Review and gap analysis of receiving-water water quality modelling in the Great Barrier Reef

Ian T Webster, Richard Brinkman, John S Parslow, Joelle Prange, Andy DL Steven, Jane Waterhouse

15 January 2008

Report to Department of Environment, Water, Heritage and the Arts
Copyright and Disclaimer

© 2007 CSIRO To the extent permitted by law, all rights are reserved and no part of this publication covered by copyright may be reproduced or copied in any form or by any means except with the written permission of CSIRO.

Important Disclaimer

CSIRO advises that the information contained in this publication comprises general statements based on scientific research. The reader is advised and needs to be aware that such information may be incomplete or unable to be used in any specific situation. No reliance or actions must therefore be made on that information without seeking prior expert professional, scientific and technical advice. To the extent permitted by law, CSIRO (including its employees and consultants) excludes all liability to any person for any consequences, including but not limited to all losses, damages, costs, expenses and any other compensation, arising directly or indirectly from using this publication (in part or in whole) and any information or material contained in it.

Cover Photograph

The cover photograph is provided courtesy of the Great Barrier Reef Marine Park Authority.
CONTENTS

LIST OF TABLES ................................................................................................................................. IV

LIST OF FIGURES ............................................................................................................................... IV

ACKNOWLEDGEMENTS .......................................................................................................................... V

EXECUTIVE SUMMARY ........................................................................................................................ VI

1 INTRODUCTION ..................................................................................................................................... 1
  1.1 The development of ReefPlan and WQIPs ....................................................................................... 1
  1.2 The potential role of models in WQIP development and assessment ............................................. 3
  1.3 Status of WQIPs and receiving water objectives .......................................................................... 5
  1.4 Report strategy and outline ........................................................................................................... 6

2 CONCEPTUAL MODELS ...................................................................................................................... 8
  2.1 Catchment Loads .......................................................................................................................... 8
  2.2 Material transport and transformation in the marine environment ............................................... 9
  2.3 Ecological Response ................................................................................................................... 20

3 MODELLING FRAMEWORKS TO SUPPORT MANAGEMENT ........................................................ 23
  3.1 The role of models ....................................................................................................................... 23
  3.2 The model framework ................................................................................................................ 25
  3.3 Large-Scale Water Quality model ............................................................................................... 27
  3.4 Ecological model ......................................................................................................................... 34
  3.5 Fine-scale impact models ............................................................................................................. 36

4 REVIEW OF EXISTING MODELS ...................................................................................................... 38
  4.1 Material transport models .......................................................................................................... 38
8.7 Observations and data needs ........................................................................... 68
8.8 Modelling strategy ......................................................................................... 69

9 REFERENCES .................................................................................................... 70

APPENDIX A ........................................................................................................ 74
APPENDIX B ........................................................................................................ 87
APPENDIX C ........................................................................................................ 114
APPENDIX D ........................................................................................................ 132
GLOSSARY .......................................................................................................... 136
List of Tables

Table 1.1 Priority catchments identified across regions.................................................... 2
Table 3.1 Essential processes and features for hydrodynamic model............................ 29
Table 3.2 Essential processes and features for sediment transport model. ................... 30
Table 3.3 Essential processes and features for biogeochemical model. ........................ 31
Table 3.4 Essential processes and features for ecological model. ................................. 35
Table 6.2 Human resource requirements for the development and application of the receiving waters model framework................................................................. 56

List of Figures

Figure 1.1 Conceptual linkages between management action targets and targets/objectives for receiving waters water quality and ecosystem health.................. 3
Figure 2.1 Spatial scales considered under the receiving water model review: a) whole of GBR showing wet and dry catchments; b) catchment to reef scale; and c) estuary scale. ................................................................................................. 10
Figure 2.2 Remote sensing images of the northeast coast of Queensland showing the Great Barrier Reef and river plumes following large rainfall events. Insets show flood plumes from: a) the Normanby River; b) the Tully and Herbert Rivers; and c) the Burdekin River.............................................................................................................11
Figure 2.3 Schematic of large-scale circulation in GBR Lagoon and Coral Sea............ 12
Figure 2.4 Mixing and exchange processes across the GBR Lagoon. .......................... 12
Figure 2.5 Sediment dynamics from catchment to reef in the Great Barrier Reef ....... 13
Figure 2.6 Flood plume excursion across the GBR Lagoon showing sediment dynamics. ......................................................................................................................... 14
Figure 2.7 Catchment to reef nutrient processes in the GBR. ........................................ 16
Figure 2.8 Transformation and fate of pesticides in the receiving waters of the GBR. ... 19
Figure 2.9 Conceptual diagram of the impacts of sediment, nutrients and pesticides on key GBR ecosystems (coral reefs and seagrass meadows)................................. 20
Figure 3.1 Model framework suggested for supporting assessment and scenario testing for the WQIPs. For simplicity, forcing and assessment models are not shown. .......... 26
Figure 3.2 Model elements of Large-Scale Water Quality model (inside box) showing internal linkages between elements and linkage to models of ecological impacts..... 28
Figure 5.1 Schematic of sediment delivery to a SedNet link (Courtesy of S. Wilkinson).51
Figure 5.2 Schematic of river flowing to GBR Lagoon illustrating lateral exchange between freshwater and estuarine reaches with adjacent floodplain. 1) Montane and slope river reaches 2) Lowland reaches 3) Estuarine reaches 4) River plume extending seaward 5) Coastal waters. Figure due to Gehrke and Sheaves (2007). ................. 54
Figure 7.1 Time series of turbidity at Buoy 1 (south western Keppel Bay). Also shown are the tidal heights at Port Alma near the mouth of the Fitzroy Estuary. ....................... 54
Figure 7.2 MODIS TERRA image showing turbidity plume in Princess Charlotte Bay – 9 February, 2007..........................................................
ACKNOWLEDGEMENTS

The authors would like to acknowledge the many people who contributed to the preparation of this report. Thanks are due to the participants of the modelling workshop held in Townsville for their time and for their energy. We appreciate also the time and attention required for the completion of the surveys sent to regional managers responsible for Water Quality Improvement Plans which provided the context for the model applications. The authors are also grateful to those modellers who completed the model surveys. Finally, we are grateful to the Department of the Environment, Water, Heritage and the Arts for the funding support and to the project Steering Committee who have provided guidance during the project development.
EXECUTIVE SUMMARY

The Reef Water Quality Protection Plan (ReefPlan) is a joint initiative of the Australian and Queensland Governments and was released in October 2003. The objectives of the ReefPlan included reducing the load of pollutants from diffuse sources in the water entering the Great Barrier Reef World Heritage Area (GBRWHA); and rehabilitating and conserving areas of the Reef catchment that have a role in removing water borne pollutants. For priority catchments, the Coastal Catchments Initiative (CCI) program funded by the Department of Environment, Water, Heritage and the Arts (DEWHA) is supporting the development of Water Quality Improvement Plans (WQIPs) as a mechanism for achieving ReefPlan objectives. Water quality (concentration) objectives/targets, as well as water quality load targets, are required to be set for nutrients and sediments in all GBR regions under existing contractual arrangements for the development of WQIPs with the DEWHA. In most regions, water quality targets are required to be set by June 2008.

The Reef Water Quality Partnership (RWQP) was established in June 2006 as a consortium between Australian and Queensland Government agencies and the regional natural resource management (NRM) bodies of the Reef catchments to improve coordination and collaboration between the consortium members in improving water quality for the Reef. To support the design and implementation of WQIPs as an adaptive management process, the RWQP has recommended that a model framework be developed which links management action in catchments to water quality and ecological responses in receiving waters. The fundamental supposition is that bridging the gap between management action and water quality and ecosystem impacts can be achieved by modelling the fates of contaminants mobilised in paddocks, transported downstream by rivers, delivered to estuaries and ultimately to coral reefs further offshore.

Such a modelling framework could play a critical role in underpinning the development of WQIPs by providing prediction of the likely impacts of alternative management strategies on indicators of environmental health under prescribed scenarios, underpinning target-setting and strategy selection. Of course, the model framework would be applied with socio-economic imperatives as the overlay. A key element of adaptive management is assessment of the success of implemented management strategies. Simulation models in combination with well-designed monitoring strategies and appropriate assessment tools provide the ability to disentangle changes in system condition due to natural variability from those that arise from management action. Further, conceptual and quantitative models have an important role to play in communication to stakeholders, and increasing understanding of system dynamics and responses.

Logically, the (biophysical) model framework can be divided into two main elements, namely catchment models which describe how management impacts on the delivery of nutrients and sediments to the ends of catchments, and the marine receiving water models which simulate the fate and impacts of these contaminants as they pass through estuaries and into the GBR Lagoon beyond. In this report, we scope the opportunities for modelling the water quality and ecological impacts in the receiving waters of the GBR.
The model framework for receiving waters

The model framework recommended by this review has three components; namely:
- large-scale water quality model (LSWQ model)
- ecological response model
- fine-scale impact models

The LSWQ model

The highest priority would be the development of the LSWQ model which is effectively a materials transport and transformation model. It takes as its inputs catchment loads of fresh water, sediments, nutrients and pesticides derived from catchment modelling or from measurement, and it simulates the transport and transformation of these substances in the receiving waters including their impact on primary production. It would also provide concentrations required by the ecological model and the appropriate flow, water level, salinity, and contaminant concentrations for fine-scale impact models that might be developed.

This model would be applied at the scale of the GBR Lagoon and so would allow for the effects of the interaction between plumes from multiple rivers. Applied at timescales of decades, the LSWQ model would address also the issue of acute exposure of the reef by contaminants in flood plumes as well as more chronic exposure during the dry season. Timely model development would allow its use to support the review of WQIPs.

The LSWQ model would be comprised of linked hydrodynamic, sediment transport, and biogeochemical models. There are several models that meet the suitability criteria and that have had application to the GBR Lagoon.

Ecological models

We propose that ecological models be developed to simulate coral cover, coral recruitment, macroalgae and Crown-of-Thorns Starfish (COTS) abundance as indicators of reef health. The ecological impact models needn’t be spatially explicit, but impacts to individual reefs could be considered as consequences of their exposure to contaminants determined by the LSWQ model described above. Thus, the LSWQ model is a necessary precursor to the ecological impact models.

We have identified that a fruitful modelling approach is likely to be the modelling of ecological recovery after impact due to freshwater immersion, cyclone damage, coral bleaching or COTS. The underlying hypothesis is that recovery after reef damage depends on the relative ability of coral and macroalgae to recolonise. The growth response of juvenile coral versus macroalgae depends on water quality parameters including nutrients and underwater light. The HOME and CO2RAL models are based on this fundamental impact-recovery principle, but both are likely to require further development to meet management needs.
Fine-scale models

We have not identified the particular fine-scale models that might be required. Their specification might depend on management needs and the requirements of the LSWQ model and ecological models. An example of a model that might be required is an estuarine response model. With depth scales and width scales which are mostly less than those likely to be adopted for the grid in the LSWQ model, the latter model is not likely to be adequate for simulating estuarine response. Further, estuaries include a suite of processes that will not be included in the LSWQ model including mangrove-estuary and floodplain-estuary interactions.

Fine-scale models might also be implemented to better understand how to represent and parameterise processes in the larger scale model. For example, high-resolution models of the flow around the reef matrix and through channels between reefs might be used to test and improve parameterisation of these effects in the large-scale model.

The linkage to catchment models

The LSWQ model carries fresh water and contaminants from the river end and transports them throughout the GBR Lagoon. Accordingly, it requires as input time series of catchment delivery of these materials at appropriate time intervals (a day) and over the decades for which we wish to run the LSWQ model. This catchment delivery needs to be specified as loads (or concentrations) of the species of contaminants that are of relevance to the modelling of sediment transport and biogeochemistry of the receiving waters. The nutrients in river discharge take a number of forms including dissolved inorganic, dissolved organic, and particulate. Specification of fine sediment loads by grain size would be highly desirable.

SedNet is the catchment model that has been applied extensively for estimating nutrient and sediment loads to the GBR Lagoon. E2/WaterCAST is another modelling framework that has been recommended for the same purpose. Neither of these models meets all of the requirements of receiving waters models at present. SedNet models decadal average loads and these would need to be disaggregated into daily steps. E2/WaterCast would require the disaggregation of its daily total nutrient and sediment loads into constituent components. These limitations will be partly addressed by planned further development of E2/WaterCAST.

Water carrying sediments and nutrients spreads out over lowland agricultural regions during times of high river flow. There is currently little data on how much of the nutrient and sediment load is deposited on the floodplain, or how much of it returns to the main channel when the flood recedes. The role of floodplains in mediating material delivery to the GBR Lagoon is an area of current research.

Modelling strategy

Our recommendation for the GBR-wide LSWQ models and integrated ecological response models implies a commitment to the development of an integrated and coordinated approach to the development of community models to support the WQIPs. It is vital that model development is seen as an ongoing long-term commitment, analogous to a commitment to monitoring, not a one-off short-term project. Ongoing development
will ensure that the modelling initiative remains vigorous and responsive to the evolving needs of management.

We suggest also that two-way communication between modellers and stakeholders is an issue of high priority through model development and application. Significant resources need to be applied to the application of tools such as simulation visualisation to ensure that the results of model analyses are effectively conveyed to those who would use them.

The timetable for model development over the next 6 years proposed here takes account of the need to review WQIPs in approximately 7 years. It is envisaged that the LSWQ, ecological response models and assessment models could be developed to the point where they can inform the review of targets, and refinement of monitoring programs, by 2010.

We estimate that the modelling program proposed here would require about 10 FTEs per year over the first few years, and about 6 FTEs per year ongoing. That represents a substantial investment of around $1M to $2M p.a., depending on the levels of co-investment by participating agencies. However, it is still a relatively modest investment in the context of overall GBR monitoring, management and research.

The range of modelling and analysis skills required by the framework are available within Australian governmental, university and consulting institutions, but it is likely that no one institution will be able to provide the breadth of skill and human resources required to meet the above timeframe. Consequently, a consortium of modellers and analysts drawn from several institutions is the recommended approach as it is certain to be the only viable option for shorter term model development and implementation. Establishment of a multi-institutional modelling team, as opposed to a single contractor, is also likely to encourage innovation.
1 INTRODUCTION

CSIRO and AIMS have been commissioned by DEWHA to undertake the consultancy ‘Review and gap analysis of receiving-water water quality modelling in the Great Barrier Reef’. The overall aim of this project is to review existing modelling activities, identify strengths and weaknesses of these activities for achieving a nested suite of models, and to recommend a systematic framework for developing further water quality and ecological response models that can be applied generically in the GBR catchments, estuaries and Lagoon to support WQIP development and implementation. This report is the final deliverable for this project. The recommendations made in this report have been greatly informed by consultation with stakeholders and with the modelling community though a number of targeted questionnaires and a workshop.

The remainder of this chapter is comprised of four sections. Firstly the management context; that is, the initiatives of ReefPlan and WQIPs as strategies intended to maintain water quality and ecological amenity in the GBR World Heritage Area (GBRWHA) are described. The next section considers how models can support WQIP development and assessment, particularly by playing a central role between management action and system response. This is followed by a brief review of the status of marine water quality and ecological objectives in the current WQIP process. Finally, we outline the structure of the report in the context of the more detailed aims of the consultancy.

Throughout the report a number of technical terms are used. A glossary describing the meaning of some common technical terms is included in the report. For readability we have only given key references relevant to this report; much of the conceptual descriptions given in Chapter 2 are uncited.

1.1 The development of ReefPlan and WQIPs

The ReefPlan is a joint initiative of the Australian and Queensland Governments and was released in October 2003. The ReefPlan focuses on identifying actions, mechanisms and partnerships to build on existing Government policies and industry and community initiatives with the ultimate goal to ‘halt and reverse the decline in water quality entering the Reef within 10 years’. More specifically, the objectives of the ReefPlan are to reduce the load of pollutants from diffuse sources in the water entering the GBR; and rehabilitate and conserve areas of the GBR catchment that have a role in removing waterborne pollutants.

The ReefPlan is underpinned by nine key strategies with detailed actions to improve decision making in landuse planning, adopt sustainable production systems, rehabilitate damaged wetlands and riparian areas and conserve existing wetland and riparian areas. ReefPlan actions (H1, H2, and D4) refer to the development of water quality and management action targets in high-risk, high-priority GBR catchments with the aim of reducing loads of pollutants entering the GBR Lagoon.

The contaminants of concern for ReefPlan are suspended sediments, nutrients (nitrogen and phosphorus), and pesticides. Thirteen priority catchments (Table 1.1) have also been identified in ReefPlan; these are catchments that are recognised as posing a risk to the GBR Lagoon and require focused and regionally specific actions to ameliorate catchment loads.
For some of these priority catchments, DEWHA’s Coastal Catchments Initiative (CCI) program is supporting Natural Resource Management (NRM) bodies and local government to develop Water Quality Improvement Plans (WQIPs) as a mechanism for achieving ReefPlan objectives. Water quality (concentration) objectives/targets, as well as water quality load targets, are required to be set for nutrients and sediments in all GBR regions under existing contractual arrangements for the development of WQIPs with the DEWHA. In most regions, water quality targets are required to be set by June 2008.

The CCI is designed to deliver significant reductions in the discharge of pollutants to agreed hotspots, where those hotspots have been identified through agreement with the relevant jurisdictions. The WQIPs in particular catchments identify the most cost-effective investments to achieve water quality outcomes and the management strategies to sustain these improvements consistent with the National Water Quality Management Strategy.

In Queensland, the rollout of the CCI is being undertaken in collaboration with regional NRM bodies, and with local and state governments. Regional NRM investment strategies are being developed to guide implementation of regional plans to achieve water quality, biodiversity and sustained use of natural resources within the region. A number of regional investment strategies in GBR catchments already recognise the development and implementation of WQIPs as a mechanism for achieving some of their goals. Priority catchments across the GBR, including those where WQIPs are being developed, are shown in Table 1.1.

<table>
<thead>
<tr>
<th>NRM regions</th>
<th>Priority catchments*</th>
<th>WQIP/CCI investments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cape York</td>
<td>Normanby</td>
<td>No</td>
</tr>
<tr>
<td>FNQNRW</td>
<td>Daintree &amp; Mossman</td>
<td>Yes (Douglas WQIP)</td>
</tr>
<tr>
<td></td>
<td>Barron</td>
<td>Yes (Barron WQIP)</td>
</tr>
<tr>
<td></td>
<td>Mulgrave-Russell</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Johnstone</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Tully &amp; Murray</td>
<td>Yes (Tully WQIP)</td>
</tr>
<tr>
<td></td>
<td>Herbert</td>
<td>No</td>
</tr>
<tr>
<td>BDTNRW</td>
<td>Burdekin &amp; Haughton</td>
<td>Yes (Burdekin &amp; Black-Ross WQIPs**)</td>
</tr>
<tr>
<td></td>
<td>Don</td>
<td>No</td>
</tr>
<tr>
<td>MWNRM</td>
<td>O’Connell, Pioneer and Plane</td>
<td>Yes (Mackay-Whitsunday WQIP)</td>
</tr>
<tr>
<td>FBA</td>
<td>Fitzroy</td>
<td>Yes (CCI investment into regional plan)</td>
</tr>
<tr>
<td>BMRGNRM</td>
<td>Burnett &amp; Baffle</td>
<td>Yes (Burnett WQIP)</td>
</tr>
<tr>
<td></td>
<td>Mary &amp; Burrum</td>
<td>Yes (unfunded Mary WQIP)</td>
</tr>
</tbody>
</table>

* priority catchments listed are those that have been identified as high risk in the ReefPlan
** Black-Ross WQIP is being undertaken by Townsville and Thuringowa local governments.

Table 1.1 Priority catchments identified across regions

The Reef Water Quality Partnership (RWQP) was established in June 2006 to improve coordination and collaboration between governments and regional natural resource management (NRM) bodies in improving water quality for the GBR. The RWQP supports the implementation of the ReefPlan and regional water quality plans by providing a strong science foundation for setting targets, monitoring and reporting progress.
Members include Australian and Queensland Government agencies and the regional NRM bodies of the GBR catchments.

1.2 The potential role of models in WQIP development and assessment

The conceptual linkages between catchment agricultural activities and receiving water quality targets are illustrated in Figure 1.1 Conceptual linkages between management action targets and targets/objectives for receiving waters water quality and ecosystem health. In effect, contaminants are delivered from the paddock to rivers, to end of catchments, to estuaries and ultimately to coral reefs further offshore. At each stage, their presence can affect water quality as well as ecosystem health. Our fundamental supposition is that bridging the gap between management action and water quality and ecosystem impacts can be achieved by modelling across the freshwater, estuarine and marine systems. Accordingly, one of the priority actions of the RWQP is to facilitate the development and utilisation of a suite of modelling tools to link land management, water quality and GBR health, to improve understanding of broad-scale processes, and to assess alternative management strategies. Such a modelling framework could be used to support WQIP development through the evaluation of the impacts of hypothetical management scenarios. Also, the framework can be used in combination with well-designed monitoring programs to assist in the assessment of the success of WQIPs.

Here we describe the potential role models can play in supporting target-setting and decision-making, and assessment and evaluation within the context of development and implementation of the WQIPs and of the ReefPlan implementation more broadly. WQIPs must be developed within an adaptive management process - target setting, performance assessment and evaluation - under DEWHA guidelines.

Figure 1.1 Conceptual linkages between management action targets and targets/objectives for receiving waters water quality and ecosystem health.
Target-setting

There are two key types of choices managers need to make in designing and implementing adaptive management strategies. One is the translation of broad objectives into explicit targets. The other is the selection of management actions or decision rules to achieve those targets. These are obviously closely related. In order to choose targets and management actions, we need to have some way to link input actions to output indicators; that is, to predict the consequence of management actions for indicators. This is a fundamental and traditional role of models in environmental management and this is the role we ascribe to the model framework we describe in this report.

In target setting, model scenarios are typically used to explore options and evaluate plans and strategies. We might in principle use models in both a forward and reverse engineering mode. In forward mode, for different alternative set of actions, what would be the likely outcome in terms of output indicators? In reverse mode, given a set of output targets, what class of actions would likely allow us to reach them?

In the absence of suitable models linking catchment loads to Lagoon water quality, and water quality to reef health indicators, it will be difficult to make further progress in refining targets for Lagoon water quality and reef health indicators, or evaluating the likely performance of current catchment WQIPs with respect to these indicators and targets. This report suggests how such models might be developed.

Monitoring, assessment and evaluation

Models also have an important role to play within the adaptive management framework of monitoring, assessment and decision-making. Models can be used to assess the data resulting from monitoring, compute measures of performance against management targets, which can inform decisions to adopt management actions.

The assessment role of the model framework that we develop in this report derives primarily from its ability to attribute cause and effect (assuming the underlying processes are properly represented). It is necessary however to be able to discriminate changes in particular system indicators that are directly related to management actions from those that are the result of many other pressures, perturbations and inherent variability. Such confounding changes in indicators can result in misleading feedback to managers, or greatly extend the time period required to reliably detect effects of management actions. If assessment models can be used to effectively partition the variability in indicators, and identify that component due to management actions, it may be possible to provide timely and useful feedback. An example here is the ability to disentangle the impacts on water quality of multiple river discharges at a particular location in the GBR Lagoon.

A characteristic of the GBR region is its high interannual variability in rainfall and runoff. The annual discharge of the Fitzroy River may vary as much as a hundred-fold. Unless ways can be found to correct for variability in discharge, measuring benefits (as reduced loads) from improved management practice in catchments with any statistical reliability could take 50 years or more. Further, Reef health indicators such as coral cover are strongly affected by events such as floods, cyclones, Crown of Thorns Starfish (COTS) outbreaks, and more recently, increased bleaching events and potential seawater acidification resulting from climate change. Catchment loads and Lagoon water quality are expected to interact strongly with the event impact and recovery cycle of reef
ecosystems, but identifying impacts of changes in catchment loads against these high
levels of variability will not be straightforward. Models provide an opportunity to attribute
the relative impacts of climate variability and change from those due to management
action.

While monitoring programs are established to track system responses to management
actions, it's generally only feasible to acquire observations of specific indicators at a
limited number of points in space and time. But management objectives typically relate
to system properties over extended domains of space and time. Statistical assessment
models are used to compute estimates of these extended system properties based on
point observations, and importantly to assess the likely error in these estimates. In some
cases, system properties are not directly observable at all, but must be inferred from
observations of surrogate variables. The cause-and-effect models we describe in this
report can support the design of monitoring programs by suggesting effective indicators
(or sets of indicators) for achieving an appropriate assessment of impact and an
estimation of assessment reliability. There has been little explicit focus to date on how
monitoring programs should inform reviews of management plans and actions. It is not
yet clear what form this process will take in the context of the required adaptive
management strategy.

1.3 Status of WQIPs and receiving water objectives

As noted in Table 1.1, WQIPs are being developed for a number of priority catchments
draining to the GBR Lagoon. A common approach to target setting was agreed upon by
the ReefPlan Intergovernmental Operational Committee (the Reef IOC) and RWQP
Management Committee in November 2006. It was agreed that the end of catchment
load-based targets should be based upon our best available understanding of:

1. Environmental values and the link between end-of-catchment loads and the
   receiving water quality objectives
2. Current pollutant loads (and estimates of pre-European loads in the Tully and
   Douglas)
3. Achievable objectives based on modelling the outcomes of management action
   scenarios and stakeholder consultation.

The meeting highlighted that currently, receiving waters targets can only be crudely
related back to end-of-catchment targets and subsequently to management practice
targets, and this has limited the rate of progress towards setting water quality targets.

WQIPs must include consideration of the impacts on marine receiving waters in setting
management targets. The draft water quality objectives being developed for the Tully,
Mackay-Whitsunday, Burdekin and Black-Ross WQIPs have objectives for marine
concentrations of suspended sediments, nutrients, chlorophyll and pesticides. In the
Douglas WQIP, water objectives for marine receiving waters are not linked to
management targets as this was not a requirement at the time this plan was developed.

These marine water quality objectives are based on a combination of water quality
objectives (or trigger values) presented in the national ANZECC guidelines (ANZECC,
2000), by draft GBRMPA guidelines (Honchin et al, 2007) and by the Queensland Water
Quality Guidelines (EPA, 2006). The objectives also consider other impacts on water quality such as sewage, aquaculture and boating discharges, or other human uses.

The draft GBRMPA Water Quality and Ecosystem Health Guidelines (Honchin et al., 2007) suggests we need to stay below certain levels of contaminants in order to maintain the health of the marine ecosystem. The levels of contaminants identified in these interim guidelines are not targets, but are guideline trigger values that, when exceeded, should trigger management responses. The guidelines recognise that management responses are a part of the adaptive management strategies in water quality improvement plans in the GBR catchments and in regional natural resource management plans.

The maintenance of the ecological amenity (e.g. the commercial and recreational benefits that derive from a healthy GBR) of the GBR is a stated aim of the ReefPlan, but ecological objectives do not appear explicitly in the WQIPs. Rather, they are expressed implicitly as water quality objectives required to maintain this amenity.

It is intended that all WQIPs currently under development in the region be implemented by the end of 2008 with a view to their review after 7 years (Vaughn Cox, pers. comm.). Accordingly, when considering a schedule for the development of models to support WQIP review and renewal, we shall assume that we are working within this timeframe.

1.4 Report strategy and outline

The remainder of this report is comprised of eight chapters and four appendices. Here we outline the content of each.

Chapter 2 - Conceptual models

This chapter presents a broad conceptual understanding of natural processes and the impacts of pollutants (sediments, nutrients, pesticides) on water quality and ecology in the GBRWHA. The spatial scales considered extend from estuaries to coral reefs and temporal scales consider the impacts of events as well as chronic conditions.

Chapter 3 - Modelling framework to support management

This chapter presents an overview of the requirements of a modelling framework to support management. A model framework is suggested to meet management needs, which is comprised of a number of model elements. These elements are described including their essential processes, how they fit together, their data requirements, model gaps, and how uncertainty and reliability might be treated.

Chapter 4 - Review of existing models

Models that might be considered as being implemented as part of the modelling framework are described in this chapter. The focus is on models that have been applied to the GBR region and on models that are being applied. The suitability of these models for framework implementation is also considered.

Chapter 5 - Strategies for linking to catchment models – an integrated approach

This chapter discusses the desirable properties of catchment models that will allow their effective linkage to marine receiving waters models as part of a modelling framework to support management decision making. These properties include time steps, simulation
duration and speciation of sediment and nutrient loads. The catchment models SedNet and E2 are discussed in this context.

Chapter 6 - Modelling strategy and implementation plan

Chapter 3 recommends a model framework to meet management needs, but chapter 6 treats issues surrounding the implementation of such a framework. A possible timeline for model development is described in the context of the evolution of the WQIPs. Other issues considered in this chapter are the resource requirements for framework implementation and ongoing application, modelling capacity, custodianship and governance of the process.

Chapter 7 – Data needs, data issues, and ongoing data collection

Here we consider first the data needed to support model development and application in relation to supporting monitoring and assessment, understanding prediction uncertainty, supporting model improvement and development, and for forcing the models. Issues surrounding data utilisation including problems due to unresolved temporal and spatial variability are addressed as are the opportunities arising from remote sensing and data assimilation techniques. Finally, we summarise ongoing monitoring programs and other studies being undertaken in the GBR Lagoon including the Marine Monitoring Program being undertaken to support the ReefPlan.

Chapter 8 – Summary and conclusions

This chapter summarises how a model framework linking catchment management to receiving waters impacts can be used to support the ongoing development and assessment of WQIPs. It presents our recommendations for the model elements in such a framework that would be used to simulate water quality and ecological impacts in marine receiving waters. We summarise also considerations for the implementation of such a framework to support management.

Appendices A, B, C, D

The project involved consultation with stakeholders and with the modelling community. A questionnaire was prepared and distributed to regional managers responsible for the preparation of the WQIPs. The questionnaire was designed to canvas information on the development of the individual WQIPs including their status, content and needs. The responses from this survey are presented in Appendix A.

A second survey was conducted amongst the modelling community to obtain information on the breadth and features of the varieties of models that might ultimately contribute to a model framework. Results of this survey are summarised in Appendix B.

On 16-17 July, 2007 a technical workshop was held in Townsville with GBR modellers and other scientists to scope the conceptualisations that need to be included in models designed to address management needs. The workshop developed the model framework that is recommended by this report. A report on the workshop proceedings and conclusions appears in Appendix C.

Appendix D describes monitoring and data collection programs that are underway or are planned in the GBR and that could potentially support the development and application of a model framework.
2 CONCEPTUAL MODELS

Conceptual models have a number of specific uses and applications, but the brief review of conceptual models in this chapter is primarily intended to explain and motivate recommendations towards the development of quantitative receiving water models for the GBRWHA.

There has been considerable effort devoted to the development of conceptual models for the impact of catchment loads on GBR water quality and coral reefs over the last few years. Recent examples include reviews by Haynes et al. (2007), developed to support the design of marine monitoring programs under the ReefPlan, and a report by Fabricius (2007) summarising current understanding of the key interactions and processes linking catchment loads to coral health. Many other implicit and explicit conceptual models have been developed as part of data analyses and modelling studies for the GBRWHA. Generic conceptual models for Australian estuaries were developed as part of the National Land and Water Resources Audit (National Estuaries Assessment and Management project), and conceptual models for specific estuaries within the GBR have been developed as part of recent studies such as for the Fitzroy Estuary (Webster et al. 2003). There has also been substantial effort devoted to the development of conceptual models for GBR catchments, linking land use practices at the paddock scale to end of catchment loads (e.g. Kuhnert et al, 2007). As this study is focused on receiving water models, catchment models are only briefly considered. Greater detail on the needs, application and development of catchment models for the GBR are to be found in Grayson (2007).

Given the complexity of environmental systems, any particular conceptual model or diagram represents a dramatic simplification, and there are typically many different models or views of a system which might be developed. The approach we adopt in this chapter is to combine bottom-up and top-down perspectives, starting with the material transport and transformation of catchment loads in the marine environment, and concluding with the ecological response to the stresses resulting from catchment loads and other factors.

2.1 Catchment Loads

Catchment loads of sediment and nutrients into the GBR Lagoon have increased substantially over the last 150 years as a result of human activities. Increased erosion has resulted from land clearing, cultivation and grazing practices. Efficiency of delivery may have increased as a result of floodplain disturbance and catchment modification. Increased delivery of nutrients has resulted from both increased erosion and fertilizer application. Pesticides applied to crops wash off the land and are transported to coastal waters.

A variety of key processes control and mediate the generation of loads from paddocks, and the transport and transformation of these loads through streams and rivers to catchment ends. Understanding these processes is clearly critical for the prediction of the composition and temporal variation in end-of-catchment loads, and for the design and selection of effective management actions to reduce loads. These processes have been addressed in catchment modelling reports (Grayson, 2007).
Importantly, climate and catchment processes impose a large scale spatial and temporal structure on catchment loads into the receiving waters of the GBR Lagoon (Figure 2.1). Of the forty or so catchments draining into the GBR Lagoon, most are small, but the Burdekin and Fitzroy catchments are both over 100 000 km$^2$. The Wet catchments in the tropical north are steep and receive high rainfall concentrated in the summer wet season. Rivers typically flow year round, but discharges and loads are much higher in summer being dominated by major runoff events associated with tropical depressions and cyclones. The extensive dry catchments (Fitzroy and Burdekin) receive unreliable wet season rainfall, so runoff and loads show very high interannual variation, and are even more concentrated in rare major events, while flows may cease during the dry season. Because of their size, dry catchments deliver the majority of nutrient and sediment loads to the GBR Lagoon, although wet catchments deliver higher loads per unit catchment area.

A significant issue in the setting of end-of catchment load targets for the reef is the fact that many kilometres of river and estuary flowing through the coastal plains where agriculturally-intensive activities occur are ungauged because flow-gauging stations are located beyond the limits of tidal intrusion to prevent confounding of the unique stage height-flow relationship. Thus it is assumed that pollutant loads measured here are what is discharged to coastal waters. In fact, much of the load may be deposited—either through flocculation or trapping within the estuary or redeposited on adjacent floodplains.

Given that flood events are responsible for most of the long-term load, floodplains potentially play an important role in mediating the delivery of catchment loads to the GBR Lagoon. Floodplain processes have historically received little attention, because the critical phenomena are ephemeral, and they have tended to fall into the gap between catchment and marine research. While this scientific neglect is now being redressed (e.g. Wallace et al. 2007), floodplains still represent a serious gap in our quantitative understanding of the material exchange between catchments and Lagoon.

