Great Barrier Reef WaterCAST Application Project: Stage 1

Carroll C, Ellis R, Hateley L, Fentie B, Rohde K, Waters D
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Executive Summary

The Great Barrier Reef World Heritage Area is an area of both national and international significance, with outstanding natural, social and economic values. Over the past 150 years reef catchments have been extensively modified leading to a decline in water quality entering the GBR lagoon. A joint Queensland and Australian government initiative has responded to these water quality concerns and threats with the production of the Reef Water Quality Protection Plan.

An aim of the eWater CRC Application Projects is better develop and apply products to real world scenarios and problems. The GBR eWater Application Project provided an opportunity to:

- Undertake hydrology and Water Quality Modelling in selected reef catchments to inform WQ monitoring.
- Quantify the uncertainty in modelled runoff and pollutant loads and parameter uncertainty, focussing on the Fitzroy basin, and
- Communicate current and emerging modelling tools to support delivery of the Reef Water Quality Protection Plan.

The Barron, Burdekin, Fitzroy, and Pioneer were the four reef catchments where WaterCAST was applied.

Although key land uses generating constituent loads were identified in each of the four catchments it was acknowledged there is still uncertainty on the spatial and temporal contribution of erosion processes, both sources and sinks; particularly in the larger reef catchments such as the Burdekin and Fitzroy.

In addition sediment and nutrient transmission losses and nutrient decay within stream are required to support future model predictions. Importantly, in all catchments monitoring the presence of herbicides continue to emerge as constituents of concern that are not currently being modelled by WaterCAST.

Calibration of model parameters was undertaken within the WaterCAST framework, rather than in a secondary environment like the Rainfall Runoff Library. The calibration was able to consider all internal interactions and resulted in an improved statistical fit. Calibrating parameters in such a way currently requires the use of optimisation software, such as PEST. Using PEST has also allowed a quantifiable assessment of parameter and prediction uncertainty.
1 Introduction

The Great Barrier Reef World Heritage Area is an area of both national and international significance, with outstanding natural, social and economic values. Over the past 150 years reef catchments have been extensively modified leading to a decline in water quality entering the GBR. The health of the Great Barrier Reef is a concern with the degradation of coral reefs attributed to elevated levels of sediment, nutrients and pesticides entering the reef lagoon from adjacent coastal catchments (Brodie et al. 2008).

In 2003 a joint Queensland and Australian government initiative has responded to these water quality concerns and threats with the production of the Reef Water Quality Protection Plan (RWQPP). The RWQPP has since been updated in 2009, however the main goals remain to halt and reverse the decline in water quality entering the reef, with the specific objectives to:

- Reduce the load of pollutants from diffuse sources in the water entering the Reef.
- Rehabilitate and conserve areas of the Reef catchment that have a role in removing water borne pollutants.

A reef catchment water quality monitoring program (Action I5) commenced in 2004. In a review Grayson (2007) stated that an integrated use of monitoring and modelling 'is the only way to establish loads and trends and begin to assess the impacts of management actions at the scales required for the GBR'. Grayson also recognised that while the use of modelling to inform expectations in trends and load estimation is a powerful approach, 'the associated uncertainty must be conveyed to all users'.

Previous modelling for high priority GBR catchments had been undertaken using the SedNet and ANNEX models (Cogle, Carroll, Sherman 2006). In Stage 1 (2007-2009) the GBR Application Project aimed to apply and test the E2 framework in 4 GBR catchments: Barron, Burdekin, Fitzroy, and Pioneer.

Three main activities were:

- Hydrology and Water Quality Modelling to inform WQ monitoring.
- Quantify the uncertainty in modelled runoff and pollutant loads and parameter uncertainty in the Fitzroy.
- Communication of current and emerging modelling tools to support delivery of the Reef Water Quality Protection Plan.

Stage 2 commenced in January 2010 and is a significant expansion on the work started in Stage 1. Stage 2 will include the modelling of all catchments in the GBR using Source Catchments as a requirement of state and federal government reef reporting. Detailed reporting of Stage 2 will be provided in 2011.

2 Outcomes

2.1 Hydrology and water quality modeling to inform WQ monitoring.

Following WaterCAST modelling (Appendix 1) and along with other modelling sources, a series of questions were addressed to inform the water quality monitoring in the four GBR catchments (Appendix 2). The questions were:

1. What land use, management systems are generating the highest end of system runoff and constituent loads (identify key constituents & catchments)?
2. What are the dominant erosion processes occurring in the catchments, sub-catchments?

