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Prioritisation of Reef Restoration and Enhancement Site Selection – Phase 2 and 3 Report

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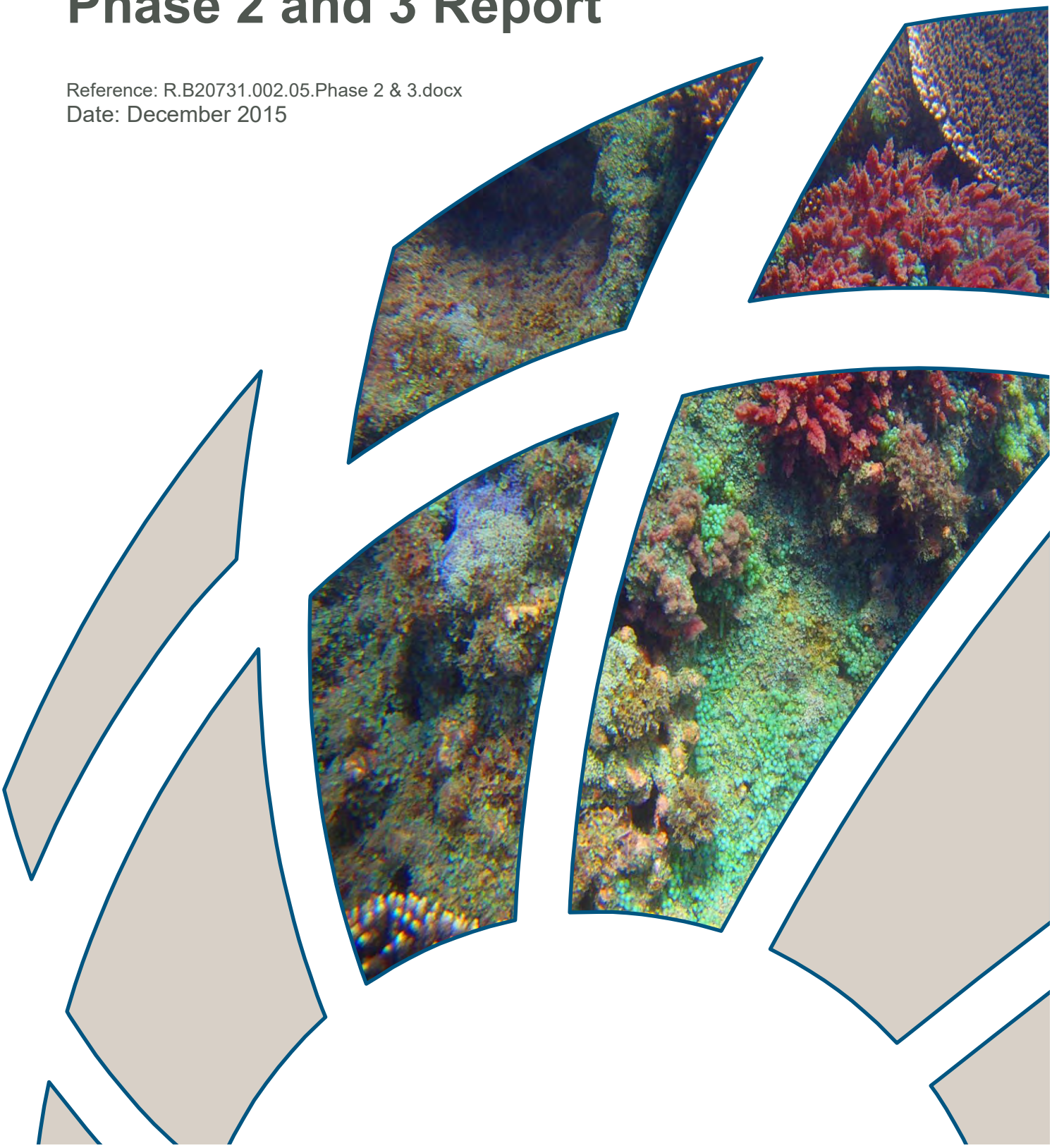

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Synopsis: **This report describes changes in hard coral cover in Port Curtis and uses integrated catchment and hydrodynamic models to examine the impact of recent and hypothetical flood events. This information is used to prioritise active and passive restoration sites to support listed and threatened species as per the Biodiversity Offset Strategy.**

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Executive Summary

Project Background

Gladstone Ports Corporation (GPC) is in the process of developing and implementing a range of offset strategies and environmental monitoring programs, in accordance with Western Basin Dredging and Disposal Project (WBDDP) environmental impact statement (EIS) recommendations and approval conditions. A key requirement of the Commonwealth approval was to develop a Biodiversity Offset Strategy (BOS). The BOS outlines actions to undertake mapping and restoration of corals in the wider bioregion, and annual monitoring to assess the effectiveness of restoration activities.

The present study (the project) was commissioned to provide information on the health of corals in the region and wider bioregion and to identify priority areas that may be suitable for any future habitat restoration and enhancement projects. The project specifically considers corals and coral reef habitats and specifically calls for prioritisation of sites for direct restoration/enhancement; however, some indirect restoration works, such as catchment remediation or passive restoration, are also considered.

This report outlines the findings of Phase 2 and 3 study components of the project, and should be read in conjunction with the Phase 1 report (BMT WBM 2014).

Study Approach and Coral Health Survey Findings

Three potential direct restoration/enhancement options for reefs were identified:

- Coral transplantation, i.e. relocating corals from a source reef to a reef with low coral cover.
- Larval capture, rearing and transplant.
- Installation of artificial reefs.

Benefits and constraints for each restoration/enhancement option were identified based on a review of case-studies and best-practice guidelines. Assessment criteria were then developed to prioritise locations that could represent suitable reef restoration sites.

A key step in prioritising restoration/enhancement sites is to identify areas that presently support (or historically supported) hard coral communities, and to determine the present-day condition/health of these communities. Quantitative reef community surveys were carried out at 15 sites throughout the BOS study area, which included areas within Port Curtis, nearshore waters between Port Curtis and Rodds Bay, and nearshore reefs along the eastern coastline of Facing Island.

Reef communities within Port Curtis have experienced a major change in community structure since baseline surveys in 2009. In contrast to 2009 surveys, Port Curtis reefs had negligible living hard coral cover, and were numerically dominated by turfing algae and bare substrate (typically dead coral), and macroalgae. Reef communities between Port Curtis and Rodds Bay (mainly Seal Rocks) also had low hard coral cover, which differed from the results of a rapid survey in 2012 which recorded coral cover >30%. Nearshore reefs along the eastern coastline of Facing Island had diverse and abundant hard coral cover, which was similar to survey results from 2010.

Port Curtis reefs have been affected by flood waters in recent years, with lowered salinities and high turbidity likely to be a major driver of change in coral cover. This has important implications from a restoration site selection perspective in terms of:

- Reefs that experience ongoing water quality stress do not represent suitable restoration sites, as restoration attempts may be thwarted by poor water quality
- Reefs that are degraded by infrequent flood events, and which have limited capacity to recover, represent potential candidate sites for coral restoration.

Hydrodynamic and Catchment Modelling

Integrated hydrodynamic and catchment modelling were performed to assess the impact of the recent 2010-11 and 2013 flood events, as well as the "average" summer event, and a 1:10 year event. Further simulations investigated the effect of land use alterations from the pre-clearing catchment to present, then to a hypothetical future scenario, using a major rainfall event (2013) as a point of comparison. The 2013 event was substantially larger than all other rainfall scenarios. Published salinity thresholds were greatly exceeded during the 2013 event and there was a strong correlation between observed community changes and predicted salinity impacts. Historical rainfall data and coral community observations suggest that freshwater plumes of similar magnitude to the 2013 event have been rare occurrences.

Comparisons between the pre-clearing catchment, the present case and a future scenario (including 20 years of residential development and the full realisation of the Gladstone State Development Area [GSDA]) show that during extreme events, present day clearing has resulted in substantially more freshwater, suspended solids and nutrients entrained in floodwaters entering Port Curtis. By comparison, changes resulting from the future scenario are very small. There have been little changes in deposition rates on reef sites and this will probably continue into the future given the strong tidal current and wave regimes.

Priority Restoration Sites

Direct restoration and enhancement works are appropriate where reefs are recruitment limited and/or have limited capacity to recover from disturbance without direct management intervention. The scope of the present study was to prioritise potential restoration sites, on the assumption that reefs would benefit from direct management intervention. Based on modelling results and trends in coral condition, the following potential candidate sites for direct restoration activities were identified.

(1) Manning Reef (western Facing Island) – this site supported high *Acropora* coral cover in 2009, indicating that habitat conditions were once suitable for coral community development. No live coral was recorded at this reef in 2014. Modelling indicates that the major flood event in 2013 would impact on this reef, whereas smaller flood events such as the 1:10 year event and the 2010-11 flood would not cause major impacts to water quality. The previous dominance of *Acropora* indicates that the site would be suitable for *Acropora* transplants.

(2) Seal Rocks Reef – This reef supported a diverse and abundant coral community in 2012, and may represent a stepping stone that provides connectivity between reefs in and adjacent to Port Curtis. Surveys carried out in 2014 identified several large *Porites* coral colonies, but live coral cover was low and recently dead coral was evident. While this reef is located in open waters, hindcast modelling indicates that water quality here would be adversely impacted by very large flood events (e.g. 2013 floods), but not smaller events such as the 2010-11 flood. The presence of large *Porites* colonies and diverse coral communities prior to the 2013 flood supports this conclusion, and suggests that water quality conditions are typically suitable for sustaining diverse and abundant coral communities. On this basis, Seal Rocks Reef represents a priority restoration site. If coral communities are slow to

recover due to recruitment limitation, direct coral restoration could be considered (i.e. transplants) to enhance recovery rates. The site is also is workable under a range of tidal conditions.

While reefs in North Passage supported moderate coral cover in 2009, there are several constraints to undertaking restoration works here including strong currents, limited visibility, the shallow depth zone occupied by corals (approximately <2 m), and potential interference to recreational vessel traffic by artificial reefs.

Reefs on the east coast of Facing Island were in good condition and/or did not appear to have changed markedly after recent floods. These reefs therefore do not represent targets for direct reef restoration activities.

The installation of artificial reefs in adjacent soft sediment habitats could enhance connectivity between these reefs, although there are uncertainties whether this would significantly enhance the resilience and biodiversity values of natural reefs. Artificial reef placement should also consider the potential for increased fishing pressure potentially conflicting with the objectives of the BOS. Further investigations into stability of benthic substrates would be required to determine their ability to support reef structures.

Prior to active restoration, it is critical to determine whether reef communities have the capacity to naturally recover, and therefore whether management intervention is required. This is essential to determining the need or otherwise for restoration /enhancement measures

It is recommended that restoration efforts focus on catchment management for long-term improvement in water quality and ecosystem health of Port Curtis. Potential restoration sites in the catchment have been identified for further investigation in this regard.

Contents

List of Figures

List of Tables

1 Introduction

1.1 Background

Gladstone Ports Corporation (GPC) is responsible for the management, operation and development of the Port of Gladstone. GPC is currently overseeing development and expansion of the facilities in the Western Basin of the Port of Gladstone, in which dredging is a substantial component of the works. Stage 1A of the Western Basin Dredging and Disposal Project (WBDDP) involved the deepening and widening of existing channels and swing basins, as well as the creation of new channels, swing basins and berth pockets. These new areas and the existing channels will require annual maintenance dredging to maintain navigable depths.

GPC is in the process of developing and implementing a range of offset strategies and environmental monitoring programs, in accordance with WBDDP EIS recommendations and approval conditions. A key requirement of the Commonwealth approval was to develop a Biodiversity Offset Strategy (BOS), which aims to provide a means for offsetting unavoidable impacts to the values of the Great Barrier Reef World Heritage Area and National Heritage Place, and *Environmental Protection and Biodiversity Conservation Act 1999* (EPBC Act) listed threatened and migratory species.

The Commonwealth approval conditions, particularly condition 38(a)(i), require that the BOS includes actions to enhance and restore habitats. In response, Section 5.8 of the BOS outlines actions to undertake mapping and restoration of corals in the wider bioregion, and annual monitoring to assess the effectiveness of restoration activities.

The present study (the project) was commissioned to provide information on the health and distribution of corals in the region and wider bioregion and to select priority areas that are suitable for future habitat restoration and enhancement projects. The project specifically considers corals and coral reef habitats, noting that other projects consider potential enhancement and restoration actions for other habitat types.

1.2 Study Scope

The project includes the following phases:

- Phase 1 - Development of a methodology for identifying the ecological condition of reefs and the selection of reef sites for investigation
- Phase 2 - Characterisation of the ecological condition of reefs
- Phase 3 - Identification of suitable areas for reef restoration, and potential restoration actions.

The present report outlines the methodology and findings of Phase 2 and 3 study components. This report refers to, and should be read in conjunction with, the Phase 1 report (BMT WBM 2014). The Phase 1 report provides a review of existing information to define biodiversity values and stressors acting on BOS study area reefs, and prioritised reef sites to be investigated in the Phase 2 reef health/condition survey (i.e. the present report).

This study considers shallow-water coral reef areas that support listed and threatened species, specifically marine turtles. Deep water ahermatypic (non-reef forming) reef / rubble communities

were not included in the scope of this assessment given significant information gaps regarding their distribution, extent and environmental value. Although ahermatypic reefs are extensive within Port Curtis and likely serve as important refuges from plume impacts, they are also less likely to have been damaged by recent water quality impacts. With the goal of the project being restoration, habitats most at risk (hermatypic reefs) were the focus.

The study area for the project is defined as the BOS region and wider region, as shown in Figure 1-1.

1.3 Aims and Objectives

The overall aim of this report is to assess and prioritise sites on the basis of their potential for direct reef restoration/enhancement. However, given some of the issues associated with direct restoration, some preliminary advice has been provided regarding indirect restoration options (including catchment revegetation etc.). The specific objectives of this report are to:

- Identify potential reef restoration/enhancement options that could potentially be undertaken to address the requirements of the Biodiversity Offset Strategy and the preliminary management objective established in the Phase 1 report
- Identify the critical issues to consider when determining the need or otherwise for implementing reef restoration/enhancement actions and site selection
- Assess the current condition of reef communities in the BOS study area
- Examine the spatial extent of recent and potential future flood events using catchment and hydrodynamic modelling:
  - to better understand plume impacts; and
  - determine the suitability of potential restoration / enhancement sites.
- Develop assessment criteria for identifying potentially suitable locations for reef restoration/enhancement
- Based on these criteria, define priority locations that may be suitable for reef restoration/enhancement works, and the types of techniques that may be appropriate at each site.

1.4 List of Acronyms

Table 1-1 List of acronyms used in this report

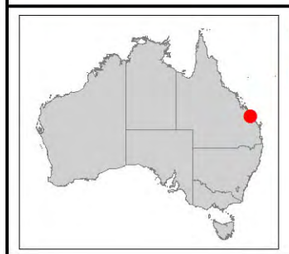
Acronym	In Full
BOS	Biodiversity Offset Strategy
DEHP	Department of Environment and Heritage Protection
DSITI	Department of Science Information Technology and Innovation
EIS	Environmental Impact Statement

Acronym	In Full
EPBC Act	*Environmental Protection and Biodiversity Conservation Act 1999*
GAWB	Gladstone Area Water Board
GBR	Great Barrier Reef
GBRMPA	Great Barrier Reef Marine Park Authority
GBRWHA	Great Barrier Reef World Heritage Area
GPC	Gladstone Ports Corporation
GSDA	Gladstone State Development Area
PPT	Parts per thousand
PSU	Practical salinity units
TN	Total nitrogen
TP	Total phosphorus
TSS	Total suspended solids
WBDDP	Western Basin Dredging and Disposal Project

Peak Island
Keppel Bay
Fitzroy River
Sea Hill
Cape Capricorn
Rundle Island
Balaclava Island
Curtis Island
The Narrows
North Entrance
Pelican Banks
Gladstone Harbour
Facing Island
Gladstone
Callope River
Port Curtis
See INSET
Coral Sea
Seal Rocks
Boyne River
Rodds Bay
Bustard Head
Colosseum Inlet
Awoonga Dam

Google™ earth
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat

INSET
The Narrows
Graham Creek
Curtis Island
North Entrance
APLNG
QCLNG
GLNG
Pelican Banks
Fishermans Landing Wharves
WICT Wharf
RG Tanna Coal Terminal Wharves
Quoin Island
Facing Island
Marina
Auckland Point Wharves
Barney Point Wharf
Callope River
South Trees Wharves
Boyne Smelter Wharf
Gatcombe Head
Boyne Island



LEGEND

Biodiversity Offset Strategy Boundary

Shipping Channel (Dredged)

Cadastral Boundary

Title:

Locality plan and location of the region and wider bioregion referred to in the Biodiversity Offset Strategy (GPC 2012)

Figure **1-1**

Rev: **A**

N

0km 10 20
Scale - Main Map

0km 5 10
Scale - Inset

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2 Potential Restoration Activities

2.1 Definition of Restoration

Edwards (2010) defines the following terms which have been adopted here:

- *Restoration*: the act of bringing a degraded ecosystem back into, as nearly as possible, its original condition.
- *Rehabilitation*: the act of partially or, more rarely, fully replacing structural or functional characteristics of an ecosystem that have been diminished or lost, or the substitution of alternative qualities or characteristics than those originally present with the proviso that they have more social, economic or ecological value than existed in the disturbed or degraded state.
- *Remediation*: the act or process of remedying or repairing damage to an ecosystem.
- *Mitigation*: the reduction or control of the adverse environmental effects of a project, including restitution for any damage to the environment through replacement, restoration, or creation of habitat in one area to compensate for loss in another.

The term 'active restoration' has been used in this report to describe active management measures used to promote the biodiversity of reefs. Passive or indirect restoration pertains to management of under-lying stressors (e.g. water quality improvement), or management of human activities on reefs (e.g. management zoning).

2.2 Direct (Active) Reef Restoration Measures

Active reef habitat restoration measures can be broadly classified into two types (Abelson 2006):

- Coral transplantation. The primary justification for undertaking coral transplantation is that the coral community would fail to recover naturally, usually due to the absence of natural recruitment (Edwards and Clark 1998 in Abelson 2006). Larval rearing, larval capture, and subsequent transplantation can be considered to fall within this broad classification of transplantation.
- Creation of new reef habitats. This involves the installation of artificial reefs to increase the area of available reef habitat. There are many reasons for creating new reefs including enhancement of biodiversity values or the enhancement/creation of ecosystem services (e.g. fisheries habitat, shoreline stabilisation).

These measures are not mutually exclusive; coral transplantation activities can be undertaken to enhance biodiversity values of artificial reefs.

The two types of restoration measures differ in their potential benefits and disadvantages (Table 2-1). Abelson (2006) argues that the main benefit or appeal of coral transplantation as a restoration tool is that it provides a rapid and prominent achievement in terms of converting bare to low cover substrate to a high cover reef. It is less clear whether such benefits are ecologically meaningful at all but highly localised spatial scales (i.e. at the scale of the reef patch), particularly since cost limitations typically restrict the size of the reef that can be effectively restored (typically measured in 10's of metres). There is also a lack of precedence in a Queensland context; while

trials have been undertaken in the Great Barrier Reef (GBR) region (Harriott and Fisk 1987), the Great Barrier Reef Marine Park Authority (GBRMPA) recognises that it is a costly and time consuming process, and is not considered common practice in the GBR Marine Park (GBRMPA 2004).

Larval capture, rearing and transplant techniques are typically more expensive than direct transplants, but can be potentially advantageous in situations where the supply of donor material is limited (Edwards 2010). Where data exists, larval rearing from donor colonies is approximately 7 times more expensive than coral transplanting asexually reared fragments (Edwards 2010). While this technique has been performed in small scale projects, it is yet to be performed as a part of a large-scale restoration project, and is considered largely still an experimental technique.

Table 2-1 Potential benefits and disadvantages to coral transplantation and artificial reef installations (Edwards and Clark 1998; Abelson 1996)

Management measure	Potential advantages	Potential disadvantages
Coral transplantation	• Immediate increase in coral cover and diversity • Increase in coral larvae and possibly recruitment • Survival of locally rare species when their primary habitat is destroyed • Reintroduction of corals to areas where larval supply is limited • Increase in micro-habitat complexity • Promote public awareness	• Promotes common species • Loss of colonies from donor sites • High mortality rates of transplanted corals • Low growth rates of transplanted corals • Low fecundity of transplants due to stress • Change in community structure • Limited knowledge and prediction ability • Reduction in substrate for natural recruitment • Very costly (~$500,000 USD/ha)
Larval capture	• Immediate increase in coral cover and diversity • Increase in coral larvae and possibly recruitment • Survival of locally rare species when their primary habitat is destroyed • Reintroduction of corals to areas where larval supply is limited • Increase in micro-habitat complexity • Promote public awareness	• Promotes common species • Larval capture highly weather sensitive • High mortality rates of transplanted corals • Change in community structure • Limited knowledge and prediction ability • Very costly (~$500,000 USD/ha)
Artificial reef installation	• Increase in available substrates for reef biota • Increase in structural complexity	• Slow development of communities • Poor control of community development • Limited knowledge and prediction

Management measure	Potential advantages	Potential disadvantages
	• Increase in settlement • Increase in species diversity • Improved connectivity between sites • Relatively easy to remove if failure • Attractive projects can assist public awareness	ability • Reduction in larval supply to natural reefs • Attraction of organism from natural reefs rather than increased productivity • Possible adverse effects on neighbouring reefs • Promotes common species • Costly ($60-550,000 USD/ha)

In-situ mass culture of coral recruits from the slicks of mass spawning events (Heyward *et al*. 2002) can reduce laboratory rearing costs, but these methods are subject to good weather conditions, and are only feasible for relatively small restoration areas. The technique essentially involves capturing larvae from surface slicks, and holding them in outdoor floating ponds until competent to settle, then releasing them to the seafloor.

There are numerous examples of artificial reef installations projects in Queensland waters, including within the GBR region. Artificial reefs are typically installed for the provision of ecosystems services, particularly for fishing, recreational diving, and shoreline protection (Pears and Williams 2005).

There is presently little evidence to suggest that artificial reefs enhance biodiversity values or fish stocks (Abelson 2006; Pears and Williams 2005). This is mainly because fish and benthic fauna populations are not entirely controlled by habitat availability; density-independent factors such as larval supply are also important controls on populations (e.g. Richardson 1996; Pears and Williams 2005). An important consequence of this is that artificial reefs potentially reduce available larvae to natural reefs. It is generally thought that the main benefits provided by artificial reefs are socio-economic and political rather than ecological (Pears and Williams 2005), and if inappropriately managed, can lead to adverse impacts to natural reef systems (Abelson 2006).

A third direct restoration measure was also considered in the present study: facilitation of coral recruitment by physically removing the macroalgae canopy. Macroalgae competes with coral for space, and can interfere with coral recruitment (e.g. Jompa and McCook 2003; Barott *et al*. 2012; Bonaldo and Hay 2014). However, BMT WBM is unaware of any studies that demonstrate that macroalgae removal/pruning is an effective coral restoration technique (except within coral nurseries). There are uncertainties regarding the role of macroalgae in mitigating thermal stress and facilitating community development. Macroalgae also represents a food resource for turtles, and therefore, its removal potentially conflicts with the preliminary management objective of the study. This management measure should only be considered if future investigations demonstrate that macroalgae continues to dominate reefs, and that its removal would not cause unintended adverse impacts to biodiversity values.

2.3 Indirect (Passive) Reef Restoration

Indirect reef habitat restoration can occur through a variety of management actions, including the reduction of fishing pressure through changes in zonation and legislation, reducing physical damage through the use of no-anchoring areas (NAAs), and improvements in water quality via reductions in point-source contaminants, or changes to catchment management.

Indirect reef restoration (via improvements in receiving water quality) has been the focus of reef restoration on the GBR since Reef Water Quality Protection Plan (Reef Plan) was created in 2003. Catchment modelling software (Source developed by eWater), in combination with monitoring data, has been used to estimate the amount of sediment, nutrient, and pesticide entering the GBR Lagoon. Source software has also been used to identify hotspots for different types of pollutants within the catchment, which has led to management actions to reduce pollutant loads in particular areas.

This catchment-based approach has been the focus of reef remediation efforts for the GBR, largely because water quality impacts are regarded as being one of the key immediately controllable threats to the reef after climate change (including storm damage and coral bleaching, Johnson *et al.* 2011). Revised 2018 water quality targets for priority areas include a 50% reduction in inorganic nitrogen, a 20% reduction in anthropogenic sediment and particulate nutrients, and at least a 60% reduction in pesticide loads, compared to levels recorded in 2009.

Potential indirect restoration actions could include catchment revegetation, targeted to areas of the greatest sediment and nutrient export, bank stabilisation works in areas of high erosion, and alterations to flow management in association with Gladstone Area Water Board (GAWB) to reduce high-flow impacts from water storage such as Awoonga Dam.

2.4 Assessment Approach

2.4.1 Preliminary Management Objective

Notwithstanding the above, in some circumstances, active restoration measures may be appropriate if there is strong evidence that reef communities have a low likelihood of recovering naturally following a disturbance (Abelson 2006). The decision to undertake direct reef restoration, and the type of measures to be undertaken, are fundamentally driven by the overall management objective of the program.

BMT WBM (2014) defined the preliminary management objective of the program as follows:

To restore or enhance self-sustaining nearshore subtidal reef habitats in order to promote the resilience and diversity of Commonwealth listed threatened and migratory species potentially affected by the Western Basin Dredging and Disposal Project (WBDDP).

The key elements of this objective are: (i) the actions must benefit Commonwealth listed threatened and migratory species; and (ii) the action must create a self-sustaining system. BMT WBM (2014) identified the Commonwealth listed threatened and migratory species most likely to use reefs, and the potential biological functions provided by reefs for these species. Marine turtles

were considered to be the key listed species in this context[1], with reefs providing habitat and potential food resources (i.e. macroalgae, coral, sessile macroinvertebrates) for most species found in the BOS study area.

2.4.2 Assessment Framework and Approach

Edwards and Fisk (2010) describe the stages in planning a reef restoration project, which have been adopted for the present study:

(1) Initial scoping

(2) Fact-finding for restoration plan

(3) Develop detailed restoration plan

(4) Implement restoration plan

(5) Monitoring, evaluation and feedback to stakeholders.

The present study considers the first and, in part, the second stage of this process. The ultimate aim of the initial scoping study is to determine whether direct restoration should be attempted, and if so, where. The decision tree outlined in Figure 2-1 was used to determine whether restoration is appropriate, or whether other measures may be as effective in the long-term (Edwards and Fisk 2010).

A review of existing information, a pilot field survey of reef community structure (Section 3), and catchment and hydrodynamic modelling (Section 4) were undertaken to address the questions outlined in the decision tree presented in Figure 2-1. The effects of catchment runoff were examined thoroughly to investigate the extent of past and potential future catchment runoff impacts. This was done using BMT WBM's calibrated hydrodynamic model and Source catchment modelling using a range of rainfall event scenarios. These scenarios included the 2010-2011 and 2013 flood events, a 1/10 year event, and the median summer flow event for the last 20 years. The 2013 event was also simulated to occur prior to clearing of the catchment (prior to European settlement) and in the future, considering 20 years of residential development and the full realisation of the Gladstone State Development area (GSDA) . These hind- and forecast scenarios were run to examine how changes in land use have, and will continue to affect catchment runoff and the suitability of habitats for corals.

Existing condition, the influence of catchment runoff and other issues outlined in restoration manuals and guidelines were considered in terms of assessing potential sites and potential activities (Harriott and Fisk 1987; Abselson 2006; Barber *et al.* 2009). Key issues and constraints from both a coral transplantation and artificial reef installation perspective were identified, and selection criteria were developed on this basis (see Section 5.4). Constraints were mapped using GIS, and on this basis, a list of potential restoration sites was identified (Section 6).

[1] It is also acknowledged that several wader bird species also feed on intertidal reef habitats

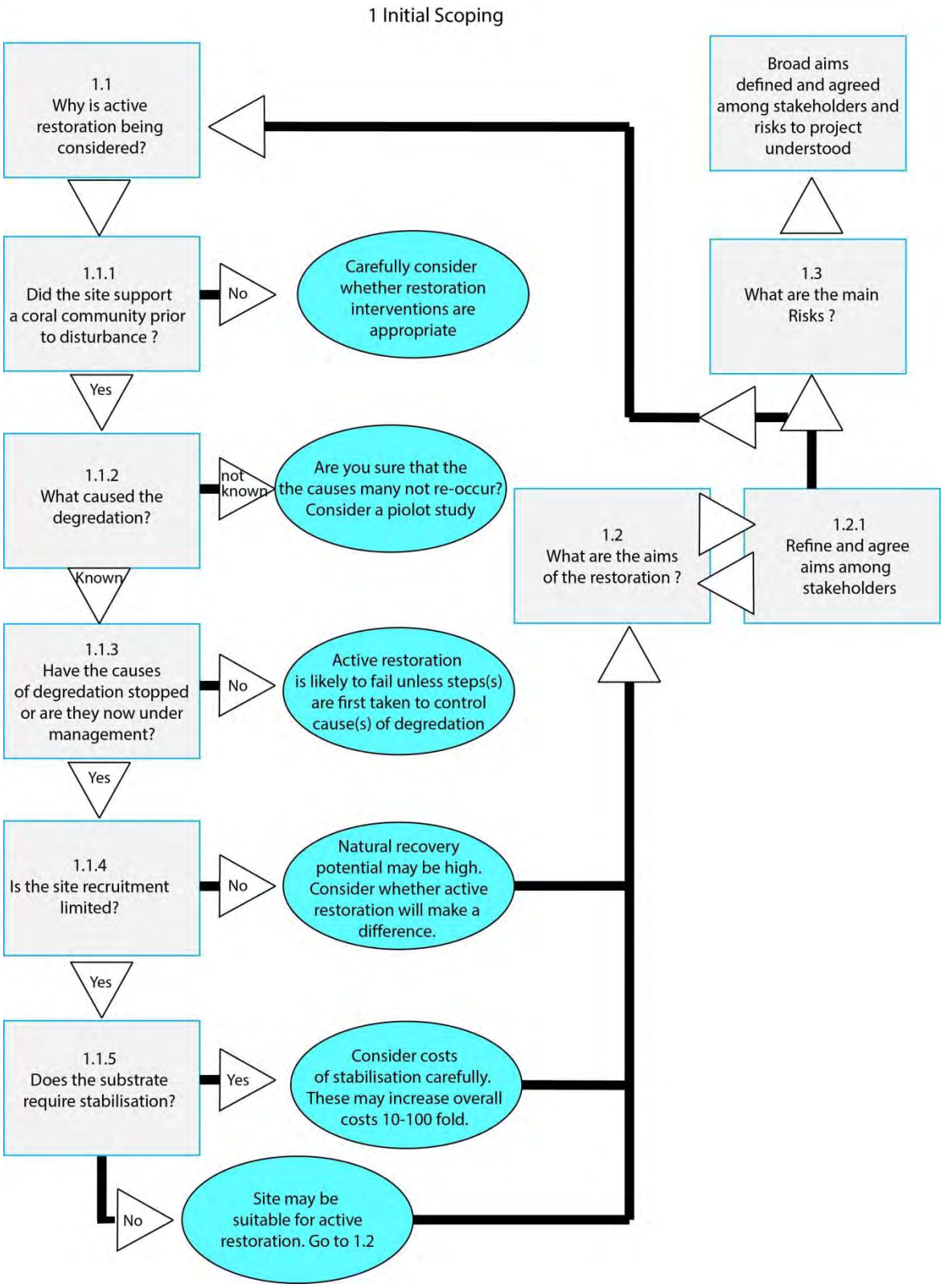

Figure 2-1 Decision tree for initial scoping questions to guide discussion of whether active restoration is an appropriate response to the reef degradation (based on Edwards and Fisk 2010)

3 Reef Community Survey

3.1 Methodology

The field survey included two components:

- Quantitative reef community surveys at the top 15 priority sites defined in the Phase 1 report (BMT WBM 2014). This was undertaken to provide an up-to-date description of the reef benthic communities and their condition within the BOS study area.
- Qualitative surveys of reef communities. This was undertaken to identify and map the presence of any rich and abundant reef benthic communities that might not have been identified through previous studies.

3.1.1 Sites and Timing

Site coordinates for qualitative and quantitative sites are listed in Table 3-1 and Table 3-2.

Quantitative community surveys were conducted at 13 sites previously sampled by BMT WBM (2009a) for Queensland Gas Company, and Sea Research (2012) for GPC as a part of material placement monitoring. All sites where quantitative data had previously been collected were revisited in 2014. Additional quantitative sites were added at Gatcombe Head (south) and Seal Rocks Reef; the latter site was visited by GBRMPA in 2012 but the coordinates of this assessment were not available. In addition, 53 sites were surveyed qualitatively using a drop camera, shown in Figure 3-1 and Figure 3-2. These qualitative data were used to map the extent of reef in combination with satellite imagery.

Surveys were conducted May 4th to 9th 2014 inclusive, during neap tides from MV *Rush*. Conditions were excellent with wind speeds generally below 8 knots for the duration of the assessment. Visibility was poor at Turtle Island (0.5 m), while most other inner harbour sites had visibilities of between 1-3 m. East of Facing Island, visibility approached 10 m at Sable Chief Rocks Reef. Still imagery collected under poor visibility conditions had a larger non-useable frame surrounding each image. Images that were out of focus were not analysed.

3.1.2 Sampling Methodology

At each quantitative site, three transects were run along a depth contour where coral was present along a depth contour detailed in Table 3-1. Transects were positioned along the reef or reef slope (when present) and conducted over 30 m. Each transect start position was marked using a hand-held GPS tethered to the diver's surface float. Transect imagery was collected using paired high-definition submersible cameras with dual 1800 lumen video lights to maximise image quality. Imagery was collected from 20-30 cm above the seafloor, providing a 0.5-1 m wide swath of imagery. One camera collected still imagery every two seconds while the other filmed continuously. This approach allowed for objective selection of still imagery because stills were collected randomly, and a video recording to aid in identification if necessary.

Drop camera footage was acquired using a high-definition submersible camera with 1800 lumen external lighting and a live feed to surface. Assessments were made of seafloor and reef habitats near reefs of interest to examine the substrate type and presence of flora and fauna.

Flat Rock Reef
Split Rock Reef
Jabiru Shoals
Peak Island Reef
Girt Island Reef
Arch Rock Reef
Hummocky Island Reef
Ship Rock Reef
Fairway Rock Reef
Quartz Rock Reef
Timandra Bank
Keppel Rocks Reef
Unnamed Reef
Station Point Reef
Cape Keppel Reef
Heron
Wistari Reef
Unnamed Reef
Erskine Island Reef
Unnamed Reef
Mast Head Island Reef
Irving Reef
Rundle Island Reef
Polmaise Reef
Bass Shoals
Rock Cod Shoal
Curtis Island Reef (No 3)
Curtis Island Reef (No 4)
Turtle Island Reef
North Point Reef (Facing Island Reef No 1)
Rat Island Reef
Facing Island Reef (No 2)
Pearl Ledge (Facing Island Reef No 3)
Farmers Reef
Sable Chief Rocks Reef
Facing Island Reef (No 4)
Bushy Island Reef
East Point Ledge (Facing Island Reef No 5)
Manning Reef
Gatcombe Head Reef (Facing Island Reef No 6)
East Banks (West)
East Banks (East)
Curtis Rock Reef
Seal Rocks Reef (No 1)
Seal Rocks Reef (No 2)
Richards Point Reef
Unnamed Reefs
Clews Point Reef
Seal Rocks Reef (No 3)
See Figure 3-2

Google™ earth
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat

LEGEND

Biodiversity Offset Strategy Boundary

Shoreline

Waterways

GBRMPA Reef Extent (kml)

Reef Extent (Present Study)

Diver Transects (Quantitative)

Drop Camera Assessments (Qualitative)

Title:

Investigation Sites (May 2014)

Figure 3-1

Rev: A

BMT WBM endeavours to ensure that the information provided in this map is correct at the time of publication. BMT WBM does not warrant, guarantee or make representations regarding the currency and accuracy of information contained in this map.