2.2 Material transport and transformation in the marine environment

Circulation and mixing

Hydrodynamic processes of advection and mixing govern the movement of water and the transport of dissolved and particulate substances in the marine environment. These processes take place over a wide range of scales, from the thousands of kilometres associated with ocean basin circulation and boundary currents, to scales of metres associated with vertical gradients in floodwater plumes, and turbulent mixing. We consider here hydrodynamic processes at three scales: whole of GBR, inner shelf and estuaries (Figure 2.1).
Figure 2.1 Spatial scales considered under the receiving water model review: a) whole of GBR showing wet and dry catchments; b) catchment to reef scale; and c) estuary scale.

Within estuaries, the dominant drivers of advection and mixing are river flow and tides, with additional contributions in lower estuaries and embayments from wind-driven circulation and waves. As already discussed, river flow is highly variable over events that last a few hours to days, to characteristic seasonal summer wet and winter dry patterns that collectively contribute to high interannual differences in the quantity and timing of discharge to the GBR Lagoon. During major floods, estuarine hydrology is dominated by river discharge, which may flush the estuary ‘fresh’ to the mouth and into the Lagoon; when water discharge exceeds the volume of the estuary channel it also spills onto surrounding floodplains.

Tidal amplitudes are moderate to high within the GBR Lagoon and estuaries there are generally classified as tidally dominated. During low flow periods, estuaries are typically vertically well-mixed by tidal energy. After flood cessation, an along-estuary salinity gradient is re-established which advances up the estuary as seawater is mixed towards the estuary head. In the dry catchments, river flow may cease in the dry season, and evaporation can lead to hypersaline conditions in the upper estuary. The large subtropical rivers have extensive deltas composed of mudflats, mangroves, and branching tidal channels and creeks.

Throughout the GBR Lagoon, currents are tide and wind dominated, with some influence from offshore circulation discussed below. Over much of the year, the dominant southeast (SE) trade winds drive net transport to the north. The water column is generally vertically well-mixed, except during flood events, or on a transient basis due to diurnal heating and cooling. Major flood events produce shallow surface plumes of low salinity water. Plumes from the major rivers may extend hundreds of kilometres along shelf, usually northward under the influence of SE trades. Flood plumes tend to be constrained to within 20 km of the coasts by buoyancy and wind stress, although cross-shelf excursions are observed. Plumes carry both dissolved and particulate constituents from catchments, and given that floods deliver the majority of catchment loads, the direction and extent of plumes obviously has a major influence on the initial fate and impact of these loads (Figure 2.2).
Figure 2.2 Remote sensing images of the northeast coast of Queensland showing the Great Barrier Reef and river plumes following large rainfall events. Insets show flood plumes from: a) the Normanby River; b) the Tully and Herbert Rivers; and c) the Burdekin River.

At the scale of the whole GBR Lagoon, the effect of offshore ocean circulation and exchange must be taken into account. The westward flowing South Equatorial Current impinges on the Australian coast between around 14°S and 19°S, and bifurcates, part flowing northward and recirculating in the Coral Sea, but most turning southward to form the East Australian Current (EAC) which flows southward along the edge of the continental shelf (Figure 2.3). The pressure gradient associated with the EAC tends to drive a net southerly flow along the GBR Lagoon, although this is usually reversed due to wind forcing. The EAC occasionally intrudes onto the shelf through the reef matrix. Mesoscale eddies are known to have a major effect on ocean-shelf exchange in southeast and southwest Australia, but their effect in the GBR is not well known. Continental shelf waves are thought to have an important effect on ocean–shelf exchange, particularly for the nutrient budget, because they are known to result in upwelling of nutrient rich water from below the ocean mixed layer, and its incursion onto the shelf.
Circulation in the GBR Lagoon and exchange between the Lagoon and the ocean is complicated by the presence of the more than 2900 reefs making up the GBR. These modify the local tidal and wind-driven circulation within the Lagoon, and strongly constrain the exchange between the Lagoon and the open ocean, particularly in the northern GBR where the ribbon reefs form a more or less continuous barrier along the shelf edge, and exchange is restricted to narrow tidal passages (Figure 2.4). The detailed exchange of water between individual reefs and the open Lagoon has important implications for the local environmental conditions experienced by reef communities, and for connectivity and recruitment among reefs. This exchange depends on complex local processes, including tidal and wind-driven flows, and interactions of far-field currents with complex local topography.

Figure 2.3 Schematic of large-scale circulation in GBR Lagoon and Coral Sea.

Figure 2.4 Mixing and exchange processes across the GBR Lagoon.
Sediment dynamics

While the transport of dissolved substances is determined by currents and mixing, the net transport of particulate materials is subject to additional processes. Particles settle through the water column, at rates that depend on their size and composition. Particles are also exchanged between the water column and the seabed by sedimentation and resuspension processes (Figure 2.5)

Figure 2.5 Sediment dynamics from catchment to reef in the Great Barrier Reef

In general, the balance between sedimentation and resuspension is determined by the local shear stress over the seabed, which in turn reflects the local mean and turbulent velocities due to currents and waves. Sediment models typically invoke a critical (minimum) shear stress for resuspension. This critical shear stress depends on particle size (it takes more energy to resuspend larger, heavier particles), but it is also affected by a large number of other factors. Bed sediment often contains mixtures of particle sizes, and in some cases larger heavier particles may armour the bed, preventing resuspension of fine particles. Benthic biota, ranging from tube worms to seagrass to mangroves, have the effect of increasing friction and reducing velocities and shear close to the sediment surface. In fine sediments, chemical and biological processes can result in bonding of particles, greatly increasing the critical shear stress.

Analyses of sediment dynamics typically distinguish between fine (cohesive) sediments, and coarse sediments. Often a practical divide is made at particle sizes of 63μm. Fine sediments have lower sinking rates and may take many days to settle out under quiet conditions. Under turbulent conditions, they can be mixed throughout the water column. Fine particles are also more subject to electro-chemical attraction forces which cause aggregation (flocculation) resulting in increased particle sizes and sinking rates and more rapid sedimentation. Flocculation depends on particle concentrations and water column turbulence which increases particle collision rates. Turbulence can also break up flocs under some conditions. The surface chemistry of particles also depends on salinity, and it is common for fine sediment loads in river plumes to undergo rapid flocculation and sedimentation as salinities increase to a few PSU (above 5% of seawater or so).

Suspended coarse particles sink rapidly, and are often confined to a thin layer near the bed (bed load), except under extreme conditions. Coarse (sandy) particles may dominate bed sediments under conditions of moderate to high energy and low terrigenous input, and their net movement determines bathymetry and bedforms, at
scales from sand ripples (scales of 10s of centimetres), to sand waves (scales of 10s of metres) to major geomorphological features.

Estuaries are the point of delivery of catchment sediment loads. However, these loads are delivered predominantly in flood events, and under these conditions there may be little net sedimentation in estuary channels — in fact, major floods can result in scouring of bed sediments from estuary channels. A considerable part of the suspended sediment load from the catchment in major floods may be deposited and retained on the coastal floodplain, but this fraction is not well quantified for GBR catchments.

A striking feature of coastal sediment transport is that the interaction of horizontal transport in the water column with vertical exchange processes can produce counter-intuitive effects in which the net movement of sediments is opposite to the net transport of water and dissolved substances. In macrotidal estuaries, it is common to see a net transport of sediment up-estuary as a result of interactions between tidal transport and resuspension, against a weak down-estuary transport of fresh water. It appears that the long-term balance of sediments in these systems is governed by a net flux of sediment into estuaries from the adjacent coastal region during periods of low flow, balanced by scouring of channels and export of sediment during flood events. High tidal energy and sediment transport processes can result in maintenance of turbidity maxima at intermediate positions along macrotidal estuaries during periods of low river flow. Suspended sediment concentrations in turbidity maxima may exceed those in river discharge during flood events.

As noted above, flood plumes from the large rivers may extend hundreds of kilometres along the coast. Most of the suspended sediment in flood plumes is thought to settle out fairly rapidly and within a short distance of the estuary, because large particles rapidly sinking, and fine particles flocculate and settle ([Error! Reference source not found.]). A small fraction of fine sediment may remain in suspension for long periods and eventually settle to the bottom far from the river mouth.

Figure 2.6 Flood plume excursion across the GBR Lagoon showing sediment dynamics.

Following initial sedimentation, and the dissipation of the flood plume, the freshly deposited material is subject to further transport and redistribution through processes of tidal and wind-driven resuspension and settling. One would generally expect this to lead eventually to the net movement of most sediment into deposition zones where it is not subject to frequent resuspension, because the water column is deep, and/or wave and
current energy is low, or resuspension is inhibited as a result of features such as mangroves. It has been argued that most of the fine sediment in inshore waters in the GBR Lagoon ends up trapped in northward facing bays. These bays are relatively sheltered from waves and currents driven by the prevailing SE trade winds.

It follows that the amount of fine sediment in suspension, averaged over tide and wind events, would peak following major flood events, and then decay with time. However, the impact of increases in catchment loads on background turbidity in the inner Lagoon remains a matter of controversy. It has been argued by some that there is a large pool of mobile sediment available for resuspension in the inner Lagoon, and that additional catchment loads may have increased the rate of accumulation of bed sediments, but have not substantially changed the background turbidity. This seems to amount to questioning whether turbidity is limited by the continuing supply of mobile fine sediment. However, there is large variability in both the available pool of fine sediment and the shear stress available for resuspension, at a range of time and space scales. So the answer is likely to be that the available sediment pool is limiting at some times and places. If so, we need to understand how the spatial and temporal variability in turbidity is affected by catchment loads and how this affects reef health. It is certainly true that, in nearshore shallow areas along much of the GBR mainland coast, there appears to be a pool of fine sediments which is readily resuspended under appropriate wind and tidal forcing, resulting in frequently elevated background turbidity.

Suspended particles include a mixture of inorganic mineral material and organic detritus. Some fine terrigenous sediment may be transported across the shelf and offshore, but in the offshore Lagoon, organic or at least biogenic material may dominate the suspended particulates except during floods. Concentrations offshore are much lower, but in water depths of thirty to fifty metres, relatively small increases in suspended matter and light attenuation can drastically reduce irradiance at the sea floor potentially affecting deep corals and benthic plants.

Catchment loads of particulate material are predominantly inorganic, but include some terrestrial organic matter either as separate particles or attached to mineral particles. The fate of nutrients discharged into the GBR Lagoon is not only determined by the movements of water which carry dissolved forms, but also by the movements of the fine sediments. Further, even in the inshore zone, there is increasing attention being paid to the interaction of marine organic material and inorganic sediment. Addition of organic matter to inorganic sediments can affect the surface properties of particles, and their tendency to aggregate, and consequently their distribution and fate. It also appears to affect their impact on benthic biota.

Given that the fate and impact of catchment sediment loads depend strongly on their size and mineral / chemical composition, it will be important for receiving models that this information is provided by monitoring and modelling of catchment loads.

**Nutrient cycling**

This section focuses on the role and cycling of macronutrients (nitrogen, phosphorus) in the GBR, although other micronutrients such as iron may play a role in specific processes. Macronutrients control or affect the biomass and productivity of planktonic and benthic primary producers in coastal systems. Nutrient cycling within corals reefs, estuaries and the inshore surface waters of the GBR Lagoon are considered below.
Coral reefs are usually found in strongly nutrient limited (oligotrophic) waters, with low nutrient supply, and low phytoplankton biomass. Increased nutrient supply to oligotrophic systems (eutrophication) results in increased primary production and phytoplankton biomass, increased sedimentation of detritus and oxygen consumption, and decreased light penetration through the water column. All these changes potentially have deleterious effects on benthic communities adapted to low nutrient, high light conditions.

The Coral Sea and outer GBR Lagoon are oligotrophic, and believed to be nitrogen-limited. Despite this, nutrient budgets for the GBR Lagoon as a whole have shown that the open ocean is the dominant external source of nutrients. However, this is not surprising, as it is true for most continental shelf ecosystems. Given that concentrations of dissolved inorganic nitrogen in the surface mixed layer in the Coral Sea are vanishingly small, offshore injections of dissolved inorganic nutrients onto the shelf must rely on intermittent upwelling and mixing processes at the shelf break which allow water from below the nutricline to intrude onto the shelf. Large scale maps of chlorophyll on the GBR suggest that inputs of nutrient from the ocean may be elevated in the south, and the far northern reaches of the GBR Lagoon.

Nutrients in the Lagoon are intensively recycled (Figure 2.7). In oligotrophic systems, phytoplankton rapidly take up any available dissolved nutrient, and assimilate it into organic matter. In turn, phytoplankton are subject to intense grazing pressure by zooplankton which return nutrients to the water column through excretion or when they die and decompose. Thus, organic matter is rapidly recycled, either in the water column, or in sediments after sedimentation of detritus.

Figure 2.7 Catchment to reef nutrient processes in the GBR.

Benthic processes are likely to play an important role in nutrient cycling in the GBR Lagoon. Benthic microalgae in soft sediments have been found to maintain substantial biomass and production to depths of 60 m or more on continental shelves under clear water and may make an important contribution to integrated primary production in the GBR Lagoon. Benthic macroalgae and seagrass make important local contributions to primary production. Benthic filter feeders remove phytoplankton, zooplankton and organic detritus from the water column, and can contribute significantly to pelagic-benthic transfers of carbon and nutrients. Conversely, remineralisation of organic matter in sediments results in generation and efflux of dissolved inorganic nutrients.
Denitrification in sediments converts nitrate to N$_2$ gas, which is generally biologically unavailable. Denitrification can constitute a major or dominant sink for available nitrogen in shallow systems with long flushing times. Recent modelling studies have yielded very long flushing times (100s of days) for the Lagoon at large scales suggesting that internal sinks such as denitrification may play an important role in overall nutrient budgets. Conversely, nitrogen fixation converts N$_2$ gas into available nitrogen. Nitrogen fixation is known to occur on the GBR through planktonic cyanobacteria (especially Trichodesmium) and benthic cyanobacterial mats, but the relative contribution to the overall budget is not well known. Nitrogen fixation may increase in the presence of high concentrations of phosphate and possibly micronutrients such as iron, and at high light levels.

The net contribution of coral reef communities to nutrient cycles and budgets in the GBR Lagoon has not been quantified. Historically, reefs have been seen as accumulators of nutrients, harvesting nutrients by filtering plankton and detritus from the surrounding water column and using this to support high local biomass and production.

The processes described above would take place on the GBR even in the absence of catchment loads. Rivers however deliver additional nutrients to the GBR via estuaries in a variety of forms, as dissolved inorganic nutrients, inorganic and organic nutrients bound to sediments, dissolved organic matter and particulate organic matter. The relative partitioning across these fractions will vary depending on the catchment and landuse patterns. Nutrient loads from undisturbed catchments tend to be low, and predominantly in the form of refractory organic matter which breaks down very slowly in the marine environment. Nutrient loads from disturbed catchments are larger and more bioavailable. There may be substantial loads of dissolved inorganic nutrients especially where fertilizers are applied. In fresh water, phosphate tends to be strongly adsorbed to sediments, and concentrations of dissolved phosphate tend to be very low and often limiting. This phosphate may be partially desorbed in salt water especially under low oxygen conditions, so there is often a transition from phosphorus to nitrogen limitation of primary producers along estuary.

As with sediments, the bulk of nutrient delivery from catchments to the GBR Lagoon occurs during flood events. Dissolved nutrients are advected with flood plumes. While small injections of available nutrients into oligotrophic waters are taken up by phytoplankton almost immediately, the uptake of high nutrient concentrations in flood plumes may be delayed by a number of factors including light attenuation due to high turbidity, the time taken to grow the phytoplankton biomass, and to the inability of marine phytoplankton initially entrained into the bloom to survive or grow at low salinities. Consequently, high phytoplankton biomass tends to occur on the outer edge of plumes, some days after peak discharge (Figure 2.7 above).

Refractory dissolved organic matter in flood plumes is unlikely to undergo significant breakdown on time scales of days to weeks and much of the dissolved organic matter from catchments may be exported from the Lagoon without being remineralized to bioavailable inorganic forms. Particulate organic matter tends to sediment out along with inorganic sediments. The ultimate fate of this matter is not well understood. Part may be remineralized in coastal sediments, releasing nitrogen and phosphorus in bioavailable forms and part may be buried in deposition zones.
Following runoff events, dissolved inorganic nutrient concentrations can be expected to return rapidly to background levels. The additional nutrients will be recycled within and between planktonic and benthic communities, with net losses over time due to internal sinks (burial, denitrification) or export. As noted above, for the inner Lagoon as a whole, export rates are thought to be low and flushing times long, so that nutrients may be expected to be retained, and internal sinks relatively important. While ocean nutrients are thought to be the dominant external source for the GBR Lagoon as a whole, catchment loads are locally important and believed to represent the dominant source for the western side of the Lagoon within 20km or so from the coast.

High concentrations of dissolved inorganic nutrients can accumulate in pore waters in organic rich sediments. Continual release of these nutrients into the water column occurs through diffusion, often enhanced by bio-irrigation, but rapid release can result from wind-driven resuspension events. Studies have shown that elevated nutrient concentrations in shallow nearshore waters in the GBR result from wind-driven resuspension events. Tropical cyclones produce current and wave-driven resuspension to considerable depths over much of the GBR Lagoon, potentially resulting in large injections of bioavailable nutrients, and subsequent phytoplankton blooms.

The residence time of waters in estuaries during flood events is too short to allow significant phytoplankton biomass accumulation. During low flow periods, residence times are longer, but light attenuation in turbid mid-estuary zones can be too high to allow phytoplankton growth. High phytoplankton biomass can accumulate in clearer upper estuary zones and benthic microalgae on intertidal flats may also contribute significantly to primary production. Studies suggest that turbid macrotidal estuaries may be net heterotrophic with dissolved inorganic nutrients increasing down-estuary as a result of remineralization of suspended organic matter. Inputs of dissolved inorganic nutrients from the breakdown of sedimented material deposited on the floodplain can occur through tidal creeks and channels. Mangroves and intertidal and subtidal seagrasses also make an important contribution to primary production in estuaries and adjacent coastal embayments.

**Pesticides**

There is increasing concern about the potential effects of pesticides, including insecticides, herbicides and fungicides, on GBR marine communities (Figure 2.8). In considering transport and fate, it’s useful to divide pesticides into polar compounds, which are relatively water soluble and so travel as dissolved substances, and non-polar compounds which attach strongly to sediments and are generally transported with particulate material. This differentiation is likely to affect the pattern of mobilization and export from paddocks into streams and rivers, with soluble compounds being more susceptible to export during low to moderate runoff events. As pesticides are solely due to human application to crops, there may be pronounced first-flush effects in the timing of pesticide delivery to the GBR Lagoon or delivery associated with the timing of application.
Figure 2.8 Transformation and fate of pesticides in the receiving waters of the GBR.

The soluble pesticide fraction is likely transported further from the estuary in flood events, whereas a relatively higher proportion of the particulate fraction is deposited closer to the estuary mouth. Still, the adsorbed compounds are likely to be preferentially associated with the finest particles, and so transported further than the coarser fractions of the sediment which may comprise the bulk of sediment delivery.

In Queensland, the use of persistent organochlorine pesticides has substantially declined and a number of these compounds have been banned altogether due to their toxicity and bioaccumulation in the food chain. On the other hand, modern pesticides are designed to have shorter half-lives in the environment and thus have less potential to bioaccumulate, but may still have adverse ecological impacts. The effective half-life of pesticides in the marine environment depends on their chemical properties and environmental conditions, including temperature, exposure to light, UV radiation and biological degradation. The ecological impact of pesticides is dependant on the grouping (i.e. herbicide, insecticide, fungicide) of the particular pesticide in question. For example, diuron is a herbicide that inhibits photosynthetic activity of the plant that the chemical is applied to. Thus, in receiving waters, diuron also has the potential to disrupt the photosynthesis of marine plants such as seagrass and zooxanthellae within corals.

Pesticides, albeit at low levels, are a ubiquitous contaminant in the inshore GBR (Prange, 2007). As with the concentrations of nutrients in receiving waters, pesticide concentrations are observed to vary spatially and temporally depending on land-use patterns, chemical use and river flow. There is a potential ecological impact of these pollutants through short-term exposure to high concentrations in flood plumes, and through chronic exposure to elevated concentrations in estuaries and nearby embayments. In the case of flood events, exposure to dissolved pesticide concentrations may be estimated by considering source concentrations and dilution. Exposure to pesticides adsorbed to sediment particles can be deduced from consideration of transport and sedimentation. Chronic near-field concentrations will depend on local retention and remobilization, possibly augmented by intermittent or continuing inputs from small rainfall and runoff events, balanced against decay rates. Several studies of seagrass, crabs and dugongs have shown measurable quantities of pesticides within their tissues.
2.3 Ecological Response

The GBR Lagoon contains extraordinary diversity at the level of ecosystems, communities, species and genomes. Estuarine and nearshore communities occur in mangrove forests, on intertidal flats, and in seagrass meadows. Inter-reefal communities include sponges, seagrasses and macroalgae. The coral reefs themselves are a third type of community and open-water pelagic communities of phytoplankton, zooplankton, and fish are a fourth type.

There is a corresponding large and potentially bewildering set of potential pathways by which catchment loads of sediments, nutrients and pesticides could affect community and ecosystem health. For the purpose of this review, the focus for conceptual model development is directed at key communities (coral reefs and seagrass meadows), and key functional groups responsible for structuring or maintaining those communities (Figure 2.9).

Coral Reefs

Attention has naturally focused on coral reefs as icon communities in the GBR. A conceptual model of effects of terrestrial runoff and loads on corals and coral reefs has recently been published by Fabricius (2007). This model adopts an impact-recovery framework as the conceptual basis for representing coral reef responses to environmental factors. Coral reefs experience major damage and mortality through acute events including exposure to flood plumes, cyclone damage, COTS infestations and more recently coral bleaching due to elevated sea surface temperature. These events can occur over relatively short periods (days to months) at irregular intervals, and on local to regional scales. Recovery from these events occurs through coral recruitment and growth. Recovery rates and outcomes are strongly influenced by the background environmental conditions experienced by reefs between events. Long-term outcomes therefore depend on the balance between the frequency and severity of acute impacts, and the rates and success of recovery in intervening periods.

It follows from the impact-recovery model that we cannot consider the impacts of terrestrial runoff in isolation from impacts of other events and drivers. Moreover, it’s clear that there are a number of highly nonlinear interactions and thresholds involved, so that
ecological outcomes do not necessarily depend linearly or smoothly on pressures they are subject to.

The acute impacts of flood plumes on coral reefs can result from exposure to low salinities, from effects of sedimentation, or from acute exposure to elevated levels of pesticides and nutrients.

The potential impacts of background (non-flood) environmental conditions on reef recovery are diverse. As noted above, coral reef communities are adapted to oligotrophic conditions. High levels of dissolved inorganic nutrients can directly and adversely affect the physiology of corals and other key groups such as coralline algae which also contribute to the underlying structural integrity of reefs. Background concentrations of dissolved inorganic nutrients are unlikely to be persistently high in the GBR Lagoon except under local eutrophic conditions in estuaries. However, increases in the supply rates of inorganic nutrients will tend to favour macroalgae, which can shade and outcompete corals for substrate.

Decreased light penetration, due either to increased suspended sediment, or increased phytoplankton biomass, reduces light availability to all benthic plants. Corals and seagrass which have a higher light requirement are likely to be disproportionately affected compared with some macroalgae and microalgae.

Chronic or persistent sedimentation represents a severe stress for corals and coralline algae. Sediment mixed with organic matter appears to adhere more strongly to coral surfaces, and have greater impact. Some species of coral are capable of taking up, and benefiting from, increased levels of particulate organic matter, however at high levels particulate organic matter promotes the growth of macroalgae and other filter feeders, which as mentioned above can shade and outcompete corals.

Recent studies have shown that pesticides, albeit at low levels, are ubiquitous contaminants in the inshore GBR. Pesticides can affect corals in a number of different ways. For example laboratory studies have shown that low concentrations of herbicides can reduce the photosynthesis of coral symbionts (zooxanthellae), whereas insecticides and fungicides have been shown to affect coral early life-history stages in particular. Thus, the timing of the acute exposure to pesticides may be a critical factor for the risk to corals. Further research is required to understand the impacts of chronic and acute exposure of corals to environmentally relevant pesticide concentrations.

All of the water quality stresses mentioned above tend to have much greater impact on juvenile coral, coral recruits and early life-history stages and recruitment. This sensitivity means that declines in chronic water and sediment quality resulting from catchment loads have a disproportionate impact on coral recovery following acute impacts. In particular, coral settlement is directly affected by light intensity, depends on the presence of coralline algae, and is inhibited by the presence of macroalgae. Furthermore, the early life stages of coral occur during a prescribed time period. Mass spawning of corals typically occurs in November and December and is followed by a window of up to one month when the coral larvae must disperse and settle. These events usually occur in the latter part of the year and if they are coincident with a first flood event, long-term consequences could occur for coral recruitment.
As well as these direct physiological impacts resulting from local water quality, broader changes in Lagoon water quality may have indirect ecological effects on corals. It is hypothesized that increased phytoplankton biomass and productivity has resulted in higher COTS larval survival and recruitment, increasing the frequency and severity of COTS outbreaks. Herbivorous fish abundance is believed to partially control benthic algal biomass, and it has been suggested that losses of herbivorous fish may lead to macroalgal dominance on reefs. Reductions in fish biomass can result from fishing pressure, but it has also been suggested that herbivorous fish densities are reduced in turbid environments. In general, the potential effects of changes in GBR water and sediment quality on pelagic and benthic fish communities in the GBR Lagoon are poorly understood.

As some of these ecological interactions involve positive feedbacks, and/or affect multiple life history stages, there is the potential for thresholds, hysteresis and multiple equilibria. For example, it seems likely that a reef dominated by macroalgae would resist recolonisation by corals, even if environmental conditions for corals were to improve.

**Seagrass**

Seagrass communities play a critical role in coastal marine systems as a nursery habitat for fish and crustaceans, and are also recognised to be particularly vulnerable to increases in catchment loads. Seagrass typically have high light requirements, and are vulnerable to reductions in light availability due either to turbidity, sedimentation or fouling by epiphytic microalgae and over-growing macroalgae. Widespread loss of seagrass, with major consequences for dugong populations, has been observed following major flood events in Hervey Bay at the southern end of the GBR.

Seagrass have access to dissolved nutrients in pore water and therefore have a competitive advantage over macroalgae when water column nutrient concentrations are low. They become vulnerable to fouling from epiphytic algae and overgrowth and shading by macroalgae when water column nutrient concentrations increase. Seagrass meadows, particularly those close to estuaries, are also potentially vulnerable to herbicides and sedimentation.

Healthy seagrass beds help to trap fine sediments and reduce resuspension, thereby reducing chronic turbidity. Once seagrass beds are lost, increased resuspension may maintain turbidity at levels which inhibit or prevent recolonisation. Similar thresholds have been observed in temperate seagrass beds located on sandy sediments in areas of moderate wave activity. Healthy seagrass beds help to bind sediments and reduce erosion. Once seagrass beds and the associated roots are lost, the sand bed becomes mobile, preventing seagrass recolonisation.
3 MODELLING FRAMEWORKS TO SUPPORT MANAGEMENT

3.1 The role of models

Models of receiving waters should play an important role in target setting in the formulation of catchment management plans. A second key purpose of receiving waters models is to support the assessment of the degree of success of management actions in achieving prescribed targets of water quality and ecological condition in receiving waters. The following section elaborates on these roles and on the requirements they impose on the form of the modelling frameworks.

Target Setting

If models are to be used for target setting they need to be able to link management actions to indicators of water quality condition or ecological condition. For the full paddock to reef health hierarchy, we need a system of models which links practices at paddock scale to reef health indicators. For receiving water models under discussion here, we need models which link end of catchment flows and loads of fresh water, sediments, nutrients and pesticides to Lagoon water quality indicators, and reef health indicators. This could in principle be done in one integrated model, or as two separate steps: i.e. loads to water quality, and water quality to ecosystem health.

The key water quality indicators are salinity, turbidity, inorganic nutrients, organic carbon and nitrogen, chlorophyll a, dissolved oxygen, pesticide concentrations, plus linked sediment properties (e.g. sedimentation rates, sediment respiration rates, sediment nutrient fluxes). Ecosystem health indicators for the GBR (or the ReefPlan) are not finalised, but proposed indicators include coral cover and broad composition (e.g. soft versus hard, massive versus branching), coral health (ecophysiological) indicators, coral recruitment, macroalgal cover and herbivorous fish stocks.

The bulk of catchment load is delivered in short periods during and immediately following major flood events. Models need to be able to represent the transport, transformation and impact of load constituents over the short time scales which these events occur. Materials delivered during floods are subject to further transport, transformation and cycling post-flood, potentially resulting in changes in baseline water quality. It is unclear to what extent the long-term ecological impacts of loads are due to acute effects during floods, versus effects of chronic changes in water quality. Models need to address both timescales and the associated processes. Note that it follows that catchment models or load scenarios also need to resolve event time scales.

There is very large interannual variability in runoff and loads into the GBR Lagoon. The GBR is also subject to other major events (e.g. COTS outbreaks, bleaching, shifts in ocean circulation) on time scales or intervals of years to decades. Consequently, models must be capable of simulating scenarios of multiple decades if they are to provide useful management support.

Impacts are spread over a range of space scales. Major flood plumes from the large catchments may extend hundreds of kilometres along shelf, and tens of kilometres cross-shelf. The chronic effects of loads on water quality and reef health are believed to occur primarily in the inner Lagoon, and on inshore reefs, but may still extend hundreds of kilometres along shelf. While there may be sharp gradients in properties within
estuaries, water quality indicators in the Lagoon would typically be assessed on space scales of kilometres or larger, and reef health indicators managed at the level of individual reefs or groups of reefs. Models need to resolve these scales, while recognising that many important processes occur at much smaller scales (metres or less in some cases), and will need to parameterised as sub-gridscale processes in models.

On time scales of months to years, horizontal advection and mixing can be expected to move dissolved substances over length scales comparable to the dimensions of the GBR system. On these time scales, one might expect significant interactions among catchments, and between catchment inputs and offshore ocean inputs of nutrients. Ecological connectivity among reefs may also extend over substantial distances, at least for species with long-lived larvae. Models will need to deal with these large-scale interactions.

All model predictions involve some uncertainty, and we can expect uncertainties associated with processes, parameters and forcing of GBR models to be substantial. The receiving water modelling framework must supply users with some capacity to assess the uncertainty associated with model scenarios.

Assessment

Receiving water assessment models can play a number of roles in management of catchment loads. They should at minimum allow calculation of agreed management performance measures from data produced by monitoring programs. These performance measures have not yet been defined for the GBR. But, one would expect measures to be defined as statistical properties, aggregating point observations of indicators over prescribed spatial domains and temporal windows. Models used for assessment should provide estimates of these properties, and of the likely error or confidence limits about these estimates.

While there is a natural hierarchy of spatial scales from paddocks to subcatchments to catchments, the hierarchy in the marine domain is not so obvious. Cross-shelf and long-shelf gradients in influence away from river mouths ought to underpin the definition of a spatial structure for marine performance measures.

Assessment models also have a potentially critical role to play in attribution. The marine water quality and reef health indicators are subject to a wide variety of other perturbations, and can be expected to show substantial variability on time scales of years to decades which is unrelated to catchment loads and/or land use practices. If these confounding variations in indicators cannot be partially or wholly removed or compensated, then it is questionable whether monitoring and assessment will provide feedback to managers on useful time scales. It is unlikely to be sufficient to look for long-term trends in indicators. It may be possible to use spatial patterns (gradients away from catchment inputs) as a crude form of attribution. Spatial-temporal correlation techniques have shown promise in linking some water quality indicators to loads. Water quality indicators ought to be more easily related to catchment loads than ecological health indicators given the potential importance of other phenomena (COTS, bleaching, cyclones) for ecological indicators such as coral cover. This is an argument for separating water quality models and ecological response models. It may also be an argument for focusing on diagnostic indicators of water quality such as physiological metrics.
3.2 The model framework

Transport is a fundamental process controlling the fate and impact of fresh water, sediment, nutrients and pesticides delivered from catchments. We believe the modelling community is currently in a position where it is feasible to build a realistic hydrodynamic model for the whole of the GBR, nested within an operational global model, which provides useful predictions of the movement of dissolved and particulate substances on time scales which resolve flood events and span interdecadal variation. By building this at whole of GBR scales, we can address interactions across catchments, and between terrestrial and ocean inputs.

While sediment dynamics and biogeochemistry are less well understood, there are existing process-based models which have demonstrated useful performance at scales ranging from estuaries to continental shelves. By coupling these models to the whole-of-GBR hydrodynamic model, one could provide a capacity to predict impacts of catchment loads on water quality under acute flood event conditions, and chronic post-flood and dry season conditions. The combined water quality model would provide a single integrated and consistent platform to predict changes in water quality in space and time in response to land use and load scenarios for any or all GBR catchments. Such model scenarios could be used directly to support the development of water quality targets for the GBR Lagoon, and to link these targets to end-of-catchment load targets.

At present, ecological targets are not included explicitly in the WQIPs, but the purpose of the WQIPs is to protect and improve the ecological amenity of the GBR through best-practice water quality management. Ecological response models are less well-defined at this time, and experimentation is likely to be required. Rather than integrate ecological response models tightly into the computationally intensive whole-of-GBR water quality model, it makes more sense to develop ecological response models as an independent module, and allow the dynamics of individual reefs or other ecological units to be driven by the output of the water quality model.

The whole-of-reef water quality model will not resolve some key processes occurring in estuaries, or around reefs and reef passages due to insufficient spatial resolution, but we will need to parameterise these sub-grid scale effects into the large-scale model. We suggest that an appropriate strategy would be to build a number of high-resolution local models which resolve these effects, and use these to test and improve these parameterisations in the whole of reef model. If it turns out that these high-resolution local models perform substantially better than the large model, and/or allow users to address management issues not accessible through the large-scale models, they may be developed as management tools in their own right.

The key to assessment is the concept of a performance measure, which measures how management is tracking against a target. Note that a performance measure is usually more than a single data point, and is typically based on a synthesis of data. Examples of possible quantitative performance measures for the GBR Lagoon include mean or percentile chlorophyll within some spatial region around a catchment, or for the inner Lagoon as a whole, or percent coral cover over a specified region.
Figure 3.1 shows our recommended model framework for supporting target setting and assessment in the receiving waters of the GBRWHA and its relationship with catchment models and the management process. The framework has three main elements namely:

- large-scale water quality model (LSWQ model)
- ecological model
- fine-scale impact models

Figure 3.1 Model framework suggested for supporting assessment and scenario testing for the WQIPs. For simplicity, forcing and assessment models are not shown.

