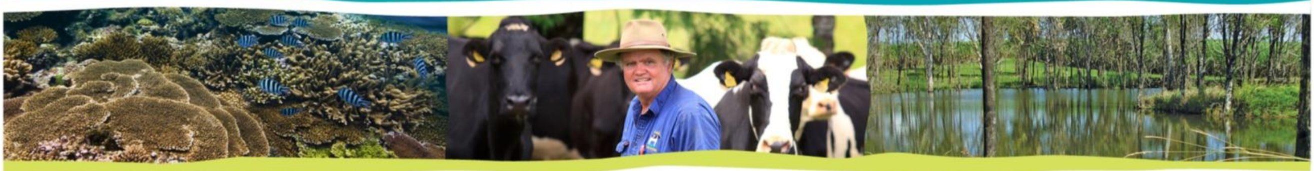
Reef Water Quality Protection Plan 2013



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

Mackay Whitsunday NRM region

Technical Report

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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 provides a summary of the Mackay Whitsunday (MW) modelled estimates of loads in streamflow resulting from investment in improved management practices to reduce sediment, nutrients and herbicides exports. The report outlines the progress made towards Reef Plan targets for four reporting periods 2008–2010, 2010–2011, 2011–2012 and 2012–2013, (Report Card 2010–Report Card 2013). The Mackay Whitsunday region is one of six NRM regions adjacent to the GBR. It is approximately 2% (~9,000 km^2) of the total GBR catchment area (~423,122 km^2). Cattle grazing (~44%), sugar production (~19%) and conservation / forestry (~28%) make up the majority of land use in the region. This report provides a summary of the estimated loads of sediment, nutrient and commonly used herbicides from the four Mackay Whitsunday regional basins: Proserpine, O'Connell and Pioneer Rivers and Plane Creek, including modelled reductions in loads due to the adoption of improved land management practices.

The eWater Ltd Source Catchments modelling framework was used to model constituent loads entering the GBR lagoon. Major additions and improvements to the generic modelling framework were made to enable the interaction of soils, climate and land management to be modelled. These 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 are set against the anthropogenic baseline load (2008–2009 land use and management). On–ground investments in improved management practices were modelled for Report Cards (Report Card 2010–Report Card 2013). These were compared to the 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 later years after implementation of the improved land management practices. In order to reduce the effect of climate variability a

representative climate period was used (1986–2009) for all scenarios. The average annual loads and the relative change in loads due to industry and government investments were then used to report on the percentage load reductions for the four Report Cards. It is important to note that this report summarises the modelled, not measured, average annual loads and load reductions of key constituents and management changes reflected in the model were based on practice adoption data supplied by regional Natural Resource Management (NRM) groups and industry.

Fit for purpose models generated the daily pollutant loads for each individual land use. The paddock scale models, HowLeaky and APSIM, were used to calculate loads for a range of typical land management practices for cropping and sugarcane areas respectively. For grazing areas, the Revised Universal Soil Loss Equation (RUSLE) was used to calculate daily hillslope soil loss estimates using relative changes in ground cover (C–factor) resulting from an improved grazing management practice derived from the grazing systems model GRASP. An Event Mean Concentration (EMC) approach was used to calculate loads for conservation and the remaining minor land use areas. Hydrology calibration was undertaken using an independent Parameter ESTimation Tool (PEST) coupled to Source Catchments.

Source Catchments was coupled to an independent Parameter EStimation Tool (PEST) to perform hydrology calibrations. A multi–objective function was used to minimise differences between (1) modelled and observed daily discharges (2) modelled and observed monthly discharges and (3) exceedance curves of modelled and observed discharges. Once calibrated, three criteria were used to assess model performance: daily and monthly Nash–Sutcliffe Coefficient of Efficiency (NSE) and difference in total gauging station streamflow volumes. The Nash–Sutcliffe is a measure of how well modelled and observed data agree, where NSE values of 0.8–1 for monthly flows is considered a good fit. Modelled flow showed good agreement with observed flows with 7 of the 9 gauges having monthly Nash–Sutcliffe values >0.8 (good fit) and the majority of gauges had total runoff volumes within 2% to 5% of observed flow.

Modelled outputs for the current scenario (2008–2009) indicate a total suspended sediment (TSS) load of approximately 511 (kt/yr) exported to the GBR from the MW NRM region, with the Pioneer basin contributing ~40% of the regions TSS load. The modelled regional TSS load is ~three times the modelled predevelopment load. A total nitrogen (TN) load of 2,819 tonnes per year (t/yr) is estimated to be exported to the GBR from the MW region, with the Plane Creek basin contributing 28% of the total load (Table 1). A total phosphorus (TP) load of 439 t/yr is estimated to be exported to the GBR from the region, with the O'Connell basin contributing 30% of the total load, followed closely by the Pioneer River basin at 26%. TN and TP loads are estimated to have increased more than two times natural loads. The photosystem–II (PSII) herbicide baseline load was approximately 3,944 kilo grams per year (kg/yr) for the MW region, with 39% of the load originating from the Plane Creek basin.

Three main approaches were used to validate the GBR Source Catchments loads modelling. Comparison to previous estimates, a long–term comparison (1986–2009) against available measured data and thirdly a short-term comparison (2006–2009) against the Queensland Government loads monitoring program data. In general, the modelled average annual loads of constituents are lower than previous modelled estimates for the Mackay Whitsunday region. Modelled loads and loads estimated from measured data specifically for model validation are much closer in agreement than previous estimates.

Moriasi et al. (2007) recommended that if the per cent difference in loads (PBIAS) was within 55% of measured loads for TSS and 70% for nutrients, the result could be considered satisfactory. Comparing loads for the 23 year period at a monthly time–step, PBIAS for TSS, TN and TP were 26%, 35% and 46% respectively. Using Moriasi et al. (2007) criteria, the modelling results rate as 'good' for TSS and TN and 'satisfactory' for TP when monthly modelled loads are compared to Joo et al. (2014). Using the same approach, Nash Sutcliffe Coefficient of Efficiency (NSE) statistics for TSS, TN and TP of 0.91, 0.68 and 0.64 respectively, produced ratings of 'very good', 'good' and 'satisfactory' respectively. Overall, this indicates a good fit between modelled and measured loads. Modelled load estimates show good agreement with loads calculated from recent water quality monitoring results with TSS, TP, Dissolved Inorganic Nitrogen (DIN) and Dissolved Inorganic Phosphorus (DIP) all within 30% of measured loads for the 2006–2009 period.

Streambank erosion contributed ~45% of the total modelled TSS load followed by sugarcane and grazing areas (25% and 14% respectively). Modelled bank erosion also contributed the highest modelled load of PN (26%) followed by sugarcane areas (23%). Lands used for sugarcane production contributed the majority of TN (43%), DIN (64%), TP (29%) and DIP (39%), while grazing lands contributed ~25%, 22%, 28% and 36% of TN, DIN, TP and DIP respectively. DOP contributions were similar for grazing and sugarcane (38% and 37%) and 23% of the modelled PP load came from both grazing and sugarcane land uses. The MW region contributes ~24% of the PSII load, ~11% of the DIN load, ~8% of TN load and ~6% of the total TSS load exported to the GBR lagoon on an average annual basis.

A summary of the current modelled constituent load, percent contribution to the GBR and percent change in load due to management change for the MW region is presented in Table 1.

Table 1 Summary of Mackay Whitsunday total baseline and anthropogenic average annual loads and the load reductions due to investment

	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	511	2,819	1,129	950	739	439	132	35	271	3,944
Anthropogenic baseline load	360	1,741	856	552	333	247	80	21	147	3,944
Anthropogenic load reduction due to investment (2008 to 2013) %	9	17	24	11	10	14	17	16	13	42

Model outputs suggest that there has been good progress towards meeting water quality targets proposed under Reef Plan. Modelled loads indicate a reduction in constituent exports following investment for changes to management in the MW region. Results include a modelled decline in the average annual load of PSIIs by ~42%, DIN ~24%, TN ~17% and TSS by ~9%. These modelled reductions are due to the investment in management change across the region including changes to sugar production management via the 'Six Easy Steps' nutrient management program and improved ground cover management in the grazing industry.

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 current modelling framework is flexible, innovative and is fit for purpose. It is a substantial improvement on previous GBR load modelling applications and produces estimations of reductions in constituents due to on–ground land management change. While the current modelled loads differ from previous estimates, the only change from the current 'baseline' model is the inclusion of 'management change data'. Therefore, regardless of the current accuracy of modelled average annual 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), a reasonable degree of confidence can be placed in the relative percentage reduction in average annual loads calculated from the provided management change data. Using a range of published performance criteria, model performance was rated as 'good' to 'satisfactory' for TSS, TN and TP at a monthly time–step for the 23 year modelling period the Pioneer and O'Connell basin monitoring sites.

Major recommendations for enhanced model prediction include:

- 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
- Improved gully and streambank erosion input data
- Better representation of sediment sources from land uses modelled using EMCs/DWCs

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

- Methods to implement and calibrate an underlying hydrological model that produces reliable flow simulations for gauged sites and increased confidence in modelled flows for ungauged sites.
- Daily time–step capabilities allow flow volumes and loads of constituents to be estimated at catchment scale for periods ranging from events lasting a few days to weeks, months and annual time periods.
- 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 Great Barrier Reef catchment.

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Acronyms

Acronym	Description
ANNEX	Annual Network Nutrient Export- SedNet module speciates dissolved nutrients into organic and inorganic forms
BoM	Australian Bureau of Meteorology
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 for base or lowflow generated from a functional unit to calculate total constituent load.
E2	Former catchment modelling framework – a forerunner to Source Catchments that could be used to simulate catchment processes to investigate management issues.
EMC	Event mean concentration – a fixed constituent concentration to quickflow generated from a functional unit to calculate total constituent load.
EOS	End–of–system
ERS	Environment Resource Sciences
FRCE	Flow Range Concentration Estimator – a modified Beale ratio method used to calculate average annual loads from monitored data.
FU	Functional Unit
GBR	Great Barrier Reef
GBRCLMP	Great Barrier Reef Catchment Loads Monitoring Program
HowLeaky	Water balance and crop growth model based on PERFECT
NRM	Natural Resource Management
NRW	Natural Resources and Water (incorporated in the Department of Environment and Resource Management, now incorporated into the Department of Natural

	Resources and Mines)
NSE	Nash Sutcliffe Coefficient of Efficiency
Paddock to Reef Program (or P2R)	Paddock to reef integrated monitoring, modelling and reporting program
PET	Potential Evapotranspiration
PSII herbicides	Photosystem-II herbicides – ametryn, atrazine, diuron, hexazinone and tebuthiuron
Reef Rescue	An ongoing and key component of Caring for our Country. Reef Rescue represents a coordinated approach to environmental management in Australia and is the single largest commitment ever made to address the threats of declining water quality and climate change to the Great Barrier Reef World Heritage Area.
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 km2) to identify patterns in the material fluxes
Six Easy Steps nutrient management program	Integrated sugarcane nutrient management tool that enables the adoption of best practice nutrient management onfarm. The Six Easy Steps nutrient management program forms part of the nutrient management initiative involving BSES limited, CSR Ltd and the Queensland Department of Environment and Resource Management (DERM). It is supported by CANEGROWERS and receives funding from Sugar Research and Development corporation (SRDC), Queensland Primary Industries and Fisheries (PI&F) and the Australian Department of the Environment, Water, Heritage and the Arts.
STM	Short term modelling project

Units

Units	Description
g/ml	grams per millilitre
kg/h	kilograms per hectare
kg/h/yr	kilograms per hectare per year
kg/yr	kilograms per year
kt/yr	kilo tonnes per year
L/h	litres per hectare
mg/L	milligrams per litre
mm	millimetres
mm/hr	millimetres per hour
m^3	cubic metres
cumecs	cubic metres per second
ML	megalitres
ML/day	megalitres per day
GL	gigalitres
t/yr	tonnes per year
t/h	tonnes per hectare
t/h/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).

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Advancements and assumptions in Source Catchments modelling

The key modelling advancements to note are:

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

The key modelling assumptions to note are:

- Loads reported for each scenario reflect the modelled average annual load for the specified model run period (1986–2009).
- Land use areas in the model are static over the model run period and were based on the 2009 QLUMP data.
- The predevelopment land–use scenario includes all dams, 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 and fertilisers 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. Dissolved inorganic nitrogen reductions

are not being modelled in the grains system, as there is no dissolved inorganic nitrogen model available currently in HowLeaky. Management of tebuthiuron (PSII herbicide used in grazing) is not modelled. Similarly, effects of management of phosphorous on P runoff loads is not modelled, except that practices which affect sediment generation will affect P runoff.

- It is possible that the load reductions are over estimated from the model, as herbicide, nutrient and soil management practices are currently modelled as a whole system rather than representing the individual practices in which investments are made. However, these over estimates may in turn be offset by the fact that the pollutant contributions from a number of land uses are not being modelled. In the near future, this limitation will be circumvented in sugarcane with the development of a more detailed modelling system where more specific practice combinations are modelled.
- 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 subcatchment.
- The benefits of adoption of a management practice (e.g. reduced tillage) are assigned in the year that an investment occurs. Benefits were assumed to happen in the same year.
- Modelling for Report Cards 2010–2013 represent management systems (e.g. A soil, A nutrient and A herbicides practices) rather than individual practices. The potential to overstate the water quality benefits of an A herbicide or nutrient practice through also assigning benefits from adoption of A practice soil management needs to be recognised.
- Gully density mapping is largely based on the coarse–scale NLWRA mapping, with opportunities to improve this particular input layer with more detail mapping.
- Within the current state of knowledge, groundwater is not explicitly modelled and is represented as a calibrated baseflow and ‘dry weather mean concentrations’ 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.

Introduction

1.1 GBR Paddock to Reef 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, using modelling validated by monitoring data at paddock, 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 report card represents the cumulative management changes occurring due to improved management practice adoption for the period 2008–2013. All Report Cards are available at www.reefplan.qld.gov.au.

The changes in water quality predicted by the modelling will be assessed against the Reef Plan targets. The Reef Plan water quality targets for Reef Plan 2009 (Report Card 2010–Report Card 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 Mackay Whitsunday (MW) catchment modelling methodology and results used to report on the predicted average annual end of catchment pollutant loads entering the GBR for total baseline, predevelopment, anthropogenic baseline (total baseline minus predevelopment) and post investment from the four regional basins: Proserpine, O'Connell and Pioneer Rivers and Plane Creek.

1.2 Previous approaches to estimate catchment loads

This modelling project builds on and adds to previous modelling efforts. Over a period of more than thirty years there has been a series of empirical and catchment modelling approaches to estimate constituent loads from GBR catchments. Previous estimates vary depending on the different methods, assumptions, modelling and monitoring periods covered, and types of data used.

The SedNet catchment model has been applied in the past to provide estimates of average annual sediment and nutrient loads from GBR catchments (Brodie et al. 2003; McKergow et al. 2005a, 2005b; Cogle et al. 2006). Most recently, Kroon et al. (2010) used Brodie's et al. (2009) collated modelling and monitoring information as a starting point, along with the linear regression estimator (LRE) tool (Kuhnert et al. 2009) to estimate natural and total catchments loads from available catchment monitoring data. For the Mackay Whitsunday region Kroon et al. (2010) estimated a total suspended sediment (TSS) load of 1,542 kt/yr, total phosphorus (TP) load of 2,172 t/yr, total nitrogen (TN) load of 8,092 t/yr and an estimated photosystem–II (PSII) inhibiting herbicide load of 10,019 kg/yr.

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

1.3 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, 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 conservation and the remaining land use areas. The paddock model outputs are then linked to Source Catchments to produce relative changes in catchment loads.

Improved spatial and temporal resolution of remotely sensed ground cover, riparian areas, soils information, water quality data are included, plus small coastal catchments are incorporated into the Mackay Whitsunday catchment modelling. A consistent modelling approach was used to generate predevelopment, total loads and subsequent anthropogenic baseline loads for the 35 reef basins, and six NRM regions.

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

Regional background

The Mackay Whitsunday NRM region is a coastal strip in Central Eastern Queensland stretching from the towns of Bowen in north to Clairview in the south (~300 km). The region covers ~9,130 km^2 and is made up of the Pioneer, Proserpine and O'Connell Rivers, and Plane Creek basins draining to the Great Barrier Reef lagoon. The Whitsunday Islands group is situated off the coast between Bowen and Mackay (Figure 1).

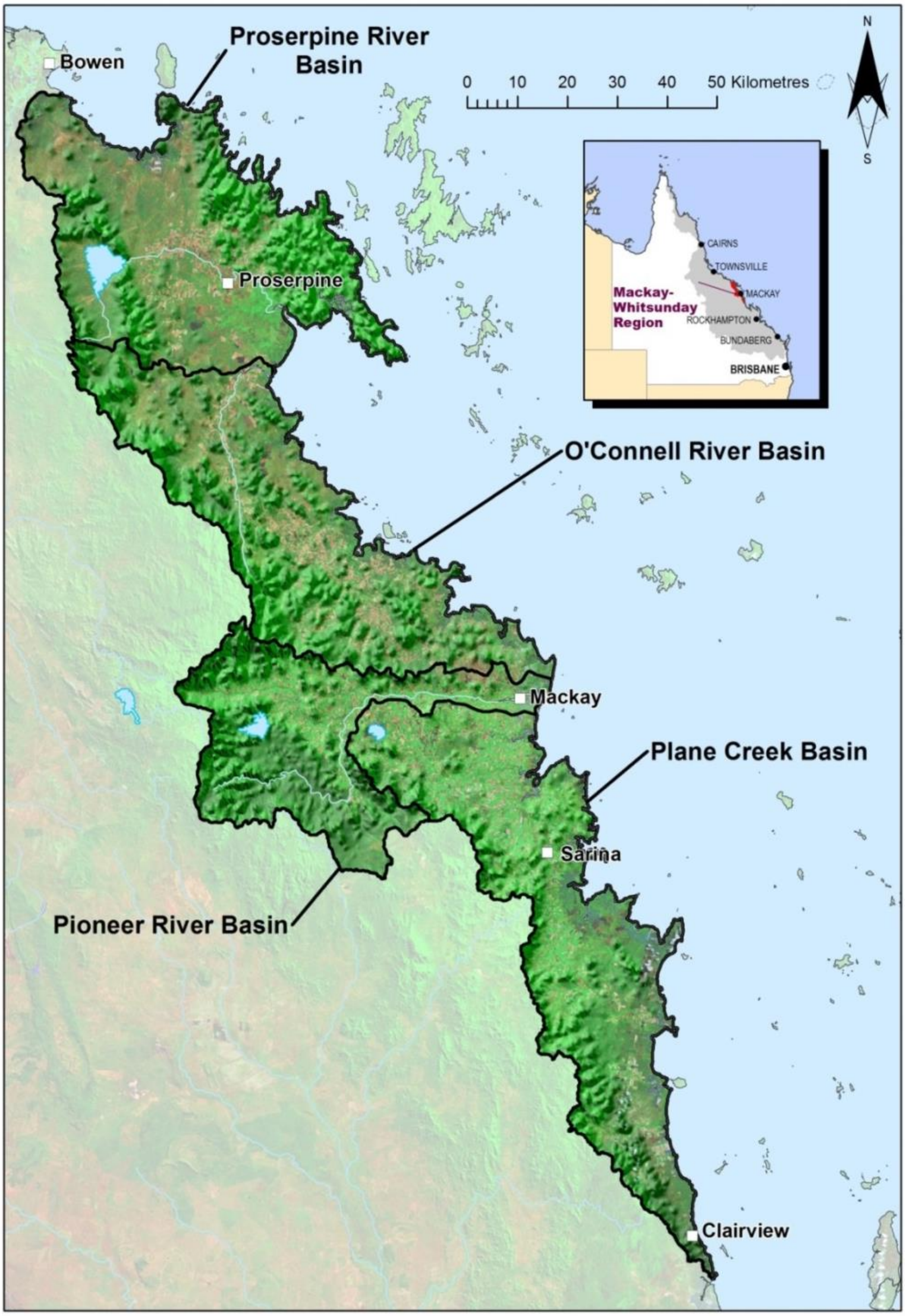


Figure 1 Mackay Whitsunday region

2.1 Climate

The climate of the Mackay Whitsunday region is subtropical with warm wet summers and mild dry winters. Average annual rainfall varies from ~1000 mm per year in the western regions to ~1800 mm per year in the east (Figure 2), with higher average totals falling in the coastal and hinterland ranges north of Mackay and east of Proserpine. The region is considered tropical savannah (Aw) in the northern parts (Proserpine region) and temperate (Cwa) in southern areas under the Koppen–Geiger classification system (Peel et al. 2007).

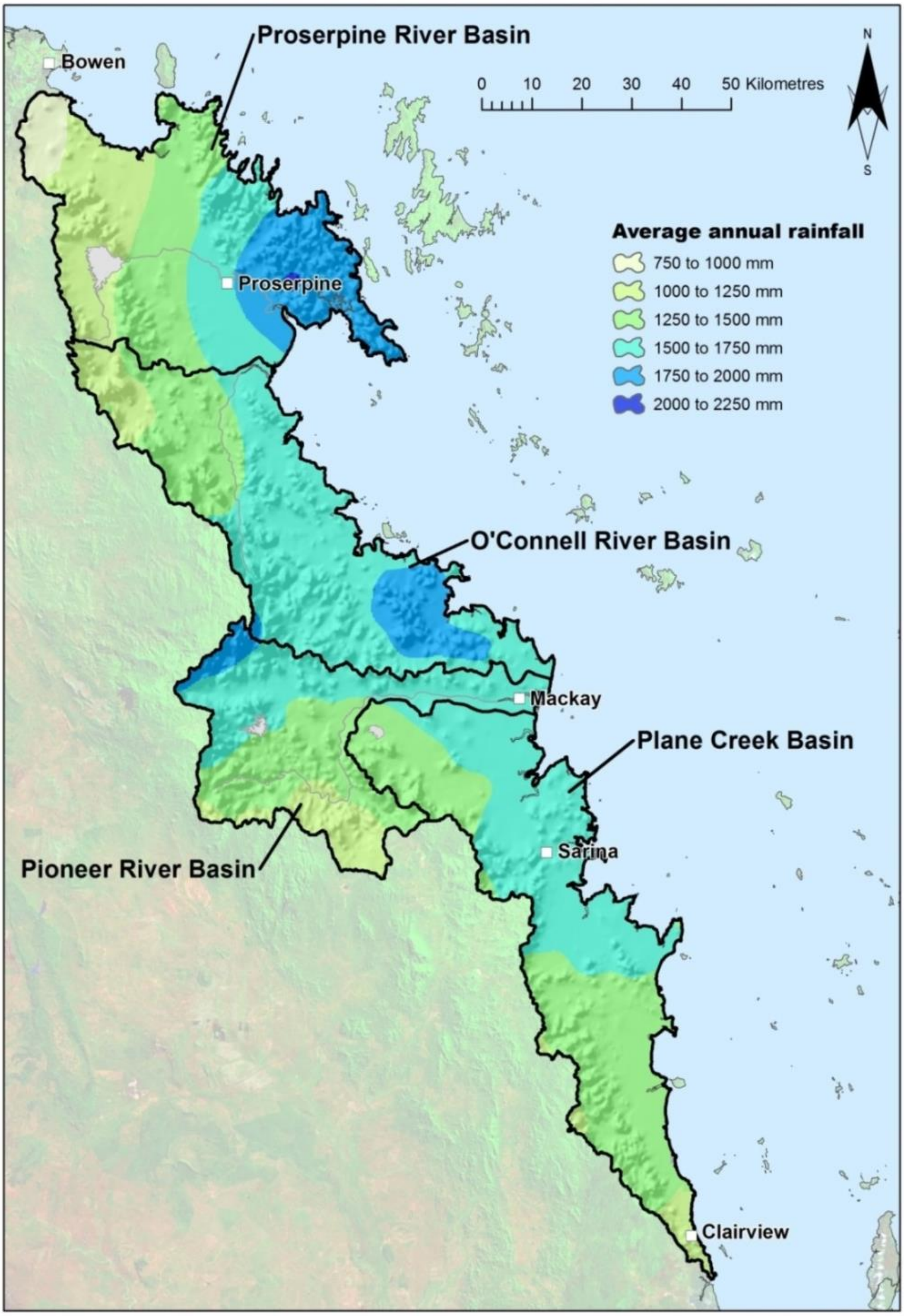


Figure 2 Mackay Whitsunday region average annual rainfall

2.2 Hydrology

The majority of rainfall and stream flow occurs during the December to March wet season (summer). Modelled average annual discharge for the region is ~5,100,000 ML representing ~8% of the total annual GBR catchment discharge. The modelled area covers 4 drainage basins located in the North East Coast Division (1), defined by the Australian Water Resources Council. The 4 drainage basins cover an area of ~9,130 km^2 (Table 2). A number of smaller coastal catchments were also included in the modelling. Overall, the MW the region represents ~2% of the total GBR catchment.