3. Based on the modeling, and monitoring, what locations would you recommend further loads WQ monitoring is undertaken?

4. What would be the highest priority catchments for I5 to monitor? Why?

Although key land uses generating constituent loads were identified in each of the four catchments there is still uncertainty on the spatial and temporal contribution of erosion processes, both sources and sinks; particularly in the larger reef catchments such as the Burdekin and Fitzroy. In the Barron cropping is estimated to have a TSS aerial delivery ratio (ADR) of 2 (% of load delivered by land use to the GBR, divided by the % of catchment occupied by the land use). Thus, cropping contributes twice as much TSS as you would expect from the area of land; whereas, sugar cane has an ADR of 1.6. Coastal sub-catchments of Barron and Trinity have high TSS, TN and TP but there is no monitoring below the final gauging station monitoring point. The Barron catchment is seen as a priority monitoring site to support water quality modelling, along with Mareeba and Myola gauging stations.

In the Fitzroy basin the Connors/Isaac and the Mackenzie sub-catchments were seen as high priority areas for water quality monitoring, and further gully erosion monitoring. A measure of soil erodibility in the Clarke Connors range would be valuable in validating the modelled sediment loads that have been previously derived via SedNet.

In the Pioneer sugar cane is the major land use that contributes DIN and DIP nutrients to the reef. In the Mackay region the Pioneer and Sandy creek catchments have the largest area of sugar cane along with flow gauging stations, hence should be a priority monitoring site to build on existing water quality data.

In addition sediment tracing analysis would be useful to identify and help verify relative contributions of erosion processes; hill, gully, streambank, particularly in the basins with extensive grazing. In addition sediment and nutrient transmission losses and nutrient decay within stream are required to support future model predictions. Importantly, in all catchments monitoring the presence of herbicides continue to emerge as constituents of concern that are not currently being modelled by WaterCAST.

2.2 Quantify the uncertainty in modelled runoff and pollutant loads and parameter uncertainty in the Fitzroy (Ellis et al. 2009)

To investigate hydrologic parameter estimation and uncertainty the Fitzroy River Catchment was represented in a WaterCAST scenario by 396 subcatchments (figure 1). These sub-catchments were the result of an automated WaterCAST DEM process, with additional sub-catchments placed to allow representation of major water storages within the stream network. Each sub-catchment had 7 ‘Functional Units’ nominally assigned based on land use. Each functional unit instance was assigned a SIMHYD rainfall-runoff model, each link in the node-link network was assigned a Laurenson non-linear flow routing model, except for 12 links where a water storage model was applied. A calibration period from 1st January 1985 to 31st December 2005 was selected. Climate inputs for rainfall-runoff models were sourced from the SILO Data Drill.

For constituent generation (total suspended solids – TSS) parameter estimation and uncertainty analysis, a smaller region within the Fitzroy Catchment was studied. This 40,000 km² ‘Beckers’ area comprises most of the Dawson River Valley (figure 1), and is represented in the WaterCAST project by 119 subcatchments. A calibration period from 1st January 1986 to 31st December 2005 was selected.
2.2.1 Calibration approach
The study area was broken into 20 calibration ‘regions’ according to the subcatchments contributing to the 20 gauging stations with daily flow observations (figure 1). Throughout these regions the WaterCAST entities of subcatchments, functional units, links and nodes continued to operate as discrete units, however models belonging to similar ‘types’ were grouped for calibration using PEST (Parameter ESTimation), a model independent suite of parameter estimation and uncertainty analysis tools. This method of parsimony implies uniformity within, but not between, calibration regions. Each SIMHYD model presented to PEST had 7 parameters available for adjustment. Each Laurenson non-linear flow routing model had 2 parameters available for adjustment. Parameter ranges were limited to those recommended in the relevant user guides.

PEST utility was used to compare modelled flow outputs with observed data in a 60-part multi-component objective function. This objective function was comprised of the weighted, sum of squared residuals for daily flows, daily ‘baseflows’, and monthly volume accumulations at each calibration gauging station. The combination of various flow ‘functions’ in an objective function was shown to give satisfying ‘fits’ in small scale trials.

2.2.2 Flow predictions
Statistically the ‘calibrated’ hydrology parameter set yields flow predictions that provide a good match between observed and modelled flows at 20 locations throughout the catchment. The PEST derived calibration parameter set was able to consider all model interactions and individual climate inputs throughout the 20 regions simultaneously, which is an advantage over most other calibration methods.
Also of importance to modellers is the visual ‘fit’ when predicted flows are shown with observed. Figure 2 illustrates a visual comparison for the PEST derived calibration.