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0km 10 20

Scale - Main Map

BMT WBM
www.bmtwbm.com.au

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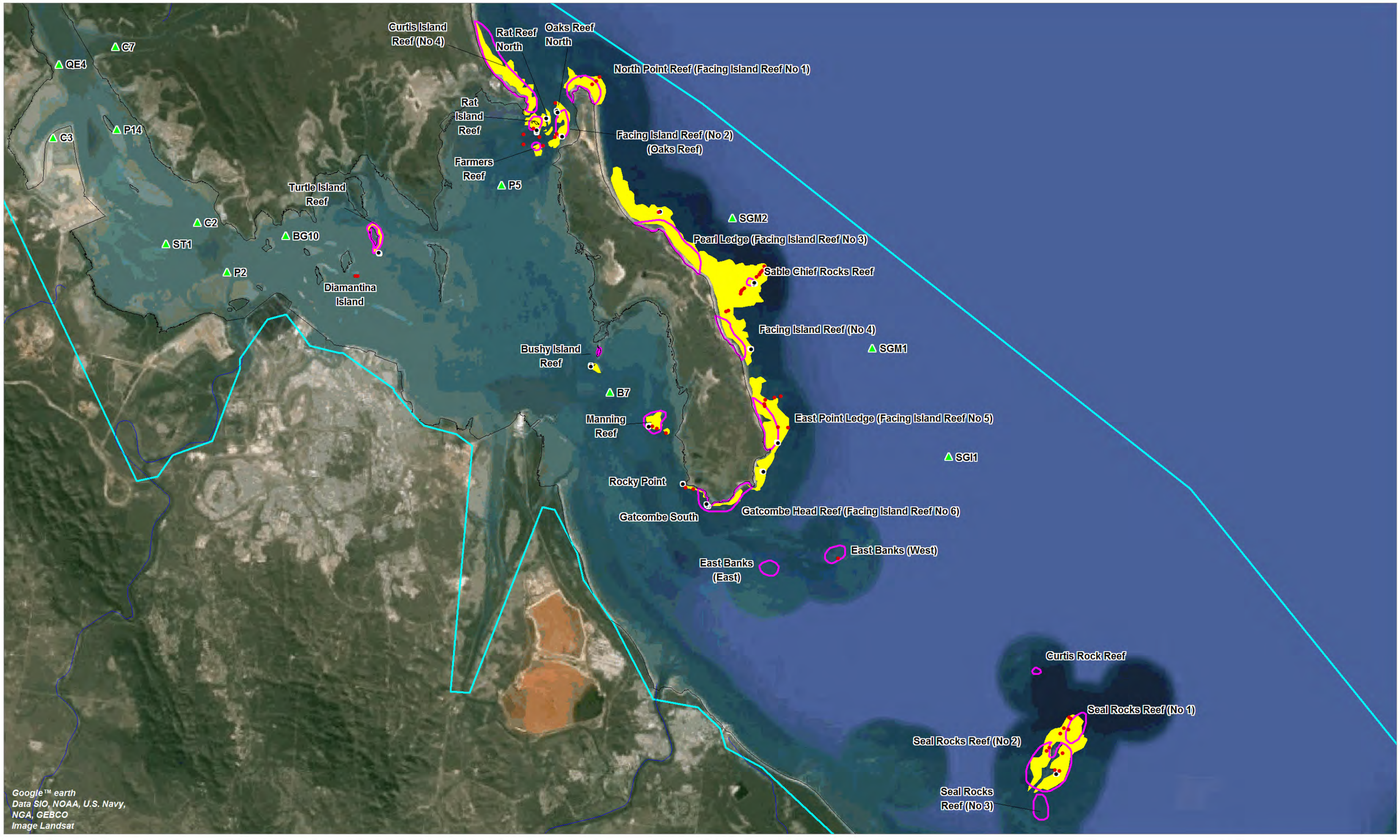

LEGEND

- Biodiversity Offset Strategy Boundary
- Shoreline
- Waterways
- GBRMPA Reef Extent (kml)
- Reef Extent (Present Study)
- Diver Transects (Quantitative)
- Drop Camera Assessments (Qualitative)
- Vision Environment Water Quality Instruments

Title:

Investigation Sites Detail (May 2014)

Figure 3-2

Rev: A

N

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Scale - Inset

BMT WBM

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Table 3-1 Positions and Nomenclature of Quantitative Sites

2014 Site (GBRMPA Reef name)	BMT WBM (2009) nomenclature	Sea Research (2012) nomenclature	Rep	WGS 84 Zone	Easting	Northing	Approx. Depth (m LAT)	Area (Section 5-6)
Turtle Island (Turtle Island)	Turtle Island	Not assessed	1	56K	323346	7366434	-2 to -3	1
			2	56K	323357	7366443		
			3	56K	323328	7366466		
Sable Chief Rocks Reef (Sable Chief Rocks)	Not assessed	Impact 4	1	56K	335992	7365435	-3	3
			2	56K	335949	7365417		
			3	56K	335966	7365457		
Oaks (Facing Island # 2)	Oaks North	Not assessed	1	56K	329308	7371213	-1 to -1.5	2
			2	56K	329322	7371248		
			3	56K	329339	7371185		
Rat Reef South (Rat Island Reef)	Rat Reef South	Not assessed	1	56K	328643	7370515	-2 to -3	2
			2	56K	328650	7370535		
			3	56K	328644	7370581		
Pearl Ledge (Facing Island #3)	Not assessed	Impact 5	1	56K	332793	7367835	-3	3
			2	56K	332794	7367845		
			3	56K	332785	7367845		
Gatcombe South (Facing Island #6)	Not assessed	Not assessed	1	56K	334419	7357943	-3 to -5	2
			2	56K	334368	7357981		
			3	56K	334361	7358028		
Bushy Island (Bushy Island Reef)	Bushy Islet	Not assessed	1	56K	330473	7362692	-3 to -5	2
			2	56K	330472	7362660		
			3	56K	330466	7362639		
Rat North (Rat Reef)	Rat Reef North	Not assessed	1	56K	328996	7370976	-1.5 to -3	2
			2	56K	328987	7370987		
			3	56K	328970	7370991		
Seal Rocks (Seal Rocks Reef #2)	Not assessed	Not assessed	1	56K	346144	7348990	-3 to -5	4
			2	56K	346138	7348970		
			3	56K	346118	7348956		
Manning Reef (Manning Reef)	Manning Reef	Not assessed	1	56K	332412	7360677	-2 to -3	2
			2	56K	332410	7360661		
			3	56K	332417	7360632		
Rocky Point South (Facing Island #6)	Rocky Point South	Not assessed	1	56K	333559	7358714	-2 to -3	2
			2	56K	333555	7358701		
			3	56K	333557	7358693		
Gatcombe East (Facing Island #6)	Not assessed	Impact 1	1	56K	336245	7359127	-5	3
			2	56K	336260	7359125		
			3	56K	336269	7359111		
East Point Ledge (Facing Island #5)	Not assessed	Impact 2	1	56K	336723	7360104	-5	3
			2	56K	336736	7360085		
			3	56K	336755	7360073		
Facing Island #4	Not assessed	Impact 3	1	56K	335826	7363248	-3 to -5	3
			2	56K	335852	7363241		
			3	56K	335860	7363226		
Facing Island # 2	Farmers Reef 2	Not assessed	1	56K	329482	7370388	-0.5 to -1	2
			2	56K	329491	7370389		
			3	56K	329492	7370376		

Table 3-2 Positions of Qualitative Sites

Location Description	Waypoint	WGS 84 zone	Easting	Northing	Area (Section 5-6)
near Rat Reef	1	56K	328729	7370322	2
	2	56K	328193	7370425	
	3	56K	328529	7370612	
	4	56K	328206	7370090	
near Farmers	5	56K	329258	7370335	2
near Facing Is. #2	6	56K	329264	7371470	2
Pearl Ledge	7	56K	332742	7367806	3
Diamantina Island	8	56K	322637	7365659	1
	9	56K	322552	7365659	
near Farmers Reef	14	56K	329309	7370438	2
Farmers reef	15	56K	328851	7370038	2
Seal Rocks Reef	16	56K	346372	7350464	4
	17	56K	346519	7350415	
	18	56K	346539	7350838	
	19	56K	346608	7350789	
	20	56K	346254	7350277	
	21	56K	345880	7349805	
	22	56K	345792	7349697	
	23	56K	346215	7349019	
	24	56K	346067	7349058	
	25	56K	346323	7349619	
near Gatcombe (Facing Island #6)	26	56K	333650	7358547	2
	27	56K	333916	7358498	
Manning Reef	28	56K	332530	7360612	2
	29	56K	332687	7360533	
	30	56K	332992	7360376	
East Banks West	31	56K	338772	7356167	4
East Point Ledge (Facing Island #5)	32	56K	337091	7360563	3
	33	56K	336757	7360573	
	34	56K	336846	7361625	
	35	56K	336629	7361576	
	36	56K	336324	7361497	
	37	56K	336305	7361360	
	38	56K	336315	7361281	
Sable Chief Rocks Reef	39	56K	335006	7364464	3
	40	56K	335090	7364490	
	41	56K	335497	7365058	
	42	56K	335619	7365251	
	43	56K	335542	7365193	
	44	56K	335509	7365135	
	45	56K	336038	7365626	
	46	56K	336135	7365710	
	47	56K	336180	7365781	
	48	56K	336238	7365851	
	49	56K	336296	7365987	
North Point Reef (Facing Island #1)	50	56K	330755	7372348	3
	51	56K	330645	7372212	
	52	56K	330516	7372109	
Keppel Rocks Reef	53	56K	300963	7407552	NA

3.1.3 Data Analysis

Coral Point Count (Kohler and Gill 2006) was used to quantify benthic cover. Twenty points were identified on each photo on a selection of ten randomly selected photos per transect, giving a total of 200 point identifications per transect. Corals were identified to genus and placed in higher groupings to allow comparisons with previously collected data.

Patterns in community attributes such as % cover and taxonomic richness were summarised with simple descriptive statistics (mean, standard error). Patterns in assemblage structure at different sites and times were analysed using multivariate methods with Primer 6 (Clarke and Gorley 2006). Differences in communities among sites and times were visualised with non-metric multi-dimensional scaling plots of Bray-Curtis resemblance matrices of square-root transformed data. Changes among times are presented for site-averaged data. Relative differences in major cover types were overlain as bubbles to show changes in the cover of macroalgae, turfing algae, hard and soft corals through time.

3.1.4 Reef Mapping

Satellite imagery (Google Earth, July and August 2003) together with qualitative survey data, were used to refine the current mapped extent[2] of coastal reefs along the east coast of Facing Island. This was undertaken because it is known that existing mapping significantly under-estimates the extent of subtidal reefs in this area. Digitisation and mapping was undertaken using the GIS package MapInfo 12.5.

3.2 Results and Discussion

3.2.1 Reef Extent

Coral reef extent mapped in the current study and the extent mapped by GBRMPA are shown in Figure 3-1. The primary differences between these layers are an increase in reef extent surrounding Sable Chief Rocks Reef and altered boundaries around North Entrance and Seal Rocks. The change in extent does not represent a recent expansion in coral reef area, but more accurate mapping of the likely reef boundaries, particularly around North Entrance and along the eastern shores of Facing Island. Reefs can be seen clearly in these areas on historical aerial imagery on Google Earth from July and August 2003 and this corresponds with field observations in the present study.

Two reefs at East Banks mapped on the GBRMPA spatial layer do not appear to exist as coral reefs in 2014. These are, confusingly, named East Banks East (located west) and East Banks West, (found in the east). East Banks East (sic) falls within the shipping channel, which is subject to regular maintenance dredging. East Banks West (sic) consisted entirely of sand when assessed in May 2014; however, hard substrates may exist beneath the sand. No background data are available for these reefs, apart from the broad-scale habitat classifications conducted nearby by Rasheed *et al*. (2003).

Coral reefs are presently not mapped at the Jenny Lind Bank, north-east of Seal Rocks, but likely occur here given the highly complex bathymetry and appropriate conditions for coral growth. While

[2] http://www.gbrmpa.gov.au/resources-and-publications/spatial-data-information-services/explore-the-gbrmp-with-google-maps

not visited during the present survey, previous acoustic surveys and species described on fishing reports suggest that coral substrates are present.

3.2.2 Condition

Generally speaking, there was a reduction in the cover of hard and soft corals at sites within Port Curtis between 2009 and 2014, while cover metrics were similar at sites east of Facing Island between 2012 and 2014. Examples of these changes are shown pictorially in Figure 3-3.

At sites such as Oaks Reef (Facing Island #2, North) extensive *Porites* colonies observed in 2009 were still present, but cover was greatly reduced and colony colour appeared lighter (Figure 3-3A). The most significant changes in cover were observed at Bushy Island (Figure 3-3B) and Manning Reef (Figure 3-3D), where *Turbinaria* and dense stands of *Acropora* had died and become covered in turfing algae. Many of the reefs around North Entrance, such as Rat Island Reef south, had significantly more macroalgae (mostly *Sargassum*) than they did in 2009, and coral genera such as *Pocillopora* (Figure 3-3C) were absent in 2014.

Temporal changes in each of the four major cover types are shown in Figure 3-4 and Figure 3-5. Coral cover was substantially lower (beyond the range of observed variability between standard errors) in 2014 than 2009 at most sites in Port Curtis (e.g. Bushy Island, Manning, Oaks, Rat South, Rat North, Rocky Point South, and Turtle Island reefs). East Point Ledge also appeared to have slightly lower hard coral cover in 2014 than 2012[3]. Changes in hard coral cover on the eastern side of Facing Island at Gatcombe (east), Facing Island #4, Pearl Ledge were within the range of standard error variability, indicating that changes in cover over time were probably not statistically significant. Estimates of hard coral cover at Sable Chief Rocks Reef were very similar between 2012 and 2014.

Figure 3-5 shows the relationships between reef communities in 2D space, where similar communities are proximal, and different communities are widely separated. The size of each bubble represents the relative percent cover contributing to each benthic cover type, and the ordination remains the same among all four plots. Arrows show the direction in change from 2009 to 2014. Sites that were sampled once only have no arrows pointing to another location in the plot. This is the case for some of the Facing Island sites because the raw data from Sea Research (2012) were unavailable, and because some sites such as Diamantina Island were not sampled again in 2014. The plot shows that sites which were sampled in 2009 tended to move directionally, towards the upper left hand side of the plot (Turtle Island, Bushy Island, Facing #2, and Manning), or to the lower left had side of the plot (Oaks and Rat). Bubble plots show that this division was related to sites in the upper left hand side of the plot becoming dominated by turfing algae, and sites that moved to the lower left hand side of the plot became dominated by macroalgae.

[3] Sea Research (2012) does not include raw data so statistical comparisons were not undertaken

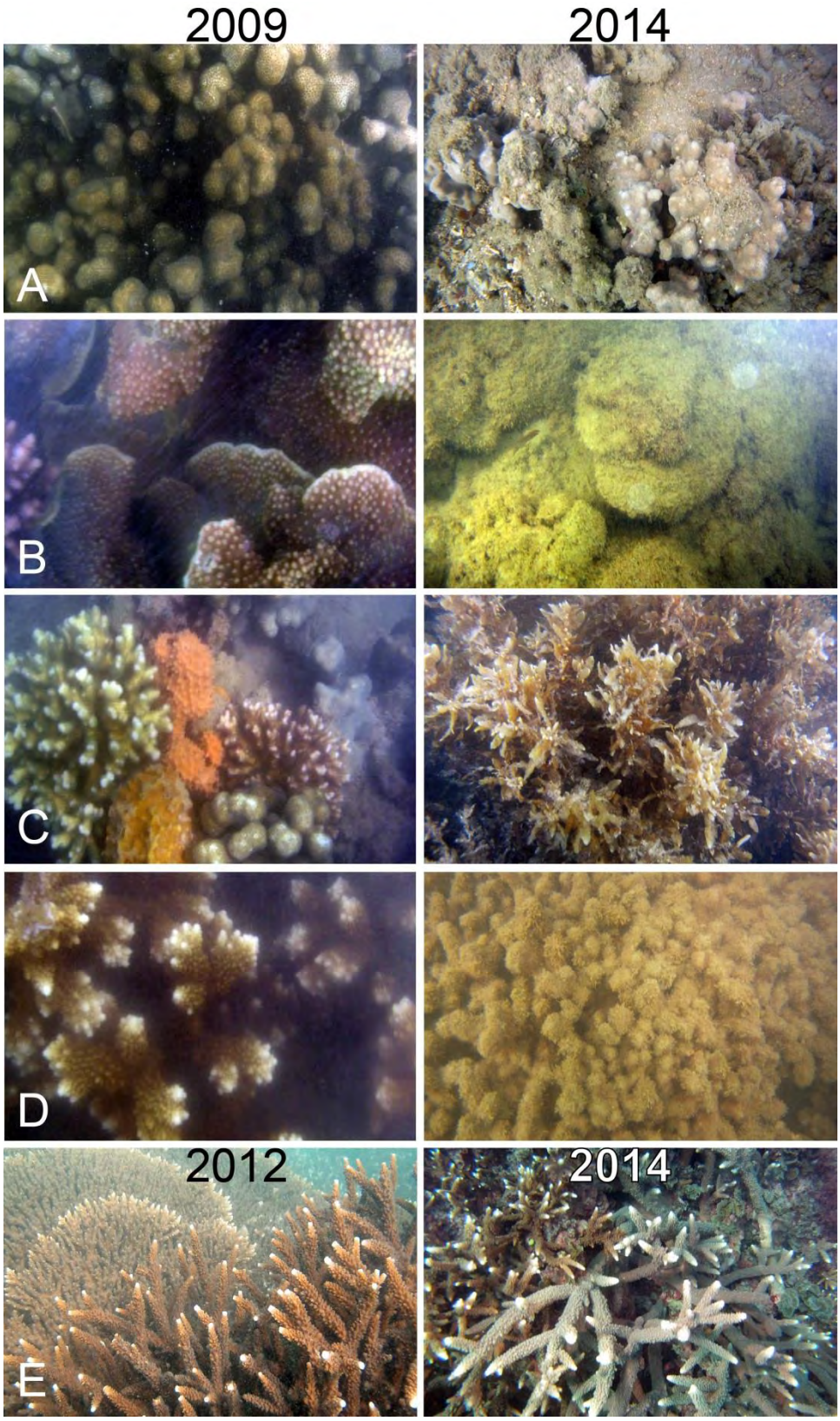


Figure 3-3 Photographic examples of changes in condition between 2009 and 2014: (A) Oaks Reef a.k.a. Facing Island #2; (B) Bushy Island; (C) Rat Island South; (D) Manning Reef; (E) Sable Chief Rocks Reef

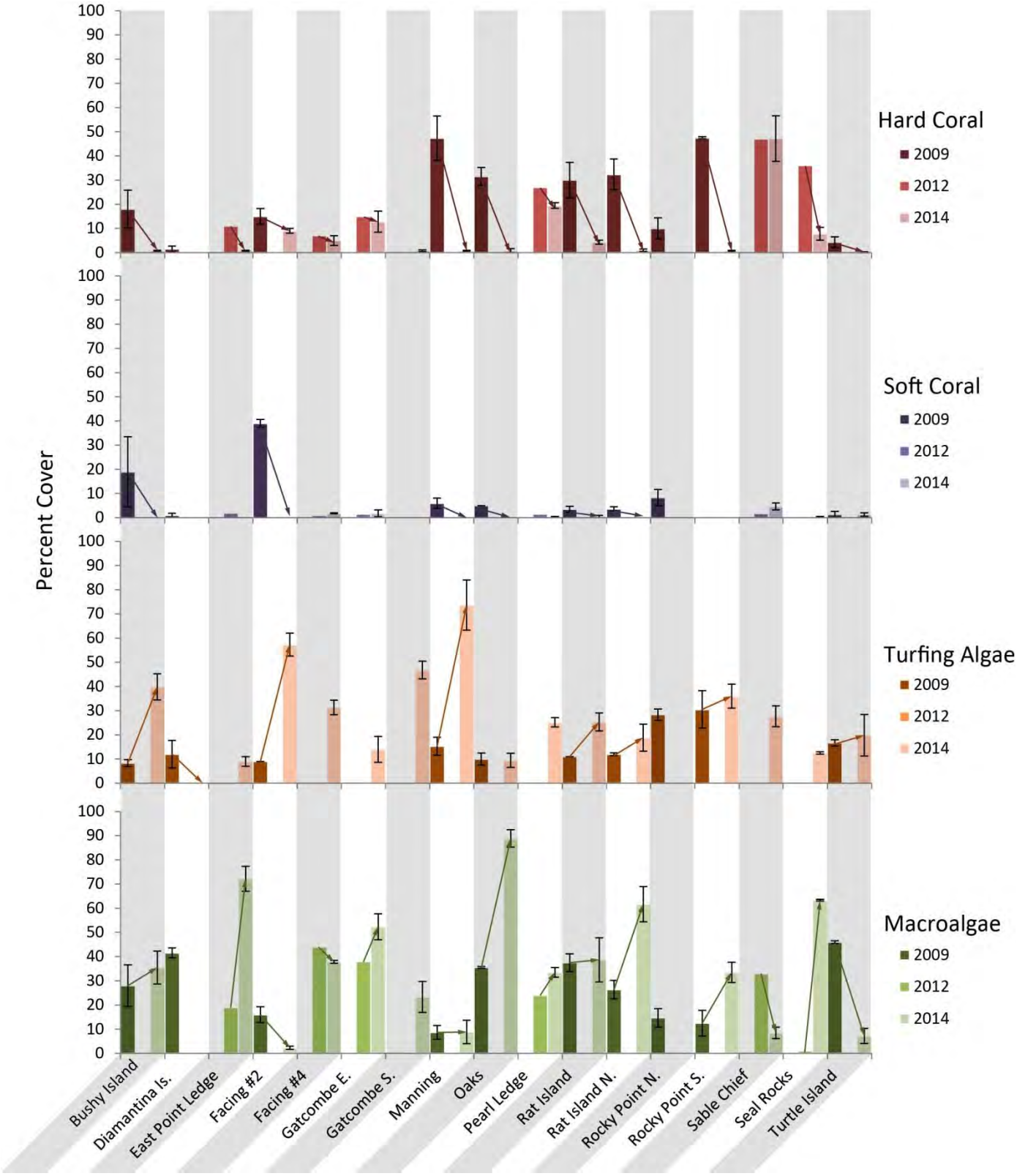
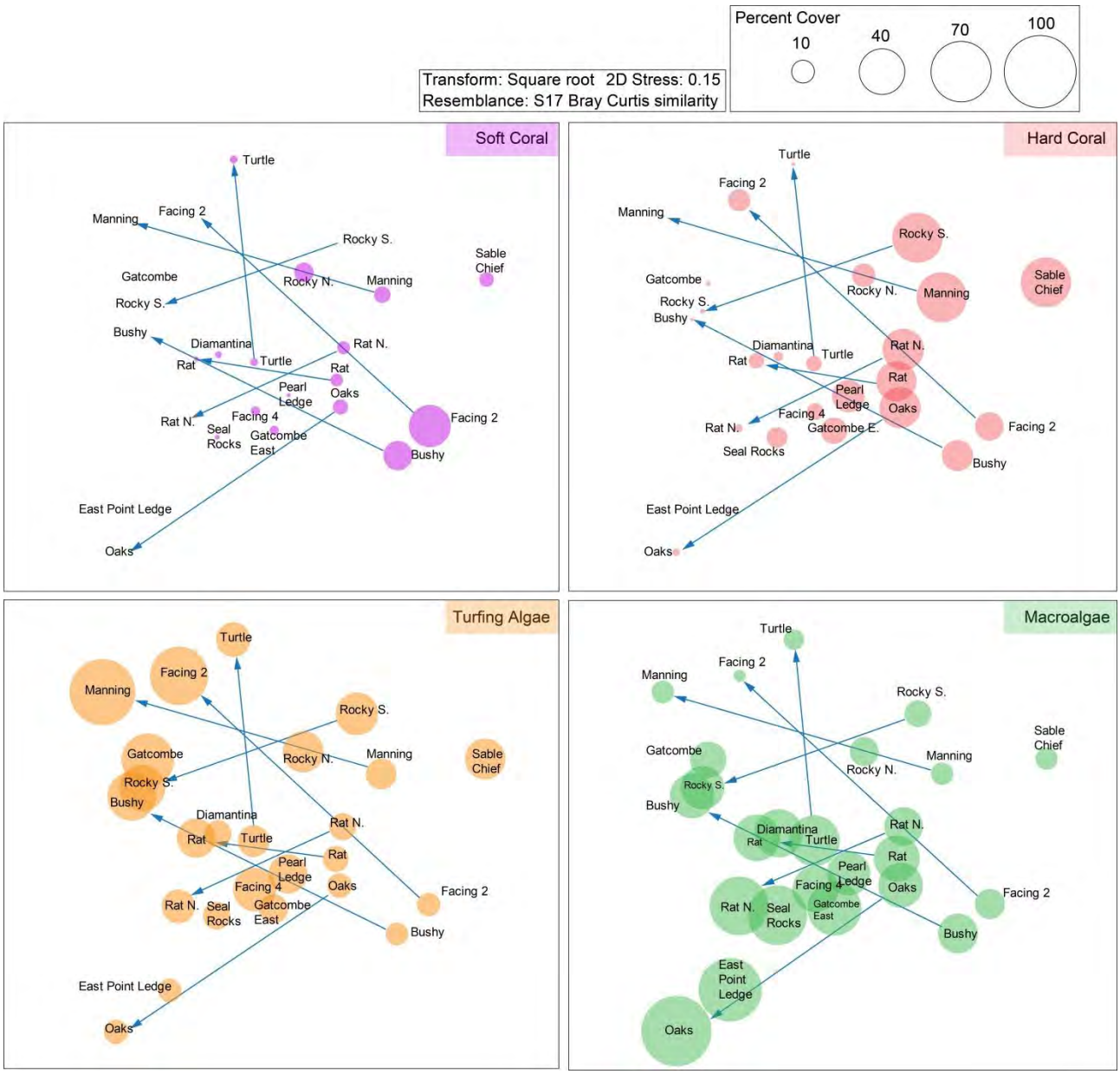


Figure 3-4 Changes in mean (±SE) percent cover for hard coral, soft coral, turfing algae and macroalgae. Means without error bars for Facing Island sites in 2012 have been estimated from Sea Research (2012), and Seal Rocks 2012 data is from GBRMPA (2013)



Note: Bubble size indicates relative percent cover for soft coral, hard coral, turfing algae, and macroalgae. Arrows indicate the direction of change between 2009 and 2012, sites without arrows were sampled in 2014 only

Figure 3-5 nMDS ordination of site-averaged benthic community data, based on square root transformed Bray-Curtis similarities

Seal Rocks Reef also appeared to have experienced a major loss of hard coral cover. Although GBRMPA (2013) did not provide site coordinates for their surveys, the present study conducted transects in the area of highest hard coral density that could be located, from a selection of 10 drop camera placements around Seal Rocks Reef. Living hard coral was scant at most locations with only occasional large living poritids observed. Most of the reef was covered in turfing and macroalgae growing on coral skeletons that appeared to have died recently. The exception to this was one site located along the eastern edge of Seal Rocks Reef #2. Therefore, the May 2014

estimate was conducted in an area of Seal Rocks which had some of the highest coral cover at the time, but this was still far less than the 36% cover reported by GBRMPA in January 2012 (GBRMPA 2013). In 2014, the densest living hard coral was observed on the eastern side of Seal Rocks, in a position that would be most sheltered from freshwater plumes from Port Curtis.

The change in soft coral cover was less pronounced at most sites, with obvious changes only occurring at Bushy Island and Facing Island #2, where reductions were significant. These losses in hard and soft coral cover tended to be replaced by increases in algal cover, consistent with the hypothesis that this was a disturbance-related change (see Discussion below).

Changes in all major cover types are shown in Figure 3-6. Acroporid corals were lost completely between 2009 and 2014 at Bushy Island, Manning Reef, Rat Reef and Rocky Point South. Hard coral communities at Bushy Island, Manning and Oaks reefs consisted only of *Porites;* other genera such as *Turbinaria, Pocillopora, Goniopora,* and *Favites* which were common in 2009 were not observed in 2014.

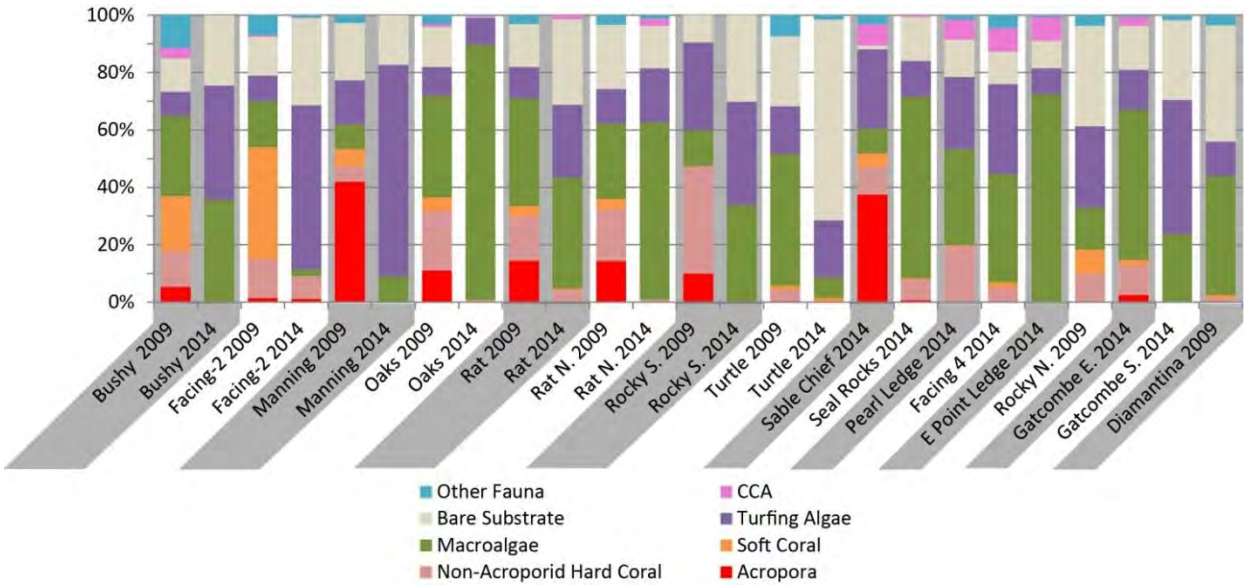


Figure 3-6 Percent cover of all major cover types

Reductions in cover and species richness between 2009 and 2014 were not restricted to hard corals; total richness and the richness of soft corals also declined over this period (Figure 3-7). No soft coral taxa were recorded at Bushy Island, Manning, Oaks and Rat reefs in 2014, despite 1-2 taxa consistently recorded at those locations in 2009.

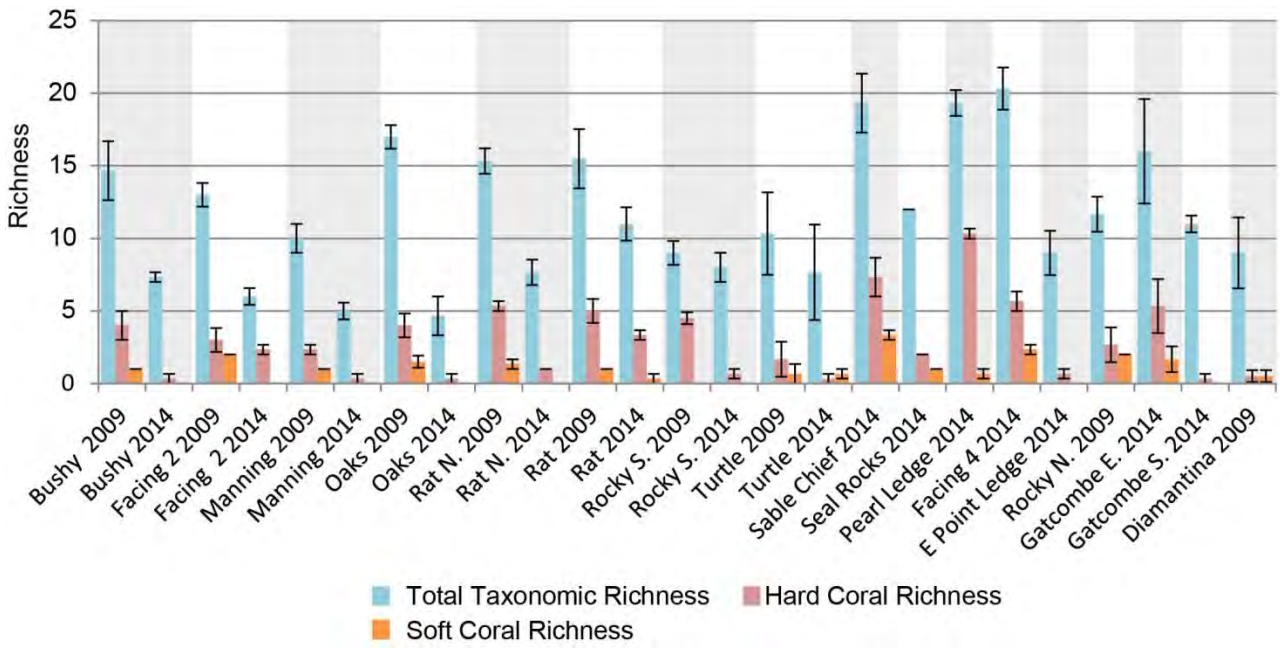


Figure 3-7 Changes in mean (±SE) total, hard coral, and soft coral richness between sites visited in 2009 and 2014.

3.3 Discussion

3.3.1 Patterns in Numerical Dominance

The present study builds on the limited information base describing patterns in the structure of benthic communities on the BOS study area reefs (i.e. BMT WBM 2009a; Sea Research 2012). Within Port Curtis there is a spatial gradient in water quality (particularly turbidity) moving from west to east, with the more oceanic influenced waters of North Passage and the western shoreline of Facing Island generally having lower turbidity than areas to the west. Reef habitats and benthic community structure reflect this spatial gradient; reefs surrounding the inner islands supported low benthic cover (except for oysters in the intertidal zone; BMT WBM 2009a), whereas subtidal reefs in North Passage and the western shoreline of Facing Island were numerically dominated by turfing algae and macroalgae, with hard and soft coral being sub-dominant. This spatial pattern was consistent with BMT WBM (2009), although as discussed below; there have been major changes in community structure over time.

Hard corals tended to numerically co-dominate with algae in the more oceanic influenced reefs on the east coast of Facing Island, which was consistent with the findings of Sea Research (2012). The benthic communities on reefs located south of Facing Island (i.e. various reefs described as Seal Rocks) had a variable character which changed over time. In the present study, benthic communities at Seal Rocks were found to be numerically dominated by macroalgae growing on recently dead coral skeletons. This contrasts the results from rapid surveys by GBRMPA in 2012, where macroalgae was sub-dominant (1% cover) and hard coral was dominant (36% cover). The GBRMPA site visit took place after the 2011-12 floods, during the WBDDP, and prior to the 2013 flood event (Figure 3-8). Modelled dredge plumes from the WBDDP show very little potential for

impact at Seal Rocks, (BMT WBM 2014) therefore, the change in community at Seal Rocks is most consistent with a 2013 flood impact.

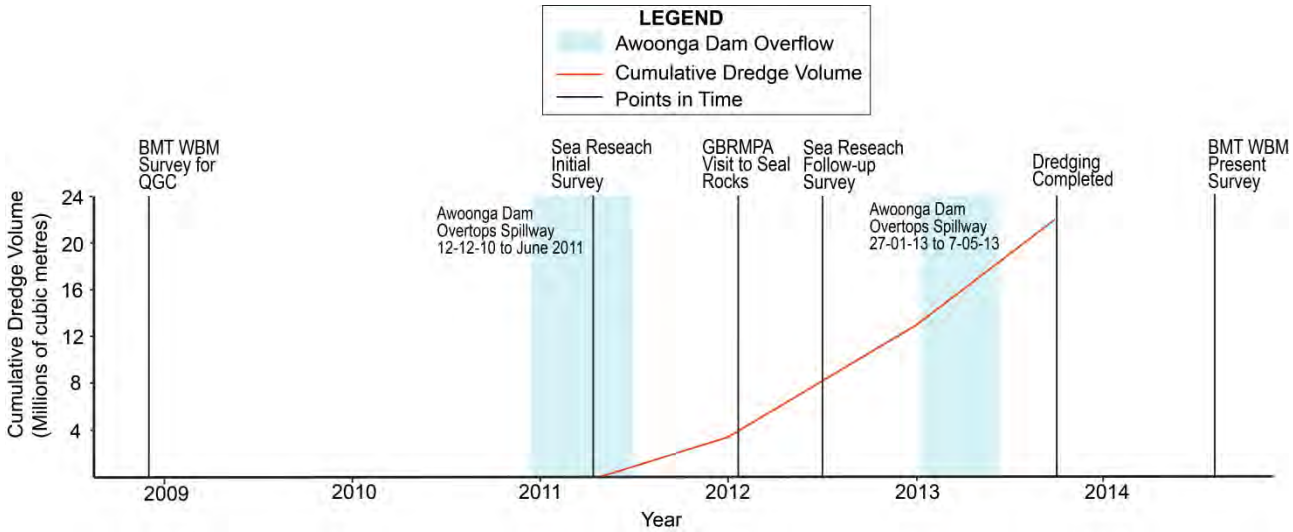


Figure 3-8 Timeline of recent survey and disturbance events

The percentage cover of corals of BOS reefs was generally lower than many nearshore reefs within the Great Barrier Reef region (Van Woesik 1992; Ayling *et al*. 1998). Van Woesik (1992) surveyed nearshore reefs in the central Queensland region and found that most reefs were algae dominated, consistent with reefs in the BOS area. Van Woesik (1992) reported coral cover values ranging from 5.3% around Percy Isles to 41% around Prudhoe Island, with a grand mean of 19%. Shoalwater Bay reefs had a grand mean cover of 38% (Ayling *et al*. 1998), which was higher than the grand mean cover recorded in BOS reefs in 2009 (28%) and 2014 (8%).

3.3.2 Coral Community Condition

The results of the present study indicate that coral community structure showed great changes across the study area between 2009 and 2014. It is possible that some differences in sampling effort and transect placement may explain some of the differences between studies. However, the magnitude and consistent direction of change strongly suggest that differences between time periods were due to real changes in reef benthic communities.

Within Port Curtis reefs, almost all coral taxa declined in cover between time periods, but most especially *Acropora* spp. *Acropora* spp. are among the most susceptible hard corals to flooding-related changes in water quality (e.g. Johnson and Neil 1996), as well as long-term chronic changes to light climate and sedimentation (Hughes *et al.* 2007). Macroalgae and turfing algae cover, as well as the proportion of bare substrate, were also higher than recorded previously.

The temporal resolution of surveys is insufficient to determine the trajectory of change (i.e. acute or chronic effect), so it is not possible to determine the precise cause/s of observed changes. Notwithstanding this, there are multiple lines of evidence suggesting that the observed changes in coral condition were consistent with responses to broad-scale disturbance/s. A reduction in coral cover occurred throughout Port Curtis and in Rodds Bay, at Seal Rocks, indicating that the

process/es responsible for changes were operating at spatial scales measured in >10's of kilometres. Similar major declines in ecosystem condition and resilience have been reported throughout the nearshore zone of the Great Barrier Reef coast over this same period (Johnson *et al*. 2011), as a result of successive wet periods causing water quality stress. There is insufficient information to determine the relative contribution of other processes operating at local spatial scales (including dredging and other anthropogenic disturbance) to the observed changes. The exception to this is Seal Rocks Reef, which was surveyed more recently and appears to have been damaged by the 2013 floods.