Table 2 Major Mackay Whitsunday basins modelled and area in square kilometres

Basin name	Australian Water Resource No.	Area (km^2)
Proserpine River	122	2,535
O’Connell River	124	2,435
Pioneer River	125	1,490
Plane Creek	126	2,670
Total area		**9,130**

Modelled estimates of average annual discharge from the 4 major sub–regions result in the O’Connell contributing the largest flows into the GBR at ~1,556,000 ML per year (~31% of total). The Pioneer contributes the least at ~866,000 ML per year (~17% of total) and the Proserpine and Plane Creek regions contribute about 1,324,000 and 1,346,000 ML per year (~26% of total each) respectively.

2.3 Geology and soils

The geology of the MW region is diverse, with over 20 geological formations identified in the Mackay/Proserpine region. Massive faulting, volcanism and aggradation have resulted in a complex topography. The regional topography is dominated by low slope coastal plains in the east, with relatively steep sloping highland/coastal ranges are intersected by undulating terrain in the western regions. A diverse range of soils types, ranging from cracking clays and texture contrast soils in the western regions to alluvial plains with clay loams, sandy and acid sulphate soils in the eastern regions. Details of geology, topography and soils for region can be found in the land suitability studies of Holz and Shields (1985) and Wills and Baker (1985).

2.4 Land use

Approximately 44% of the MW area is used for cattle grazing, particularly in the western regions. Significant areas of steep country are allocated to conservation and in combination with forestry on lower slopes, accounts for ~28% of land use (Table 3).

Table 3 Mackay Whitsunday region land use areas

Land use	Area km^2	% of Total area
Grazing forested	2,551	28
Sugarcane	1,677	19
Nature conservation	1,567	17
Grazing open	1,410	16
Forestry	957	11
Water	653	7
Urban	157	2
Other	69	1
Horticulture	13	<1
Irrigated cropping	3	<1
Dryland cropping	<1	<1

Sugarcane production dominates the eastern and central regions around Proserpine and Mackay with ~19% of the regional area under sugarcane (Figure 3). A summary of major regional land uses in relation to exported constituents is presented in the results section.

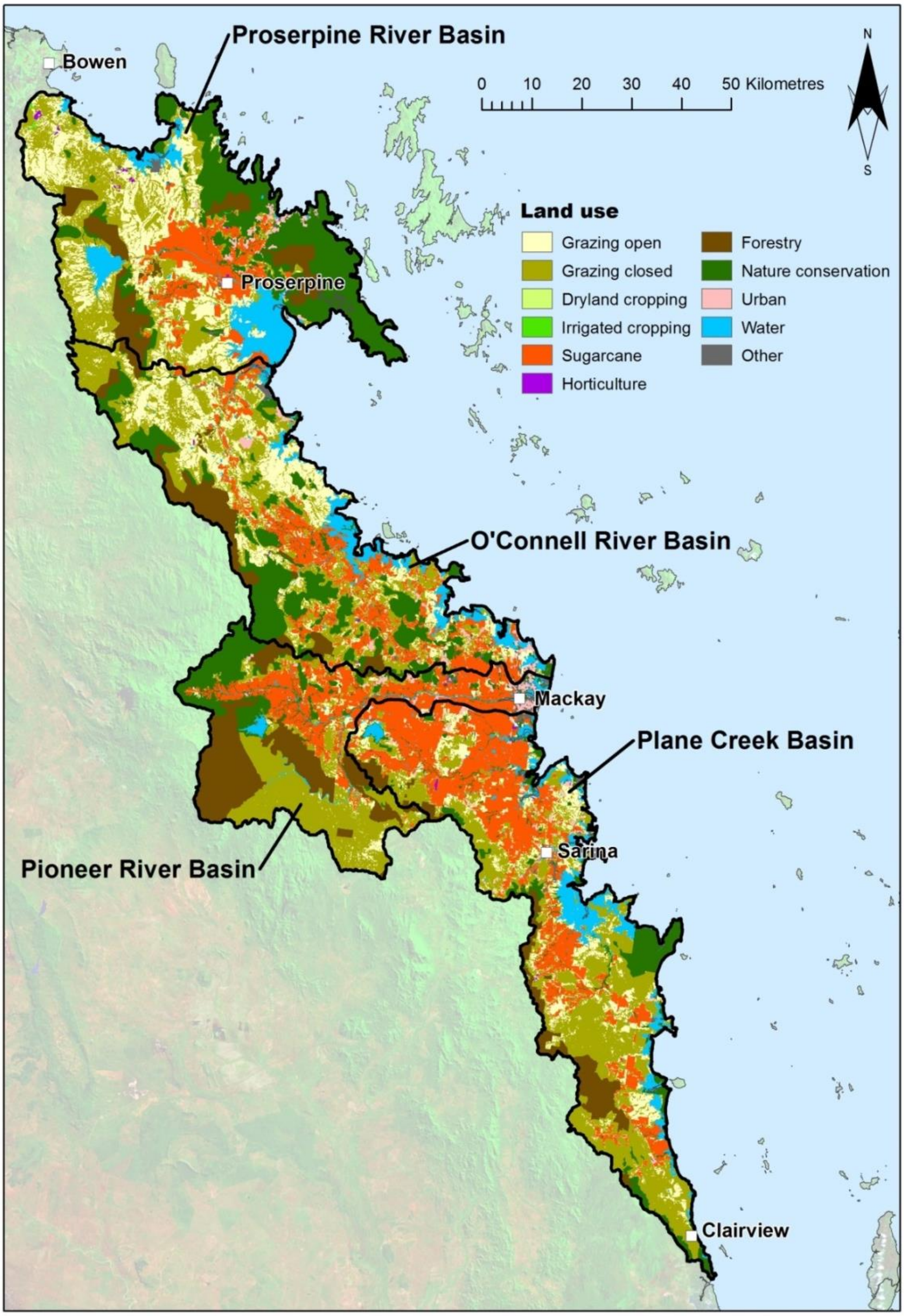


Figure 3 Mackay Whitsunday region land use

2.5 Mackay Whitsunday regional water quality issues

Tree clearing, grazing and intensive agriculture are thought to have led to a substantial increase in sediment and nutrient exports from the MW region to the GBR lagoon since European settlement. These increased exports are thought to have led to a widespread decline of coral assemblages of local inshore coastal waters (van Woesik et al. 1999). A state of the waters report found that the MW region exported relatively high concentrations of nutrients to GBR lagoon (Brodie 2004) and Mitchell et al. (2005) found that elevated herbicide and nutrient concentrations in river flood plumes from the MW region were most likely from areas used for sugarcane cultivation. Scientific consensus statements regarding GBR water quality rate the MW region as high risk for nitrogen and PSll exports compared to other reef catchments (The State of Queensland 2008, 2013). More recently, high levels of nitrogen and herbicides in flood waters have been associated primarily with sugarcane production (Brodie et al. 2009).

In summary, numerous studies suggest that the MW region (along with other Wet Tropics catchments) has undergone land use changes which have led to a substantial decline in water quality exports to the GBR lagoon and a decrease in marine ecosystem health.

Methods

Source Catchments is a water quantity and quality modelling framework that has been developed by the eWater Cooperative Research centre (CRC). This framework allows users to simulate how catchment and climate variables (such as rainfall, land use, management practice and vegetation) affect runoff and constituent transport, by integrating a range of component models, data and knowledge. Source Catchments supersedes the E2 and WaterCAST modelling frameworks (eWater Cooperative Research Centre 2012). A number of the model input data parameter sets are provided in Appendix E. A summary of input data sets are also available in Waters & Carroll (2012).

3.1 GBR Source Catchments framework

A Source Catchments model is built upon a network of subcatchments, links and nodes (Figure 4). A subcatchment is further delineated into 'functional units' (FUs) based on common hydrologic response units or land use (eWater Cooperative Research Centre 2012). In the case of the GBR Source Catchments framework, FU's were defined as land use categories. Two modelling components are assigned to each FU to represent 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.

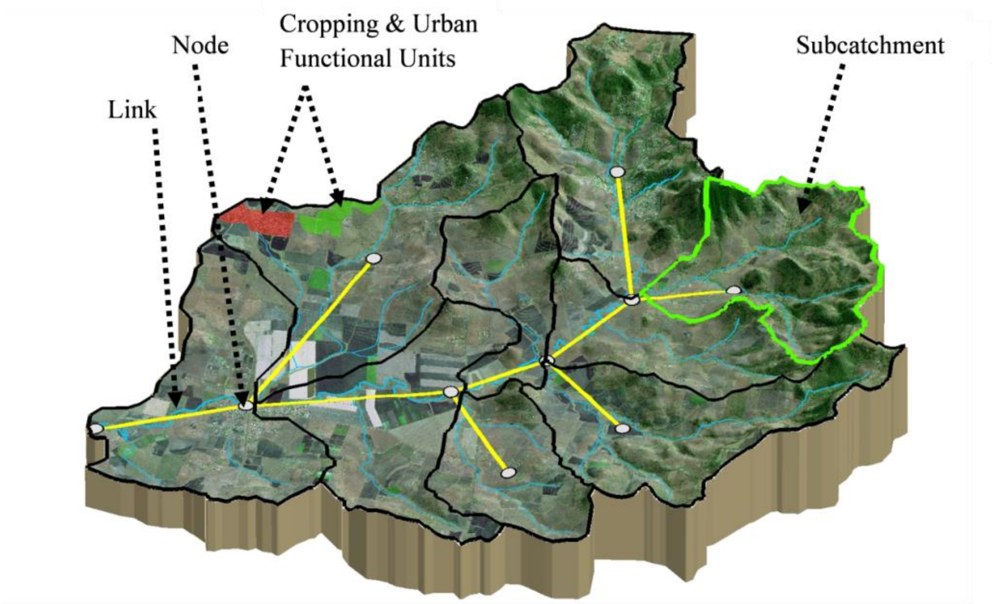


Figure 4 Example of a functional unit and node link network generated in Source Catchments

3.1.1 Land use functional units

In the Mackay Whitsunday region, the most recent land use mapping from the Queensland Land Use Mapping Project (QLUMP) (DSITIA 2012a) was used to define the FUs. The original detailed QLUMP categories were reclassified into 13 major land uses. 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 Protective 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 during calibration. 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. 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. Customisations of the modelling software and specific data pre–processing techniques have provided a way to capture the effects of spatial distribution of land uses within each subcatchment.

3.1.2 Subcatchment generation

The Mackay Whitsunday 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 aerial photography.

The final subcatchment map was then re–imported into Source Catchments. A total of 191 subcatchments (including 27 manually defined low–relief coastal catchments) were generated with an average subcatchment area of 47 km^2 (Figure 5). The addition of these flat coastal areas, some of which were not included in previous models, will improve the overall load estimates to the end–of–system (EOS). An arbitrary node was created in the ocean as an 'outlet' node to enable the aggregation of loads for the entire region for reporting purposes. The selection of the most appropriate stream threshold value for subcatchment 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).

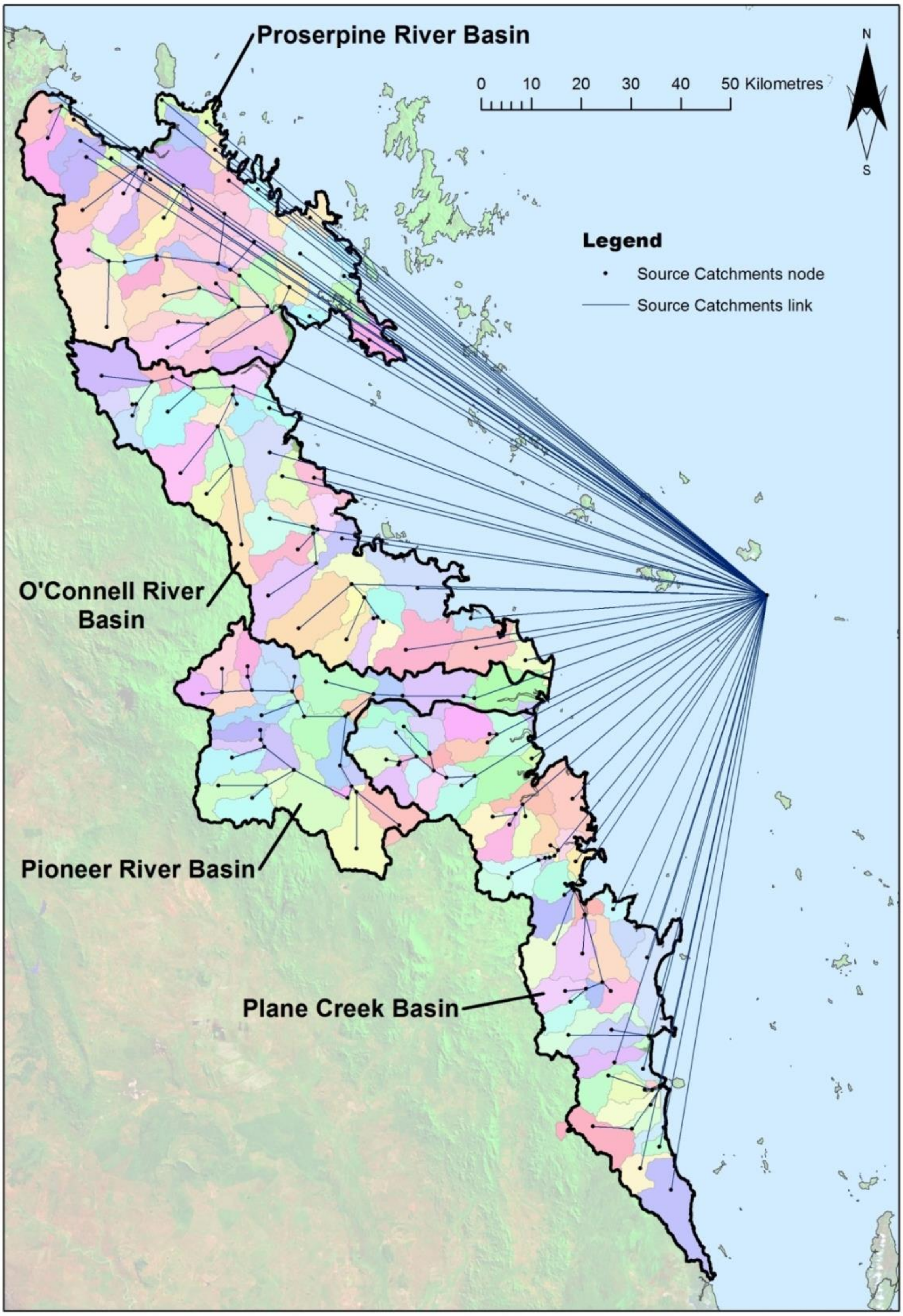


Figure 5 MW modelled subcatchments with node and link network

3.1.3 Runoff generation

Six rainfall–runoff models are available within Source Catchments. A comparison of the six models (Vaze et al. 2011) concluded that there is little difference between these six models for broad scale application. The SIMHYD rainfall–runoff model was chosen due to its extensive application and proven performance to satisfactorily estimate streamflow across Australia (Chiew et al. 2002) and in particular for a large catchments in the GBR (Ellis, Doherty & Searle 2009). An investigation of the performance of a number of other models available in Source Catchments was undertaken following the release of Report Card 2011. As a result of this work, the Sacramento model will be applied in future model calibration to improve runoff simulation (Zhang, Waters & Ellis 2013).

SIMHYD is a catchment scale conceptual rainfall–runoff model that estimates daily stream flow from daily rainfall and areal potential evapotranspiration (PET) data (eWater Ltd 2013). Each FU possesses a unique instance of the SIMHYD rainfall–runoff, and constituent generation models (Chiew et al. 2002). Typically, a rainfall–runoff model converts time series climate inputs to runoff, with a constituent load created by the generation model 'carried' by the runoff. Water and constituent loads are routed through the node–link network to the catchment outlet. Nodes represent stream confluences, features such as gauging stations and subcatchment outlets. Links connect nodes, and represent streams. A range of models can be applied to links to route or process water and constituents throughout the network (eWater Ltd 2013).

3.1.4 Constituent Generation

In the GBR Source Catchments framework there is the ability to link to external models and or add your own component models as specific 'plug–ins' to customise for particular modelling objectives. This capability has been extensively used to incorporate the most appropriate constituent generation models across the GBR (Figure 6). SedNet modelling functionality has been incorporated to generate gully and streambank erosion and floodplain deposition, within the daily time–step model. This process uses a daily disaggregation of long–term average annual estimates of gully and streambank generation. 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.

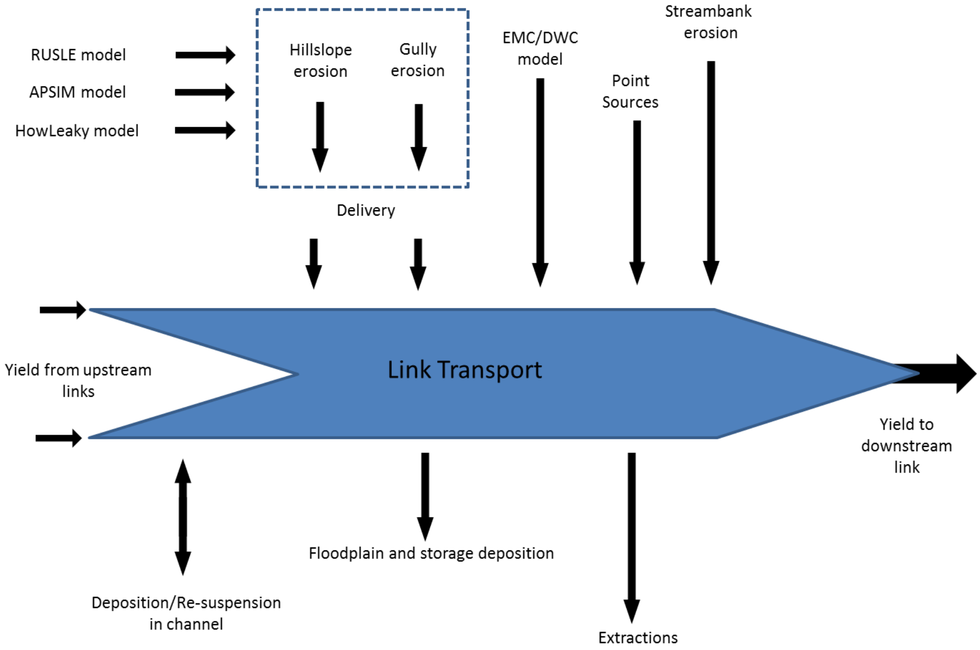


Figure 6 Conceptual diagram of GBR Source Catchments model

The APSIM (Agricultural Production Systems Simulator) was chosen for modelling sugarcane (Keating, 2003), particularly for dissolved inorganic nitrogen in runoff. The HowLeaky model, with some enhancements, was used to model herbicides and phosphorus in sugarcane and all constituents for grain cropping areas (Robinson et al. 2011; Rattray et al. 2004). It has been recognised there will be an increasing demand to improve and re–interpret the models at subannual (seasonal, monthly, recognised event) temporal scale, and this is the reason the daily time–step of the GBR Source Catchments framework has been selected. Future work will look to examine the underlying concepts and available daily input data with the aim that these models become more robust at subannual time–steps.

3.1.5 Climate Simulation Period

A 23 year climate 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 of bare ground satellite imagery from 1986, 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) this period included a range of high and low flow periods which is an important consideration for hydrology calibration.

Daily climate input files generated for each subcatchment were used to calculate daily runoff. Rainfall and potential evapotranspiration (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 interpolating the Bureau of Meteorology's station records. The data are supplied as a series of individual files of interpolated daily rainfall or PET on a 5 km grid. Source Catchments 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). The climate period will be extended for Reef Plan 2013 to include the extreme wet years post 2009.

3.2 Hydrology

The calibration process was developed by building on previous calibration work in the GBR (Ellis et al. 2009). The SIMHYD rainfall–runoff model was selected as the preferred model. The rationale for selecting SIMHYD is outlined in section 3.1.3. Runoff and 'slowflow' (subsurface seepage and low energy overland flow) aggregated at a subcatchment outlet, are transferred to the stream network then routed through the link system via the Laurenson flow routing model (Laurenson and Mein, 1997). Storage dynamics (dams/weirs) were modelled, as well as irrigation extractions, channel losses, and inflows such as sewage treatment plant discharges, through specific node models.

3.2.1 PEST calibration

Hydrology calibration was undertaken using PEST (a model–independent Parameter EStimation Tool) (Doherty 2009). Parameter optimisation incorporated both the SIMHYD rainfall–runoff parameters and the two Laurenson flow routing parameters within a subcatchment. Estimation of rainfall–runoff and flow routing parameters was undertaken simultaneously. A full list of the Simhyd and Laurenson parameters are listed in Appendix C.

A three–part objective function was employed, using log transformed daily flows, monthly flow volumes and flow exceedance to achieve an optimum calibration. The monthly flow volume component works to ensure modelled volumes match measured volumes over long periods, the exceedance values work to ensure the flow volumes are proportioned into baseflow and event flow, while the log transformed daily flows work to obtain replication of the hydrograph shape. The three objective functions have been used successfully in other modelling applications (Stewart 2011). For all observation groups the absolute value of component will vary widely depending on the magnitude of the values contained within each component and the number of values in each time series. This does not mean however 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 20 MW gauges used in the calibration process. Performance was assessed for the calibration period 1/1/1970–31/3/2010. Most gauges had the full flow record for the 40 year 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)

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

3.2.2 Stream gauge selection for calibration

A total of 13 gauging stations, out of the 20 available, were initially identified as suitable for PEST calibration. This was based on the following criteria:

- Located on the stream network but not immediately below a dam
- A minimum of 10 years of flow record (post 1970) with corresponding quality codes <=60 and 130 (data of suitable quality)

Duplicate gauges were merged where the station had been moved during its recording period. Nine gauging stations were eventually used for the Mackay Whitsunday region to calibrate rainfall–runoff and flow routing parameters (Table 4).

Table 4 Mackay Whitsunday Gauging stations chosen for model hydrology calibration

Site name	Gauge No.	Catchment area (km^2)	Years of record
Lethe Brook at Hadlow Road	122012A	89	12
O'Connell River at Staffords	124001A+B	342	40
St. Helens Creek at Calen	124002A	118	36
Andromache River at Jochheims	124003A	230	33
Pioneer River at Pleystowe	125001A+B	1,434	74
Pioneer River at Sarich's	125002A+B+C	757	51
Cattle Creek at Gargett	125004A+B	326	23
Sandy Creek at Homebush	126001A	326	43
Carmila Creek at Carmila	126003A	84	36

Daily flow observations for these gauges were extracted from DERM's Hydstra surface water database.

3.2.3 Node models

Nodes represent points in a stream network where links are joined and are used to incorporate catchment flow characteristics. For example, water can be added at a node as inflow to represent discharge from a sewage treatment plant (STP), or extracted from the stream network at a node to reflect irrigation extractions. For the description of these models refer to the Source Scientific Reference Guide (eWater Cooperative Research Centre 2012). In the GBR model irrigation extractions, STP inflows, channel losses and storages or dams were represented at nodes. The following section outlines how this was undertaken.

3.2.3.1 Extraction, inflows and loss node models

To simulate the removal of water from a storage or river, daily extraction estimates for a river reach were incorporated at relevant nodes, the data was obtained from previous Integrated Quantity and Quality Model (IQQM) runs. Characteristics of demand were summarised from data supplied by the Water Resource (Whitsunday) Plan (DERM 2010). Demands for water include, town water supply, irrigators and unregulated users. An extraction node model was placed at the node immediately downstream of storages to represent demands taken directly from the storage. Extraction node models were implemented in the Proserpine Basin for the Proserpine River at Peter Faust Dam Tailwater (122003A) and at Lethe Brooke at Hadlow Road (122012A). In the Pioneer Basin, node models were implemented for the Pioneer River at Pleystowe Mill (125001A), Sarich's (125002C), Marion Weir (125003A), Mirani Weir Tailwater (125007A) and Dumbleton Pump Station (125013A). Additional node models were implemented for Teemburra Creek at Teemburra Dam Tailwater (125014A), Cattle Creek at Gargett (125004A) and in the O'Connell Basin for the O'Connell River at Caping Siding (124001A).

3.2.3.2 Storages

Storages such as dams and weirs are modelled using the inbuilt storage model (eWater, 2012). The model is applied to a link within a subcatchment. Storage locations, dimensions and flow statistics are required to model runoff, flow and storage volume in the model. In general, only storages with a capacity greater than 10,000 ML were incorporated into the model. Storages >10,000 ML located in the Mackay Whitsunday region include Teemburra Dam and Peter Faust Dam (Table 5). During calibration of the Pioneer River Basin it became apparent that the model was generating too much runoff at gauging station locations downstream of two weirs. Further investigation of the river and the weirs located upstream of Mackay showed that the cumulative impact of a number of weirs that are in series but individually <10,000 ML may have been impacting on model results. A number of additional weirs less than 10,000 ML capacity were therefore incorporated into the model improving runoff estimates, however, no trapping models for particulates were implemented for these low volume weirs.