The highest priority would be the development of the large-scale water quality model which is effectively a materials transport and transformation model. It takes as its inputs catchment loads of fresh water, sediments, nutrients and pesticides derived from catchment modelling or from measurement, and it simulates the transport and transformation of these substances in the receiving waters including their impact on primary production. It would also provide concentrations required by the ecological model and the appropriate flow, water level, salinity, and contaminant concentrations for fine-scale impact models that might be developed.

This model would be applied at the scale of the GBR Lagoon and so would allow for the effects of the interaction between plumes from multiple rivers. Applied at timescales of hours to decades, the LSWQ model would address the issue of acute exposure of the reef by contaminants in flood plumes as well as more chronic exposure during the dry season. Timely model development would allow its use to support the review of WQIPs.

We propose that ecological models be developed to simulate coral cover, coral recruitment, macroalgae and COTS as indicators of reef health. The ecological impact models needn’t be spatially explicit, but impacts to individual reefs could be considered as consequences of their exposure to contaminants determined by the LSWQ model.
described above. Thus, the LSWQ model is a necessary precursor to the ecological impact models.

We have not identified the particular fine-scale models that might be required. Their specification might depend on management needs and the requirements of the LSWQ model and ecological models. An example of a model that might be required is an estuarine response model. With depth scales and width scales which are mostly less than those likely to be adopted for the grid in the LSWQ model, the latter model is not likely to be adequate for simulating estuarine response. Further, estuaries include a suite of processes that will not be included in the LSWQ model including mangrove-estuary and floodplain-estuary interactions.

Within this framework, it is likely that a number of supporting models will be needed also. Models for describing forcing or inputs necessary for the main models and models for assessment will be required. In the following sections, we describe the requirements of the main models in more detail and outline some of the supporting models required.

### 3.3 Large-Scale Water Quality model

**Form and function**

The LSWQ model has three model elements (Figure 3.2) which simulate the hydrodynamics, fine-sediment dynamics and the biogeochemistry. Briefly, the hydrodynamic element simulates currents and mixing that are important for transporting contaminants. It should also simulate water temperature and salinity. The sediment transport model includes the processes of settling, resuspension, and transport to obtain predictions of fine-sediment concentrations and distributions. Fine sediments are important for transporting attached nutrients as well as having the potential for significantly reducing the light required for the growth of primary producers in the water column and on the sea bed. The biogeochemistry model simulates the transport and transformations of nutrients including primary production. Outputs of this model include the concentrations of nutrients in receiving waters as well as the form and stocks of primary producers. The hydrodynamic model can be implemented independently whereas the other two models depend on its predictions of currents and mixing. There are additional dependencies of the biogeochemical model on the simulations obtained from the sediment transport model.

The LSWQ model is linked to the ecological impact model through provision of the basic habitat properties (e.g. salinity, temperature and underwater light regime) that define and delineate different habitats, It would also simulate the rate and form of primary production which determines the food supply of aquatic organisms and may also affect substrate availability (coral settlement vs. macroalgae). Linkages to fine-scale models occur through the provision of boundary conditions.

The LSWQ model would be process-based and deterministic and would simulate physico-chemical habitat, contaminant concentrations, and primary production as these respond to riverine inputs of fresh water, fine sediments, pesticides, and nutrients and to oceanographic and meteorological conditions within the GBR Lagoon. Model outputs would be time series of water properties of interest that could be used as drivers for the ecological or fine-scale models or as inputs to assessment models that could be used to summarise the water quality conditions as required by WQIPs.
Figure 3.2 Model elements of Large-Scale Water Quality model (inside box) showing internal linkages between elements and linkage to models of ecological impacts.

**Essential processes and features**

Tables 4.1-4.3 summarise the essential processes and features of the three elements of the LSWQ model that are required for the model to achieve its intended purpose.
Hydrodynamic model

<table>
<thead>
<tr>
<th>Essential processes and features</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-dimensions</td>
<td>plume dynamics are fundamentally three dimensional</td>
</tr>
<tr>
<td>scale of GBR Lagoon</td>
<td>must allow for interactions between river plumes along length of GBR and impact zones which may include offshore coral reefs</td>
</tr>
<tr>
<td>decades-long simulations</td>
<td>must resolve interannual variability</td>
</tr>
<tr>
<td>spatial resolution as small as feasible</td>
<td>spatial resolution will be determined by computer run time constraints</td>
</tr>
<tr>
<td>must resolve tides</td>
<td>tidal currents may be the dominant agents of sediment resuspension and contaminant mixing</td>
</tr>
<tr>
<td>should include ability to simulate currents, mixing, temperature, salinity</td>
<td>currents &amp; mixing are necessary for describing transport of contaminants, phytoplankton and larvae; temperature and salinity are important properties of aquatic habitat</td>
</tr>
<tr>
<td>should include forcing by winds and longshore pressure gradients in Coral Sea</td>
<td>prevailing south easterlies drive currents towards the NW for most of year, but offshore pressure gradients can reverse flows on shelf</td>
</tr>
<tr>
<td>ideally should be nested inside large-scale eddy-resolving ocean models</td>
<td>mesoscale processes in ocean circulation are likely to strongly affect exchange between the Coral Sea and the GBR Lagoon.</td>
</tr>
<tr>
<td>requires capacity to link with models of smaller scales</td>
<td>a major role of the large-scale model would be providing boundary conditions for smaller nested models</td>
</tr>
<tr>
<td>requires capacity to provide transport framework for sediment and biogeochemical models</td>
<td>sediment and biogeochemical models require specification of currents and mixing at suitable grid scales</td>
</tr>
</tbody>
</table>

Table 3.1 Essential processes and features for hydrodynamic model.
# Sediment transport model

<table>
<thead>
<tr>
<th>Essential processes and features</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>domain, grid selection, time of application should be consistent with hydrodynamic model</td>
<td>sediment dynamics model likely to be applied in parallel with hydrodynamic model or embedded in it; sediments dynamics model requires specification of currents and mixing</td>
</tr>
<tr>
<td>must resolve at least several size classes of sediments</td>
<td>sediment dynamics depend very much on particle sizes and real sediments show a continuum of particle sizes; importance of suspended sediments in determining u/w light depends on particle size as does their importance for carrying attached nutrients and agrichemicals</td>
</tr>
<tr>
<td>must include dynamics of resuspension and flocculation</td>
<td>initial deposition of plume sediments strongly determined by flocculation; subsequent sediment transport and suspended sediment concentrations determined by cycles of settling and resuspension</td>
</tr>
<tr>
<td>should include wave resuspension</td>
<td>in parts of GBR Lagoon sediment resuspension is dominated by waves</td>
</tr>
<tr>
<td>outputs should include suspended sediment concentrations during times of flood and during the dry, sediment transport fluxes and deposition rates</td>
<td>suspended sediments and secchi depth are WQIP targets in their own right</td>
</tr>
</tbody>
</table>

Table 3.2 Essential processes and features for sediment transport model.
### Biogeochemical model

<table>
<thead>
<tr>
<th>Essential processes and features</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>model should simulate both N and P dynamics</td>
<td>WQIP targets include both N and P species; we expect that the GBR Lagoon is carbon replete mostly and production is mainly limited by the availability of N or P</td>
</tr>
<tr>
<td>needs to include nutrients in various forms including dissolved inorganic, dissolved organic, particulate, and biotic in both the water column and in the sediments</td>
<td>nutrient dynamics involves cycling of nutrients between all these potentially important forms; benthic processes including diagenesis and primary production are important processes in nutrient cycling between the water column and sediments</td>
</tr>
<tr>
<td>needs to cover whole Lagoon</td>
<td>exposure of coral along the entire length of the GBR Lagoon is a potential issue</td>
</tr>
<tr>
<td>decades long simulation</td>
<td>needs to simulate interannual variability of the response to flood plumes and during the dry season</td>
</tr>
<tr>
<td>required output includes simulations of concentrations of DIN, DON, TN, DIP, TP, chla during both flood times and during the dry</td>
<td>these nutrient forms are WQIP targets within marine receiving waters</td>
</tr>
<tr>
<td>primary producers should include one or more groups of phytoplankton, microphytobenthos (benthic microalgae), macroalgae, corals</td>
<td>in the clear waters of the GBR Lagoon all these primary producers are potentially important agents in nutrient cycling; chlorophyll concentration in the water column is a potential WQIP target in its own right</td>
</tr>
</tbody>
</table>

Table 3.3 Essential processes and features for biogeochemical model.

### Pesticides

There are a number of herbicides which are being considered by the WQIPs including diuron, atrazine, 2-4D, hexazinone, ametryn, simazine, and tebuthiuron. Concentrations in river water are dependent on time and extent of application, and rainfall so that it is difficult to predict concentrations at ends-of-catchments using contaminant delivery models. At least one WQIP (Mackay-Whitsunday) is assuming that concentrations in marine receiving waters are simply a reflection of the dilution of measured concentrations in the river discharge and is setting the target for maximum pesticide concentrations accordingly. Decay times for these herbicides are weeks or longer, so that for the purposes of assessing the likely acute exposure from pesticides dissolved in flood plume waters one could assume that the concentrations in river water dilute conservatively. The hydrodynamic model coupled to a model that carries a suite of pesticides could be used to simulate pesticide concentrations in receiving waters. The addition of a decay timescale for each pesticide would be a feature that would be straightforward to implement.
Forcing & linkages

Linkage to catchment models

The LSWQ model carries fresh water and contaminants from the river end and transports them throughout the GBR Lagoon. Accordingly, it requires as input time series of catchment delivery of these materials at appropriate time intervals and over the decades for which we wish to run the LSWQ model. This catchment delivery needs to be specified as loads (or concentrations) of the species of contaminants that are of relevance to the modelling of sediment transport and biogeochemistry of the receiving waters. Strategies for linking catchment and receiving waters models are presented in more detail in Chapter 5.

Forcing of LSWQ model

Water motions throughout the GBR Lagoon are caused by a number of forcing phenomena which need to be represented in the hydrodynamic model. Oceanographic and meteorological forcing are spatially and temporally variable and would be best specified using output from data-assimilating models rather than interpolations of measured time series.

Meteorological forcing includes wind stress on the water surface and the surface fluxes of water vapour (evaporation), sensible heat and radiation. Historical data on wind stress can be obtained from meteorological hindcasting. Estimates of evaporation require knowledge of the humidity regime over the GBR Lagoon and air temperature is required for calculating sensible heat flux. Radiation flux can be estimated from measured cloudiness. Waves are important agents of sediment resuspension over much of the GBR Lagoon so the implementation of a wave generation model that depends on wind speeds and directions would be desirable.

It is apparent that long-shelf pressure gradients in the Coral Sea associated with the East Australian Current are important determinants of circulation within the Lagoon and may even reverse the general flow towards the NW caused by the SE trades (Luick et al., 2007). The hydrodynamic model needs to be able to accommodate these gradients if dispersal of contaminants in the Lagoon is to be modelled properly. Upwelling along the shelf break can introduce nutrients and cooler water onto the shelf through the seaward coral matrix. The potential for significant amount of nutrients input from the Coral Sea also needs to be considered. Mesoscale processes are likely to have an important effect on exchanges between the Coral Sea and the GBR Lagoon. Nesting the LSWQ model within an eddy-resolving ocean model will be important in order to represent these processes.

Climate change will influence the meteorological and oceanographic drivers of Lagoon circulation as well as the volume of run-off from the land. For example, an increase in the frequency of cyclones is a predicted consequence of climate change. On the assumption that climate change is significant for the GBR future, then its impact on the drivers needs to be included.

Uncertainty and error

Models are imperfect and simplistic representations of reality and as such their simulations are subject to uncertainty and error. In the deterministic LSWQ model, error and uncertainty arise from a number of sources:
1. Structural errors arising from the necessary simplification of the real world processes and system elements by a much smaller number of ‘connections’ and ‘boxes’ within the model. Examples include the representation of the continuum of sediment particle sizes by several discrete sizes in the model.

2. The necessity of imposing a grid size for models means that the model can only represent phenomena occurring at larger scales. This may have dynamical implications such as for the behaviour of freshwater plumes.

3. Models require the specification of parameters such as reaction rates and mortality rates and these are subject to uncertainty as they have generally been adapted from studies elsewhere. Further, in reality, parameters for a particular process (such as phytoplankton sinking) are likely to take on a range of values rather than a single number as specified in the model.

4. Time series of forcing for models are usually subject to some error due to the necessity to interpolate forcing functions from limited measurements. Examples include interpolating wind stress over the GBR Lagoon from several wind stations or inferring loads of dissolved and particulate nutrients from catchment models or from sporadic measurements of riverine concentrations.

5. Measurements used for the calibration (parameter adjustment) or validation of models may be subject to some incompatibility due to the large spatial heterogeneity usually evident in real systems and the limitation for models of only being able to represent variations at space scales larger than the grid scale.

Uncertainty and error can be minimised by strategies including careful implementation of the forcing functions and appropriate analysis of comparisons between model simulations and measurements. The only practical approach to assess uncertainty arising from parameter and structural uncertainty is to undertake an analysis involving numerical experiments. Of course, the predictive ability of the LSWQ model can be assessed by using one part of the measurement data set for calibration and another part for comparison against observations.

Model gaps
We have identified a number of gaps in understanding which if addressed would reduce modelling uncertainty and error.

1. Delivery rates and composition of materials from catchments could be better defined. This includes improved times series of loads of fine sediments, nutrients and pesticides from catchments along with estimates of their accuracies. We need to know more about the particle size distribution and geochemical properties of fine sediments particularly as these relate to flocculation rates and sinking speeds when these encounter seawater. Improved speciation of nutrients in riverine inflows has been identified as a goal for catchment modelling in Chapter 5. For phosphorus associated with sediments, we need differentiation between adsorbed (inorganic) and organic forms for example. The significance of smaller river and groundwater discharges directly to the coast in the Wet Tropics needs to be assessed.

2. The spatial resolution of the large-scale hydrodynamic model is likely to be not less than a few kilometres. Reef matrix and bathymetric features having spatial scales below the resolution of the model will affect momentum balances and mixing in the real world, but these can’t be accounted for directly. We need to
develop means for parameterising these sub-grid scale effects so their impact on the larger scale water motions is properly accounted for. Progress on fine-scale circulation has been achieved in recent finite-element modelling (Lambrechts et al., 2007).

3. The dynamics of fine-sediment transport have received relatively little attention in the scientific and engineering literatures. In contrast to coarse sediments such as sands, fine sediments are subject to geochemical and biological processes that have profound influences on their propensity to be resuspended. These processes include their cohesiveness (electro-chemical property) as well as biotic films and bioturbation. Another area needing investigation concerns the fate of fine sediments including the importance of mangroves and tidal creeks for trapping sediments.

4. There are a number of biogeochemical processes that require further investigation. Denitrification is a potentially important process for eliminating bio-available forms of nitrogen from the GBR Lagoon. Conversely, nitrogen fixation by organisms such as cyanobacteria that are present in the water column can represent a significant input of bio-available nitrogen to the system. We need better understanding of the importance of these two processes as well as the development of calibrated computer algorithms to represent them within the larger biogeochemical model. We need improved understanding of the relationship between fine benthic and suspended sediments and nutrients and organic matter. What is the role of carbonate in phosphorus dynamics and in the precipitation of this nutrient from the water column? The importance of nutrients upwelled at the shelf break on Lagoonal nutrient budgets also needs to be established.

3.4 Ecological model

Form and function

Ecological indicators and targets are not explicitly included in the WQIPs, but they may be in future. If this happens, then ecological models could play a direct role in assessment and in scenario analyses. In the shorter term, a potential function of ecological modelling would be to inform what water quality properties need to be considered to maintain reef health. In this role, they would be used to support the development of assessment criteria (and models) for assessing water quality impacts.

A review of important indicators and performance measures for water quality and ecosystem health for the reef environment (Fabricius, 2007) suggests that key indicators identified to date include coral recruitment, macroalgal concentrations and Crown of Thorns Starfish (COTS). Other potential indicators include herbivorous fish, coral ecophysiological indicators and coral cover. Coral recruitment, COTS, and coral ecophysiological indicators have the advantage of being relatively short term indicators of response, whereas coral and algal covers have the disadvantage of being larger scale and longer term. Of course, the latter two indicators are more direct measures of the ecological amenity of the reefal system. A combination of these shorter and longer term indicators is likely to be most useful.

We have identified that a fruitful modelling approach is likely to be the modelling of ecological recovery after impact due to freshwater immersion, cyclone damage, coral
bleaching or COTS. The underlying hypothesis is that recovery after reef damage depends on the relative ability of coral and macroalgae to recolonise. The growth response of juvenile coral versus macroalgae depends on water quality parameters including nutrients and underwater light. The HOME and CO2RAL models (described in Chapter 4) are based on this fundamental impact-recovery principle, but both are likely to require further development to meet management needs. The ecological impact models would most likely not be formulated directly on the hydrodynamic model grid, but would adopt an individual-based framework, with impacts to individual reefs considered as consequences of their exposure to environmental quality determined by the LSWQ model described above. As with the LSWQ model, we would expect that the ecological models would be applied on the scale of the whole GBR Lagoon.

**Essential processes and features**

The structure of the suitable ecological models is not prescribed here. It could be deterministic (HOME) or probabilistic (CO2RAL). Nevertheless, there are some key features that need to be included (Table 4.4)

<table>
<thead>
<tr>
<th>Essential processes and features</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>model needs to consider all likely determinants of reef degradation including temperature, salinity, nutrients, turbidity, sedimentation, and pesticides</td>
<td>impact on reef is a combination of factors that act synergistically</td>
</tr>
<tr>
<td>model needs to link to water quality receiving waters models</td>
<td>need to establish the link between management action and reef health in setting reef ecological objectives</td>
</tr>
<tr>
<td>model should be time resolving and applied for decadal time periods including both times of plumes and during the dry season</td>
<td>recovery of the reef after severe impact is likely to be the best indicator of underlying reef health and resilience; impacts from plumes may be acute or due to chronic decrease in water quality during the dry season</td>
</tr>
<tr>
<td>model needs to simulate indicators that are measurable and are relevant</td>
<td>verification against measurements is necessary for model confidence</td>
</tr>
</tbody>
</table>

Table 3.4 Essential processes and features for ecological model.

**Forcing & linkages**

As proposed, the ecological impact models would rely on the LSWQ model to simulate the exposure of reefs and other receiving waters to changing environmental quality. In particular, the LSWQ model would provide estimates of the exposure of reefs to acute and chronic nutrient concentrations, phytoplankton, and salinities during plume events, pesticide concentrations, and water temperature. The LSWQ model might also provide currents and mixing for coral larvae dispersal if required. The outputs from the LSWQ model need to be formulated appropriately (time series and/or statistics) to be useful to the ecological response models requiring that the two groups of modellers maintain active cooperation with each other.
Uncertainty and error

The ecological models are subject to many of the same sources of error and uncertainty as is the LSWQ model framework described above. All confront issues of structural simplification and process approximation, parameter uncertainty and errors in forcing. Ecological systems and interactions are arguably more complex, and one might expect greater uncertainty around ecological predictions. One might look to ecological models to predict qualitative impacts and responses, and to provide insight into the time scales of impact and recovery. Given the greater uncertainty in ecological models, adoption of a stochastic modelling framework (e.g. Bayesian Belief Networks or Bayesian Hierarchical Models) has potential advantages.

Model gaps

The modelling workshop identified a number of knowledge gaps pertinent to the development of impact-response models. These include:

1. The HOME model for example incorporates an inverse relationship between herbivorous fish populations and water quality (especially turbidity). By grazing on macroalgae, herbivorous fish are hypothesized to exert a major influence on the outcome of competition between coral and macroalgae. Given its potential significance, the interaction among herbivorous fish, turbidity and macroalgae deserves further investigation.

2. There is potential for the use of fish as indicators of reef health in their own right. This would require models linking fish population or community dynamics to catchment loads, water quality and productivity, as well as other pressures, including harvesting. Models of this kind have been developed for other systems (see Chapter 4).

3. We require better understanding of the relationship between macroalgae (and corals) and dissolved inorganic nutrients. Knowing the growth rates of macroalgae and how they respond is crucial to simulating how a reef might respond to nutrient enrichment.

3.5 Fine-scale impact models

Form and function

We have identified the need for a series of higher resolution case studies to meet specific purposes. These fall into several categories:

1. To resolve water quality response in areas where the resolution of the LSWQ model is too coarse. The LSWQ model is likely to have a horizontal resolution of ~2 km which will be inadequate for modelling water quality response in estuaries, embayments, tidal creeks, and coastal lagoons. Small coastal catchments draining directly to the GBR Lagoon may deliver significant pesticide concentrations whose impact would not be well resolved by the LSWQ model. A smaller scale water quality model nested within the larger LSWQ model might be required here. The modelling of fine-sediment transport particularly is likely to benefit from higher resolution model grids.

2. To investigate water quality and/or ecological response in zones where processes represented in the LSWQ and ecological models may be inadequate. One application of this type is the modelling of water quality and ecological
response in estuaries. This will require representation of additional local processes such as exchange of dissolved and particulate nutrients with mangrove wetlands bordering the estuary. A related example is the modelling of flows and contaminant exchange between floodplains and estuaries that will need to be undertaken if (as we suspect) they cause significant changes to material delivery to the coastal zone. Modelling of impacts of water quality on seagrass may require some different processes as well as more accurate modelling of suspended sediment concentrations and turbidity.

3. To better understand how to represent and parameterise processes in the larger scale model. For example, high-resolution models of the flow around the reef matrix and through channels between reefs might be used to test and improve parameterisation of these effects in the large-scale model.

It is likely that models for case studies would be similar in principle and processes to the LSWQ and ecological models. These might be the same models applied at a smaller scale, or include modified or enhanced process representation where appropriate.

The modelling workshop considered that it would be useful and feasible to undertake a number of high resolution case studies to support the WQIPs and assess ecological impacts in the receiving water zones of the major river basins. The Douglas, Barron, Tully, Black/Ross, Burdekin, Mackay/Whitsunday, Fitzroy, and Burnett regions were considered. Of these, it seems that the best opportunities are available in the Tully, Mackay/Whitsunday and Fitzroy regions. The Tully is the focus of studies aimed at deriving an understanding of estuarine exports and of floodplain-estuary interactions. The Mackay/Whitsunday has extensive water quality and ecology data and a clear spatial definition. The Fitzroy has the benefit of significant data collection and water quality modelling having been undertaken in the last few years. In addition, it was suggested that a pristine, far northern area such as Princess Charlotte Bay should be considered.

**Essential processes and features**

Features required by the LSWQ and ecological models as outlined in previous sections might be relaxed for the case-study models. For example, an estuarine model might be a series of boxes along an estuary rather than a full 3-D model. Conversely, if the case study models are used to define water quality in receiving waters zone, they might have the same essential properties except for the scale of their application. Depending on what is being modelled, the case study models might require more or different processes than the larger scale models. For example, estuarine models might need to include floodplain and mangrove forest interactions and extensive intertidal areas. Different sets of organisms might need to be included.

**Forcing & linkages**

An essential feature is that the fine-scale case studies be properly linked to the LSWQ model or the ecological models as necessary. LSWQ model would provide boundary conditions for fine-scale models as required such as water levels, currents, large scale concentration distributions.
4 REVIEW OF EXISTING MODELS

A series of models have been applied within the GBR to simulate biophysical and ecosystem processes across relevant temporal and spatial scales. These models range in capability from statistical reef exposure indices, coupled hydrodynamic, sediment and biogeochemical models, through to a limited number of ecological models. Each of these models has aimed to simulate key processes driving the dynamics of material transport, the fate and impacts of nutrients, and ecological response as described in Chapter 2. The time scales of model drivers range from tidal to decadal with large interannual variability in both runoff volume and suspended loads. Further, water quality and ecological responses are often cumulative and lag acute impact events, so it follows that if models are to be used to inform management through enhanced knowledge of natural variability and/or scenario testing, then they must be capable of providing simulations that span multiple decades. From a spatial perspective, there are key processes with ecological consequences that occur at fine-scales, such as sharp gradients within river plumes and reef- and passage-generated circulation features. Models across all categories need to capture these processes, either by parameterising sub-grid scale processes, resolving appropriate scales, or a combination of both.

In this chapter, we describe the key capabilities of a range of models with an emphasis on models that are presently implemented or have a history of recent application to the GBR. We identify and discuss how these models have been used in the context of GBR water quality planning or target setting, and explore opportunities for the application of existing modelling capabilities.

4.1 Material transport models

Material transport models simulate processes influencing the transport of water and sediment and the movement and transformations of dissolved and particulate waterborne material. These models are, with few exceptions, process-based and deterministic, and conform to a general hierarchy of application as follows:

- hydrodynamic models provide transport trajectories and dilutions for waterborne material as driven by tides, regional ocean circulation, atmospheric fluxes, river inflows and density gradients;
- sediment transport models simulate three-dimensional distributions of fine sediment in response to velocity and salinity fields from hydrodynamic models and prevailing wave conditions.
- biogeochemical models simulate nutrient concentrations and primary production in response to velocity, salinity and temperature fields from hydrodynamic models, and estimates of dispersal of sediment-bound nutrients and underwater light penetration (turbidity) from sediment transport models.

The connected suite of hydrodynamic, sediment dynamics and biogeochemical models form the basic elements of the LSWQ model identified as a priority component of our recommended model framework in Chapter 3.

There are numerous modelling packages, both proprietary and in the public domain, that could in principle provide the necessary understanding of material transport and transformation on the GBR Lagoon. Accepted public domain models such as ROMS
(Wilkin et al., 2005), MOM (Griffies et al., 2004), POM (Blumberg and Mellor, 1987) are representative of 3-dimensional, primitive equation coastal ocean circulation models that have found application in shelf scale modelling activities throughout the world. These are generally finite-difference models applied on linear orthogonal or curvilinear orthogonal computational grids. An exception is FVCOM (Chen et al., 2007) which uses a finite-volume approach on an unstructured-grid, and is emerging as a well supported tool for shelf applications. Many of these models include some form of coupled sediment and biogeochemical models with various degrees of complexity.

Proprietary modelling packages such as Delft3D, Mike 21, and RMA offer similar functionality to public domain models. For pragmatic reasons, we limit our discussion below to models implemented by groups that have active or recent involvement in modelling activities on the GBR.

**Hydrodynamics models**

**Hydro** (AIMS - Brinkman, King, Wolanski)

Hydro is a general-purpose, finite-difference, depth-averaged, hydrodynamic model (see King and Wolanski, 1992; Brinkman, 2002), primarily applicable to lagoonal transport processes driven by sea level (tidal and sub-tidal frequency) and wind. It is not suitable for stratified environments. It is applied on an orthogonal grid which provides uniform spatial resolution across the entire model domain. Standard outputs include two-dimensional distributions of sea level and depth-averaged velocity. Inputs and outputs are resolved at sub-tidal to inter-annual time scales. A coupled advection/diffusion model simulates the trajectories of waterborne material/organisms with simple behaviour (decay, locomotive ability). Inputs and outputs are resolved at sub-tidal to inter-annual time scales.

The primary region of application of Hydro has been the central section of the GBR from Bowen to Cooktown, modelled using a uniform rectangular grid with 2-km resolution. Finer resolution (down to 500 m) local applications have been achieved through a nesting approach. In addition to the GBR, Hydro has been applied to King Sound and Darwin Harbour.

**Bode and Mason** (JCU and AMC - Bode, Mason)

The model of Bode and Mason is a finite-difference, depth-averaged, hydrodynamic model. An important feature of the model is the incorporation of a reef parameterisation scheme (Bode et al., 1997) which permits incorporation of sub-grid scale dynamics into flow simulations without requiring the sub-reef scale topographical features themselves to be resolved by the model grid. The model is forced by sea level (tidal and sub-tidal frequency) and wind, and is not suitable for stratified environments. Standard outputs include two-dimensional distributions of sea level and depth-averaged velocity. Inputs and outputs are resolved at sub-tidal to inter-annual time scales. The model of Bode and Mason represents the most accurate tidal model available for the GBR shelf.

A recent application of this model to the GBR (see Luick et al., 2007) employed a uniform orthogonal grid of ~1.8 km resolution covering the region from Fraser Island to the Torres Strait. The model has been used to investigate flow trajectories and residence time along the GBR Lagoon through coupling to a Lagrangian particle tracking scheme.
**SLIM** (Catholic University of Louvain - Deleersnijder)
SLIM (Second-generation Louvain-la-Neuve Ice-ocean Model) is a finite-element, barotropic, hydrodynamic model implemented on an unstructured grid in either two or three dimensions. The use of a variable-resolution unstructured grid allows the model to increase resolution in areas of complex, non-uniform topography where small scale motions are relevant, while allowing coarser resolution in areas of reduced complexity of flow. SLIM is not suitable, at present, for stratified environments. Standard outputs include two-dimensional distributions of sea level and depth-averaged velocity, resolved at sub-tidal to inter-annual time scales.

The implementation of SLIM on the GBR (Lambrechts et al., 2007) extends from Fraser Island to Cape York Peninsula, and is forced by wind, tides, and the low-frequency sea level fluctuations along the boundary with the adjoining Coral Sea. The variable-resolution grid has element sizes that range from 150 metres to ten kilometres which allows the model to accurately represent fine scale features of the reef topography. A model of passive material transport allows investigation of the transport of an arbitrary number of scalar variables.

**MECCA** (AIMS, CRCReef - King)
MECCA (Model of Estuarine and Coastal Circulation Assessment) is a three-dimensional, finite-difference hydrodynamic model suitable for the prediction of tidal, wind- and density-driven flows in bays and shallow continental shelves (Hess, 1989). The model allows forcing by the wind, surface heat and freshwater fluxes, and by open boundary conditions such as temperature, salinity and sea level. Standard outputs include three-dimensional distributions of velocity, temperature, salinity, density and two-dimensional distributions of sea level.

MECCA has been adapted to simulate the discharge trajectories, distributions and dynamics of flood plumes originating from the Burdekin, Herbert, Tully, Johnstone, Russell, Barron, Daintree, Endeavour, Jeannie and Normanby Rivers for the period 1969–1998 (King et al., 2002), as forced by river discharges (freshwater fluxes) and wind. Tidal influences are included implicitly via an enhanced mixing parameter. The numerical grid is orthogonal with a resolution of 2.7 km in the horizontal and 5 layers in the vertical using a sigma coordinate representation. The model covers a large portion of the northern and central regions of the GBR.

MECCA was the first model applied to simulate the distribution of flood plumes on the GBR and has underpinned a number of subsequent water quality models (Reef Exposure and Chlorosim) and ecological model (HOME and Tropical Seagrass BBN) described later in this section.

**SHOC** (CSIRO Marine and Atmospheric Research - Herzfeld)
SHOC (Sparse Hydrodynamic Ocean Code) is a general-purpose finite-difference baroclinic, hydrodynamic model applicable in either one-, two- or three-dimensions to scales ranging from estuaries to ocean basins (Herzfeld et al. 2004). SHOC is applied on a curvilinear-orthogonal grid which allows gradually changing grid resolution to provide higher resolution in regions of interest. The model allows forcing by the wind, atmospheric pressure gradients, surface heat and freshwater fluxes, and by open boundary conditions including temperature, salinity and sea level. Wave forcing can also specified to represent the effects of wave-enhanced bottom friction in shallow water. Standard outputs include three-dimensional distributions of velocity, temperature,
salinity, density, and mixing coefficients, as well as two-dimensional fields such as sea level and bottom friction. Inputs and outputs are resolved at sub-tidal to inter-annual time scales. SHOC forms part of a fully coupled Environmental Modelling Suite (EMS), that includes a sediment transport model (MECOSED) and a biogeochemical reaction model (SERM).

SHOC has been applied to the Fitzroy Estuary and Keppel Bay system in the southern GBR as an assessment tool to simulate the downstream effects of changes in catchment land use (Robson et al., 2006). It has also found previous application in systems such as the Derwent and Huon Estuaries in Tasmania, the Gulf of Carpentaria and Torres Strait.

SHOC is currently implemented along the Queensland coast from Moreton Bay to Cairns using a nested grid approach as part of the Marine and Tropical Science Research Facility (MTSRF) Program 5. The nesting approach uses a coarse grid with 3-10 km resolution, bounded inshore by the coast and offshore by the 2000m isobath. An intermediate grid with 2 km resolution covers the areas from Burnett Heads to Broad Sound, and a local reef-scale grid of 50-500 m resolution centred on the Capricorn-Bunker Group of islands. The coarse grid model is forced with BLUElink global ocean model products.

Reef Exposure (ACTFR - Brodie, Devlin)
The Reef Exposure model (Devlin et al., 2003) is a statistical model of hydrodynamic transport that simulates probabilities of river plume dispersion, dilution and sedimentation. Probabilities of the direction of river plume dispersal are based on observed and modelled plume behaviour driven by winds, tides and modified by the Coriolis force. The model utilises the plume distributions as predicted by the MECCA flood plume modelling (King et al., 2002). Dilution and sedimentation are modelled from empirical data on the dispersion of particulate and dissolved materials in plumes. For a given ensemble of inputs including river discharge, flow frequency, suspended sediment load, nitrogen load, phosphorus load, herbicide (total proxy) the model predicts a numerical indicator of exposure at a particular point (e.g. a reef) to each pollutant. The model is only applicable in regions where data exist on flood plume extent (observed or modelled).

The model is presently being applied to show the effect of different loads of pollutants (derived from credible catchment management scenarios) from individual catchments. The model can be used in ‘reverse’ to link exposure at a particular reef to a particular and identified set of rivers. Results of the original version (as in Devlin et al. 2003) have been used widely to identify areas of the GBR exposed to high pollutant exposure and thus prioritise catchments for management.

An improved Reef Exposure Model is presently under development (Maughan et al., in prep.). The improved model builds on the approach followed by Devlin et al. (2003), but predicts dilutions for an enhanced suite of pollutants delivered through the 51 main rivers along the GBR coast. The model predicts a numerical indicator of exposure at each of the ~3000 reefs of the GBR compared to 30 assessment points in the previous version. The new model also incorporates improved dispersal equations and better input data for pollutant loads.
Sediment transport models

**MECOSED** (CSIRO Marine and Atmospheric Research - Margvelashvili)

MECOSED (Model for Estuarine and COastal SEDiment transport) is a three-dimensional, fine-resolution, process-based model of estuarine, coastal and shelf scale suspended sediment transport. The model simulates advection and turbulent diffusion in the water column, resuspension and deposition at the seabed, and bioturbation within the seabed. It is forced by three-dimensional fields of currents and wave characteristics (orbital velocities, direction and period). A spatial description of seabed texture (e.g. the distribution of mud/sand/gravel deposits) is required for initialisation, and mandatory model input includes sediment loads/concentrations at point sources (rivers) and at open-sea boundaries. MECOSED is generally coupled with SHOC as part of the CSIRO Environmental Modelling Suite.