![Graph showing comparison of predicted daily flow with observed daily flow at gauging station 130003AB for 1998 – 2001.]

Figure 2. Comparison of predicted daily flow with observed daily flow at gauging station 130003AB for 1998 – 2001.

PEST utilities were then used to produce 50 alternative parameter sets that satisfied the statistical requirements of the calibration objective function. These 50 ‘realisations’ of calibrated parameter sets can be used to provide a quantitative assessment of uncertainty around parameter values and the resulting model predictions. Figure 3 shows this analysis graphically for the ranges of 2 SIMHYD parameters, figure 4 shows the range of model predictions of stream flow for a selected event.
Figure 3. Frequency histograms representing the range of values for individual parameters within 50 calibrated realisations of parameter sets, categories that include the parameter value from the initial regularised calibration have a darker shading. Parameters represented range from a ‘high’ objective function sensitivity (A) to low objective function sensitivity (B).

Figure 4. Model predicted daily flow (and observed daily flow) for gauge 130003AB for the period March – July 1990, including predictions from 50 calibrated parameter set.
For generation of TSS using the EMC/DWC model in the Dawson Valley project area, PEST was used to produce 133 ‘realisations’ of EMC/DWC parameter values that satisfied the objective function achieved during calibration, each realisation retaining the user defined ratios of parameter values between Functional Units. Figure 5 shows the results of this analysis for a selected period.

![Figure 5: Daily model predictions of TSS concentration at gauge 130324A between November 1995 and March 1996. Model predictions are made from the calibrated parameter set and 133 random parameter sets that also satisfy the calibration objective function.](image)

2.2.3 Outcomes

By calibrating model parameters within the WaterCAST environment, rather than in a secondary environment like the Rainfall Runoff Library, the calibration was able to consider all internal interactions. This has resulted in a statistical fit that is a clear improvement. Calibrating parameters in such a way currently requires the use of optimisation software, such as PEST. Using PEST has also allowed a quantifiable assessment of parameter and prediction uncertainty.

2.3 Communication of current and emerging modelling tools to support delivery of the Reef Water Quality Protection Plan.

In February 2009 regional visits were undertaken to Reef Natural Resource Management groups to provide an overview on the WaterCAST modelling framework and associated uncertainty analysis approach using PEST.

In addition a workshop on ‘Calibration and Predictive Uncertainty Analysis of WaterCAST Models using PEST’ was conducted for Queensland eWater CRC stakeholders in March 2009. Participants were invited to bring their own WaterCAST projects for analysis and discussion, along with any observation data they had to use for calibration, or any other data that may help to communicate the composition and structure of their scenario. The workshop covered: traditional parameter estimation, demonstration & implementation of PEST, WaterCAST as a command line program, regionalisation of model parameters, classical approach to parameter estimation,
calibration of surface water models, traditional uncertainty analysis, highly parameterised analysis along with hands WaterCAS/PEST command line exercises.

3 Conclusions

The GBR Application Project successfully applied the WaterCAST modeling framework in four reef catchments; Barron, Burdekin, Pioneer and Fitzroy. The WaterCAST modeling along with previous SedNet/Annex modeling was able to inform the catchment monitoring program on prioritizing critical water quality monitoring sites. An approach to quantify modeling uncertainty using the Parameter ESTimation tool with WaterCAST was demonstrated to both Regional Natural Resource Management groups and Queensland eWater CRC stakeholders, with training supplied to key stakeholder users.

Although challenges remain to timely and efficiently run WaterCAST and PEST on large reef catchments it has now been adopted to report on water quality targets outlined in the 2009 Water Quality Improvement Plan.
References


APPENDIX 1: Outline of WatCAST Modelling

Barron – Louise Hateley

- WaterCAST modelling was conducted on the Barron River catchment (2,138 km²), Trinity Inlet (340 km², including Cairns city, part of the Mulgrave River catchment), and the Northern Beaches of Cairns (92 km², part of the Mossman River catchment). The Barron River has the largest discharge and is sourced from small, forested, freshwater tributaries on the Atherton Tablelands. Small creeks drain the Northern Beaches and Trinity Inlet sub-catchments.

