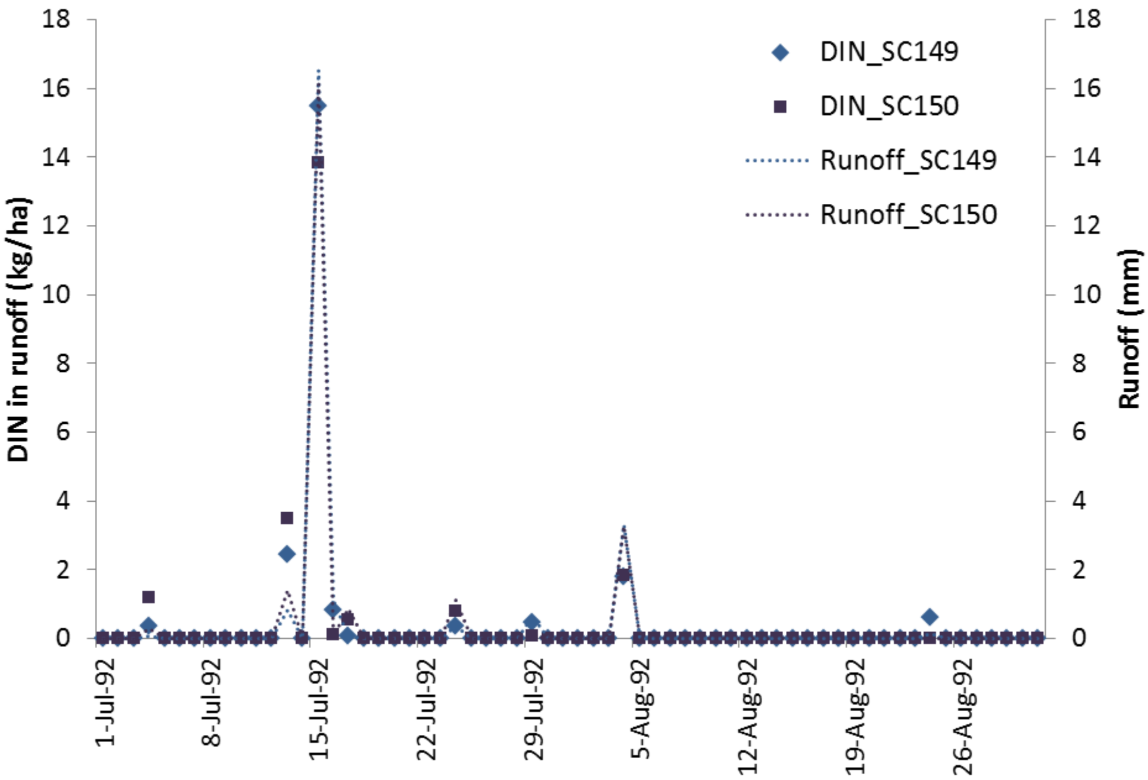

Figure 57 Runoff amounts and the loss of DIN in runoff (kg/ha) on the same days (July–August 1992) in SC149 vs SC150. While both subcatchments have similar annual rainfall and runoff amounts, differences in runoff on days soon after the application of fertiliser have an influence on annual DIN losses

PSII herbicides

Sugarcane and cropping (dryland and irrigated) are the only two land uses where the application of PSII herbicides was modelled. The top ten subcatchments in terms of PSII export are shown in Table 56. Cropping was only represented as a very small area in one of the top 10 subcatchments and therefore was not included in this analysis. The PSII export rates for the highest contributing subcatchments ranged from 43–69 g/ha/yr. The load of PSIIs exported from sugarcane ranged from 53–112 g/ha/yr.

Differences in the loss of PSIIs from adjacent subcatchments under the same level of management (e.g. within the Johnstone Basin) could be attributed to the distribution of soils within these subcatchments and slight differences in the timing of rainfall events soon after the application of herbicides. The APSIM soil types mapped to SC150 were predominantly the brown chromosol (60%) and the brown dermosol (39%) while the main soil in SC393 was the redox hydrosol (67%). The loss of PSII herbicides was modelled as >2x from the redox hydrosol than from the brown chromosol or the brown dermosol for an equivalent application scenario (Figure 58) which contributed to the higher rate of PSII export from SC393.