MECOSED has been used in a number of coastal and shelf scale applications around Australia, including macrotidal environments (Fitzroy Estuary, North West Shelf, Torres Strait), baroclinic salt-wedge estuaries (Derwent), and temperate lagoons (Boston Bay). In the Fitzroy Estuary and Keppel Bay (Coastal CRC study), the main objective of simulations was to assess the impact of dynamic processes within these water bodies on mediating the delivery of fine sediments from catchments to the GBR Lagoon under conditions of altered landuse practices. In the Torres Strait region (Torres Strait CRC), the model was used to investigate the temporal and spatial variability of fine-sediment transport aiming at better understanding of processes influencing seagrass variability on the shelf.

**Cohesive Sediment Transport model** (AIMS - Wolanski)

The cohesive sediment transport model developed by Wolanski includes parameterisation of key processes including physical filtering (e.g. flocculation due to horizontal salinity gradients and the vertical current structure in estuaries), biological filtering and the formation of muddy marine snow, tidal pumping, the formation of a turbidity maximum zone and sediment dilution. The model is also able to take into account net erosion or siltation, and thus can simulate changes to the bathymetry leading to feedback to the hydrodynamics. The model can be applied in one-, two ½ - or three-dimensional modes depending on the dimensionality of the forcing hydrodynamics.

The model has been applied in tropical estuaries (Fly River and Ord Estuary) and in macrotidal environments on continental shelves (King Sound). For examples see Wolanski et al. (1995), Wolanski et al. (2001), Wolanski and Spagnol, (2003).

**NephDyn** (AIMS - Brinkman)

NephDyn (Nepheloid Dynamics) is 2 ½ -dimension model of coastal nepheloid layer dynamics (Brinkman et al. 2004). The model is driven by depth-averaged currents and the baroclinic nepheloid layer behaviour is explicitly parameterised. Outputs are 2-dimensional distributions of fine-sediment concentrations. The model has been applied only in the Cairns region of the GBR.

**Biogeochemical models**

**SERM** (CSIRO Marine and Atmospheric Research - Parslow)

SERM (Simple Estuarine Response Model) is the biogeochemical module of the CSIRO Environmental Modelling Suite. SERM simulates the transport and transformation of nutrients (carbon, nitrogen, and phosphorus) in both the water column and sediments,
either as a box model, or coupled to a (multi-dimensional) transport model and applied in one-, two- or three-dimensions. It predicts concentrations of nutrient species, dissolved oxygen, dissolved organics and detritus, growth rates of primary producers including phytoplankton (multiple classes), zooplankton, macroalgae, and benthic microalgae and seagrass as well as turbidity and light attenuation. Primary production by coral zooxanthellae could be added.

SERM requires specification of currents, mixing, salinity and temperature that may be provided by a hydrodynamic model and possibly also fine-sediment concentrations from a sediment model. Additional requirements of SERM include time series of solar radiation and specification of nutrient concentrations along boundaries. Inputs should also include river and point-source loads of nutrients specified in appropriate forms (i.e. inorganic, organic, particulate etc.) SERM represents processes including transport, deposition and resuspension, nutrient uptake and primary production, grazing, remineralisation, adsorption-desorption, denitrification, nitrogen fixation, and benthic-pelagic exchanges. An important feature of the SERM is its representation of nutrient cycling processes within seabed sediments. Processes such as benthic organic matter degradation and the return of nutrients to the water column (benthic-pelagic fluxes) are particularly important in shallow, energetic systems.

SERM has been used widely to run scenarios linking nutrient loads to water and sediment quality and so has been used to directly influence management decisions in many case studies: Port Phillip Bay (Murray and Parslow, 1999), Gippsland Lakes (Webster et al. 2001), Huon Estuary & D’Entrecasteaux Channel, Ord Estuary (Parslow et al., 2004), and the Fitzroy Estuary (Robson et al., 2006). SERM has also been used in shelf-scale applications to underpin ecosystem models on the North West Shelf and South Western Australian coasts (Herzfeld et al., 2006; Wild-Allen and Rosebrock, 2006).

**ChloroSim (AIMS - Wooldridge)**

ChlorSim is a spatial model of water quality, in the central and northern sections of the GBR Lagoon using chlorophyll a concentration as a proxy (Wooldridge et al., 2006). The model uses flood plume extent and minimum salinity data (as predicted by the MECCA flood plume modelling) to relate predicted dilution ratios to dissolved inorganic nitrogen (DIN) and chlorophyll a concentrations for specified river discharges and nitrate loads. ChloroSim provides a methodology that links a quantitative river discharge parameter (DIN) with a quantitative indicator of health in the marine environment (Chl a concentration), thus providing a means to estimate the level of reduction in fluxes of a land-sourced material (DIN) necessary to achieve specified lagoonal water quality standards. ChloroSim relies on regional in-situ observations of chlorophyll for parameter estimation, and on a spatial description of flood plume dilution factors. It is only applicable under wet season conditions, and its application is limited to the central and northern GBR, using the MECCA flood plume modelling of King et al. (2002), at that same spatial resolution.

**ARWQ (CRC eWater - Lawrence)**

The Australian Receiving Water Quality (ARWQ) Multi-Reach and Stratified Estuary Model is a box model of estuary water quality (Lawrence, 2007). The model captures water column physico-chemical and biological response processes, and sediment diagenesis to predict estuarine/instream water and sediment quality and ecological indicators for comparison against ANZECC Guidelines. Model inputs include catchment
inflows and loads, and tidal exchanges. Where significant longitudinal changes occur in conditions within the waterway, or the waterway is vertically stratified, multiple longitudinal boxes or vertical layers can be implemented. The model is spreadsheet based and this accessible form of implementation provides a useful tool for rapid assessment of changes in catchment landuse and management practices within simple estuaries. The ARWQ suite of models has been developed mainly for lake and water treatment pond applications. Its basic parameterisation appears to be appropriate to such systems though in principle this could be modified for marine systems. ARWQ has been applied to the estuary of the Mary River, but we do not know how successful this application has been.

4.2 Ecosystem Response Models

Ecosystem response models aim to capture the response of some component(s) of an ecosystem to changes in external drivers. On the GBR, the primary driver of relevance for this review is receiving water quality in a landscape of frequent disturbance by floods, cyclones and coral bleaching events. In contrast to the broad range of material transport models available, ecological models are less well-developed; they tend to focus only on selected functional groups of coral reef communities.

**CO2RAL** (AIMS - De’ath)

CO2RAL is a 2-dimensional, probabilistic model of coral reef ecosystem response to various water quality drivers and other disturbance events. The primary driver of the model is the interaction between Crown-of-Thorns Starfish (COTS) and coral cover. The model uses empirical relationships between chlorophyll concentration and the probability of COTS larval survival to drive COTS population dynamics on the GBR. Parameter estimation within the model benefits from long term spatial ecological and water quality data sets. COTS are controlled at the larval stage by survival (a function of chlorophyll concentrations) and by hard coral food supply as juveniles and adults. Drivers of early juvenile stage COTS such as fish predation and food supply (coraline algae) are also included. Bleaching and cyclone events are also included in the model. The model is reef based in the spatial domain and the dynamics of individual reefs are linked through knowledge of inter-reefal connectivity from hydrodynamic models and/or simulated connectivities based on known patterns of hydrodynamic drivers (e.g., the EAC). The model is formulated and coded in such a way that additional components based on empirical or theoretical linkages can be added easily. Inputs to the model include indicators of water quality (primarily chlorophyll concentration but water clarity could be added), connectivity, and time-series of disturbance (e.g. coral bleaching, fish predation). All inputs can be deterministic or stochastic, with uncertainties propagated through the system and reflected in the outputs. The model operates on time scales of years (typically 10s – 100s), and can be used for prediction, scenario testing and sensitivity analysis to determine critical parameters. The model currently has a ‘single-step per year’ set up. This has the advantages of speed (runs of 100 years on 500 reefs are completed in ~10 secs) and simplicity, but a disadvantage is the requirement for ‘end of year adjustments’. It would be straightforward to refine the model to include within-year steps.

**HOME** (AIMS - Wolanski)

HOME is a deterministic, ecological model of coral and algal abundances on coral reefs (Wolanski et al., 2004). It is a response-recovery model which simulates reef recovery following major disturbance events such as tropical cyclones and turbid river floods.
Reefs are represented as discrete ecosystems, with the main ecosystem driver being the interaction between coral, algae and herbivorous fish. Corals and algae compete for limited substrate, and herbivorous fish consume algae, with the abundance of herbivorous fish related to water clarity through an observed relationship. In effect, the relative success of recolonisation of reefs by corals and macroalgae following major disturbance is assumed to be due to ambient water and substratum quality. A key parameter controlling coral recovery is ambient cross-shelf gradient in water clarity during the dry season; the spatial distribution of this parameter is estimated from long term secchi disk observations throughout the GBR. Coral cover is also impacted by the abundance of COTS, which are the subject of a separate sub model (Wolanski and De’ath, 2005). Disturbance events (cyclones, flood, bleaching events) are represented by a step decrease in coral cover with the magnitude of the decrease being dependant on the type and location of disturbance. For cyclone events, the rate of disturbance is related to cyclone intensity and path; for flood events the model uses the MECCA flood plume modelling of King et al. (2002) to spatially represent variability in magnitude and duration of exposure to water of reduced salinity. Hydrodynamic models provide larval connectivity pathways to link individual reef models. Input to the model includes spatial descriptions of water clarity (as an indicator of water quality in response to landuse practice) and flood plume distribution characteristics, inter- reef connectivity, and time-series of disturbance (e.g. cyclones, flood events.). All inputs are deterministic and errors are not estimated explicitly. The model has been applied over time scales from months to decades.

**Tropical Seagrass Bayesian Belief Network** (Monash University - Colette Thomas)

Tropical Seagrass Bayesian Belief Network is a decision support tool for seagrass management decision making. Bayesian Networks (BNs) provide capacity to summarise small-scale, unpredictable, and unmanageable processes via probabilistic expressions, which can be updated as new information comes to hand. BNs require a coherent conceptual model and specification of key functional relationships within the system of interest. Data derived from experiments, process models, or statistically derived relationships are used to support and refine the understanding of key drivers, and expert knowledge may be used to fill data gaps. BNs allow uncertainties in the description of functional relationships to be propagated through to the model solution. The capacity to summarize system processes facilitates the testing of various management actions and encourages analytical focus to be directed toward the most critical factors.

The Tropical Seagrass BN predicts spatial and temporal changes in seagrass biomass and health in response to environmental (climate, weather, tides, light availability, benthic geomorphology), ecological (growth, recruitment, predation, mortality) and physiological (herbicide toxicity) drivers. Model inputs include description of river inflow intensity, duration and concentrations of suspended sediment, dissolved inorganic nitrogen, dissolved inorganic phosphorus, and diuron. The model has been applied to the Dugong Protection Areas of Hinchinbrook Island and Taylor’s Beach in the central GBR.

**Management strategy evaluation**

In addition to the ecosystem models described above, we describe two whole-of-ecosystem models that explicitly include management action and socio-economic drivers as model input in order to evaluate outcomes of different management strategies. Management Strategy Evaluation (MSE) frameworks generally include explicit estimates of uncertainty in the dynamics of the ecosystem and socio-economic system, the effects
of human uses or activities, and the implementation of monitoring and management measures. MSE thus provides a tool to analyse the potential effectiveness of various management strategies to achieve objectives despite known uncertainties.

The two models described below have not been used on the GBR but have been, or currently are, employed in regional scale applications elsewhere along Australia’s northern coast.

**InVitro**  
(CSIRO Marine and Atmospheric Research - Gray, Fulton)  
InVitro is an agent-based whole-of-ecosystem stochastic model for MSE. The model captures processes covering material transport, ecological interactions, and human activities including dredging, shipping, oil and gas exploration, production and processing, fisheries and conservation activities. The agent-based nature of InVitro allows other models of any kind (e.g. biogeochemical cycling) to be linked into the modelling framework. InVitro requires initial conditions for all components modelled. Forcing can include time series of hydrodynamics and contaminants, climate variability and management actions.

As part of the North West Shelf Joint Environmental Management Study, NWS-InVitro was used in a regional scale application to assess the effectiveness of management strategies in a region of multiple use (Gray et al., 2006) and it is currently being used for a whole of regional system MSE for the Ningaloo Reef - Exmouth Gulf area.

**Atlantis**  
(CSIRO Marine and Atmospheric Research - Fulton)  
Atlantis is a deterministic, whole of ecosystem model that can range in complexity from a simple NPZD (nutrient-phytoplankton-zooplankton-detritus) model through to entire trophic web + fisheries + impacts of pollutant sources and climate drivers. Components include physical forcing, sediment resuspension, sediment and water column biogeochemistry, trophic and non-trophic ecological interactions, and anthropogenic forcing and exploitation. Anthropogenic influences can be incorporated using fisheries assessment, management and socio-economic models. It is principally a fisheries MSE tool, but accommodates capacity to predict a range of ecological indicators including nutrient and chlorophyll concentration, productivity, biomass and habitat cover. Required forcing includes physical transport and light availability. Additional forcing includes point source inputs (river loads), temperature, salinity, rainfall, and fisheries related information such as spatial management definitions and historical catch and effort forcing, market data and fuel costs. Atlantis is primarily suited for testing management scenarios and estimates of uncertainty are generated through multiple runs with alternative scenarios or parameter sets. Versions with a more water quality focus have been developed at proof of concept level for Westernport (Victoria) and the Clarence River (NSW). Enhancement of estuarine processes capabilities, including linkages to catchment models, is under development.

### 4.3 Use of models for planning in the GBR

A subset of the models described above have been used to inform, in a limited way, management and planning activities in the GBR, primarily through estimates of the response of key water quality indicators to changes in volume and quality of catchment loads delivered to the GBR.
The MECCA flood plume modelling by King et al. (2002) has been employed to underpin the establishment of the Reef Exposure and ChloroSim models. The results of the Reef Exposure model have been used to inform decision making in the Fitzroy Basin and in the preparation of the WQIP for the Mackay Whitsundays. In the preparation of the Tully and Mackay-Whitsunday WQIPs, ChloroSim has been used to relate objectives for chlorophyll concentrations in marine receiving waters to riverine loads of DIN.

The Fitzroy study was the first integrated hydrodynamics (SHOC), fine-sediment dynamics (MECOSED), and biogeochemical (SERM) modelling study of the delivery of riverine material to the Lagoon. This model suite has been and continues to be used to evaluate the impacts of a series of landuse scenarios in the Fitzroy Basin on nutrient and sediment dynamics in the Fitzroy Estuary and in Keppel Bay. A WQIP is not being developed for the Fitzroy Basin, but the model results are being used to inform management decision making.

4.4 Model status and suitability
There are a number of models from the selection described above that are suitable for components of an integrated modelling framework. If we begin with the hydrodynamics, a critical selection criterion is the capacity to simulate the 3-dimensional dynamics of river plume dispersion driven by winds, tides and regional circulation influences. Using this as a guide, then models like SHOC, MECCA, ROMS, POM, and MOM seem like suitable candidates, but the track record of application to the GBR reduces the candidates to SHOC and MECCA.

The ability to nest within a large-scale ocean model is seen as being crucial, in order to provide accurate temporal and spatial (in 3-dimensions) description of open boundary conditions, including shelf-edge upwelling. There are a number of large-scale operational models available (such as BLUElink, HYCOM, NLOM, Pacific ROMS) and nesting within such a model is not technically challenging. As described above, SHOC is currently implemented on a large section of the GBR using a multiple nested grid approach, forced with BLUElink global ocean model products.

There are a limited number of models of fine-sediment dynamics models that are suitable to capture the range (and time and space scales) of sediment transport processes on the GBR. Initial deposition from flood plumes is controlled by flocculation and influenced by salinity. Subsequent resuspension by current and waves determines variability in background or chronic turbidity and sediment transport. Thus, the sediment transport model must be capable of using input of water velocity, salinity and wave energy time series. Both MECOSED and the cohesive sediment transport model of Wolanski appear to be suitable. MECOSED can be coupled to SHOC and SERM as part of the CSIRO Environmental Management Suite, and has found application in this arrangement to the Fitzroy Estuary and Keppel Bay in the southern GBR.

Of the biogeochemical models described here that might be applied on the scale of the GBR, SERM is the only candidate that captures essential nitrogen and phosphorus process dynamics, primary production and benthic-pelagic interactions. The model links with SHOC and MECOSED in an integrated modelling suite. ChloroSim has been used to relate DIN loads to chlorophyll concentrations in receiving waters following floods and
could still be used with MECCA or other hydrodynamic models for this purpose. Its limitations are in inability to represent dry season conditions and its restriction to chlorophyll prediction.

Another model that might be considered for application to estuaries in the GBR region is AWRQ. AWRQ has the advantage of having a relatively simple Excel implementation, but has very limited experience in applications to estuaries. It is certain to require extensive work to develop parameterisation suitable for the estuaries of the GBR.

The ecological models HOME and CO$_2$RAL both provide useful underlying frameworks upon which ecosystem components can be added as knowledge becomes available. Both models treat individual reefs as distinct ecosystems, with ecosystems dynamics governed by a set of rules and interactions. Reefs are linked through information of interreefal connectivity (from transport models). The primary difference between these models is the way that they deal with uncertainty. HOME is process-based and deterministic, and does not provide estimates of uncertainty as standard output; this is obtained through multiple runs with various parameter sets. CO$_2$RAL, in contrast, is probabilistic and uses primarily empirical relationships described as probabilities with uncertainties reflected in the outputs.

Whatever models are chosen, there will be careful research required in each element of the modelling framework to ensure that relevant processes necessary for the reliable simulation of water quality processes and ecosystem response on the GBR are fully captured or suitably parameterised. This will involve careful scrutiny of parameterisation algorithms and associated process rates and constants. Targeted process studies are also likely to be required in situations where process knowledge is lacking.
5 STRATEGIES FOR LINKING TO CATCHMENT MODELS – AN INTEGRATED APPROACH

Catchment models perform the essential function of linking the riverine delivery of water, nutrients and fine sediments at end of catchment to land management. As such, they are essential to understanding how changes in management practice will effect changes in water quality and ecological condition in the receiving waters of the GBRWHA. The link between the GBR receiving waters models and the catchment models occurs at the point of discharge of rivers into the coastal zone whether it is the head of an estuary or directly into the ocean. Mostly, water flows from catchment to ocean so there is little or no feedback between the two. This allows the catchment models to be implemented separately from the coastal receiving waters models. Nevertheless, receiving waters models do have particular data input requirements from catchment models, namely in terms of the specification of the particular materials that are delivered and of the timing of delivery. In the Wet Tropics, there can be two-way exchange of water between floodplains and estuary during times of flood. The importance of such exchange with floodplains in mediating the delivery of water, nutrients and sediments to estuaries and the coastal zone is not known properly. An initiative to address this issue is being undertaken and will be described later in this section.

In the following sections, we first describe key characteristics of the outputs of catchment models if they are to link effectively with receiving waters models. Next, we describe SedNet and E2/WaterCAST which are the two catchment models that are likely to be used for load simulation. MUSIC is a third model that simulates urban stormwater runoff. It is an example of a suite of models available from eWater that are designed to simulate features of water and constituent delivery from catchments. The three delivery models SedNet, E2/WaterCAST and MUSIC are also considered in terms of their suitability to meet the needs of receiving waters models. Finally, we describe the state of modelling floodplain-estuarine interactions in the Tully floodplain.

5.1 Catchment modelling requirements

River flow

The volume of fresh water delivered to the coastal zone is an important driver of the receiving waters hydrodynamic response through its impact on currents, plume formation and stratification. Also, salinity in receiving waters is an important environmental variable which will be determined in large part by the volumes of freshwater input. Consequently, the estimation of how river flows might be affected by land management changes is a desired output of catchment modelling.

Sediments

Sediments can be broadly classified as fine and coarse. Fine sediments are those somewhat arbitrarily defined as having grain sizes < 63μm. These are sediments that sink slowly in the water column and can be readily maintained in suspension by flow turbulence. We can expect that fine sediments affect the biogeochemical response of receiving waters in two main ways. Significant concentrations of fine sediments suspended in the water column restrict the light necessary for pelagic and benthic primary production. Also, a major proportion of the nutrients carried by the river are bound to fine sediments. Consequently, fine sediments are an important agent for the
input and redistribution of nutrients within the system. The large-scale water quality model we propose for the receiving waters of the GBRWHA should model the fate and impact of these introduced fine sediments and the nutrients associated with them. Thus, the catchment model would be required to simulate loads of these sediments to the coastal zone.

Further differentiation of the loads of fine sediments by particle size would be desirable. In our modelling of the Fitzroy Estuary, the modelled fine sediments were divided into two classes, one less than 10μm in grain size (clays) and one greater (silts). The fates of these two size classes in the receiving waters were predicted to be quite different from one another. The impact of coarse sediments (sands) by rivers to the coastal zone is not considered by the proposed receiving waters impact models, but the delivery of these sediments might be of interest in the context of their potential to alter the morphology of the coastal zone.

**Nutrients**

The nutrients normally considered to be the major determinants of primary production in the coastal zone are nitrogen (N) and phosphorus (P). The receiving waters impact model we suggest for the GBR would simulate the fates and impacts of these nutrients in their various forms. The specification of the loads of N and P from the landscape is the fundamental requirement of the catchment models employed. The nutrients in river discharge take a number of forms including dissolved inorganic, dissolved organic, and particulate. The particulate form can be further differentiated according to whether the nutrient is present as an organic coating on sediment, whether it is organic particle or, in the case of P, whether it is inorganic material adsorbed to the surface of sediments. It is necessary that the biogeochemical model proposed for receiving waters resolves these forms because the transport, transformation and significance of nutrients depend critically on them. In turn, the catchment models providing the nutrient loads to these models also require that the composition of these loads is specified in the same categories.

**Time resolution**

The rivers flowing to the GBR Lagoon show pronounced seasonal variability with largest flows typically occurring during the summer months. Highest flows are associated with the passage of tropical depressions or of cyclones. These floods persist for a few weeks and can be associated with large changes in discharge occurring from one day to the next. It would seem that the hydrodynamic response of the coastal system depends critically on the magnitude and duration of the freshwater inflows. Consequently, the distribution of fine sediments and nutrients introduced by the freshwater inflows immediately following the floods will also depend on the timing and magnitude of the flows. Ideally then, a catchment model should be able to resolve the shape of the river hydrograph. Daily resolution of the inflows should be sufficient.

**Simulation duration**

Over the past century, the annual discharge of the Fitzroy River varied by a factor of over 100. The rivers in the Wet Tropics show much less interannual variation in discharge, but the annual discharge of the Tully River still varies by a factor of 5 or so (Furnas, 2003). Since input loads of fine sediments and nutrients are likely to vary by at least as much as the input flows, the likely impact of these loads in receiving waters is certain to vary significantly from year to year. Simulations from catchment models need
to encapsulate the interannual variability which requires that the models are applied for extended numbers of years or that they are applied for representative flow years (High flow year, median flow year, low flow year for example).

5.2 Catchment delivery models

SedNet

SedNet constructs sediment and nutrient (N and P) budgets for regional scale river networks (2,000 - 1,000,000 km²) to identify patterns in the material fluxes. Targeting erosion control and other management measures at dominant sources can achieve a large benefit in reduced sediment and nutrient loads downstream with comparatively less resources than for non-targeted management.

A budget is an account of the major sources, stores and fluxes of material. SedNet defines a stream network as a series of links extending between stream junctions, and constructs sediment and nutrient budgets for each link (Figure 5.1). These budgets use conceptualisations of erosion, transport and deposition processes that are modelled using spatial datasets of terrain, soils, climate, vegetation cover and river discharge.

![Figure 5.1 Schematic of sediment delivery to a SedNet link (Courtesy of S. Wilkinson).](image)

Features of SedNet relative to other catchment water quality models include:

- Supply processes are modelled independently (hillslope, gully riverbank erosion, diffuse and point nutrient supply) to assist targeting of specific management measures.
- The connectivity between upstream sources and the catchment outlet is modelled by predicting the contribution of each sub-catchment to downstream yield. This considers local erosion rates and also opportunities for losses to floodplain and reservoir deposition, and nutrient processing within the river network, between each sub-catchment and the catchment outlet. These processes can trap large proportions of sediment and nutrients from some areas.
- The effects of temporal variability in climate and stream flow etc. are integrated to predict material budgets that represent average conditions for periods of twenty plus years, rather than estimates over short time-steps. This temporal integration identifies the spatial patterns of contribution to downstream reaches, and is appropriate for assessing scenarios of future management, since management
actions such as riparian revegetation take decades to reach their full effect and it is their long-term impact that is of interest.

- **SedNet** models suspended sediment and bed material movement. Suspended sediment yields can impact water quality and primary production, and many nutrients and contaminants are transported bound to sediment particles. Bed material can accumulate in downstream reaches if supply exceeds transport capacity, affecting river pool depth and morphology.
- **The ANNEX (Annual Network Nutrient EXport)** module speciates dissolved nutrients into particulate and dissolved organic and inorganic forms.

The SedNet model has been and is being used widely across the catchments of the GBR to examine scenarios for the potential impacts of changed land management on pollutant delivery and is being used to inform the development of WQIPs in the region. Since it effectively describes load delivery over timescales of decades and resolves neither interannual, nor seasonal, nor daily delivery of water and other materials to catchment ends, its output is not directly suitable as input to the receiving waters models. However, predicted yields can be disaggregated to predict daily loads using empirical rating curves and flow time-series if required. Such disaggregation and temporal modelling is being undertaken in modelling the receiving waters impact of load reduction scenarios on the behalf of the Fitzroy Basin Association. The speciation of the nutrient loads provided by ANNEX is suitable for input into receiving waters models.

**E2/WaterCAST**

E2 is the catchment model recommended for implementation in a scoping study by Rodger Grayson by NRW (Grayson 2007). The model has been developed by the CRC for Catchment Hydrology and is a successor to EMSS. These models perform the basic function of generating sediments and nutrients off the landscape using event mean concentrations specific to landuse and catchment runoff which is generally simulated using rainfall-runoff models. Materials are transported downstream through a river channel network.

Pollutant discharge is modelled as a time varying process. Timescales for simulation are not fixed but are limited by the temporal resolution of forcing data (rainfall) so daily predictions are the norm. Peaks in stream hydrographs are routed downstream to simulate the gradual broadening of flood peaks as they propagate downstream. Constituent concentrations change downstream as the runoff from different parts of the catchment combines. Changes due to deposition on floodplains or transient storage in the river network are not represented, but these may be critical for sediments. The temporal pattern of constituent delivery is generally calibrated to try and reproduce an observed ‘rating curve’ at a downstream location. Not all storage and re-entrainment terms are represented (particularly for sediment-bound constituents). Therefore, the long-term statistics of temporal variation in loads may be reasonably represented, but not temporal sequences in yield.

The constituents modelled by E2 include TSS, TN and TP, although the development of algorithms to simulate the nutrient constituents (DIN, DON, DIP, DOP) is presently being undertaken by eWater and will be available over the next ‘few’ years. Other planned developments in E2 include improved representation of the pollutant generation rates. Some of these improvements will represent processes that are akin to those represented in SedNet. Improvements to generation algorithms and in the user interface will be incorporated in the improved version of E2 called WaterCAST. Pesticides are not
included in E2 at this time. Present applications of E2 in the GBR region are restricted to
the Fitzroy and Barron catchments.

E2/WaterCAST has the ability to simulate the daily hydrograph and sediment and total
nutrient loads directly which is a key requirement of catchment delivery models in the
context we are considering. However, the ability to disaggregate the nutrient loads into
their constituents is not yet available, but this might be undertaken de facto by assuming
proportionalities based on measured concentrations in river water.

MUSIC

MUSIC (Model for Urban Stormwater Improvement Conceptualisation) is a user-friendly
decision support system that enables users to evaluate conceptual designs of
stormwater management systems to meet water quality objectives. It is designed to
simulate urban stormwater systems operating at a range of temporal and spatial scales.
Catchments range from 0.01 km\(^2\) to 100km\(^2\) in area and modelling time steps range from
6 minutes to 24 hours to match the catchment scale. More specifically, MUSIC enables
urban catchment managers to:

- determine the likely water quality emanating from specific catchments
- predict the performance of specific stormwater treatment measures in protecting
  receiving water quality
- design an integrated stormwater management plan for each catchment
- evaluate the success of specific treatment measures, or the entire catchment
  plan, against a range of water quality standards.

MUSIC has had widespread applications around Australia, and is being used to help
establish the WQIP for the Ross-Black region. For its application in Townsville, it is used
directly to assess the loads of nutrients in stormwater discharged to the coastal zone. It
has suitable time-resolving properties to integrate with receiving water models, but the
nutrient concentrations are expressed as total nitrogen and total phosphorus and are not
disaggregated.

Floodplain delivery – MTSRF Project

The northern catchments of the GBR region are characterised by mostly pristine
mountainous regions draining into flat floodplains extensively developed for agriculture.
During the wet season when river levels are high, extensive flooding of the lowland
agricultural regions occurs (several times each wet season). Water carrying sediments
and nutrients spreads out over the floodplains. There is currently little data on how much
of the nutrient and sediment load is deposited on the floodplain, or how much of it
returns to the main channel when the flood recedes. However, it is likely that significant
loads of nutrients and sediments are picked up from the agricultural areas and returned
to the main river channel or directly to the estuary at the river mouth. Data on these
processes will help to test and constrain catchment wide models such as SedNet and
E2/WaterCAST. E2 is not currently designed to simulate the effects of lowland flooding
on the net delivery of material to the river, estuary and coastal zone.
The issue of describing the transport and transformation of material across the Tully-Murray floodplain and its ecological impacts is being addressed by a project proposed for MTSRF funding (Wallace et al., 2007). The project will build on hydrodynamic modelling work already carried out by Main Roads in the Tully-Murray catchments in support of the redesign of the road south of Tully. The Main Roads model (MIKE21) only deals with water quantity. This MTSRF project will focus on developing and testing the sediment and nutrient transport routines that will quantify the sinks, sources and movement of materials across the floodplain during flood events. The floodplain model is fed by number of sub-catchment rainfall-runoff models and as water ponds on the floodplain and breaks the banks of the Tully and Murray Rivers, the hydrodynamic model moves water across the surface according to elevation and surface roughness. Measurements of nutrient and sediment concentrations during floods will be used to support the analysis of material movement. The hydrodynamic model will also be used to describe how the connectivity of wetlands could be quantified by combining the model dynamics with maps of the floodplain wetlands.

Other related MTSRF projects will deal with ecological impacts (Wallace et al., 2007). Biogeochemical and ecological modelling is not formally part of the floodplain project at this time, but it is recognised as having potential for inclusion. Ultimately, if the floodplain-estuary exchange of fine sediments and nutrients proves to be of first-order importance in estuary and coastal zone budgets, then these exchanges will need to be considered by the receiving waters model frameworks.
6 MODELLING STRATEGY AND IMPLEMENTATION PLAN

6.1 Model development timeline

In this section, we suggest a timeline for the development and implementation of the proposed modelling strategy. As outlined in Chapter 3, the strategy comprises the development of three types of models, namely the Large Scale Water Quality Model, ecological models and the finer scale case study applications. Of course, the feasibility of the timeline proposed below depends on adequate resources being available. We propose that the implementation of a modelling strategy would be phased to match its use in supporting the review and renewal of WQIPs.

We suggest that the initial phase of model development be phased to provide models that can be used to underpin the review of targets and to support assessment and monitoring design for WQIPs. The focus during this phase would be on the development and application of the LSWQ model. The LSWQ model, implemented at the scale of the GBR Lagoon, would perform the essential function of linking catchment delivery of fresh water, fine sediments and nutrients to concentrations in receiving waters. It would be employed in predictive mode for scenario analyses and in diagnostic mode for assessment. The implementation of the LSWQ model has an immediate priority and its simulations of contaminant movement and concentrations at the large scale are required by the ecological models and those finer scale models that might be developed.

The current WQIPs are expressed in terms of water quality targets, but the development of ecological targets is an aspirational goal. Ecological assessment is a difficult task and is one in which modelling should assist. Consequently, we propose that the development of ecological models commences within the first stage so that this initiative will be ready to inform the establishment of assessment criteria at the appropriate time. Ecological model development and implementation would be the prime focus of the medium-term stage of the modelling strategy. We have suggested in Chapter 4 that the ecological models HOME and CO2RAL predict ecological indicators that are useful for ecological assessment in the GBR Lagoon so we propose that these models or derivatives of them be used as bases for further model development. We have also suggested the possibility of applying models to finer scale case studies. The identification of these applications could follow from the review of WQIPs. A key objective of the modelling strategy in phase 2 ought to be the development of an integrated approach – the LSWQ model and ecological impact models are part of one framework that links catchment delivery to water quality and ecological impact, that is applied at the appropriate time and space scales, and which informs the WQIP assessment and planning processes effectively.

The model development and implementation strategy could follow several pathways depending on the results of the WQIP review. If the model framework is to be used for ongoing assessment and planning, there will be a continuing requirement for model application and for the analyses and interpretation of simulation results in the context of ongoing data collection and monitoring. As more measurements become available through monitoring and measurement programs, there will be opportunity for further validation, calibration, and improvement of the modelling suite that has been developed. Further, it might become apparent that the selection of water quality and ecological indicators chosen for assessment could be modified or expanded and that other types of models may be needed.
### 6.2 Resource requirements

The workshop considered the resources required for the development, implementation, and application of the model framework. In presenting these resource estimates, we separate the tasks of model development and implementation per se from the ongoing application of these models. Model development and implementation would involve setting up model equations and grids, developing the appropriate boundary conditions and time series of forcing functions, and calibrating and validating the models against available measurements. Ongoing application would include applying models for assessment through integration with monitoring results and for scenario analyses. Ongoing application would certainly also include some continuing model development in response to new measurements as well as model maintenance. Further, the requirements of models will evolve and recognition of this evolution also drives model modification. The estimates of the resources required for model development are based on the assumption that these models are derived largely from existing model structures. Actual model development and application resources required will depend on a number of factors that can’t be specified at present including what institution undertakes the modelling and the nature and level of engagement with users. Table 6.1 summarises our estimated resource requirements.