The widespread loss of coral cover was accompanied by an increase in cover of macroalgae, turfing algae and bare substrate. Macroalgae can rapidly colonise bare substrate, and can form a dense cover following disturbance to coral reefs (Done 1999). The period between the 2009 and 2014 surveys had above average rainfall, leading to flood plumes extending to reef habitats. High macroalgae cover on coral reefs is typically a transient feature (Done 1999); however, prolonged periods of high nutrients can result in persistent macroalgae cover, resulting in reduced coral reef resilience (Hughes *et al*. 2007).

3.3.3 Resilience and Recovery

Coral species differ in their sensitivity to disturbance (i.e. resistance) and capacity to recover following disturbance (i.e. resilience). The degree of resistance and resilience in corals depends on a number of often interactive factors including:

- Adaptations that allow corals to tolerate the stressor (e.g. low light, high sediment etc.) (resistance)
- Energy reserves to draw on during low light periods (resistance)
- Settlement and subsequent recruitment rates (resilience)
- Interactions with other plant (e.g. macroalgae) and animal (e.g. other corals etc.) species
- Historical and future disturbance regimes, including the frequency, timing, duration and intensity of disturbances, and synergistic effects (resistance and resilience).

In terms of resistance, Port Curtis has naturally high turbidity levels, and therefore, corals must have adaptations to cope with periods of low light and high sedimentation rates. This includes for example, (i) the capacity for some corals to switch from phototrophic to heterotrophic feeding strategies by feeding on suspended sediments; (ii) rapid replenishment of energy reserves between turbidity events; (iii) rapid rates of photo-acclimation; and (iv) energy conservation through reduced respiratory and excretory losses (Anthony and Larcombe 2000). Many nearshore turbid water species also produce mucus to slough settled sediment.

The degree of resilience of corals varies among taxa. Acroporid corals, for example, can show great changes in cover over time but are generally considered to be resilient. While most acroporid species are photophilic (sensitive to light deprivation) and break easily, they are also capable of high growth rates and high reproductive output (Thompson *et al*. 2010). By contrast, many coral families such as the Faviidae, Porititidae and Fungiidae, are relatively resistant to physical

disturbance, relatively tolerant of low light conditions (many species can switch to suspension feeding) and high rates of sedimentation, but have low growth rates and recruitment levels.

Nearshore turbid water coral reefs in the Great Barrier Reef region are thought to be resilient to change, showing rapid recovery following disturbance (e.g. Browne *et al*. 2010). Notwithstanding this, recovery rates and growth of corals are highly dependent on ambient environmental conditions. Browne (2012) for example found that coral growth (calcification) at Middle Reef in Townsville was lowest in summer months when sea surface temperatures (monthly average 29° C) and rainfall (total >500 mm) were high. She suggested that while corals on Middle Reef were resilient and robust to their marginal environmental conditions (i.e. high turbidity and sedimentation, periodic low salinities), they would be most susceptible to anthropogenic disturbances in summer months, when other climatic disturbances are more frequent and severe.

Within the nearby Keppel Bay group of reefs, large discharges of freshwater from the Fitzroy catchment (Queensland's largest catchment) have resulted in a series of freshwater bleaching events (Van Woesik, 1992; Berkelmans *et al.,* 2012; Jones and Berkelmans, 2014). These widespread events have been followed by remarkably rapid recoveries, suggesting that the Keppel communities are highly resilient to flood plume impacts. Genetic studies (Van Oppen *et al.* 2015) and monitoring (Diaz-Pulido *et al.,* 2009) on these reefs have shown that recovery primarily results from rapid regrowth of surviving tissues. Corals within the Keppel Bay group are genetically isolated from other parts of the GBR, but there is extensive gene flow within parts of the Keppel Islands (Van Oppen *et al.* 2015). Therefore, following regular freshwater plume disturbances, recovery is primarily driven by asexual expansion of surviving tissues, but there is also some recolonisation that occurs from larvae, mostly from within the Keppel reefs.

While the Keppel reefs are highly resilient to plume impacts, being situated in close proximity to the Fitzroy River mouth, there is an absence of information on natural coral recruitment and settlement rates within the southern BOS area. It is, therefore, not possible to determine the capacity of reefs to recover, and the likely rate of recovery. Reefs in Port Curtis may share ancestry with Keppel Reefs and be highly resilient, or they may be less adapted to plume impacts due to less frequent and severe plume impacts from the much smaller Boyne and Calliope River catchments. At Manning, Gatcombe and Bushy Island Reefs, not a single living acroporid colony was observed, so regeneration from living tissue (as occurs in the Keppel Group) could not occur.

4 Catchment and Hydrodynamic Modelling

4.1 General Approach

Integrated catchment and hydrodynamic models were used to assess the extent of freshwater plumes, nutrients (total nitrogen [TN] and total phosphorus [TP]), total suspended solids (TSS), and sedimentation in Port Curtis after recent major and hypothetical flood events. The basic workflow consisted of understanding catchment input (runoff) from different land uses and calibrating the Source catchment model (eWater CRC 2010) to observed flows and constituent concentrations with available data. Once calibrated to a known event, the catchment model could be used to examine differences in land use or differences in rainfall via the development of various scenarios. These scenarios consisted of:

- The 2013 floods (used in validation)
- The 2010-11 floods (henceforth referred to as the 2011 event for brevity) (used in calibration)
- The "average" major wet season event – based on the median 3 day flow event from a group of the highest summer flow events over 25 years (1990-2014), hereafter referred to as the median summer maxima
- A 1:10 ten year event – based on the annual recurrence interval (ARI) determined through analysis of historical rainfall data
- The 2013 flood event, simulated to occur over a fully vegetated (pre-European) catchment without Awoonga Dam
- The 2013 flood event, simulated to occur in the future, after 20 years of expected residential development, and the full realisation of the GSDA into industrial lands.

Once catchment runoff inputs for the above scenarios were generated, these freshwater plumes, (including entrained nutrients and sediments), were modelled to advect throughout Port Curtis using BMT WBM's hydrodynamic model (TUFLOW FV). This was done in three dimensions to address differences in density between fresh and salt water. Outputs for all constituents except salinity are presented as depth-averaged estimates, because of better calibration with water quality instruments, recording near the surface. Due to the substantial density differences between fresh and salt water, modelled salinity was shown for the lower 3 m of the water column, which was most likely to interact with corals.

Comparisons have been made among each of the four rainfall scenarios (2013, 2011, 1:10 ARI, and median summer maxima), and among catchment land-use scenarios that include the present day, pre-clearing and future development, using the 2013 event for consistency. Details for the choice of presentation and depth averaging method are shown in Table 4-1.

Difference charts are presented using the 2013 flood event, simulated over the pre-clearing catchment, the present case, and the future catchment. They are displayed with the present case minus the pre-clearing scenario, and as the future scenario minus present case, to show the change that has been reached or will be reached, respectively.

Table 4-1 Exceedance Plots and Depth Averaging Methods

Parameter	Depth Averaging Method	Percentile
Deposition Rate	N/A	95th, 50th
Salinity	Bottom 3 metres	Minimum, 5th
TSS	Depth averaged over the entire water column	95th,50th
TN	Depth averaged over the entire water column	50th
TP	Depth averaged over the entire water column	50th

Detailed catchment and hydrodynamic modelling methodologies are available in Appendices B and C, respectively.

4.2 Results and Discussion

The 2011 and 2013 flood events were very different in nature, with the 2011 event being more prolonged and less intense than the 2013 event which was shorter in duration and much greater in magnitude. The 2011 highest 24hr total rainfall was only a 1:2 year ARI, with the bulk of the rainfall falling gradually, outside the 24hr measurement period, while the 2013 event had 24hr totals approaching a 1:100 year event (see Appendix B). These differences are most obvious in the higher spectrum of percentile plots (95th and 100th percentile), which display the most acute impacts over shorter time frames. The 100th percentile plot is equivalent to a duration of 15 minutes, the 95th percentile exceedance is equivalent to about 1.5 days, the 90th percentile is 3 days, while the median (50th percentile) shows a 15 day duration.

4.2.1 Salinity

Differences in the 95th percentile exceedance plots show that the 2013 event had a much more significant effect on salinity within Port Curtis than any of the other present day scenarios (the 2011 event, the 1:10 ARI, or the median summer maxima) (Figure 4-1). The 2013 model (lower 3 m of the water column) shows significant bodies of freshwater developed west of Facing Island with plume of water salinity well below 20 ppt extending into Rodds Bay and over Seal Rocks reefs. Salinities of approximately 15 ppt or less were experienced for three days in the cluster of reefs around North Entrance, while Bushy Island and Manning Reef experienced salinities less than 10 ppt. Time series data (Vision Environment) at water quality instrument B7, located between Bushy Island and Manning reef, shows that surface salinities fell below 5 ppt at the peak of the 2013 event and fell below 20 practical salinity units (PSU) (PSU ≈ ppt) for at least a week (Figure 4-2, see Appendix C for further details).

Berkelmans *et al.* (2012) have suggested a salinity dose-time threshold for acroporid corals, based on observed responses to the Fitzroy River 2010-2011 flood plume and its effects on reefs in the Keppel group. While coral salinity thresholds will likely vary according to species and local conditions (Berkelmans *et al.* 2012, Coles 1992), the Keppel reefs are the nearest significant inshore coral community to Port Curtis. Berkelmans *et al.* (2012) suggest that inshore acroporids (among the more sensitive coral genera to osmotic stress) have a dose-time linear threshold of 22 PSU for three days grading to 28 PSU over 16 days.

The calibration plot in Figure 4-2 shows that the model tended to under-estimate the reduction in salinity after the peak flow by about 5 PSU. Given this slight under-prediction, the 5th percentile (1.5 day) salinity plots were used to show areas of likely impact based on Berkelmans *et al.* (2012) thresholds. These plots show that the 2013 flood event was likely to have caused significant mortality at Bushy Island, Manning Reef, Gatcombe head, Seal Rocks and the cluster of reefs inside North Passage. These patterns in salinity are consistent with the observed changes in coral cover between 2009/2012 and 2014 (see Section 3.2.2).

All other rainfall scenarios were not likely to have resulted in salinity impacts (direct mortality), based on the Berkelmans *et al.* (2012) thresholds, and modelled 5th percentile (Figure 4-1) and minimum salinity plots (see Appendix D).

Comparisons between the pre-clearing and future case scenarios show that clearing in the catchment for an event such as the 2013 flood would have resulted in reduced salinity at some locations, particularly around Manning Reef and Bushy Island, and south of Gatcombe Head (Figure 4-3). In other words, major events such as the 2013 flood event now result in more freshwater entering Port Curtis, more quickly, due to vegetation clearing.

The extent of this change has been difficult to quantify in the Calliope Basin because there is so little forested catchment remaining. Without real runoff data (from forests that no longer exist), reconstructing the land's ability to shed or retain water has been difficult and is under continued examination by BMT WBM (see Appendix B).

By contrast, the difference between the present land use and the future land use was much less pronounced (Figure 4-3). The smaller magnitude of difference is due to the smaller area of change in catchment between the present and the hypothetical future scenario compared to the past vs present comparison. Future reductions in salinity would be expected to occur primarily west of Facing Island, with very little change east of Facing Island.

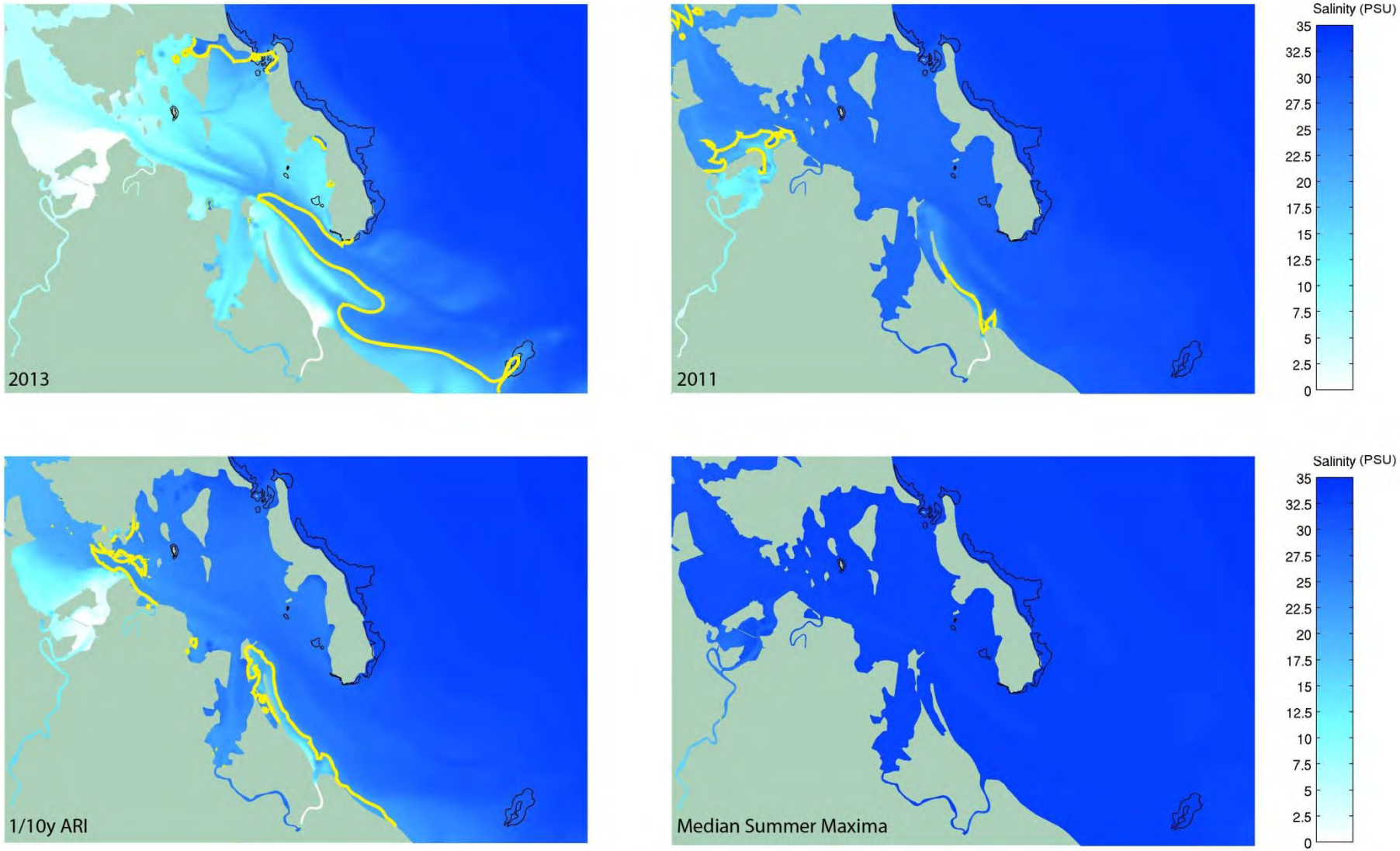


Figure 4-1 5th percentile salinity under various rainfall scenarios; a yellow line shows where salinity was < 22 PSU for 1.5 days

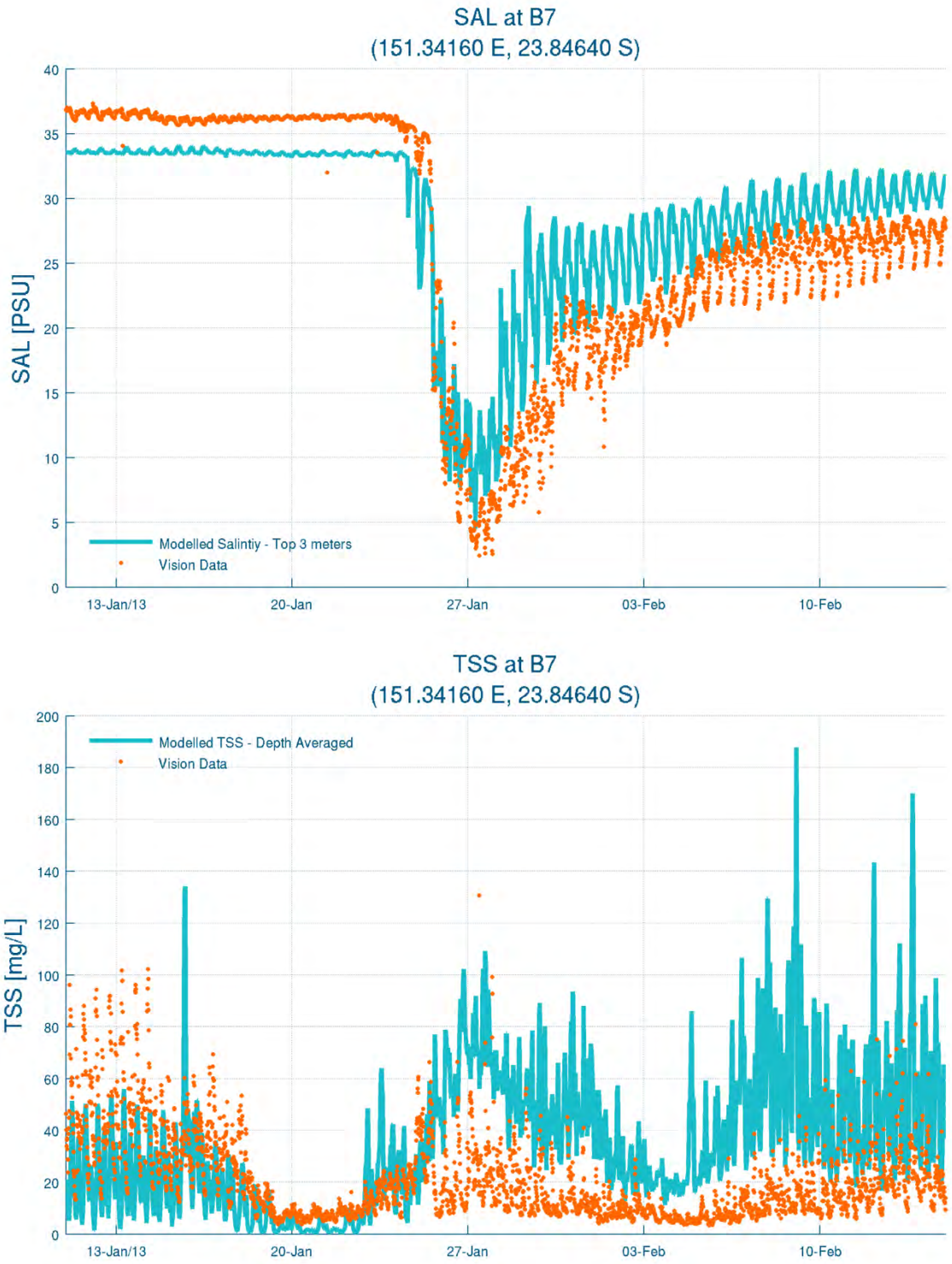
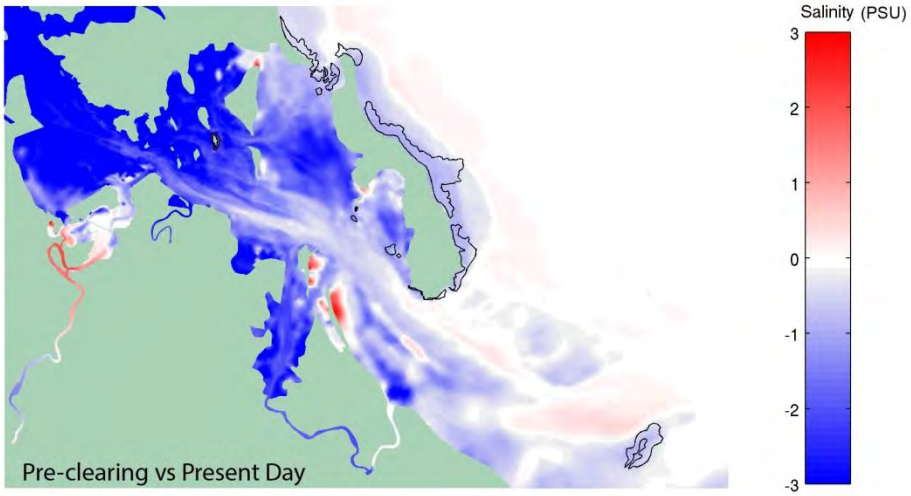
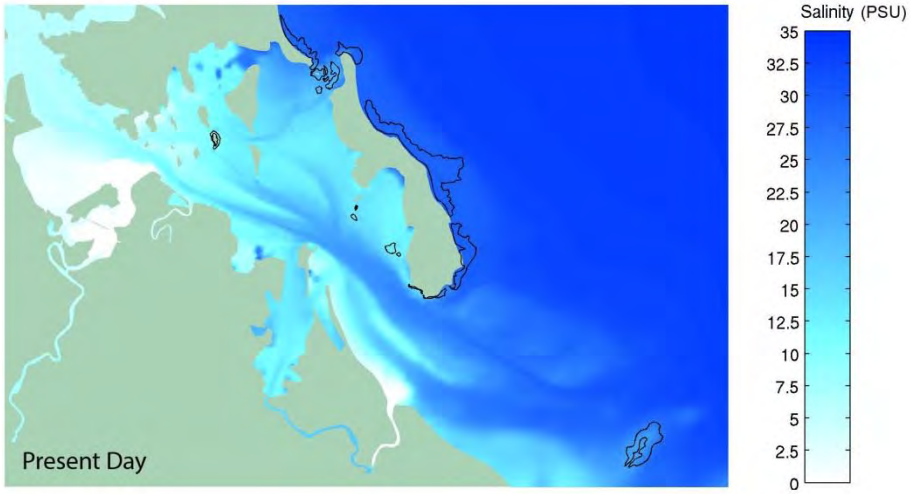


Figure 4-2 TSS and Salinity Calibration at Site B7

This plot shows differences in salinity between the pre-clearing catchment and the present day catchment for a flood similar to the 2013 event. Large dark blue areas show that the present catchment allows much more fresh water to be delivered rapidly to Port Curtis. Small red areas show where the present catchment would be more saline than the pre-clearing catchment.



This plot shows modelled salinity for the 2013 flood event. Dark blue areas indicate seawater (35 psu) and white areas depict completely fresh water (0 psu).



This plot shows differences in salinity between the present-day catchment and the future catchment for a flood similar to the 2013 event. Extensive light blue areas show that the future catchment allows slightly more fresh water to be delivered to parts of Port Curtis, particularly the western and central port.

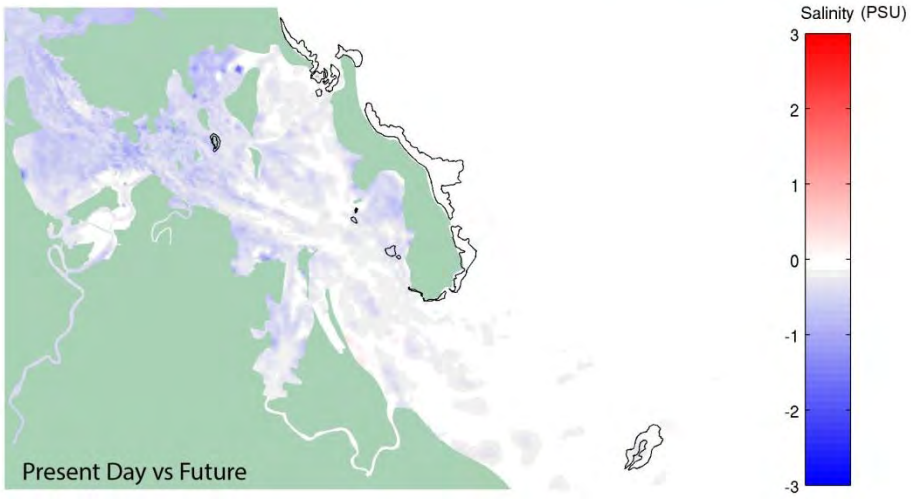


Figure 4-3 Plots showing modelled 5th percentile salinity from the 2013 flood event: differences between the past (pre-clearing) and present catchment (top); the present catchment in the 2013 flood (middle); and differences between present catchment and the future catchment (bottom)

4.2.2 Total Suspended Solids (TSS)

The effect of a particular TSS concentration on coral varies considerably depending on the intensity and duration of the exposure, and the level of naturally occurring TSS stress in that environment (Erftemejer *et al.,* 2012). For example, inshore corals subject to frequent and intense turbidity plumes from wind driven and tidal re-suspension occasionally experience TSS concentrations of >220 mg/L (Anthony and Larcombe 2000), while corals from clear offshore waters can experience impacts in concentrations as low as 10 mg/L (Rogers 1990). The GBRMPA Erftemejer *et al.,* (2012) suggest that rates of deposition may be more important than suspended concentrations in high TSS environments.

Again the 2013 flood event showed much higher predicted TSS concentrations than any of the other modelled scenarios. During the 2011 event at the water quality instrument B7, TSS concentrations were occasionally recorded above 100 mg/L (Figure 4-2) whereas modelled TSS concentrations in the 2013 event exceeded 200 mg/L at Bushy Island and some of the reefs surrounding North Entrance in the 95th percentile exceedance plot (Figure 4-2).

Ambient TSS in Port Curtis can be relatively high during tidal resuspension events that occur during spring tidal cycles. For example, the B7 water quality instrument recorded TSS of over 100 mg/L prior to the 2013 event (Figure 4-2). This suggests that TSS thresholds for corals within Facing Island may be quite high, however; considering the lack of certainty regarding exact TSS thresholds for mortality from the literature (Erftemejer *et al.,* 2012), it is difficult to understand the exact nature of TSS impacts from the 2011 and 2013 events.

From a qualitative perspective, communities at North Point Reef still had reasonably high coral cover, despite experiencing rather significant TSS concentrations (above 200 mg/L) during the 2013 event. Because salinity impacts from the 2013 event were also not expected at North Point Reef, it is likey that hypo-osmotic stress, rather than TSS was more influential during this event. In other words, reefs that had substantial coral cover (above 10% cover) were always located outside of the zone of low salinity (22 PSU) but occasionally located inside predicted areas of high TSS.

Changes in the catchment show that vegetation clearing to present has had an enormous impact on the concentration of TSS entering Port Curtis during major events such as the 2013 flood (Figure 4-5). While these changes have been most pronounced west of Facing Island and in Rodds Bay, they have also resulted in significant (~20 mg/L) changes at the reefs along the eastern shores of Facing Island. Changes to the catchment in the future scenario would generally result in increased peak TSS loads of between 20-40 mg/L for an event such as the 2013 flood. The areas west of Facing Island and south of Gatcombe Head would see the greatest increases in TSS.

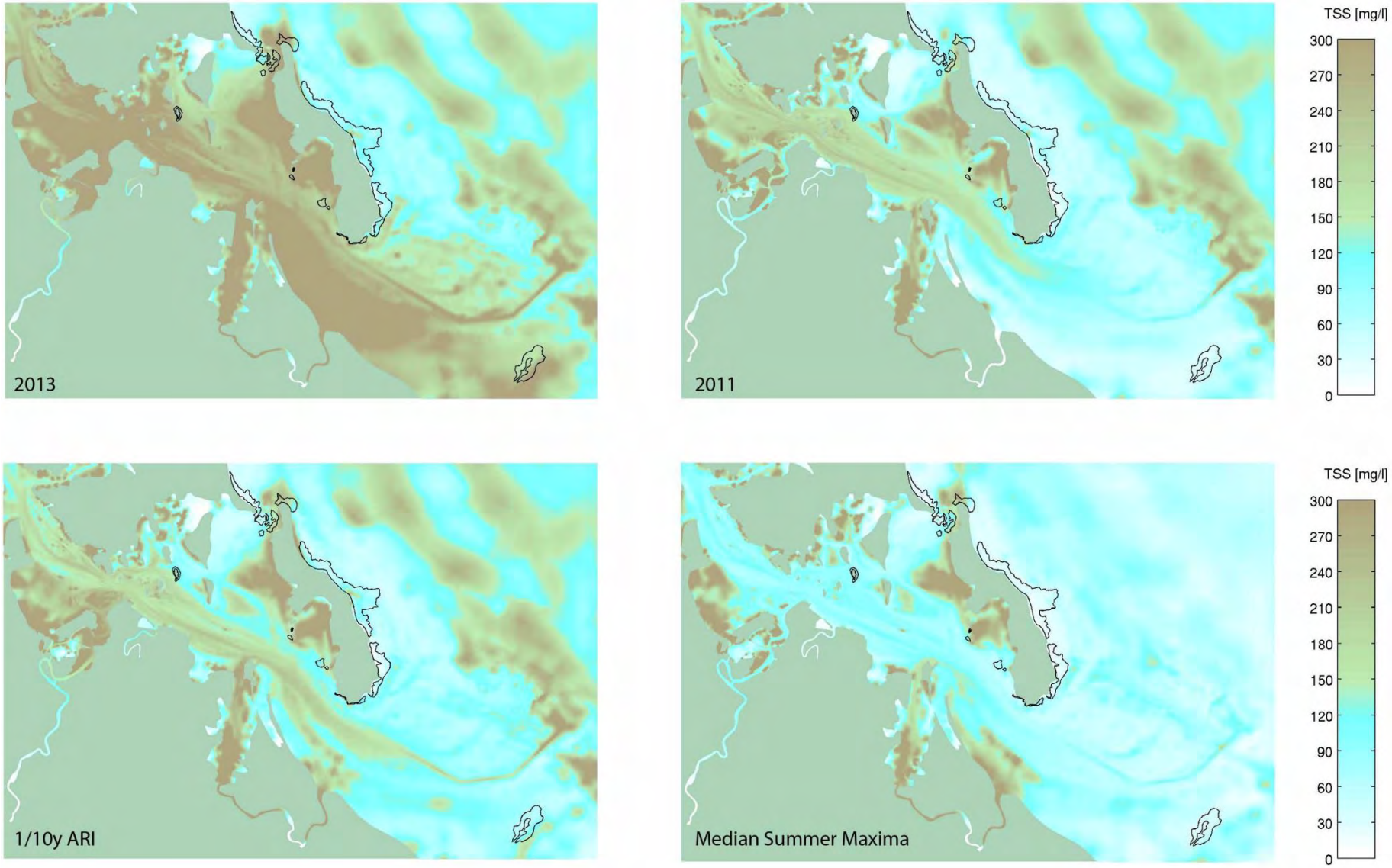
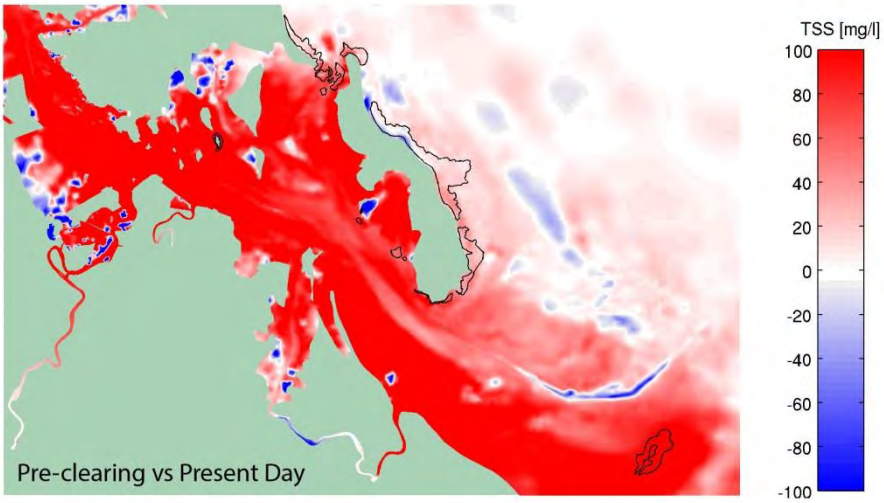
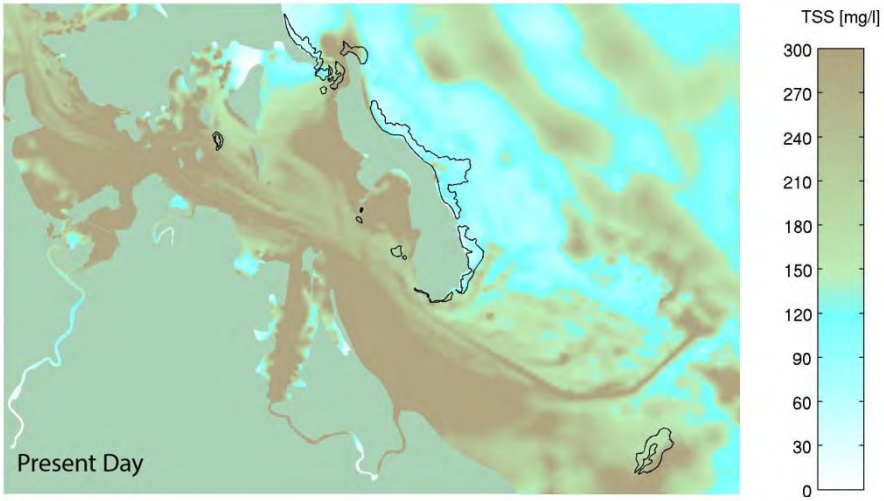


Figure 4-4 95th percentile TSS under various rainfall scenarios

This plot shows differences in TSS between the pre-clearing catchment and the present day catchment for a flood similar to the 2013 event. Large dark-red areas show that the present catchment allows much more TSS to be delivered rapidly to Port Curtis. Small blue areas show where the present catchment would have less TSS than the pre-clearing catchment.



This plot shows modelled TSS for the 2013 flood event. Brown areas indicate heavy TSS loads (300 mg/L) and white areas depict completely clear water (0 mg/L).



This plot shows differences in TSS between the present-day and future catchments for a flood similar to the 2013 event. Extensive light-red areas show that the future catchment will result in slightly more TSS to be delivered to Port Curtis. Small blue areas show where the future catchment would have less TSS than the present day catchment.

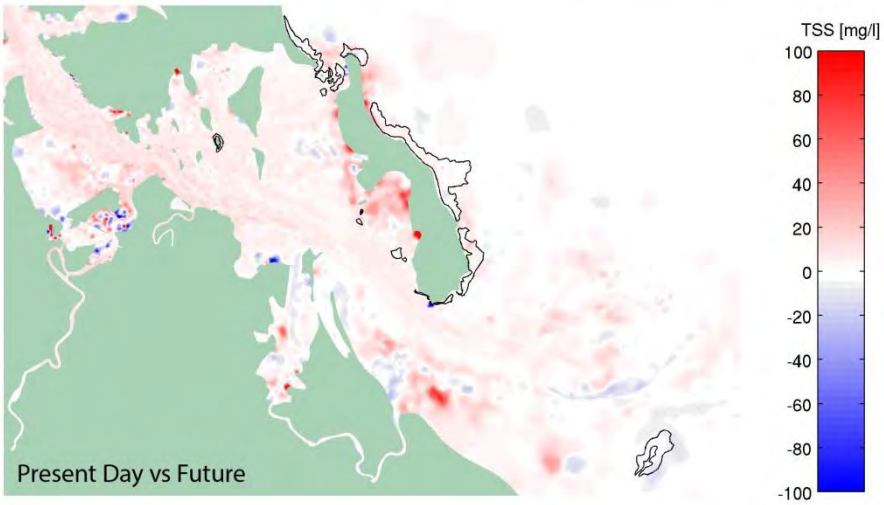


Figure 4-5 Plots showing modelled 5th percentile TSS from the 2013 flood event: differences between the past (pre-clearing) and present catchment (top); the present catchment in the 2013 flood (middle); and differences between present catchment and the future catchment (bottom)

4.2.3 Deposition

Similar to TSS, the effects of sediment deposition on corals depend largely on the species involved, the regularity and intensity of the sedimentation regime in the existing environment, and the duration of the sedimentation impact (Erftemejer *et al.,* 2012). Published thresholds for daily sedimentation rates vary from 10 to 300 mg/cm^2/ d (Rogers, 1990; Bak and Elgershuizen 1976). De'ath and Fabricius (2008) suggest that an annual daily average of 3 mg/cm^2/ d is required for the health of coral recruits, while the daily maximum is closer to 15 mg/cm^2/ d.

Rates of sedimentation (95th percentile) for the 2013 event show that most reefs were likely to experience rates of sedimentation less than 50 mg/cm^2/ d, and in many cases, peak deposition rates would be less than 10 mg/cm^2/ d (Figure 4-6). Despite relatively high TSS, there are relatively low deposition rates occurring due to the strong hydrodynamic forces throughout Port Curtis, preventing deposition. These estimated sedimentation rates are probably not high enough to elicit mortality on the scale observed between 2009/12 and 2014, and areas of high sedimentation do not necessarily correlate with observed community changes. For example, low rates of sedimentation in the 2013 simulation were predicted at Seal Rocks and the cluster of reefs surrounding North Entrance, yet substantial mortality was observed in both of these locations.

Changes in rates of deposition between the pre-clearing, present, and future scenarios were less than 1mg/cm^2/ d, and too small to be meaningfully considered.