Table 5 Storages included in Mackay Whitsunday model

Storage name	Capacity (ML)
Peter Faust Dam	491,400
Teemburra Dam	147,500
Mirani Weir	4,660
Marian Weir	2,800
Dumbleton Weir	8,780

3.2.4 Rainfall–runoff model parameterisation

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

3.2.5 Model regionalisation

To reduce the number of adjustable parameters for PEST to consider during calibration, rainfall–runoff models belonging to the same functional units were ‘grouped’ across the subcatchments of an identified ‘region’. Flow routing models were also grouped according to the same regions. Functional units, links and nodes continued to operate as discrete units within the Source Catchments structure. Regions were based on the contributing area to a gauge. Nested gauge (gauged upstream or downstream by other gauges) regions had contributing areas minus the contributing area of the upstream gauge. Proserpine, O’Connell and Plane Creek basins were divided into calibration regions each representing the subcatchments contributing to one gauging station. In the Pioneer Basin, four gauging stations are situated at various locations on the river resulting in serial flow recording data. These gauging stations were clustered into one calibration region. The nearest neighbour approach (Chiew & Siriwardena 2005, Zhang & Chiew 2009) was used for subcatchments which did not contribute to a gauge. The coastal mountain range north east of the Proserpine River, however, was considered to have more hydrological similarities to the Plane Creek southern region and therefore adopted the parameters from this region. The nine gauging station drainage areas used for calibration were divided into eight calibration regions were used in the hydrology calibration (Figure 7).

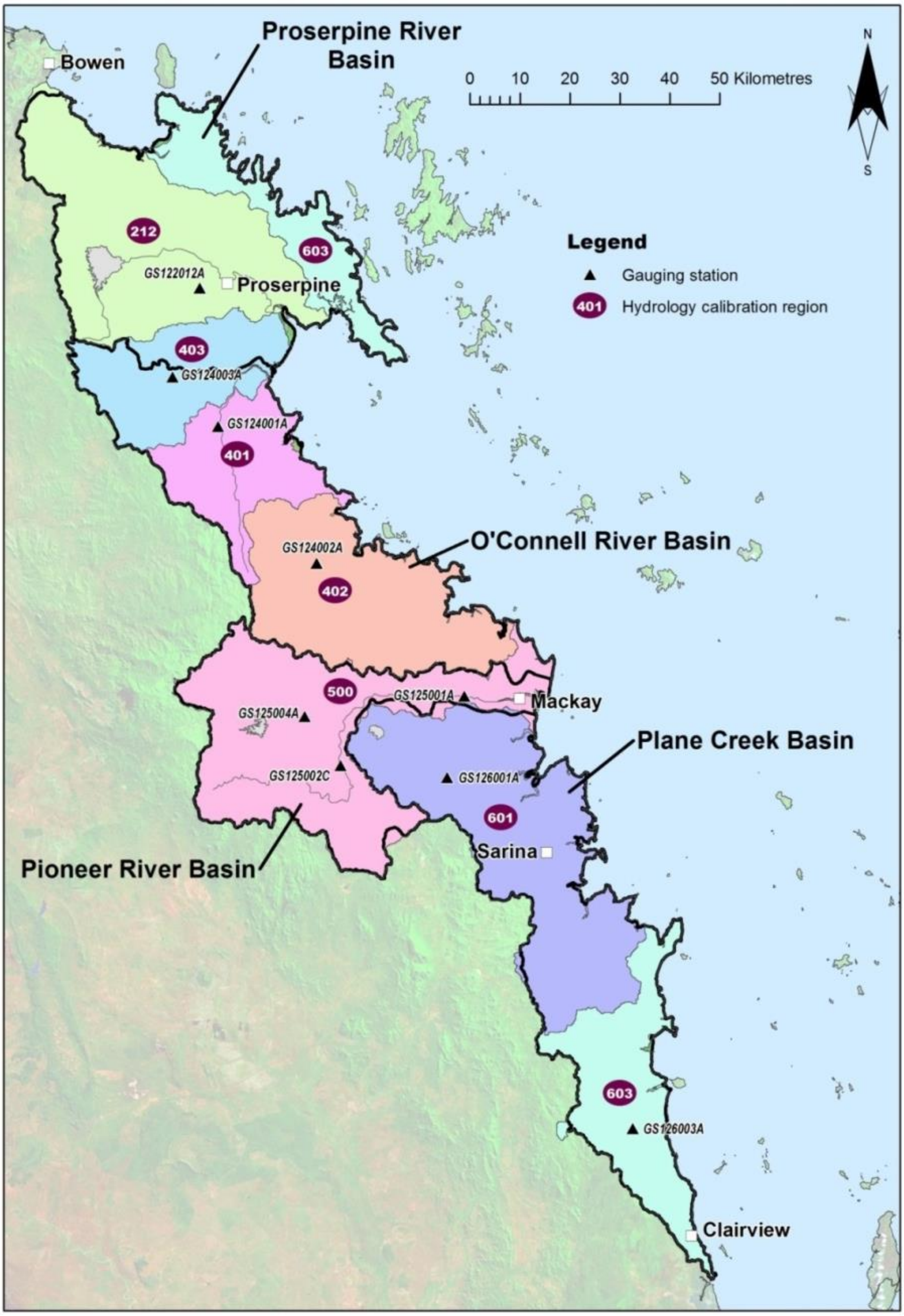


Figure 7 MW PEST hydrology calibration regions (ovals) and gauges (triangles)

To further simplify the number of adjustable parameters considered by PEST during calibration, functional units of assumed similar hydrologic characteristics were grouped into 3 broad ‘hydrologic response units’ (Table 6). These broad groupings were selected from previous research in central Queensland, which suggested these land uses have measurably different hydrologic characteristics between virgin scrub, and land that has been cleared for grazing and cropping (Yee Yet & Silburn 2003; Thornton et al. 2007). Flow routing models were also grouped according to the same regions. Functional units, links and nodes continued to operate as discrete units within the Source Catchments structure.

Table 6 The 11 land use classifications were grouped into three hydrologic response units

Functional unit	Hydrological unit
Conservation	Forest
Grazing forested	Forest
Grazing open	Grazing
Sugarcane	Agriculture
Forestry	Forest
Water	Not considered
Urban	Grazing
Horticulture	Agriculture
Irrigated cropping	Agriculture
Other	Grazing
Dryland cropping	Agriculture

3.3 Constituent Modelling

The key water quality constituents modelled, are outlined in Reef Plan and are shown in Table 7. where total suspended sediment is based on the international particle size fraction classification and is restricted to the <20 µm fraction (National Committee on Soil and Terrain 2009). Fine sediment (<16 µm) is the fraction most likely to reach the Great Barrier Reef lagoon (Brodie et al. 2013). The choice of a <20 µm to determine the fine sediment fraction is also consistent with previous SedNet modelling studies, which used a clay percentage layer from the ASRIS database based on the international particle size fraction classification, to calculate particulate nutrient (PN and PP) loads. Moreover, Packett et al. (2009) found that for the in–stream sediment sampled for some subcatchments, and at the Fitzroy Basin outlet, >95% of the total suspended sediment was 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, based on application data it was only modelled in the Fitzroy and the Burnett Mary basins.

Table 7 Constituents modelled

Sediment	
total suspended sediment (TSS)	
Nutrients	
total nitrogen (TN)	total phosphorus (TP)
particulate nitrogen (PN)	particulate phosphorus (PP)
dissolved inorganic nitrogen (DIN)	dissolved inorganic phosphorus (DIP)
dissolved organic nitrogen (DON)	dissolved organic phosphorus (DOP)
PSII herbicides	
atrazine, ametryn, diuron, hexazinone, tebuthiuron	

The most appropriate paddock scale model outputs were used to generate data for Source Catchments. These were APSIM for sugarcane, with the HowLeaky model for pesticides and phosphorus, HowLeaky for cropping, RUSLE for grazing and EMC/DWC models for the remainder. A detailed summary of the models used for individual constituents for sugarcane, cropping and grazing are shown in Table 8. 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 et al. (2014).

Table 8 Summary of the models used for individual constituents for sugarcane, cropping and grazing

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

Dynamic SedNet is a Source Catchments 'plug–in' developed by DERM/DSITIA specifically for this project. The plug–in provides a suite of constituent generation and in–stream processing models that simulate the processes represented in the SedNet catchment scale water quality model (that is, gully, streambank erosion, as well as floodplain deposition processes) at a finer temporal resolution than the original average annual SedNet model. The Dynamic SedNet plug–in has a variety of data analysis, parameterisation and reporting tools. 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 functional unit (land use) within a subcatchment, link (in–stream losses, decay, deposition and remobilisation) and node (extractions and inputs to the stream).

3.3.1 Grazing constituent generation

Rainfall and ground cover are two dominant factors affecting hillslope runoff and erosion in the GBR. Previous studies report that gully erosion is also a significant source of sediment to the GBR (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 (Renard et al. 1997, Lu et al. 2001, Renard & Ferreira 1993) (Equation 1). This modified version is based on the Revised Universal Soil Loss Equation, and is referred to as the RUSLE in this document (Lu et al. 2001, Renard & Ferreira 1993). The RUSLE model was chosen due to its proven ability to provide reasonable estimates of hillslope erosion worldwide including the GBR in the SedNet model, 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:

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

Where

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

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

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

L = Slope length (static value)

S = Slope steepness (static value)

C = Cover management factor (1 value generated per year for each 25 m x 25 m grid cell)

P = Practice management factor

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

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). 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.

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

Slope factor (S) was calculated by methods outlined in (Lu et al. 2003). The slope values for these calculations are derived from the STRM 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 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 basin.

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

Cover 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. Seasonal cover will be incorporated to further improve erosion estimates when data is available, as it will better represent inter–annual variability in RUSLE predictions. However, using an annual time–step for the C–factor ensures that extended wet and dry periods are reflected in hillslope erosion processes. This is an improvement on previous modelling where a single static C–factor was applied both spatially and temporally for each land use. Seasonal cover will be incorporated to further improve erosion estimates when data is available.

Ground cover is estimated using Bare Ground Index (BGI) (Scarth et al. 2006) (version CI2). This product is derived from Landsat TM Satellite (25 m) imagery. BGI values were subtracted from 100 to provide a ground cover index (GCI). The GCI was calculated each year using a single NRM region BGI mosaic of images captured between July and October (dry season). The GCI is currently only considered to be accurate in areas where the Foliage Projected Cover (FPC) (Goulevitch et al. 2002) is <20%. To deal with this, the GCI was classified into 'no tree' areas (FPC <20%) and 'tree' areas (FPC >20%).

The 2009 FPC coverage was used to represent the 'tree' coverage, for all years. 2009 was chosen to correspond with the latest land use mapping, also mapped to 2009.

'No tree' (where FPC <20%) C–factors (C_f) were derived as follows (Rosewell 1993) (Equation 2):

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

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

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

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

Practice management factor (P) is the support practice factor, a measure of the effect on erosion of soil conservation measures such as contour cultivation and bank systems (Rosewell 1993). There was insufficient information available to apply P factors in this study, therefore P was set to 1 in all regions. The daily RUSLE soil loss calculation provides an estimate of the sediment generation rate at the hillslope scale. To estimate the suspended fraction of the total soil loss, the RUSLE load is multiplied by the proportion of clay and silt located in the ASRIS layers (the best data source available to generate this layer at the GBR scale). The proportion of clay and silt is based on the International particle size fraction classification (<20 µm) (National Committee on Soil and Terrain, 2009).

The use of a particle size distribution raster in the current modelling to determine the fine sediment fraction (and calculate fine sediment load transported to the stream network) is an improvement from previous modelling studies that used SedNet (e.g. Brodie et al. 2003 and Cogle et al. 2006). These SedNet studies used a hillslope delivery ratio (HSDR) to alter the RUSLE–estimated eroded soil mass into a 'suspended sediment' in–stream mass, rather than the product of the fine fraction and HSDR as applied in this study (Equation 4). The clay and silt fraction (%) values in the ASRIS data layer are derived as a function of many laboratory analysed soil samples from a range of soil types, hence the data incorporates the spatial variability of fine fractions across the GBR.

A sediment delivery ratio (SDR) was then applied to this load, and was selected based on past research using a standard 10% delivery ratio (Wilkinson, Anderson and Chen, 2004). However, in some regions the SDR was increased so that the generated fine sediment load better matched monitored data. The SDR for the MW region was set at 15%.

The equation takes the form (Equation 4):

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

This estimates TSS load which reaches the stream. (Appendix E – Dynamic SedNet global parameters and data requirements).

Nutrient generation models

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

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

This estimates the total suspended nutrient load which reaches the stream (Appendix E – Dynamic SedNet global parameters and data requirements. For the dissolved nutrient load, an EMC/DWC value (mg/L) is multiplied by the quick and Slowflow output (Appendix E – Dynamic SedNet global parameters and data requirements). These models are described in more detail in the accompanying Model Reference Guide (Ellis and Searle 2014) and replicate the original SedNet approach to dissolved and particulate nutrient generation modified to a daily time–step.

Enrichment ratios and load conversion factors are outlined in (Appendix E – Dynamic SedNet global parameters and data requirements). Three rasters are required as inputs to these models, two nutrient rasters (surface nitrogen and phosphorus), as well as a surface clay (%) raster. The surface soil nutrient layers were from the Queensland ASRIS database.

Herbicide generation models

Tebuthiuron, a PSll herbicide is a primary herbicide used in grazing lands for control of woody weed (tree and shrub) regrowth. Tebuthiuron is applied to selected areas of land and is not normally re–applied on a regular basis. This makes it difficult to model an accurate representation of the usage pattern across a 23 year climate period. Because of this, a static EMC/DWC concentration model was used, based on measured in stream data from the Fitzroy Basin, to ensure a conservative estimate of the average annual total baseline load was generated in the model. Tebuthiuron has not been detected by the GBR Catchment Loads Monitoring Program (GBRCLMP) in the Mackay Whitsunday for 2009–2010 or 2010–2011 wet seasons and was therefore not modelled in the MW.

3.3.1.2 Gully – sediment, nutrient generation models

Gully modelling was based on well published SedNet gully modelling methodology (Prosser et al. 2001a) that has been extensively used across the GBR (McKergow et al. 2005b, Hateley et al. 2005). Gully TSS 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 functional unit is calculated for a subcatchment, this volume is converted to an 'eroded' soil mass. This eroded mass is then distributed over the model run period as a function of runoff.

The gully Average annual Sediment Supply (AASS) is calculated by (Equation 6):

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

Where:

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

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

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

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

Age = Years of activity to time of volume estimation

(e.g. year of disturbance to year of estimation)

To derive a daily gully erosion load, the long–term average annual gully erosion load is multiplied by the ratio of daily runoff to annual runoff to apportion a daily gully load. Spatial raster inputs and parameter global values are shown in (Appendix E – Dynamic SedNet global parameters and data requirements. The gully density layer (National Land and Water Resources Audit (NLWRA)) was used the input raster (km/km^2) for gully density (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 MW 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 MW model, a uniform value of 1870 was applied. This value was chosen as it coincides with a large increase in domestic livestock numbers within the Burdekin basin (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/h), calculated by APSIM are combined with the daily gully erosion estimate as outlined in section 3.3.2.2.

3.3.2.1 Hillslope – sediment, nutrient, herbicide generation

Daily time series loads of fine sediment and DIN in runoff were supplied from APSIM model runs for sugarcane FUs. All APSIM model scenarios were run using only a single climate file for Report Card 2010. This was revised for Report Card 2011 where scenarios were run to include each climate file from subcatchments in which sugarcane was mapped. For Report Card 2010, four soil types were represented in the APSIM scenarios and this was revised for Report Card 2011 to include seven unique soils. 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 digital elevation map (DEM) and slope values were capped at 8%.

Runoff in APSIM was modelled using the curve number approach. Model runs for the four (Report Card 2010) and seven (Report Card 2011) soil types were assigned to mapped soils 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 time series data are transferred to Source Catchments, to ensure that loads are transferred to the Source Catchments streams only when Source Catchments has runoff generated. This analysis attempts to ensure pollutant load mass balance is consistent on a monthly basis.

DIN loads modelled by APSIM were imported directly as supplied (under the procedure for runoff analysis above). Herbicide and phosphorus loads were modelled using HowLeaky functions based on the outputs of the APSIM model of sugarcane systems for water balance and crop growth. The HowLeaky herbicide and phosphorus models are described for dryland and irrigated cropping below. Further details on the APSIM and HowLeaky models and the parameters used to define simulations of sugarcane are provided Appendix E – Dynamic SedNet global parameters and data requirements and in Shaw et al. (2014).

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

3.3.2.2 Gully – sediment, nutrient generation

Gully modelling for sugarcane used the same methodology as for grazing lands. Similar to grazing area modelling, the total subcatchment contribution for sugarcane FUs combined the hillslope and gully loads. Gully nutrients are derived as a function of the gully particulate sediment load, the 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/h), calculated by HowLeaky (Rattray et al. 2004) are combined with the daily gully erosion estimate as outlined in section 3.3.2.2.

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 et al. 2014). DIN and DON were modelled using an EMC approach. Simulations of a range of typical cropping systems 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 and 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 un–tilled soil. This Curve Number was modified within the HowLeaky model daily to account for crop cover, surface residue cover and surface roughness.

Hillslope erosion was predicted in HowLeaky using the modelled runoff, USLE K, L and S, and a cover–sediment concentration relationship derived by Freebairn & Wockner (1986). This generalised equation applies anywhere where the cover–sediment concentration relationship holds. In addition, the Freebairn & Wockner equation has been tested and calibrated for 14 sites 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 DEMand applied in the soil loss equation.

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

Herbicide mass balance and runoff losses were modelled using an enhanced version of HowLeaky (Shaw et al. 2011). 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. A detailed description of the HowLeaky model and the parameters used to define simulations of dryland and irrigated cropping is available in Shaw and Silburn (2014).

3.3.3.2 Gully sediment, nutrient generation

Gully modelling for cropping lands used the same methodology as for grazing lands, where the total subcatchment contribution for cropping FU's combines the hillslope and gully loads. Gully nutrients are derived as a function of the gully particulate sediment load, the subsurface clay % and the soil nutrient concentrations.

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

For the remaining land uses of forestry, nature conservation, urban, 'other', horticulture, dairy and bananas, Event Mean Concentration/Dry Weather Concentration (EMC/DWC) models were applied. 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 to give an estimate of the daily load, where (Equation 7):

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

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

Where there was insufficient data available a value of 50% of the applied EMC was used for the DWC. Low flow periods were defined as the lowest 20^{th} percentile of daily flows. It is important to highlight that the EMC/DWC applied in this model represent 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.

An EMC/DWC model was chosen for nature conservation due to problems with the application of the RUSLE style model in previous modelling efforts. The estimation of soil erosion especially from steep rainforest areas with RUSLE has overestimated sediment loss (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 separately.

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

3.3.5 Subcatchment models

3.3.5.1 Point sources

Sewage treatment plants (STP’s) were considered a point source contribution to nutrient loads exported to the GBR. The larger STP’s were included with an arbitrary criterion of a minimum 10,000 equivalent person’s (EP) capacity. Table 9 lists the STPs included in the model. STP details and data were provided by DERM’s (formerly Environment Protection Agency) Point Source Database (PSD). The sewage treatment plants are maintained by the Mackay City Council. Annual flow and loads data was provided for 2000–2004. The flows and load data were then used to calculate an average annual runoff volume and load.

Table 9 Sewage Treatment plants >10,000 equivalent persons (EP)

STP	Discharge point	Catchment	Lat	Long	EP
Mackay North	Reliance Creek	O’Connell River	–21.021610	149.131720	10,000 to 50,000
Mackay Southern	Bakers Creek	Plane Creek	–21.205730	149.125050	50,000 to 100,000

The point source parameteriser 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 Total N, Total P and Ammonia (as N–NH3). Twelve STP’s from QLD with recorded concentrations of DIN, DON, DIP, DOP Total N and Total P were used to calculate the mean percentage of each constituent to the total. Of the 12 STPs, 8 were tertiary and 4 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, STPs sources only account for a small fraction of the total nutrient budget. Out of the 12 STP plants 550 samples were used to calculate N speciation mean percentages and 469 samples used to calculate P speciation (Table 10). Data pairs were discarded where the speciation concentration added together was > than the total N or Total P concentration.

The fixed percentages were applied to total N and total P data to get the speciation. Annual loads (kg/yr) were then calculated by multiplying the average annual flow (2007–2010) 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 10 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, in–stream deposition, decay, remobilisation and floodplain deposition. The models that have been applied are: the *SedNet Stream Fine Sediment* model and *SedNet Stream Coarse Sediment* model which simulate sediment generation, deposition and remobilisation in–stream and coarse sediment deposition. The *SedNet Stream Particulate Nutrient* model has been applied to generate, deposit and remobilise particulate nutrients in–stream. Dissolved nutrients and herbicides were not generated at a link scale. Coarse sediment 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 in (t/yr) as a function of riparian vegetation extent, streambank erodibility and retreat rate. The mean annual streambank erosion is disaggregated as a function of the daily flow. This eroded mass is then distributed over the model run period as a function of runoff. For a full description of the method refer to Ellis and Searle (2014) see Appendix E – Dynamic SedNet global parameters and data requirements 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 (t/yr) 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 deposition and remobilisation of fine and coarse sediment. However with limited data available to validate this component at the time of model development, remobilisation and in–stream deposition was not included in any of the GBR models.

The assumption was made that all coarse sediment deposits in the main stream with no remobilisation occurring. Hughes et al. (2010) note that in–channel benches are an important store of large volumes of sediment in the Fitzroy catchment, however these benches are predominantly comprised of sand. A small fraction of fine sediment may be trapped in these coarse (bedload) deposits, however the time scale for fine sediment movement is much shorter and thus this fraction is ignored in the bedload budget (Wilkinson, Henderson and Chen, 2004).

For fine sediment it was assumed that there was no long–term fine sediment deposition in–stream, and that all suspended sediment supplied to the stream network is transported (Wilkinson, Henderson and Chen, 2004). As new science becomes available on fine sediment in–stream deposition (and remobilisation) processes, applying these models will be investigated. Currently research is being undertaken in the Fitzroy, Burdekin and Normanby basins (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 and Searle (2014).

The in–stream decay of dissolved nutrients was not implemented in the MW 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 and 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 Bob Packett 2012, unpublished data).

Monitoring in the Fitzroy River designed to target the same ‘parcel’ of water in the upper catchments and again at the mouth of the Fitzroy River indicated that the half–life of atrazine and diuron in–stream was in the order of three to six days, while for tebuthiuron the half–life estimates ranged from approximately 15 – 60 days (Bob Packett, 2012, unpublished data). Where values were not available in the PPDB for a specific herbicide in the PPDB database, a value was assigned from a compound with similar chemical properties or derived from the monitored data. The herbicide half–life parameters applied are presented in Appendix E.

3.3.6.3 Floodplain (deposition)

Floodplain trapping or deposition occurs during overbank flows. Floodplain deposition is determined through the parameter ‘sediment settling velocity’ applied in the *SedNet Stream fine Sediment* model. The amount of fine sediment deposited on the floodplain, adjacent to a link, is also dependent on the floodplain area, and the total fine sediment supply to the link (Wilkinson 2010). The particulate N and P contribution from streambanks is calculated by taking the mean annual rate of fine soil erosion from the stream network (t/yr) multiplied by the ASRIS subsurface soil N and P concentrations. The *SedNet Stream Particulate Nutrient* model also calculates the particulate nutrients deposited on the floodplain as a proportion of fine sediment deposition. The loss of dissolved nutrients and herbicides on the floodplain was not modelled.

3.3.6.4 Node models

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

3.3.6.5 Storage models

Storages (dams and weirs) with a capacity >10,000 ML were incorporated into the model on links. In general, 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. However, for the Pioneer Basin, two weirs (Mirani and Marian) were included due to the reasons outline in section 3.2.3.2.

Storage locations, dimensions and flow statistics were used to simulate the storage dynamics on a daily basis. Additional storage information is located in Appendix E – Dynamic SedNet global parameters and data requirements. Trapping of fine sediment and particulate nutrients in storages is modelled by the *SedNet Storage Lewis* model and the *SedNet Storage Particulate Nutrient Deposition* model, respectively. Here, fine sediment and particulate nutrient is captured using a 'trapping' algorithm based on daily storage capacity, length and discharge rate.

The implemented trapping algorithm is a daily modification of the Churchill fine sediment trapping equation (Churchill 1948). Lewis et al. (2013) reviewed and tested an annual weighted version of this equation against measured data for the Burdekin Falls Dam and storages in the U.S.A, 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.

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 (Equations 8 and 9, and Figure 8).