<table>
<thead>
<tr>
<th>Task</th>
<th>Model development and implementation (FTE)</th>
<th>Ongoing application (FTE/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrodynamic model (LSWQ model)</td>
<td>2.0 (includes supporting models, wind, waves)</td>
<td>0.3</td>
</tr>
<tr>
<td>Sediment model (LSWQ model)</td>
<td>1.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Biogeochemical model (LSWQ model)</td>
<td>1.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Ecological models</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Case study models</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Data management</td>
<td>0.5-1.0</td>
<td>0.5-1.0</td>
</tr>
<tr>
<td>Assessment models</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Visualisation and reporting</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Project coordination</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 6.1 Human resource requirements for the development and application of the receiving waters model framework.

Hydrodynamic model development is relatively mature compared to the other model types required. As part of model implementation though there will be the necessity to develop time series of forcing functions likely to include the wave fields and meteorology over the GBR Lagoon interpolated to appropriate time and space scales. There are existing fine-sediment and biogeochemical models that could be incorporated into the LSWQ model framework, but considerable effort would be required for their implementation to the GBR Lagoon, especially including validation and calibration using existing measurements and remote sensing products.
The HOME and CO2RAL models presently exist and could be used as foundations for the ecological models to be used within the model framework being proposed here. Development will be required for such models both in terms of indicators modelled and for effective integration with the LSWQ model. Ongoing resources are required both for the continuing application of these models for assessment and scenario evaluation, but also to enhance model capability in response to developing criteria for assessment through to the end of the WQIPs and beyond. The case study models have been assigned resources for implementation and for ongoing application. At this stage, the resources specified for these tasks are nominal and ultimately will depend on what is chosen to be done.

During model development and implementation, there will be the necessity for bringing past measurements together to support calibration and validation of models. These data comprise the results of past monitoring studies of water quality, ecological studies, water level measurements, bathymetry, meteorology, current measurements etc. and very likely satellite images as well. The collation of these data and their analyses to forms that are useful to modelling will be the task of the data manager. After the initial development and implementation of models, the data manager will have the ongoing task of organising collected monitoring data and data from other studies for the modelling framework. Table 6.2 shows a range of estimated times for the data manager. This range reflects the degree to which satellite remote sensing data will be incorporated into the framework.

We have allocated resources to the implementation and application of assessment models. We anticipate that as part of this activity, the results of the LSWQ modelling would be used to support the Risk Exposure model which has been developed and implemented by Devlin et al. (2001). To date, the likelihood of exposure of particular reefs to flood plumes has been estimated using the model simulations of King et al. (2002), but these could be updated if the LSWQ model were to be implemented. Assessment models would also be used to integrate the results of simulations of the other model types with measurements into simpler indices of progress against water quality and/or ecological objectives. As such, they play a key role in facilitating the interpretation of modelling and monitoring initiatives by stakeholders.

The usefulness of model applications to support management is often compromised by the failure to communicate results in readily understandable terms to decision makers and other stakeholders. Consequently, we propose that significant resource be attached to the task of developing appropriate visualisation of model simulations and of other tools that assist in communicating results to target audiences.

The project coordinator performs the fundamental roles of directing the modelling effort, ensuring effective two-way communication with the stakeholders, and managing project resources and effort. The coordinator will be responsible for implementing the scientific vision underlying the formulation of the framework and ensuring that it is coherent. The framework is a multi-disciplinary one with essential interdependencies between its elements. The coordinator will ensure that the modelling components interact with one another effectively; that is, that appropriate input/output information is exchanged at the relevant time and space scales. He/she will be responsible for communication of project results to stakeholders in forms that are most useful, but also to engage with stakeholders to ensure that their needs are being addressed. Finally, the coordinator will
undertake the role of resource management; that is to oversee the allocation and expenditure of resources within the project.

6.3 Modelling capacity
The development and implementation of the full model framework we propose requires the commitment of ~10 FTEs and its ongoing application requires 6 FTEs/year. The range of modelling and analysis skills required by the framework is available within Australian governmental, university and consulting institutions. It is likely that no one institution will be able to provide the breadth of skill and human resources required in the timeframes that need to be followed if the models are to inform review of the WQIPs several years hence. Consequently, a consortium of modellers and analysts drawn from several institutions is the recommended approach as it is certain to be the only viable option for shorter term model development and implementation. In the long term, an alternative strategy might be feasible. One team (research providers) might be responsible for the ongoing maintenance and development of the model framework, whereas a second team might be responsible for delivering outputs (management agency or consultants). The Cooperative Research Centre, eWater, has adopted such a strategy. It develops models works with State agencies that often collect data to calibrate and validate these models for specific applications. These models are then often made publicly available for use.

6.4 Custodianship and ongoing application
Which institution should be responsible for the task of maintaining the framework is unclear, but two possibilities are AIMS and CSIRO. Operational housing, that is storage and access to data sets and simulations that can be used for further analyses and interpretation, could be housed in another institution. GBRMPA might be a possibility for this function. Ongoing maintenance, development, and application of the framework will require continuation of resources. Elements of the framework are likely to be useful to other agencies including, for example, include the Navy (hydrodynamics & sediments) and Bureau of Meteorology (climate).

6.5 Governance
The success of the proposed modelling strategy depends critically on strong leadership, management and governance arrangements being in place throughout the life of the initiative. Internal leadership and management would be provided by the project coordinator. Guidance and direction for the initiative needs to be provided by a group external to the teams developing and applying the framework. For example, the mechanism for how the framework might contribute to the process of adaptive management is not at all clear at present. This situation needs to be resolved if the framework is to be an integral part of the adaptive management process. Adaptive management will require model simulation for assessment and for scenario evaluation, but the detail on how these will occur and what they will produce will require dialogue with the external group. An external group that could provide this governance role is the Reef Water Quality Partnership – a group that represents stakeholders and which oversees the interaction between stakeholders and the NRM processes designed to protect the water quality and ecological amenity of the GBR receiving waters.
7 DATA NEEDS, DATA ISSUES, AND ONGOING DATA COLLECTION

In this chapter, we consider the data needed to implement the recommended modelling strategy in relation to existing and planned monitoring and observation programs in the GBR. The recommended modelling strategy involves the development of simulation models which predict the impacts of catchment loads on water quality and ecosystem health indicators under alternative management scenarios. Data are needed for implementation and calibration of these models. The modelling strategy also involves the development of assessment models which are designed specifically to analyse and interpret data from monitoring programs.

Here we discuss general principles around model data needs and design of observation programs. The detailed design and specification of observation strategies to support modelling is a technical task, which should be undertaken as part of the proposed model development.

7.1 Data needs of models

Supporting monitoring and assessment

We suggest that the only way of attributing cause and effect to system change over time periods shorter than decades is through the diagnosis of ongoing observed variability and changes in system state using a modelling framework. For example, suppose a management action resulted in a decrease in long-term average annual nutrient loads by a few percent per year. Real annual loads will likely vary by orders of magnitude from year to year, due to interannual variation in rainfall and runoff. There may be a corresponding long-term trend in indicators such as annual median or 95\%ile chlorophyll, but these indicators will also likely be subject to large interannual variations due both to interannual variation in runoff, and potential other effects (cyclones, changes in ocean exchanges, etc). We will likely have to wait many decades to measure trends in loads and in chlorophyll with sufficient accuracy to detect and attribute effects of catchment management, unless we can find a way to identify and remove as covariates the effects of rainfall variation, and other confounding factors. To the extent they capture the effects of these confounding effects, simulation models can serve as a valuable tool to help design and test diagnostic models and techniques for assessment.

Understanding uncertainty in prediction

A second imperative for model development and application is the need to understand uncertainty in prediction. Models are imperfect representations of reality and if we are to make management decisions based on model simulation, then it is desirable to know the risk involved. The identification and quantification of model error is important not only for decision making, but can also highlight those areas where the model needs most improvement.

Comparison between model prediction and observation is the most powerful way of assessing model error. It can be undertaken on historical data and on data collected as part of an ongoing monitoring program. Direct comparisons between model and measurement time series may not be the best way of assessing ‘error’. Rather, we may be more interested in the statistical behaviour of water quality parameters and so
comparison with model simulations (and estimation of error) on this basis may be more appropriate.

Classical approaches to hydrodynamic and water quality models have treated models as deterministic, and dealt in terms of model calibration and model validation. At the same time, we have recognised that these models involve substantial approximations and process errors. Modern approaches are attempting to reformulate these models as stochastic models and represent model error explicitly. Ideally, we would think of models as producing a probability distribution for predicted variables, rather than a single value. This formulation is in principle applicable both to data assimilation techniques used in operational models, and to understanding error propagation and uncertainty in model scenarios. In practice, this field is still just developing, and there are serious computational constraints in applying these approaches to models with high spatial and temporal resolution.

Model improvement

We have the capability for improving model performance as measured by reduced uncertainty and increased accuracy in simulation through ongoing development. This development may involve incorporation of improved algorithms for model processes or better definition of model parameters. Either way, data collection through monitoring programs or targeted process studies underpins model development.

Data to support model improvement is an important use of measurements. It is likely that important gauges of model performance may be missing from the existing suite of measurements or from those yet to be collected in monitoring programs. These may be particular chemical species or they may be collection of measurements at a particular site or frequency. Such extra data needs can be identified and redressed through modifications to existing measurement programs. Similarly, we might consider additional process studies to target elements of the model where our knowledge is wanting and we suspect that our process representation is deficient. In Chapter 3, we have identified areas for the modelling framework proposed which would benefit from directed studies.

Model forcing

The LSWQ model and ecological models require forcing information directly for them to run. The prescription of riverine inputs of fresh water, fine sediments, and of nutrients in the required forms for the LSWQ model input is essential if the model is to be run for ‘real’ situations. In Chapter 5, we have elucidated what these forms should be as outputs from catchment models, but the same suite applies to model simulations using ‘measured’ loads. Ideally, nutrients need to be resolved by their species, organic matter by its chemical reactivity and sediment loads differentiated by size-class if possible. Typically during floods, the species concentration varies over the hydrograph and this needs to be described by measurement or by some other means.

Other types of forcing for the model framework include oceanographic and meteorological forcing. Meteorological models are available that allow wind fields (and stresses) to be interpolated dynamically across the whole area of the Lagoon. Using data derived from such a source is superior to using simple interpolation from a few meteorological stations typically located near the coast. Similarly, data-assimilating ocean models can be used to provide ‘best estimates’ of sea level, velocities, temperature, salinity and nutrients along the offshore Coral Sea boundary.
7.2 Issues and opportunities for data collection and model integration

Spatial and temporal aliasing

Figure 7.1 shows measured turbidity in Keppel Bay near the mouth of the Fitzroy Estuary. If it is assumed that turbidity can be used as a surrogate for suspended sediment concentration, then it is evident that TSS undergoes major variation both over the semi-diurnal and spring-neap tidal cycles at this location. In other parts of the GBR Lagoon, the tidal currents are generally not as strong as they are in the Fitzroy region, but nevertheless sporadic resuspension events do occur due to the wind.

![Buoy 1](image)

Figure 7.1 Time series of turbidity at Buoy 1 (south western Keppel Bay). Also shown are the tidal heights at Port Alma near the mouth of the Fitzroy Estuary.

Satellite images of flood plumes usually show these to be patchy, presumably reflecting variation in TSS concentrations. This is illustrated in Figure 7.2 which shows a satellite image obtained during the floods of February 2005. Clearly, spot measurements of water properties may significantly misrepresent the ambient conditions where the measurements were made and this possibility needs to be considered in interpreting such measurements and when comparing them to model simulations. It is also often the case that spatial and temporal variability are closely related to one another. Thus, a patch of turbidity advected past an observation point by a current will result in a temporal change in turbidity at that point. The problem of temporal variability can be addressed by using continuously logging measurement devices and that of spatial variability by using satellite remote sensing imagery.
Satellite remote sensing

The MODIS satellite pair TERRA and AQUA traverses the Earth’s surface providing images that can be analysed to obtain maps of estimated chlorophyll and suspended concentration at or near the water surface. In the absence of cloud cover, suitable images can be obtained every few days of the length and breadth of the GBR Lagoon. Unfortunately, cloud cover is most common during the wet season when flood plumes occur, but nevertheless these satellite images are becoming an important tool for monitoring water quality in the GBR Lagoon. Remote sensing now forms an element of the GBR Marine Monitoring Program (see Appendix D).

Remote sensing complements modelling by providing data with much greater spatial and temporal coverage than in situ measurements allow. These data can be used to calibrate models, validate predictions, or to improve model accuracy through data assimilation. Conversely, modelling provides a means to interpret satellite observational data, for example allowing assessment of whether observed areas of high turbidity are due to local resuspension or river plumes, insight into what concentrations may be beneath the observable surface layer, and estimates of material fluxes between one region and another. While remote sensing can provide estimates of optically measurable substances, including estimated concentrations of suspended sediment concentrations and chlorophyll a, models can be used to simulate concentrations and fate of a broader range of constituents that may affect GBR ecosystem health.

As is true with models, remote sensing products must be calibrated and validated against in situ measurements for the region to which they are applied. Progress has recently been made in this area for the GBR Lagoon from CCI and GBRMPA initiatives.

Data assimilation into models

As applied in numerical weather forecasting and operational ocean prediction, data assimilation involves the use of observations (remotely sensed and in situ) to update model predictions in a way that gives an improved estimate of the current system state.
Observations are generally sparse in space and/or time, and represent a subset of model variables. The challenge is to compute error correction fields throughout the domain and across variables, in a way which is dynamically consistent and gives the best estimate of the current state. This can be an extremely powerful way to interpolate and indeed extrapolate from limited observations.

Data assimilation techniques are now well established for open ocean circulation models, incorporating data from satellite altimetry, sea surface temperature (SST), and \textit{in situ} profiling floats. The extension of these techniques to biogeochemical models and into coastal waters, incorporating data from coastal radar, and sensor networks is an active research area. Pilot observing systems and models are being developed for the southern GBR, and it would be reasonable to expect establishment of routine data-assimilating hydrodynamic models, and potentially water quality models, for the GBR over the next decade.

Operational models are normally designed to provide short-term forecasting capability. This may have value for GBR users, but is unlikely to be particularly valuable for catchment management per se. The value of data assimilation for catchment management is two-fold. The ‘now-casts’ resulting from data assimilation are likely to provide a radical advance in our knowledge and understanding of the 3-dimensional system state of the GBR Lagoon, as they have for open ocean basins. In this sense, they will revolutionise our approach to assessment. The advances in quantitative understanding of model and observation error as a result of data assimilation will spill over into monitoring design, but also into improved quantitative understanding of uncertainty and error in predicted system responses to changes in catchment loads in management scenarios.

7.3 Adequacy of existing program to fill data gaps

There are a number of monitoring and other data collection initiatives (summarised in Appendix D) that are currently underway or planned within the GBR Lagoon. The Marine Monitoring Program has been specifically designed to support assessment as part of the ReefPlan. The Stream and Estuary Assessment Program (SEAP) is being trialled in a number of GBR catchments and has as one of its objectives the collection and assessment of data to inform the ReefPlan.

These programs will provide a broad range of physical, biological and ecological data sets. We believe that data generated from these activities, together with the large volumes of existing historical physical, biological and ecological data from the GBR, will provide sufficient information to support initial implementation of the modelling strategy, both in the development of the individual components, and in the ongoing assessment of model performance.

We acknowledge, however, that there may be specific knowledge and/or data gaps within in any of the modelling components that will emerge as our understanding develops. Filling these data gaps may require alteration to existing monitoring programs (for example through additional observational sites or parameters, changes to sampling strategy) or targeted process studies.
8 SUMMARY AND CONCLUSIONS

The WQIPs are required to adopt an adaptive management approach. Models play a number of critical roles in design and implementation of adaptive environmental management strategies:

- Simulation models predict the likely impacts of alternative management strategies on indicators of environmental health under prescribed scenarios, supporting target-setting and strategy selection;
- Assessment models process data from environmental monitoring programs to produce robust performance measures to inform management responses;
- Both predictive and assessment models can assist with selection of indicators and design of monitoring programs.
- Conceptual and quantitative models have an important role to play in communication to stakeholders, and increasing understanding of system dynamics and responses.

The RWQP promotes the implementation of an end-to-end modelling framework which would link paddock scale actions in catchments to environmental indicators throughout the GBR. For the marine environment, the framework treats end-of-catchment discharges and loads as inputs, and seeks to relate targets for those inputs to objectives and targets for water and sediment quality in the GBR Lagoon, and ultimately to direct indicators of reef ecosystem health.

This report focuses on models for the marine receiving environment component of the framework. It is important to keep in mind that the catchment-to-reef modelling capability is required for management, and the report considers the link between marine models and catchment model outputs.

Fundamentally, marine models need to address the fate and impact of the fresh water, sediments, nutrients, organic matter and contaminants delivered from catchments into GBR waters. In itself, this is a challenge, as it involves diverse physical, biogeochemical and ecological processes on a wide range of time and space scales. However, there are multiple other drivers and influences on the GBR, and it would be unrealistic and ultimately not very useful to deal with impacts of catchment loads in isolation from these. The extent to which models of catchment impacts explicitly address these other drivers in the short term will be a matter of judgement and resources.

We can broadly think of models of fate and impact as dealing with three classes of processes: physical transport, biogeochemical cycling and transformation, and ecological response. These are dealt with respectively by hydrodynamic and sediment transport models, by biogeochemical or water quality models, and by ecological models.

8.1 Hydrodynamic models

Hydrodynamic models predict the advection and mixing of water, and substances dissolved in water. The circulation and mixing within the GBR Lagoon is driven by tides, winds, waves, internal stratification, episodic injections of floodwaters, ocean boundary conditions, and strongly constrained by the coastline and underlying bathymetry, including the presence of the reefs. There is a strong history of hydrodynamic modelling
on the GBR, but it is largely a history of compromises, with models confined to sub-regions, and or constrained to address only some of these forces e.g. depth-averaged tidal models or flood plume models. Past modelling has been strongly constrained by computational resources and the availability of key data required for oceanographic/meteorological forcing, as material inputs, and for calibration/verification.

It is the view of this report that these constraints have been sufficiently reduced that it is now both feasible and desirable to develop a whole of GBR hydrodynamic model that includes all of the important factors affecting currents, mixing, temperature and salinity within the GBR Lagoon. The successful development of global and regional data-assimilating eddy-resolving models reflects the computational and technical advances in hydrodynamic modelling, and means that high-quality offshore ocean boundary conditions are now available. Some compromise will still need to be made with respect to model spatial resolution as computational capacity is large but not infinite. The idea of a 3-D model of the whole of GBR with approximately 2-km horizontal resolution seems feasible. New techniques for 3-D finite volume models offer the possibility of variable grids, with much finer resolution in key areas. Further evaluation of finite difference versus finite volume approaches is needed.

A high-resolution hydrodynamic model of this kind should provide accurate prediction of the advection and dispersion of individual flood plumes, and of Lagoon circulation and exchange with offshore waters between flood events. It would underpin the sediment dynamics and biogeochemical models discussed below, and also allow the prediction and analysis of connectivity and exchange of material, including larvae, throughout the GBR. The model could be forced with output from global and regional climate models to provide realistic climate change scenarios for the GBR. Such a model would constitute a fundamental community resource for management and research for the GBR.

At 2-km resolution, there will be a need to parameterise sub-gridscale effects of interactions with complex reef and channel bathymetry. Finer resolution models may be required to address some issues, near river mouths and estuaries, or around key environmental assets. These can be nested within the GBR model.

8.2 Sediment transport models

Sediment transport models predict the advection and mixing of inorganic and organic particles suspended in the water column, and their exchange with the underlying bed through sinking and deposition, and resuspension. The transport and fate of inorganic sediments discharged from catchments is potentially important because of their effect on water column turbidity and light attenuation, and the effects of sedimentation on benthic communities. Moreover, many hydrophobic contaminants and some nutrients are strongly attached or adsorbed to sediments.

We recommend that a whole-of-GBR sediment model be implemented, building on the hydrodynamic model described above. This would provide a large-scale far-field prediction of the fate of sediments from catchments, and their effects on turbidity and deposition, not only during flood events, but as a result of repeated episodes of resuspension and deposition following flood events.

Again, it will be necessary to parameterise key sub-gridscale processes, especially those associated with local changes in bottom relief and roughness, in a large scale sediment
model. Predicting the fate and effect of sediments in estuaries and in the inner Lagoon near estuaries will require higher resolution local models to be developed and nested within the large scale model.

8.3 Biogeochemical process models

Biogeochemical process models predict the cycling of nutrients and carbon through inorganic and organic forms, including primary production by phytoplankton, benthic plants, and coral zooxanthellae. Other processes include grazing, respiration and remineralisation. In coastal waters, these models are used to assess the risk of eutrophication as a result of nutrient loads, and to predict consequent changes in nutrient availability, in organic matter production and deposition, in oxygen depletion and in light attenuation.

Again, we recommend that a whole-of-GBR biogeochemical model be implemented, building on the hydrodynamic and sediment transport models. Such a model would predict the effects of nutrient and sediment loads from catchments on primary production and water quality in the GBR, and importantly allow users to place these effects in the context of the natural nutrient cycle in the GBR Lagoon, which is strongly driven by ocean exchange, and in the context of future changes in ocean circulation due to climate change. The biogeochemical model can be simply extended to predict the fate and distribution of contaminants such as pesticides, allowing for simple representations of decay or transformation, and for exchanges between dissolved and particulate phases.

It will be necessary to parameterise sub-gridscale effects in the biogeochemical model, particular those associated with production and respiration of benthic communities that vary on fine spatial scales. Fine-scale nested biogeochemical models will be required to represent fate and impact in estuaries and nearby embayments. The integrated suite of hydrodynamic, sediment dynamics and biogeochemical models applied on the scale of the GBR Lagoon is what we refer to as the Large-Scale Water Quality (LSWQ) model.

8.4 Connecting water quality models to catchments

In principle, it should be simple to take the end-of-catchment discharge and loads predicted by catchment models, and use these as inputs into the LSWQ model, or nested higher resolution water quality models. There are in practice a number of difficulties. The receiving water quality models require time series of catchment loads, resolved at least to the level of daily loads. The widely used SedNet catchment model predicts only long-term average loads. The E2 catchment model (and its derivative WaterCAST) temporally resolves flows and loads, but is not yet capable of predicting the load composition required by water quality models. One is effectively faced with a choice of using empirical relationships to either disaggregate decadal average loads from SedNet into daily time series, or disaggregate the daily total nutrient and sediment loads predicted by E2/WaterCAST into constituent components. Both approaches are subject to the criticism that empirical models based on historical observations may not apply under changed land use regimes. Parallel and convergent development and implementation of catchment and receiving water models is required. The limitations of E2/WaterCAST will be partly addressed by planned further development of this model.

End-of-catchment loads are typically defined and measured at the end of the river, or head of estuary, in fresh water, and often above tidal influence. This situation already raises questions about storage and transformation of loads within estuaries. But most of
the load from GBR catchments is delivered during major flood events when the river spills out onto adjacent coastal floodplains. The net exchange with these floodplains, and its dependence on floodplain land use, is thought to be important, but poorly understood or quantified. This imposes considerable uncertainty about the delivery of catchment loads to the GBR Lagoon. This is currently a topic of research and, depending on the outcome, will require parameterisation or detailed local modelling of estuaries and floodplains as load filters or load generators.

8.5 Using the LSWQ model for target setting and assessment

The whole-of-GBR hydrodynamic, sediment transport and biogeochemical models together constitute an integrated large-scale water quality (LSWQ) model for the GBR. This model would initially find primary use as a simulation tool to generate management scenarios, linking hypothetical catchment loads to water quality indicators, and thus catchment load targets to water quality targets. As noted above, ocean hydrodynamic models have already made the transition to operational data-assimilating status. Over time, as GBR observing systems grow, and techniques for data assimilation improve, we can expect to see data-assimilation implemented in these GBR models, resulting in improvements in accuracy, and formal quantification of model error. At that point, these models are likely to become powerful tools for assessment as well as prediction.

In the short-term, we can expect to continue to rely on simpler empirical or semi-empirical water quality assessment models. This has recently been an active area of research and model development in the GBR, and we can expect this to continue. Current approaches are largely based on assessment of spatial pattern, relying purely on analysis of spatial data, or combining data with spatial footprints derived e.g. from hydrodynamic plume models. We expect that these latter techniques can be extended by spatial analysis of outputs from the LWSQ models under both flood and non-flood conditions. We also expect that analysis of new data sources, especially satellite monitoring of turbidity and chlorophyll, and time series from moored water quality sensors, will lead to dramatic improvements in assessment models.

A key challenge for water quality assessment models will be the development of techniques to correct for or remove effects on Lagoon water quality of interannual variation in rainfall and runoff from long-term records. Interannual variation is very large, especially in the dry subtropics, and its effect on catchment loads and on GBR water quality and health will likely mask any effects of incremental changes in landuse practices for many decades, unless it can be corrected. Again, it should be possible to use the LSWQ model to develop spatio-temporal footprints for catchment loads to assist with this, in a manner analogous to the current use of spatial footprints from flood plume models.

8.6 Ecological response models

GBR ecosystems are extraordinarily diverse, and there is a corresponding diversity of potential indicators of ecosystem health, and corresponding ecological response models. Current monitoring strategies focus on a small number of key community indicators, in particular coral cover and composition, coral recruitment, macroalgal abundance on reefs, and seagrass cover and distribution. The corresponding ecological response models focus on a few key processes linking changes in water quality (nutrients, light attenuation, turbidity and sedimentation, and pesticides) to these indicators. Models tend to adopt an impact-recovery formulation, in which large losses in benthic cover occur as
a result of acute impacts, from flood events, but also from other causes (bleaching, COTS outbreaks, cyclones), and recovery occurs through recruitment or regrowth which is strongly dependent on background water quality. These models are required therefore to deal with interactions between catchment loads and other acute pressures.

Ecological response models could be embedded directly in the LSWQ model, but it is likely to prove more efficient to develop them as a spatially-referenced set of individual-based models which accept the output from the LSWQ model as input, given mismatches in space and time scales. Connectivity predicted from the hydrodynamic model could also be incorporated into recruitment / recovery models.

Current GBR ecological response models have been developed as both deterministic simulation models, and as stochastic / Bayesian semi-empirical models. Given the complexity and uncertainty surrounding ecological responses, there is a strong argument for the use of stochastic models and Bayesian inference. Such models can be used for both scenario evaluation and assessment.

There exist another class of more complex, process-based ecosystem models which combine biogeochemistry, trophodynamics, and benthic community dynamics. Two of these, Atlantis and In Vitro, have been developed for ecosystem-based fisheries management, and regional multiple-use management. In Vitro is currently being implemented for the Ningaloo Reef system in WA, with a particular focus on tourism development. Atlantis also incorporates human dynamics and economics, and has recently been recognised by FAO as the world’s leading fisheries ecosystem model. Implementation of these models for the GBR would be particularly attractive if and when it is decided to integrate catchment management with resource use.

8.7 Observations and data needs

There are already a number of initiatives to develop observation and monitoring programs for the GBR. The Marine Monitoring Program is managed by GBRMPA and includes components addressing virtually all the indicators and processes mentioned above. The Great Barrier Reef Ocean Observing System (GBROOS) is a new regional initiative designed to establish and demonstrate new high-tech, near real-time marine observing methods, including coastal radar, and sensor networks. These are especially suitable for data assimilation into the LSWQ model.

Current approaches to the design of these monitoring programs and strategies are largely qualitative and heuristic. As assessment models and techniques for data assimilation into process models are established, we should see the emergence of formal quantitative approaches to the design of sampling strategies. In principle, we should be able to objectively and quantitatively measure the information value of alternative observation strategies, in terms of errors in prediction, and/or confidence and power to detect change in assessments. In the meantime, without specification of which models are eventually included in a model framework and what the precise aims of such a framework should be, it is not possible to be prescriptive about data needs for model development and application in this report.
8.8 Modelling strategy

The report recommends the development of certain kinds or classes of models to meet corresponding management needs. Suggested timelines, deliverables and resource needs to meet upcoming management milestones are proposed. However, there are some implicit propositions underlying these recommendations which are worth stating explicitly.

The recommendation for the GBR-wide LSWQ models and integrated ecological response models implies a commitment to the development of an integrated and coordinated approach to the development of community models to support the ReefPlan. To date, there has been no such formal coordinated approach. Individual models have been developed by researchers or consultants in response to particular problems, or in support of management in particular catchments. The advantages of a coordinated approach are:

- Establishment of critical mass, combining skills and resources across multiple institutions, to take advantage of the latest methods and technologies.
- Establishment of consistent models and approaches across the GBR.

The potential disadvantage is a loss of diversity in approach, and in the longer term, stagnation of the model development or resistance to change.

We believe that the advantages are important, especially given the limited national capacity and resources, and the desire for an integrated approach to GBR management. We believe that the disadvantages can be managed by continuing to encourage experimentation and innovation in the research domain, and by ensuring that the coordinated models implemented for management are subject to ongoing review, including independent peer review. In this regard, it is vital that model development is seen as an ongoing long-term commitment, analogous to a commitment to monitoring, not a one-off short-term project. Without ongoing intellectual investment and renewal, models rapidly end up parked on shelves, or treated as black boxes with diminishing value, divorced from management. Establishment of a multi-institutional modelling team, as opposed to a single contractor, is also likely to encourage innovation. We suggest also that two-way communication between modellers and stakeholders is an issue of high priority through model development and application. Significant resources need to be applied to the application of tools such as simulation visualisation to ensure that the results of model analyses are effectively conveyed to those who would use them.

We estimate that the modelling program proposed here would require about 10 FTEs per year over the first few years, and about 6 FTEs per year ongoing. That represents a substantial investment of around $1M to $2M p.a., depending on the levels of co-investment by participating agencies. However, it is still a relatively modest investment in the context of overall GBR monitoring, management and research.
9 REFERENCES


APPENDIX A

Responses from ‘Receiving WQ Modelling-WQIP questionnaire’

On 20 June 2007, an email was sent to managers preparing WQIPs requesting more detail on the nature of their WQIP and associated modelling and data issues. We sought elaboration on a number of issues including definition of the zone of interest, parameters of interest, and timescales of WQIP implementation. Also, we inquired as to how the managers envisaged models might be used to support the development of their WQIPs. Responses to the questionnaire were obtained from:

A: Nathan Johnston - Fitzroy
B: Frederieke Kroon – Wet Tropics
C: Chris Manning – Black/Ross
D: Ian Dight – Burdekin
E: Sandra Grintner – Burnett/Mary

A questionnaire was also sent to the Mackay/Whitsunday management group, but no response was received.

In the following, the questionnaire results are presented. Answers to questions posed are blue text. The questionnaires have been reformatted, but the text remains as received.

A Fitzroy Basin – Nathan Johnston

A1 NRM Region

a What is the name of your region? FBA What WQIPs are proposed, under development or finalised in your NRM region? Project to support WQ targets within the CQSS@ (our NRM plan). We are currently considering the development of a WQIP, but this is not finalised. What segments of the GBR Lagoon are protected through those WQIPs (please delineate the portion of the GBR to which the WQIP(s) apply)? Portion modelled by your Model is the primary area. Whole of GBR as a secondary interest – For which we use the Risk assessment Model (Brodie) and hope to use a future whole of GBR hydrodynamic model

A2 Status of WQIP:

a What is the completion date of your WQIP(s) and what is its present status (in prep, draft, final etc.)? WQ target support project – June 2008. WQIP (if it gets up 2008/09. Support

b What is the nominated date for achievement of WQIP objectives (i.e. the long term total maximum load)? Would be a 50 year objective (has not been set) What is the timing of achievement of the interim load(s) ten years and how do these relate to the long-term loads? It would use the same modelling & monitoring techniques to set target and monitor progress

A3 Catchment WQ:
a What models or processes are used to infer the relationship between land use and land management activities and end-of-catchment loads and concentrations (SedNet, other etc)? SedNet. We have a current project that refines the 2005 version. Some preliminary work within Qscape to test the E2 catchment model – but this is not at whole of catchment scale (and not likely to be for 3-5 years).

b What parameters are included in end of catchment loads (dissolved N, TN, pesticides etc)? Primarily sediment. Nutrients and pesticides are derived from this

c Does the WQIP include event-mean concentrations as well as ambient river concentrations? We currently use load based discharges but these are calculated from EMCs. Ambient conditions have not been our focus to date – but are important How does the WQIP parameterise the desired load target? This question confuses me…Our load targets are developed by looking at changes in land management actions and modelling them accordingly. Focus is on Sediment with nutrients a coefficient of sediment

d What are the river basins/sub-catchments subject to the WQIP (some set of rivers discharging to the GBR Lagoon perhaps)? Fitzroy and coastal catchments

A4 Receiving water WQ:

a What models or processes have been used to determine long term/aspirational receiving waters water quality targets or objectives and who is providing scientific support? Your MECO model for receiving waters along with Risk exposure model.

b What is the geographic extent of the receiving waters subject to this modelling/process support? Do the receiving waters include estuaries, a coastal zone and beyond? As per models

c What are the parameters included in the targets and objectives (concentrations of pesticides, dissolved N, total N etc)? Investigating the parameters that are best indicators of reef and seagrass health and those needed to derive these indicators. TSS, Nutrients Chlorophyll. Light attenuation measures (PAR). Smothering measures

d What is the basis for setting water quality objectives (ANZECC, QEPA, GBRMPA guidelines, etc)? Have not been set but will be modified from ANZECC focussing on WQ needed to protect reef and seagrass communities defined through the EV process as being high value

e What monitoring is undertaken to support calibration/continuous improvement of the WQIP models and/or the implementation of the WQIP? QLD EPA, GBRMPA marine monitoring, SEAP, PNCWQM Can you provide a copy of the documented monitoring programme designed to support the modelling effort for WQIP development/implementation? PNCWQM monitoring plan is available on our website. Call me if you have trouble locating. All other monitoring programmes are external to FBA
A5 Can you think of any issues or barriers surrounding the use of catchment or receiving water quality models to support development or continuous improvement of WQIP or the assessment of its success to protect the GBR Lagoon? As per FBA Modelling Needs Workshop summary (attached) and Updated WQ target Setting Approach – available on our website

A6 Who is the custodian for water quality data used or required by you to support modelling for the WQIP? As above. Are there any issues surrounding data access, collection etc.? not at this stage

B Wet Tropics – Frederieke Kroon

B1 NRM Region
a What is the name of your region? What WQIPs are proposed, under development or finalised in your NRM region? What segments of the GBR Lagoon are protected through those WQIPs (please delineate the portion of the GBR to which the WQIP(s) apply)? Name is Wet Tropics. Douglas WQIP delivered and being implemented. Tully WQIP developed and being delivered (implementation is commencing). Barron WQIP being developed, and remaining WT catchments (Herbert, Russell/Mulgrave and Johnstone) being scoped. WT receiving waters and north.