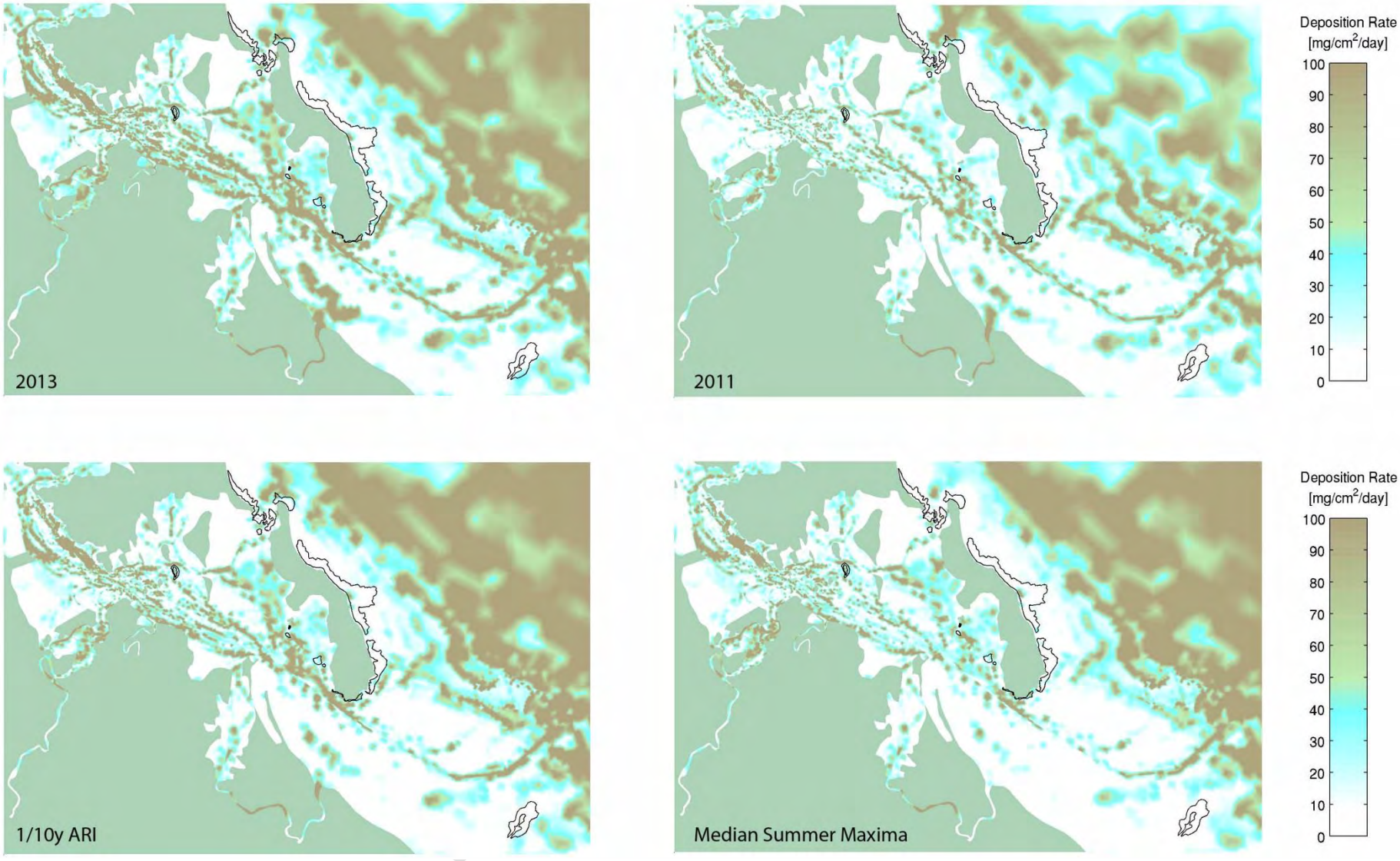


Figure 4-6 95th percentile deposition rate under various rainfall scenarios

4.2.4 Nutrients

Effects of nutrient enrichment on coral reefs tend to be chronic in nature rather than acute and generally do not result in direct mortality after short term pulses (Fabricius 2005; Koop *et al.* 2001). Long term nutrient enrichment experiments show that eutrophication can reduce calcification rates, tissue growth, fecundity, and tend to increase the photosynthesis and zooxanthellae densities (Fabricius 2005). As previously mentioned, high nutrient concentrations also support increased macroalgal growth which can compete with corals and reduce coral recruitment. This is particularly important for TN which is generally has a greater effect on macroalgal growth than TP (Larned 1998).

Figure 4-7 and Figure 4-8 show that the 2013 event contributed to very high concentrations of TP and TN in Port Curtis. These were much more extensive than any of the other events, with high concentrations of TN forming west of Facing Island. Central Port Curtis and the Fisherman's Landing areas experienced extremely high TN and TP concentrations relative to the median summer maxima where concentrations were generally ten-fold lower. The Calliope River can be seen contributing much greater nutrient loads under all rainfall scenarios than the Boyne River.

Spatial patterns in eutrophication during 2013 event flows associated with catchment clearing were similar for both TN and TP (Figure 4-9 and Figure 4-10), with the greatest change occurring between the pre-clearing catchment and the present. Future development scenarios suggested a greater relative increase in TN coming from the Calliope and influencing the western parts of Port Curtis. While some very slight increases in eutrophication would be expected east of Facing Island based on peak TN concentrations, no such changes were predicted for TP.

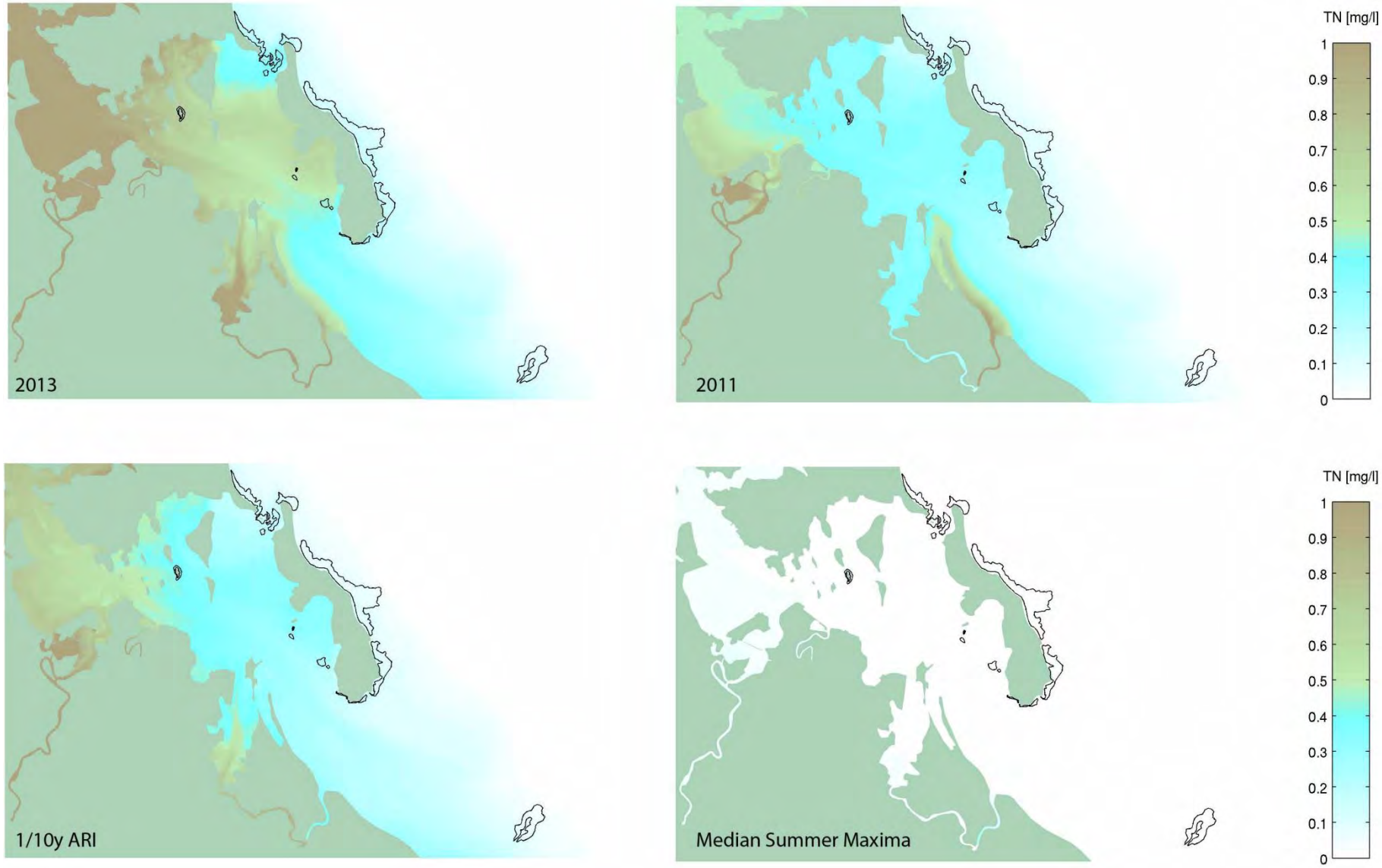


Figure 4-7 50th percentile TN under various rainfall scenarios

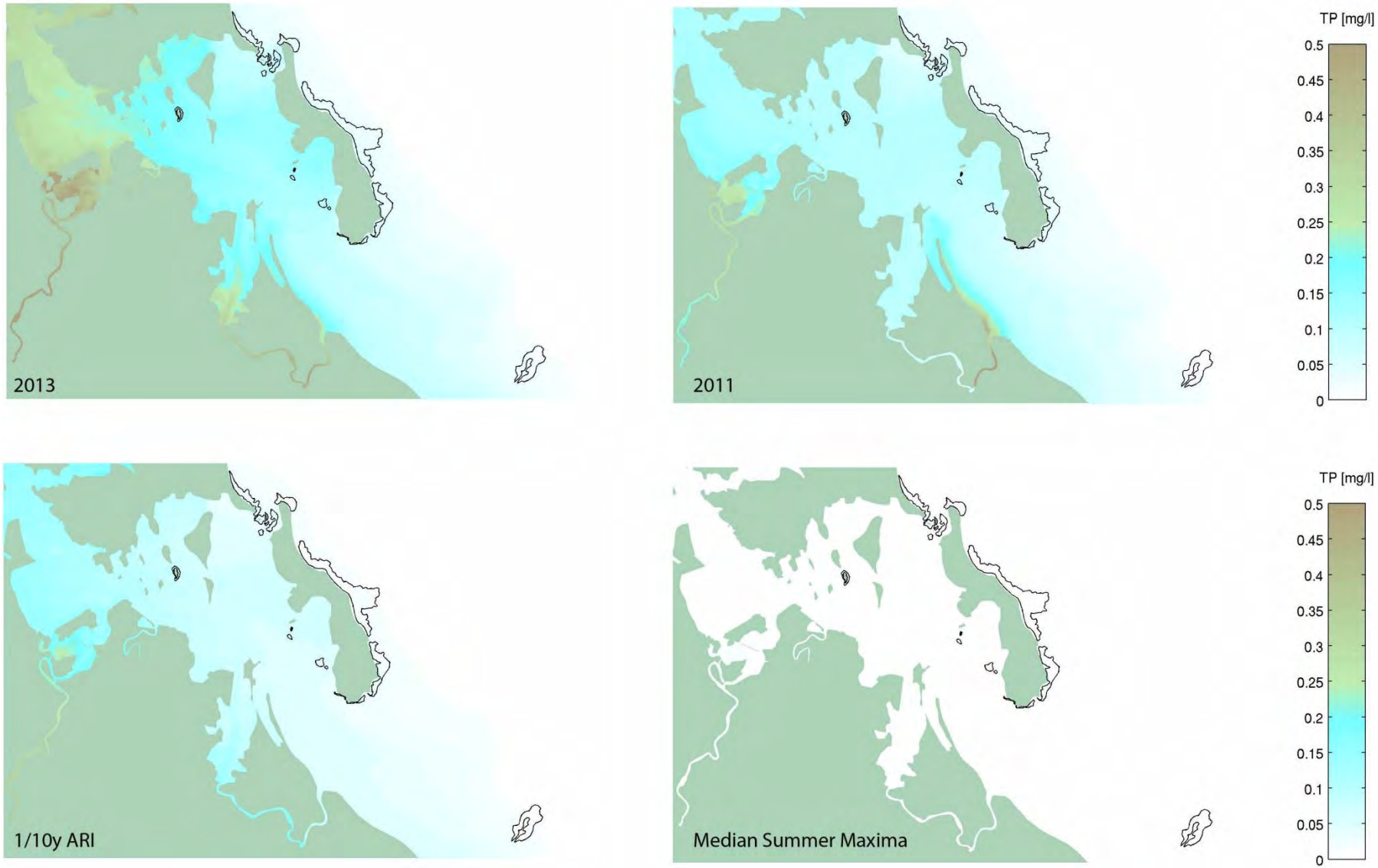
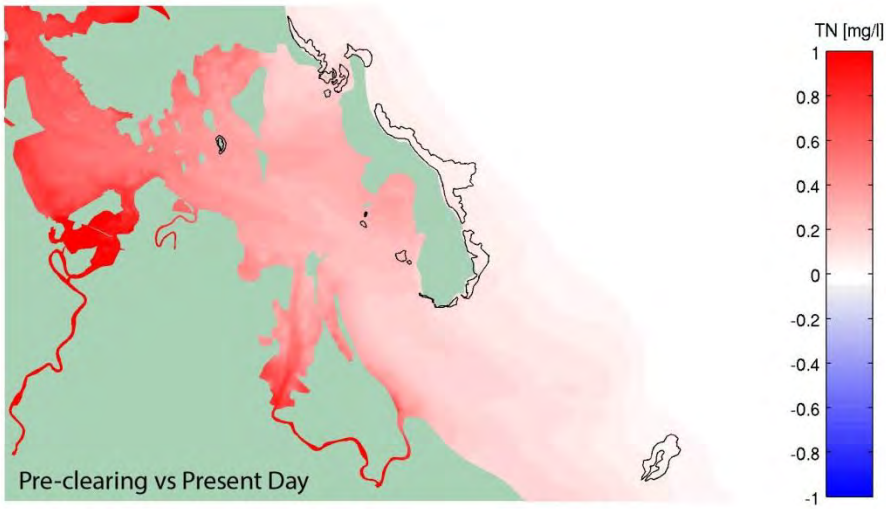
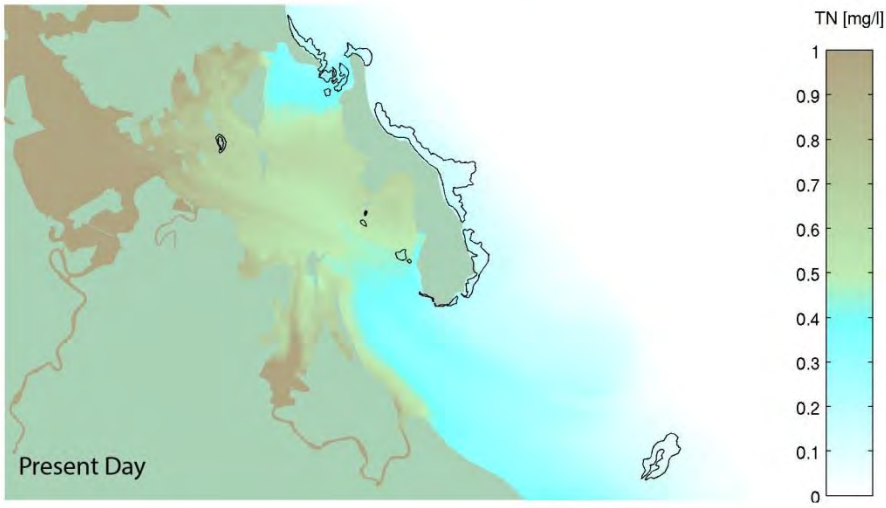


Figure 4-8 50th percentile TP under various rainfall scenarios

This plot shows differences in TN between the pre-clearing catchment and the present day catchment for a flood similar to the 2013 event. Large dark red areas show that the present catchment allows much more TN to be delivered rapidly to Port Curtis, particularly in the western parts of the harbour.



This plot shows modelled TN for the 2013 flood event. Dark brown areas indicate high TN concentrations (1 mg/L) and white areas depict low TN concentrations (0 mg/L).



This plot shows differences in TN between the present-day catchment and the future catchment for a flood similar to the 2013 event. Extensive light red areas show that the future catchment allows slightly more TN to be delivered to most of Port Curtis, with higher concentrations coming from the Calliope River.

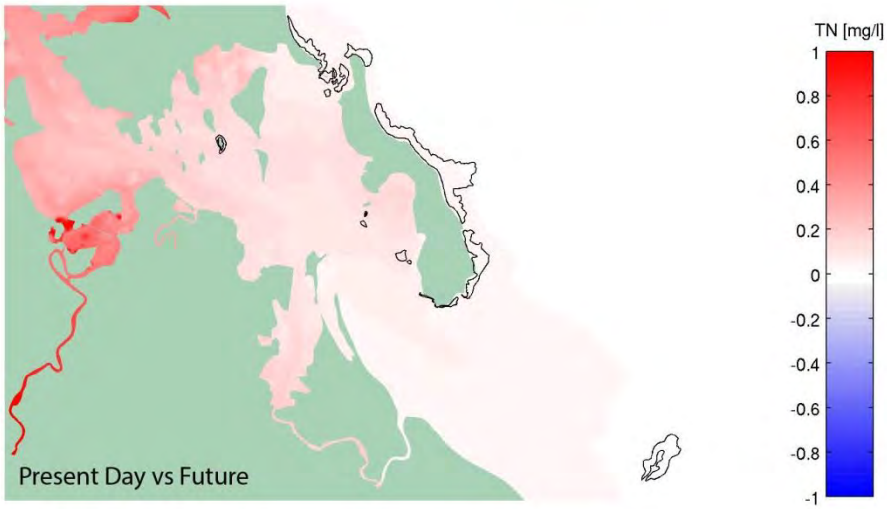
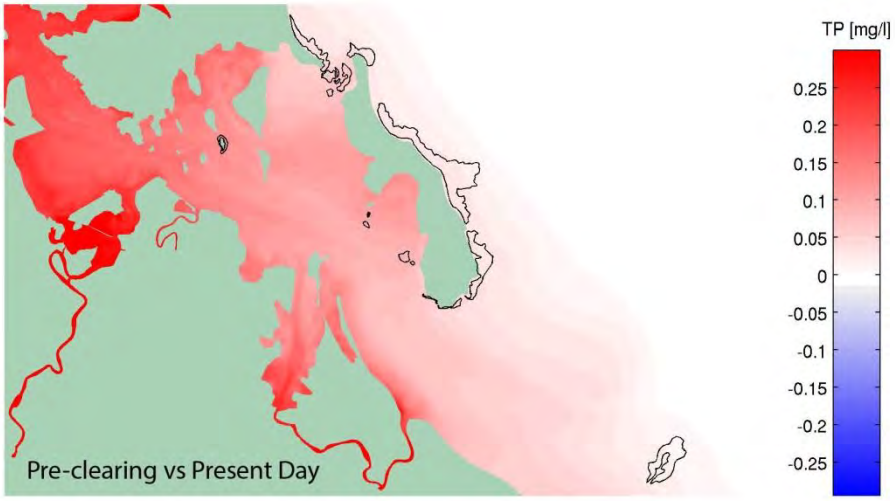
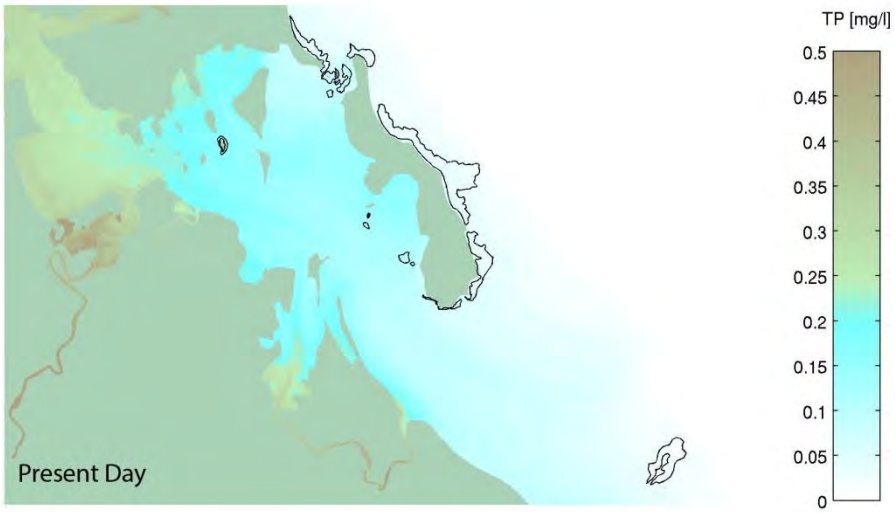


Figure 4-9 Plots showing modelled 50th percentile TN from the 2013 flood event: differences between the past (pre-clearing) and present catchment (top); the present catchment in the 2013 flood (middle); and differences between present catchment and the future catchment (bottom)

This plot shows differences in TP between the pre-clearing catchment and the present day catchment for a flood similar to the 2013 event. Large dark red areas show that the present catchment allows much more TP to be delivered rapidly to Port Curtis, particularly in the western parts of the harbour.



This plot shows modelled TP for the 2013 flood event. Dark brown areas indicate high TP concentrations (0.5 mg/L) and white areas depict low TP concentrations (0 mg/L).



This plot shows differences in TP between the present-day catchment and the future catchment for a flood similar to the 2013 event. Extensive light red areas show that the future catchment allows slightly more TP to be delivered to most of Port Curtis, with slightly higher concentrations coming from the Calliope River.

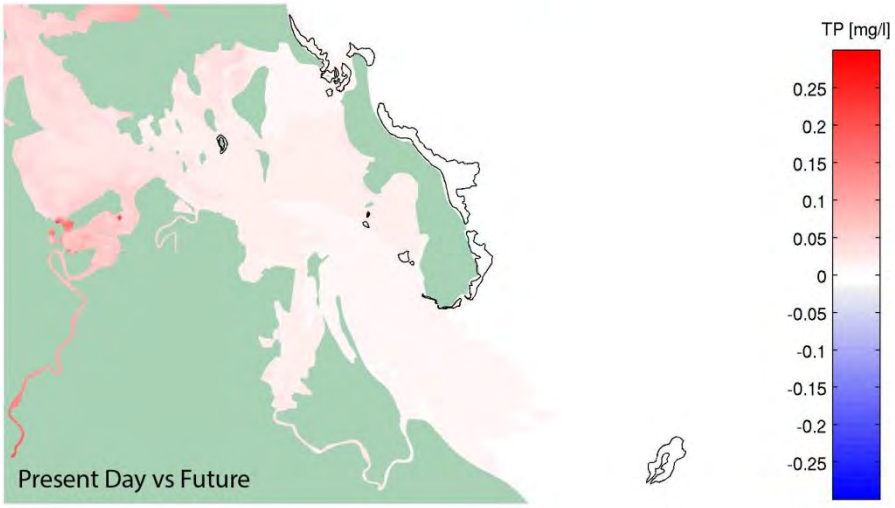


Figure 4-10 Plots showing modelled 50th percentile TP from the 2013 flood event: differences between the past (pre-clearing) and present catchment (top); the present catchment in the 2013 flood (middle); and differences between present catchment and the future catchment (bottom)

4.2.5 Modelling Conclusions

It should be noted that while thresholds for the impacts of TSS, nutrients, and sedimentation have been derived experimentally, these stressors rarely act in isolation in nature. Despite the challenges in applying derived thresholds to modelled plume outputs, there was a very strong agreement between predicted salinity impacts and observed impacts. While other flood-related impacts such as sedimentation, eutrophication, and TSS may have contributed to the observed impacts, it is likely that freshwater (hypo-osmotic) stress caused significant mortality to corals within the defined geographical salinity threshold.

The 2013 event was clearly much more significant than any of the other rainfall scenarios, in terms of rapid delivery of freshwater, nutrients and entrained sediment. While Port Curtis regularly experiences high TSS during spring tides and strong weather events, such extreme reductions in salinity are likely to be very rare and were probably very damaging to the reefs which they contacted.

Comparisons among past, present, and potential future catchment scenarios showed that the majority of catchment impact has already occurred. While future development will increase the severity of freshwater runoff, nutrients, and TSS, these changes are relatively insignificant. In terms of salinity impacts, future clearing will likely exacerbate the reductions in salinity occurring west of Facing Island. Future changes in TSS during large events will generally be more evenly spread, with the bulk of additional TSS impact likely to occur west of Facing Island and south of Gatcombe Head. Changes in deposition rate are likely to be negligible due to the intense hydrodynamic regime. Changes in eutrophication during peak flows will likely be stronger for TN than TP, with more low-range increases in TN occurring east of Facing Island.

5 Management Considerations for Direct Restoration

5.1 Scoping Issues Relevant to Coral Transplantation

Section 2.4.2 presents the steps that need to be considered whether evaluating coral transplantation is appropriate (Edwards and Fisk 1995). Each of the issues outlined in the decision tree shown in Figure 2-1 are considered based on the outcomes of the reef condition survey, hydrodynamic and catchment modelling, and findings of the Phase 1 report (BMT WBM 2014).

5.1.1 Reef Stressors

There are three key questions (as per Figure 2-1) that are relevant here:

- 1.1.1 - Did the site support a coral community prior to disturbance?
- 1.1.2 - What caused the degradation?
- 1.1.3 - Have the causes of degradation stopped?

Table 5-1 is a summary of the biological characteristics of BOS study area reefs. In this table, reefs are classified into one of four reef types based on hard coral cover, temporal patterns in coral cover between 2009 and 2014 and likely key stressors/processes controlling reefal benthic community structure. These reef types were:

- Area 1 - Turbid fringing reefs within the western sections of Port Curtis (e.g. Turtle Island Reef)
- Area 2 - Reefs within North Passage and along the western margin of Facing Island to Gatcombe Head (e.g. Rat Reef, Farmers Reef, Facing Island Reef #2, Bushy Island, Manning Reef, Gatcombe Head Reef)
- Area 3 - Reefs along the eastern margin of Facing Island (e.g. North Point Reef, Pearl Ledge, Sable Chief Rocks Reef, Facing Island Reef #4, East Point Ledge)
- Area 4 - Reefs within southern Port Curtis and Rodds Bay (Seal Rocks Reef.

Consistent with BMT WBM (2009a), the turbid nearshore reefs within Area 1 had low to no living hard coral cover, except for the occasional small *Turbinaria* (<5 cm diameter) colony. These reefs are not considered to support coral communities, and therefore, do not represent candidate restoration sites. The other three reef areas (areas 2-4) have supported hard coral communities between 2009 and 2014.

The findings of reef surveys presented in Section 3.3 demonstrate that reefs within Area 2 (North Passage, western Facing Island) and Area 4 (southern Port Curtis) were in poor condition, and have experienced a major decline in living hard coral cover since 2009. By contrast, the reef communities along the eastern margin of Facing Island (Area 3) did not show major changes over time, with hard coral cover similar between 2011 (Sea Research 2012) and 2014 (present study).

Table 5-1 Reef types and their environmental characteristics

Reef Type	Sites	Benthic community characteristics	Stressors/drivers	Management regime
1. Port Curtis turbid fringing reefs	Reefs west of Quoin Island, Turtle Is, T	• <0.5% hard coral cover • Low macroalgae cover • High levels of fine sediments in the water column and on reef substrates	• Chronic elevated ambient TSS levels • Strongly influenced by pulsed floodwater events and freshwater • Limited influence from large waves	• Outside GBRMP • Within GBRWHA
2. North Passage & western Facing Island reefs	Farmers Reef, Rat Is., Bushy Is., Manning Reef, Gatcombe Head, Oyster Rock	• Cyclic changes in hard coral and macroalgae cover in time in response to disturbance • Mod-high living hard coral cover (10-50%) 2009, <5% living coral cover in 2014 • Boulder coral colony size typically <0.1 m diameter, possibly indicates periodic storm/flood disturbance • High macroalgae and turfing algae cover, particularly in 2014	• Ambient TSS levels low c.f. within Port Curtis due to oceanic influence • Influenced by major episodic flooding events, which can lead to complete loss of coral cover, less affected by decadal disturbances • Popular recreational fishing area • Adjacent channel receives high levels of high speed vessel traffic	• Outside GBRMP • Within GBRWHA
3. Eastern Facing Island reefs	North Point, Pearl Ledge, East Point etc.	• Little change in hard coral and macroalgae cover between 2012 and 2014 • High macroalgae and turfing algae cover in places	• Ambient TSS levels low within Port Curtis due to oceanic influence • Limited influence of flooding events, but exposed to large waves during storm events and cyclones • Popular recreational fishing area • Adjacent channel receives high levels of high speed vessel traffic	• Within GBRMP (Habitat Protection Zone) • Within GBRWHA
4. Southern coastal reefs	Reefs east of East Banks inc. Curtis Rock, Seal Rocks	• Insufficient information to assess temporal patterns in hard coral and macroalgae cover • High macroalgae and turfing algae cover in 2014 • Low living coral cover in 2014 (<5%) • Massive coral colony size up to 0.5 m diameter, possibly indicates infrequent disturbance	• Ambient TSS levels low c.f. within Port Curtis due to oceanic influence • Influenced by major episodic flooding events, but complete loss of coral cover not observed in 2014 • Popular recreational fishing area • Navigation channel >0.5 km from nearest reef	• Within GBRMP (Habitat Protection Zone) • Within GBRWHA

As discussed in section 3.3, no other studies have examined in detail the factors controlling reef communities in the BOS study area, nor the relative degree of influence of processes causing degradation.

Based on integrated catchment and hydrodynamic modelling, it appears that the 2013 flood event had the potential to cause a significant decline in coral cover in Areas 2 and 4, and a flood event of that magnitude has an annual recurrence interval of ~100 years. Thus, reefs within Area 2 and a lesser extent Area 4 are only influenced by riverine discharges during large flood events, but this will continue to occur in the future and likely worsen as clearing in the catchment continues, with impacts potentially compounded by the effects of climate change. The reefs along the eastern margin of Facing Island (Area 3) are less affected by flood plumes, but are more exposed to wave action (especially compared to those west of Facing Island), and showed no sign of substantial degradation.

Based on the decision tree in Figure 2-1, coral transplantation and other active restoration measures could be expected to fail in Area 2 if an event of large magnitude (such as the 2013 flood event) were to occur again, unless flooding related changes to salinity and other climatic disturbances were removed or significantly constrained. However, the 1:10 ARI event would not likely result in major plume-related impacts. Although the 2013 event was extreme and rare from a statistical perspective, there is no certainty that past recurrence intervals will continue into the future. With this in mind, areas suitable for transplantation include reefs within Port Curtis (Area 2) and Area 4 (southern Port Curtis/Rodd's Bay). Other management actions to improve coral health and resilience should also be considered for these (and other) areas (see Section 6.1).

Although Seal Rocks Reef in Area 4 appeared to have been affected by recent floods, it also possessed several large *Porites* colonies (50 cm to 2 m, some living while others were recently dead), suggesting that the time between major disturbance events had been long enough (multiple decades) for these to grow. There was also some living *Acropora* at Seal Rocks Reef, compared to those in Area 2 where *Acropora* was completely destroyed. More living coral observed along the eastern edge of Seal Rocks Reef is consistent with the wake effect (Wolanski *et al*. 1996) also reported in the Keppel Islands (Berkelmans *et al*. 2012). These observations, and the modelled salinity threshold of Berkelmans *et al.* (2012) suggests that Seal Rocks Reef is located near the boundary of acute plume impacts from major events such as the 2013 floods. Further away from this boundary, there is less chance that reefs are degraded, and further inside this boundary, the more chances there are of reoccurring disturbance.

5.1.2 Recruitment Limitation

The next question in the decision tree (Figure 2-1) is whether the site is recruitment limited (Question 1.1.4). This is critical consideration in the context of:

- Determining the need for active restoration measures. If rates of coral recruitment are high then natural processes will be far more effective in re-establishing coral communities than any active restoration measures (which are typically small-scale).

- The effectiveness of other management methods to enhance coral assemblages and their resilience. In particular, the installation of artificial reefs to create new coral habitat will only be effective if there is a supply of coral recruits for colonisation.

The loss of coral cover from Port Curtis represents a reduction in the local supply of coral recruits. Based on incidental field observations during the 2014 survey, few coral recruits were observed at reefs in Area 2 (Port Curtis) and 4 (southern area), and at Area 3 there was a range of coral size classes. The lack of recruits at Areas 2 and 4 could reflect a number of factors, such as coral propagule limitation, lack of suitable substrate for coral settlement (i.e. due to dense turfing and macroalgae cover) or biological processes and interactions (e.g. grazing).

As recruitment supply underpins any decision regarding undertaking coral transplantation or reef habitat creation (artificial reefs), further investigations are required to address this issue. Recommendations are provided in Section 6 in this regard.

5.1.3 Substrate Stability

The final question in the decision tree relates to whether physical restoration of reef is required to stabilise the substrate. This is relevant where that has been physical disturbance to reef structure, e.g. wave damage, shipping grounding, dynamite fishing etc.

Physical disturbance to reef substrate is not the key cause of coral loss in the context of reefs in the BOS study area. This question is therefore not relevant here.

5.2 Scoping Issues Relevant to Artificial Reef Site Selection

Barber *et al.* (2009) defined criteria for selecting artificial reef site, based on a review of case-studies world-wide. These criteria are listed in Table 5-2.

Table 5-2 Criteria used for selecting sites for artificial reef placement (modified after Barber *et al*. 2009)

Criterion	Description
Accessibility	Area needs to be suitable for safe small boat operation and recreational use of the reef, (if access is a key consideration) and in a location that does not interfere with commercial vessel traffic.
Current	Areas with strong tidal currents avoided to prevent scouring and to allow SCUBA monitoring of the reef.
Water depth	Required water depths shallow enough for hard coral development. Study area reefs support hard coral to a maximum depth of 5 m, but high diversity epibenthic communities can occur in deeper waters.
Wave exposure	Sheltered areas preferred to minimise potential for physical disturbance. See also water depth.
Established habitat and/or proximity to established habitat	Existing natural reefs should be avoided to minimize further impacts to hard-bottom habitat. Areas nearby to natural reefs preferred to aid connectivity.
Substrate	Substrate consisting of firm sediment types that provided a stable platform preferred. Soft, muddy sediments, silt, and shifting fine sand should be avoided to minimize reef sinking.
Slope	Sites with slopes over 5° should not be considered to ensure reef stability.

Criterion	Description
Water quality	Water around the potential sites needed to have low turbidity and low siltation rates. Adequate light penetration was necessary to establish primary productivity.
User conflicts	Consideration should be given to potential conflicts with other user groups, including commercial and recreational fishers.

Many of the scoping issues relating to coral transplantation (Section 5.1) are relevant to the installation of artificial reefs and associated site selection (Table 5-2). These issues include:

- Are key stressors (water quality, physical disturbance) present, and are they likely to interfere with the development of robust and resilient coral assemblages?
- Are areas recruitment limited?
- Is the substrate stable?

In the context of substrate stability, the issue is related to geotechnical stability of the substrate and its capacity to support artificial reef structures. The installation of artificial reef structures in areas containing mobile sands, wave exposed areas and areas with a high slope should be avoided to minimise the risk of burial or over-turning of the structure, or physical damage to the structure and its communities.

Water depth is also a key consideration from a range of perspectives, as follows:

- Control of benthic community structure on reefs - autotrophic hard corals and algae are restricted to shallow waters. These species in turn influence the distribution on other fauna species through competition. Green turtles could potentially benefit from installation of shallow water reefs containing macroalgae food resources, whereas other turtle species known from the area consume a range of sessile invertebrates including sponges, soft corals, ascidians etc. (depending on species; see BMT WBM 2014). While enhancement of hard corals is preferred in terms of enhancing general biodiversity values, it is not necessarily a key requirement in terms of supporting turtle species.
- Wave exposure – wave energy decreases with increasing water depth. Moderately shallow areas (<5-10 m) are likely to be affected by wave disturbance during large storm events (particularly in open waters outside Port Curtis), whereas waters <5 m at exposed sites will be regularly affected by wave action.
- Accessibility by SCUBA divers – it is desirable (but not essential) to locate reefs in shallow waters to maximise bottom times for SCUBA divers undertaking installation or monitoring.

In terms of substrate type, it is not desirable to locate artificial reefs on natural reefs, nor should reefs be located in areas containing mobile sands that could bury the reef structure (see also above). However it may be desirable to locate artificial reefs near (~500 m to 1 km) natural reefs for the following reasons:

- Potentially promoting connectivity (fish, turtles, corals and invertebrates) by providing hard substrates between reef systems.

- Sourcing of recruits from natural reef systems. While this is desirable in terms of establishing a benthic community on the artificial reef, it could result in uncertain outcomes for natural reef systems. This is particularly important for recruitment limited populations, such as most reef fish species, which may lead to a reduction in productivity on natural reefs (see Section 2.2).
- Proxy indicator for long-term water quality conditions. If water quality conditions allow the maintenance of diverse and abundant communities at a natural reef site, it is likely that this will also be the case at a neighbouring artificial reef site[4].

Accessibility is a key issue from an operational perspective (i.e. suitable for safe small boat operation during monitoring, installation), and potentially also in terms of promoting community awareness. Potential areas should also not interfere with commercial vessel traffic, and minimise impacts to other users.

One of the key risks of installing artificial reefs is that they will likely promote the aggregation of reef fishes, reducing the density of herbivores on existing reefs and making them more subject to fishing pressure. Herbivory by large fishes is very important in reducing algal competition with coral and promoting resilient reefs (Hughes *et al.* 2007). To support biodiversity values, any artificial reef structures deployed need to protect herbivorous fish through the exclusion of spearfishing and potentially line-fishing. While line-fishing generally does not result in the capture of herbivores, anchor damage to benthic invertebrates from small vessels can be significant.

5.3 Management Regime and Governance

The success or otherwise of active restoration measures is largely dependent on the underpinning management regime (Edwards and Fisk 1995). Edwards and Fisk (1995) argue that reefs outside management control (i.e. marine protected areas, sanctuaries etc.) are “almost certain doomed to fail”, and that active restoration should form just one component of a broader overarching coastal management plan which also manages the primary stressors.

While this is most certainly the case outside Australia, there are a range of statutory controls at the Commonwealth and State level which minimise the risk of activities resulting in direct impacts to reefs and their biota. This is particularly the case for coastal areas within the Great Barrier Reef World Heritage Area (GBRWHA), which along with threatened and migratory species are explicitly protected under the *Environment Protection Biodiversity Conservation Act 1999* (EPBC Act). The entire BOS study area is included within the GBRWHA, and offshore sections are also included in the Great Barrier Reef Marine Park (which is also protected under the EPBC Act).

One of the major issues facing indirect restoration relates to the jurisdiction of the waterways within Port Curtis. There is no recognised legal framework for zonation and enforcement within Port Controlled waters, so management actions such as fishing closures, no anchor zones, and go-slow zones cannot be achieved without changes to legislation.