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

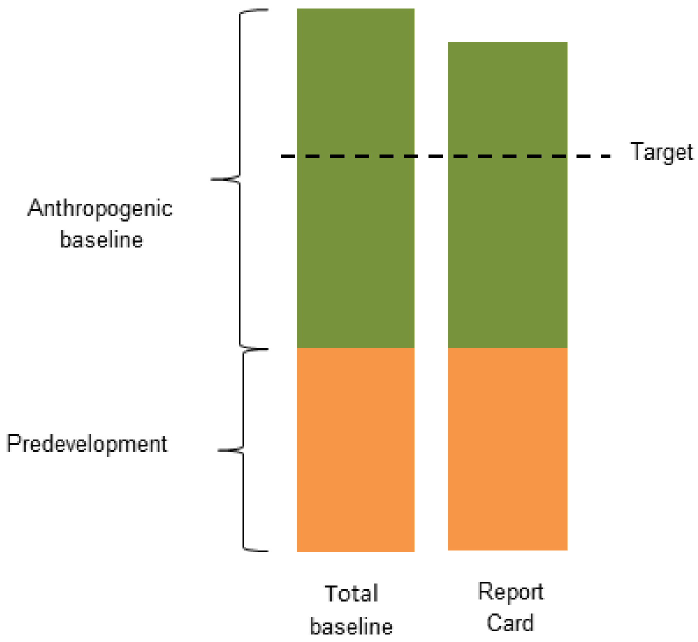


Figure 8 Example of modelled long–term load reduction as a result of improved management practice adoption

The percentage reduction in load is calculated from (Equation 9):

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

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

Report Cards, measuring progress towards Reef Plan's goals and targets, are produced annually as part of the Paddock to Reef program. The first Report Card (Kroon et al. 2010) was released in August 2011. Report Cards 2010 to 2013 represent management changes based on a yearly period.

The total and anthropogenic baseline load was based on land use and management status during the 2008 to 2009 period. All scenarios were run using the same modelling period 1986–2009 (23 years) see Table 11 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 (that is, Report Card 2013 = Report Card 2010 + Report Card 2011 + Report Card 2012 + Report Card 2013).

Table 11 reporting period and management years for modelling

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

*(note: Report Card 2010 period covers two years of investment)

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 (subject to review) attributed with achieving improvements in land management which would result in improvements in offsite water quality. It is important to note that not all reported investments are assumed to have achieved this management system change. This is particularly the case in cropping systems where several specific and inter–related practice changes are often required to complete the transition to a new management system (Kevin McCosker, 2014, pers. comm.). For a summary of typical management practice changes attracting co–investment, refer to Appendix E, Table 39.

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 et al. 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 ABCD was then reflected in the total baseline model. The proportion of area of ABCD then changed each year between 2008 and 2013 (Report Cards 2010–2013) based on adoption of improved practices. For more information on the ABCD framework and associated management practices see the Reef Plan website: [www.reefplan.qld.gov.au.](http://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, cropping, and horticulture.

For each of the major industries where investment occurred in the MW (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 progress towards meeting reef water quality targets. The variety of sources of information collected in the baseline year (start of 2008/2009 financial year) and adoption of improved management practices from industry and government investments are outlined in Queensland Government Department of the Premier and Cabinet (2013a).

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 Mackay Whitsunday region, baseline and management change data was provided at a river basin scale (e.g. Proserpine, Pioneer etc.). The threshold and progress towards target definitions are provided in Table 12.

Table 12 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 et al. (2014). 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. No management information was available for DON and therefore was not modelled.

For sugarcane nutrient, soil and herbicide management, the majority of the nutrient baseline management was B practice (45%), for soil and herbicide C practice (75%) and (48%) respectively (Table 13). Changes in Report Card 2010 – Report Card 2013 are outlined in the results.

Table 13 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	0.0	13.8	79.3	6.9
	2008-2010	6.2	27.1	60.4	6.3
	2008-2011	9.2	34.4	50.8	5.6
	2008-2012	13.3	40.3	41.2	5.3
	2008-2013	14.6	44.6	35.6	5.2
Herbicide	Baseline	0.0	9.5	84.7	5.8
	2008-2010	6.5	23.1	64.7	5.7
	2008-2011	10.1	31.8	53.4	4.8
	2008-2012	11.3	39.1	44.9	4.7
	2008-2013	14.3	42.4	38.8	4.5
Soil	Baseline	0.0	8.4	85.1	6.5
	2008-2010	16.6	31.8	45.3	6.3
	2008-2011	21.4	40.0	32.5	6.1
	2008-2012	30.3	37.5	26.2	6.0
	2008-2013	33.5	38.5	22.2	5.8

3.4.1.2 Grazing

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

In grazing the GRASs Production model (GRASP) (McKeon et al. 1990) provided scaling factors for adjusting RUSLE C–factors where management practice changes occur. These C–factor scaling factors have been derived for a range of climates and pasture productivity levels or land types that occur within the GBR catchments. The GRASP model was chosen for grazing given it has been extensively parameterised for northern Australian grazing systems (McKeon et al. 1990).

The C–factor decreases (ground cover increases) related to an improvement in management practice were then applied to the GCI derived C–factor values used to model the baseline. For management changes (e.g. from C to B) to be assigned in a reportable and repeatable fashion, the farms ('properties' as discernable from cadastral data) representing grazing needed to be spatially allocated into a baseline A, B, C or D management class according to the average GCI conditions observed at that property over time.

A methodology was adopted which compared GCI in properties for two very dry years a decade apart (Scarth et al. 2006). Properties that maintained or increased cover over this time were considered to be well managed while properties where cover decreased were considered to have been poorly managed. Higher ranked properties were assigned into 'A' management until the area matched the required regional baseline area, and this was repeated for B, C and finally D management classes. Changes were assigned randomly within the relevant management class in each region. For example, changes from C to B were assigned randomly to areas defined as 'C' management for the baseline year within the river basin specified.

For further detail on the GRASP modelling and spatial allocation of the derived C–factor changes refer to Shaw et al. (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 C class, Table 14 provides % area of the ABCD framework for the baseline for Report Cards 2010–2013.

Table 14 Summary of the baseline management and management changes for grazing (% area) for the baseline, Report Cards 2010–2013

Management system	Period	A	B	C	D
		%			
Soil	Baseline	8.3	13.7	55.8	22.2
	2008-2010	8.5	19.9	49.3	22.2
	2008-2011	8.5	23.7	45.6	22.2
	2008-2012	8.6	25.6	43.7	22.1
	2008-2013	9.1	26.7	42.2	22.0

Riparian fencing

Improved grazing management (in particular cover management) can have both a direct and indirect effect on gully and streambank erosion rates. Indirect effects of improved grazing management or increasing cover on hillslope can reduce runoff rates and volumes from upstream contributing areas to a gully or stream. This process is represented in the model by implementing relative reductions in rates of erosion per management class, as described by Thorburn & Wilkinson (2012), (Table 15). The direct effects of riparian fencing are a result of increased cover on the actual stream or gully.

Table 15 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 'current condition' and change scenarios. Indirect effects of improved grazing management on gully and streambank erosion have been applied in MW in the relevant subcatchments where investment in improved grazing management on hillslope occurred. For assessing the direct effect of riparian fencing, the riparian vegetation percentage for the stream was increased linearly with respect to the proportion of the stream now excluded from stock. A total of ~290 km of riparian fencing occurred in the MW region over the reporting period.

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 Foliage Projected Cover (FPC) was created to represent 100% riparian cover in the Stream parameteriser, and
- 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, dams and weirs were left unchanged in models in which they are present. Therefore, the load reductions reported were solely due to land management change, the predevelopment scenario was run from 1986 to 2009.

3.5 Constituent load validation

Data used for current model validation can be divided into three main sub–groups, firstly, catchment load estimates (1986 to 2009) calculated specifically for the modelling period based on selected recent and historical data, secondly load calculations based on data collected specifically for the current modelling application from 2006 onwards (GBRCLMP) and thirdly historical (raw) data and previous load estimates.

3.5.1 Long–term FRCE load estimates (1986 to 2009)

Annual sediment and nutrient load estimates are required to validate the GBR Source Catchments outputs for the period July 1986 to June 2009 (23 years). Prior to the Catchment Loads monitoring program, water quality data was collected sporadically and often was not sampled for critical parts of the hydrograph. There have been previous attempts to calculate long–term load estimates from this sporadic data. Joo et al. (2014) has collated all appropriate data sets to generate estimates of daily, monthly, annual and average annual loads for all end of system gauging stations. The standard approaches were examined including averaging, developing a concentration to flow relationship (regression), and/or the Beale Ratio (Joo et al. 2014; Richards. 1999; Marsh & Waters 2009). It is acknowledged that these can result in large errors in the load estimates especially when extrapolating far beyond the sampled flow ranges due to lack of representative data (Marsh & Waters 2009). Joo et al (2014) has applied a Flow Range Concentration Estimator (FRCE) method (a modified Beale ratio method) to provide estimates of annual loads. The mean modelled loads were compared with the likely upper (95^{th} percentile concentration) and likely lower (5^{th} percentile concentration), and mean, FRCE load for all modelled constituents except PSIIs across 23 water years (1/7/1986 to 30/6/2009).

In addition to the annual and average annual comparison, Moriasi (2007) developed statistical model evaluation techniques for streamflow, sediment and nutrients. Three quantitative statistics were recommended: Nash–Sutcliffe coefficient of efficiency (NSE), percent bias (PBIAS) and the ratio of the root mean square error to the standard deviation of validation data (RSR). Model evaluation performance ratings were established for each recommended statistic, and are presented in Table 16. Modelled monthly loads were also assessed against these ratings.

Table 16 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

3.5.2 Catchment load monitoring – (2006 to 2010)

In 2006 the State Government commenced a water quality monitoring program designed to measure sediment and nutrient loads entering the GBR lagoon (Joo et al. 2012). The water quality monitoring focussed at the end–of–system (EOS) of ten priority rivers: Normanby, Barron, Johnstone, Tully, Herbert, Burdekin, O'Connell, Pioneer, Fitzroy, Burnett and 13 major sub–basins. Water sampling of pesticides commenced in 2009/2010 in eight GBR catchments and three subcatchments (Smith 2011). Analysis was conducted on the five priority PSII herbicides that are commonly detected from GBR catchments: atrazine, ametryn, diuron, hexazinone and tebuthiuron. The 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).

3.5.3 Historical data and previous load estimates

A number of historical water quality data sets are available for the Mackay Whitsunday region. These include data stored in the DNRM Hydstra database and data from various projects (government and non–government agencies) and regional NRM groups. For model validation, a number of primary data sets were used. These include the estimates from Furnas (2003) which mainly dealt with data from the outlets of some of the major rivers in the MW region. Other key load estimation studies are those of Brodie et al. (2009) and a baseline loads report produced by Kroon et al. (2012). Both were concerned with collating data from earlier monitoring and modelling. The baseline loads report also generated a number estimates for current, pre–European and anthropogenic loads for the 35 reef catchments (in six NRM regions) from available data. The Report Card 1 loads by catchment are presented in Appendix A.

Results

This section is separated into hydrology and water quality. For hydrology, the results of the calibration process will be presented, as well as a general summary of the hydrology of the GBR regions. The water quality results section includes modelled average annual sediment, nutrient and herbicide loads, and the anthropogenic baseline and predevelopment loads for the 23 year modelled period. Management changes for Report Card 2010 to Report Card 2013 (2008–2013) are reported against the anthropogenic baseline load. Validation of the MW results is then presented using load estimates from measured data and previous modelled data. For a full list of the Mackay Whitsunday region loads for Report Card 2010–Report Card 2013 refer Appendix F–I.

4.1 Hydrology

4.1.1 Calibration Performance

Hydrology model calibration results for key sites in the Mackay Whitsunday basins are shown in Table 17 Daily flow duration curves for all sites are also listed in Appendix D to highlight at what discharges differences occur in modelled and measured flow. Of the nine gauging stations initially selected to calibrate the hydrology model, one station did not fulfil the criteria for acceptable model performance and was not used in the calibration. The gauge site not used was station number 122012A, situated below a highly regulated reach of the Proserpine River downstream of Peter Faust Dam. Irrigation and other unknown extractions combined with limited (low flow) releases from the dam may account for the site not meeting the calibration criteria. The results for the three performance criteria, daily Nash Sutcliffe coefficient of Efficiency (NSE) (>0.5), monthly NSE (>0.8) and total modelled volume difference ± 20% of observed volume are listed. Eight of the nine gauges had monthly NSE values >0.9 and were within 10% of measured flows.

Table 17 Model hydrology calibration performance for Mackay Whitsunday regional hydrology calibration

Gauging Station Name	Gauge	Daily NS	Monthly NS	Modelled Volume	Measured Volume	Volume difference (%)
Lethe Brook at Hadlow Road	122012A	0.71	0.77	10,381	14,142	–27
O'Connell River at Staffords	124001A	0.81	0.93	93,112	90,824	3
St.Helens Creek at Calen	124002A	0.87	0.93	55,246	58,129	–5
Andromache R at Jochheims	124003A	0.81	0.89	36,645	33,603	9
Pioneer River at Pleystowe	125001A	0.89	0.99	163,313	160,658	2
Pioneer River at Sarich's	125002C	0.85	0.94	164,181	159,802	3
Cattle Creek at Gargett	125004A	0.87	0.94	155,522	151,947	2
Sandy Creek at Homebush	126001A	0.80	0.91	78,504	77,161	2
Carmila Creek at Carmila	126003A	0.67	0.92	20,195	19,843	2

At an annual time–step, the model also showed good agreement to measured flows, particularly where long periods of observed flow data was available (Figure 9).

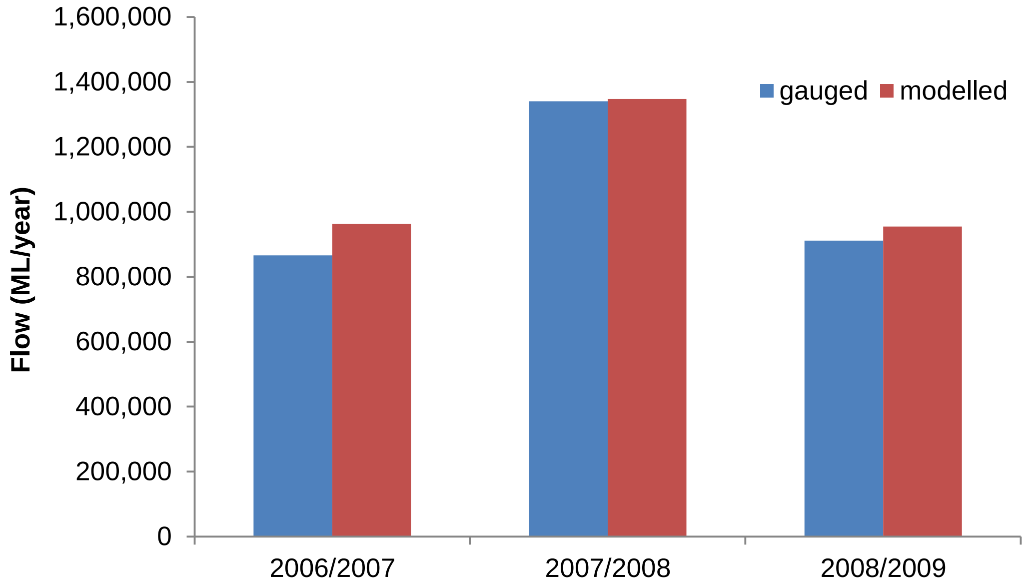


Figure 9 Annual gauged and modelled flow volumes for the lower Pioneer River (GS 125016A)

The runoff comparison presented in Figure 9 (Dumbleton Weir GS 125016A) for the 2006 to 2009 period coincides with the period where measured constituent loads data was available. This period is therefore significant for modelled constituent loads and validation. Daily discharge for the same period also shows good agreement with measured data with the model slightly under predicting maximum gauged discharge for the lower pioneer gauge (Figure 10) for large events.

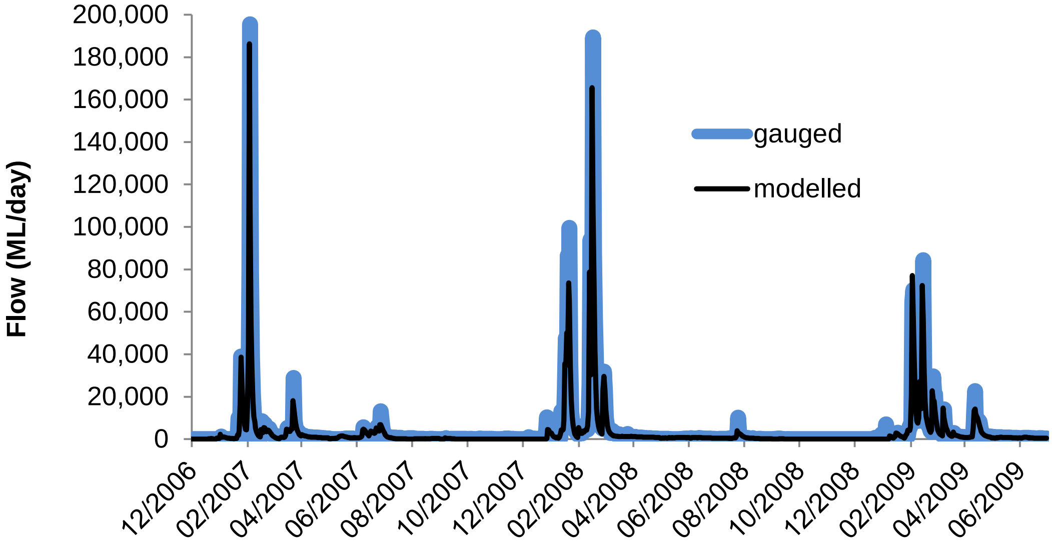


Figure 10 Daily modelled and gauged flow volumes for the lower Pioneer River (GS 125016A)

However there is a notable difference between modelled and gauged discharge for the O'Connell River Basin (Stafford's Crossing GS 124001B) from 2006 to 2009 as shown in Figure 11.

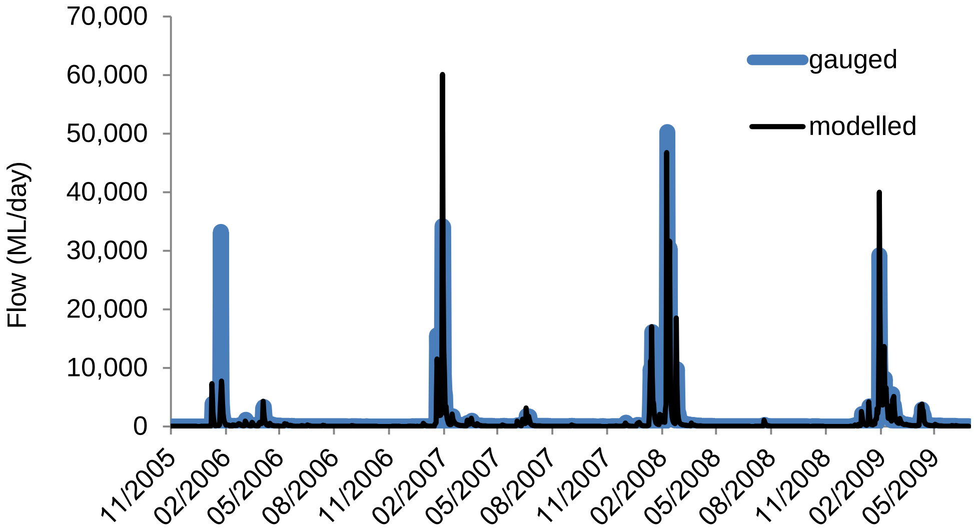


Figure 11 Daily modelled and gauged flow volumes for the lower O'Connell River (GS 124001B)

It is thought that the differences in modelled flow compared to the gauged data during the 2006 and 2007 wet seasons may be due to poor spatial rainfall recording in this sub–region. Overall the model is performing well at simulating long–term discharge volumes and short term events where there is widespread heavy rainfall. For example, there was close agreement between the modelled and gauged flow for the 2006 to 2009 period at the lower Pioneer River site (Figure 10), however, there were substantial differences for the same period at the O'Connell River site. The modelled flow was substantially lower than the gauged flow for the 2006 event and substantially higher than gauged flow for the 2007 event at the O'Connell River site (Figure 11).

The differences between gauged and modelled flow for the 2006 and 2007 wet seasons in the O'Connell basin were investigated and are thought to be due to rainfall data not truly reflecting actual catchment wide rainfall totals leading up to the major runoff events. Rain gauge station maps and daily rainfall maps produced for the MW region by the Bureau of Meteorology (Australian Bureau of Meteorology 2014a, 2014b) were examined for the 2006 to 2009 period and it was found that:

- there is a high density of rain gauges in the Pioneer region (compared to the O'Connell) with ~20 stations within a radius of 50 km of the lower Pioneer River flow gauge,
- there is a single rain gauge in the northern O'Connell River subcatchment and the nearest additional rain gauges are ~64 km to the west, ~37 km to the south, ~21 km to the north, with no gauges to the east (~20 km to the coast),
- 2006, 2007, 2008 and 2009 event rainfall totals for the 5 days either side (10 days in total) of peak discharge for the O'Connell flow gauge site (GS 124001B) were ~300, 600, 1200 and 900 mm respectively,
- 2006 (January) rainfall maps show that <200 mm fell in the days leading up to peak discharge with <100 mm falling in the 24 hr period for 27/01/2006 and a clear delineation of heavy rainfall to the north with little or no rain to the south of the rain gauge,
- 2007 (January / February) rainfall maps show ~200 mm fell on the day of peak discharge (02/02/2007) and the rainfall was predominantly from the east with lower totals in western regions,
- 2008 and 2009 (February) rainfall maps show that heavy rains fell over extensive areas to the north, south and west with no clear delineation over the O'Connell River Basin.

The gauged O'Connell flow data for 2006 and 2007 are very similar at ~35,000 ML/Day, however, the rainfall totals and the rainfall patterns from rainfall maps are substantially different (Australian Bureau of Meteorology 2014a, 2014b). The observations outlined above suggest that during the 2006 event heavy rains fell in the upper parts of the catchment that were not recorded at the lowland rain gauge and this resulted in lower modelled flows. Whereas in 2007 the opposite is suggested, where coastal rainfall was recorded at the gauge and this was applied to the (western) upper catchment where rainfall totals were far less, resulting in higher modelled flows. Overall these patterns of rain originating from the north and east are consistent with the long–term rainfall patterns for this region (Figure 2).

4.1.2 Regional discharge – GBR

The modelled average annual discharge for the Mackay Whitsunday region was 5,103,000 ML and represents ~8% of the average annual flow into the GBR (~64,161,000 ML). Modelled average annual discharge for the model run period (1986–2009) is shown in Figure 12 for all GBR catchments at the regional scale.

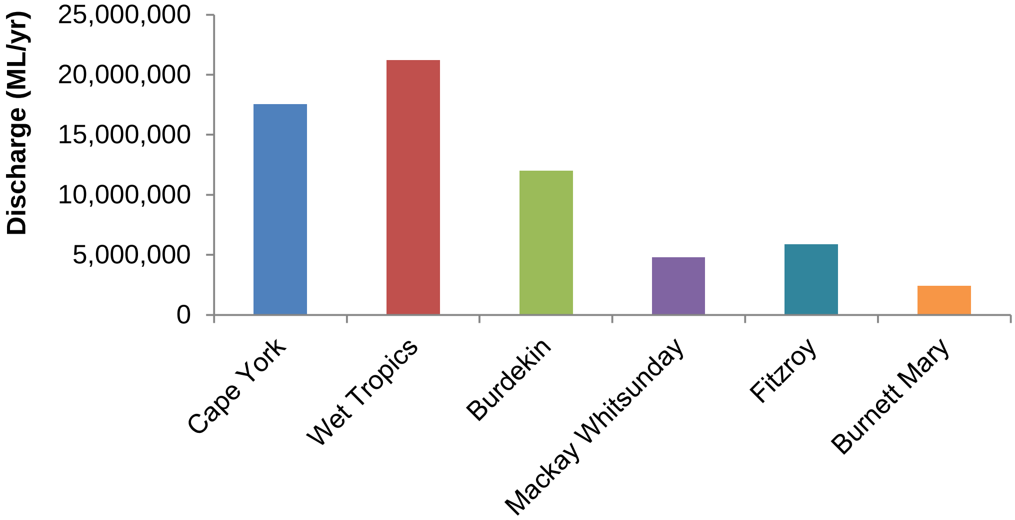


Figure 12 Average annual modelled discharge from the six GBR NRM regions (1986–2009)

The Wet Tropics has the biggest average annual flow for the modelled period compared to the five other regions. The second largest flow comes from the Cape York region (~17,536,000 ML/year), which is approximately double the area of the Wet Tropics region. The Mackay Whitsunday region contributes a significant proportion of the average annual discharge to the southern GBR lagoon (~8%) considering the region area is approximately 2% of the total GBR catchment.

4.1.3 Mackay Whitsunday regional flow characteristics

The O'Connell Basin contributes the largest average annual flow volumes for the modelling period (Figure 13). The modelled annual flow volumes for the primarily inland Pioneer Basin are considerably lower than the remaining coastal catchments.