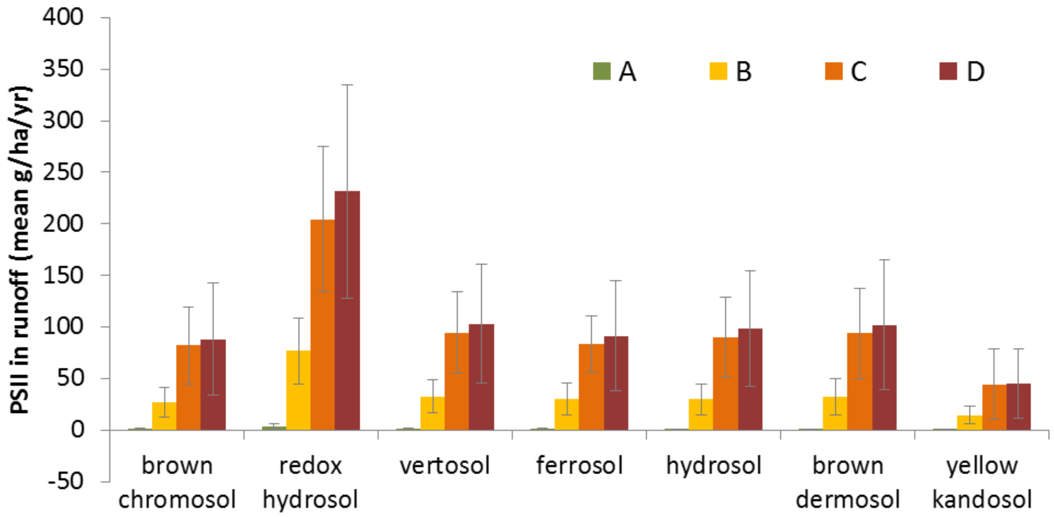

Figure 58 Loss of PSII herbicides in runoff (mean g/ha/yr) from sugarcane for each of the soil types modelled in APSIM

Table 54 Top ten subcatchment hotspots for fine sediment by land use

Sub-catchment	Basin	TSS areal rate for whole subcatchment for land uses (t/ha/yr)	Total subcatchment area (ha)	Runoff from subcatchment (t/ha/yr)	Dominant land use	Dominant land use area as a per cent of total subcatchment (%)	Areal export rate of dominant land use (t/ha/yr)	General location
SC3	Daintree	3.14	141	16	Grazing	97	4.9	Bairds landing/Peirces Hill area (east of Wujal Wujal)
SC115	Johnstone	2.50	307	23	Sugarcane	84	2.9	Wangan/Mundoo
SC113	Johnstone	2.39	3,103	23	Sugarcane	77	3.0	Wangan/Mundoo
SC395	Johnstone	2.15	128	22	Sugarcane	67	3.0	Wangan/Mundoo
SC96	Russell-Mulgrave	1.97	1,895	30	Sugarcane	68	1.9	Babinda/Miriwinni
SC150	Johnstone	1.92	5,981	24	Sugarcane	91	2.4	Silkwood/El Arish
SC141	Johnstone	1.77	3,244	23	Grazing	61	2.0	Rankin Falls area
SC162	Tully	1.71	1,012	23	Sugarcane	81	2.3	Lower section of Travelling Dairy creek
SC95	Russell-Mulgrave	1.71	1,051	29	Sugarcane	80	1.6	Babinda/Miriwinni
SC122	Johnstone	1.70	3,364	24	Sugarcane	65	2.2	Wangan/Mundoo

Table 55 Top 10 hotspots by subcatchment for DIN

Subcatchment	Basin	DIN areal export rate for whole subcatchment (kg/ha/yr)	Total subcatchment area (ha)	Runoff from subcatchment (ML/ha/yr)	Proportion of sub-catch that has intensive agriculture of total area (%) ^	Sugarcane DIN areal load (kg/ha/yr)	Average sugarcane DIN application rate (accounting for ABCD%) (kg/ha/yr)	General location
SC150	Johnstone	23	5,981	24	75	30	147	Silkwood/El Arish
SC113	Johnstone	22	3,103	23	73	29	147	Wangan/Mundoo
SC115	Johnstone	22	307	23	72	29	147	Wangan/Mundoo
SC122	Johnstone	19	3,364	24	56	29	147	Wangan/Mundoo
SC395	Johnstone	15	128	22	49	28	147	Wangan/Mundoo
SC147	Johnstone	14	577	22	44	30	147	Silkwood/El Arish
SC96	Russell-Mulgrave	14	1,895	30	70	17	129	Babinda/Miriwinni
SC149	Johnstone	14	5,391	25	38	32	147	Silkwood/El Arish
SC158	Tully	14	4,043	24	72	18	134	Southwest of Tully
SC164	Tully	13	872	20	82	16	134	Southwest of Tully

^ Intensive agriculture = sugarcane, horticulture, cropping and bananas

Table 56 Top 10 hotspots by subcatchment for PSII herbicides

Subcatchment	Basin	PSIIs areal export rate for whole subcatchment (g/ha/yr)	Total subcatchment area (ha)	Average PSIIs application rate (accounting for ABCD%) (g/ha/yr)	Runoff from subcatchment (ML/ha/yr)	Proportion of sub-catch that has sugarcane (%) #	Sugarcane PSIIs areal load (g/ha/yr)	General location
SC393	Tully	69	588	2,611	22	62	112	Southwest of Tully
SC96	Mulgrave-Russell	68	1,895	2,271	30	70	96	Babinda/Miriwinni
SC158	Tully	65	4,043	2,611	24	68	95	Southwest of Tully
SC95	Mulgrave-Russell	55	1,051	2,271	29	84	66	Babinda/Miriwinni
SC177	Murray	53	3,081	2,611	20	64	84	Southwest of Tully
SC92	Mulgrave-Russell	52	67	2,271	29	97	53	Babinda/Miriwinni
SC150	Johnstone	49	5,981	2,838	24	72	67	Silkwood/El Arish
SC194	Herbert	48	711	2,696	11	82	59	North of Ingham
SC164	Tully	43	872	2,611	20	67	64	Southwest of Tully
SC91	Mulgrave-Russell	43	2,101	2,271	30	42	101	Babinda/Miriwinni

Sugarcane and cropping (irrigated and dryland cropping) are the only two land uses that were modelled for PSIIs. Cropping only occurs in SC150 and covers 0.01% of the total subcatchment area. Due to small area, it is not included in the above table.