Another consideration in terms of site selection may be environmental permit requirements. Consultation will need to be undertaken with GBRMPA to determine their views and permitting requirements. It is expected that such works would be incompatible with the management intent of the Marine National Park (green) zone. In terms of potential coral transplantation, recipient and

[4] Of course other controls (such as differences in substrates, depth, exposure etc.) may result in differences between neighbouring sites

donor sites (Seal Rocks Reef and the east coast of Facing Island, respectively) are located within the Habitat Protection Zone of the marine park. Artificial reef placement may be less constrained outside of the GBR Marine Park.

5.4 Assessment Criteria

The prioritisation of active (direct) restoration and enhancement sites and actions depends on the environmental characteristics of the site, as well a range of logistical and other issues described in the preceding sections. Table 5-3 below outlines the assessment criteria used to prioritise potential restoration/enhancement sites. Criteria are classified as follows:

- Absolute negative constraint – restoration works cannot be undertaken if this feature is present
- Absolute positive constraint – restoration works can only be undertaken if this feature is present
- Moderate (negative) constraint – this feature may represent a constraint, but there is insufficient information at this stage to determine the level of constraint
- Preferred but non-essential feature – such features would facilitate restoration efforts but are not considered essential.

Table 5-3 also identifies data sources and data quality used to assess each criterion. Data quality ratings are as follows:

- High – underpinning data are spatially accurate and current, and high spatial resolution
- Moderate – underpinning data are generally spatially accurate, but have low spatial resolution
- Low – while the data underpinning the criterion are robust, the assessment is based on qualitative interpretations.

Information gaps and recommended additional studies relating to each criterion are discussed in Section 6.

Table 5-3 Assessment criteria for coral transplant and artificial reef sites

Criteria	How Assessed	Source	Data Quality	Coral Transplants	Artificial Reefs
Outside BOS study area	• BOS mapping	GPC data	High		
Low coral cover (present day), but once supported reefs with moderate to high cover	• Present study	Section 4	High		N/A
Reef substrate present	• Reef habitat mapping	GBRMP Gazetteer Phase 2 mapping	Moderate (subtidal reefal areas >3-5 m poorly resolved at present)		
Water quality stress	• Presence of degraded reef with low coral cover (Area 1 and 2) • Areas influenced by flood plumes	Coral surveys Plume modelling	Moderate (based on interpretation)		
Slope >5°	• Data gap (bathymetry data are insufficient to assess high relief areas)	Not available	Not available		
Water depth – reef benthos	• Bathymetry data: Water depths <5 m (corals)	Navigation charts	Moderate (coarse spatial scale)		
	• Bathymetry data: Water depths 5-10 m (sessile non-photosynthetic biota)	Navigation charts			
Substrate stability & limited exposure to waves	• Qualitative assessment of shoreline configuration and incidental observations of bed form during field surveys	Shoreline mapping and field assessment	Low (based on qualitative interpretation)		
Navigation channel	• Within 200 m of navigation channel	Navigation charts	High		
Areas outside navigation channel but frequented by small craft	• Data gap (limited available data are insufficient to assess areas)	Not available	No available data		
GBRMP – green zones	• Marine Park boundaries	GBRMP Zoning map	High		

Absolute (negative) constraint – excluded if present
Absolute (positive) constraint – only included if present
Moderate (negative) constraint
Desirable but non-essential

6 Site Assessment and Recommendations

6.1 Coral Transplantation and Larval Rearing

The nearshore reefs of the BOS region experienced a significant decline in live coral cover in response to major flood events and therefore, represent potential candidate sites for direct restoration. Priority restoration sites are identified below on the assumption that natural recovery potential is poor due to recruitment limitation. Sites for active restoration are prioritised based on assessment criteria in Table 5-3.

6.1.1 Area 1 - Port Curtis Turbid Fringing Reefs

Area 1 does not presently (nor has it historically) supported hermatypic hard coral cover and is not suitable for coral transplantation or larval rearing. High ambient turbidity levels are likely to be a key process restricting coral development in this area.

This area does not meet the required criteria outlined in Table 5-3, and therefore, is not considered to represent candidate active restoration sites.

6.1.2 Area 2 - North Passage and Western Facing Island Reefs

Based on the criteria in Table 5-3 some of the reefs in Area 2 represent candidate sites for direct restoration. Surveys carried out in 2009 indicated that reefs in this area formerly supported high coral cover, indicating that ambient conditions here are suitable for coral community development. While there uncertainties regarding frequency of future events under climate change, modelling suggests that this area is infrequently affected by flood events (except major infrequent events such as the 2013 flood). On this basis, reefs in this area represent potential candidate site for active restoration.

Manning Reef meets the required criteria for active restoration set out in Table 5-3, and is considered a potential priority restoration site. This reef once supported the most abundant and rich coral communities west of Facing Island (BMT WBM 2009a), this would be considered a priority site for coral transplantation (Table 6-1; Figure 6-2). This site is shallow and contains a relatively large reef flat with easy access, which is desirable from an operational perspective (i.e. undertaking works and monitoring). Coral transplantation may be a suitable option at this site, should natural recovery be slow. The situation at Bushy Island (west of Manning Reef) was similar, except coral cover in 2009 was not as high, and the site is located farther inside Port Curtis.

Reefs within North Passage (particularly the Oaks and Rat Island) also supported high coral cover in 2009 (BMT WBM 2009a), but are not preferred from an operational perspective due to:

- Strong currents (constraining works to the top of the tide – visibility is a limitation at low tide)
- Shallow depth zone occupied by corals (approximately <2 m water depth)
- Significant vessel traffic and potential for conflict with other users
- This area does not meet the required criteria outlined in Table 5-3, and therefore, is not considered to represent candidate active restoration sites.

Reefs in North Passage do not meet the required criteria outlined in Table 5-3, and therefore are not considered to represent candidate active restoration sites.

6.1.3 Area 3 - Eastern Facing Island Reefs

Area 3 contains diverse and abundant reef communities, including extensive hard coral cover. There is no evidence of coral degradation and on this basis active coral restoration to natural reefs is not justified. Similar to Area 4, this area is relatively remote and exposed, creating logistical difficulties from a works perspective. Reefs in this area do not meet the required criteria outlined in Table 5-3, and therefore are not considered to represent candidate active restoration sites.

6.1.4 Area 4 - Southern Coastal Reefs

Parts of Area 4, specifically Seal Rocks Reef (southern Port Curtis/Rodds Bay) were within the zone of flood plume impact during 2013, but less so than reefs in Area 2. Although the community had been affected by the 2013 flood plumes, its composition and size of colonies at Seal Rocks Reef suggested that this was not likely to experience regular flooding impacts. Unlike some of the reefs in Area 2, living *Acropora* was observed suggesting that regeneration of damaged colonies was possible.

The Seal Rocks area has value as a turtle feeding habitat. The waters surrounding Seal Rocks reef support relatively large numbers of turtles (BMT WBM 2014), and it is possible that the reef provides a feeding habitat for green turtles as they transit between the extensive seagrass meadows at Rodds Bay and Pelican Banks.

On this basis, reefs within Area 4 (particularly Seal Rocks) have been identified as a potential coral transplantation site. Furthermore, should artificial reefs be installed in this area, coral transplantation could potentially be undertaken to expedite coral development. Seal Rocks meets all other criteria set out in Table 5-3, but it is relatively remote and exposed, creating logistical difficulties from an operational works perspective. However, its central location between Rodds Bay and Gladstone Harbour seagrass meadows, and between the reefs of Facing Island and Rodds Peninsula suggest that it is important from a habitat connectivity perspective.

6.2 Artificial Reefs

Similar to the case for coral transplantation, water quality stressors could constrain the development of coral assemblages on artificial reefs installed in Areas 1 and in parts of Area 2. The high turbidity in Area 1 prevents the establishment of diverse and abundant coral or macroalgae assemblages, and is not known to represent a key feeding area for reef-associated turtle species. For this reason, Area 1 is not considered an optimal site for installation of artificial reefs to support coral assemblages.

Given the modelled extent of various flood plumes, the placement of artificial reefs in Area 2 would be subject to impacts from events similar to the 2013 floods, but perhaps not for smaller magnitude events such as the 2011 or 1:10 ARI. Given that flood plumes probably rarely affect these reef systems (i.e. decadal temporal scales), then artificial reefs may be considered a potential option here. As outlined in Table 5-3, it is critical that artificial reefs be located adjacent to reefs that once (or continue) to support high coral cover. Unconsolidated sediment habitats between Manning

Reef and Bushy Island Reef are considered as potential priority sites in this regard. Unlike North Passage reefs, the waters immediately adjacent to Manning Reef are not known to represent a major thoroughfare for recreational vessels, potentially minimising the risk of user conflict here.

Areas 4 and 3 are less constrained than Areas 1 and 2 from a water quality perspective, but area 3 exists almost wholly within the GBR marine park, as does Seal Rocks Reef. Similar to the case for coral transplantation, both areas are relatively remote and exposed, creating logistical difficulties from a works perspective. Wave action during major storms and cyclones would also present significant challenges in terms of maintaining a stable reef structure. This is particularly the case for nearshore sections of Area 3, which represents a high energy environment and based on visual observations of bed-forms, appears to have highly unstable substrates. Further investigations into substrate stability would be required before Area 3 could be considered as a potential location for artificial reefs. Assuming substrates are stable, soft sediment nearshore habitats between North Point Reef and Pearl Ledge, and Facing Island Reef 4 and East Point Ledge could represent candidate artificial reefs sites.

Area 4 is slightly more sheltered from wave action than the reefs in Area 3, and is potentially less constrained from a substrate stability perspective. Bathymetric data presented in the Phase 1 (BMT WBM 2014; see also Figure 5-1) report shows areas where the target water depth of 4-10 m is present, and which may be suitable for artificial reef placement.

A critical issue that needs to be further considered is potential conflict with other users. As artificial reefs would need to be located in relatively shallow water to allow coral and macroalgae development, they would represent a navigation hazard if inappropriately sited. It is also important that reefs are not located in areas where they could: (i) be moved into navigation channels during storms; (ii) constrain commercial fishing activities (i.e. areas that are trawled or netted). Additionally, as mentioned in Section 5.2, the risks additional fishing pressure conflicting with the objectives of the BOS may be difficult to manage within Port Curtis. Further investigations and/or consultation would be required in this regard.

Table 6-1 Priority sites for restoration

Priority	Location	Potential sites	Restoration
Passive/ Indirect Restoration			
1	Calliope River	Catchment revegetation	Increasing riparian width generally throughout catchment, targeting erosive landforms and wetlands
2	Calliope River	Eroding banks along sections of Calliope River	Bank profiling and stabilisation and increasing riparian width
3	Boyne River	Catchment revegetation	Increasing riparian width generally throughout catchment targeting erosive landforms and wetlands
4	Boyne River	Awoonga Dam	Flow regulation in collaboration with GAWB to reduce severity of overtopping events
Active / Direct Restoration			
1	Area 4	Seal Rocks Reef	Coral transplantation at subtidal reef areas [1, 2]
		Unconsolidated sediment habitats in the vicinity of Seal Rocks Reef	Artificial reefs[3] at waters <10 m deep at least 500 m from natural reefs
2	Area 2	Manning Reef	Coral transplantation at subtidal reef areas [1, 2]
		Unconsolidated sediment habitats in the vicinity of Manning Reef	Artificial reefs[3] in unconsolidated sediment habitats adjacent to Manning Reef in <5 m water
3	Area 2	Bushy Island	Coral transplantation at subtidal reef areas [1, 2]
		Unconsolidated sediment habitats in the vicinity of Bushy Island	Artificial reefs[3] in unconsolidated sediment habitats adjacent to Manning Reef in <5 m water
4	Area 4	Seal Rocks Reef	Coral transplantation at subtidal reef areas [1, 2]
		Unconsolidated sediment habitats in the vicinity of Seal Rocks Reef	Artificial reefs[3] at waters <10 m deep at least 500 m from natural reefs
5	Area 3	Soft sediment between Facing Island Reef 4 and East Point Ledge	Artificial reefs in unconsolidated sediment habitats in all waters <10 m deep at least 500 m from natural reefs [3]
6	Area 3	Soft sediment habitats between North Point Reef and Pearl Ledge	Artificial reefs in unconsolidated sediment habitats in all waters <10 m deep at least 500 m from natural reefs [3]
7	Area 3	Natural reefs	-
8	Area 1	None	-

1 = could be undertaken at artificial reef sites; 2 = subject to further investigations (see below); 3 = subject to assessments of bed suitability/stability

6.3 Indirect Reef Restoration

6.3.1 Catchment Activities

Indirect restoration measures to reduce the delivery of catchment sediments and nutrient and fresh water have the potential to provide significant long-term benefit to inshore coral reef ecosystems. While outside the scope of the present study, initial advice is provided here regarding the benefits of indirect restoration measures.

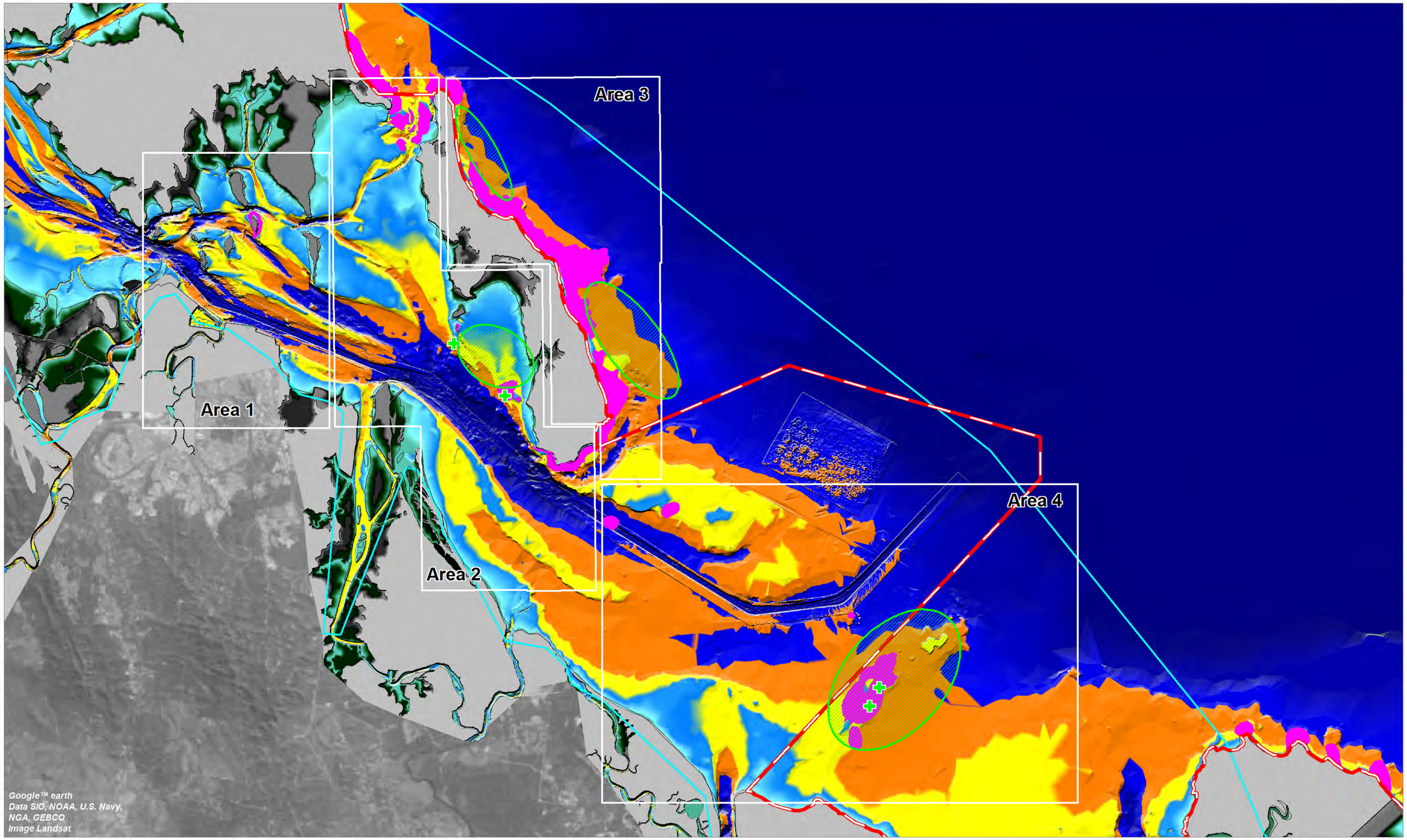
The Calliope catchment has been extensively cleared, and modelling results show that this has greatly increased pollutant loads and the rate of freshwater delivery into Port Curtis (see Figure 4-3 and Figure 4-5). There are extensive areas of bank erosion within the catchment (Figure 6-1), representing an additional source of sediment to the Calliope River and Port Curtis receiving waters.

Figure 6-1 Examples of eroding banks on the Calliope River (Beecher section)

Catchment and riparian revegetation provides a means to reduce pollutant delivery to Port Curtis. Re-vegetation and increasing riparian widths can have flow-on benefits to other aquatic and terrestrial ecosystems within the catchment and it's receiving waters.

Targeting of priority areas is dependent on a range of factors, including locations of key sediment sources, landowner access, landscape connectivity etc. GBRMPA has recently used Blue Maps, a tool to show changes in pre-clearing and existing vegetation to target revegetation areas for maximum benefit. A similar high-level approach has been applied in Appendix E, which includes preliminary recommendations regarding potential candidate sites.

While Awoonga Dam pre-releases have the potential to minimise the severity of acute salinity impacts from overtopping events, such regulation may not be practical for a number of reasons. Modelling data suggests that acute salinity impacts only occurred during the 2013; hence, changes to flow regulation may only be beneficial during very extreme events At such times, downstream flooding, water storage and property loss are over-riding considerations. Given these constraints, there may be little benefit achieved from changes to dam release policy. Presently, the impact of low salinity on downstream coral communities is not listed as one of the ecological outcomes of the GAWB's water resource plan.



LEGEND

- Biodiversity Offset Strategy Boundary
- Artificial Reef Installation Areas
- Potential Transplant Sites
- Reefs (GBRMPA and Present Study)
- Shoreline
- Rehabilitation Areas
- GBRMPA Boundary

Meters (AHD)

-40 -20 -10 -5 0

Title:

Priority Sites for Active Restoration

Figure **6-2**

Rev: **A**

BMT WBM endeavours to ensure that the information provided in this map is correct at the time of publication. BMT WBM does not warrant, guarantee or make representations regarding the currency and accuracy of information contained in this map.

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Approx. Scale

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6.3.2 Marine Waters

There are a range of indirect measures that could be considered to improve reef resilience in marine waters. Programs such as the Keppel Bay Resilience Project have attempted to reduce anchor damage and increase resilience of reefs through the creation of no anchoring areas (NAAs). While NAAs have reduced anchor damage within designated areas, the program has also experienced reductions in anchor damage in adjacent control areas (Beeden *et al.,* 2014). As discussed in section 5.3, this form of indirect restoration may not be feasible in areas of the BOS outside the GBR Marine Park.

6.4 Further Work to Support Restoration

Additional work that could be performed by GPC or other institutions:

- Determine whether reef communities have the capacity to naturally recover, and therefore whether active restoration is required. This is essential to determining the most appropriate restoration activities. If natural recruitment is occurring, then direct restoration in the form of artificial reef installation may be more appropriate than transplantation.
- Determine the physical stability of substrates at Areas 3 and 4, and their capacity to support artificial reef structures. This should consider bed slope, wave action and substrate stability. This information is required in the context of assessing the potential for reef structures to fail (i.e. topple, become buried etc.), but also provides a basis for ensuring that coral transplantation works are not undertaken in reef areas subject to sand burial.
- Should catchment revegetation be considered, undertake modelling to determine the most critical parts of the catchment for revegetation, building on initial recommendations in Appendix E

Table 6-2 summarises studies required to address these issues. These studies are considered priority actions prior to moving forward into consultation and planning phases (see below). Consultation with stakeholders (agencies, Harbour Master, fishers, other port users, land owners etc.) to identify issues and constraints to any constraints to any restoration works.

Table 6-2 Information gaps and recommended further technical studies

Issue	Information requirement	How addressed
What parts of the catchment should be revegetated to maximise water quality during event flows? What areas will provide the most benefit at lowest cost?	Will optimise restoration efforts	Source catchment modelling and GIS-based vegetation and catchment mapping
What is the capacity of reefs to recover naturally? Is there evidence of natural recruitment	Critical question is terms of assessing need for active coral restoration	Reef community monitoring
		Monitoring of natural settlement and recruitment on reefs
Will physical disturbance result in loss of artificial reef structures at Areas 3 and 4?	Critical issue in terms of assessing stability of artificial structures	Morphological modelling
		Substrate monitoring
		Wave measurement/modelling data

Based on the outcomes of these investigations, the preliminary management objective and management measures set out in this report should be reviewed and refined. If direct restoration is considered viable, a management plan should be developed to guide future works based on steps outlined by Edwards (2010) (see Section 2.4.2).

7 Conclusions

Reef communities in Port Curtis have experienced major changes in community structure since baseline surveys in 2009. In contrast to 2009 surveys, reefs west of Facing Island had negligible living hard coral cover and were numerically dominated by turfing algae, bare substrate and macroalgae. Reef communities between Port Curtis and Rodds Bay also had low hard coral cover, but there was little baseline data from these sites to determine changes over time. Nearshore reefs along the eastern coastline of Facing Island had diverse and abundant hard coral cover, which was similar to survey results from 2010.

Port Curtis reefs have been affected by flood waters in recent years, and this has co-occurred with major dredging campaigns. Lowered salinities and high turbidity likely to be a major driver of changes in coral cover, as observed in the Keppel Islands, and as predicted by catchment and hydrodynamic modelling.

For long-term improvement in water quality and ecosystem functioning, indirect restoration of the catchment is likely to have the greatest value for money. Changes to flow regulation of Awoonga Dam during peak events may also reduce plume impacts, but this is unlikely to be practical given other priorities.

Direct restoration sites have also been prioritised. Assuming that reefs will be irregularly affected by flood plumes (e.g. 1 in 100 year events) then potential priority sites for restoration within Port Curtis include Seal Rocks Reef and reefs on the west coast of Facing Island (for coral transplantation). For artificial reef installations, unconsolidated sediment between Manning Reef and Bushy Island Reef is the highest priority location. However, installing artificial reefs without appropriate management of fishing pressure may conflict with the goals of the BOS. While reefs in North Passage supported moderate coral cover in 2009, there are several constraints to undertaking restoration works here, including strong currents and potential conflict with other users.

Reefs on the east coast of Facing Island were either; rich and abundant, or remained unchanged between survey periods. Therefore, these reefs do not require restoration or other management attention. The installation of artificial reefs in adjacent soft sediment habitats could enhance connectivity between these reefs, potentially promoting resilience and biodiversity values of natural reefs, but this area mostly falls within the GBRMP. Further investigations into stability of benthic substrates would be required to determine their ability to support reef structures.

There are several critical information gaps that need to be addressed in order to:

- Focus indirect restoration efforts within the catchment
- Determine whether reef communities have the capacity to naturally recover, and therefore, whether management intervention is required
- Determine the physical stability of substrates at potential sites are their capacity to support artificial reef structures
- Determine potential conflict with other users.

8 References

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Appendix A Reef Community Survey Data – 2014

Table A-1 Cover data for quantitative sites visited in 2014

	Hard Coral (Scleractinia)																						Soft Coral (Octocoral)										Algal coverings															CCA	Fauna					Abiot
Reef	Acanthastrea	Acropora	Alvepora	Astreopora	Bleached Coral	Coeloseris	Cyphastrea	Echinopora	Favia	Favites	Galaxea	Goniastrea	Gonipora	Hydnophora	Montipora	Moseleya	Other Hard Coral	Platygyra	Pocillopora	Podobacia	Porites	Turbinaria	Briareum	Clavularia	Heteroxenia	Junceella	Lobophytum	Sarcophyton	Sinularia	Soft Coral Other	Tubipora	Palythoa	Turfing Alg	Acanthophora	Amphiroa	Asparagopsis	Caulerpa	Dictyota	Halimeda	Hypnea	Laurencia	Padina	Peyssonnelia	Sargassum	Other Macroalgae	Crustose CA	Cyanobacteria	Echinoderm	Bryozoa	Sponge	Ascidian	Other Fauna	Sand or Mud
Bushy Island-1																																	31.5			3.0		5.0	2.0			8.0			5.5								45.0
Bushy Island-2																					0.5												49.5		12.5			2.5	0.5			16.5			4.0								13.5
Bushy Island-3																																	38.0		3.0	2.0		3.0				9.5			3.0								15.0
E. Point Ledge-1																																	5.5		1.0							2.0		59.5		17.5							14.5
E. Point Ledge-2															0.5																		9.0		2.5	0.5						2.0	1.5	73.0	0.5	4.0		0.5					6.0
E. Point Ledge-3															0.5																		12.5		6.0	0.5						3.5		59.0	5.0	3.5				1.0			8.5
Facing #2-1					0.5																9.6												51.7												1.0					2.5			34.7
Facing #2-2										1.3											6.3												53.6												3.0								36.4
Facing #2-3		3.3															0.8				5.8												66.7												2.9	0.4							2.0
Facing #4-1	0.5		0.5								0.5	1.0			0.5								0.5					1.0	0.5				26.0						0.5	0.5	4.5	1.5	29.5	2.5	9.5		1.0		2.5	0.5		16.5
Facing #4-2										0.5		0.5			1.0						0.5	0.5	1.0							0.5			36.5						0.5	1.5	4.0		27.0	4.5	8.5			0.5	1.5	0.5		1.5
Facing #4-3	0.5						0.5		2.5					1.5	2.0				1.0			1.0		0.5				1.5					31.5		1.5	1.0		13.0			1.5	7.5	0.5	8.0	4.0	6.5		1.0		1.5	4.5		7.0
Gatcombe South-1																																	5.5		1.0	0.5					2.0	17.5		4.0	1.5	0.5		0.5		0.5			21.5
Gatcombe South-2						1.0																											5.5		0.5		1.0	0.5				9.0		2.5	1.0			1.0				15.0
Gatcombe South-3																																	39.5		1.0	0.5		1.5	1.0			3.5		2.0	1.5			2.0		0.5	0.5		46.5
Gatcombe East-1		7.5											0.5	0.5	1.0																		4.0									1.5		49.5	1.5	3.5				0.5			3.0
Gatcombe East-2						1.0		1.5	3.5	1.0		0.5			5.5				3.0		2.5	3.0				0.5		2.5	1.5				22.5		0.5			0.5			1.5	2.5	1.0	34.5	2.5	3.5		0.5					4.5
Gatcombe East-3																		1.0		1.5	5.0		0.5					0.5					15.5					1.5		1.5	1.0		56.5	1.0	2.5					0.5		11.5
Manning -1																					0.5												82.5			0.5			2.0			1.0											13.5
Manning-2																																	85.5			4.0								0.5									1.0
Manning-3																																	53.0			16.5		1.5				0.5											28.5
Oaks-1																																	14.0									3.0		8.5	1.0	1.0				0.5			
Oaks-2																																	4.0											96.0									
Oaks-3																					2.5												1.5			5.5						1.0		79.5									1.0
Pearl Ledge-1	0.5						2.0		3.5	0.5		1.0	1.0		0.5				0.5		2.5	7.5						0.5					23.5									27.0	2.0		2.0	8.5				2.5			14.5
Pearl Ledge-2	1.0	0.5				0.5	2.5		1.0			3.0			3.0			0.5			2.0	3.5							0.5				29.0							0.5	1.0	21.0	4.5	1.5	3.5	5.0				0.5			15.5
Pearl Ledge-3				1.0	1.0	0.5	6.5				4.0	5.0	0.5		1.5			0.5	0.5		0.5												23.0									31.5	2.0	2.5	1.5	7.5				1.5			9.0
Rat South -1							2.0								0.5						1.0												2.0			13.5		3.0				22.0		9.5	1.0	1.0						26.5
Rat South -2							2.0									1.0					0.5												32.5			1.5						19.0		16.0	1.0							17.5
Rat South -3							1.0								0.5						0.5	4.0					1.5						23.5			7.5				0.5		9.0		3.0	0.5	3.0						45.5
Rat North-1																					0.5												1.5									0.5		75.0		0.5						13.0
Rat North-2																					2.0												16.5											58.0	0.5	3.5				1.0	1.0		17.5
Rat North-3																						0.5											29.5									5.5		45.0	0.5	3.5				0.5	1.0		14.0
Rocky Point S-1																					0.5												28.0		1.0	3.0		7.5	2.0			2.0		2.5	15.0								38.5
Rocky Point S-2																																	35.0		3.0			6.0				4.5		5.5	1.5							34.5
Rocky Point S-3																	0.5																4.7		4.7							3.5		2.7	8.7							11.7
Sable Chief-1		3.0					1.0		2.0	1.0		0.5	1.5		4.0			0.5	5.0		2.5							0.5	2.5		0.5		21.5	0.5						0.5	1.0	8.5	0.5		1.0	12.5				0.5			2.0
Sable Chief-2		57.0	3.5							0.5					0.5			0.5	1.0				0.5					0.5	2.0				25.5								0.5	2.0	0.5		1.0	3.5							1.0
Sable Chief-3		25.5	2.0				0.5						0.5		1.0				1.0				1.5					4.0	1.0		1.0	9.0	36.0			3.5	1.0					1.0			4.0	6.0	0.5						1.0
Seal Rocks-1												1.0										9.5							0.5				13.0		3.0	21.0		0.5				7.5		28.0	3.0	0.5							12.5
Seal Rocks-2												1.0										9.5							0.5				13.0		3.0	21.0		0.5				7.5		28.0	3.0	0.5							12.5
Seal Rocks-3		2.0																				0.5	0.5										11.5		0.5	18.0		2.0				21.0		21.5	1.0	0.5							21.0
Turtle Island-1						0.5																			2.0								37.0		0.5	0.5			2.0			1.0		6.0	3.0			2.0		1.0	0.5	1.0	43.0
Turtle Island-2																									2.0								12.0		0.5	3.5									2.0								8.0
Turtle Island-3																																	1.5			2.5																	87.0

Table A-2 Summary cover and richness for sites visited in 2009 and 2014

Location	year	Acropora	Non-acroporid Hard Coral	Soft Coral	Macroalgae	Turfing Algae	Bare Substrate	CCA	Other Fauna	Hard Coral Richness	Soft Coral Richness
Bushy Island-1	2014				23.5	31.5	45.0				
Bushy Island-2	2014		0.5		36.0	5.0	13.5			1	
Bushy Island-3	2014				47.0	38.0	15.0				
E. Point Ledge-1	2014				62.5	5.5	14.5	17.5			
E. Point Ledge-2	2014		0.5		8.0	9.0	6.0	4.0	0.5	1	
E. Point Ledge-3	2014		0.5		74.0	12.5	8.5	3.5	1.0	1	
Facing #2-1	2014		1.5		1.0	51.7	34.7		2.5	2	
Facing #2-2	2014		7.5		3.0	53.6	36.4			2	
Facing #2-3	2014	3.3	6.7		2.9	66.7	2.0	0.4		3	
Facing #4-1	2014		3.0	2.0	39.0	26.0	16.5	9.5	4.0	5	3
Facing #4-2	2014		3.0	1.5	37.5	36.5	1.5	8.5	2.5	5	2
Facing #4-3	2014		9.0	2.0	37.0	31.5	7.0	6.5	7.0	7	2
Gatcombe South-1	2014				26.5	5.5	21.5	0.5	1.0		
Gatcombe South-2	2014		1.0		32.5	5.5	15.0		1.0	1	
Gatcombe South-3	2014				11.0	39.5	46.5		3.0		
Gatcombe East-1	2014	7.5	2.0		52.5	4.0	3.0	3.5	0.5	4	
Gatcombe East-2	2014		21.5	4.5	43.0	22.5	4.5	3.5	0.5	9	3
Gatcombe East-3	2014		7.5	1.0	61.5	15.5	11.5	2.5	0.5	3	2
Manning -1	2014		0.5		3.5	82.5	13.5			1	
Manning-2	2014				4.5	85.5	1.0				
Manning-3	2014				18.5	53.0	28.5				
Oaks-1	2014				84.5	14.0		1.0	0.5		
Oaks-2	2014				96.0	4.0					
Oaks-3	2014		2.5		86.0	1.5	1.0			1	
Pearl Ledge-1	2014		19.5	0.5	31.0	23.5	14.5	8.5	2.5	1	1
Pearl Ledge-2	2014	0.5	17.0	0.5	32.0	29.0	15.5	5.0	0.5	1	1
Pearl Ledge-3	2014		21.5		37.5	23.0	9.0	7.5	1.5	11	
Rat South -1	2014		3.5		49.0	2.0	26.5	1.0		3	
Rat South -2	2014		3.5		46.5	32.5	17.5			3	
Rat South -3	2014		6.0	1.5	2.5	23.5	45.5	3.0		4	1
Rat North-1	2014		0.5		75.5	1.5	13.0	0.5		1	
Rat North-2	2014		2.0		58.5	16.5	17.5	3.5	2.0	1	
Rat North-3	2014		0.5		51.0	29.5	14.0	3.5	1.5	1	
Rocky Point S-1	2014		0.5		33.0	28.0	38.5			1	
Rocky Point S-2	2014				26.5	35.0	38.5				

Reef Community Survey Data – 2014

Location	year	Acropora	Non-acroporid Hard Coral	Soft Coral	Macroalgae	Turfing Algae	Bare Substrate	CCA	Other Fauna	Hard Coral Richness	Soft Coral Richness
Rocky Point S-3	2014		0.5		41.0	45.0	13.5			1	
Sable Chief-1	2014	3.0	18.0	3.5	12.0	21.5	2.0	12.5	0.5	1	3
Sable Chief-2	2014	57.0	6.0	3.0	4.0	25.5	1.0	3.5		6	3
Sable Chief-3	2014	25.5	5.0	7.5	1.0	36.0	1.0	6.0	9.0	6	4
Seal Rocks-1	2014		1.5	0.5	63.0	13.0	12.5	0.5		2	1
Seal Rocks-2	2014		1.5	0.5	63.0	13.0	12.5	0.5		2	1
Seal Rocks-3	2014	2.0	0.5	0.5	64.0	11.5	21.0	0.5		2	1
Turtle Island-1	2014		0.5	2.0	13.0	37.0	43.0		4.5	1	1
Turtle Island-2	2014			2.0	6.0	12.0	8.0				1
Turtle Island-3	2014				2.5	1.5	87.0				
Oaks-1	2009	14.0	22.0	5.0	36.0	7.0	14.0		2.0	5	1
Oaks-2	2009	8.0	19.0	5.0	35.0	13.0	14.0	2.0	4.0	3	2
Rat North-1	2009	24.0	21.0	5.0	19.0	13.0	17.0		1.0	5	1
Rat North-2	2009	9.0	16.0	4.0	28.0	11.0	25.0		7.0	6	2
Rat North-3	2009	1.0	17.0	2.0	32.0	12.0	25.0		2.0	5	1
Rat South-1	2009	24.0	15.0	2.0	33.0	11.0	11.0		4.0	6	1
Rat South-2	2009	5.0	16.0	5.0	42.0	11.0	19.0		2.0	4	1
Facing #2-1	2009	3.0	16.0	41.0	12.0	9.0	13.0	1.0	5.0	4	2
Facing #2-2	2009		11.0	37.0	2.0	9.0	14.0		9.0	2	2
Bushy Island-1	2009	8.0	24.0	5.0	39.0	8.0	1.0		15.0	5	1
Bushy Island-2	2009	8.0	9.0	4.0	34.0	11.0	12.0	11.0	11.0	5	1
Bushy Island-3	2009		5.0	48.0	11.0	6.0	22.0		8.0	2	1
Manning -1	2009	41.0	1.0	5.0	12.0	18.0	12.0		2.0	3	1
Manning-2	2009	29.0	1.0	1.0	11.0	2.0	26.0		3.0	2	1
Manning-3	2009	56.0	5.0	3.0	3.0	8.0	22.0		3.0	2	1
Rat North-1	2009		18.0	15.0	7.0	24.0	33.0		3.0	5	2
Rat North-2	2009		3.0	6.0	19.0	29.0	36.0		7.0	1	2
Rat North-3	2009		9.0	4.0	18.0	32.0	36.0		1.0	2	2
Rocky Point S-1	2009	7.0	4.0		6.0	4.0	7.0			5	
Rocky Point S-2	2009	13.0	35.0		19.0	21.0	12.0			4	
Turtle Island-1	2009	1.0	5.0	4.0	46.0	14.0	22.0		8.0	4	2
Turtle Island-2	2009				47.0	18.0	23.0		12.0		
Turtle Island-3	2009		7.0		45.0	18.0	28.0		2.0	1	
Diamantina-1	2009				39.0	5.0	56.0				
Diamantina-2	2009		3.0	2.0	44.0	19.0	25.0		7.0	1	1

Appendix B Catchment Modelling Methodology and Calibration

Catchment Model

The "Source Catchments" model platform was used to assess the catchment derived flows (rainfall runoff) and associated loads of diffuse constituents. Source was developed by the eWater CRC, a federally funded Cooperative Research Centre combining Australia's pre-eminent research organisations, State Government water regulators and industry practitioners. It has been used extensively by the Reef Plan to set catchment water quality targets and assess performance (Dougall *et al.* 2014, Hateley *et al.* 2014).

The Source catchment model encompassed the Boyne and Calliope catchments, and did not consider the Fitzroy catchments. Despite its substantial fluvial input from the Fitzroy, connectivity between Port Curtis and the Fitzroy River Delta is relatively minor due to the lengthy, narrow, and shallow passage of water between the two systems (The Narrows), and this has consistently been observed in BMT WBM's previous hydrodynamic models. Therefore, catchment modelling focused on the Boyne and Calliope catchments.

The Source modelling framework allows for individual rainfall, runoff, stream routing, and constituent generation parameters to be applied to each Functional Unit (i.e. landuse category), within each subcatchment. Regional models were built in the Source Catchments modelling framework, which comprise subcatchments connected through a series of nodes and links which represent the stream network. Figure B-1 presents the catchment model developed in Source catchments model platform.