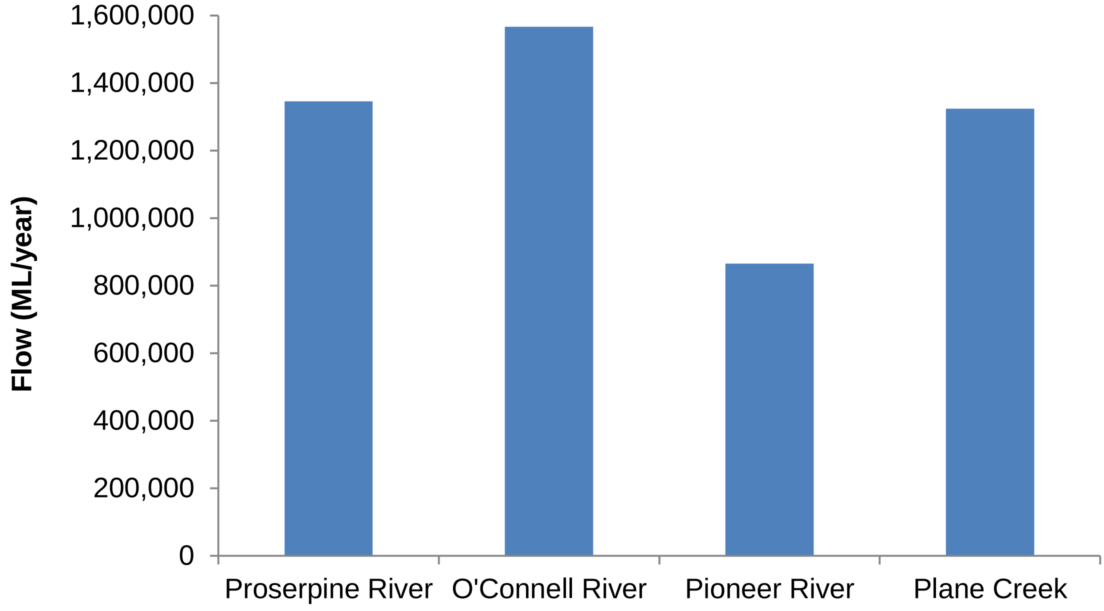


Figure 13 Modelled annual discharge for the Mackay Whitsunday region

4.2 Modelled loads

Source Catchments GBR regional loads (2008–2009 year) are shown in Table 18. The current modelling estimates that 8,545 kt/yr of fine sediment is exported from the six GBR NRM regions.

Table 18 Total average annual Source Catchments constituent baseline loads for all GBR regions for the (1986–2009) model run period based on 2008–09 land use/management

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	21,710	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
Total	**423,122**	**8,545**	**36,699**	**10,532**	**14,320**	**11,847**	**6,294**	**1,155**	**606**	**4,532**	**16,740**

The MW regional total TSS load of 511 kt/yr represents ~ 6% of the total GBR Source Catchments load (Table 19), while TP and TN represent ~ 7 % and 8% of the total GBR load.

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

NRM region	Area	Flow	TSS	TN	DIN	DON	PN	TP	DIP	DOP	PP	PSIIs
	(%)											
Cape York	10	27	5	14	5	26	9	8	8	32	5	0
Wet Tropics	5	33	14	33	42	27	32	26	20	21	29	51
Burdekin	33	19	47	28	25	22	36	35	29	25	37	12
Mackay Whitsunday	2	8	6	8	11	7	6	7	11	6	6	24
Fitzroy	37	9	23	12	12	13	10	17	24	9	17	3
Burnett Mary	13	4	5	6	5	6	7	6	7	6	6	9
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

The modelled GBR PSII herbicide export load was 16,740 kg/yr. The MW total PSII load was 3,944 kg/yr (24% of GBR total export) and was the second highest load after the Wet Tropics.

4.2.1 Mackay Whitsunday regional loads

Regional loads results are presented by initially summarising the land use characteristics for the contributing basins. Grazing is the dominant land use by area for all basins, while a large proportion of the Plane Creek Basin is used for sugarcane production (Figure 14).

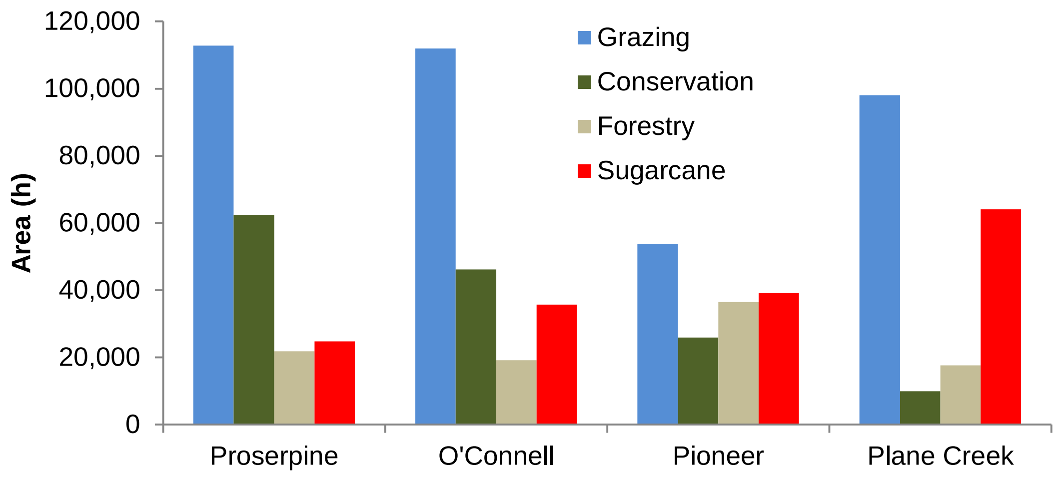


Figure 14 Summarised major land use categories by area (h) for the Mackay Whitsunday region

Modelled average annual loads of constituents for the Mackay Whitsunday basins are given in Table 20 based on the 2008 – 2009 land use/management baseline year (current condition for that period).

Table 20 Total average annual baseline Source Catchments constituent loads for MW region for the (1986–2009) model run period based on 2008–2009 land use/management

Basin name	TSS (kt/yr)	TP (t/yr)	PP (t/yr)	DIP (t/yr)	DOP (t/yr)	TN (t/yr)	PN (t/yr)	DIN (t/yr)	DON (t/yr)	PSII (kg/yr)
Proserpine River	66	90	44	36	10	573	130	220	223	539
O'Connell River	156	129	84	35	9	774	186	303	284	1,027
Pioneer River	203	115	93	17	5	686	298	222	166	859
Plane Creek	85	105	50	44	12	786	124	384	278	1,519
Regional total	**511**	**439**	**271**	**132**	**35**	**2,819**	**739**	**1,129**	**950**	**3,944**

The Pioneer River Basin contributes the majority of the particulate load (TSS, PP and PN) compared to the other three MW basins (Table 22) despite being the smallest in area and annual flow volume. Plane Creek contributes the highest modelled DIN, DIP and PSII loads.

4.2.2 Anthropogenic baseline and predevelopment loads

The anthropogenic baseline load was calculated by subtracting the predevelopment (or natural) load from the total baseline load.. Figures 15 to 18 give the modelled export loads for TSS (Figure 15), TN (Figure 16), TP (Figure 17) and PSII (Figure 18) herbicides respectively, and show the estimated predevelopment and anthropogenic baseline loads combined to represent the total baseline loads presented in Table 20.

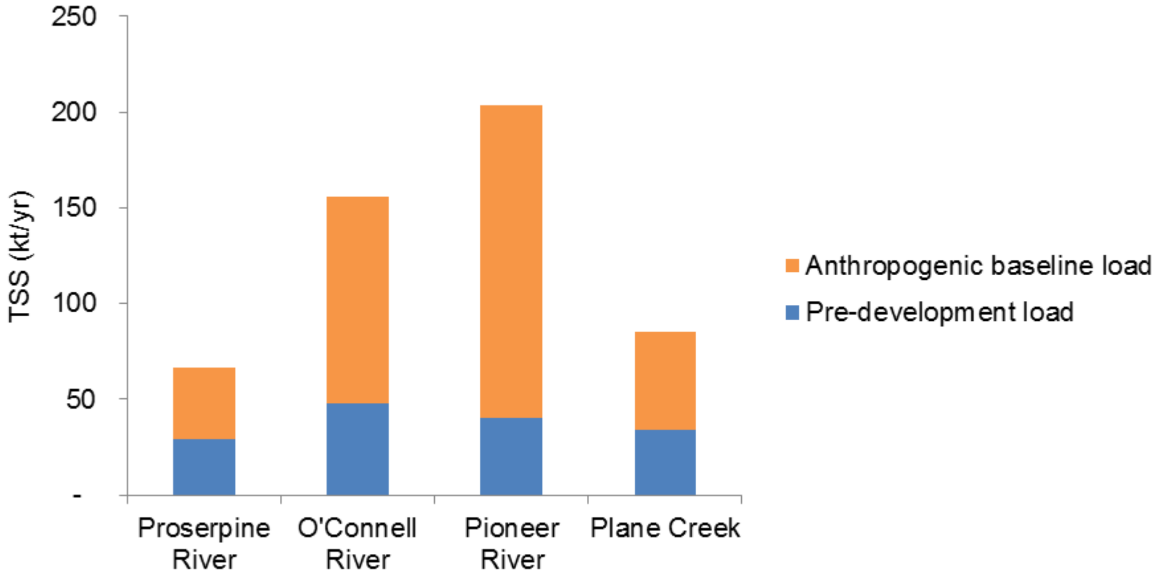


Figure 15 Modelled average annual TSS export load for the Mackay Whitsunday region

It is of interest that the smallest basin in area (the Pioneer) contributes the largest modelled average annual baseline load of TSS, while the Proserpine region contributes the least even though it has the largest area of grazing as a major land use.

Modelled total nitrogen exports (Figure 16) show similar patterns to TSS in regard to predevelopment loads with the O'Connell, Pioneer and Plane Creek basins contributing similar anthropogenic loads.

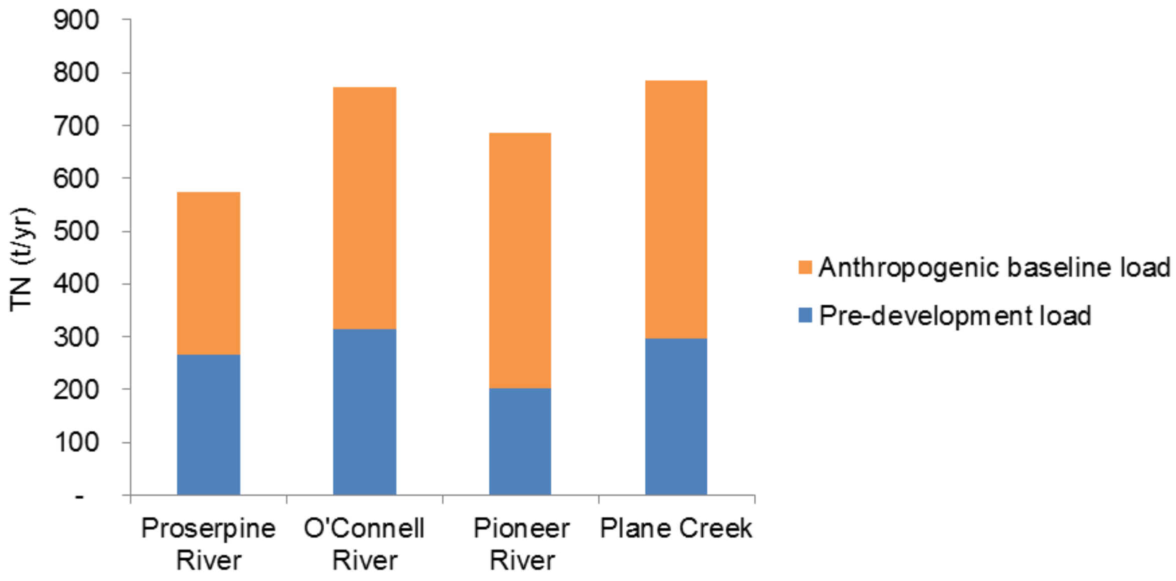


Figure 16 Modelled average annual TN export load for the Mackay Whitsunday region

Modelled total phosphorus loads (Figure 17) show similar regional patterns of export to TN in regards to predevelopment loads, with the Pioneer contributing the largest anthropogenic load.

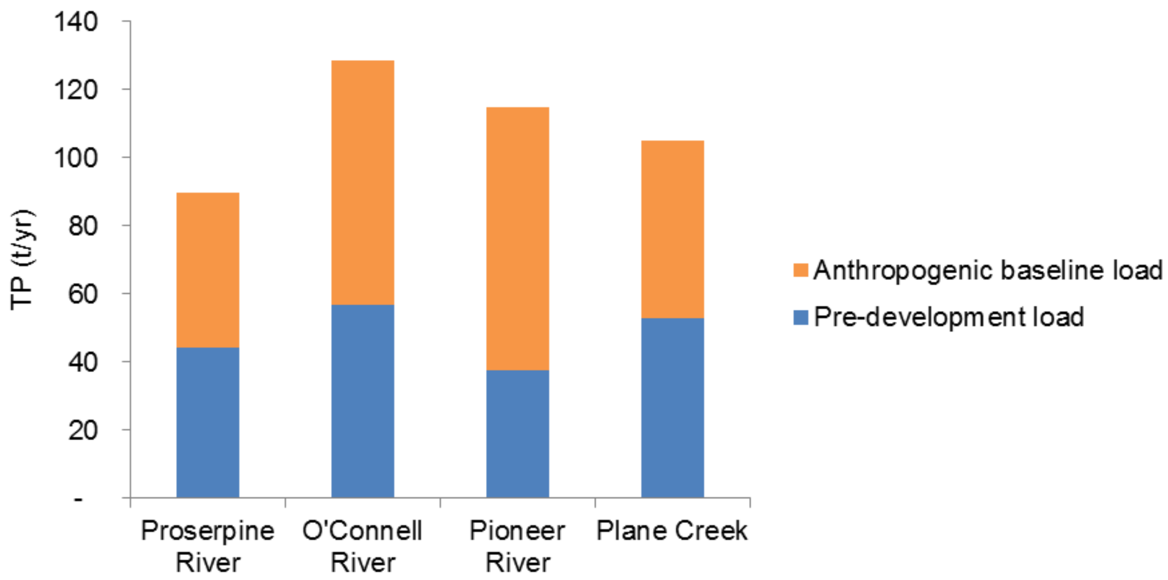


Figure 17 Modelled average annual TP export load for the Mackay Whitsunday region

Modelled PSII herbicide loads (Figure 18) have no predevelopment component and the Plane Creek basin exports the largest modelled load, it is of interest to note that this region has the largest area of sugarcane production.

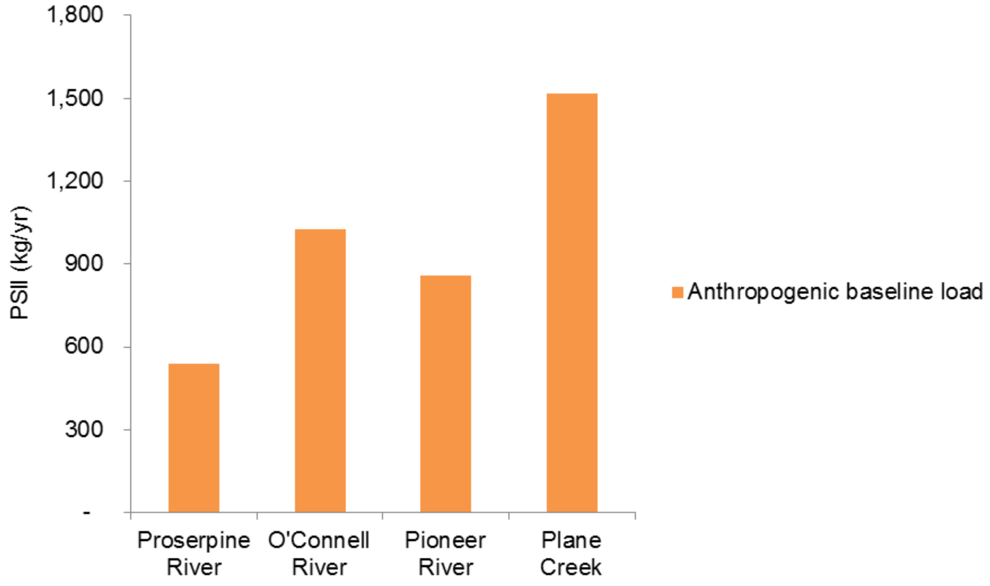


Figure 18 Modelled average annual PSII export load for the Mackay Whitsunday region

4.3 Constituent load validation

Validation data to compare model outputs to is limited for most basins in the Mackay Whitsunday region. The available data used for validation falls into three main groups, load estimates for the modelling period (1986 to 2009), load monitoring estimates (2006 to 2010) and previous estimates from monitoring and modelling.

4.3.1 Previous estimates

A summary of previous average annual estimates compared to current model outputs are given in Table 21 and a more detailed version in Appendix A. The estimates listed were selected from a number of previous studies and take into account previous estimates based on both modelled average annual loads and those calculated from limited water quality monitoring.

Table 21 Current model average annual constituent loads compared to previous estimates

Previous estimates	TSS	TP	PP	DIP	DOP	TN	PN	DIN	DON	PSIIs
MW region	(kt/yr)	(t/yr)	(t/yr)	(t/yr)	(t/yr)	(t/yr)	(t/yr)	(t/yr)	(t/yr)	(kg/yr)
Furnas (2003)	1,560	727	572	111	44	3,919	2,240	1,013	666	
Kroon et al. (2012)	1,542	2,172	1,933	84	288	8,092	5,212	1,746	1,570	10,019
Source Catchments model	511	439	271	132	35	2,819	739	1,129	950	3,944

Figure 19 shows a comparison of the averaged previous estimates and the Source Catchments derived average annual load for the range of constituents modelled.

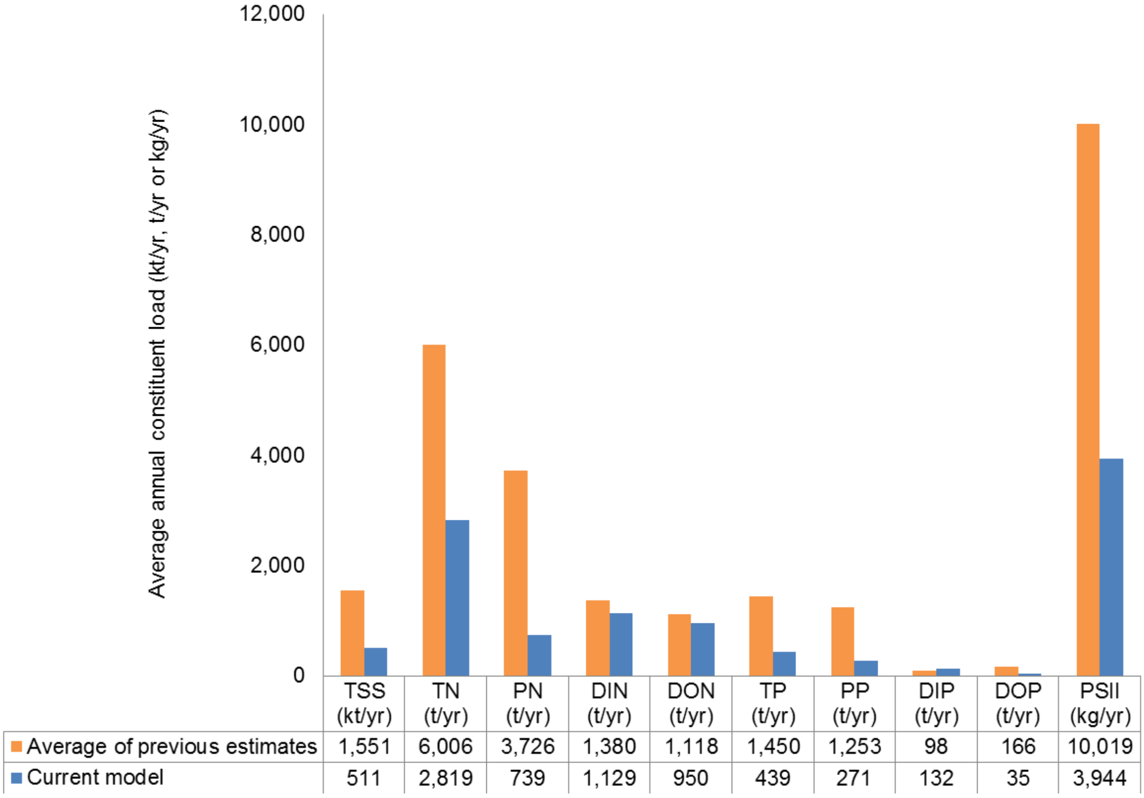


Figure 19 Averaged previous estimates and current baseline model average annual loads for the MW region (note TSS is in kt/yr and PSIIs in kg/yr)

The modelled average annual loads are lower than previous estimates particularly for fine sediments and total and particulate nutrients. Estimates for herbicides loads are not presented given the data was only recently available due to a lack of historical data.

4.3.2 Long–term FRCE loads (1986 to 2009)

Estimates of basin loads were calculated by Joo et al. (2014) for a number of key sites where suitable water quality data was available for the modelling period (Figure 20).

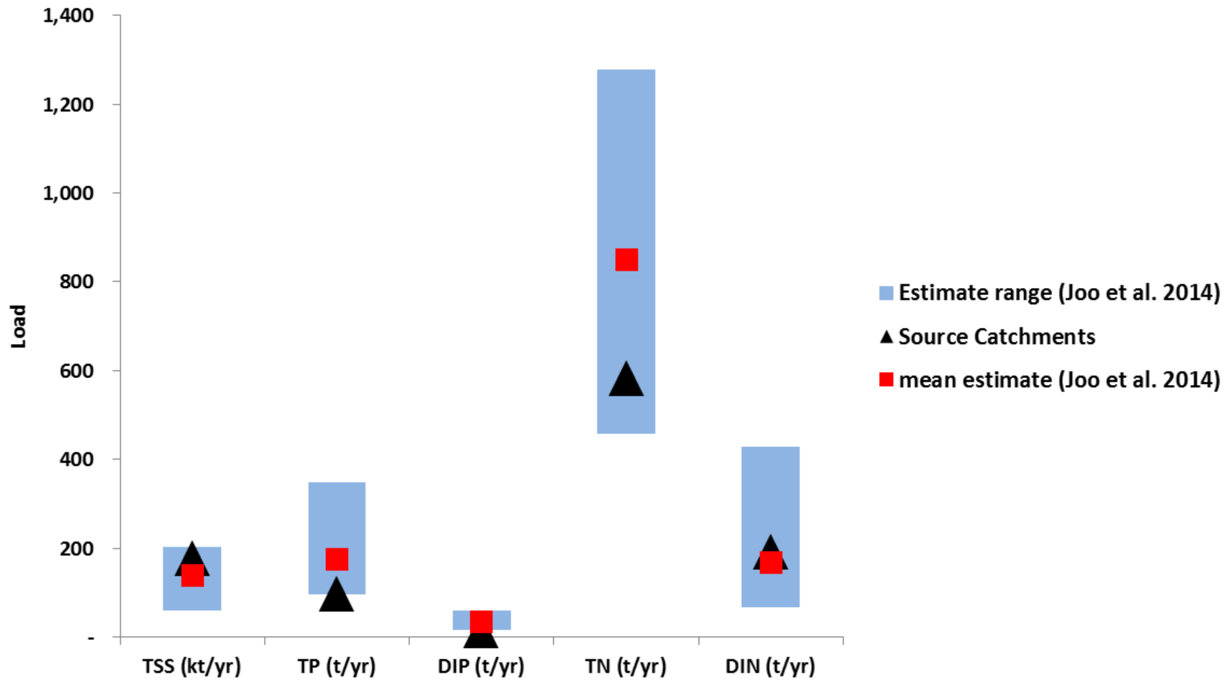


Figure 20 Comparison between modelled loads and loads estimated by Joo et al. (2014) for the Pioneer River between 1986 and 2009 (modelling period)

The average annual modelled loads for the Pioneer River are in relatively close agreement with the estimated loads for the same period with % differences ranging from 30% for TSS to –44% for TP. All modelled annual loads apart from DIP fit within the likely range. In addition to the average annual comparison, model performance for the Pioneer basin was tested at the monthly time–step using three performance criteria NSE, RSR and PBIAS (Table 22). Model performance was rated as 'Very Good to Good' for TSS and TN across all three performance criteria at a monthly time–step for the 23 year modelling period (Moriasi et al. 2007). For TP, ratings were 'Good to Satisfactory'. The results indicate that all modelled loads were within 50% of loads estimated from measured data for the 23 year modelling period.