B2 Status of WQIP:
a What is the completion date of your WQIP(s) and what is its present status (in prep, draft, final etc.)? See above

b What is the nominated date for achievement of WQIP objectives (i.e. the long term total maximum load)? What is the timing of achievement of the interim load(s) and how do these relate to the long-term loads? Douglas 25 yrs (Peter Bradley to provide more detail). Tully not yet set, still in discussion, but would be about the same I suspect.

B3 Catchment WQ:
a What models or processes are used to infer the relationship between land use and land management activities and end-of-catchment loads and concentrations (SedNet, other etc)? To estimate WQIP targets and identify potential management measures that would reduce pollutant loads to receiving waters in the Tully WQIP area, scenarios were developed to examine the effect of changes in land management on (i) sediment, nutrient and pesticide generation and transport (Armour et al. 2007, Roebeling et al. 2007), and (ii) (plot level) financial-economic consequences of BMP implementation (Roebeling et al. 2007).

The first set of scenarios (Scenario 1) modelled the current pollutant loads (Table 2), based on current land use (Table 1) and BMP uptake (McMahon, BSES, pers. comm. 2007, Lindsay DPI&F, pers. comm. 2007, Roebeling and Webster 2007). The second set of scenarios (Scenario 2) estimated the required event mean concentration (EMC) at end-of-river to achieve the GBRMPA draft water quality guidelines (GBRMPA 2007). This second set of scenarios could only be run for nitrate, due to the unavailability of
receiving water models (e.g. TSS, pesticides) or draft GBRMPA guidelines (e.g. TSS) for other pollutants. A third set of scenarios (Scenario 3) was conducted to estimate changes in pollutant loads and gross margins with implementation of practical and achievable management measures, given current land use.

i. Receiving water models (Wooldridge model, Devlin model)

ii. Production system simulation models (APSIM, LUCTOR and PASTOR) and a hydrological model (SedNet/ANNEX)

iii. Pesticide risk indicator models (REXTOX and PIRI)

b. What parameters are included in end of catchment loads (dissolved N, TN, pesticides etc.)? Nitrate / DIN, Suspended sediment (including, by default, PN and NN) (loads), atrazine and diuron (concentrations).

c. Does the WQIP include event-mean concentrations as well as ambient river concentrations? How does the WQIP parameterise the desired load target? See above (2d).

d. What are the river basins/sub-catchments subject to the WQIP (some set of rivers discharging to the GBR Lagoon perhaps)? The Tully WQIP area refers to the combined geographical area of the Tully and Murray rivers (Johnson 1998) and the Cardwell Shire Local Government Area (Figure 1) (Bohnet et al. 2006 2007). Johnson (1998) includes the following major subcatchments: Hull River and coastal tributaries, Tully River (comprising Upper Tully River and Nitchaga Creek, Lower Tully River tributaries, David Creek and Echo Creek, Jarra Creek, Banyan Creek, and Lower Tully River), Murray River, Dallachy Creek, Meunga Creek and Kennedy Creek, and Coastal creeks to Hinchinbrook Channel.

B4 Receiving water WQ:

a. What models or processes have been used to determine long term/aspirational receiving waters water quality targets or objectives and who is providing scientific support? See above (2d). Armour et al, Brodie et al, Roebeling et al.

b. What is the geographic extent of the receiving waters subject to this modelling/process support? Do the receiving waters include estuaries, a coastal zone and beyond? Approximately 2,000 km² of the GBR Marine Park and World Heritage Area are directly influenced by discharge from the Tully WQIP area (Figure 1), with the exact area dependent upon the volume and duration of flow, as well as the direction of currents and winds in the area (Brodie et al. 2007a). Based on plumes from several Tully-Murray flood events from 1994 to 1999, the receiving water body includes at least the waters south to Hinchinbrook Island, east to beyond the Brooks and Family Islands, and north to the Barnard Islands and up to near Innisfail. Importantly, this receiving water body is also affected by discharge from both the Herbert and Burdekin rivers (Lewis et al. 2006). Recent satellite imagery shows that plumes from Wet Tropics rivers, including the Tully, can extend eastwards across the entire reef shelf and beyond into the Coral Sea (Brodie et al. 2007a).
c What are the parameters included in the targets and objectives (concentrations of pesticides, dissolved N, total N etc.)? Total ammonia N, NOxN, Organic N, Total N, PO4, Total P, Chla, Turbidity, Secchi, Tss, Diuron, Atrazine, Chlorpyrofos, Endosulfan, Ametryn, Simazine, Hexazinone, 2-4-D, Tebuthiuron, MEMC, Diazinon.


e What monitoring is undertaken to support calibration/continuous improvement of the WQIP models and/or the implementation of the WQIP? Can you provide a copy of the documented monitoring programme designed to support the modelling effort for WQIP development/implementation? A combination of monitoring and modelling data has been used to calculate current pollutant loads for the Tully WQIP area. First, the relative contribution of five diffuse sources (forest, sugarcane, grazing, forestry, bananas) and one point source (urban) to current pollutant loads of sediments and nutrients was monitored during two wet seasons (06/07 and 07/08) (Faithful et al. 2007). Water samples were also analysed for ten herbicides residues (ametryn, atrazine, desethyl atrazine, desisopropyl atrazine, diuron, fluometuron, hexazinone, prometryn, simazine, and tebuthiuron). Other pesticides were not included due to either the unavailability or costs of the analyses required.

Second, current pollutant loads, and the relative contribution of seven diffuse sources (forest, sugarcane, grazing, water, forestry, bananas, horticulture) and one point source (urban) to these, were modelled (Armour et al., 2007a). Sediment and nutrient loads were estimated using SedNet/Annex, (Sediment River Network/Annual Nutrient Export). This model estimates a long-term, annual average load, rather than predicting short-term events. To estimate current sediment and nutrient loads, current management practices were included for all major industries (Armour et al., 2007a; Hateley et al., 2006). Monitored and modelled DIN and TSS concentrations at six sampling locations were in general agreement, providing confidence in the outcomes of the models (Armour et al., 2007a). Pesticide loads could not be estimated, as appropriate models do not exist.

Finally, preliminary estimates of sediment and nutrient loads delivered to receiving waters by overbank flooding were made using measurements of rainfall, flood depth and sediment and nutrient concentrations (Wallace et al. 2007).

B5 Can you think of any issues or barriers surrounding the use of catchment or receiving water quality models to support development or continuous
improvement of WQIP or the assessment of its success to protect the GBR Lagoon? Models need to be supported / validated by monitoring.

B6 Who is the custodian for water quality data used or required by you to support modelling for the WQIP? Are there any issues surrounding data access, collection etc.? FNQ NRM, but data are based with CSIRO and JCU. Shouldn’t be an issue.

C Black/Ross – Chris Manning

C1 NRM Region
a What is the name of your region? What WQIPs are proposed, under development or finalised in your NRM region? What segments of the GBR Lagoon are protected through those WQIPs (please delineate the portion of the GBR to which the WQIP(s) apply)?
i Burdekin Dry Tropics NRM region
ii Black and Ross River basins (Townsville / Thuringowa – managed by the Creek to Coral program). The Burdekin Basin WQIP is managed by BDTNRM
iii Cleveland and Halifax Bays are the receiving waters for the Ross and Black rivers respectively. The extent of the influence (in terms of exposure to sensitive marine areas) of these rivers (and other smaller ones in our region) will be determined through the GBR exposure modelling project currently being undertaken by ACTFR for all the WQIP’s in the GBR catchment.

C2 Status of WQIP:
a What is the completion date of your WQIP(s) and what is its present status (in prep, draft, final etc.)? September 2009 (our WQIP is in prep)

b What is the nominated date for achievement of WQIP objectives (i.e. the long term total maximum load)? What is the timing of achievement of the interim load(s) and how do these relate to the long-term loads? We have not got to point in our WQIP development to be able to put some timelines around this. We have begun discussions with BDTNRM about how our WQIP could be integrated with their NRM plan, particularly with regard to targets and objectives. If this is achieved then it could be envisaged that these components will be reviewed (at the very least) as part of a NRM Plan review. This will also have to be coordinated / integrated with Council planning and institutional review processes.

C3 Catchment WQ:
a What models or processes are used to infer the relationship between land use and land management activities and end-of-catchment loads and concentrations (SedNet, other etc)? Urban area specific models such as MUSIC.

b What parameters are included in end of catchment loads (dissolved N, TN, pesticides etc.)? As yet undetermined but likely to include suspended sediment, species of nitrogen and phosphorus and perhaps
herbicide/pesticides. Hydrocarbons and other chemicals may also be relevant in specific locations.

c Does the WQIP include event-mean concentrations as well as ambient river concentrations? How does the WQIP parameterise the desired load target? As yet undetermined but likely to include both event-mean concentrations (and loads) and an ambient river component (where relevant). The load target parameters will be based on the issues identified in the event (and ambient) monitoring program undertaken in 2007.

d What are the river basins/sub-catchments subject to the WQIP (some set of rivers discharging to the GBR Lagoon perhaps)? Black and Ross River basins (includes the major rivers, Black and Ross and several minor river/creek systems including those on Magnetic Island).

C4 Receiving water WQ:

a What models or processes have been used to determine long term/aspirational receiving waters water quality targets or objectives and who is providing scientific support? Targets as yet undetermined – but SedNet models have been used for the Black and Ross rivers in previous modelling studies (for GBR catchment). ACTFR and CSIRO have provided this support.

b What is the geographic extent of the receiving waters subject to this modelling/process support? Do the receiving waters include estuaries, a coastal zone and beyond? Inshore GBR Lagoon, including the coastal zone and beyond. It is my understanding that the estuarine zone is problematic and not included (except as an assumption to behaving the same as the freshwater areas – which we know is incorrect).

c What are the parameters included in the targets and objectives (concentrations of pesticides, dissolved N, total N etc.)? As in e and f above

d What is the basis for setting water quality objectives (ANZECC, QEPA, GBRMPA guidelines, etc.)? Based on a combination of GBRMPA, ANZECC, QEPA and local water quality guidelines (to be developed as part of our WQIP process) as relevant.

e What monitoring is undertaken to support calibration/continuous improvement of the WQIP models and/or the implementation of the WQIP? Can you provide a copy of the documented monitoring programme designed to support the modelling effort for WQIP development/implementation? Extensive and detailed monitoring of the 2007 event, ongoing and targeted (on a smaller scale) event monitoring into the near future (based on 2007 results and opportunistic monitoring of BMP effectiveness etc) and an ambient monitoring program (yet to be developed) to inform the WQ guideline development process.

Monitoring in the short term based on condition assessment, issue identification, model calibration and guideline development etc while monitoring into the future to be based on measuring BMP effectiveness,
achievement of WQ objectives, continuing issue identification and model calibration and informing the Plan’s adaptive management strategies.

Our monitoring program is still in development but a Draft copy may be possible if required. A modelling strategy has not been developed as yet.

C5 Can you think of any issues or barriers surrounding the use of catchment or receiving water quality models to support development or continuous improvement of WQIP or the assessment of its success to protect the GBR Lagoon? Townsville is situated on a broad floodplain with short river systems, small catchments, large (relative to catchment/river system size) estuarine areas, flat terrain, and small headwater areas with moderate inclines. These factors make SedNet type models (utilising erosion coefficients) largely unsuitable in this region (also related to response i above).

The predominant landuse is urban/industrial making urban centric models (like MUSIC) most relevant here. These models could be used (in terms of developing scenarios) to inform the end of catchment modelling and perhaps ideally also the receiving water models.

Of concern is the apparent disjunct between models that measure/model the effectiveness of the BMP (effectiveness and uptake) such as MUSIC models (for the urban environment) and the models that quantify end of catchment loads and more importantly those that quantify the ramifications for the ecosystems of the receiving waters (of the GBR).

Models (and monitoring) for determining and quantifying the effects of declining water quality (from adjacent land use and subsequent BMP adoption) in the local freshwater (receiving waters) environment is a major area of need.

To my mind this is one of the most important components in the story of improving GBR water quality because in order for us to make a difference in the GBR we have to get local communities involved in the process (creating ownership or buy in to our WQIP and its targets) of improving local water quality etc which will then have a flow on effect in downstream environments. Local communities are most interested in their local area – local water quality, local ecosystem health, local actions and initiatives and local investment. This is not to say that they do not care about the GBR but it may not be as high a priority as many people think (or would hope). This ‘local centric’ concept has only a limited extrapolation potential to regional scales and becomes ‘weaker’ at scales larger than this. The concept is of course applicable across all communities in WQIP (and other) regions in my opinion.

C6 Who is the custodian for water quality data used or required by you to support modelling for the WQIP? Are there any issues surrounding data access, collection etc.? Various custodians but the primary custodian is the Creek to Coral program (representing Townsville and Thuringowa City Councils, and the Black and Ross WQIP). The Creek to Coral program will or has already sought to enter into sharing / use agreements for relevant data collected by third parties.
C7 How and when do you propose to review your WQIP targets, and what do you expect the role of models to be in that process? **Timings for the review of these WQIP targets should be linked with other relevant planning and institutional timelines (such as NRM Plan and Council planning and institutional processes) but this is not yet determined. Any timing determined timings will be reflected in the adaptive management strategy for the WQIP.**

This process will be outlined in our adaptive management strategy (as yet undeveloped). I expect that a combination of monitoring and modelling will be used to directly (and indirectly through model calibration etc) inform this process. This could include measuring (and modelling) of BMP effectiveness and the effect of their uptake (including scale of uptake and continual improvement of these BMP’s) on local and end of catchment water quality objectives and consequently on the downstream marine environment.

**D Burdekin – Ian Dight**

**D1 NRM Region**

a What is the name of your region? What WQIPs are proposed, under development or finalised in your NRM region? What segments of the GBR Lagoon are protected through those WQIPs (please delineate the portion of the GBR to which the WQIP(s) apply)? **Burdekin Dry Tropics Region. WQIP will cover Burdekin-Haughton catchments (upper and floodplain). A separate WQIP is being undertaken for the Black & Ross River catchments by C2C (Townsville). The GBR Lagoon that is influenced by the Burdekin WQIP extends from Upstart Bay northwards (as far as Cairns during large events)**

**D2 Status of WQIP:**

a What is the completion date of your WQIP(s) and what is its present status (in prep, draft, final etc.)? **March 2008 – in preparation**

b What is the nominated date for achievement of WQIP objectives (i.e. the long term total maximum load)? What is the timing of achievement of the interim load(s) and how do these relate to the long-term loads? **Not yet determined but likely to be around 2010, 2013 and onwards**

**D3 Catchment WQ:**

a What models or processes are used to infer the relationship between land use and land management activities and end-of-catchment loads and concentrations (SedNet, other etc)? **SedNet, APSIM-Sugarcane**

b What parameters are included in end of catchment loads (dissolved N, TN, pesticides etc.)? **TSS, TN, PN, DIN, DON, TP, PP, DIP, DOP, pesticides**

c Does the WQIP include event-mean concentrations as well as ambient river concentrations? How does the WQIP parameterise the desired load target? **EMC & ambient; measured EMC/load is expected to be normalized to mean discharge conditions**
d What are the river basins/sub-catchments subject to the WQIP (some set of rivers discharging to the GBR Lagoon perhaps)? Burdekin River, Barratta Creek and Haughton River

D4 Receiving water WQ:

a What models or processes have been used to determine long term/aspirational receiving waters water quality targets or objectives and who is providing scientific support? SedNet/CSIRO & ACTFR; APSIM-Sugarcane/CSIRO

b What is the geographic extent of the receiving waters subject to this modelling/process support? Do the receiving waters include estuaries, a coastal zone and beyond? Central GBR; yes

c What are the parameters included in the targets and objectives (concentrations of pesticides, dissolved N, total N etc.)? Not yet completed but expected to be pesticides, DIN, TSS

d What is the basis for setting water quality objectives (ANZECC, QEPA, GBRMPA guidelines, etc.)? ANZECC, QWQG 2006 & GBRMPA guidelines

e What monitoring is undertaken to support calibration/continuous improvement of the WQIP models and/or the implementation of the WQIP? Can you provide a copy of the documented monitoring programme designed to support the modelling effort for WQIP development/implementation? Sub-catchment monitoring program has been supported with the explicit objective of validating modelling and identifying ‘hot spots’. Reports available through our website: http://www.bdtnrm.org.au/cci/monitoring/wq_monitoring.html

D5 Can you think of any issues or barriers surrounding the use of catchment or receiving water quality models to support development or continuous improvement of WQIP or the assessment of its success to protect the GBR Lagoon? Understanding the trapping efficiency and parameterization of the Burdekin Falls Dam.

More accurately reflecting particulate nutrient contributions from different catchments and oil types

Better representation of hillslope and floodplain delivery

Better representation of property-scale delivery in relation to different land management practices

D6 Who is the custodian for water quality data used or required by you to support modelling for the WQIP? Are there any issues surrounding data access, collection etc.? BDTNRM/ACTFR; no

D7 How and when do you propose to review your WQIP targets, and what do you expect the role of models to be in that process? Possibly in about 3 and 6 years; very important role in evaluating predicted achievements based on BMP implementation rates
E  Burnett/Mary – Sandra Grintner

E1  NRM Region
   a  What is the name of your region? Burnett Mary

   b  What WQIPs are proposed, under development or finalised in your NRM region? Burnett/Baffle is under development. Also the Mary/Burrum WQIP is being developed but this is not funded through CCI but through the Regional Investment Strategy of the NRM plan.

   c  What segments of the GBR Lagoon are protected through those WQIPs (please delineate the portion of the GBR to which the WQIP(s) apply)? GBRMPA have defined an approximate area of terrestrial influence which extends from the southern GBR boundary out to Lady Elliott and Lady Musgrave islands and up to the port of Gladstone to the north. Although the Mary and Burrum are recognised as GBR catchments the wqip will focus on Hervey Bay and GSS.

E2  Status of WQIP:
   a  What is the completion date of your WQIP(s) and what is its present status (in prep, draft, final etc.)? Both are funded until June 08 and both are in preparation.

   b  What is the nominated date for achievement of WQIP objectives (i.e. the long term total maximum load)? What is the timing of achievement of the interim load(s) and how do these relate to the long-term loads? This has not been determined as yet.

E3  Catchment WQ:
   a  What models or processes are used to infer the relationship between land use and land management activities and end-of-catchment loads and concentrations (SedNet, other etc)? SedNet has been run twice recently for the Burnett. The first project did not include Paradise Dam (short term modelling project) but had some scenarios. The other report includes paradise dam and some other future infrastructure upgrades (raising of weirs) but no scenarios. Possibly CMSS will be used to give more useful information in the future and I understand further modelling will be carried out by eWater.

   b  What parameters are included in end of catchment loads (dissolved N, TN, pesticides etc.)? TN, TP, sediment although many point sources were not included in the nutrient modelling. Most CCI contracts state that TN, TP and TSS should be included in the WQIP.

   c  Does the WQIP include event-mean concentrations as well as ambient river concentrations? How does the WQIP parameterise the desired load target? Ideally we would include an event-mean concentration if possible. The CCI contract states that we should estimate total maximum pollutant loads and take account of seasonal variation in loads.
d What are the river basins/sub-catchments subject to the WQIP (some set of rivers discharging to the GBR Lagoon perhaps)? Baffle and the small coastal catchments of the baffle basin (including deepwater, littabella, eurimbula cks etc), kolan, burnett, Elliott rivers are all within the Burnett/Baffle wqip area. The small coastal catchments of the baffle basin drain into high ecological value receiving waters/estuaries although I am not sure what detail we can go into for target setting etc.

E4 Receiving water WQ:

a What models or processes have been used to determine long term/aspirational receiving waters water quality targets or objectives and who is providing scientific support? No models/processes used to date except the basic risk modelling that Jon Brodie and others are completing as part of reef wide project. No scientific support has been negotiated and is limited in this local area.

b What is the geographic extent of the receiving waters subject to this modelling/process support? Do the receiving waters include estuaries, a coastal zone and beyond?

c What are the parameters included in the targets and objectives (concentrations of pesticides, dissolved N, total N etc.)?

d What is the basis for setting water quality objectives (ANZECC, QEPA, GBRMPA guidelines, etc.)?

e What monitoring is undertaken to support calibration/continuous improvement of the WQIP models and/or the implementation of the WQIP? Can you provide a copy of the documented monitoring programme designed to support the modelling effort for WQIP development/implementation? Basic water quality monitoring is being set up in a few test and reference sites for freshwaters relying on existing community monitoring efforts and aims to monitor ambient and event conditions. Support is expected to be provided (subject to approval by board) to start monitoring by funding some positions to assist community monitoring activities. Marine monitoring is limited to ambient monthly monitoring close to Bundaberg although plans are to extend this monitoring and link to HEV (High ecological value) areas identified by EPA for WQIP. Several estuaries are included in the joint project State of the Estuarine Environment between BMRG and EPA (David Scheltinger). No specific document outlines this monitoring programme. Graeme Esslemont is managing the water quality monitoring for BMRG. Clear indication of what WQ information is a priority for modelling activities needs to be provided to BMRG when modelling is carried out to assist in improving monitoring activities.

E5 Can you think of any issues or barriers surrounding the use of catchment or receiving water quality models to support development or continuous improvement of WQIP or the assessment of its success to protect the GBR Lagoon? Lack of regional support for re-running catchment models and we have had difficulty in getting Brisbane NRW staff to rerun models (we have estimated
pasture cover for the WQIP area but have not been able to organise the rerunning of SedNet to include this, although the sediment trapping effect of Paradise Dam may make this exercise relatively pointless).

Lack of local scientific support.

Lack of data on pollutants of concern for each catchment, event monitoring for all rivers, event monitoring for Burnett due to drought, sediment trapping efficiency of Paradise Dam, plume extent and water quality of plume.

Community reluctance to accept information generated by models (ie SedNet) used in the Short Term Modelling Project.

E6 Who is the custodian for water quality data used or required by you to support modelling for the WQIP? Are there any issues surrounding data access, collection etc.? We have a datashare agreement for NRW (freshwater) WQ data and have some EPA estuarine data (but not for the Burnett/Baffle WQIP area only the Mary/Burrum WQIP area).

E7 How and when do you propose to review your WQIP targets, and what do you expect the role of models to be in that process? Not determined yet but I expect that we would have to rely heavily on models due to the lack of WQ data and the currently patchy-at-best-but-improving community WQ monitoring network for the Burnett/Baffle area.
APPENDIX B

Responses from’ Review and gap analysis of receiving-water water quality modelling in the Great Barrier Reef’ questionnaire.

A survey was conducted amongst the modelling community to obtain information on the breadth and features of the varieties of models that might ultimately contribute to a model framework. The recipients of the survey were restricted, for pragmatic reasons, to modellers that have active or recent involvement in modelling activities (physical/biogeochemical/ecological) on the GBR.

The questionnaire was circulated to:

Lance Bode – James Cook University
Lou Mason – Australian Maritime College
Brian King – Applied Science Associates Asia Pacific (formerly of AIMS)
Eric Deleersnijder – Catholic University of Louvain (UCL)
Mike Herzfeld – CSIRO Marine and Atmospheric Research -
Nugzar Margvelashvili – CSIRO Marine and Atmospheric Research -
John Parslow – CSIRO Marine and Atmospheric Research -
Beth Fulton – CSIRO Marine and Atmospheric Research -
Richard Brinkman – AIMS
Eric Wolanski – AIMS
Scott Wooldridge – AIMS
Glenn De’ath – AIMS
John Brodie – James Cook University, Australian Centre for Tropical Freshwater Research
Colette Thomas – Monash University
Ian Lawrence – CRCeWater

The questionnaire is set out in the following pages and responses are summarised in the subsequent tables.
Linking catchment action to ecological outcomes

Conceptually our model framework will consider catchments, rivers, estuaries, and the GBR Lagoon as a series of connected compartments through which matter (water, nutrients, sediments, pesticides) is transported. Ecological impact will likely be derived from biophysical condition and resource use. Material will be sourced from the landscape at rates that are dependent on landuse and transported by streams and rivers to the heads of estuaries. Recommendations for the modelling frameworks that can be employed to relate landuse to the nutrient and sediment generation rates and the delivery rates of these materials to the end-of-catchment have been proposed through a separate scoping study completed by Rodger Grayson. Accordingly, the scoping study for the modelling of receiving waters being undertaken considers the fate of material and its impact in estuaries and the GBR Lagoon only, but the eventual framework must match with catchment modelling outputs. The major elements of the receiving waters’ modelling framework will include the following major elements, but some of these may be collapsed into one model covering multiple compartments and scales.

Major elements of receiving waters modelling framework

1. Estuarine-embayment & coastal floodplain
   a. Management-related inputs: Catchment freshwater flows & loads, flood-plain mgmt, coastal engineering
   b. Outputs: estuarine/inshore water & sediment quality, ecological indicators, export to GBR Lagoon
   c. Time scales: tidal, event, to interannual
   d. Forcing: weather, climate, tide, Lagoon boundary
   e. Processes: transport (flow, wind, tide & wave), deposition & resuspension, biogeochemical transformations, benthic-pelagic exchanges, ecological responses

2. Lagoon water quality
   b. Outputs: Lagoon water & sediment quality
   c. Time scales: tidal / diel /event to interannual
   d. Forcing: weather & climate, ocean boundary exchange
   e. Processes: as for Estuaries

3. GBR Ecosystem Health
   a. Management Inputs: Lagoon water & sediment quality, resource uses
   b. Outputs: Ecosystem health indicators
   c. Time scales: event to interannual
   d. Forcing: climate, weather, recruitment, …
   e. Processes: connectivity & recruitment, physiological response, trophic interactions, habitat dynamics, ….

Survey of Models
1. Model name
   a. What is the model name?

2. Model owner
   a. Who is the prime custodian of the model?

3. Model description
   a. What type of model is it (hydrodynamic, ecological etc.)
   b. What is the dimensionality of the model?

4. Model scope and application
   a. Which of the above elements of the modelling framework / spatial scales does the model address?
   b. What management related inputs does it treat (in the context of the major elements of the receiving waters modelling framework above)?
   c. What outputs / indicators does it predict?
   d. What time scales does it resolve inputs & outputs at?
   e. What forcing does it allow/require?
   f. What processes does it represent?
   g. Does it allow explicit representation of uncertainty / error in predictions?
   h. Can it be used in diagnostic mode i.e. for assessment? If so, what data sets can/should it be applied to?
   i. Can it be used in prognostic mode i.e. for scenarios and prediction? If so, what data sets are required for initialisation, for forcing, for calibration / validation?
   j. How has it been used previously to support management? (For example, in setting objectives and targets? In assessment? In decision support? Provide examples of case studies.

5. IP considerations
   a. Is the model proprietary?
   b. Are there charges associated with running the model software?
   c. Is the source code available for third party modification?

6. Participation and present status
a. What is the present status of the model? Is it under active development and application?

b. Are you interested in your model being a component of a modelling framework?

7. Are there any significant attributes of your model that you would like to mention that are not covered in the answers to the above questions?

Responses to the above questionnaire are summarised in the following tables.
<table>
<thead>
<tr>
<th>Name (Owner)</th>
<th>Type</th>
<th>Dimension</th>
<th>Modelling framework component</th>
<th>Proprietary</th>
<th>Charges</th>
<th>Source code</th>
<th>Active</th>
<th>Interested?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical Seagrass BBN (Thomas)</td>
<td>Ecological</td>
<td>Spatial and Temporal</td>
<td>Estuarine - Coastal Flood plain</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mgmt. Inputs</td>
<td></td>
<td></td>
<td>Catchment freshwater flows &amp; loads Suspended sediment concentrations, diss inorganic N, diss inorganic P, diuron, fresh water intensity and duration.</td>
<td>Y</td>
<td>?</td>
<td>-</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Output/indicators</td>
<td></td>
<td></td>
<td>estuarine/inshore water quality, export to GBR Lagoon; Phytoplankton blooms, seagrass biomass and health.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/O Time Scales</td>
<td></td>
<td></td>
<td>week, month, seagrass growing season (biannual), event &amp; interannual (ENSO), weekly input/output</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forcing allowed/required</td>
<td></td>
<td></td>
<td>current seagrass biomass and health, climate, weather (incl. tide), growth/recruitment, predation/toxicity, benthic geomorphology.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Processes</td>
<td></td>
<td></td>
<td>seagrass growth and mortality, physiological response, trophic interactions, herbicide toxicity, algal blooms, sediment resuspension River plume dilution</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Explicit representation of uncertainty</td>
<td></td>
<td></td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diagnostic mode</td>
<td></td>
<td></td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prognostic</td>
<td></td>
<td></td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Previous management use</td>
<td></td>
<td></td>
<td>It is a prototype and has not been deployed. It is designed for decision support, and can also be used to set and assess targets, or in ecological risk assessment.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Other Comments

i) Expert knowledge is a key data source for the model. ii) The Tropical Seagrass BBN isn’t ready for use; it has not been developed to a stage suitable for quantitative evaluation. The model was created primarily as a demonstration case for development and communication of a BBN knowledge engineering methodology for ecological risk assessment. This applies to model structure and parameterisation equally. For example aspects of seagrass meadow size and fragmentation are not represented, the influence of sediment quality or deposition could not be explored. These secondary system elements were simply beyond the project scope. iii) the focal causal pathway represented is light availability, but predation/herbivory (dugong), diuron toxicity (to marine phytoplankton and seagrass), competitive exclusion (Zostera only) and physical disturbances from cyclone-derived scour and burial are also represented at varying granularities.
<table>
<thead>
<tr>
<th>Name (Owner)</th>
<th>Type</th>
<th>Dimension</th>
<th>Modelling framework component</th>
<th>Ecosystem Health</th>
</tr>
</thead>
<tbody>
<tr>
<td>ChloroSim</td>
<td>Ecological</td>
<td>Spatial</td>
<td>Estuarine - Coastal Flood plain</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lagoon Water Quality</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Proprietary</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Charges</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Source code</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Active</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Interested?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N</td>
</tr>
</tbody>
</table>

**Mgmt. Inputs**
End-of-catchment dissolved inorganic nutrients (nitrogen)

**Output/indicators**
Chlorophyll a concentration (ug/L)

**I/O Time Scales**
Summer wet season runoff event (weeks – month)

**Forcing allowed/required**
Minimum (Lagoon) salinity, Salinity and exposure times from MECCA (King)

**Processes**
Conservative mixing of dissolved inorganic nutrients

**Explicit representation of uncertainty**
No

**Diagnostic mode**
Yes – past flood events (minimum salinity) can be used to assign lagoonal Chl a, which can be tested against in-situ measurements

**Prognostic**
Yes – changes in end-of-catchment DIN can be projected into the GBR Lagoon based on design flood events (e.g. 1-in-15yr flood)

**Previous management use**
ChloroSim has been used to: (i) predict chl a levels arising from specific runoff events, (ii) test scenarios for the impacts of post-European settlement on GBR water quality, (iii) assess changes in end-of-catchment DIN needed to achieve lagoonal water quality targets, and (iv) link to catchment flux models (SedNet).

**Other Comments**
<table>
<thead>
<tr>
<th>Name (Owner)</th>
<th>Type</th>
<th>Dimension</th>
<th>Modelling framework component</th>
<th>Proprietary Charges</th>
<th>Source code</th>
<th>Active</th>
<th>Interested?</th>
<th>Mgmt. Inputs</th>
<th>Output/indicators</th>
<th>I/O Time Scales</th>
<th>Forcing allowed/required</th>
<th>Processes</th>
<th>Explicit representation of uncertainty</th>
<th>Diagnostic mode</th>
<th>Prognostic</th>
<th>Previous management use</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂RAL</td>
<td>Ecological</td>
<td>Spatial and Temporal</td>
<td>Estuarine - Coastal Flood plain</td>
<td>Lagoon Water Quality</td>
<td>Ecosystem Health</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>All inputs can be stochastic or deterministic. Uncertainties are propagated through the system and reflected in the outputs.</td>
<td>Y – Long term spatial ecological and WQ data sets.</td>
<td>Y – scenarios and prediction, and also (perhaps more importantly) for sensitivity analyses – i.e. what parameters are most critical to the outputs.</td>
<td>It's fast, easily modifiable and has graphical and numeric outputs to assist interpretation. It's all written in R – can be made more efficient by converting some parts of the code to C</td>
</tr>
<tr>
<td>Name (Owner)</td>
<td>Type</td>
<td>Dimension</td>
<td>Estuarine - Coastal Flood plain</td>
<td>Lagoon Water Quality</td>
<td>Ecosystem Health</td>
<td>Proprietary Charges</td>
<td>Source code Active</td>
<td>Interested?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>------</td>
<td>-----------</td>
<td>--------------------------------</td>
<td>----------------------</td>
<td>-----------------</td>
<td>-------------------</td>
<td>-------------------</td>
<td>-------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Home (Wolanski)</td>
<td>Ecological</td>
<td>Spatial and Temporal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Inputs**
- River flows, nutrient loads
- River plume extent and dilution (from MECCA), connectivity, cyclone activity

**Output/indicators**
- % Coral Cover as a proxy for ecosystem health, as a function of land-use and oceanic/ atmospheric forcing

**I/O Time Scales**
- Hours to centuries

**Forcing allowed/required**
- River flows and Nutrient loads
- Hydrodynamics, Turbidity, cyclones,

**Processes**
- Connectivity,
- Fully linked physics-biology-ecosystem-ecology niches

**Explicit representation of uncertainty**
- As scenarios

**Diagnostic mode**
- Yes, sensitivity analysis

**Prognostic**
- Yes, as forecasts

**Previous management use**
- Yes, Guadiana Estuary with EU Water acts and Portugal governments under UNESCO sponsorship; Airai Bay with state government; Enipein River catchment with the local government; Fouha Bay with US government.
<table>
<thead>
<tr>
<th>Name (Owner)</th>
<th>Type</th>
<th>Dimension</th>
<th>Mgmt. Inputs</th>
<th>Output/indicators</th>
<th>I/O Time Scales</th>
<th>Forcing allowed/required</th>
<th>Processes</th>
<th>Explicit representation of uncertainty</th>
<th>Diagnostic mode</th>
<th>Prognostic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reef Exposure (Brodie)</td>
<td>Crude hydrodynamic 2D</td>
<td></td>
<td>Inputs from land (multiple rivers) : water volume, flow freq, suspended sediment load, nitrogen load, phosphorus load, herbicide (total proxy) load.</td>
<td>It predicts a numerical indicator of exposure of a point (eg a reef) to each pollutant.</td>
<td>Inputs and outputs are annual averages.</td>
<td>Relies on function which simulates probabilities of river plume water being forced in certain directions from the river mouth. The function is based on modelled and observed plume behaviour actually driven by winds, tides and Coriolis. Uses output from MECCA (King)</td>
<td>Dilution and sedimentation are modelled from empirical data on the dispersion of particulate and dissolved materials in plumes</td>
<td>No</td>
<td>It can be used in ‘reverse’ i.e. to link exposure at a particular reef to a particular and identified set of rivers.</td>
<td>Yes can be run (and is being run) to show effect</td>
</tr>
</tbody>
</table>
of different loads of pollutants (management scenarios) from individual catchments. Data requirement is changed individual river load based on credible catchment management scenario.