- Twenty three sub-catchments were generated based on 25 m, hydrologically correct Digital Elevation Model (DEM), location of gauging stations and water quality monitoring sites.
- Eleven Function Units (FU’s) were used, comprising 10 for land use and 1 for point sources to represent the 8 sewage treatment plants.
- The Sacramento rainfall runoff model was chosen to generate the sub-catchment runoff generation component of the WaterCAST model. It relates runoff to rainfall with daily data using soil moisture accounting to simulate the water balance. Sacramento parameters have been obtained by calibrating observed rainfall, PET and runoff using the eWater CRC’s Rainfall Runoff Library (RRL). Seven of the 31 stream gauges were suitable for calibration using the Sacramento model.
- The Event Mean Concentration (EMC), Dry Weather Concentration (DWC) model was chosen to generate the constituent component. The water quality constituents or pollutants chosen for this project are Total Suspended Solids (TSS), Total Nitrogen (TN) and Total Phosphorus (TP). Sediment and nutrient generation is based on the application of EMC) and DWC for each constituent and FU. EMC is typically much higher than the DWC as run-off volumes are greater during events and therefore the constituent loads transported by surface run-off are higher than the loads transported by sub-surface flow during ambient conditions.
- Over the long term, the hydrology of the catchment is well represented. Predicted volumes were within 10% of the observed volumes at 7 gauges used for hydrologic calibration, as well as at 6 regulated gauges (not used for calibration).
- Predicted loads were similar (105-139%) to long term average annual loads of TSS, TN and TP. For intensively monitored events over 3 years, predicted volumes were usually higher than observed volumes (140% to 260% of observed). Predicted loads were also higher than observed loads for TSS (130%), TN (220%) and TP (170%).
- High predicted areal loading ratios are Cropping (TSS and TN), Sugarcane (TN) and Urban (TN and TP). These are recommended priorities for further research and extension, including more intensive water quality monitoring.
Burdekin - Bantie Fentie
- As shown in figure below, a WaterCAST project of the catchment with 55 subcatchments (total area of 128,606 km²) using the 2004 land use map of the catchment has been developed.

- The SIMHYD rainfall-runoff model was calibrated in Rainfall Runoff Library (RRL) and historical flow data monitored at a number of gauging stations in the catchment. However, this is now being revised due to uncertainty about the optimality of the first calibration.
- Event Mean Concentration (EMC) and Dry Weather Concentration (DWC) values for TSS, TN and TP have been estimated from monitoring data and entered in the model. However, these are being revised using a novel approach of estimating land-use-specific EMC and DWC values.
- The original EMC and DWC values in the model have been scaled against erosion hazard indices. This scaling will be re-done once the revised EMC and DWC values have been estimated and entered into the model.
- A storage model of the Burdekin Falls Dam is being developed.

Pioneer – Ken Rohde
- Base scenario was developed to estimate average annual sediment and nutrient loads from 1960 to 2006. Existing water quality monitoring data was used to populate and calibrate.
- The Pioneer catchment is 1500 km²
- Sixty one sub-catchments were created, with a 25 km² stream threshold used.

- The SIMHYD rainfall runoff model was chosen to generate the sub-catchment runoff.
- Nine FU's were used.
- Four storages were included, 1 dam and 3 in-stream weirs.
• The EMC/DWC model was chosen to generate the constituent component of the E2 model. The water quality constituents or pollutants chosen for this project were Total Suspended Solids (TSS), Total Nitrogen (TN) and Total Phosphorus (TP). Sediment and nutrient generation is based on the application of Event Mean Concentrations (EMC) and Dry Weather Concentrations (DWC) for each constituent and FU. (this will be completed in next iteration of Source Catchments)
• SILO gridded daily rainfall data was used with PET derived from NLWRA national monthly maps