Table 22 Performance statistics based on three evaluation guidelines in Moriasi et al. (2007) at the monthly time–step for the Pioneer River Gauge 125001A

Gauging station	Constituent	NSE		RSR		PBIAS	
		Value	Result	Value	Result	Value	Result
Pioneer River GS 125001A	TSS	0.91	Very good	0.30	Very Good	26.20	Good
	TN	0.68	Good	0.57	Good	35.37	Good
	TP	0.64	Satisfactory	0.60	Good	46.13	Satisfactory

4.3.3 GBR Catchment Loads Monitoring Program (2006 to 2009)

The Great Barrier Reef Catchment Loads Monitoring Program (GBRCLMP) was implemented in 2006 to secure constituent load data specifically for GBR model validation. Calculated loads for a number of GBR regions and sub–basins are given in Joo et al. (2012) Figure 21 gives a summary of measured and modelled loads of key constituents for the 2006 to 2009 period at a node (Dumbleton Weir) on the lower reaches of the Pioneer River.

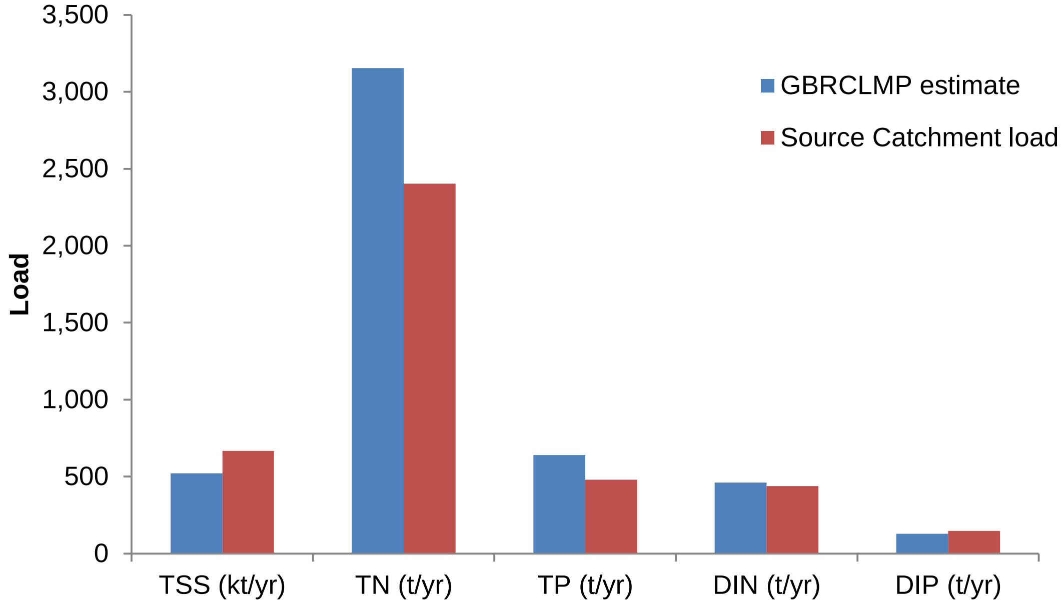


Figure 21 GBRCLMP estimate and Source Catchment load of constituents for lower Pioneer River during 2006 to 2009 period

There was good agreement between measured and modelled loads with the modelled loads for TSS, TP, DIN and DIP all within 30% of the observed loads or loads calculated from monitoring data. Measured and modelled loads for the same period are shown in Figure 22 for the O’Connell Basin at a node upstream of the basin outlet on the O’Connell River (gauge station 124001A).

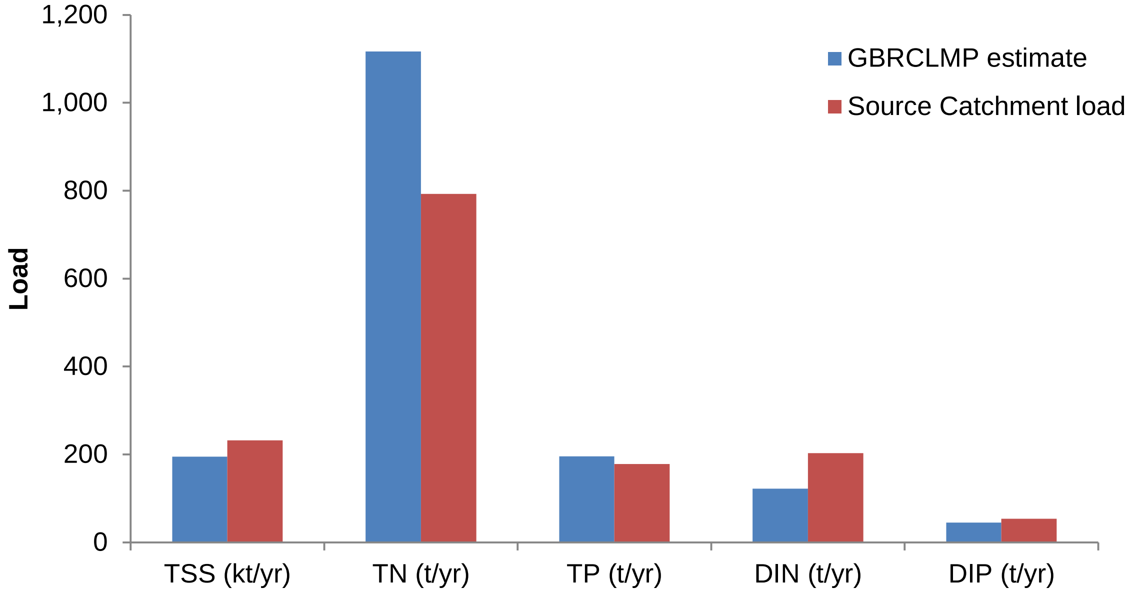


Figure 22 GBRCLMP estimate and Source Catchment load of constituents for mid O'Connell River during 2006 to 2009 period

Similar to the Pioneer River example in Figure 21 there is good agreement between measured and modelled loads for the O'Connell River site (Figure 22) with modelled loads within 30% of measured loads.

4.4 Contribution by land use

Contributions to modelled average annual load by land use are given in Figure 23 and show that sugarcane and grazing land use contribute the largest percentage loads of TSS and PN.

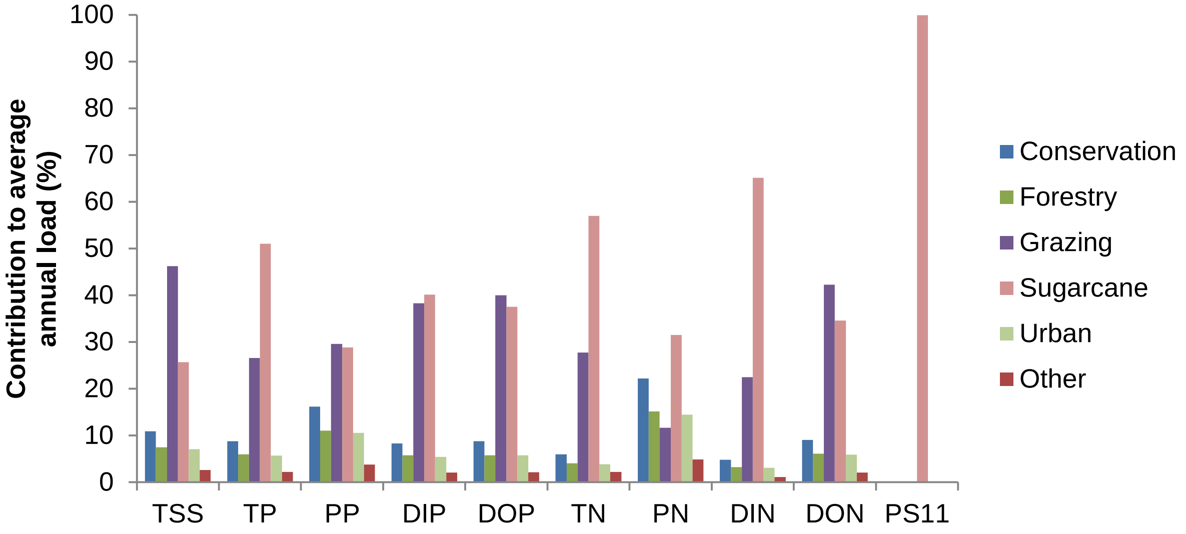


Figure 23 Modelled percent contribution to average annual constituent load by land use for the Mackay Whitsunday region.

The modelled percentage of all other constituents from the Mackay Whitsunday region is dominated by contributions from sugarcane production and grazing land use while substantial exports of PP and PN originate from conservation areas.

4.4.1 Land use contribution to export per unit area

Modelled contributions for TSS, TP and TN per unit area for major land uses are summarised in Figure 24.

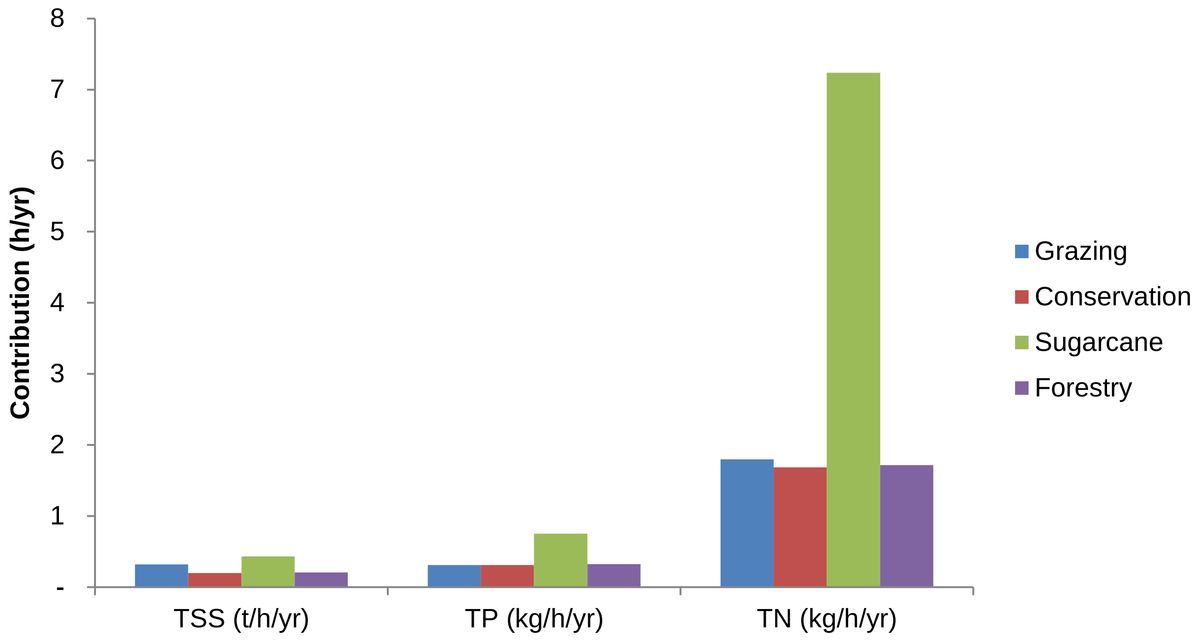


Figure 24 Modelled contribution of major land use by unit area for the Mackay Whitsunday region (note units, TSS in t/h/yr while TN&TP are in kg/h/yr)

It can be seen that sugar production dominates the TSS and total nutrient exports per hectare/year, while grazing, forestry and conservation have similar and lower values than sugarcane land use.

4.5 Sources and sinks

Modelled sources and sinks (losses) are given in Table 23 for TSS DIN and PSIIs. Streambank erosion is the dominant modelled source for TSS closely followed by hillslope erosion.

Table 23 Modelled sources and sinks for TSS, DIN and PSIIs by process (%) for the MW region

Process	TSS (kt/yr)	TSS (%)	DIN (t/yr)	DIN(%)	PSII (kg/yr)	PSII (%)
SOURCE	**553**	**100**	**1,228**		**4,648**	
Hillslope	204	37				
Gully	13	2				
Streambank	252	46				
Point source			27	2		
Diffuse Dissolved			1,053	86		
Undefined	84	15	148	12	4,648	100
SINKS (loss)	**42**	**100**	**98**	**100**	**704**	**100**
Extraction	25	61	85	87	85	12
Floodplain Deposition	3	7				
Reservoir Deposition	9	22				
Reservoir Decay						
Residual Link Storage	4	10	13	13	33	5
Stream Decay					586	83
Stream Deposition						
EXPORT	**511**		**1,129**		**3,944**	

The largest modelled sources for TSS were streambank and hillslope erosion at 46 and 37% respectively which, when combined, equate to >80% of the total TSS contribution. There are only minor modelled contributions of TSS from gully erosion (~2%). Of the 553 kt/yr generated ~8% of TSS is lost via deposition and extraction. Modelled sources for DIN are primarily from diffuse dissolved processes which account for ~86% of the total while extraction is the major process for DIN loss. Total PSII losses are ~15% with in–stream decay the primary loss process at ~13%. Modelled TSS contributions by process for regional basins in the MW region are given in Table 24.

Table 24 Modelled TSS contributions by process to total export (%)

Basin	Hillslope	Gully	Streambank
Proserpine	72	5	23
O'Connell	60	3	38
Pioneer	34	1	65
Plane Creek	75	4	21
MW region	**51**	**3**	**46**

It can be seen that hillslope erosion is the dominant process for TSS contributions in the Proserpine, O'Connell and Plane Creek basins (all >60%) while streambank erosion is the dominant process in the Pioneer basin at ~65%. Modelled gully erosion is a minor process for TSS contributions in all basins at ~5% or lower.

4.6 Progress towards Reef Plan 2009 targets

The modelling results suggest there was an 11% reduction in average annual suspended sediment load leaving all GBR catchments from 2008 – 2013 investment period (Figure 27). In the case of total nitrogen and total phosphorus the average annual load was reduced by 10% and 13% respectively. The average annual PSII herbicide load was reduced by 28%. The GBR wide load reductions were similar to the Mackay Whitsunday reductions with the exception of nitrogen and PSIIs with Mackay Whitsunday reductions much greater than the GBR wide numbers (Figure 27). In the Mackay Whitsunday NRM region there was a 9% reduction in fine sediment load which is rated as 'Very Good' progress towards the targets (Table 12). TP and DIN modelled load reductions were 14% and 24% respectively both of which are rated as 'Poor' progress towards the water quality targets. The PSII herbicide load has decreased by 42% which is rated as 'Good' progress.

Large reductions in PSII loads for the MW region is the results of large reported changes in sugarcane land use management from C to B and B to A classes. The largest reductions appear to have occurred between Report Card 2010 and Report Card 2011 (Figure 26) with similar reductions achieved across years from Report Card 2011 to Report Card 2013. Investment in improved management practices to reduce constituent loads across the MW region has occurred predominantly in grazing lands and sugarcane areas. Cumulative reductions in key constituents from Report Card 2010 to Report Card 2013 are shown in Figure 25.

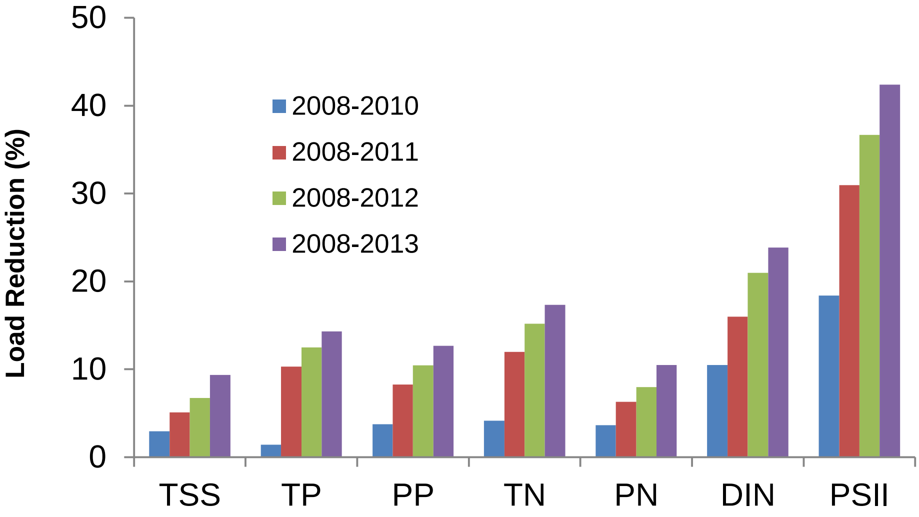
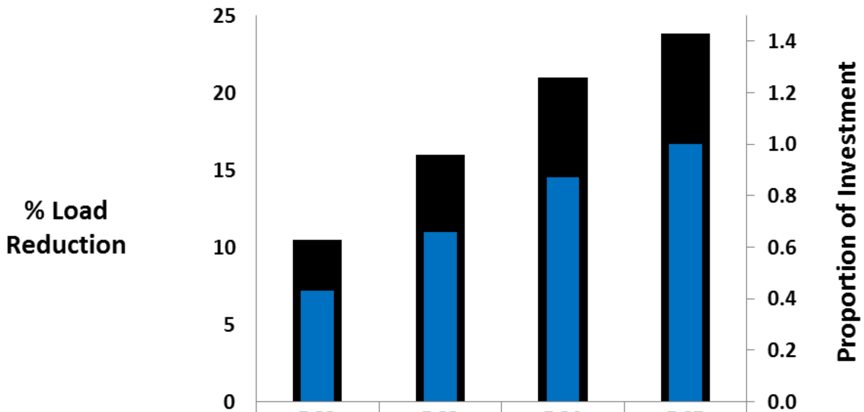


Figure 25 Total cumulative percent load reduction resulting from management change practice for Report Card 2010 to Report Card 2013 for the Mackay Whitsunday region

The relationship between cumulative reductions in loads and the proportion of investment in management change for DIN in sugarcane (as an example) from baseline to Report Card 2013 is summarised in Figure 26.



	RC2	RC3	RC4	RC5
% reduction DIN loads	10.5	16.0	21.0	23.8
proportion of investment SUGAR	0.43	0.66	0.87	1

Figure 26 Load reduction in DIN from investment in sugarcane management change from Report Card 2010 (RC2) to Report Card 2013 (RC5) for the MW region

It can be seen from Figure 26 that there is a proportional relationship between investment in sugarcane management change and the modelled average annual DIN loads for the MW region. Overall progress towards targets for key constituents in the MW region are shown in Figure 27.

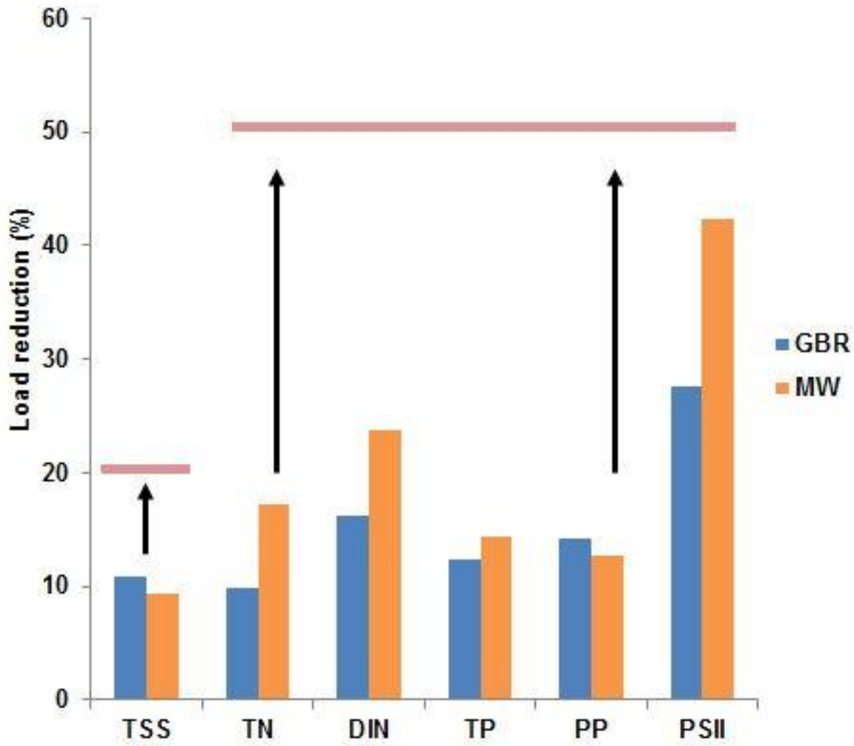


Figure 27 Reductions in key constituents for the MW and GBR regions and progress towards targets

It can be seen from the modelled reductions in Figure 27 that there is good progress towards targets at both a GBR and MW regional scale.

Discussion

The development and application of a modified Source Catchments modelling framework for the entire GBR region builds on previous modelling projects. This iteration of GBR catchment modelling has estimated the effects of improved agricultural land management practices on water quality from government investment. The results are assessed against the Reef Plan 2009 water quality targets and the associated focus on the quality of water discharged to the GBR Lagoon. The use of a consistent modelling platform and methodology across all GBR regions enables the direct comparison of outputs from each region, as well as from each scenario (current total, anthropogenic baseline, predevelopment and management change loads). This study is an updated estimate of the pollutant loads from those in Report Card 1 (Kroon et al. 2012) utilising the most recent point and spatial data sets. It is the first GBR–wide modelling since 2005 that separates the predevelopment (or natural component) from current total loads (McKergow et al. 2005a, McKergow et al. 2005b).

One of the main improvements since the first report card (Kroon et al. 2012) was the use of the same modelling platform across the GBR and the inclusion of coastal catchments below the end gauging station to enable the prediction of a total exported load to the GBR. Previous estimates were either not capable of modelling minor coastal subcatchments, or a near neighbour scaling approach was used to account for runoff and loads generated from these areas. Other improvements included an increase in the temporal and spatial resolution of input datasets such as ground cover and the ability to apply a specific model to each landuse within the Source Catchments model. 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 at key sites.

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 is a further improvement. Other advantages of the current modelling approach include a high level of transparency (that is, repeatability) and flexibility in analysing the model outputs at a range of scales and time–steps. The collection of recent loads data at key GBR catchment sites has provided high quality validation data sets for the current modelling project, whereas many previous studies did not have access to validation data for a number of GBR basins. These collective enhancements have resulted in a comprehensive improvement in modelling constituent loads and reporting on the reduction of loads discharging from GBR catchments due to changes in land use management.

5.1 Hydrology

An improved spatial and temporal representation of hydrology has been a substantial enhancement of the GBR Source Catchments modelling project. The more detailed hydrology modelling allowed investigation into the source of flows within the GBR catchment. It also allows for estimation of flow where there is missing data and extrapolates flows within ungauged areas, particularly for small coastal catchments. There are now hydrology models for all GBR catchments and these have been calibrated using a consistent process. Modelled and gauged flow volumes are in close agreement at the sites used in the calibration for the MW region, particularly at the average annual time–step with eight of the nine sites calibrated having total modelled runoff volumes within 9% of measured volumes. The majority (8 of 9) of gauges had monthly Nash Sutcliffe Coefficient of Efficiency (NSE) >0.9. Moriasi et al. (2007) in a global review of hydrology model performance rated NSE values >0.75 as 'very good'.

Overall, modelled flow for large events is in good agreement with, and generally tends to be less than, gauged flow. One potential reason for this under–prediction is the uncertainty in the SILO rainfall grids (DSITIA 2013f) due to a lack of rain gauging stations across the catchments leading to an under estimation of high flow events. For example, while there are just under 60 rain gauge stations scattered throughout and near–bye the Mackay Whitsunday region, the majority are clustered around populated areas like Mackay (Pioneer sub–region with 13 stations), Proserpine and Airlie Beach (Proserpine sub–region with 10 stations). Whereas, the Plain Creek and the O'Connell basins have much fewer rain gauges, with just 7 and 6 stations respectively.

A comparison of modelled and gauged flow data (section 4.1.1) during the 2006 to 2009 wet seasons for the Pioneer (high rain gauge density) and the O'Connell (low rain gauge density) River basins suggests that rain gauge density is critical for accurate flow simulation. Modelled flows from regions with a high spatial density of rain gauges appear to show better agreement with gauged flow data compared to regions with low rain gauge density. These observations are most likely applicable to other GBR catchment regions where there are clear rainfall gradients from the ocean to inland areas. A lack of well distributed rain gauges across wetter catchments such as the MW region may result in a smoothing of rainfall and inaccurate daily rainfall calculations in the SILO gridded rainfall surfaces compared to actual rainfall in the catchment. While the hydrology component of the model is performing well for the long–term predictions future work could investigate scaling of rainfall data to better reflect the spatial variability of the point data. Re–calibration of catchment hydrology with a bias towards high flow events may also improve load predictions.

5.2 Modelled constituent loads and validation

Source Catchments modelling framework was used to report the reduction of constituent loads exported to the GBR lagoon as a result of a change in land management practices. Prior to reporting of results, it was important that modelled loads were tested and validated against available water quality monitoring data to ensure load estimates were in agreement with measured data. In the Mackay Whitsunday region there was a range of water quality monitoring data available, although in most cases, the data was sporadically collected at a small number of sites and over short timeframes (1–3 years). An advantage of the Source Catchments modelling framework is its capacity to use much of this disparate water quality data, taken at different times and at different locations to assess the performance and validation of the model loads.