**Previous management use**

Results of original version (as in Devlin et al 2003) have been used widely to identify areas of the GBR exposed to high pollutant exposure and thus prioritise catchments for management.

<table>
<thead>
<tr>
<th>Other Comments</th>
<th>It's a very simple model and easy to run. However it entirely lacks a temporal element at present which could deal with the sharp temporal variability in exposure between wet season plume conditions and dry season residual exposure.</th>
</tr>
</thead>
</table>

**Reference**

<table>
<thead>
<tr>
<th>Name (Owner)</th>
<th>Type</th>
<th>Dimension</th>
<th>Estuarine - Coastal Flood plain</th>
<th>Lagoon Water Quality</th>
<th>Ecosystem Health</th>
<th>Proprietary</th>
<th>Charges</th>
<th>Source code</th>
<th>Interested?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlantis (Fulton)</td>
<td>Whole of ecosystem, ≤ entire trophic web + fisheries + impacts of pollutant sources and climate drivers</td>
<td>≤ 3D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Mgmt. Inputs**
- management actions, levers and fleet dynamics and effort allocation is required

**Output/indicators**
- Biomass of all groups (3D distribution), age structure and condition of vertebrates, Chlorophyll a, nutrient and oxygen levels, denitrification and nitrification rates, productivity, biomass rations, biomass size spectra, habitat cover (and a range of other ecological indicators), fisheries catches, socioeconomic (including profits, costs, port activity levels)

**I/O Time Scales**
- per timestep (6-24 hours depending on users choice)

**Forcing allowed/required**
- Transport model required for representing advection between boxes, light time series; temperature, salinity, rainfall, point source input, spatial management definitions and historical catch and effort forcing, market data and fuel costs

**Processes**
- Extensive. Advection, diffusion, resuspension, nutrient cycling (including bacterial cycling and mixotrophy, bioirrigation, bioturbation, burial, decay), primary production, biomass transfer (trophic interactions, with gape limitation), non-trophic (habitat dependent) interactions, vertebrate reproduction (invertebrate reproduction not explicit, but part of the growth equation),
<table>
<thead>
<tr>
<th>Name (Owner)</th>
<th>Type</th>
<th>Dimension</th>
<th>Modelling framework component</th>
<th>Proprietary Charges</th>
<th>Source code</th>
<th>Active Interested?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlantis (continued)</td>
<td></td>
<td></td>
<td>temperature dependent metabolism, forage and density dependent movement, point source inflow, fisheries (commercial and recreational), fisheries management, socioeconomic drivers of port activities and fisheries. Work in the Clarence river means that production by mangroves and saltmarsh plants (and other particularly estuarine activities) are under development as are explicit links to catchment models (or forcing)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Explicit representation of uncertainty</td>
<td></td>
<td>Through multiple deterministic scenarios or alternative parameter sets.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diagnostic mode</td>
<td></td>
<td>No it is a strategic management strategy evaluation model.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Prognostic</td>
<td></td>
<td>It is best used in a ‘what-if’ sense and as such needs initial conditions for all groups included in the models as well as any system forcing required to run the scenario. To calibrate and validate time series of abundance or spatial snapshots of distributions are required.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Previous management use</td>
<td></td>
<td>It has been used as decisions support (to give insight into system dynamics not to set actual management lever levels) in the southeast Australian commonwealth fisheries (SESSF), NSW coastal fisheries, the NE US and west coast US ground fisheries; it has been used to consider model structure in general via a Port Phillip Bay implementation; its advising on spatial and regional management objectives in Victorian, Tasmanian and south west Australian waters (as well as California); more water quality oriented versions have been developed at proof of concept level for Westernport (Victoria) and the Clarence River (NSW) and another is in development for the Puget Sound (USA).</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other Comments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Name (Owner)</td>
<td>Type</td>
<td>Dimension</td>
<td>Estuarine - Coastal Flood plain</td>
<td>Lagoon Water Quality</td>
<td>Ecosystem Health</td>
<td>Proprietary</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------------------</td>
<td>-----------</td>
<td>---------------------------------</td>
<td>----------------------</td>
<td>------------------</td>
<td>--------------</td>
</tr>
<tr>
<td>InVitro</td>
<td>Agent-based whole of ecosystem model.</td>
<td>3D</td>
<td></td>
<td></td>
<td></td>
<td>N</td>
</tr>
</tbody>
</table>

**Mgmt. Inputs**

The model can be tailored to whatever is available, but for contaminants it needs sites of outfalls and concentrations and trigger points for changes in outflows.

**Output/indicators**

Biomass, age structure, mortality of all groups, habitat cover, plume contacts and contamination, exploitation and returns of natural resources.

**I/O Time Scales**

As required: ≥ sub-second, ≥ sub-m

**Forcing allowed/required**

Requires bathymetry, but can also take hydrodynamic, climate, habitat, point source and market forcing.

**Processes**

Advection, diffusion, ecological (trophic and non-trophic) interactions, waste, primary production, shoreline forests (with potential to expansion of more catchment components), point source contaminants, human activities such as dredging, shipping, oil and gas, fisheries and conservation activities (all of these human sectors are currently under refinement and tourism and a more refined representation of acid sulphate soils are under development); full biogeochemical cycling not explicit but it may be added. The agent-based nature of this means any model of any kind can be tied together under this framework.

**Explicit representation of uncertainty**

Yes: stochastic model and can be run over a wide range of parameter sets to get a more complete (though still only bounded) sensitivity analysis (given the number of parameters involved more than this is not possible as yet).
<table>
<thead>
<tr>
<th><strong>Diagnostic mode</strong></th>
<th>Diagnostic models can be created using the framework, but it's typically used in a strategic sense</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Prognostic</strong></td>
<td>Yes: requires initial conditions for all groups, plus any forcing desired (e.g., hydrodynamics and contaminants). For calibration and validation needs time series and distributions of components.</td>
</tr>
<tr>
<td><strong>Previous management use</strong></td>
<td>Earlier version used in PMEZ consideration of dumpings off Tasmania; NWS-InVitro was used in a regional scale multiple use management evaluation and the model is currently being used for a whole of regional system MSE for the Ningaloo-Exmouth area.</td>
</tr>
<tr>
<td>Name (Owner)</td>
<td>Type</td>
</tr>
<tr>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>ARWQ Multi-reach &amp; Stratified Estuary Model (Lawrence)</td>
<td>Bio-geochemical based time series model, incorporating algal biomass response analysis</td>
</tr>
</tbody>
</table>

**Inputs**
- Catchment land use and management practices, or changes thereof, with respect to discharges, point and non-point discharges of key drivers of the major (ANZECC Guidelines) potential threats to water quality and health of receiving waters. Catchment & tidal return inflow & loads.

**Output/indicators**
- Daily export from estuaries of key physical, chemical & biological constituents.

**I/O Time Scales**
- 6 hr tidal periods based tidal inflows & discharges, 6 hr based catchment inflows & loads. Estuarine water quality and ecological outputs and exports to the GBR Lagoon on a 6 hr tidal basis.
### Forcing allowed/required
- Seasonal change in ocean temperature, local tidal ranges, local lagoon/estuary tidal returns (volume, loads of nutrients, algae, SS), wind driven re-aeration and mixing of water column, daily inflow volumes and velocities (mixing)

### Processes
- Physical mixing & diffusion forces resulting from wind, catchment & tidal flows and their interactions
- Physical surface oxygen & carbon dioxide re-aeration and emissions
- Physical coagulation – sedimentation of particulates
- Physical mixing of tidal and catchment discharge salt loads
- Bio-physical adsorption of DRP on particulates & removal by sedimentation
- Biological coating (nutrient uptake) on surfaces of particulates & removal by sedimentation
- Photosynthesis – algal biological uptake of nutrients, lysis & sedimentation of algae & other organic particulates
- Chemical equilibrium between NOx & NH4 as a function of temperature & redox conditions
- Water column DO balances (re-aeration, sediment BOD, diffusion rates, algal photosynthesis)
- Total Carbon and alkalinity equilibrium
- pH equilibrium

### Explicit representation of uncertainty
- Model user is encouraged to undertake multiple runs, varying assumptions regarding key coefficients, to test sensitivity and confidence. Variability in major drivers is accommodated by undertaking model runs for extended periods of data (5 to 20 years).

### Diagnostic mode
- Valuable tool for diagnostic assessment, particularly related to algae, DO levels, nitrogen levels. The model can be used to interpret the
<table>
<thead>
<tr>
<th>ARWQ (continued)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Prognostic</strong></td>
</tr>
<tr>
<td>By building on the major geo-chemical and biological processes, and incorporating tests for switching between dominant processes, the model provides a powerful tool for scenario testing. The catchment export sub-model in particular, enables quick and effective means of testing changes to catchment land use and management practices.</td>
</tr>
<tr>
<td><strong>Previous management use</strong></td>
</tr>
<tr>
<td>The ARWQ Lake Model has been used extensively in the design of urban lakes, diagnostic assessment of impacted lake management options, environmental impact assessments, etc. By linking catchment land use and management practices with receiving water quality and ecology responses, and assessment against the ANZECC Guidelines for fresh and Marine Water Quality Trigger Levels for the designated protection levels, the Model provides a rigorous and transparent means of testing objectives and targets.</td>
</tr>
</tbody>
</table>

Other Comments: The ARWQ Multi-reach & Stratified Estuary Model has been developed in response to Modellers and Scientists requiring a more detailed assessment tool that reflects in more detail longitudinal and inter-tidal changes in processes and estuary conditions.
<table>
<thead>
<tr>
<th>Name (Owner)</th>
<th>Type</th>
<th>Dimension</th>
<th>Estuarine - Coastal Flood plain</th>
<th>Lagoon Water Quality</th>
<th>Ecosystem Health</th>
<th>Proprietary</th>
<th>Charges</th>
<th>Source code</th>
<th>Active</th>
<th>Interested?</th>
</tr>
</thead>
<tbody>
<tr>
<td>SERM / EMS (Parslow / Webster)</td>
<td>Biogeochemical Model</td>
<td>1D, 2D (depth averaged), 3D, Box model</td>
<td></td>
<td></td>
<td></td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

**Inputs**
River loads

**Output/Indicators**
Nutrients (water column and sediment), suspended sediments (multiple classes), turbidity and light attenuation, dissolved oxygen, detritus, dissolved organics, phytoplankton (multiple classes), zooplankton, benthic-pelagic fluxes.

**I/O Time Scales**
Tidal to inter-annual.

**Forcing allowed/required**
Transports (from hydrodynamic model, inverse model), bottom stress from HD model, loads, open boundary conditions.

**Processes**
Transport, deposition & resuspension, nutrient uptake and primary production, grazing, remineralisation, adsorption-desorption, denitrification, nitrogen fixation, benthic-pelagic exchanges.

<p>| River loads | | Estuary export &amp; offshore exchanges | | | | | | | | |
| Nutrients (water column and sediment), suspended sediments (multiple classes), turbidity and light attenuation, dissolved oxygen, detritus, dissolved organics, phytoplankton (multiple classes), zooplankton, benthic-pelagic fluxes. | macroalgae, seagrass, benthic microalgae, | | | | | | | | |</p>
<table>
<thead>
<tr>
<th><strong>Explicit representation of uncertainty</strong></th>
<th>No</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diagnostic mode</strong></td>
<td>In development</td>
<td>In development</td>
</tr>
<tr>
<td><strong>Prognostic</strong></td>
<td>Yes. Used widely to run management scenarios linking loads to water &amp; sediment quality. Requires initial values for state variables above, boundary conditions, observations of key state variables for calibration.</td>
<td>Yes. Used widely to run management scenarios linking loads to water &amp; sediment quality. Requires initial values for state variables above, boundary conditions, observations of key state variables for calibration.</td>
</tr>
<tr>
<td><strong>Previous management use</strong></td>
<td>Used to run scenarios and directly influence management decisions around diffuse and point source load targets in many case studies: Port Phillip Bay, Gippsland Lakes, Huon Estuary &amp; D’Entrecasteaux Channel, Ord Estuary, Fitzroy Estuary. Used as broad brush tool to develop pilot models of 800 Australian estuaries in SERM II</td>
<td>Used to underpin ecosystem models in NW Shelf.</td>
</tr>
</tbody>
</table>

**Other Comments**

Relative to most other biogeochemical models, the model places more emphasis on nutrient transformations within the benthos.
<table>
<thead>
<tr>
<th>Name (Owner)</th>
<th>Type</th>
<th>Dimension</th>
<th>Modelling framework component</th>
<th>Ecosystem Health</th>
<th>Proprietary Charges</th>
<th>Source code</th>
<th>Active Interested?</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHOC (Herzfeld)</td>
<td>Hydrodynamic, with sediment transport and biogeochemical modules</td>
<td>1D, 2D (depth averaged), 3D</td>
<td>Estuarine - Coastal Flood plain</td>
<td>Lagoon Water Quality</td>
<td>N</td>
<td>N</td>
<td>Y</td>
</tr>
</tbody>
</table>

**Inputs**
- Export from estuaries / inshore.

**Output/indicators**
- Temp, salinity, sea level, currents, sediments, primary production, nutrients.

**I/O Time Scales**
- Tidal to inter-annual.

**Forcing allowed/required**
- Surface atmospheric fluxes (wind, heat, freshwater), open boundary (e.g. tide)

**Processes**
- Transport, deposition & resuspension, biogeochemical transformations, benthic-pelagic exchanges.

**Explicit representation of uncertainty**
- No

**Diagnostic mode**
- Can be used for hindcasts.

**Prognostic**
- Yes. T/S, sea level & meteorological surface fluxes. Sediment and biogeochemical initial and open boundary conditions

**Previous management use**
- **Setting targets**: System-wide environmental issues for sustainable salmonid aquaculture.
- **Assessment**: Scenario modelling: simulating the downstream effects of changes in catchment land use.
- **Decision support**: ROAM: Task 5 model description and assessment.
<table>
<thead>
<tr>
<th>Other Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additional attributes: Ability to operate in a transport (offline) mode. Parallel processing capability.</td>
</tr>
<tr>
<td>Application of model:</td>
</tr>
<tr>
<td>Name (Owner)</td>
</tr>
<tr>
<td>-------------</td>
</tr>
<tr>
<td>MECCA (King)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Modelling framework component</th>
<th>Lagoon Water Quality</th>
<th>Ecosystem Health</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td>River inflows, wind</td>
<td></td>
</tr>
<tr>
<td>Output/indicators</td>
<td>Fresh water concentration – Lagoon</td>
<td></td>
</tr>
<tr>
<td>I/O Time Scales</td>
<td>Hourly – 6 hourly</td>
<td></td>
</tr>
<tr>
<td>Forcing allowed/required</td>
<td>Wind, River discharge, tides (optional)</td>
<td></td>
</tr>
<tr>
<td>Processes</td>
<td>Transport/mixing of fresh water</td>
<td></td>
</tr>
<tr>
<td>Explicit representation of uncertainty</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Diagnostic mode</td>
<td>Yes – measured plume concentration</td>
<td></td>
</tr>
<tr>
<td>Prognostic</td>
<td>Yes – river discharge, wind, tide (optional)</td>
<td></td>
</tr>
<tr>
<td>Previous management use</td>
<td>Unknown [has formed basis for other modelling activities eg, Devlin/Brodie; Wooldridge, Thomas]</td>
<td></td>
</tr>
</tbody>
</table>

Other Comments
<table>
<thead>
<tr>
<th>Name (Owner)</th>
<th>Type</th>
<th>Dimension</th>
<th>Estuarine - Coastal Flood plain</th>
<th>Lagoon Water Quality</th>
<th>Ecosystem Health</th>
<th>Proprietary</th>
<th>Charges</th>
<th>Source code</th>
<th>Active</th>
<th>Interested?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro (Brinkman)</td>
<td>Hydrodynamic Lagoon transport processes.</td>
<td>2D (depth integrated)</td>
<td></td>
<td></td>
<td></td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
</tr>
</tbody>
</table>

**Inputs**
- Passive substance concentrations

**Output/indicators**
- Sea level, currents, trajectories of material

**I/O Time Scales**
- Hours to intrannual

**Forcing allowed/required**
- Open boundary forcing by sea levels (tidal and low frequency components), surface wind stress. Can have river discharge inputs, but only in depth integrated sense.

**Processes**
- Transport

**Explicit representation of uncertainty**
- No

**Diagnostic mode**
- Hindcast

**Prognostic**
- Yes, requires open boundary sea level forcing, and wind stress.

**Previous management use**
- No

**Other Comments**
- Coupled transport model can simulate fate of waterbourne material/organisms with simple behaviour (decay, locomotive ability..)
<table>
<thead>
<tr>
<th>Name (Owner)</th>
<th>Type</th>
<th>Dimension</th>
<th>Estuarine - Coastal Flood plain</th>
<th>Lagoon Water Quality</th>
<th>Ecosystem Health</th>
<th>Proprietary Charges</th>
<th>Source code</th>
<th>Active</th>
<th>Interested?</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLIM (UCL)</td>
<td>Hydrodynamic of whole GBR Passive substance transport</td>
<td>2D (depth integrated)</td>
<td></td>
<td>Lagoon transport processes driven by transport tides, wind, oceanic circulation.</td>
<td></td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>N</td>
</tr>
</tbody>
</table>

- **Inputs**
  - Passive substance concentrations

- **Output/indicators**
  - Sea level, current speed
  - Substance transport for sediment and pollutant concentrations.

- **I/O Time Scales**
  - hours to months

- **Forcing allowed/required**
  - Exchange at the open sea boundary on the shelf break: tides, EAC; Wind stress; Variable bottom friction

- **Processes**
  - Transport

- **Explicit representation of uncertainty**
  - through ensemble runs

- **Diagnostic mode**
  - Hindcast

- **Prognostic**
  - Yes, requires forcing as described above.

- **Previous management use**
  - No

**Other Comments**

- Our model has reached a certain maturity in modelling the GBR Lagoon hydrodynamics, we are now eager to find biological and ecological applications.
- Publications related to the application of SLIM to the GBR:
<table>
<thead>
<tr>
<th>Name (Owner) (Margvelashvili)</th>
<th>Type</th>
<th>Dimension</th>
<th>Estuarine - Coastal Flood plain</th>
<th>Lagoon Water Quality</th>
<th>Ecosystem Health</th>
<th>Proprietary Charges Source code Active Interested?</th>
</tr>
</thead>
<tbody>
<tr>
<td>MecoSed</td>
<td>Fine-resolution process-based model of suspended sediment transport.</td>
<td>3D</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Inputs**

- Catchment freshwater flows & loads, export from the estuaries and lagoons
- Coastal sediment load, coastal engineering

**Output/indicators**

- Estuarine and coastal suspended sediment concentrations, deposition and erosion zones, export to the ocean

**I/O Time Scales**

- Minutes to years

**Forcing allowed/required**

- Three-dimensional field of currents and wave characteristics (orbital velocities, direction and period)

**Processes**

- Advection and turbulent diffusion in water column, resuspension and deposition at the sediment-water interface, bioturbation in sediments

**Explicit representation of uncertainty**

- No

**Diagnostic mode**

- Does not have built in capabilities for data-model fusion

**Prognostic**

- Forced by three-dimensional field of currents and wave data. The model is initialised by
<table>
<thead>
<tr>
<th><strong>MecoSed</strong> (continued)</th>
<th>specifying seabed texture (e.g., distribution of mud/sand/gravel deposits) and requires sediment loads/concentrations at open sea boundaries (and from point/distributed sources). The model should be calibrated/validated against measured suspended sediment concentrations.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Previous management use</strong></td>
<td>The model has been used in a number of coastal and shelf scale applications around Australian coast. The case study areas included macrotidal environment (Fitzroy Estuary, North West Shelf, Torres Strait), baroclinic salt-wedge estuary (Derwent), and temperate lagoon (Boston Bay). In the Fitzroy Estuary and Keppel Bay (Coastal CRC study), the main objective of simulations was to assess sediment delivery to the ocean under varying loads from catchments that would represent altered land use practices on catchments. In the Torres Strait region (Torres Strait CRC), the model was used to investigate temporal and spatial variability of the sediment transport aiming at better understanding of processes influencing sea-grass variability on the shelf. In the Derwent estuary (DPIWE CSIRO collaborative project) the model provided physical settings for the contaminant simulation and was used to support management actions aiming at reduced levels of heavy metals in the estuary.</td>
</tr>
<tr>
<td>Other Comments</td>
<td>The sediment model is fully coupled to the environmental modelling suite (EMS), which includes 3-d hydrodynamic model (SHOC), sediment transport model (MECOSED), and bio-geo-chemical reaction model.</td>
</tr>
<tr>
<td>Name (Owner)</td>
<td>Type</td>
</tr>
<tr>
<td>-------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>NephDisp (Brinkman)</td>
<td>Coastal sediment transport</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Inputs**
- Coastal sediment load

**Output/Indicators**
- Coastal sediment load
- Suspended sediment concentrations.

**I/O Time Scales**
- Hours – weeks – months if pushed

**Forcing allowed/required**
- Velocity fields.

**Processes**
- Nepheloid layer dynamics

**Explicit representation of uncertainty**
- No

**Diagnostic mode**
- Hindcast

**Prognostic**
- Yes, if flow fields are supplied.

**Previous management use**
- No

**Other Comments**
APPENDIX C

The following workshop report was distributed to workshop attendees and to the Steering Committee of our scoping study following the workshop.

Great Barrier Reef Receiving Water Modelling Workshop: Scoping modelling needs and opportunities

________________________

Workshop Notes

________________________

16 & 17 July 2007
Museum of Tropical Queensland, Townsville
Attendees

Rachel Eberhard, RWQP – Facilitator
Jane Waterhouse, RWQP
Joelle Prange, GBRMPA
Hugh Yorkston, GBRMPA (Day 1 morning only)
Carol Honchin, GBRMPA
Jon Brodie, ACTFR (Day 1 only)
Katharina Fabricius, AIMS
George Lukacs, ACTFR (Day 1 only)
Lance Bode, JCU (Day 1 morning only)
Lou Mason, Australian Maritime College
Miles Furnas, AIMS
Richard Brinkman, AIMS
Peter Ridd, JCU (Day 1 only)
John Parslow, CSIRO
Ian Webster, CSIRO

Apologies:
Scott Wooldridge, AIMS
Jim Wallace, CSIRO
Eric Wolanski, AIMS
Glenn De’ath, AIMS
Workshop Objectives

The broad goal of the workshop is to scope how model frameworks might be developed to link management action in the catchments to water quality and ecological impacts in the receiving waters of the GBR World Heritage Area. The content of the workshop is focused around four main components:

• Clarify context and management needs;
• Establish the capacity of the current models (est/marine phys-chem and ecological) to meet needs in the contexts of including necessary processes and parameters;
• Develop a strategy for linking estuarine/marine models to achieve management goals; and
• Propose strategy for long-term development and application of the models

Background and Context

Planning context – Rachel Eberhard, Reef Water Quality Partnership

Rachel provided an overview of the relevant policies/arrangements for the modelling needs including Reef Plan, Regional NRM Plans, Water Quality Improvement Plans (WQIPs) – in priority GBR catchments, and the Reef Water Quality Partnership (RWQP).

Discussion:

• Regional differences are now being recognised and are apparent in planning processes. Eg. Appropriate scales for each region, eg. subcatchment for Burdekin – clearly addressed through WQIPs.
• Scale of interest depends on the selected metric; primary metric to date has been loads so focus will be end of catchment – need to determine linkage metrics, and then can set priorities from marine objectives (top down).
• Outstanding need – relative risk across and within regions, and between parameters. Highly variable temporally and spatially.

Workshop overview – Ian Webster, CSIRO

Ian provided an overview of the scope of the review and where it fits in bigger picture. Focus is on models for management needs, parameters, linking models, at regional and GBR-wide scales. Need to consider model development and model implementation.

Discussion:

• Agreed that linkage from paddock to reef, through biophysical and socio-economic models, will not be addressed through this workshop; but recognised as a need. Needs to be identified as an outstanding need in the recommendations.
• Other major gaps: Paddock scale and marine ecosystem effects models; capacity to link models from paddock to reef, and to incorporate socio-economic information/models.
• RWQWP is proposing a regional case study to look at the current and potential future capacity to support adaptive management for reef outcomes ie this work would bring all of the modelling and other components together and look at how the current qualitative integrative framework could be made quantitative. Some of the perceived gaps in scope of this work will be addressed through the case study proposal
• Important not to consider receiving model opportunities in isolation; must be in context of overall management needs and biophysical processes, and therefore, what can be modelled back to land management actions.
John provided an overview of the role of models in the adaptive management cycle, and relevance of receiving water models in that framework.

Discussion:
- Predictive models necessary to overcome long term cycles and high variability in the GBR system. Leads to long management cycle; if performance measures are modelled – and assessment is undertaken through models – then will be sure to meet the measures (same results)! Assessment models allow variability and uncertainty to be account for, and shorten the management cycle.
- Integrate monitoring into modelling for validation (improved confidence in model results), but need to determine how to accurately assess performance/success.
- Recognise that efforts are in place to make linkages between catchment activities and marine water quality, eg. Wooldridge et al. chlorophyll (chl) and Dissolved Inorganic Nitrogen (DIN) model; need to make a series of links for the range of priority parameters.
- Complex marine processes for sediment and nutrients in GBR; need to understand the predictive capacity of ecosystem models.
- Given the complexity and long time lags in the system– modelling cannot be done in isolation – coordinated model development and implementation, and management response is required.
- Annual timescales are not realistic, but some relationships may enable 3-5 year timescale responses, eg. Chl-DIN; pesticide reduction potentially measured in much shorter periods; but what is the ecosystem response is largely unknown.
- Goal is to provide useful feedback to managers – is the management action working? For example, vegetation cover or chl in water column can be used as short term indicators, complemented with comprehensive long term monitoring to support process understanding – but still need to resolve which indicators are optimal to answer which management questions. Need sufficient information to undertake risk assessment and inform debate.
- GBRMPA WQ Guidelines provide starting point to setting trigger levels for ecosystem health – further development required of supporting ecological response models. For example, the Fitzroy region is establishing aspirational targets for improving water quality in Keppel Bay – to gain support from stakeholders, models need to be able to demonstrate improvement through reduced loads in management actions. Burdekin is likely to set up similar targets - targeting win-win approaches in the grazing industry; assume improved practices reduce runoff to the Reef. Fertiliser improvements are not as comparable – reduced losses often result in cost to landholders.
- Since development of the Reef Plan, there has been a shift from a ‘no regrets’, precautionary approach to working towards quantifying what is required to maintain GBR ecosystem health, understanding cause-effect, and measuring success.

Progress of WQIPs – Ian Webster, CSIRO

Ian conducted a survey of the status of each of the WQIPs in the GBR with regard to the role of modelling in WQIP development and implementation.
Discussion:

- Defining receiving zones – process is arbitrary across regions; would be beneficial to define a consistent approach, although definition will be variable across regions depending on the available information, eg. 10m inshore/offshore, or plume extent. Outputs from the revised Reef Risk Exposure Model (Brodie et al) may provide relevant information.

- Timeframes vary across regions. WQIPs (and Reef Plan) will be reviewed in 2010; targets are being set to 2013. In the shorter term, need to be able to demonstrate the level of implementation of management actions; in the longer term (25 years) seeking to achieve aspirational targets related to ecosystem health. **If models form part of the assessment and target setting role in 2010 review, need to be developed by at least 2009 for implementation.** Assessment in 2013 also depends on monitoring design which should also be reviewed when modelling is completed around 2010.

- Model outputs and timing:
  - Next 12 months – progress any easy ‘wins’, eg. spatial extent of receiving waters targets;
  - 2010 – models for assessment and target setting;
  - 2015 – models for evaluation.

- Need to link water quality models with vulnerability assessments related to climate change.

- Empirical models – gradient approach may be a more suitable framework than an arbitrary boundary, or zones.

- Challenges in understanding sediment and turbidity relationship – cannot establish top down connection between reef turbidity and sediment loads at end of catchment – results in current limitation in modelling capacity.

- Must identify capacity to ‘scale-up’ from regional scales to GBR wide scale incorporating regional interactions, eg. flood plumes, and incorporation of confounding issues such as climate change, COTS and cyclonic events.

- In terms of sediment influences, need capacity to determine whether extent and exposure of ecosystems to flood plumes, and ambient conditions that are influenced by resuspension, are of equal importance. Cannot address small-field context without understanding far-field issues. Load and distance are important (except pesticides – toxicity, different modelling needs – exposure and concentration); need spatially explicit measure of ecologically relevant influence.

- Process based models are required to answer management questions – results may support empirical models for management applications; a combination of models is the most likely solution.

- Need to answer management questions such as where to prioritise management to protect a specific reef or seagrass bed, eg. how can models be used to understand the delivery of disturbance, and response to that disturbance, and changes over time; and how to address changing baselines.

- Must link outputs to indicators; inputs are time series of flows and concentrations to determine loads, indicators to date are a range of water quality objectives and ultimately ecological health.

- Models are complex and require expertise to run them – major consideration in the timeframes.
Modelling opportunities

Material Transport models

Ian Webster provided an overview of hydrodynamic, sediment dynamics and biogeochemical models and how they might be linked.

1. Hydrodynamic models
2. Sediment dynamics
3. Biogeochemical models

Discussion:

- Differentiation of flood and non-flood conditions is important; to what extent are processes different conceptually? Concentrations in receiving environment are primarily about hydrodynamic dilution in flood conditions – more about surface delivery and assume biogeochemical processing has minimal influence; ambient modelling needs to incorporate sediment and nutrient interactions – resuspension, deposition and biogeochemistry.

- King et al hydrodynamic model:
  - Covers central GBR northwards; new observations are not adequately reflected, e.g. southward movement of plumes, and oceanic currents. Model could be improved by including effects of offshore pressure gradients, and updated distribution images (although images may not necessarily show freshwater distribution but use CDOM as ‘proxy’). In ‘typical’ movement northward – plume pushed as coastal wedge to the north, spatially confined; southern movement often results in more dispersion.
  - Spatial resolution – 2km, adequate; 3D model. Reef is incorporated as a dry cell, sufficient resolution if maintained at coarse resolution and determining relative risk.
  - Parameterised by one dataset only.
  - Southern GBR extension – limited by data to parameterise it and tides have greater influence.

- Same base hydrodynamic model required for flood and non-flood models – can use non-flood model with shortcuts, basically the same.

- Chronic flows – need waves and local resuspension processes. Flood modelling - limited horizontal mixing – higher resolution required to incorporate plume boundaries; but difficult to parameterise on a finer scale.

- Need to understand to what extent finer scale models are required to connect catchment loads to lagoon delivery and lagoon indicators; and how to deal with estuaries, embayments and lagoons. Potential need for a range of case studies.

- Behaviour of soil particles not well understood – differentiating the tracing component that does not settle compared to the sediment that is settled and resuspended. Particulate organic material is transported differently from nutrients.

- Concern that sediment transport model limitations related to understanding sediment behaviour are so substantial that they far outweigh other limitations of hydrodynamic models and issues with resolution. Need to determine what scales need resolving with regard to sediment dynamics.

- Luick model – great uncertainty in dilution factors and spatial differences in flushing times, depending on which parameters focusing on. Firstly need to know where does the water go (Mason and Bode); different materials have different behaviours.
*Spatial* requirements:
- Need to consider whole of system and have the capacity to extract regional results, especially to be able to incorporate influence of larger delivery catchments on others (e.g. Burdekin on Wet Tropics in significant events).
- Working at catchment scale can link delivery to gradients and regionally specific data – more relevant to management - but larger scale models can be run with various scenarios to improve relevance at regional scale.
- Need hierarchical system where can refine scale at some areas which will be demonstrated through case studies and supporting research. Eg. Scenarios – vary loads out of 1 catchment, vary loads out of multiple/alternative catchments.
- Use biogeochemistry and sediment transport as case study to address under-parameterisation, and use case studies to test coarser-scale model.
- Global scale provides boundaries to regional scales.
- Current monitoring and usefulness of the data for parameterisation needs to be determined.

**Conclusions:**
It was agreed that the following model was required that would form the basis for simulating water quality in the GBR Lagoon and its relationship with river inputs, which would allow the differentiation of the impacts of particular rivers and which could be used as the ‘background’ for nesting models of more localised impacts. It would have the following characteristics:
- GBR-wide model – hydrodynamic and materials and biogeochemistry
- 2km resolution
- 3D
- needs to run on time scale of decades to capture river flow variability and variability in other system drivers

**Model Scope:**
- Floodplain – no
- Estuary – maybe
- Embayments – maybe
- Inshore – yes
- Offshore – yes

**Input data:**
*Hydrodynamic* models –
- Wind action (difficult to incorporate and will be relatively broad characterisation, significant influence on horizontal mixing, eg. CSIRO BlueLink model). *Research need.*
- Waves
- Tides
- Effects of flows along edge of continental shelf
- Effects of buoyancy (temperature & salinity) on plume dynamics
- Temperature
- Bathymetry
- Surface-atmospheric fluxes – higher resolution atmospheric models.