Rainfall Runoff Model

Rainfall runoff was modelled using SIMHYD model available within Source platform. SIMHYD was chosen as it represents a simple lumped conceptual daily rainfall-runoff model, with relatively few parameters. SIMHYD has been successfully used across Australia to simulate daily runoff using rainfall, potential evapotranspiration, and catchment characteristics (e.g. landuse dependent hydrologic, constituent generation properties) as input data.

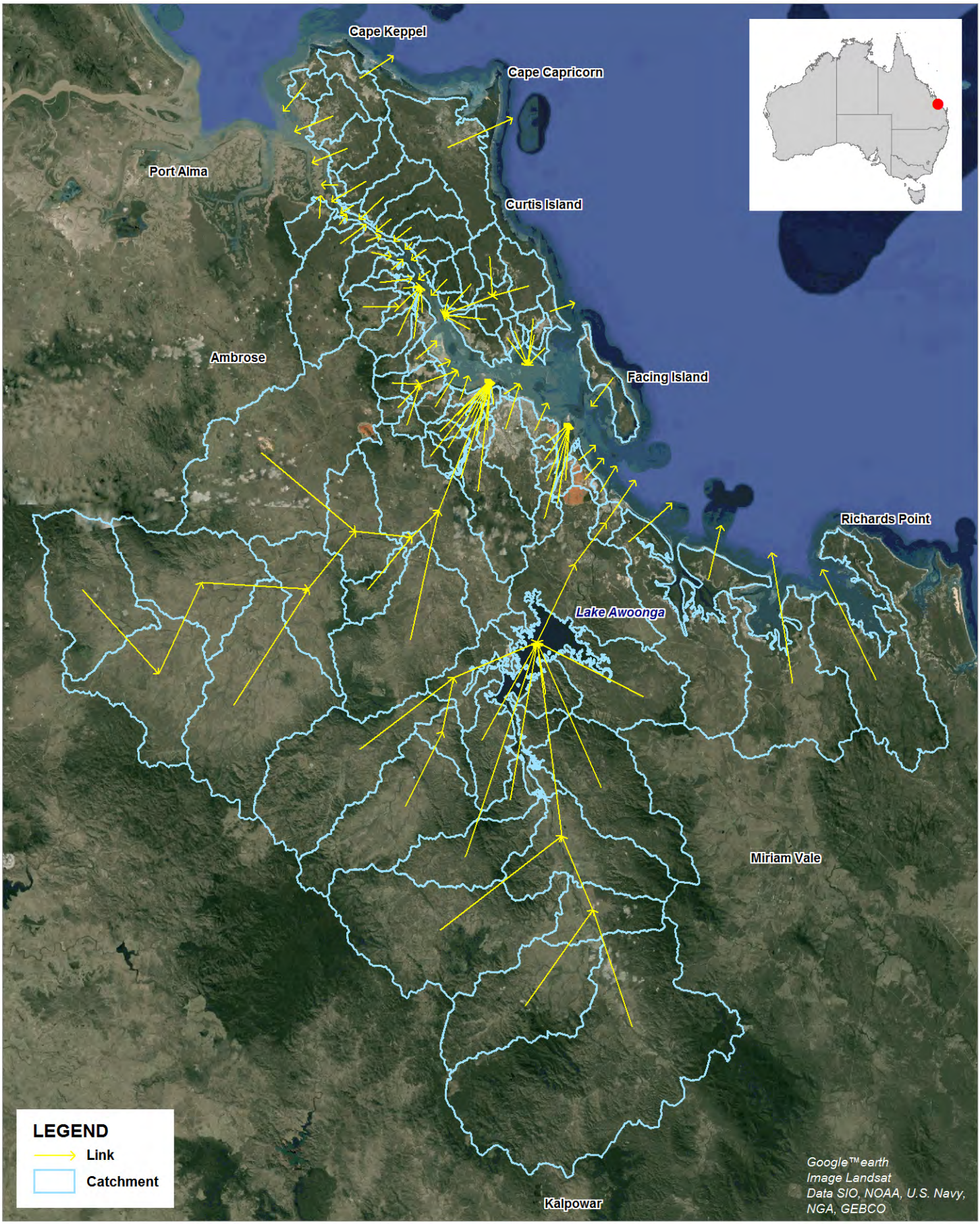
Constituent Generation Model

Catchment scale generation of TN, TP, and TSS were modelled using an event mean concentration (EMC) and dry weather concentration (DWC) model available within Source platform. The model allows for constant values to be set for base flow and event flow water quality conditions.

Input Data

The following input data were used in the catchment model to better represent land use, drainage (stormwater network), climatic, and water quality conditions of the region:

- Land use data.
- Stromwater network.
- Daily rainfall and potential evapotranspiration (PET).
- EMCs and DWCs.
- Awoonga Dam outflow and its pollutant output.



Title:

Source Catchments Modelling Network

Figure: **B-1**

Rev: **A**

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N

0km 15 30

Approx. Scale

BMT WBM

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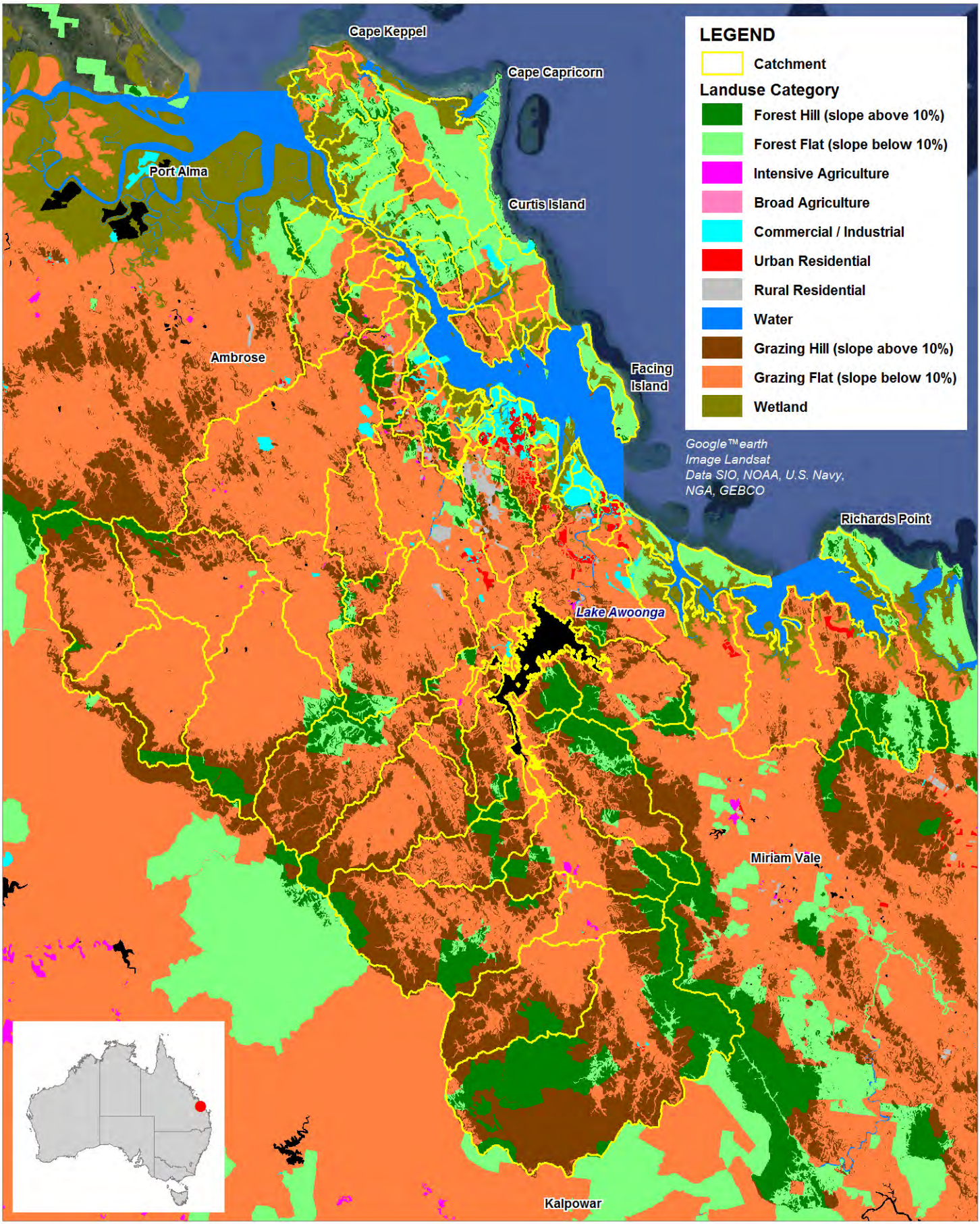
Land Use

Land use data for the present day (as on 11/28/2014) were acquired from Queensland Land use Mapping Program (QLUMP) database. While it would have been desirable to include all of these categories, numerous categories can be grouped where they are hydrologically similar and have similar land use configurations. The final land use map was modified from the original QLUMP map based on the primary and secondary usage in order to reduce the total number of land uses to 10 to provide a current conditions land use map. The final land use map included forest, grazing, intensive agriculture, broad, agriculture, commercial/ industrial, urban residential, rural residential, waterbodies, wetland, and storage. Both forest and grazing were further divided based on slope (slope threshold 10%) in order to better capture the hydrologic differences between hill and flat lands. Figure B-2 presents the land use types used in the catchment model that represented the current (or existing) conditions.

Industrial land use for future scenarios was digitised from the GSDA while future residential and commercial land use was derived from Gladstone Regional Council's layer of developments to likely occur in the next 15 years. Future land use layers are shown in Figure B-3.

Stormwater Network

The stormwater network of the region was developed by delineating a digital elevation model (DEM) (resolution 10m) available for the region. Figure B-2 presents the stormwater network of the region.



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Current Landuse Map

Figure: **B-2**

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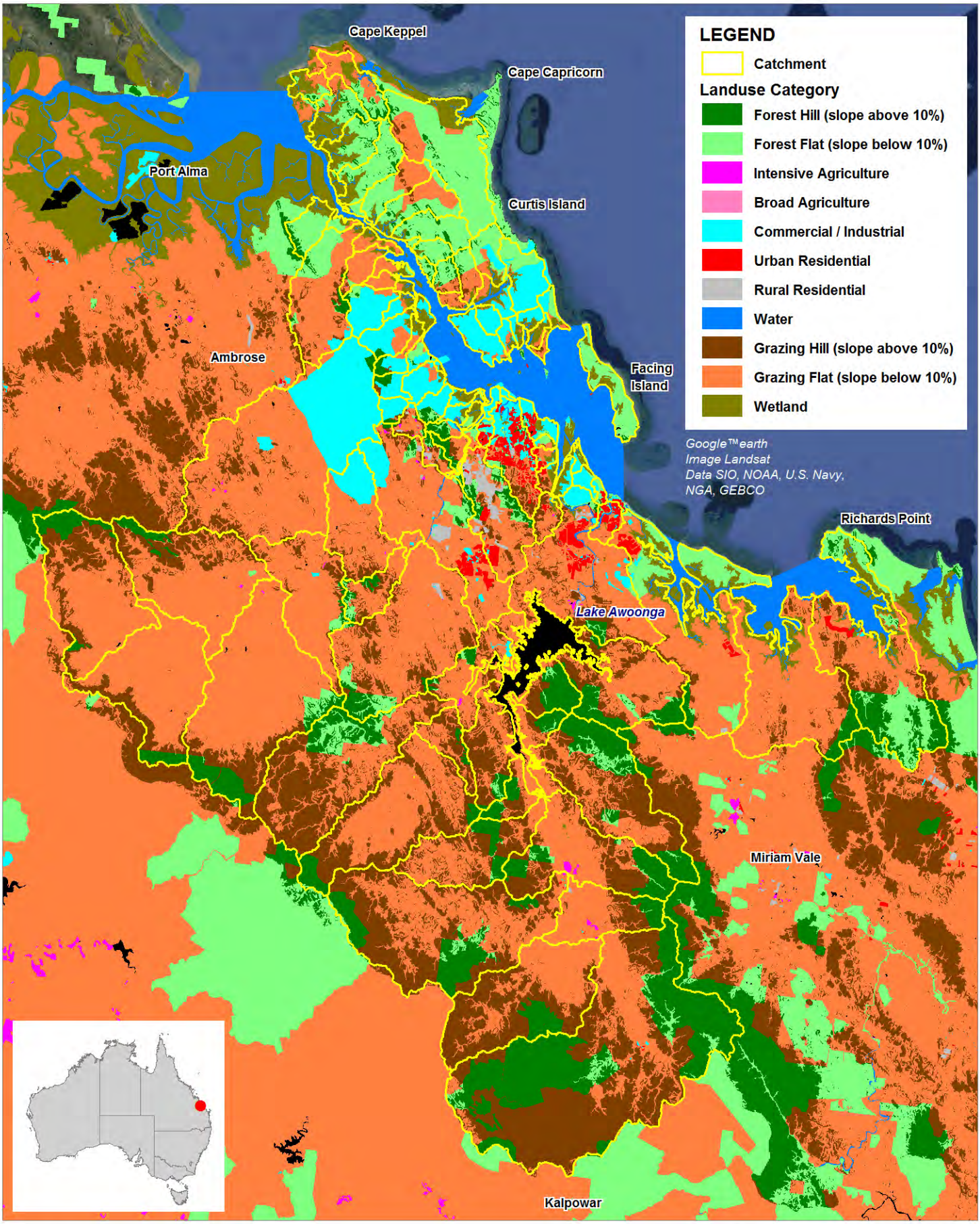

Title:

Future Landuse Map

Figure: **B-3**

Rev: **A**

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Table B-1 Landuse classification

Key Land Use in the Catchment Model	Primary Use (as per to QLUMP)	Secondary Use and Tertiary Use (as per to QLUMP)
Forest	Conservation and natural environments	Nature conservation, Managed resource protection, Production forestry, Plantation forestry, Land in transition, Irrigated plantation forestry, Irrigated land in transition, Other minimal use
Grazing	Production from relatively natural environments	Grazing native vegetation, Grazing modified pastures
Intensive Agriculture	Production from dryland agriculture and plantations	Cropping, Perennial horticulture,Seasonal horticulture, Irrigated modified pastures, Irrigated cropping, Irrigated perennial horticulture, Irrigated seasonal horticulture, Intensive horticulture, Intensive animal production
Broad Agriculture		Cropping - Cotton, Cropping - Sugar, Irrigated cropping - Cotton, Irrigated cropping - Sugar
Commercial/ Industrial	Intensive uses	Manufacturing and industrial, Services, Utilities, Transport and communication, Mining, Waste treatment and disposal
Urban Residential	Intensive uses	Residential, Urban residential
Rural Resiidential	Water	River, Channel/aqueduct,Estuary/coastal waters
Waterbodies	Water	River, Channel/aqueduct,Estuary/coastal waters
Wetland	Water	Marsh/wet land
Storage	Reservoir/Lake/Evaporative Basin	Reservoir/Lake/Evaporative Basin

Daily Rainfall and PET Data

Gridded SILO data (DSITI 2015) purchased from DSITIA (Queensland) was used to parametrise daily rainfall and PET in the catchment model.

Event Mean Concentration (EMC) and Dry Weather Concentration (DWC) values

Event based water quality data specific to the Calliope and Boyne regions was not able to be utilised as this data could not be directly related to any individual land use.

Where site specific local data was not available, a hierarchy of data was used to obtain suitable values. This hierarchy first referenced regionally appropriate studies, appropriate state data sets then national data values. Land use based EMC/DWC values (of TSS, TN, and TP) collated as part of a previous study ((BMT WBM 2009b) were used in the catchment model (see Table B-2 and Table B-3).

Table B-2 EMC parameterisation (mg/L)

Land Use	TSS	TN	TP
Natural Environment Forestry	9	0.33	0.05
Residential	130	1.6	0.28
Irrigated Sugar Cane	114	2.39	0.35
Irrigated Horticulture, Dryland Agriculture	300	1.95	0.32
Grazing	138	0.77	0.17
Intensive Uses	130	1.6	0.28

Table B-3 DWC parameterisation (mg/L)

Land Use	TSS	TN	TP
Natural Environment Forestry	1	0.22	0.02
Residential	7	1.5	0.11
Irrigated Sugar Cane	6	0.37	0.04
Irrigated Horticulture, Dryland Agriculture	10	0.7	0.07
Grazing	4	0.24	0.05
Intensive Uses	7	1.5	0.11

Awoonga Dam Outflow and its Pollutant Output

Awoonga Dam outflow and pollutant output were introduced as a point source in the catchment model. Outflow measurements estimated for Awoonga Dam as part of a previous study (based on the closed Awoonga Dam gauge 133005A) were used in the model. Constituent data immediately downstream of Awoonga Dam were not collected during peak flow by the Department of Environment and Heritage

Protection (DEHP 2013), and the Gladstone Area Water Board declined to supply discharge data. Therefore, constituent concentrations at dam's outflow were assumed to be similar to the spot measurements collected at the downstream of Awoonga Dam during 2013 flood monitoring (DEHP 2013). Unfortunately, the 2011 and 2013 events were very different in nature (see section above), with the 2011 being much longer in duration, and much less intense than the 2013 event. Disparity in the nature of these two events meant that using measured pollutant data from one event to parametrise the other may have provided inaccurate results. While differential flows can be used to calibrate flow volumes, the concentration of constituents spilling out of Awoonga Dam may vary depending on the rate of dam fill and the rate of overflow, both of which were vastly different between the two events. The major consequence of not receiving this data from the Gladstone Area Water Board, is a likely overestimation of pollutant loads exiting the dam in 2011. Moreover, the 2013 flood monitoring (DEHP 2013) did not capture constituent concentrations during peak flow but measurements made days after the peak flow are similar to discharge loads that were adopted. Hence, the constituent concentrations used to define Awoonga Dam pollutant outputs may have underestimated the actual impacts. Without peak flow data this cannot be ascertained.

Curtis Island

Measured flow and diffuse constituent data were not available for Curtis Island, so hydrologic and constituent generation parameters of the Calliope basin was used to parametrise this region.

Characterisation of 2010-11 and 2013 Flood Events

Both 2010-11 and 2013 storm events were investigated using an Intensity Frequency Duration (IFD) analysis. Here, pluviograph data (rainfall recorded at every 6 minute intervals) recorded at the Gladstone Radar gauge was analysed against the IFD rainfall chart obtained from "AR&R87 IFDs" tool (BoM) for the Gladstone Radar (BoM) coordinates. Figure B-4 and Figure B-5 present findings of the IFD analysis of both events.

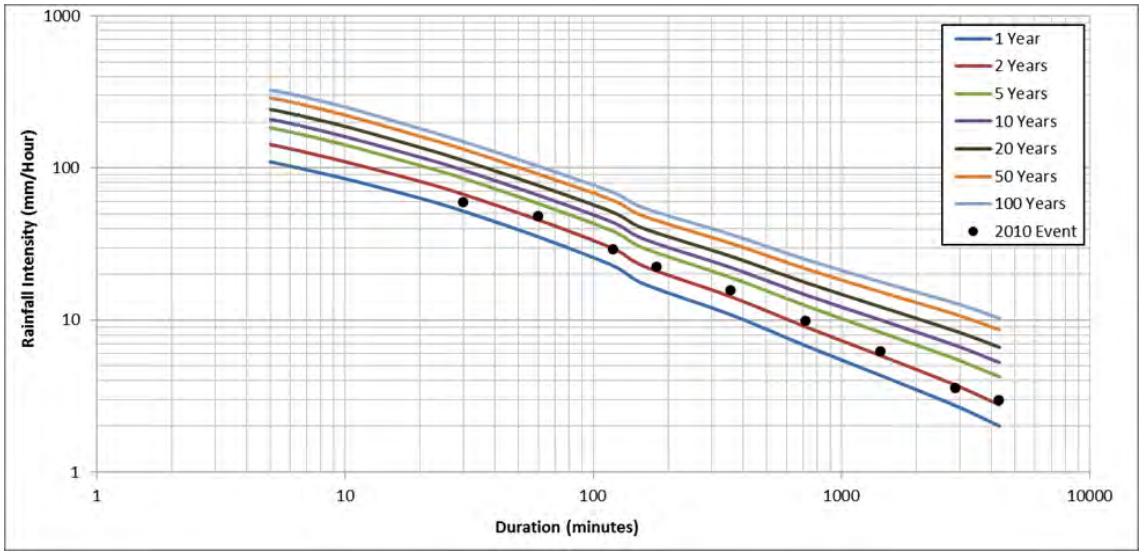


Figure B-4 IFD Analysis of 2010-11 Event

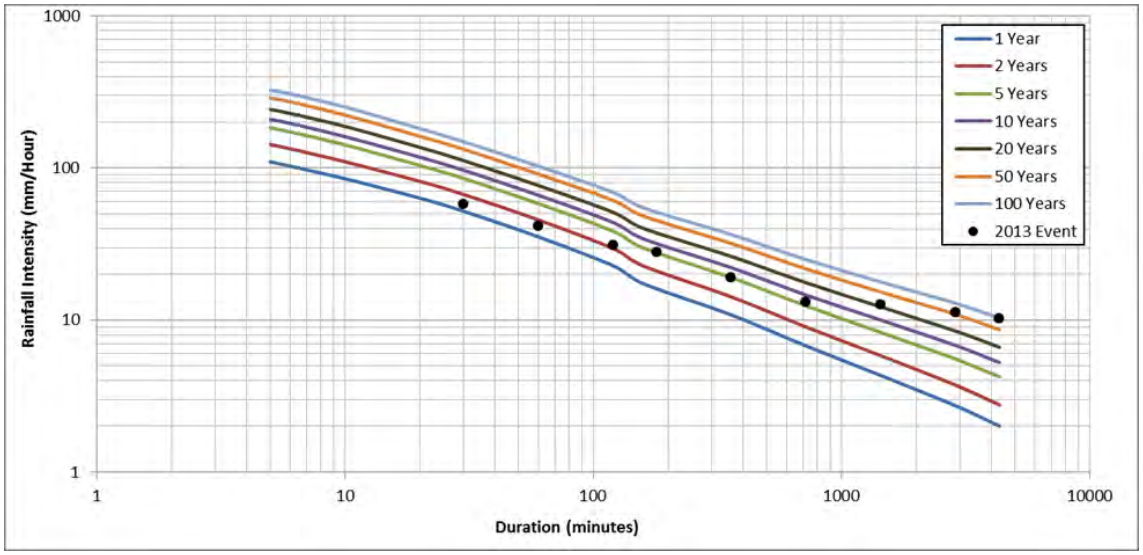


Figure B-5 IFD Analysis of 2013 Event

The IFD analysis shows that rainfall that fell during the 2010 event was closer to a 1 in 2-year event for both short and long duration storms. However, it shows that during the 2013 event the rainfall that fell was closer to a 1 in 2-year event for short duration storms (5-100 minutes) and exceeded the 20-year event for long duration storms.

Model Calibration

The Source catchment model calibration process was undertaken by adjustment of model independent variables, within realistic limits, to produce the best match between modelled and measured data. The success of the calibration was evaluated both qualitatively and quantitatively to assess the degree of correlation between model predictions and measured data.

Only the rainfall runoff model was calibrated because no water quality data measurements are available to calibrate constituent generation model. Details of the rainfall runoff model calibration are provided below.

Rainfall Runoff Model Calibration

The rainfall runoff model was calibrated for parameters of SIMHYD hydrologic model using mean flow measurements recorded at gauging stations summarised in Table B-4. Mean daily flows recorded at corresponding gauges were sourced from the water monitoring portal of Department of Natural Resources and Mines, Queensland (https://www.dnrm.qld.gov.au/water/water-monitoring-and-data/portal).

Although the Bureau of Meteorology has nine gauging stations with continuous data within the two catchments modelled, only the Calliope River at Castlehope gauge recorded flows between 2010 and 2013, while Boyne River at Milton and Nagoorin and Diglum Creek at Marlua gauges recorded flows only between 2010 and 2012. Catchments located in the upstream of Castlehope gauge were jointly calibrated using flows recorded between January 2009 and May 2012 by assuming homogeneity in hydrologic response across Calliope River catchments. Flow measurements recorded at Milton gauge during the same period were used to calibrate the upstream catchments by assuming homogeneity in hydrologic response across Boyne catchments. In this case, two separate sets of rainfall runoff model parameters were produced for catchments located in the Calliope and Boyne River Basins. The hydrologic model of the Calliope Basin was then validated using the 2013 event flows recorded in the at Castlehope gauge, while the hydrologic model of the Boyne Basin was validated using the 2010 event flows recorded at Marlua and Nagoorin gauges.

Table B-4 Gauging station information

Gauge Name (Number)	Catchment Basin	Data Download Period	Gauge Status
Calliope River at Castlehope (132001A)	Calliope	Jan/08 - Oct/14	Open
Boyne River at Milton (133004A)	Boyne	Jan/08 - May/12	Closed
Diglum Creek at Marlua (133003A)	Boyne	Jan/08 - May/12	Closed
Boyne River at Nagoorin (133006A)	Boyne	Jan/08 - May/12	Closed

Qualitative Model Performance Analysis

A qualitative model performance assessment was undertaken on the resulting model predictions as this is advantageous in that it provides an unambiguous performance measure that can be used to assess how well the model has been calibrated (in terms of flow magnitude and timing). A number of differing qualitative measures are provided through a series of graphs as described below:

- Time series (hydrograph) comparison of daily flows to assess the general response and pattern of predicted flows;
- Daily flow percent exceedance probability curve to assess the long term daily flow relationship; and
- Scatter plots for daily volumes to provide a visual observation of the scatter around the line of perfect fit (i.e. a 45° line through the origin representing a perfect calibration).

Figure B-6 through to Figure B-11 illustrate the qualitative performance of the rainfall runoff model calibration at both Castlehope and Milton gauges.

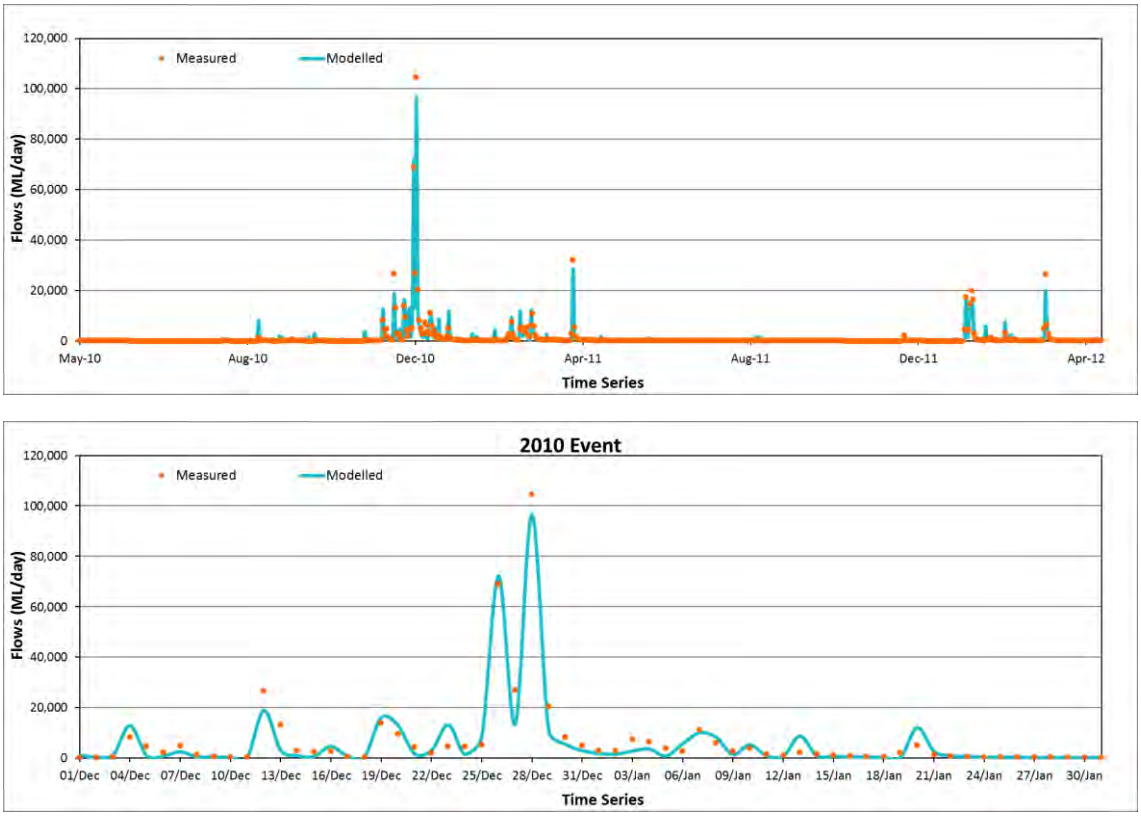


Figure B-6 Time series comparisons at Calliope River at Castlehope: the entire time series (above) and detail during the 2010-2011 flood event (below)

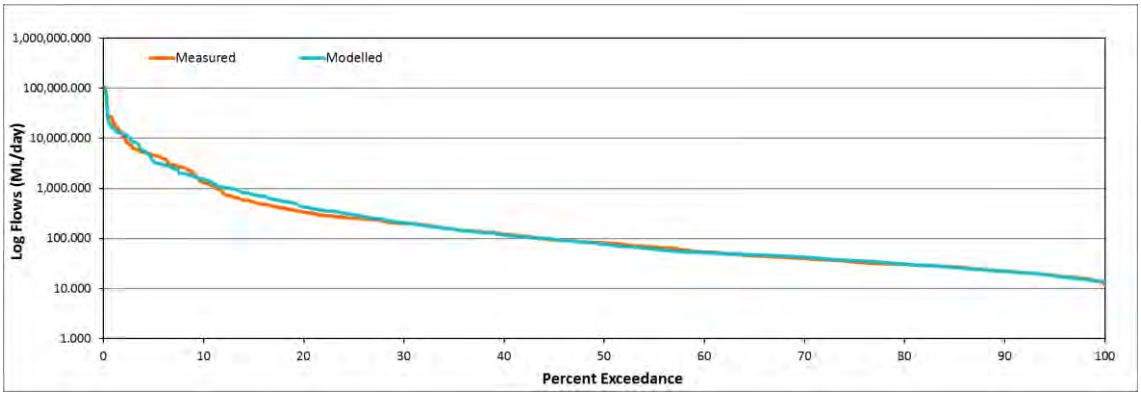


Figure B-7 Log flow duration curve comparison at Calliope River at Castlehope

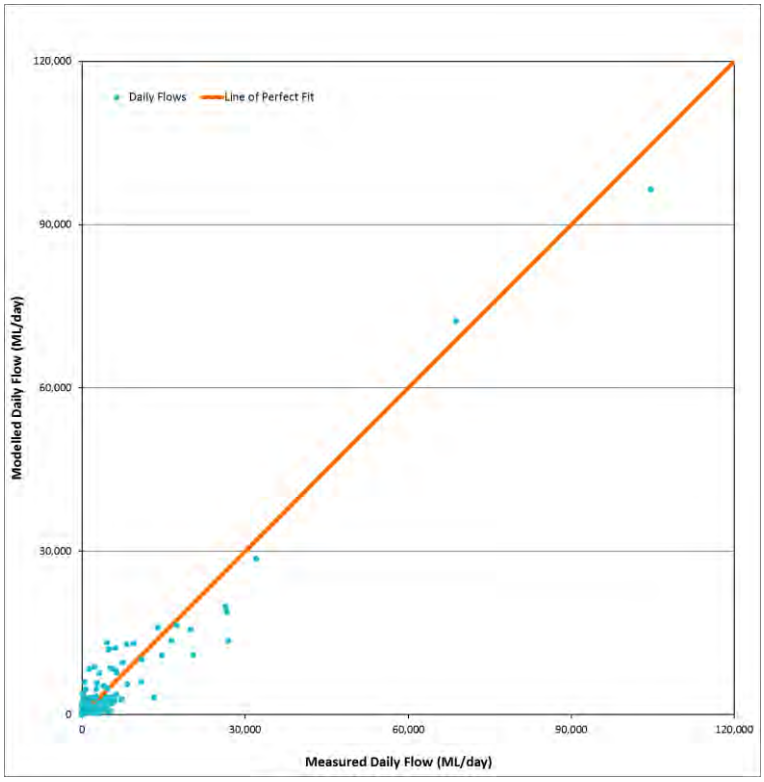


Figure B-8 Modelled vs measured daily flows at Calliope River at Castlehope

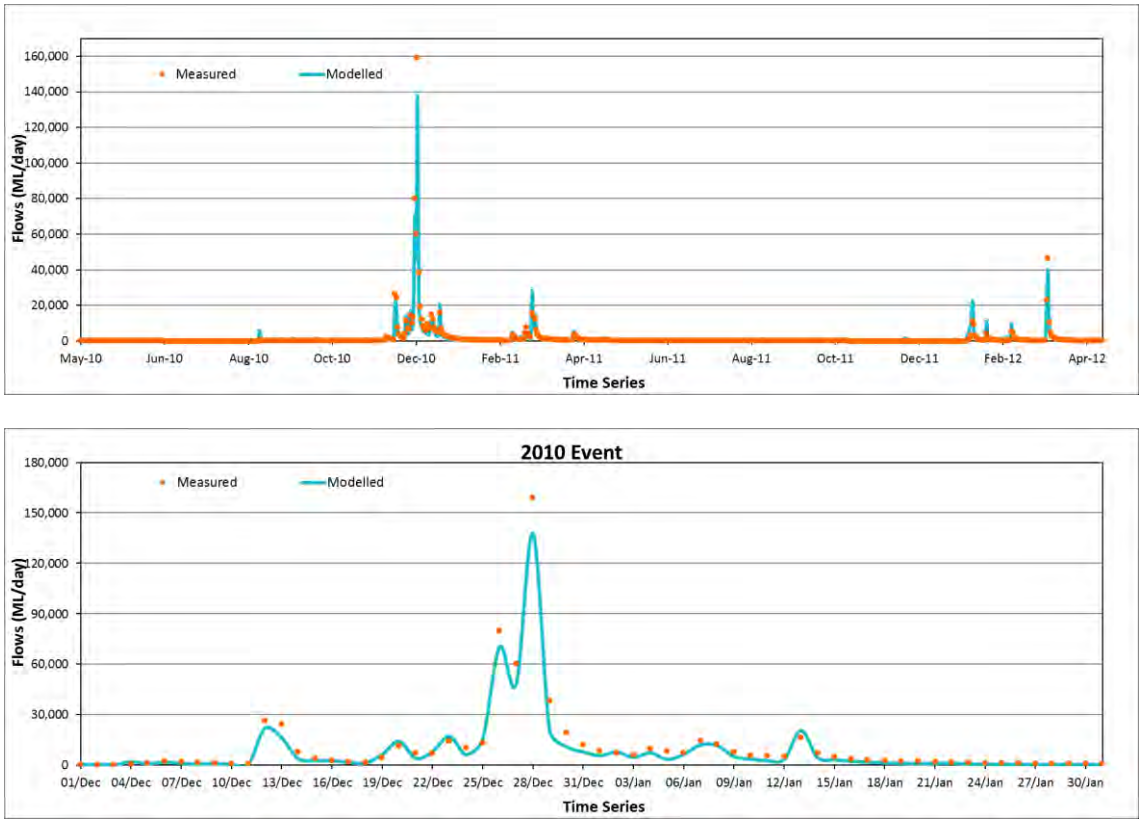


Figure B-9 Time series comparison at Boyne River at Milton: the entire time series (above) and detail during the 2010-2011 flood event (below)

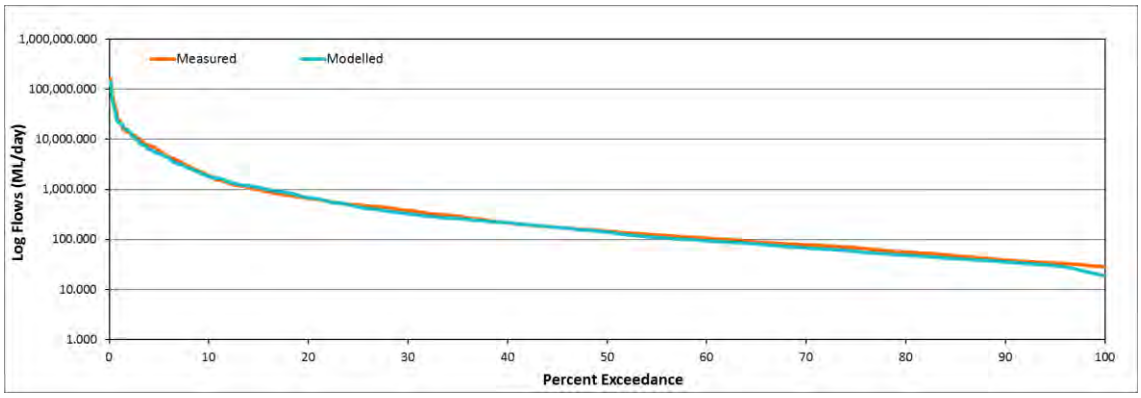


Figure B-10 Log flow duration curve comparison at Boyne River at Milton

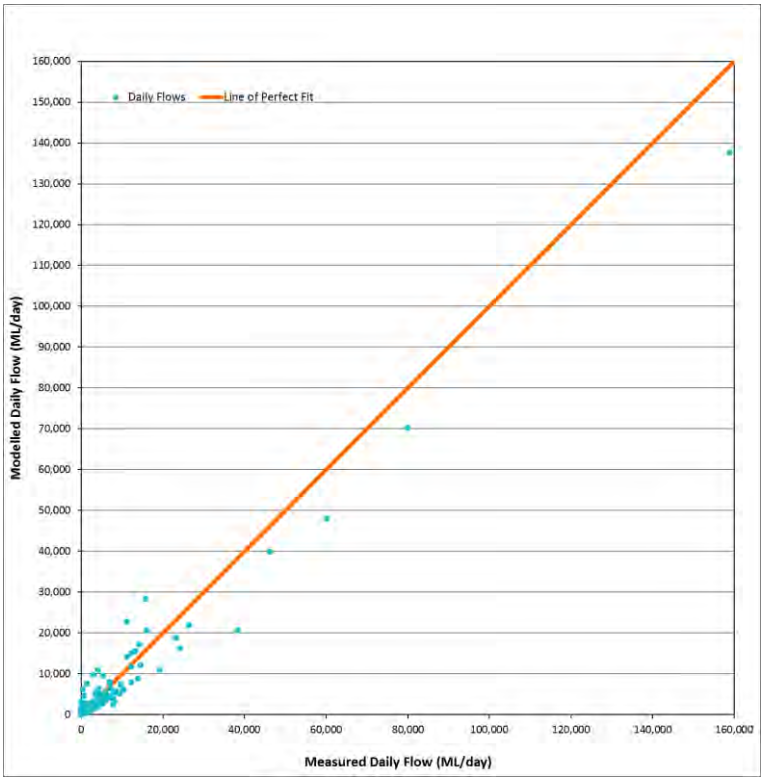


Figure B-11 Modelled vs measured daily flows at Boyne River at Milton

Quantitative Model Performance Analysis

A quantitative model performance assessment was undertaken on the resulting model predictions as this provides lumped measures of average errors in representing measured data. The statistical performance of the rainfall runoff model calibration was measured through the following four quantitative performance measures:

- Nash-Sutcliffe efficiency (NSE) coefficient: The NSE coefficient is used to assess the predictive power of hydrological models. An efficiency of 1 corresponds to a perfect match of modelled discharge to the observed data. An efficiency of 0 indicates that the model predictions are only as accurate as the mean of the observed data. An efficiency of less than 0 occurs when the observed mean is a better predictor than the model. The NSE coefficient is calculated using the following equation (Moriasi *et al.* 2007):

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n} \left(Y_i^{obs} - Y^{mean}\right)^2} \right]$$

- Percent bias (PBIAS): The average tendency of modelled data to be greater or less than the corresponding observed data. PBIAS is calculated using the following equation (from Moriasi et al, 2007):

$$\mathrm{PBIAS} = \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim}\right) * (100)}{\sum_{i=1}^{n} \left(Y_i^{obs}\right)} \right]$$

- Root Mean Squared Error (RMSE) to observed data standard deviation ratio (RSR): An evaluation statistic developed by Moriasi et al (2007) which standardises the RMSE by the standard deviation of the observed data. RMSE is the most common statistic used to measure precision. RSR is calculated using the following equation (from Moriasi et al, 2007):

$$\mathrm{RSR} = \frac{\mathrm{RMSE}}{\mathrm{STDEV}_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim}\right)^2}\right]}{\left[\sqrt{\sum_{i=1}^{n} \left(Y_i^{obs} - Y^{mean}\right)^2}\right]}$$

Table B-5 summarises the quantitative performance of the rainfall runoff model calibrated at all gauges. Monthly PBIAS, NSE and RSR values estimated for calibrations at all gauges were then compared against a general performance ratings developed by Moriasi et al (2007) (see Table B-6).