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

Three main approaches were used to validate the GBR Source Catchments modelling:1) long–term comparison (1986–2009) against available measured data 2) a short term comparison (2006–2010) against the Queensland Government loads monitoring program data and 3) comparison to previous best estimates.

The modelled average annual loads of constituents are lower than previous modelled estimates for the Mackay Whitsunday region. This is due to improvements made to constituent generation models improving load estimates in this study. Modelled loads and loads estimated from measured data specifically for model validation are much closer in agreement. Comparing loads for the 23 year period at a monthly time–step, PBIAS for TSS, TN and TP were 26%, 35% and 46% respectively. Using Moriasi et al. (2007) criteria, the modelling results rate as 'good' for TSS and TN and 'satisfactory' for TP when monthly modelled loads are compared to Joo et al. (2014). Using the same approach, NSE statistics for TSS, TN and TP of 0.91, 0.68 and 0.64 respectively, produced ratings of 'very good', 'good' and 'satisfactory' respectively. Overall, this indicates a good fit between modelled and measured loads for the current project.

5.2.1 Previous estimates and annual load comparisons

Current modelled average annual loads are generally within 50% of previous estimates. Modelled loads range from ~20% (PN) to ~47% (TN) of the averaged previous estimates for particulate nutrients and TSS. It is of interest that the Furnas (2003) estimates (Table 17) are based on substantial sets of monitored data, while the Kroon et al. (2012) estimates incorporate both monitored data (including Furnas, 2003) and previously modelled estimates. When compared to the estimates of Furnas (2003), based on measured data only, rather than the average of estimates from Furnas (2003), and Kroon et al. (2012), the current Source Catchments modelled loads range improves to ~33% for PN and ~73% for TN (in comparison). The discrepancies between previous estimates and current modelled estimates may be attributed to the previous methods overestimating average annual loads, particularly where estimates are produced by applying limited high flow loads data from water quality monitoring to neighbouring coastal catchments where little or no data exists.

5.2.2 Basin load monitoring (2006 to 2009) and model outputs

Current model outputs generally show good agreement to recent measured loads for key MW sites. Measured loads for the Pioneer and O'Connell Rivers for the 2006 to 2009 period (Joo et al. 2012) show good agreement to modelled results for the same period. Also, limited data for Sandy

Creek (2005 and 2007) (Rohde et al. 2008), a subcatchment of the Plane creek basin, suggests that modelled loads are comparable in relative terms, however, there is insufficient data to derive detailed load comparisons. There is currently insufficient data to compare modelled and measured loads for the Proserpine Basin.

The comparison of measured and model loads for the 2006 to 2009 period for the lower Pioneer River (Figure 15) suggest that the model is performing well at simulating constituent exports at this site. The major differences are the ~25% lower modelled loads for TN and TP compared to the load calculations produced from monitoring data. The modelled TSS load for the same period of 667 kt/yr is ~ 22% higher than the measured load of 522 kt/yr and loads for other constituents have less variability when modelled loads are compared to measured loads. When both measured and modelled loads are converted to EMC values, the modelled EMC for TSS is ~204 mg/L compared to a measured EMC of ~167 mg/L, while the modelled and measured total flow volumes for the 2006 to 2009 period were similar at 3,265,000 ML and 3,117,000 ML respectively (a 5% difference). Therefore the primary difference in load between modelled and measured loads will be due to the constituent concentrations, rather than flow volumes. Overall the modelled and measured loads for the period show close agreement for this site on the lower Pioneer River.

Differences in modelled and measured loads during the 2006 to 2009 period for the O'Connell River are similar to the loads for the Pioneer site in relative terms (Figure 16). The modelled TSS load is slightly higher (16%), and the TN and TP loads lower (~29 and 10% for TN and TP respectively) than the measured loads. The modelled DIN load is 40% higher than the measured load for the O'Connell, whereas the DIN load values were similar for the Pioneer, even though the areas under sugarcane production are similar for the two basins. EMC values for TSS were 140 mg/L for the modelled load and 172 mg/L for the measured load indicating a good agreement for the 2006 to 2009 period.

The modelled average annual EMC for TSS in the O'Connell River is ~102 mg/L compared to an averaged previous estimate of ~427 mg/L. The recent measured loads data suggests that previous estimates may be overestimating average annual TSS loads from the O'Connell River. In general the modelled and measured loads showed good agreement and the EMC values were in a relatively similar range shown by the Pioneer site for same period.

5.3 Source Catchments anthropogenic baseline loads

The modelled average annual constituent loads from the Mackay Whitsunday region are low in comparison to other GBR regions. For example, the annual loads of TSS (511 kt/yr), TP (439 t/yr) and TN (2.8 kt/yr) from the MW region are at the lower end of the range along with the Burnett Mary and Cape York regions (Table 18). Considering the MW region makes up only 2.1% of the total GBR catchment area these results fit with general expectations in regards to modelled contributions. The two largest regions in area, the Fitzroy and Burdekin dominate the contribution of TSS and particulate nutrients to the GBR mainly due to extensive grazing land use. The Wet Tropics region contributes large loads in relation to its relatively small GBR catchment area (~5%) mainly due to the large average annual flow volumes and extensive land use area.

5.3.1 Regional loads

The Plane Creek Basin has the highest modelled average annual exports of PSII herbicides, DIN and DIP across the MW region (Table 20). Plane Creek also has the highest area of sugarcane production (Figure 14) and a large number of small tributaries discharging directly to the ocean (Figure 5) when compared to other MW basins, therefore the results are logical considering land use, geography and close proximity to the coast. In contrast the Proserpine sub–region has the lowest area under sugarcane and the modelled annual loads for PSIIs DIN and DIP are the lowest in the region.

Predevelopment loads (Figures 15 to 18) for modelled constituents appear to fit within previous estimates derived from modelling or monitoring data (Kroon et al. 2012). The results for predevelopment loads in the current modelling exercise fit within the three to five–fold increases generally used when estimating GBR catchment changes, particularly for intensive and uses such as grazing and cropping and sugarcane production (Furnas, 2003).

The modelled Pioneer Basin loads are generally higher than or equal to other sub–regions for TSS and particulate nutrients in terms of total load and modelled anthropogenic load. Loads of dissolved nutrients and PSII herbicides from the Pioneer are either mid–range or slightly lower than the other ‘more coastal’ basins. The Pioneer has extensive western areas where the long–term average annual rainfall is substantially lower than eastern areas of the MW region (Figure 2) and extensive areas of grazing land use, relative to the catchment area. In addition, Pioneer Basin flows are restricted to a single outlet near Mackay with a well–defined main channel and limited floodplains.

5.3.2 Contribution by land use

The results for contribution by land use (Figure 23) show that grazing lands produce the largest modelled contribution of TSS (after streambank erosion), and PP from grazing is similar to sugarcane land contributions. This fits well conceptually, as grazing is the major land use in the MW region and the positive relationship between TSS and PP transport from rangelands is well established (Furnas 2003, Packett et al. 2009).

Lands used for sugar production dominate the modelled contribution of TN, DIN, DIP and PSII herbicides. Grazing lands contributions of TP, DIP and DON either equal or exceed modelled contributions from sugarcane lands. These results also make sense from a nutrient application perspective, where sugarcane farmers apply fertilisers on a regular basis and the grazing industry uses minimal broad–scale fertiliser application. The percentage of PN contribution from lands used for conservation is the third highest after streambank erosion and sugarcane production and this also fits with current observations on ratios of nitrogen species from conservation and forested areas of the GBR catchment (McKergow et al. 2005), although, Brodie and Mitchell (2005) suggest that grazing land use is also a major contributor of PN from tropical GBR catchments.

In general, the pattern of modelled constituent contributions from the various land uses fits well with current understanding regarding grazing and sugarcane production land use and, in the case of the MW region, the spatial distribution of land use in relation to coastal waters.

5.3.3 Contribution per unit area

Sugarcane production contributes the greatest modelled contribution of TSS, TP and TN per unit area in the MW region (Figure 24). Grazing contributes the next highest modelled loads of TSS per unit area, and grazing, conservation and forestry are similar on a per unit area basis for TP and TN. In general the modelled patterns of per unit area contributions for constituents are relatively consistent with experimental data in the MW region (Rohde et al. 2008) where inorganic N and P are applied on a regular basis to sugarcane production areas.

5.3.4 Constituent sources and sinks

In general streambank erosion is the dominant process for modelled contributions of TSS in the MW region (Table 21) closely followed by hillslope erosion. When sub–regional TSS contributions are examined (Table 22) hillslope erosion is the major process for the three coastal basins. The exception is the Pioneer basin results where streambank erosion is the dominant source of modelled TSS contribution to the stream network. While the O’Connell, Proserpine and Plane Creek basin results suggest a 60, 72 and 75% contribution respectively from hillslope erosion, the Pioneer hillslope result is 34% and streambank erosion 65% of TSS contributions. Gully erosion contributions for TSS are low for all catchments ranging from 1 to 5%. Further investigation is needed to determine if the high streambank erosion in the Pioneer is an artefact of model input parameters or other reasons.

At the time of writing the reasons for the high bank erosion rates are not clear and similar findings of higher than expected bank erosion rates for the Pioneer basin were reported by Rohde et al. (2006) from a previous catchment modelling study. A possible cause may be that the Pioneer has different catchment drainage characteristics to the three, primarily coastal, Proserpine, O’Connell and Plane Creek basins. The main difference being the bulk of the pioneer catchment is inland and the primary outlet channel stretches from the west to the east between the northern O’Connell and southern Plane Creek basins. The other coastal catchments have numerous streams draining to the coast. Therefore, the Pioneer is the only basin with a single channel draining the entire flow from an inland basin to the ocean and this may be impacting on the modelled export results for streambank erosion in this basin. There is a lack of empirical data for bank erosion rates in the MW region and new information will be needed in the future for validation.

5.4 Progress towards Reef Plan 2009 targets

Overall there has been ‘Very Good’ progress made towards the reef targets for TSS and PSII for the whole of GBR following 2008–2013 management practice investments. This period covers Report Card 2 through to Report Card 5, noting that each report card is cumulative. The modelling results suggest there was an 11% reduction in average annual suspended sediment load leaving all GBR catchments from 2008–2013 investment period with the greatest reduction from grazing areas. In the case of total nitrogen (TN), progress was rated as ‘Very Poor’ with the average annual loads reduced by 10%, with the greatest reduction from the Burdekin and Wet Tropics NRM regions. The average annual PSII herbicide load was reduced by 28% which is rated as ‘Moderate Progress’ with 70% of the reduction from the Wet Tropics and Mackay–Whitsunday regions. Improved herbicide management practices in the cane industry contributed to the large reduction.

Investments in improved land management practices in the Mackay Whitsunday region during the life of Reef Plan 2009 are estimated to reduce loads of TSS, TP, TN, DIN and PSII pesticides to the reef lagoon by 9%, 14%, 17%, 24% and 42% respectively. The progress towards the Reef Plan 2009 water quality targets is considered very good and good for TSS and PSII load reductions, however the nutrient loads reductions are considered poor. It is clear the 50% nutrient reduction targets for Reef Plan 2009 are very challenging, with alternative management strategies required if current and future targets are to be achieved.

The primary management change incorporated into the model for grazing involved improvements in grazing management practices resulting in increased ground cover hence reduced hillslope erosion. Management changes for 2008/2009 and 2009/2010 (Report Card 2010) were based on improved hill slope ground cover only, while changes from Report Card 2010 to Report Card 2013 incorporated improved hill slope ground cover and riparian works resulting in improved ground cover. The changes for grazing hillslope ground cover were based on reductions in soil erosion and other particulate constituents.

The scale of shifts in management change for grazing lands were similar for Report Card 2010 through to Report Card 2013 with the proportion of classes A and D remaining close to unchanged. The main changes were shifts from class C management to class B of ~7%, while changes from class B to A over the same period were ~0.5% (Table 14). Overall this combined shift from class C management to class B is significant due to the large areas that grazing land use occupies in the MW region, and contributed to an estimated 9% reduction in TSS average annual load for the Reef Plan 2009 reporting period.

Management change for sugarcane production includes soils, nutrient and herbicides scenarios in the MW region (Table 13). The primary changes for the combined management changes years are a large shifts (>50%) from C to B class, and shifts from B to A class (~20%). Nutrient and herbicide based management changes were similar and comprised shifts from C to B class (~30%) and from B to A class (~10%). Overall, the changes in sugarcane management reported for modelled scenarios are substantial and are reflected in the estimated reductions in constituent loads. These changes in management class resulted in the major l reductions in estimated nutrient modelled loads, and substantial reductions in PSII herbicides during the Reef Plan 2009 reporting period.

From a sub–regional perspective, the largest reductions in modelled TSS, TP, TN and PSII herbicide average annual loads are found in the Plane Creek Basin. This result appears logical considering the Plane Creek Basin has the highest sugarcane growing area in the region, substantial grazing areas and the lowest areas of conservation and forestry land uses. Therefore this coastal catchment should, theoretically, exhibit substantial reductions in modelled constituent loads via management change scenarios. These results afford a degree of confidence that the model is performing well in a regional (spatial) sense in regards to modelling of loads reductions.

Conclusion

The modified GBR Source Catchments model developed for the Mackay Whitsunday region is performing well as a tool for estimating load reductions due to on–ground investment and changes in catchment management. The underlying hydrological model calibration simulates stream flow volumes that show good agreement with gauging station data, particularly at the average annual, yearly and monthly time scales. These results suggest that reasonable confidence can be given to modelled flow results for streams and catchments in the Mackay Whitsunday region where no flow data exists, this alone is a substantial improvement in GBR catchment modelling. Average annual loads of constituents are lower than most previous estimates for the Mackay Whitsunday region, particularly for subcatchments where no, or sparse, water quality data exists. However, modelled loads and loads calculated at sites where recent water quality data has been collected specifically for model validation are much closer in agreement, with the modelled loads than previous estimates. Further, validation statistics used in the Moriasi et al. (2007) approach produce NSE and PBIAS ratings ranging from ’very good’ to ‘satisfactory’ for TSS, TN and TP.

As with all numerical modelling projects used to simulate natural systems, model outputs would be enhanced by improving input data and model processes. However, the current modelling framework is flexible, innovative and is fit for purpose. It is a substantial improvement on previous GBR load modelling and the use of consistent modelling approach across the six NRM regions allows for comparison across regions. It is appropriate to use the model to report on relative load reductions due to on–ground land management change given the only change in the current ‘baseline’ model is the inclusion of ‘management change data’. Therefore, regardless of the current accuracy of modelled average annual constituent loads (within reason) the ‘relative’ modelled reduction in loads due to management change will remain 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), a reasonable degree of confidence can be placed in the relative percentage reduction in average annual loads calculated from the provided management change data. 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 Great Barrier Reef catchment. In addition, methods have been developed to implement and calibrate an underlying hydrological model that produces reliable flow simulations for gauged sites and increased confidence in modelled flows for ungauged sites.

The daily time–step capability and the high resolution of Source Catchments areas allows for modelled flow volumes and loads of constituents to be reported at subcatchment scale for periods ranging from events over a few days, to wet seasons and years. This is a significant improvement on past modelling exercises and will be useful for various applications.

Finally, technical documents produced from this project will be useful for others to make use of the flexible framework which allows for various sub–models at relatively fine catchment scales and the ability to incorporate add–ins and tools to enhance the modelling process. Therefore, the enhancements and products originating from this project should be of benefit to other Source Catchments modelling applications.

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Appendix A – Previous estimates of pollutant loads

Table 25 First Report Card Pre–European (natural), current and anthropogenic loads for the MW basins

	TSS (ktonnes/yr)			**DIN (tonnes/yr)**		
Basin name	Pre-European	Current	Anthropogenic	Pre-European	Current	Anthropogenic
Prosperine River	45	313	268	83	442	359
O'Connell River	99	626	527	125	494	369
Pioneer River	50	52 *	2	84	275 *	191
Plane Creek	54	551	497	95	535	440
REGIONAL TOTAL	248	1,542	1,294	387	1,746	1,359
	TN (tonnes/yr)			**DIP (tonnes/yr)**		
	Pre-European	Current	Anthropogenic	Pre-European	Current	Anthropogenic
Prosperine River	203	1,722	1,519	4	16	12
O'Connell River	295	2,304	2,009	4	22	18
Pioneer River	205	732 *	527	2	31 *	29
Plane Creek	209	3,334	3,125	4	15	11
REGIONAL TOTAL	912	8,092	7,180	14	84	70
	DON (tonnes/yr)			**PN (tonnes/yr)**		
	Pre-European	Current	Anthropogenic	Pre-European	Current	Anthropogenic
Prosperine River	111	176	65	9	1,104	1,095
O'Connell River	152	221	69	18	1,589	1,571
Pioneer River	111	648 *	537	10	245 *	235
Plane Creek	103	525	422	11	2,274	2,263
REGIONAL TOTAL	477	1,570	1,093	48	5,212	5,164
	DOP (tonnes/yr)			**PP (tonnes/yr)**		
	Pre-European	Current	Anthropogenic	Pre-European	Current	Anthropogenic
Prosperine River	10	9	-1	19	320	301
O'Connell River	14	25	11	31	568	537
Pioneer River	10	130	120	22	74 *	52
Plane Creek	10	124	114	20	971	951
REGIONAL TOTAL	44	288	244	92	1,933	1,841
	TP (tonnes/yr)			**PSII (kg/yr)**		
	Pre-European	Current	Anthropogenic	Pre-European	Current	Anthropogenic
Prosperine River	33	345	312	0	1,782	1,782
O'Connell River	49	615	566	0	2,260	2,260
Pioneer River	34	102 *	68	0	2,648	2,648
Plane Creek	34	1,110	1,076	0	3,329	3,329
REGIONAL TOTAL	150	2,172	2,022	0	10,019	10,019

Appendix B – PEST calibration approach

The process of coupling PEST and Source Catchments is presented in Figure 28. 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.

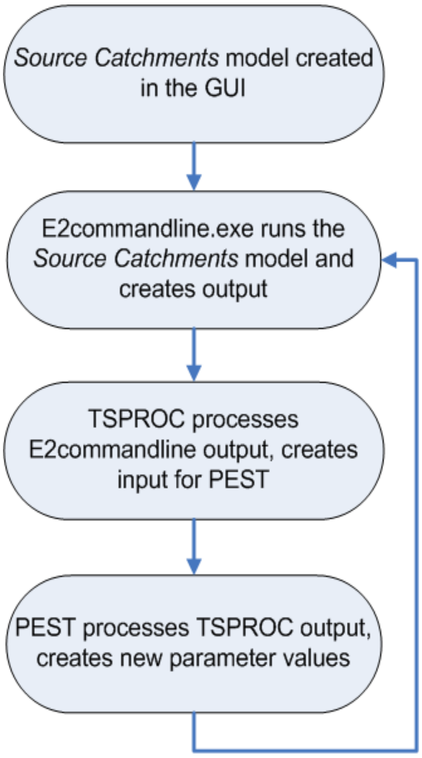

Figure 28 PEST – Source Catchments Interaction
(Stewart 2011)

A detailed description of the PEST set up and operation can be found in Doherty (2009). PEST operates largely via batch and instructional text files. The project team created a number of project specific tools to automate the compilation of these files, where possible. The TSPROC.exe (Time Series Processor) utility was also used to create the files used by PEST (the PEST control file), to manipulate the modelled time series and present the statistics to PEST for assessment (Stewart 2011). More information on TSPROC, see Doherty (2009). A three–part objective function was employed, using daily discharge, monthly volumes and exceedance times. All three objective functions were weighted equally. Regularisation was added prior to running PEST. This ensures numerical stability, by introducing extra information such as preferred parameter values, resulting from parameter non–uniqueness. Parameter non–uniqueness occurs when there is insufficient observation data to estimate unique values for all model parameters and is an issue in large models, such as those in the GBR (Stewart 2011).

The PEST 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. 150 super parameters were defined from the possible 874 parameters. The SVD–assist calibration was stopped once phi started to level out (Iteration 4). Due to IT limitations, 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 E2 commandline 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 29.

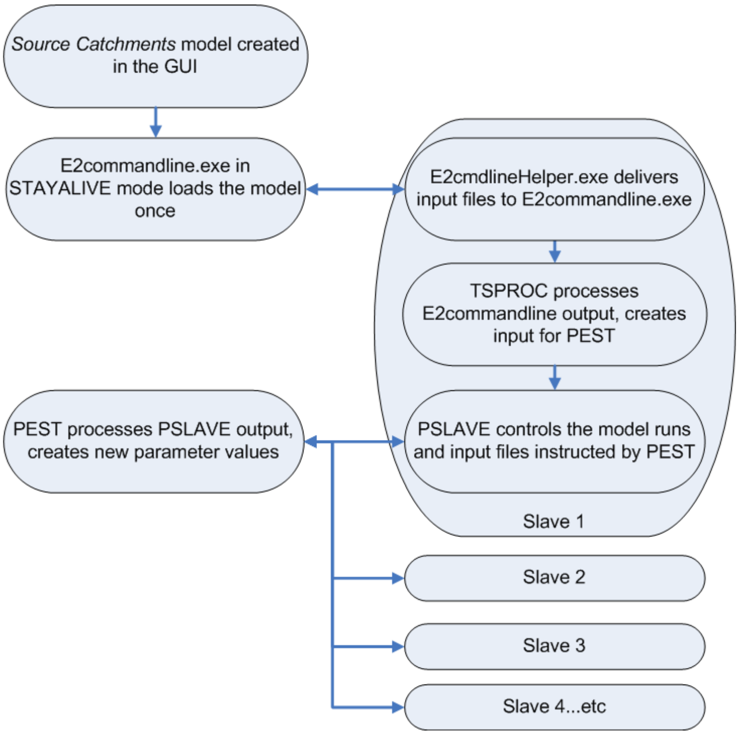

Figure 29 PEST operation
(Stewart 2011)

Appendix C – SIMHYD model structure and parameters for calibration

The reclassification of land uses (Fus) into three hydrological response units (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 26. The calibrated parameter values for three HRUs in 21 regions are provided in Table 27.