Fitzroy – Rob Ellis
• WaterCAST was conducted on Fitzroy River catchment (142,000 km²).
• 396 subcatchments were generated.
• Each subcatchment has 7 Functional Units (FU’s) based on land use.
• Each FU instance was assigned a SIMHYD rainfall-runoff model, each link in the node-link network was assigned a Laurenson non-linear routing model, with 12 links representing water storages.
• An Event Mean Concentration/Dry Weather Concentration EMC/DWC model was applied to each FU to generate sediment from each subcatchment. The EMC/DWC values used were sourced from a calibration project in Dawson Valley sub-region of the Fitzroy catchment.
• The study area was broken into 20 calibration ‘regions’ according to the subcatchments contributing to the 20 gauging stations with daily flow observations (figure 1). Throughout these regions the WaterCAST entities of subcatchments, functional units, links and nodes continued to operate as discrete units, however models belonging to similar ‘types’ were grouped for PEST assessment.
• Observed daily flow totals were extracted from NR&W’s corporate database environment ‘Hydstra Surface Water Database’. A baseflow separation algorithm was applied to the observed daily flow, with the resulting baseflow ‘observations’ also used in calibration.
• A PEST utility program, Time Series Processor (TSPROC), was used as a post-model processor to compare modelled flow outputs with observed data in a 60-part multi-component objective function.
• This objective function was comprised of the weighted, sum of squared residuals for daily flows, daily baseflows’, and monthly volume accumulations at each calibration gauging station. The combination of various flow ‘functions’ in an objective function was shown to give satisfying ‘fits’ in small scale trials, and may also help to avoid the optimisation problem of ‘local minima’.
• Statistically the ‘calibrated’ parameter set yields flow predictions that provide a good match between observed and modelled flows at 20 locations throughout the catchment. The parameter sets from the RRL made use of a variety of optimisation techniques, and considered daily flow and total volume components, however the RRL environment can not account for the effects of flow routing and water storages. The PEST derived calibration parameter set was able to consider all of these interactions throughout the 20 regions simultaneously.
• By calibrating model parameters within the WaterCAST environment, rather than in a secondary environment like the Rainfall Runoff Library, the calibration was able to consider all internal interactions.
• Applying PEST (Parameter ESTimation) to improve parameter estimation and uncertainty analysis in WaterCAST models, this has resulted in a statistical fit that is a clear improvement.
• This uncertainty analysis technique introduces a degree of subjectivity into the process. The modeller must supply estimates of likely parameter distributions prior to the production of random parameter sets. Despite these subjectivities and
simplifications, the resulting uncertainty analysis is transparent, quantifiable, readily communicable and applicable at the scale at which this type of water quality model informs land management decisions.
### Appendix 2

**Questions addressed to inform water quality monitoring in Barron, Burdekin, Pioneer and Burdekin catchments.**

<table>
<thead>
<tr>
<th>Questions</th>
<th>Barron</th>
<th>Burdekin</th>
<th>Pioneer</th>
<th>Fitzroy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. What land use, management systems are generating the highest end of system runoff and constituent loads (identify key constituents &amp; catchments)?</td>
<td>Cropping high ADR² of 2 for TSS, Sugar high ADR of 1.6 for TN, Urban high ADR of 2 for TN. Coastal sub-catchments of Barron and Trinity have high TSS, TN and TP but no gauging as below EOS monitoring. Pesticides continue to emerge as a concern – and need to be included?</td>
<td>TSS (total): Native Pastures, Forest and other reserves, Cropping, Improved Pastures, Sugarcane. <strong>TSS per unit area:</strong> Cropping, Native Pastures, Improved Pastures, Sugarcane, Forest and other reserves. <strong>Source:</strong> (Roth et al., 2003)</td>
<td>Sugar cane – dissolved nutrients and herbicides</td>
<td>Dryland cropping – EMC Grazing – TSS loads. Connors catchment in Isaacs sub-basin lowest TSS EMC and highest flows.</td>
</tr>
<tr>
<td>2. What are dominant erosion processes occurring in the catchments, sub-catchments?</td>
<td>Mareeba subcatchment to validate model output highlighting cropping in this sub-catchment.</td>
<td>Hillside (38%) Gully (39%) Streambank (23%)</td>
<td>Hillside</td>
<td>Hillside (67%) Gully (26%) Stream bank (7%)</td>
</tr>
<tr>
<td>3. Based on your modelling, and monitoring, what locations would you recommend further loads WQ monitoring is undertaken?</td>
<td>Continuation of Mareeba and Myola, consideration of Cairns coastal plain gauging/monitoring to evaluate model outputs and urban contribution.</td>
<td>EMC/DWC based WQ modelling, monitoring at the outlet of dominant land use sub-catchments based on the contributions. A nested catchment approach to monitoring could benefit from information given in response to questions 1 and 2 above.</td>
<td>Pioneer @ Dumbleton (existing site) Sandy Creek @ Homebush (new site) O’Connell @ Caravan Park (existing site)</td>
<td>Continuation of Gordonstone Creek, and Spottsworth Creek cascading monitoring sites to inform sediment and nutrient delivery ratios.</td>
</tr>
<tr>
<td>4. What would be the highest priority catchments for I5 to monitor? Why?</td>
<td>Barron is important to support WQIP.</td>
<td>See response to Question 3 above.</td>
<td>Pioneer/Sandy - largest cane catchments, current flow gauging stations have relatively good existing WQ datasets. O’Connell – no gauging station and difficult to sample. Lower priority.</td>
<td>Major basin and individual sub-basins.</td>
</tr>
</tbody>
</table>

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² ADR: Annual Runoff Factor