Table B-5 Quantitative catchment model performance

Gauge Location	NSE Daily	NSE Monthly	PBIAS (%)	RSR Daily	RSR Monthly
Calliope River at Castlehope	0.94	0.98	3.72	0.25	0.16
Boyne River at Milton	0.95	0.96	8.62	0.22	0.21

Table B-6 General performance ratings for model statistics for a monthly time step –stream flow (adapted from Moriasi et al, 2007)

Performance Indicator	NSE	PBIAS (Stream flow)	RSR
Very good	0.75 < NSE ≤ 1	PBIAS < ±10	0 ≤ RSR ≤ 0.5
Good	0.65 < NSE ≤ 0.75	±10 ≤ PBIAS < ±15	0.5 < RSR ≤ 0.6
Satisfactory	0.5 < NSE ≤ 0.65	±15 ≤ PBIAS < ±25	0.6 < RSR ≤ 0.7
Unsatisfactory	NSE ≤ 0.5	PBIAS ≥ ±25	RSR > 0.7

Table B-7 summarises the quantitative performance of the catchment model based on the general performance ratings for monthly NSE, percent bias, and monthly RSR. The indicators of model performance were very good for all calibrations, apart from percent bias at the Boyne River at Milton, which was good.

Table B-7 Catchment Model Performance against General Performance Ratings

Gauge Location	NSE Monthly	PBIAS (%)	RSR Monthly
Calliope River at Castlehope	0.98	3.72	0.16
Boyne River at Milton	0.96	8.62	0.21

Rainfall Runoff model Validation

The rainfall runoff model of the Calliope Basin was validated using the 2013 event flows recorded at Castlehope gauge, while the rainfall runoff model of the Boyne Basin was validated using the 2010 event flows recorded at Marlua and Nagoorin gauges. Figure B-12 through Figure B-14 illustrate the validation performance of the catchment model.

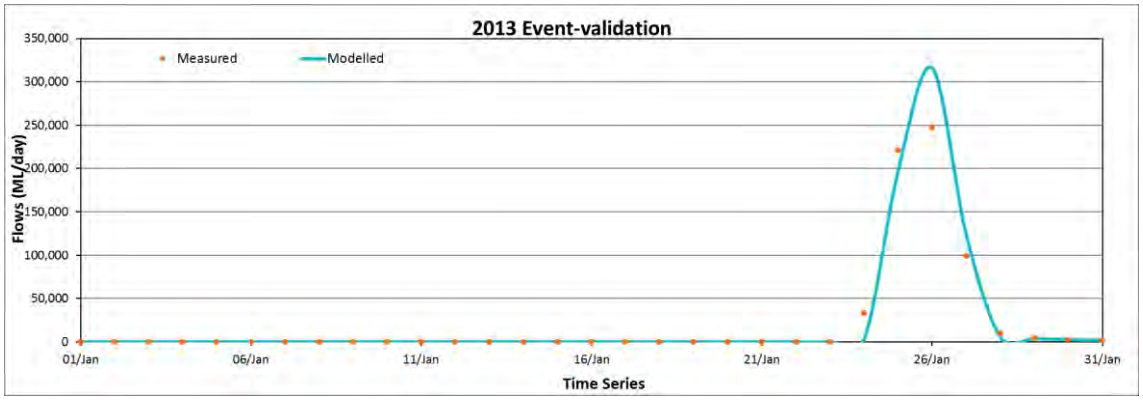


Figure B-12 Time series comparisons at Calliope River at Castlehope during the 2013 flood event

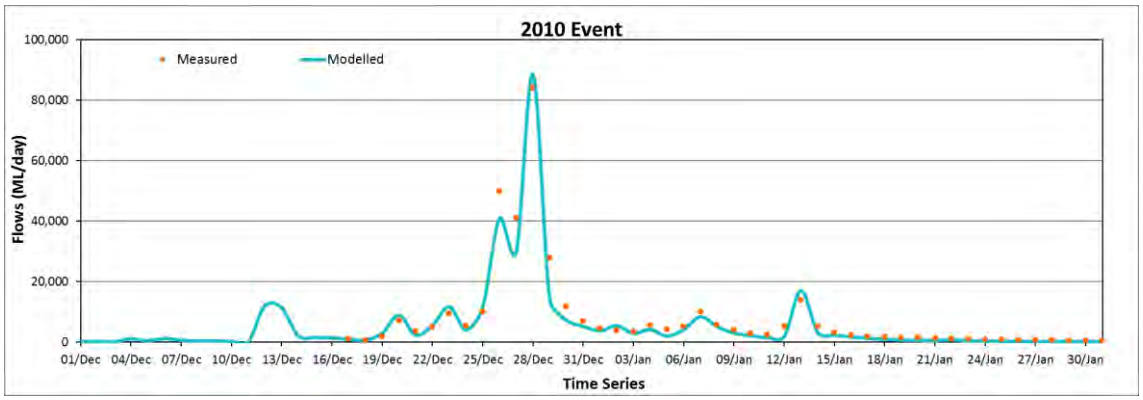


Figure B-13 Time series comparison at Boyne River at Nagoorin during the 2010-2011 flood event

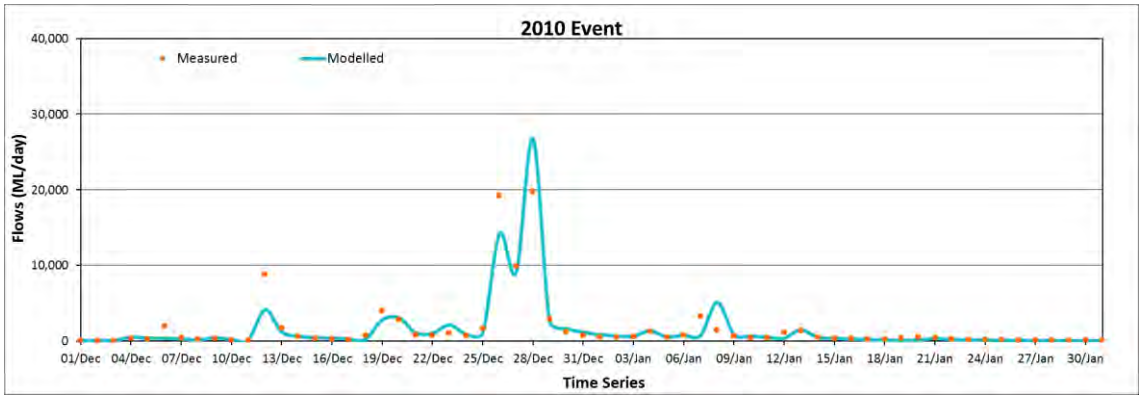


Figure B-14 Time series comparison at Diglum Creek at Marlua during the 2010-2011 flood event

Key Findings

Key findings from the rainfall runoff model calibration are presented below.

- The hydrologic calibration is considered very good for the Calliope and Boyne River basins. In particular the hydrograph plots show well developed correlations in patterns and magnitudes of flows, and the flow duration curves show good correlation in flow exceedance probability. The quantitative performance for monthly NSE, monthly RMSE, and percent bias were also within the general performance ratings for a very good model.
- The hydrologic model validation is also considered good for both the Calliope and Boyne River basins. In particular the hydrograph plots show well developed correlations in patterns. However, variations observed between measured and modelled high flows at Castlehope and Marlua gauges.

Scenario Modelling

The catchment model calibrated (and validated) to represent 2010/2011 and 2013 flood events was used to simulate the following rainfall event scenarios:

- An “average” major wet season event.
- A 1:10 ten year event.

The “average” major wet season event was simulated based on the median 3 day rain event from a group of the highest annual rain events over 25 years (between 1990 and 2014). The 1 in 10 year event was simulated based on a design rainfall estimated using intensity-frequency-duration (IFD) deign rainfall chart obtained from “AR&R87 IFDs” tool for the Gladstone Radar (BoM) coordinates. In both these scenarios rainfall across the entire Boyne, Calliope, and Curtis Island regions was assumed to be homogenous

The modified base-case catchment model was used to estimate flows and pollutant loads for the following scenarios:

- A fully vegetated (pre-European) catchment with no Awoonga Dam.
- A future scenario with predicted developments after 20 years.

Forest land use was defined across the entire Boyne, Calliope and Curtis Island catchments to simulate the pre-European scenario, while the current land use was modified based on the proposed future developments to simulate the future scenario.

Appendix C Hydrodynamic Modelling Methodology and Calibration

Hydrodynamic Model

The model used for this study is based on flexible mesh finite volume TUFLOW FV modelling software, which allows fine detail to be included in areas of interest with a lower, but sufficient, resolution elsewhere. The model was run in three dimensional mode for the purposes of this study, due to the potential for significant temperature and salinity stratification caused by large fresh water inflows from extreme rainfall events.

Model Extent

The model network extends over an area of some 2000 km^2, incorporating Gladstone Port and an ocean boundary extending up to 30km offshore. Inclusive in this model are the key areas between Curtis Island, Facing Island and the mainland, as well as all the predominant tidal flows into the Port, being the main ocean entrance at the eastern model boundary, the North Channel between Curtis and Facing Islands and The Narrows. Tidal tributaries incorporated into the model include the Calliope River, Auckland Inlet, South Trees Inlet and the Boyne River.

Model Bathymetry

The model bathymetry is based on a Digital Elevation Model (DEM) of the Port, which has been derived from the following survey components:

- Detailed hydrographic survey data of the dredged channels, swing basins and berths as provided by MSQ and GPC, together with the progressive inclusion of ongoing surveys to ensure that the model bed levels match the actual bathymetric configuration at the time of the simulation period;
- Detailed hydrographic survey data of broad areas of the Port, provided by MSQ and GPC; and
- Hydrographic survey data and outlines of the edges of the shoreline, mangroves and saltpans used in producing Boating Safety Charts of the area, as provided by MSQ.

Typical levels have been adopted for the edges of the mangroves and saltpan areas for interpolation in those upper inter-tidal zones where no specific survey level data is available. The various data components have been combined and prioritised with respect to date and detail where there is overlap in producing a base DEM. For modelling purposes, all data has been adjusted to a constant datum (AHD) using information provided by MSQ at various sites. The best available representation of the final post-LNG dredging bathymetry adjacent to Curtis Island was used in the model, and clearance survey data was used to incorporate the WICET dredging. The adopted model bathymetry and extent of the model coverage is illustrated in Figure C-1.

Model Mesh

In developing the hydrodynamic model, consideration has been given to the underlying bathymetry in defining the mesh configuration. For example, model resolution was enhanced at locations of rapidly varying bathymetry or expected high flow regions based on channel definition, as well as to represent the dredged channels, swing basins and berth pockets.

To accurately represent the stratification of the water column due to vertical gradients in temperature and salinity, three sigma layers were used in conjunction with up to 14 additional vertical z layers. These multiple layers together with inclusion of baroclinic pressure gradient terms in the solution scheme allows for the development of a stratified water column in the model.

Boundary Conditions

Tidal and river flows that drive the hydrodynamics of the system were applied as boundary conditions to the model. The tidal inflows into the model were introduced by providing time-varying water level inputs at three open boundaries:

(1) Main Ocean Boundary: Cape Capricorn on Curtis Island to Richards Point on Rodds Peninsula;

(2) North Entrance: Located across the North Channel entrance between Facing and Curtis Islands; and

(3) Division Point: The Narrows.

Catchment inflows were taken from the catchment model and placed as point sources at key locations within the model. A total of 71 contributing point sources were input to the model as a point source located within the top one metre of the water column (Figure C-2). Catchment inflows included the flow rate, salinity, temperature, suspended sediment concentration, and nutrient tracer concentrations.

Given the influence of wave energy on sediment resuspension is significant outside Gladstone harbour, it is necessary to model the effect that waves have on the sediment dynamics through the implementation of a SWAN spectral wave model (Delft University of Technology, 2006). Wave model outputs were input as a boundary condition for the TUFLOW FV model to enable the calculation of wave-related bed shear stresses. An existing SWAN model of the Gladstone region was used to generate the wave forcing for these scenarios.

Due to the large scale of the model, regional oceanic effects needed to be incorporated in the offshore open ocean boundary conditions. This was done using HYCOM global ocean circulation model hindcast outputs (www.hycom.org). This model provided 3D current, salinity and temperature data which was applied on the ocean boundary in combination with the tidal water level variation. Further boundary conditions were also applied to capture atmospheric exchanges. These boundary conditions were derived from the NOAA NCEP, Climate Forecast System Reanalysis (CFSR) (http://www.ncep.noaa.gov/) and included wind, temperature, humidity, short and long wave radiation, which were applied on a spatially varying grid throughout the model domain with a temporal resolution of one hour.

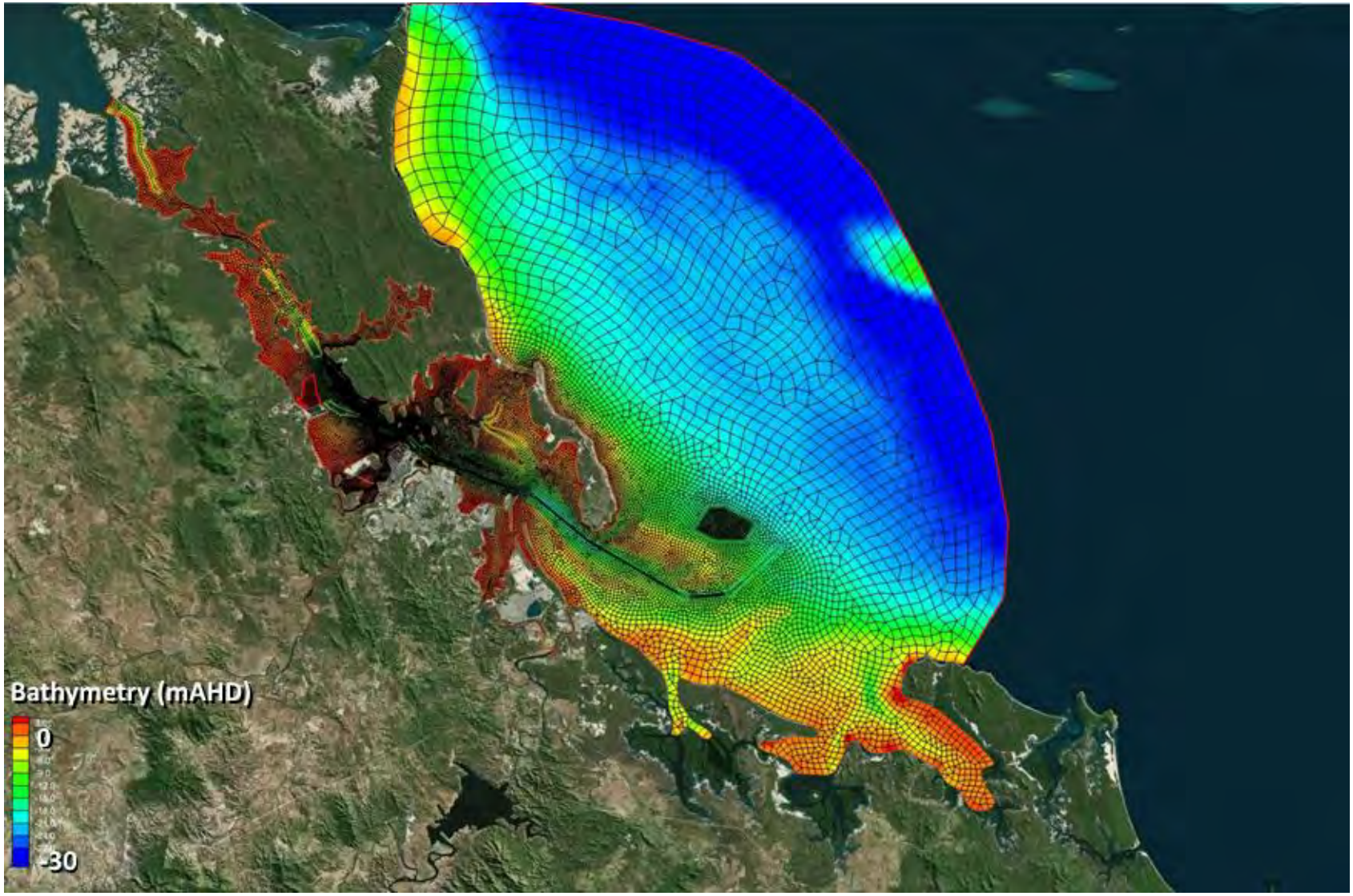


Figure C-1 TUFLOW FV Mesh of the Gladstone Region

Figure C-2 Catchment Inflow Locations

Model Calibration

The TUFLOW FV model was developed to serve as a tool to visualise and quantify the temporal and spatial variation of key parameters that may affect coral hard cover. In order to achieve this it was important to ensure that the model accurately represented the tidal hydrodynamics. This was achieved through calibration of the modelled water level with tide gauge measurements at South Trees (Figure C-3) and Auckland Point (Figure C-4). The model captures the spring and neap variation of the mixed semidiurnal tide in the Gladstone Harbour region with reasonable accuracy for both water level magnitude and timing.

Complementary to the tidal calibration, recorded data from Vision Environment was used to calibrate salinity and Total Suspended Solids (TSS) at key locations for the January 2013 flood event (shown in the context of reefs in Figure 3-2 and alone in Figure C-5). Locations chosen for primary calibration were the offshore sites SGM1, SGM2 and SGI1. Calibration was also carried out at the other locations where data was available (Figure 3-2, Figure C-5).

Calibration of the sediment dynamics is highly dependent on the conversion factor used between TSS (suspended sediment concentration [mg/L]) and turbidity (a measurement of scattered light [NTU]). This conversion factor is sensitive to a range of factors including the physical and chemical composition of the sediment as well as bio-turbidity levels in the sample. The presence of higher bio-turbidity in fresh water then in sea water means that the fresh water inflows tend to have a much lower conversion factor between NTU and TSS than measured for sea water. For this reason, calibration plots have been made by using the conversion factors (based on field measurements) of 1.6 for sea water and linearly scaled on salinity to a factor of 0.63 for fresh water.

Calibration plots of TSS and Salinity can be seen in Figure C-6 through to Figure C-21. The model displays good overall calibration for salinity especially in the western reaches of the model. Sites such as BG10 and P2 (Figure C-10 and Figure C-13) capture the sharp drops in salinity associated with large fresh water inflows from the 2013 event. Modelled salinity at the offshore site SG1 (Figure C-6) does start to fall too early when compared with the measured data. The reason for this is likely due to inaccuracies in the timing of fresh water inflows. In terms of TSS, the calibration result at all sites is good, showing close correlation to the measured data. The exception to this was site P5 (Figure C-14) where the modelled TSS is higher than the recorded TSS for a period in late January and early February. The model appears to be overestimating the TSS in the fresh water plume, which may be due to limitations in accuracy of the vertical mixing model or perhaps a problem with the level of TSS assumed in the catchment model inputs.