Table 26 Reclassification of FUs for hydrology calibration

Functional unit (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
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 seven MW calibration regions

Forest	**212**	**401**	**402**	**403**	**500**	**601**	**603**
BASE	0.24	0.06	0.06	0.02	0.22	0.45	0.22
INFC	189.89	163.85	600.00	255.07	353.66	209.31	600.00
INFS	10.00	1.49	7.82	1.26	4.33	4.39	9.85
INTE	0.00	0.50	0.16	0.48	0.47	0.23	0.06
RISC	8.55	8.93	1.02	4.05	4.31	2.30	5.08
RECH	0.01	0.30	0.80	0.06	0.27	0.10	0.58
SMSC	51.47	461.66	373.59	628.80	379.21	820.06	622.19
Grazing							
BASE	0.34	0.61	0.48	0.54	0.45	0.56	0.49
INFC	600.00	600.00	311.67	554.22	364.65	330.94	600.00
INFS	7.13	4.58	10.00	6.91	6.09	5.45	0.67
INTE	0.02	0.33	0.40	0.09	0.33	0.26	0.63
RISC	9.85	4.77	1.61	9.85	1.22	3.07	2.47
RECH	0.03	0.28	0.42	0.08	0.35	0.22	0.62
SMSC	209.39	94.04	122.20	339.25	27.99	83.86	131.64
Agriculture							
BASE	0.22	0.58	0.50	0.50	0.01	0.04	0.24
INFC	441.68	502.45	279.28	210.03	492.03	479.95	600.00
INFS	10.00	2.64	10.00	5.00	0.73	8.57	6.84
INTE	0.01	0.29	0.45	0.50	0.39	0.07	0.28
RISC	9.25	5.90	2.17	2.75	0.50	3.22	4.30
RECH	0.01	0.27	0.46	0.50	1.00	0.13	0.44
k	3,002	134,016	278,242	192,639	166,634	77,645	144,819
m	1.50	0.72	0.71	0.60	0.60	0.85	0.89

Appendix D – Pest Calibration Results

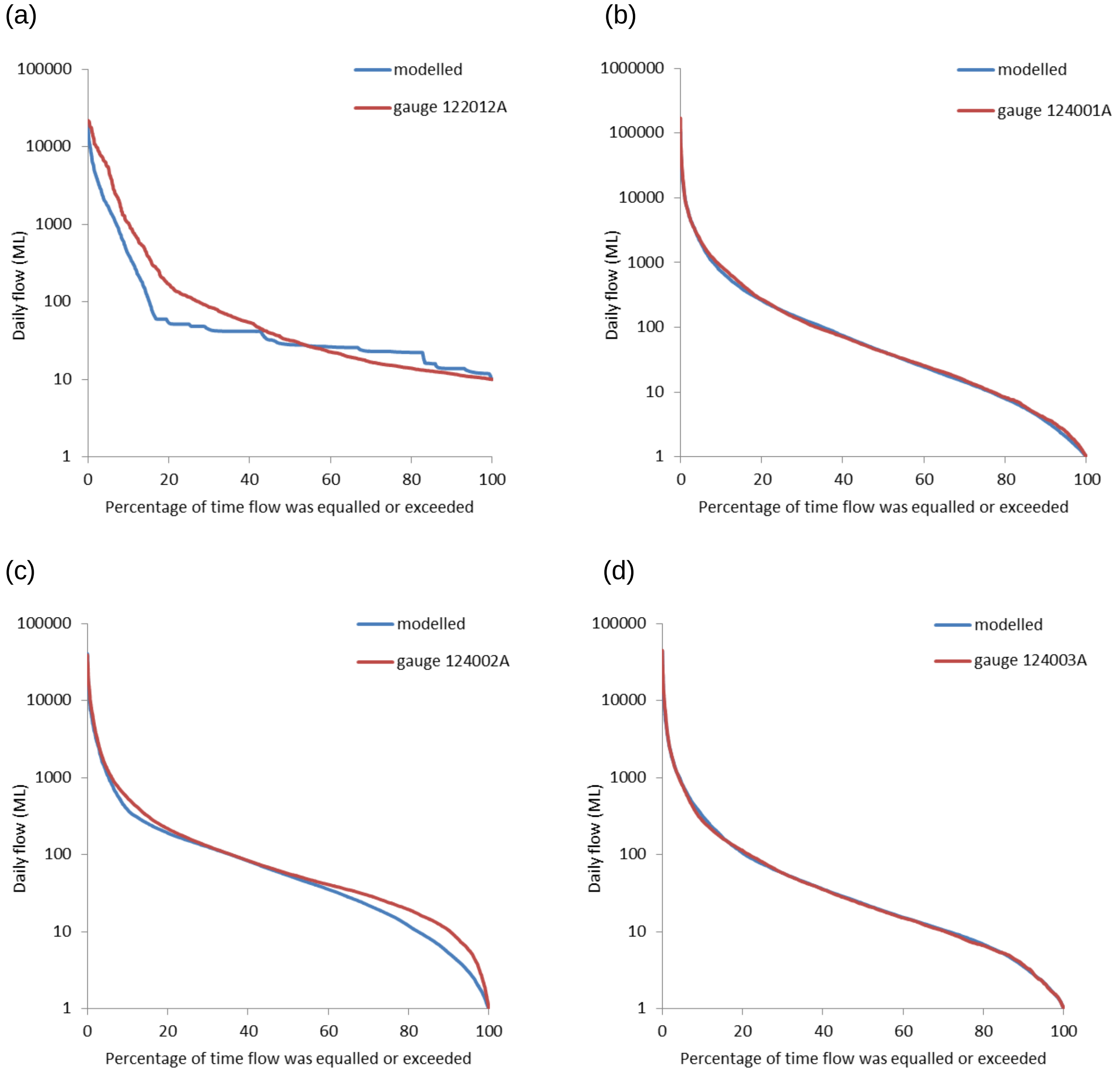

Figure 30 Flow duration curves of (a) 122012A, (b) 124001A, (c) 124002A and (d) 124003A

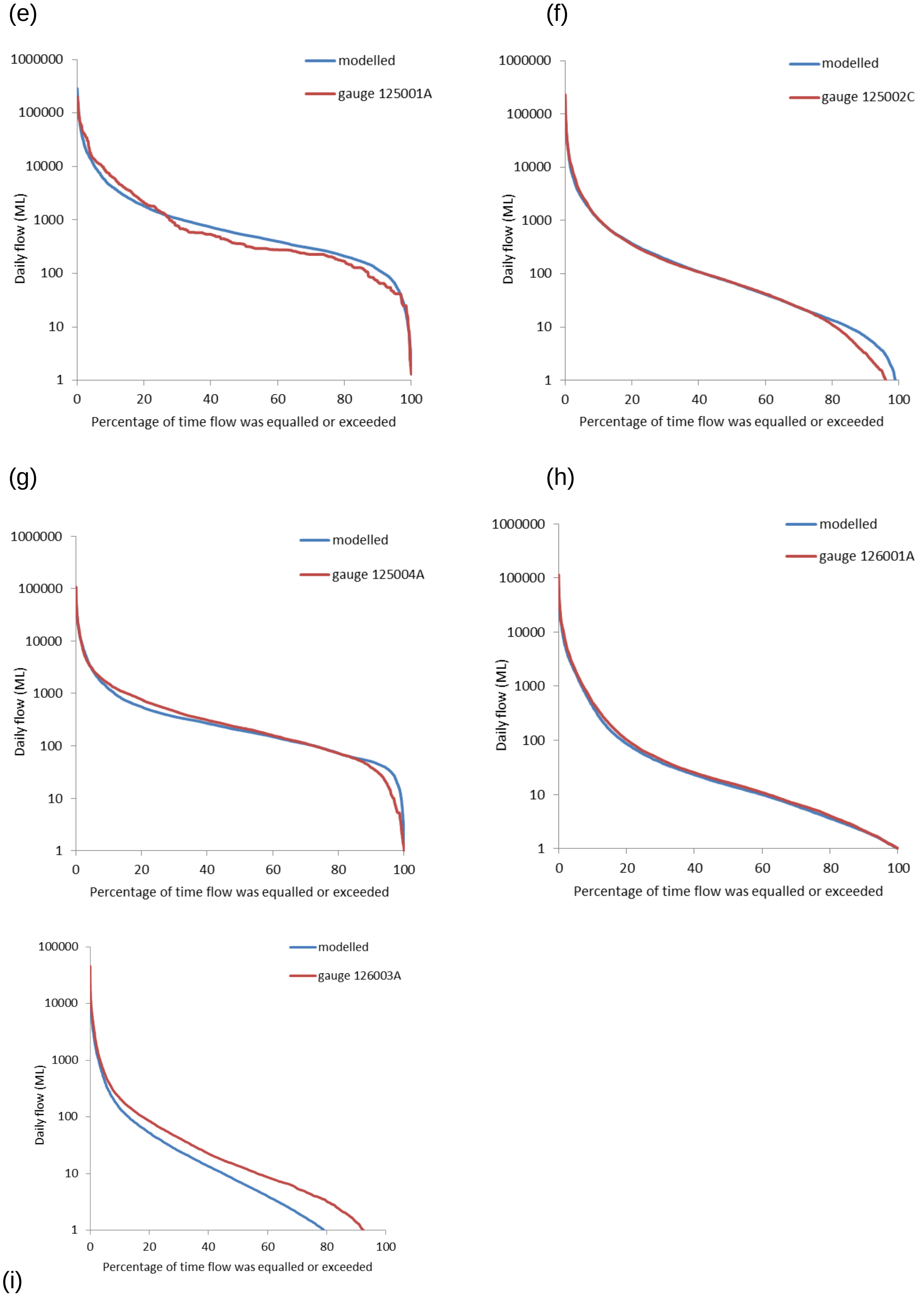

Figure 31 Flow duration curves for (e) 125001A, (f) 125002C, (g) 125004A, (h) 126001A and (i) 126003A

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 & 4/5 of the full Y extent of the area of interest. These are the Standard Parallel 1 and Standard Parallel 2 below.

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

Grazing constituent generation

Hillslope erosion

Table 29 Hillslope erosion parameters

Parameter	Value
TSS Delivery Ratio (DR) (%)	15
Coarse sediment DR (%)	0
Maximum quickflow concentration (mg/L)	10,000
DWC (mg/L)	100

Gully erosion

Table 30 Gully erosion parameters

Parameter	Value
Daily runoff power factor	1.4
Gully model type	DERM
TSS 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	1861
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)

FU	DIN EMC	DIN DWC	DON EMC	DON DWC	DIP EMC	DIP DWC	DOP EMC	DOP DWC	PN EMC	PN DWC	PP EMC	PP DWC
Sugarcane	APSIM	0.225	0.65	0.33	APSIM+HL	N/A	APSIM+HL	N/A		0.56		0.159
Cropping	0.45	0.225	0.65	0.33	HL	0.044	HL	0.008	Function of sediment	0.25	Function of sediment	0.191
Grazing	0.30	0.15	0.44	0.22	0.058	0.029	0.011	0.005		0.22		0.064

(HL) HowLeaky

Enrichment and delivery ratios (DRs) are required for nitrogen and phosphorus. The input parameter values used in the Mackay Whitsunday region are found in Table 32.

Table 32 Particulate nutrient generation parameter values

Parameter	Phosphorus	Nitrogen
Enrichment ratio	2	1.2
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 which was defined through a spatial intersection. A DERM Tools plugin linked the spatial intersection with databases of parameters to build HowLeaky simulations which could then be batch processed. The intersect shape file also contained information on clay percentage (derived from the ASRIS database) which was used to affect the delivery of fine sediment from the paddock to the stream. Time series files for each of the spatial and management combinations within each subcatchment were accumulated using spatial weighting to generate a single daily load per subcatchment. These time series files were then used as the input for the HowLeaky parameteriser in Source Catchments.

HowLeaky modelling was applied to cropping FUs including: 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 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
DR (%)	Dissolved nutrients	100
	Dissolved herbicides	50
	Particulates, sediment and particulate herbicides	20
Maximum slope (%)	sediment and particulates	8
Use Creams enrichment	Phosphorus	false
Particulate enrichment	Phosphorus	2
Particulate enrichment	Nitrogen	1.2
Gully DR (%)	Nitrogen and phosphorus	100

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

Parameter	Value
Clay (%)	22
Hillslope DR (%)	20
Maximum slope (%)	8
FU actually growing sugarcane (%)	90
Gully DR (%)	100
TSS DWC (mg/L)	136

EMC/DWC

Table 35 EMC/DWC values (mg/L)

Functional unit	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
Forestry	0.077	0.039	0.122	0.061	0.004	0.002	0.015	0.007	0.179	0.090	0.051	0.025	44	22
Conservation	0.058	0.029	0.092	0.046	0.003	0.002	0.011	0.005	0.134	0.067	0.038	0.019	33	16
Urban	0.386	0.193	0.611	0.306	0.021	0.010	0.073	0.036	0.895	0.448	0.255	0.127	218	109
Other	0.193	0.097	0.306	0.153	0.010	0.005	0.036	0.018	0.448	0.224	0.127	0.064	109	55

In–stream models

Streambank erosion

The *SedNet Stream Fine Sediment* model calculates a mean annual rate of fine streambank erosion in (t/yr) and there are several raster data layers and parameter values that populate this model. The same DEM used to generate subcatchments 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 MW 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 QLD Herbarium pre–clearing vegetation data and extracting the land zone 3 (alluvium) codes. The QLD 2007 Foliage Projective Cover (FPC) layer was used to represent the proportion of riparian vegetation. Riparian vegetation was clipped out using the buffered 100 m stream network raster. A value of 12% was used for the FPC threshold for riparian vegetation. A 20% canopy cover is equivalent to 12% riparian 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. 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 (Equation 10).

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

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

Variable bank height and width functions (Figures 32 and 33) 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, and channel height and upstream catchment area in the MW region. The equation was sourced from Wilkinson, Henderson & Chen (2004) where (Equation 11):

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

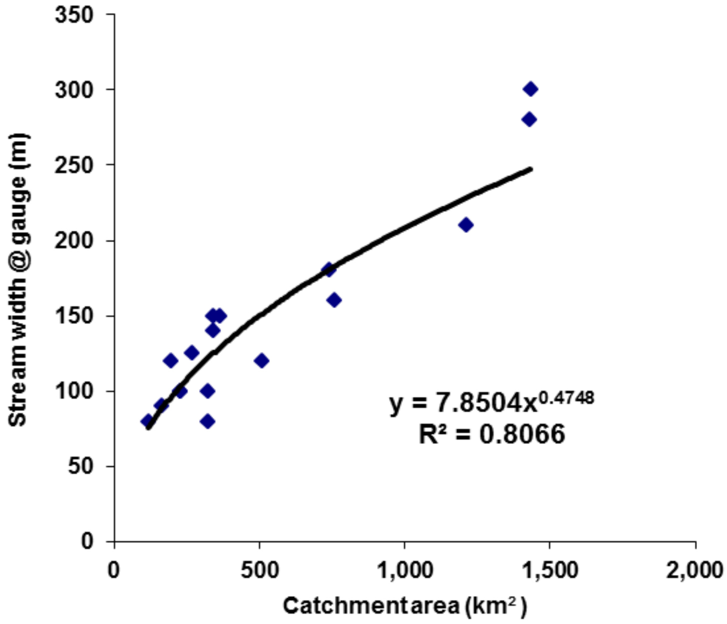

Figure 32 Catchment area and stream width used to determine variable streambank width parameters

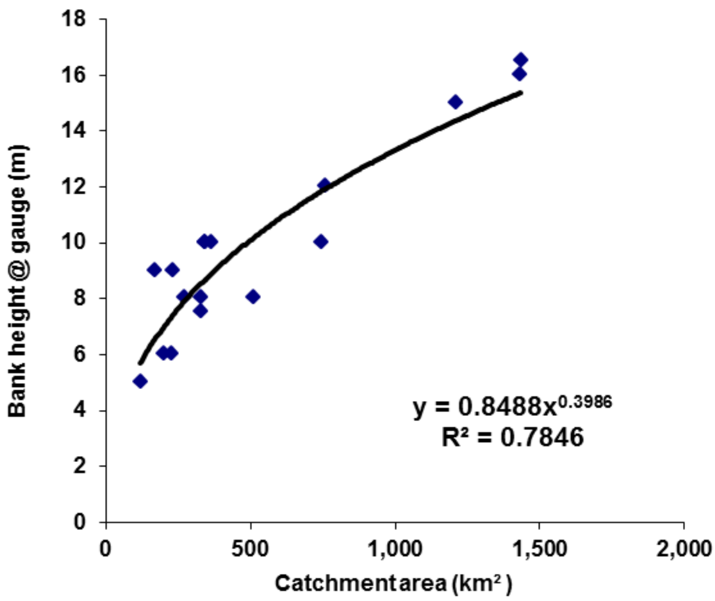

Figure 33 Catchment area and bank height used to determine variable streambank height parameters

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 MW are presented in Table 36.

Table 36 Streambank erosion parameters

Input parameters	Value
Bank Height Method: SedNet Variable – Node Based	
Proportion for TSS deposition	0.2
Catchment area exponent	0.3986
Catchment area coefficient	0.8488
Link Width Method: SedNet Variable – Node Based	
Minimum width (m)	10
Maximum width (m)	250
SedNet area exponent	0.4748
SedNet area coefficient	7.8504
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–life used in model

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 MW

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
Peter Faust Dam	585	583	553	3266	112	800	3.28	–0.2	False	False
Teemburra Dam	289	287	264	2414	112	800	3.28	–0.2	False	False

Management practice information

Table 39 Examples of improved management practices targeted through Reef Plan (including Reef Rescue) investments (McCosker pers.comm. 2014). Note: the list is not comprehensive.

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

Subsurface application of fertilisers	Changing from dropping fertiliser on the soil surface, to incorporating 10–15cm below the surface with non–aggressive narrow tillage equipment
Controlled traffic farming	Major farming system change. Changes required to achieve CTF include altering wheelbases on all farm machinery, wider row widths, re–tooling all implements to operate on wider row widths, use of GPS guidance
Nutrient management planning	Capacity building to improve skills in determining appropriate fertiliser rates
Recycling pits	Structure to capture irrigation runoff water on–farm. Also includes sufficient pumping capacity to allow timely reuse of this water, maintaining the pit at low storage level
Shielded/directed sprayers	Equipment that allows more targeted herbicide application. Critical in increasing the use of knockdown herbicides in preference to residual herbicides.
Reduced and/or zonal tillage	New or modified equipment that either reduces the frequency and aggressiveness of tillage and/or tills only a certain area of the paddock (e.g. only the portion of the row that is to be planted).
High–clearance boom sprays	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/h) within blocks or between blocks
Zero tillage planting equipment	Planting equipment for sugarcane and/or fallow crops that reduce or negate the need for tillage to prepare a seedbed.
Laser levelling	Associated with improvements in farm drainage and runoff control and with achieving improved irrigation efficiency.
Irrigation scheduling tools	Equipment and capacity building to optimise irrigation efficiency. Matching water applications to crop demand minimises potential for excess water to transport pollutants such as nutrients and pesticides.

Appendix F – Report Card 2013 modelling results

Table 40 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 (%)
Proserpine	29	66	2.3	37	63	9.1
O'Connell River	48	156	3.3	108	145	10.2
Pioneer River	40	203	5.0	163	195	4.9
Plane Creek	34	85	2.5	51	74	21.9
Regional total	**151**	**511**	**3.4**	**360**	**477**	**9.3**
TP (t/yr)	**Predevelopment load**	**Total baseline load**	**Increase factor**	**Anthropogenic baseline load**	**Report Card 2013 load**	**Load reduction (%)**
Proserpine River	44	90	2.0	46	82	18.3
O'Connell River	57	129	2.3	72	119	12.6
Pioneer River	38	115	3.1	77	111	5.2
Plane Creek	53	105	2.0	52	91	26.7
Regional total	**191**	**439**	**2.3**	**247**	**403**	**14.3**
PP (t/yr)	**Predevelopment load**	**Total baseline load**	**Increase factor**	**Anthropogenic baseline load**	**Report Card 2013 load**	**Load reduction (%)**
Proserpine River	28	44	1.5	16	42	14.1
O'Connell River	39	84	2.2	45	78	13.8
Pioneer River	27	93	3.4	66	90	4.8
Plane Creek	30	50	1.7	20	43	35.3
Regional total	**124**	**271**	**2.2**	**147**	**252**	**12.7**

DIP (t/yr)	Predevelopment load	Total baseline load	Increase factor	Anthropogenic baseline load	Report Card 2013 load	Load reduction (%)
Proserpine	12	36	2.9	24	31	20.6
O'Connell	14	35	2.5	21	33	10.5
Pioneer River	8	17	2.1	9	16	7.5
Plane Creek	18	44	2.5	26	38	21.6
Regional total	**52**	**132**	**2.5**	**80**	**119**	**16.9**
DOP (t/yr)	**Predevelopment load**	**Total baseline load**	**Increase factor**	**Anthropogenic baseline load**	**Report Card 2013 load**	**Load reduction (%)**
Proserpine	3	10	2.8	6	8	19.8
O'Connell	4	9	2.4	5	9	10.0
Pioneer River	2	5	2.0	2	4	7.5
Plane Creek	5	12	2.3	7	10	21.1
Regional total	**15**	**35**	**2.4**	**21**	**32**	**16.3**
TN (t/yr)	**Predevelopment load**	**Total baseline load**	**Increase factor**	**Anthropogenic baseline load**	**Report Card 2013 load**	**Load reduction (%)**
Proserpine	266	573	2.2	307	499	24.0
O'Connell	314	774	2.5	460	704	15.1
Pioneer River	202	686	3.4	484	653	6.9
Plane Creek	296	786	2.7	490	661	25.5
Regional total	**1,078**	**2,819**	**2.6**	**1,741**	**2,517**	**17.3**

PN (t/yr)	**Predevelopment load**	**Total baseline load**	**Increase factor**	**Anthropogenic baseline load**	**Report Card 2013 load**	**Load reduction (%)**
Proserpine	97	130	1.3	33	126	13.5
O'Connell	119	186	1.6	67	176	14.5
Pioneer River	90	298	3.3	208	291	3.7
Plane Creek	99	124	1.3	25	111	51.5
Regional	**406**	**739**	**1.8**	**333**	**704**	**10.5**
DIN (t/yr)	**Predevelopment load**	**Total baseline load**	**Increase factor**	**Anthropogenic baseline load**	**Report Card 2013 load**	**Load reduction (%)**
Proserpine	65	220	3.4	155	165	35.5
O'Connell	75	303	4.0	228	258	20.1
Pioneer River	45	222	4.9	177	199	12.7
Plane Creek	88	384	4.4	296	303	27.3
Regional	**273**	**1,129**	**4.1**	**856**	**925**	**23.8**
DON (t/yr)	**Predevelopment load**	**Total baseline load**	**Increase factor**	**Anthropogenic baseline load**	**Report Card 2013 load**	**Load reduction (%)**
Proserpine	104	223	2.1	119	208	12.0
O'Connell	119	284	2.4	165	270	8.5
Pioneer River	67	166	2.5	99	163	3.1
Plane Creek	109	278	2.6	169	247	18.4
Regional	**398**	**950**	**2.4**	**552**	**888**	**11.3**
PSII (kg/yr)	**Predevelopment load**	**Total baseline load**	**Increase factor**	**Anthropogenic baseline load**	**Report Card 2013 load**	**Load reduction (%)**
Proserpine		539		539	265	50.8
O'Connell		1027		1,027	636	38.1
Pioneer River		859		859	564	34.4
Plane Creek		1519		1,519	807	46.9
Regional		**3,944**		**3,944**	**2,272**	**42.4**

Appendix G – Report Card 2010 notes and results

The total baseline load figures changed since the production of Report Card 2010. The indirect effects of grazing management on gullies and streambanks are not considered in Report Card 2010. In Table 41 below the constituent loads for each scenario as part of Report Card 2010 are presented for reference. It is recommended that the Report Card 2012–Report Card 2013 total baseline values are used when referencing on Source Catchments loads.

Table 41 Report Card 2010 predevelopment, baseline and management change results
Note, these are different to Report Card 2012–Report Card 2013 total baseline loads which are the loads that should be cited when referencing this work

	TSS (kt/yr)	TN (t/yr)	DIN (t/yr)	DON (t/yr)	PN (t/yr)	TP (t/yr)	DIP (t/yr)	DOP (t/yr)	PP (t/yr)	PSII (kg/yr)
Predevelopment load	151	1,078	273	398	406	191	52	15	124	0
Total baseline load	514	2,916	901	1,314	701	544	227	59	258	2,045
Anthropogenic baseline load	363	1,838	627	916	295	353	175	44	134	2,045
Report Card 2010 load	504	2,839	835	1,314	690	539	227	59	253	1,669
Load reduction (%)	3.0	4.2	10.5	0.0	3.6	1.4	0.0	0.0	3.8	18.4

Appendix H – Report Card 2011 notes and results

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

- The indirect effects of grazing management on gullies and streambanks are also considered in Report Card 2011. This takes effect with regard to the gully management factor, and the streambank erosion coefficient, as described in the Methods section of this Report. This data was not available for Report Card 2010
- Between Report Card 2010 and Report Card 2011 model runs, the HowLeaky output time series for cropping land uses were also updated. The main difference between the runs was that the Report Card 2011 HowLeaky runs reverted to the curve number function algorithm from the old CREAMS modelling, and as such reduced the erosion/runoff potential

In Table 42 the Report Card 2011 predevelopment, baseline and management change loads are presented for reference. It is recommended that the Report Card 2013 baseline values are used when referencing this work, and not the values in the table below, due to the improvements to the model described above.

Table 42 Report Card 2011 predevelopment, baseline and management change results
Note, these are different to Report Card 2012–Report Card 2013 total baseline loads which are the loads that should be cited when referencing this work

	TSS (kt/yr)	TN (t/yr)	DIN (t/yr)	DON (t/yr)	PN (t/yr)	TP (t/yr)	DIP (t/yr)	DOP (t/yr)	PP (t/yr)	PSII (kg/yr)
Predevelopment load	151	1,078	273	398	406	191	52	15	124	0
Total baseline load	517	2,855	921	1,230	704	502	192	50	260	2,495
Anthropogenic baseline load	366	1,778	648	832	298	311	140	36	135	2,495
Report Card 2011 load	497	2,627	820	1,123	684	465	170	45	251	1,732
Load reduction (%)	5.6	12.8	15.6	12.9	6.7	11.8	16.1	15.8	6.2	30.6

Appendix I – Report Card 2012 notes and results

Report Card 2012 results are given in Table 43. Total baseline load numbers changed between Report Card 2011 and Report Card 2012 with minor decreases in TSS, TN, TP, DIP, DOP and DON. The decreases are due to modifications in the baseline model and re–parameterisation processes. Increases in the total baseline load between Report Card 2011 and Report Card 2012 in other constituents were primarily due to a hydrological time series error for sugarcane land use which was discovered after Report Card 2011 was published. The most noticeable increase in load was for PSIIs and to a lesser extent for DIN. This error did not affect the reduction percentages due to management change, therefore, while the modelled constituent loads for Report Card 2010 and Report Card 2011 were substantially lower than Report Card 2012–Report Card 2013, the percent reductions in modelled exports are valid in a relative sense.

Table 43 Report Card 2012 predevelopment, baseline and management change results

	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)**
Predevelopment load	151	1,078	273	398	406	191	52	15	124	0
Total baseline load	511	2,819	1,129	950	739	439	132	35	271	3,944
Anthropogenic baseline load	360	1,741	856	552	333	247	80	21	147	3,944
Report Card 2012 load	487	2,554	950	892	713	408	120	32	256	2,498
Load reduction (%)	6.7	15.2	21.0	10.6	8.0	12.5	15.6	15.0	10.5	36.7