Nature of river flow incorporated through time series of discharge – but velocity will influence hydrodynamics – useful for finer scale models, also incorporating floodplain flow. *Potential need for case study/research.*
**Sediment (particulate material) dynamics** -

- Interaction between fine sediment inorganic properties and organic matter in the system – not well parameterised. **Research need.**
- Flocculation dynamics and particle settling rates. Most of fine sediment settles out close to river mouths and is subsequently redistributed by tides and waves.
- Role of substrate, eg. roughness - not well parameterised – interaction between sediment dynamics and hydrodynamics. **Research need.**
- Speciation of sediment types, need to know nature of materials before can determine effects. Flocculation likely to depend on geochemistry of particles and be site specific **Research need.**
- Dynamics of fine sediment in tidal creeks (eg. Fitzroy, others?). These may be areas of significant deposition
- Resuspension likely to depend on sediment consolidation, bioturbation and cohesiveness which affect critical shear stresses for resuspension
- Need to understand where the fine sediment goes, Eg. Gavin Dunbar in Burdekin region – 10-15% fine sediment crosses shelf; not sure how. Predominant SE winds – coastal northward facing bays. **Research need.**
- Non-linear interaction of tidal pumping and wind driven flow – most won’t be resolved in 2km resolution. Fresh injection of sediment from river flow, more mobile available sediment in places where resuspended – and higher turbidity; random distribution to areas where not typically resuspended. Need to understand role of consolidation. Mouth of Burdekin River, fine sediment is redistributed soon after events. **Potential need for case study.**
- Need to determine the measurements that are needed to support assessment models such as primary and secondary deposition (mobilisation) data – timescales are critical for turbidity and ecology (eg. Eric Wolanski’s work in MTSRF 3.7.2). **Research need.**

**Biogeochemical models**

- Phytoplankton speciation – important influences – need GBR-specific communities.
- Influence from bare sediments versus benthic communities – how can these be parameterised in models?
- Importance of silica – not significant in GBR context.
- Knowledge gap - nutrient and sediment interactions. **Research need.**
- Pesticide transport – higher resolution modelling may be required. Useful tracer for hydrodynamics – clear source and limited timescales. Dilute conservatively, relatively short half-life. **Potential need for case study.** Temperate pesticide modelling examples available – SA – Rai Kookana, CSIRO.

**Ecosystem Response models**

John Parslow provided an overview of needs for ecosystem response models in the GBR context. Comments received on the content of the presentation:

- Add cyclonic events to confounding issues.
- Spatial patterns and scales – include variations in catchment inputs, and habitat availability and refuge in response to impacts.
- Episodic events – include oceanic upwelling and influence on material sources.
Discussion:

- Katharina Fabricius has completed a review of important indicators and performance measures for water quality and ecosystem health. Key indicators identified to date are coral recruitment, macroalgae and COTS. A combination of indicators is most likely to be most useful. Developed a series of relationships between event-based impacts and indicators eg. Water quality and juvenile coral distribution.
- Coral cover is a suitable long term, large scale indicator - otherwise there are issues arising from specificity and time scale of response, and direct and indirect effects from water quality and other influences.
- Herbivorous fish also potential indicator but there is limited understanding of the interactions in the GBR system.
- Need to develop empirical relationships between reef health and water quality. Examples exist that attempt to model the interaction between coral, algae and water quality and grazing fish.
- Existing models:
  - HOME model using dilution factor alone as measure of impact – if want to be able to link to catchment actions then need additional ability in model – currently deals with chronic conditions on the reef. Underpinning conceptual framework is sound, further refinement could be appropriate.
  - Need to be clear about the connections in the model and importance of active parameterisation; develop a framework that incorporates a range of processes and the influences of those processes – define scenarios.
  - Glenn Death’s model -CORAL– incorporates wide range of parameters – different to HOME model; statistical approach. Needs to be investigated.
  - HOME and CORAL open to modification; big difference is probability – HOME is deterministic, CORAL links real data (coral cover, WQ, bathymetry) with inbuilt connectivity models and runs scenarios, can predict response through time series.
- Priority is to address receiving water aspect of models, ecological effects will be longer term goal. Event-recovery and acute-recovery models – important for driving responses – attractive approach for GBR water quality.
- **Use driving indicator such as light as key parameter for ecological response models.**
- **Detailed effects models likely to be relevant at smaller scales. Statistical empirical models useful at broader scales.**
- Relationship between fish populations and water quality requires further investigation.
- Linking models to indicators can be achieved using quantitative or assessment approaches, depending on the different management objectives.
- Need confidence that models are going to be able to demonstrate change, ie. Measurable reef improvement, or coral recruitment increases or increased juvenile counts. Models will at least predict recovery timescales – indicates the likely timescale that measurable change will be achieved in reef health at least at a statistical level if big changes are implemented.

Conclusions:

- Agreed that the HOME and CORAL model (impact-recovery models) are founded on the right principles to meet the management needs.
- Both models require revision of the assumptions and process understanding that provide the right connection to the management objectives.
- Short term or specific indicators such as coral ecophysiological indicators or recruitment related to recovery side of models (and are represented in existing models). Large scale long term indicators such as coral cover and algal cover (that models would predict) are useful at a system level but the timescales of response to water quality are decadal or longer; also responding to a wide range of other effects.
• Consensus in terms of ecological performance indicators:
  − Branching and massive corals
  − Coral recruitment
  − Macroalgae
  − COTS
  − Fish herbivores (but coral-algae-WQ-fish interaction not well understood).
• Need to link indicators to material process models (light, turbidity etc).
• Role of herbivorous fish – uncertain about the reliance on the relationship to turbidity and how that is supported. Use of fish as indicators themselves – relationship to turbidity or coral cover – unsure whether need fish as a model output. Eg. Work in Ningaloo may have relevant findings. Glenn still determining how to incorporate.
• Require better understanding of the relationship between macroalgae and dissolved inorganic nutrients; investigate incorporation into HOME model.
• Incorporation of seagrass ecosystems. Seagrass impacts in inshore areas – poorly understood – may get shift in community composition to declining water quality, rather than abundance or biomass. Most data from intertidal monitoring; limited subtidal data; less information on variability than is available for corals. Nutrient effect on seagrass is second order – epiphyte growth. More exposed to herbicide in inshore areas. Focus of a case study area at higher resolution – couple with impact specific case studies, eg. Light attenuation (JCU). Link to Collette Thomas’ BBN, and empirical and process models.
• **Agreed that inter-reefal communities and mangroves will be excluded in the initial studies.** Limited examples of mangrove ecosystem response models, but substantial data available for parameterisation. Susceptible to herbicides, but not sediment and nutrients.
• Investigate options for ecological models for iconic species such as barramundi and mudcrabs - may be beneficial for getting support for on-ground action and making the results relate to landholders.

Information needs

Material Transport models

• In order to be able to resolve inner-outer reef processes, may need higher resolution than 2km, although questionable of anything at that scale could be parameterised usefully at this stage. **Research need.**
• Horizontal parameterisation can work but need to determine how to deal with channels etc. Scaling factor related to how much of cell is open and how much is reef; important in terms of momentum exchange. In terms of tracking nutrients for example, need to take different approach to make the results more accurate. Vertical mixing is more challenging – understanding plume dispersion. Vertical diffusion and heating – feedback mechanisms difficult to incorporate. In Global Ocean models, surface parameterisation is fixed; cannot make those assumptions to characterise water quality models.
• Need to incorporate capacity to work into inter-reefal areas over time. Set up systems that can work across resolutions – build in nested scales.
**Hydrodynamic input data** (refer to discussion on page 8 of the notes). In addition:

- Climate forcing data – temperature, humidity, height, salinity, rainfall.
- Atmospheric influences – Sunlight, cloudiness and non-cloudiness, light energy related to heating water column; timing of blooms and potential bleaching events. Develop statistical model from existing weather station data, coupled with NASA global model? Surface heat exchange challenging in the tropics. METbouy off Heron Island associated with bleaching project.
- Atmospheric nitrogen deposition (rainfall input) and dust – nitrogen or pesticides.
- Many data inputs require statistical model outputs to run them.
- If want good statistics will require to trace back many years of plume data; reasonable data only available for last 16 years. Bode model – started work in 1996 – earliest date that LAPS wind data is available. AMSET data strongly constrained by Townsville weather station – accuracy of offshore data not adequate, but long term dataset (poor boundary-forcing).
- Modify river flows during periods where limited data; simulate floods?

Potential limitations for extending the King et al approach to the southern GBR, and how to overcome them:

- *Influence of ocean upwelling* - If nested within larger ocean model then may be able to overcome issues. Data sets are available that can be used as surrogate.
- *Higher flow variability of the southern rivers (decadal scale)* - Develop a sub-project – flood frequency and statistical model/simulation. Should be able to access information for IQQM modelling from water resource planning exercises.
- *Extreme tides* - Available now to be built into the model.
- *Influence of East Australian Current*. Pressure gradients associated with EAC can reverse direction of prevailing currents within the GBR Lagoon during some times of the year.
- *Validation of the model would be based on a limited plume sampling data* - Not necessarily needed to be within-plume data. Calibration data available for Heron Island from MTSRF project looking at currents; installation of buoys and radar to monitor surface current. GBR Ocean Observing System (GBROOS) – maintaining existing monitoring moorings and extending into other areas (associated with research stations).
- *Suboptimal bathymetry information* – GBR 250m resolution DEM created through CRC Reef – collates historic data and still contains gaps. AIMS have an ongoing (4 year) project that incorporates new data and updates DEM – increasing accuracy. Initially, use same algorithms with updated data.

**Catchment model data outputs for input to marine WQ model - limitations:**

**Sediment dynamics**

- Underlying map of coastal sediment characteristics close to coast.
- Strong need for data collection to support calibration of sediment models – in situ collection.

Gaps:

- Sediment models do not differentiate sediment composition. Sediment mobilisation - >64uM settle close to coast; finer sediment is transported offshore.
- SedNet develops average annual SS load – need time resolution catchment models.
- Need to characterise particle size distribution by catchment, sub-catchments, events/energy.
- Fine sediment response to management actions (versus bedload long lag times) - incorporating geomorphic response at 2km scale is not a priority.
• Particle size and geochemical properties – flocculation properties etc. Need to understand settling properties at varying salinities, and flocculation affected by shear. Research need.
• Fate controlled by higher resolution processes (than 2km) – especially in important coastal areas, eg. Tidal influences, vertical distribution of sediment, trapping in mangroves and northern bays. Potential need for case study.
• Coastal chronic turbid zone is highly variable. How far offshore before out of turbid zone? Eg. Douglas less than 1.5km – central and northern regions turbid band is potentially more limited than southern areas where higher tidal velocities – turbid zone extends further offshore.
• Temperature and salinity can be run initially and build in other parameters over time.

**Nutrients**

• Rainfall and nutrients – primarily N, little P, Si, Fe (and some dust but probably secondary).
• Rivers have volume averaged nutrient loads but highly variable – needs parameterisation over rivers, events etc.
• Upwelling at shelf break – can estimate inputs.
• Trichodesmium? Wild guess? Order of magnitude.
• Particulate nutrient interactions – adsorption, desorption.
• Catchment models still do not deliver nutrient speciation, but monitored data delivers speciated loads (Freeman Cook, eWater pilot projects?). Possible to extrapolate fine sediment estimation to particulate fractions and calculate nutrient by difference.
• Sediment and nutrient relationships? With salinity, oxygen and carbonate (eg. carbonate and phosphorus interactions – any buffering capacity?).
• Dan Alongi sediment measurements – does not appear to be significant burial of nitrogen.
• Sources of terrestrial versus marine nutrients – not significant on mass basis; marine sources of nitrogen are quickly recycled. Potential that isotopic signature of terrestrial is lost because it is processed so quickly.
• DON and DIN may be important at outer shelf boundary - displacement modelling for upwelling events high in nitrogen– water pushed offshore is dissolved inorganic N.
• Particulate nutrient pool in nearshore zone turns over daily through resuspension.
• Demand by primary production large compared to sediment fluxes – large amount of mineralisation in water column.
• If flushing times are relatively long, then loss of bioavailable N from systems due to denitrification would be a significant component.
• Depth of oxygen penetration into sediments? Ocean shelf sediments reasonably oxic, but high metabolism to extended depths.
• Ecological response to particulate matter potentially more significant – nutrients drive organic matter production.
• Groundwater influences - significance of nutrient inputs at 2km resolution?
**Pesticides**

- Pesticide loads – could be disproportionately important depending on land use, and therefore, small coastal catchments. If more local impacts, 2km scale may not be sufficient. More relevant to particle bound pesticides, not necessarily dissolved. Also need to consider chronic impacts – different dynamics, greater concentrations in low flow events. **Potential need for case study.**
- Concentrations versus flow data curves – does pesticide concentration reduce over time (higher dilution?).
- Large scale model will look at impact and long term events; higher resolution case studies will address chronic impacts and need mass not load.

**Ecological Response models**

*Input needs to ecological models from WQ models* (2km resolution and high resolution case studies if required):

1. Light attenuation – turbidity, chl, sedimentation, CDOM
2. Nutrients – DIN, POM-DOM
3. Pesticides (herbicides)
4. Other disturbances – temperature, salinity, bleaching, cyclones/storms – waves, currents & bottom stress, COTS/predation
5. Connectivity/recruitment - currents, transport
6. Coral food sources – plankton/DOM
7. Substrate characteristics
8. Reef boundary layer – source/sink
9. ?? Macroalgae functional groups

*Other ecological inputs (not from WQ model):*

- Human use – fish extraction etc
- External GBR recruit

**Spatial requirements:**

- Strong link between model prediction and observation will be critical. Need to understand available data from supporting surveys to populate the model.
- Need to deal with variability of ecological characteristics within reefs in the scale of model that might be able to be developed GBR-wide. Reef based ecosystem model that would assume mean characteristics across the reef. Main issues where high WQ gradients close to coast and high variability – may include some case studies – that is where monitoring data will be required.
- Analysis of design of monitoring data is required to ensure that can meet model input requirements; model or monitoring may require adjustment. Possible to apply statistical observation model that relates characteristics from different reefs to predict across larger areas.
- Need to be able to run model over long time scale and across broad area.
- Suggest reef-specific data (less than 2km resolution, eg. Legrand et al) may be a research activity in parallel.

**Temporal variability:**

- Daily outputs needed if addressing event impacts- can pick up cumulative exposure over several days.
- Seasonal – recruitment.
Ecological outputs:
- Disturbance/recovery.
- Short term – coral recruitment, stress responses (eg. Gene characteristics, coral colour).
- Longer term – coral cover (including speciation), algal cover (including functional groups).

Data available:
- Recruitment and juvenile corals.
- Coral cover and structure/diversity.
- Algae – 2 phyla (but ecological function?).
- Fish surveys (offshore and limited inshore).
- COTS surveys.
- Seagrass - Intertidal seagrass – cover and extent; Subtidal seagrass – maps available, dynamics unknown; some old data. Deep seagrass – little known to date. Most likely come in as case study at higher resolution in first instance.

Data gaps (but not critical to models in first instance – research questions):
- Coralline algae – good indicator
- Perennial sargassum
- Ephemeral algal mats (drift) – overlooked! **Priority
- Fish-turbidity relationship **Priority
- Event monitoring responses (major events) eg. Cyclones, bleaching

Research question: sub-tidal seagrass maps could be analysed with back dated turbidity data – remotely sensed? Assist to help determine light requirements, and other influences.

Proposed Model Framework

The workshop proposed the following modelling framework. The Process Model (Module 1) would have the highest priority for development and would be used to support target setting and assessment of WQIPs directly as well as providing a basis for ecological models (Module 2). Additional supporting models would be required to provide forcing information for the Process Model. Other finer scale models would be developed as needed to provide simulation and support assessment for regions requiring special attention that could not be properly resolved by the larger scale models.
Module 1 – Material Transport model

1. Foundation – hydrodynamic model (priority)
2. Sediment
3. Biogeochemical

Characteristics:
- Broad scale (Fraser Island to Torres Strait)
- Long time frames (decades)
- 2km nominal
- 3D
- Build simultaneously with other required models
- Parameterisation challenge biogeochem > sediment > hydrodynamics (so keep computational capacity for this – need powerful computing platform, extensive storage capacity)

Phases:
1. Model implementation and testing
2. Hindcast and application
Ongoing commitment - immediate goal contribute to target setting and assessment

Outputs:
- Directly relevant to WQIPs and target setting – estimation of concentrations likely to get at reef locations and scenario setting.
- Inform and allow development of better assessment (empirical models), and development of hypothesis for assessment models. Assessment models also feed calibration and validation data into process models.
- Input data for ecological models (assessment or process or both, eg. Bayesian Belief Networks).
- Fine scale case studies that inform some WQIPs, feed into subset of ecological models, refine process models and define boundary conditions/nesting, eg. Specific issues - pesticides, seagrass, estuary boundary interactions and embayments, reef boundary layers (including cross shelf strip).
- Feed into catchment models, working back up the catchment – and vice versa.
Module 2 – Ecological Response model

Characteristics:
- Reef/individual approach
- Impact-recovery
- Enhancement of existing models – HOME and CORAL.

Outputs:
- WQIP targets (long term) by determining ecosystem health objectives, and inform targets set for WQ on the reef.
- Other GBR management applications, eg. COTS, fishing etc.

Models representing higher resolution case studies and research needs

Hydrodynamics:
- Vertical mixing – parameterise effects of reefs.
- Estuaries and embayments – Fitzroy foundation work; where to now? Extend to ecological impacts?
- Significance of inputs from floodplains and smaller rivers.
- Parameterisation of reefs and boundary layers – best data in the Whitsundays.
- Whole of GBR benthic mapping for bottom effects – overlay seabed biodiversity mapping data with water quality data – correlation?
- Wind action (difficult to incorporate and will be relatively broad characterisation, significant influence on horizontal mixing, eg. CSIRO BlueLink model).
- Nature of river flow incorporated through time series of discharge – but velocity will influence hydrodynamics – useful for finer scale models, also incorporating floodplain flow.
- Mediating loads – floodplain interactions, and parameterisation of boundary between estuarine and marine areas. Need to define boundary conditions (more significant in southern GBR). Simple box model to link catchment and WQ models.

Material transport:
- Interaction between fine sediment inorganic properties and organic matter in the system.
- N&P and sediment interaction.
- Role of substrate, eg. roughness– interaction between sediment dynamics and hydrodynamics.
- Speciation of sediment types – influences nature of time frames.
- Fate of fine sediment; primary and secondary deposition (mobilisation) data.
- Precipitation (sinking rates).
- Pesticide and sediment interaction
- Pesticides – best tracers for hydrodynamics with or without sediment, relatively short half life (50 days) and dilute conservatively.
- Groundwater (particularly with respect to nutrient source).
- Primary and secondary deposition (mobilisation) – deposition critical for turbidity and ecology – trial assessment model?
- Trichodesmium and the role of nitrification.

Ecological response:
- Inter-reefal communities.
- Phytoplankton differentiation – relevant to GBR.
- Standing stock of POM.
- Seagrass – intertidal, subtidal, deep water; biogeochem model will make some predictions.
- Relationship between fish populations and water quality.
- Relationship between macroalgae and dissolved inorganic nutrients.
- Roles of the reef matrix in response to nutrients.

Examples of higher resolution case studies:
- Douglas
- Barron
- Tully – sediment data available High Is.
- Burdekin
- Black/Ross
- Mackay/Whitsunday – best data ecology, WQ; clear spatial definition – no dry tropic plumes.
- Fitzroy – have estuary and Keppel Bay project data – sediment, nutrients.
- Burnett

Conclusion: Tully, Mackay/Whitsunday, Fitzroy – and potentially a far northern area, eg. Princess Charlotte Bay??

Timelines

Note: The following timeline assumes that adequate resources are available to complete the tasks.

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>Workshop and recommendations; contract let</td>
</tr>
<tr>
<td>2008</td>
<td>Dec 2008 hydrodynamic model</td>
</tr>
<tr>
<td>2009</td>
<td>First cut WQ and ecological response model (some capacity to inform progress of WQIPs and Reef Plan)</td>
</tr>
<tr>
<td>2010</td>
<td>Review WQIP &amp; Reef Plan &amp; Outlook Report</td>
</tr>
<tr>
<td>2010</td>
<td>Inform review of targets, ecological objectives</td>
</tr>
<tr>
<td>2010</td>
<td>Input and refinement to assessment models</td>
</tr>
<tr>
<td>2010</td>
<td>Improved monitoring design</td>
</tr>
<tr>
<td>2011</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>End of Reef Plan</td>
</tr>
<tr>
<td>2013</td>
<td>Improved assessment capacity and continuing refinement as part of the integrated management strategy – integrated suite of models - incorporating socio-economic aspects.</td>
</tr>
<tr>
<td>2013</td>
<td>Reef Plan II</td>
</tr>
</tbody>
</table>
### Resources

<table>
<thead>
<tr>
<th>Item</th>
<th>FTE</th>
<th>Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrodynamic model</td>
<td>1</td>
<td>All</td>
</tr>
<tr>
<td>Sediment model</td>
<td>1</td>
<td>All</td>
</tr>
<tr>
<td>Biogeochemical model</td>
<td>1</td>
<td>All</td>
</tr>
<tr>
<td>Wave model</td>
<td>1</td>
<td>Year 1</td>
</tr>
<tr>
<td>Other supporting models - refinement</td>
<td>1</td>
<td>All</td>
</tr>
<tr>
<td>Ecological model</td>
<td>2</td>
<td>All</td>
</tr>
<tr>
<td>Assessment models</td>
<td>1-2</td>
<td>All</td>
</tr>
<tr>
<td>Case studies</td>
<td>1</td>
<td>Beyond Year 1?</td>
</tr>
<tr>
<td>Data collection &amp; management</td>
<td>2</td>
<td>All</td>
</tr>
<tr>
<td>Project Management</td>
<td>1</td>
<td>All</td>
</tr>
<tr>
<td>Computing power &amp; storage capacity</td>
<td>?</td>
<td>All</td>
</tr>
<tr>
<td>New data collection</td>
<td>?</td>
<td>??</td>
</tr>
<tr>
<td>Delivery mechanisms – visualisation and reporting</td>
<td>1</td>
<td>Beyond Year 1</td>
</tr>
<tr>
<td>Science coordination</td>
<td>1</td>
<td>All</td>
</tr>
<tr>
<td>Ongoing maintenance as a management support system</td>
<td>1</td>
<td>Beyond Year 1</td>
</tr>
</tbody>
</table>

### Practical issues

- Custodianship and how the models will be developed and maintained. Consortium approach may be the best way to get going quickly.
- Address capacity of various providers to contribute to the project.
- Long term need to bring capacity together and also incorporate catchment modelling. Learn from other examples, Eg. eWater strategy – get models into form that can be handed over to consultants to be able to run them. A group developing (research provider) and a group delivering (management agency?).
- Most efficient for the models to be built on a common platform.
- Co-investment opportunities - investigate potential for investment by Navy (hydrodynamics & sediments) and Bureau of Met (climate) - follow direction of BlueLink project; other climate direction.
- Consultancy opportunities are limited prior to completion of the model; once operational could be implemented through consultants but still need ongoing development and maintenance through supporting research providers.
- Where would it be housed and maintained? AIMS, CSIRO?? Operational ‘housing’ – GBRMPA?

### Critical Linkages

- MTSRF climate change project – regional model covers approx. half - 3/4 of GBR; resolution 5-12km.
- Glenn De’ath’s models
Cross-check other existing projects including MTSRF – climate change, fish connectivity.
APPENDIX D

Monitoring and research initiatives currently underway

A significant amount of data collection is being undertaken in the GBR region now and into the future including monitoring to support ReefPlan, monitoring and process studies by the Marine and Tropical Science Research Facility, and satellite remote sensing.

ReefPlan Marine Monitoring Program

A key component of the ReefPlan is the implementation of long-term water quality, and ecosystem heath monitoring program in the GBR Lagoon that will help to assess the long-term effectiveness of the ReefPlan in reversing the decline in Great Barrier Reef water quality. GBRMPA is responsible for the implementation and reporting of the Marine Monitoring Programme (MMP) in the inshore region of the GBR.

The first stage of the MMP was initiated in late 2004 and was completed in June 2007 and the Australian government has released funding for the next four years of the Program (2007 – 2011). Management of the monitoring programme is carried out by the GBRMPA in partnership with community groups, and a consortium of monitoring providers with a long-term track record of monitoring and research in the Marine Park. The consortium (coordinated by the CRC Reef Research Centre) from 2004 - 2006 included; Australian Institute of Marine Science, University of Queensland, Department of Primary Industries and Fisheries, Department of Natural Resources and Water, Queensland Environmental Protection Agency, CSIRO, and Sea Research. The MMP is comprised of six sub-programs as follows:

1. Marine flood plume water quality monitoring

Flood plume water quality monitoring will assess concentrations and transport of major land-sourced pollutants that have the potential to adversely affect coral reef and seagrass ecosystems. Monitoring will consist of a campaign-style conventional grab sampling program in flood waters originating from major rivers flowing into the GBRWHA (e.g. Fitzroy, Burdekin, and rivers in the Mackay Whitsunday and Wet Tropics Regions). Manual sampling will occur over the wet season only (November to May) and will be complimented with limited water quality information collected with sensors and data loggers (sub-program b). Monitoring from the plumes of the first major flood plumes includes the analysis of water samples for dissolved and particulate nutrient, DOC, pesticide, chlorophyll a, suspended sediment concentrations, turbidity and salinity in the marine environment.

2. Inshore marine water quality monitoring

Water quality monitoring will be carried out in the inshore waters of the GBR to assess change over time in concentrations of key water quality indicators. This monitoring will include the measurement of chlorophyll (as a surrogate nutrient indicator), as well as the measurement of selected water indicators at key inshore reef sites. Sampling methods will include routine-grab water sampling as well as the deployment and data acquisition from state-of-the-art water quality samplers and sensors with long-term data logging capacity.

Monitoring at inshore sites includes:

- The analysis of water samples for chlorophyll a, dissolved and particulate nutrient species, DOC and suspended sediment concentrations, and salinity and turbidity analysis in inshore waters of the GBR Lagoon at data logger sites.
• The continuous measurement of chlorophyll \( a \), turbidity and temperature via autonomous data loggers deployed at 14 reef sites.

• The concentration of chlorophyll \( a \) in the water column at more than 50 sites from Cape York to the Burnett-Mary regions. This task is assisted by community groups and tourism operators.

3. Inshore marine water pesticide monitoring

Monitoring pesticide concentrations in inshore waters of the GBR will be carried out to assess change over time in the spatial and temporal distribution of pesticides in relation to catchment use and delivery. The Marine Monitoring Programme measures pesticides at 14 inshore marine sites using passive samplers to determine time-integrated pesticide concentrations.

Monitoring at inshore sites includes:

• The concentration of pesticides in the water column is monitored with the assistance of tourism operators, at 14 inshore reef and island sites;

• Bioassay analysis of the impacts of in-situ water column pesticides (extracted from passive samplers deployed at reef sites during coral spawning) on coral zooxanthellae, using the PAM system.

4. Remote sensing of GBR-wide water quality

Remote sensing techniques are beginning to be routinely incorporated into the marine monitoring as a cost-effective method to determine spatial and temporal information on near-surface concentrations of suspended solids, turbidity, temperature and chlorophyll \( a \) for the GBR. This is achieved through the acquisition, processing, validation and transmission of geo-corrected ocean colour imagery and data sets derived from MODIS satellite imagery.

5. Marine biological monitoring (inshore coral reefs)

Monitoring of inshore coral reefs will be carried out to quantify temporal and spatial variation in reef community status in relation to variations in local reef water quality. Coral monitoring sites will be co-located with the inshore marine water quality monitoring program to enable correlation with concurrently collected water quality information.

Monitoring at inshore coral reef sites includes:

• The status of inshore coral reefs is determined by monitoring benthic cover (algae, hard and soft corals), taxonomic composition and coral population demography.

• Coral larvae settlement are also measured at reefs in 12 inshore reefs (across 4 NRM regions) to provide a measure of coral larvae supply rate at inshore coral reefs.

• Innovative ecosystem water quality status indicators such as foraminifera are also collected.

6. Marine biological monitoring (intertidal seagrass)

The MMP has relied on an ‘augmented’ Seagrass-Watch program as a cornerstone for this component of the marine monitoring program. Under this community-based project, groups are monitoring seagrass cover and species composition, seagrass reproductive health and seagrass tissue nutrient status. Augmented Seagrass-Watch surveys are undertaken at the end of winter and following the wet season in April.
Monitoring at inshore sites includes:

- Intertidal seagrass meadows are monitored for percent cover, species composition, reproductive health and seagrass tissue nutrient status.
- Additional information is also collected on sediment pesticide and nutrient concentrations within seagrass tissue.

Monitoring and research conducted through the Marine and Tropical Science Research Facility

The Marine and Tropical Sciences Research Facility (MTSRF) is part of the Australian Government’s Commonwealth Environment Research Facilities programme. The aim of the MTSRF is to ensure the health of North Queensland’s public environmental assets including the GBR and its catchments. Three key programs conducted under MTSRF (2005-2010) with relevance to this review are described in the following:

1. Status and trends of species and ecosystems in the GBR (Program 1)

The AIMS Long Term Monitoring Program (LTMP) has made annual surveys of approximately 100 coral reefs for 15 years. Although this is a small sample of the ~3,000 reefs that make up the GBR, the survey reefs are widely distributed by latitude and longitude and cover all major sectors of the GBR Marine Park to provide broad-scale information on the status of the GBR and on the effects of rezoning the Park in 2004. In addition to information on current status, the long-term data provides estimates of natural variability which are critical to establishing reference points for interpreting indicators of reef health.

2. Climate change: Great Barrier Reef (Program 5i)

The regional climate scenarios project within the Climate change program will downscale physical climate change scenarios in the marine environment from global-scale to reef-scale by applying eddy-resolving regional ocean simulations of climate change, and sub-km/reef-scale ocean simulations. The project will provide projections of regional scale impacts of future climate scenarios at multi decadal timescales relevant to water quality management scenario testing.

3. Halting and reversing the decline of water quality (Program 7)

A primary objective of this program is to assess the risk to GBR ecosystems from various land-sourced pollutants entering the GBR, by tracing the fate of fine sediments from two representative river systems into the inshore GBR Lagoon, characterising dispersal, resuspension, retention and transport mechanisms from the river mouth to the coastal waters.

GBR Ocean Observing System

The GBR Ocean Observing System (GBROOS) was established as part of the Integrated Marine Observing System (IMOS) to provide long-term, high quality environmental and ecosystem data throughout the GBR to enhance the long-term conservation and management of the GBR. The GBROOS will consist of a mix of fixed (island research stations, moorings), mobile (ships of opportunity) and remote (satellite) observing platforms to collect weather, environmental, oceanographic and biological data for research and management.

Other initiatives

Closing shelf-scale nutrient budgets for the GBR (AIMS)

A sound understanding of nutrient inputs, outputs and recycling processes is essential to effectively understand, manage and communicate the effectiveness of programs to minimise the impact of anthropogenic nutrient inputs on GBR water quality, and to better...
understand how ecosystem nutrient dynamics link biogeographic distributions of communities and habitats in the GBR to regional productivity. Our understanding of nutrient processes and their ecological effects is currently limited by poorly constrained estimates of several key processes – regional N-fixation by pelagic Trichodesmium and benthic bacteria, water column nutrient turnover (i.e. uptake, mineralisation), and benthic microalgal primary production, and limited understanding of key flux components including upwelling, benthic metabolism and vertical sediment-water nutrient exchanges.

This task will construct a robust shelf-scale nutrient (N, P) nutrient budget for the GBR through improved estimates of:

- shelf-break water exchanges and upwelling from the Coral Sea
- benthic nutrient metabolism and its geographical variability.
- shelf-scale pelagic N-fixation by Trichodesmium and benthic N-fixing by bacteria.

water-column nutrient (C, N, P) cycling processes, vertical material fluxes and nutrient turnover rates.
GLOSSARY

**acidification** – increased acidity of oceans due to higher dissolved concentrations of carbon dioxide in seawater as a consequence of increasing carbon dioxide concentrations in atmosphere. Acidification is thought to be a potential problem for the development of coral skeletons.

**Bayesian Belief Network** – probabilistic graphical model that represents a set of variables and their probabilistic interdependencies. Formally, Bayesian networks have nodes representing variables and connecting arcs which encode conditional interdependencies between the variables. Nodes can represent any kind of variable including measured parameters and hypotheses. Bayesian networks can accommodate input information that is subjective. Efficient algorithms exist that perform inference and learning.

**Continental shelf waves** – low-frequency waves that propagate along continental shelves. They cause water level and current fluctuations on the shelves having periods of variation of 1-10 days or longer.

**COTS** – Crown of Thorns Starfish

**denitrification** - the process of reducing nitrate and nitrite, highly oxidised forms of nitrogen available for consumption by many groups of organisms, into gaseous nitrogen, which is far less accessible to life forms.

**deterministic model** – the relationships between variables are fixed by mathematical relationships with no random effects.

**EAC** – East Australian Current, a current that flows southward along the margin of the continental shelf beyond the edge of the GBR

**empirical model** – model relationships derived from observation or experiment.

**epiphytic algae** – algae that live as coatings on the leaves of larger aquatic plants.

**floculation** – the process of fine particle aggregation due to electro-chemical attraction forces when they encounter sea water.

**hypersaline** – salinity (salt concentration) substantially above that of normal sea water.

**macroalgae** - ('seaweeds') are an ancient class of large multicellular plants that resemble vascular plants but lack the complex array of tissues used for reproduction and water transport. They are important elements of shallow coastal waterways

**mesoscale eddy** – circular circulation patterns in the ocean which have diameters of 100km or more.

**nitrogen fixation** - converts dissolved gaseous nitrogen into a more biologically available forms such as nitrate which can be readily utilised as nutrient to support plant growth.
**nutricline** – refers to a zone in the water column where nutrient concentrations change markedly. In the ocean, nutrient concentrations are often higher below the nutricline than above it.

**oligotrophic** – relatively poor in nutrients necessary for plant growth

**plankton** - are any drifting organism that inhabits the water column of oceans, seas, or bodies of fresh water.

**phytoplankton** – the plant component of the plankton (usually microscopic) that are suspended in the water column of water bodies. They are widely considered to be some of the most important organisms on Earth as they form the basis of the food chain in oceanic systems.

**PSU** – Practical Salinity Unit. For example, 35 PSU (~sea water) refers to a salt concentration of approximately 35g/L.

**zooxanthellae** - symbiotic algae found in all photosynthetic corals and anemones. Nutrients supplied by the zooxanthellae make it possible for the corals to grow and reproduce quickly enough to create reefs. Zooxanthellae provide the corals with food in the form of photosynthetic products. In turn, the coral provides protection and access to light for the zooxanthellae. Coral bleaching occurs when high water temperatures cause the corals to eject the zooxanthellae from their bodies.

**zooplankton** - are the animal component of the plankton that drift in the water column of oceans, seas, and bodies of fresh water. Many zooplankton are too small to be individually seen with the unaided eye.