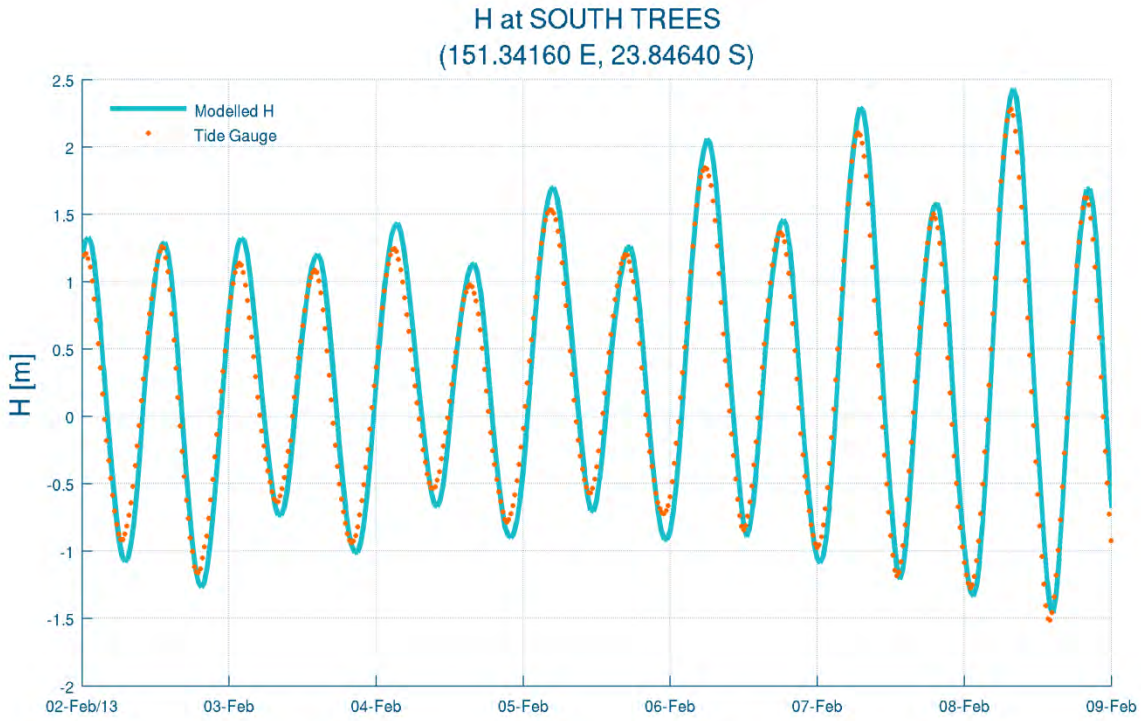


Figure C-3 Tide Calibration at South Trees

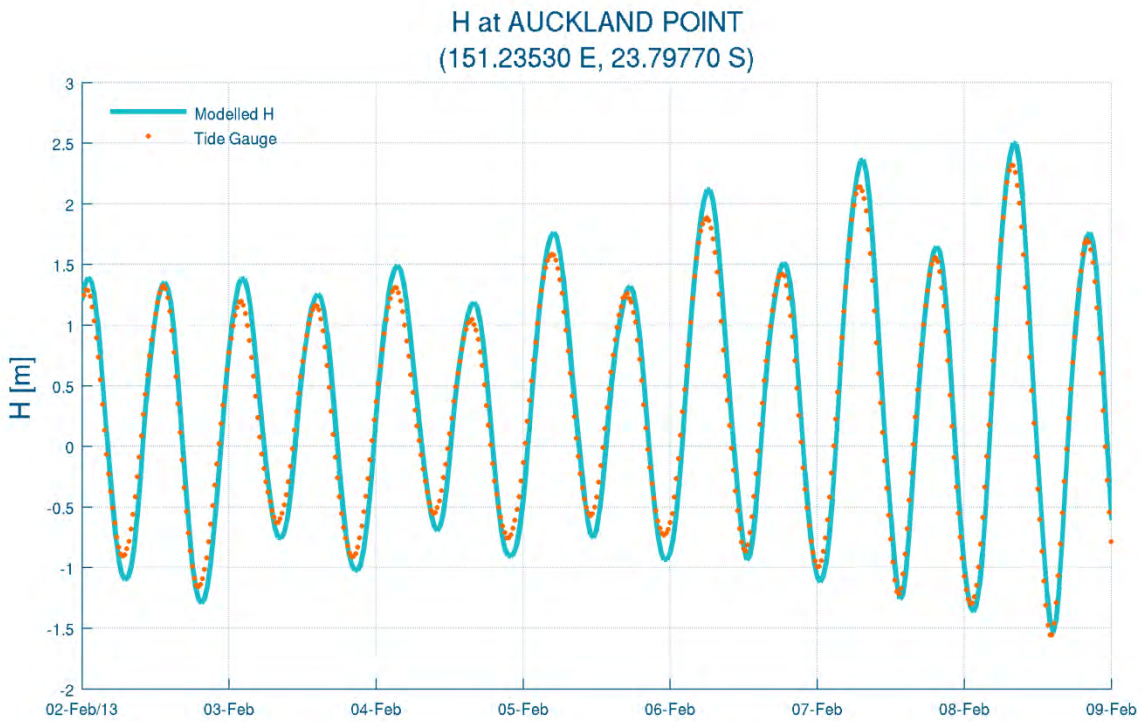


Figure C-4 Tide Calibration at Auckland Point

Figure C-5 Vision Environment's Data Collection Locations

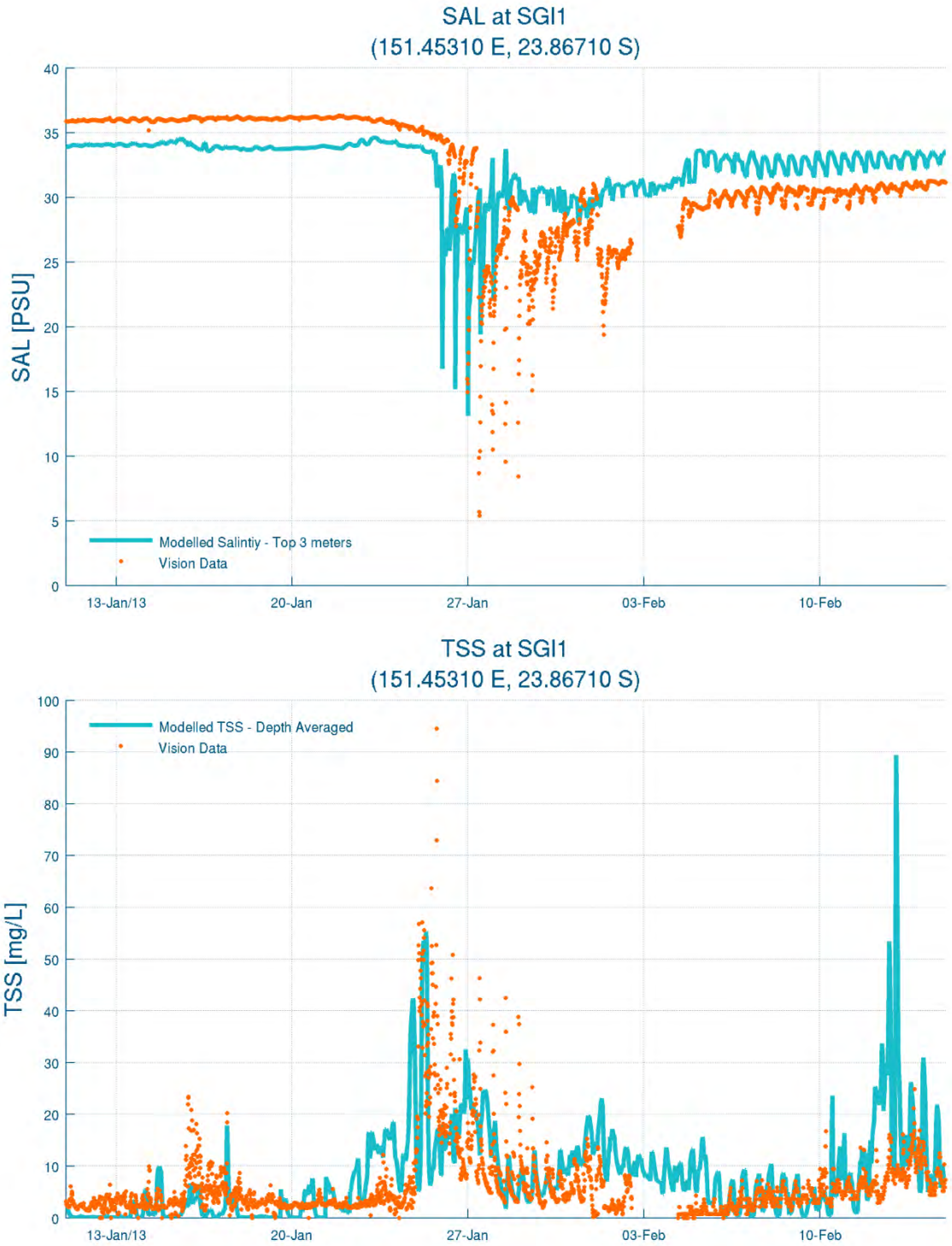


Figure C-6 TSS and Salinity Calibration at Site SG1

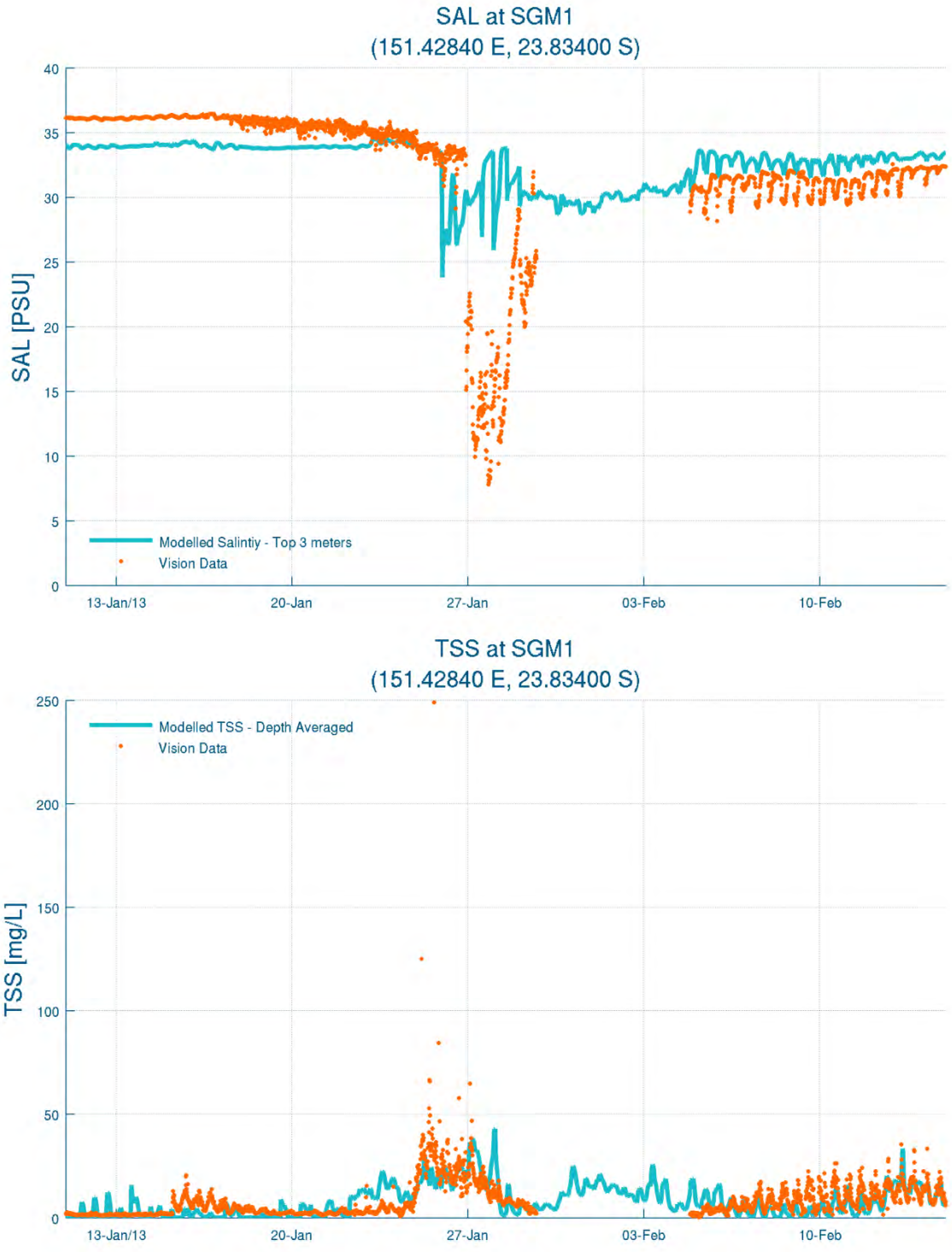


Figure C-7 TSS and Salinity Calibration at Site SGM1

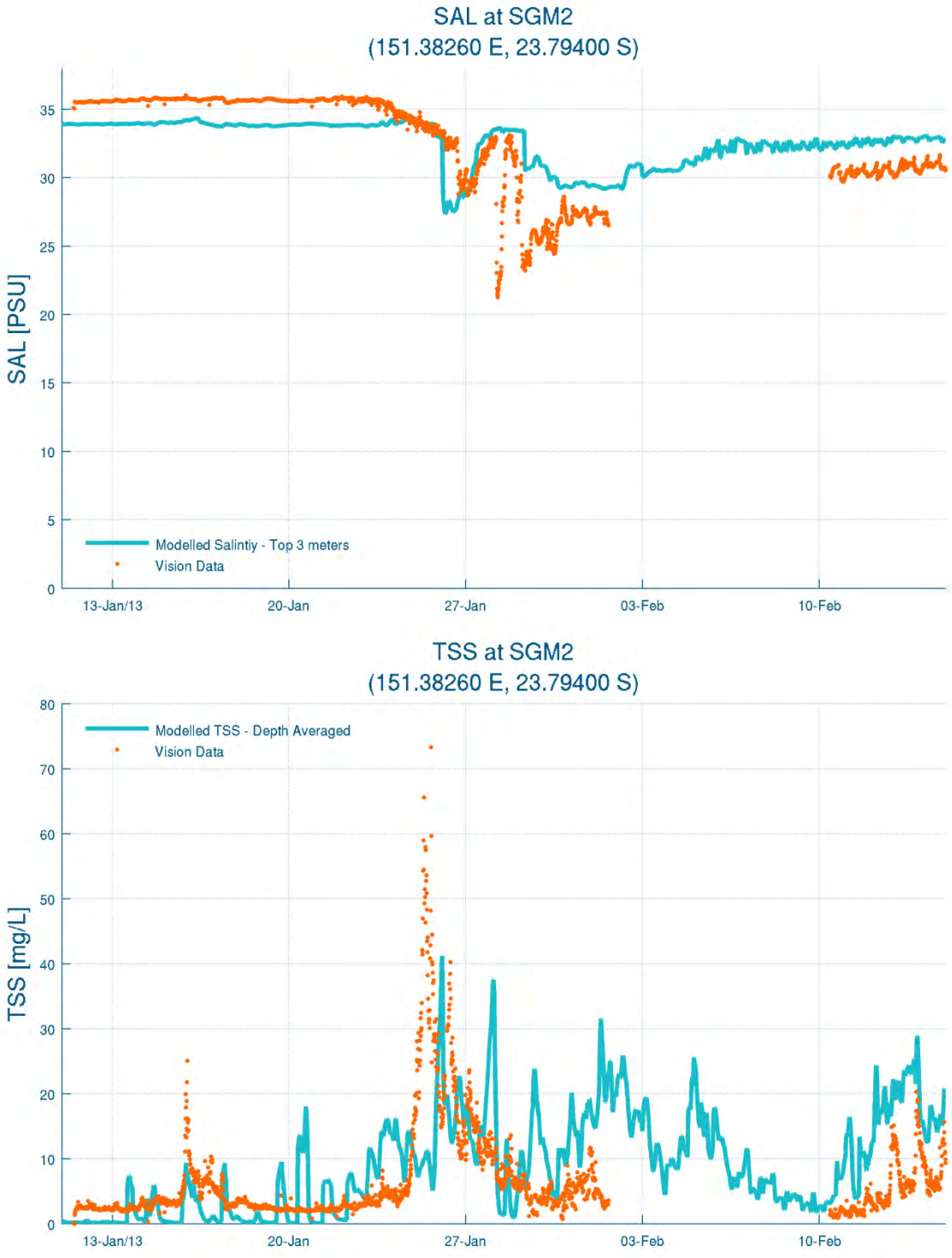


Figure C-8 TSS and Salinity Calibration at Site SGM2

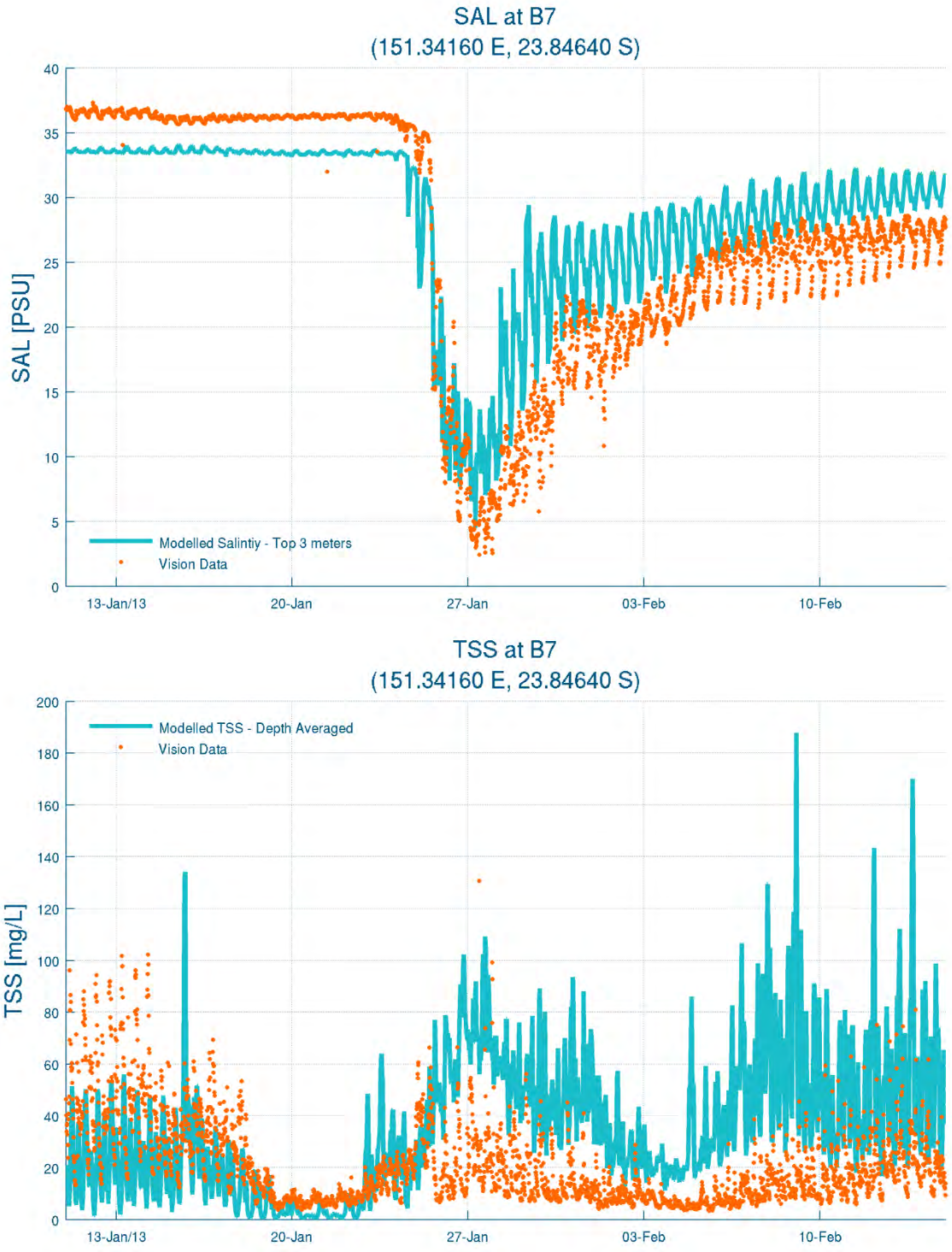


Figure C-9 TSS and Salinity Calibration at Site B7

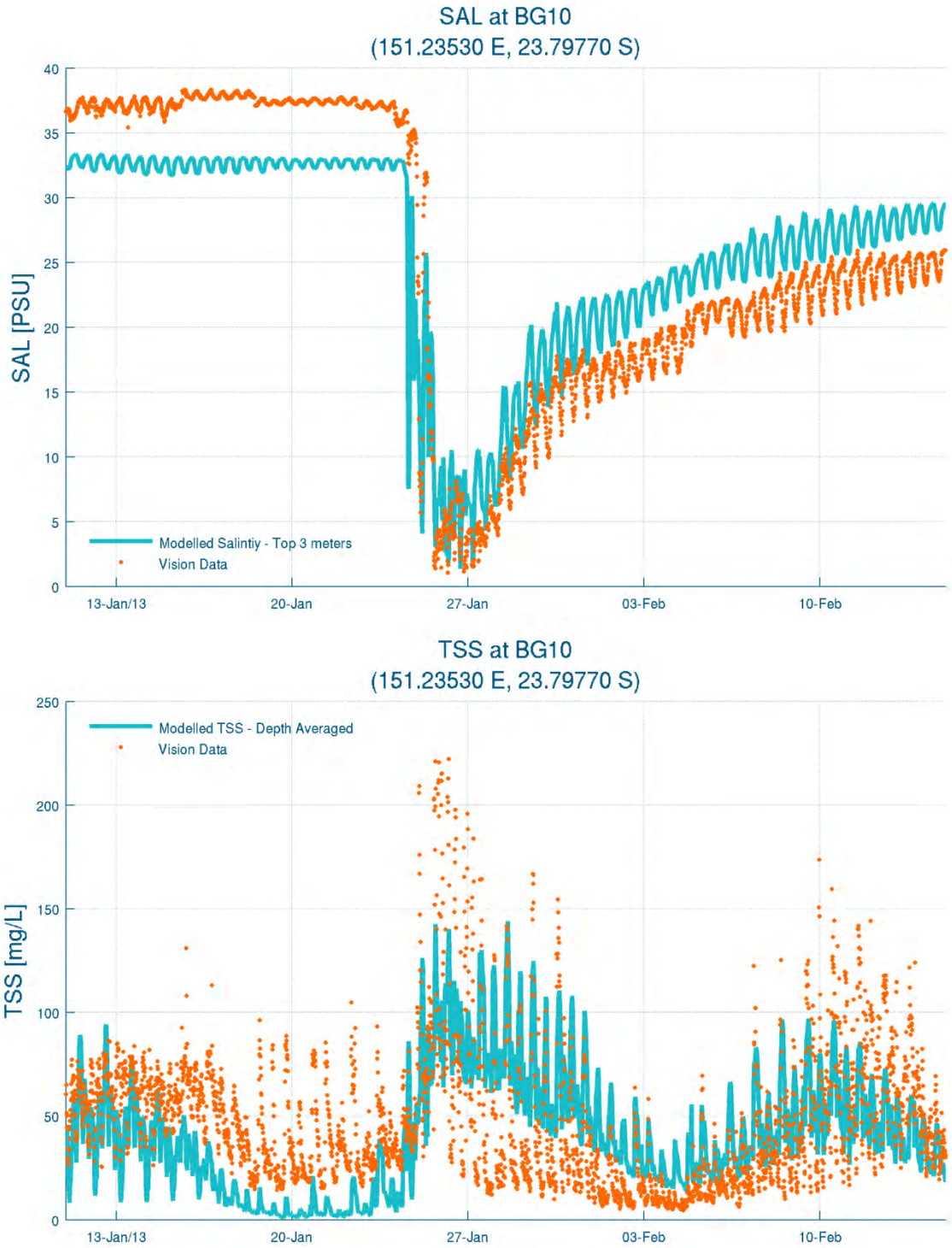


Figure C-10 TSS and Salinity Calibration at Site BG10

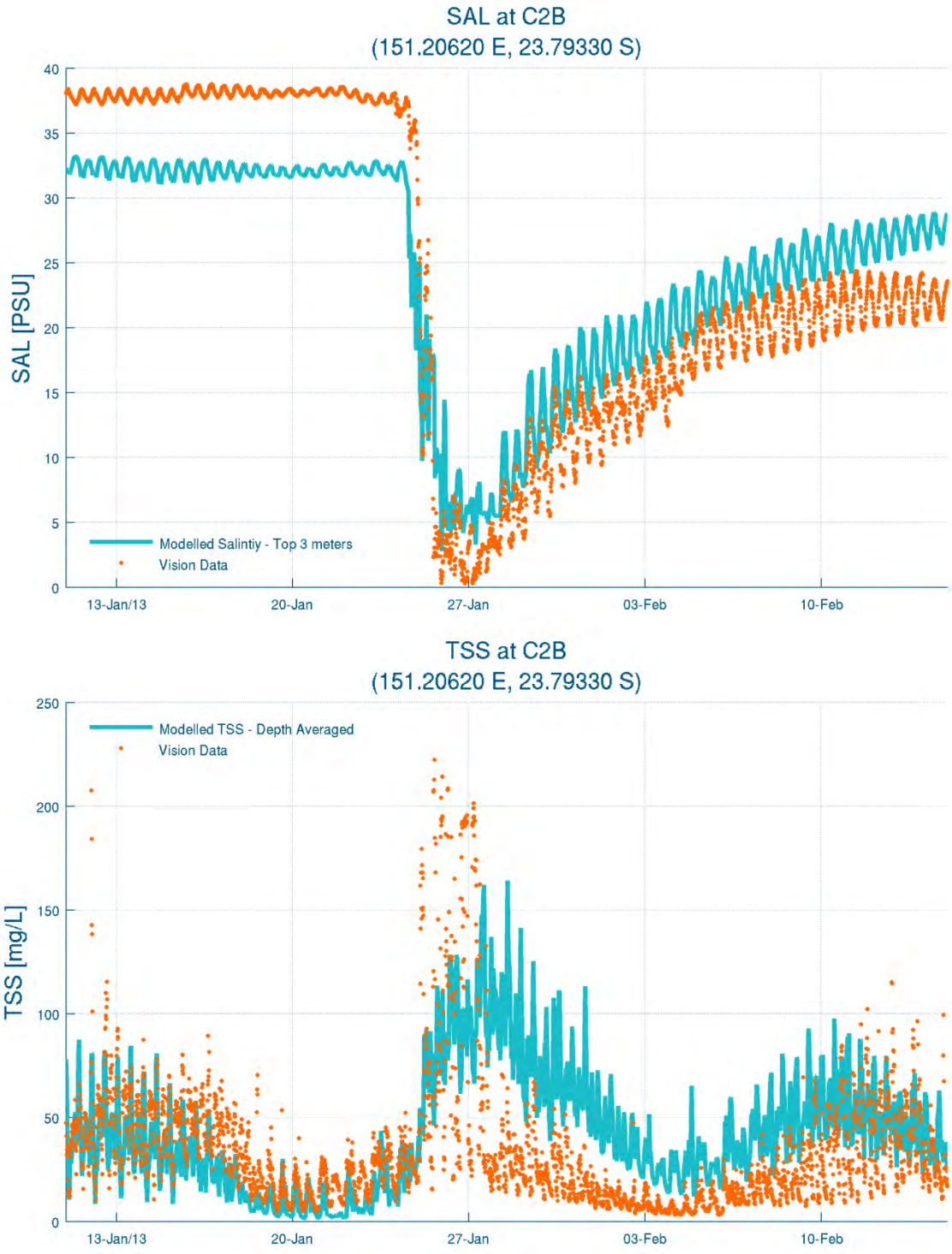


Figure C-11 TSS and Salinity Calibration at Site C2B

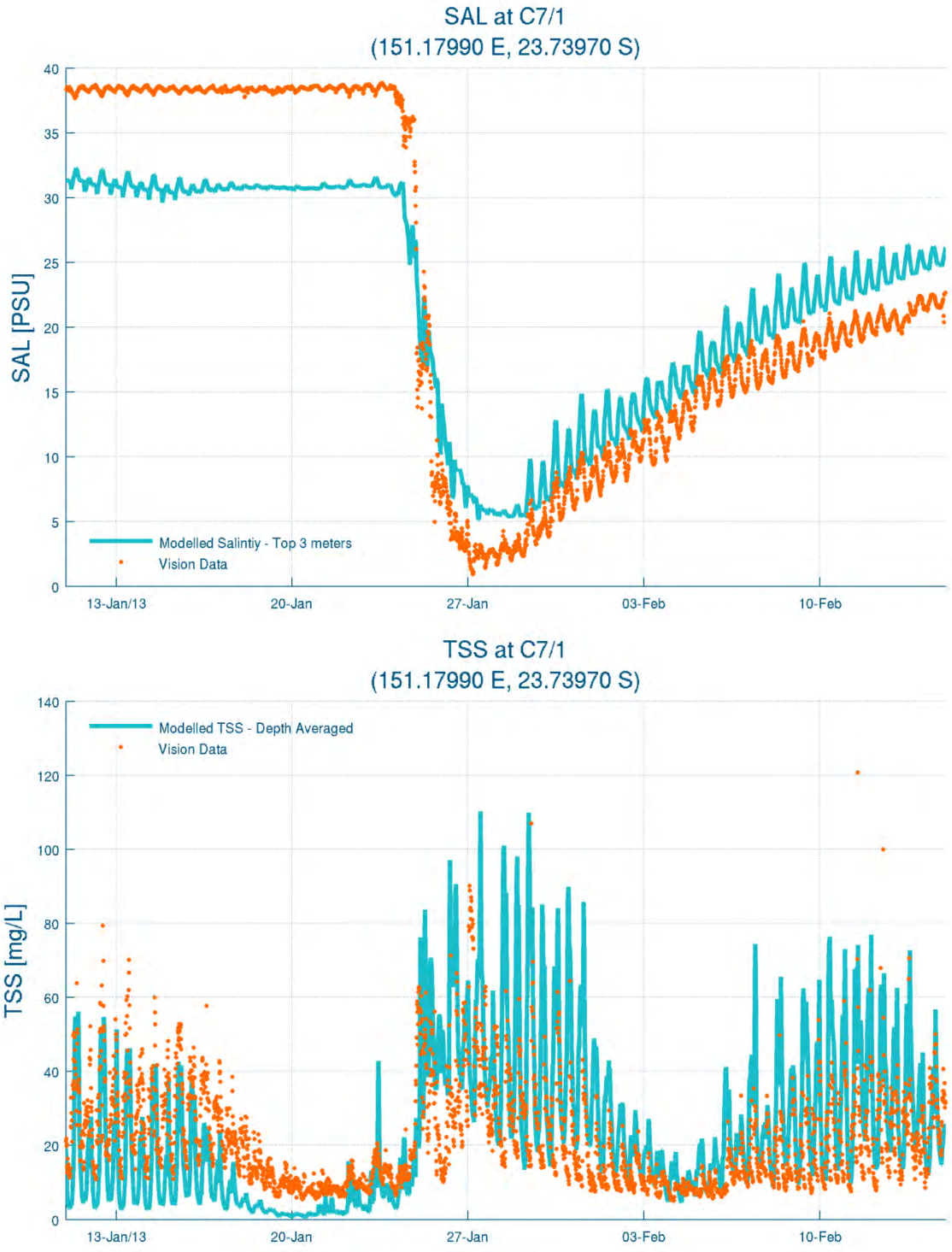


Figure C-12 TSS and Salinity Calibration at Site C7/1

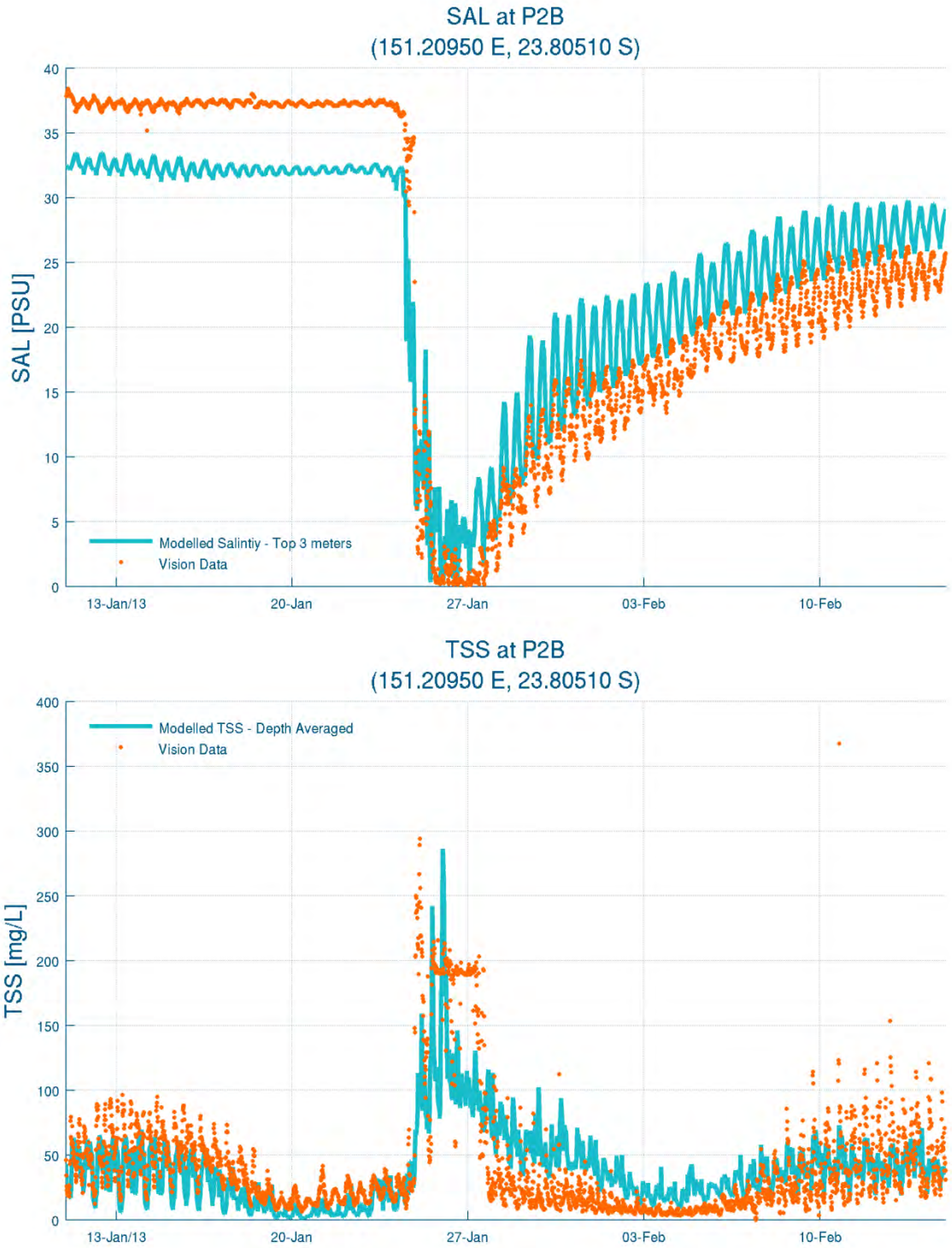


Figure C-13 TSS and Salinity Calibration at Site P2B

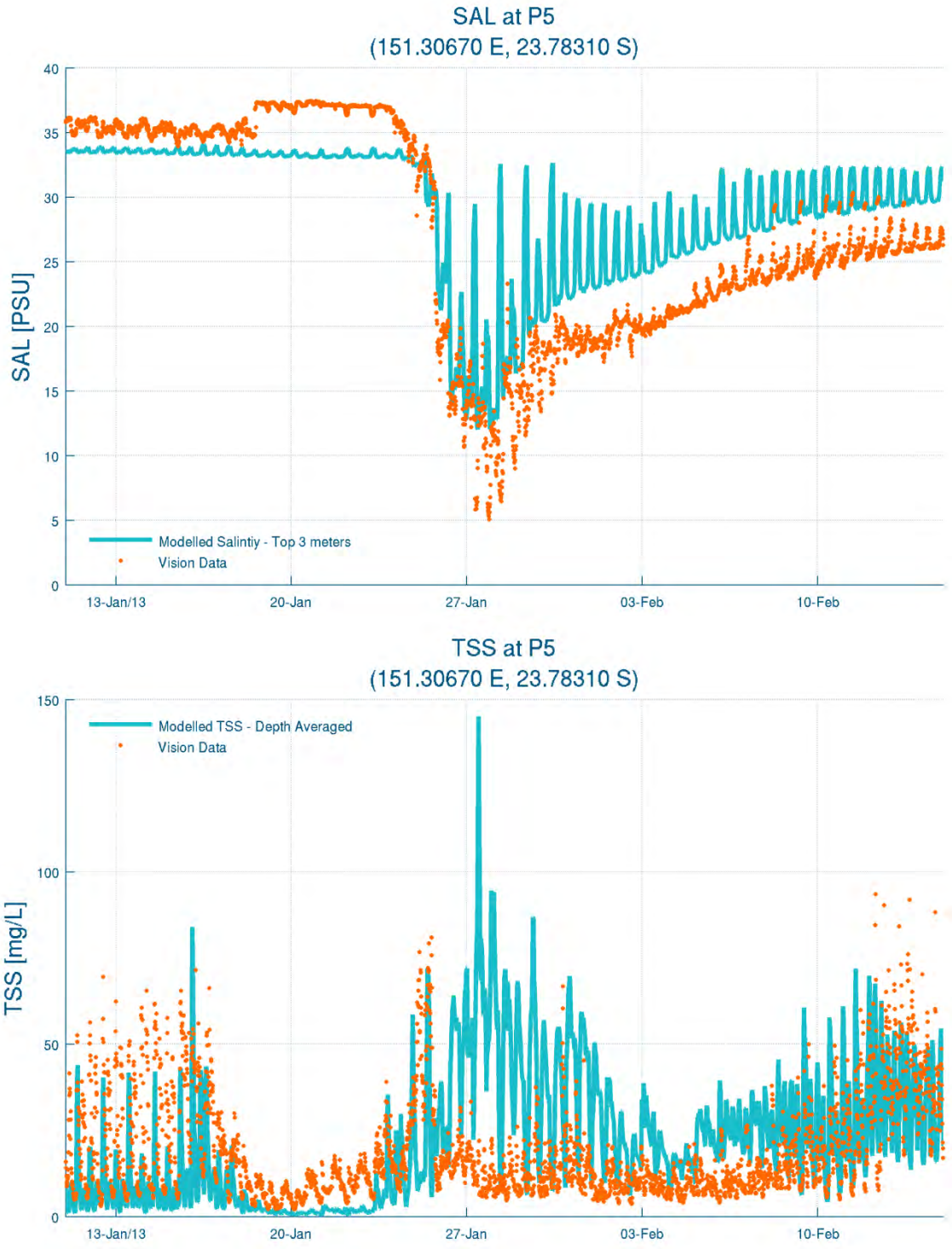


Figure C-14 TSS and Salinity Calibration at Site P5

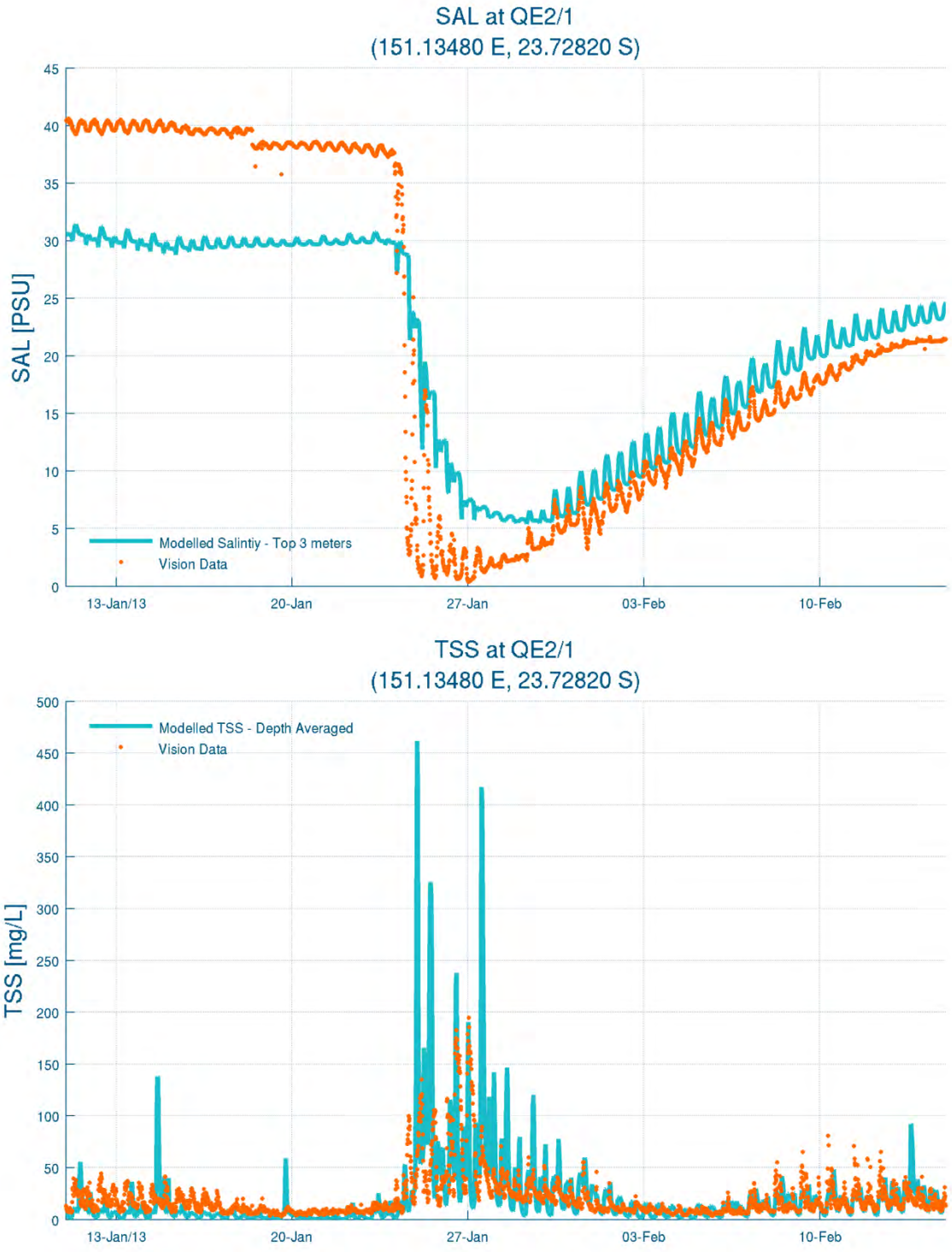


Figure C-15 TSS and Salinity Calibration at Site QE2/1

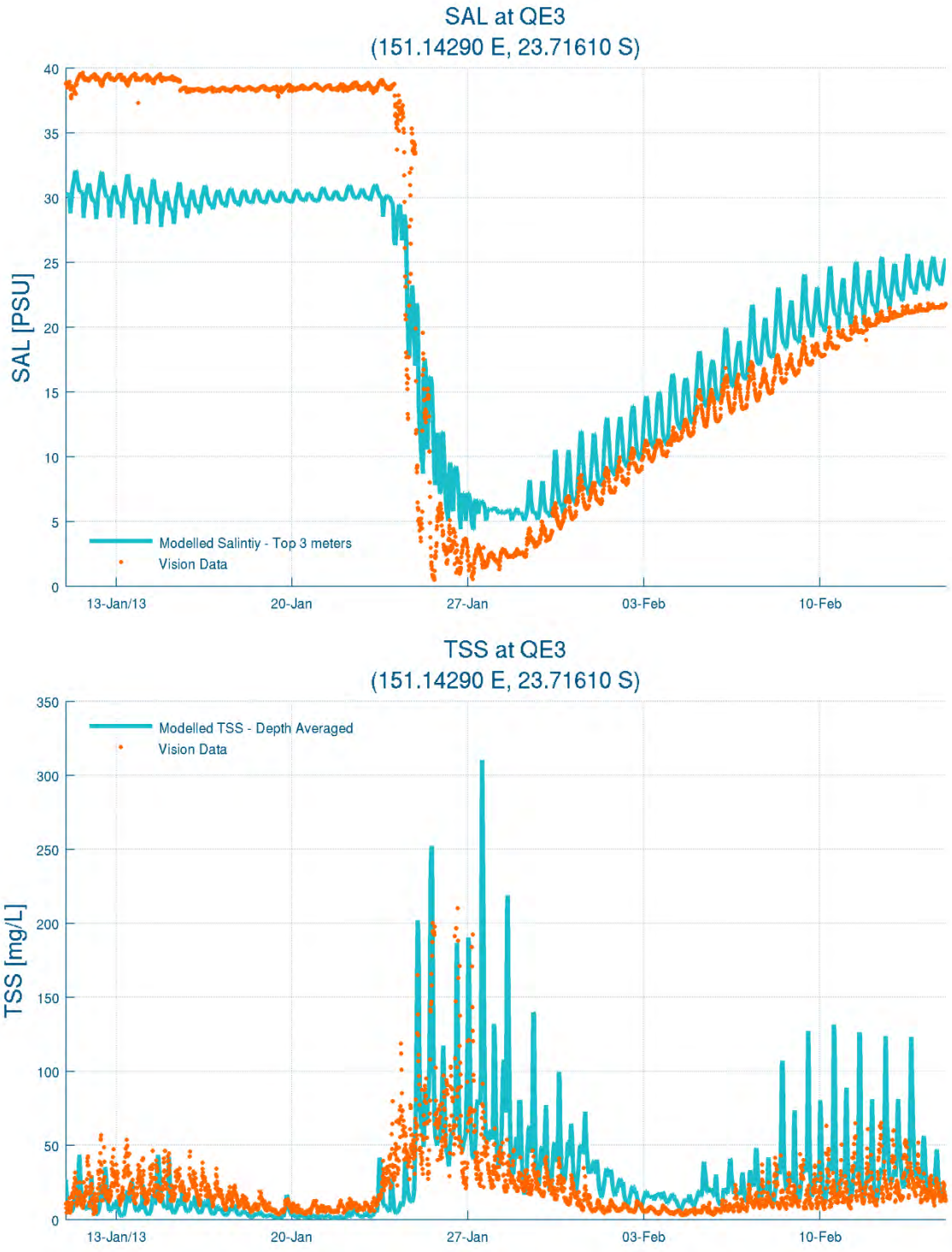


Figure C-16 TSS and Salinity Calibration at Site QE3

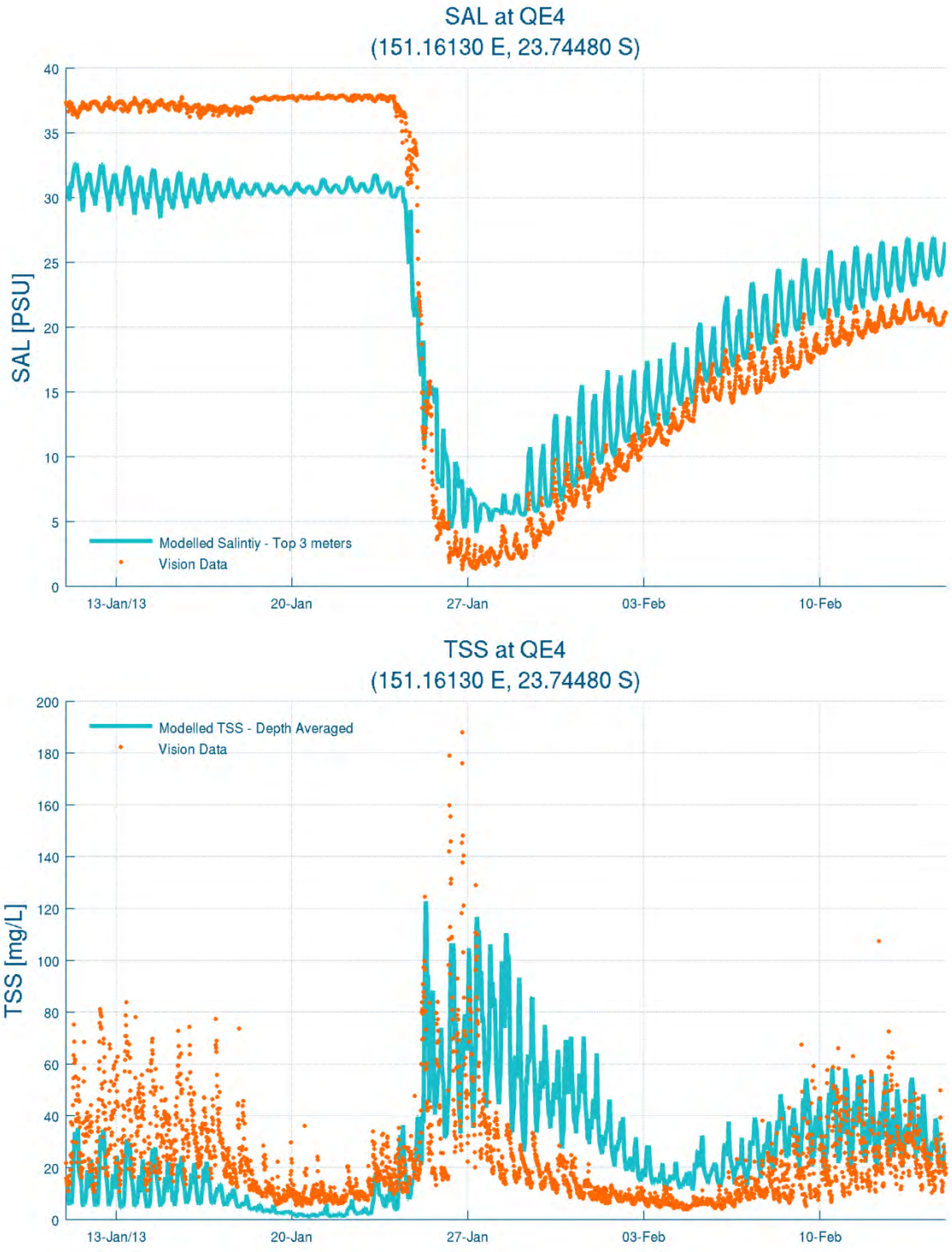


Figure C-17 TSS and Salinity Calibration at Site QE4

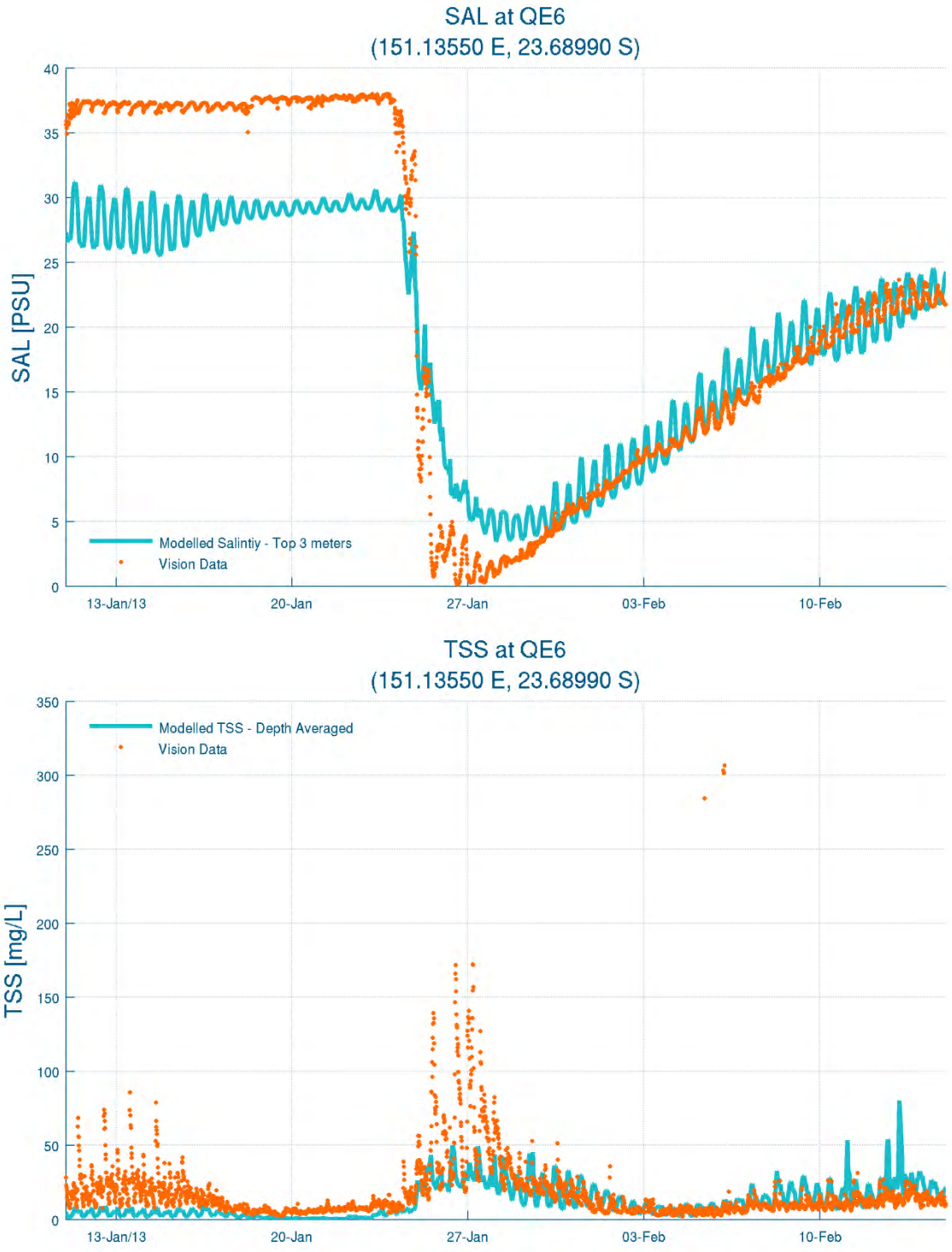


Figure C-18 TSS and Salinity Calibration at Site QE6

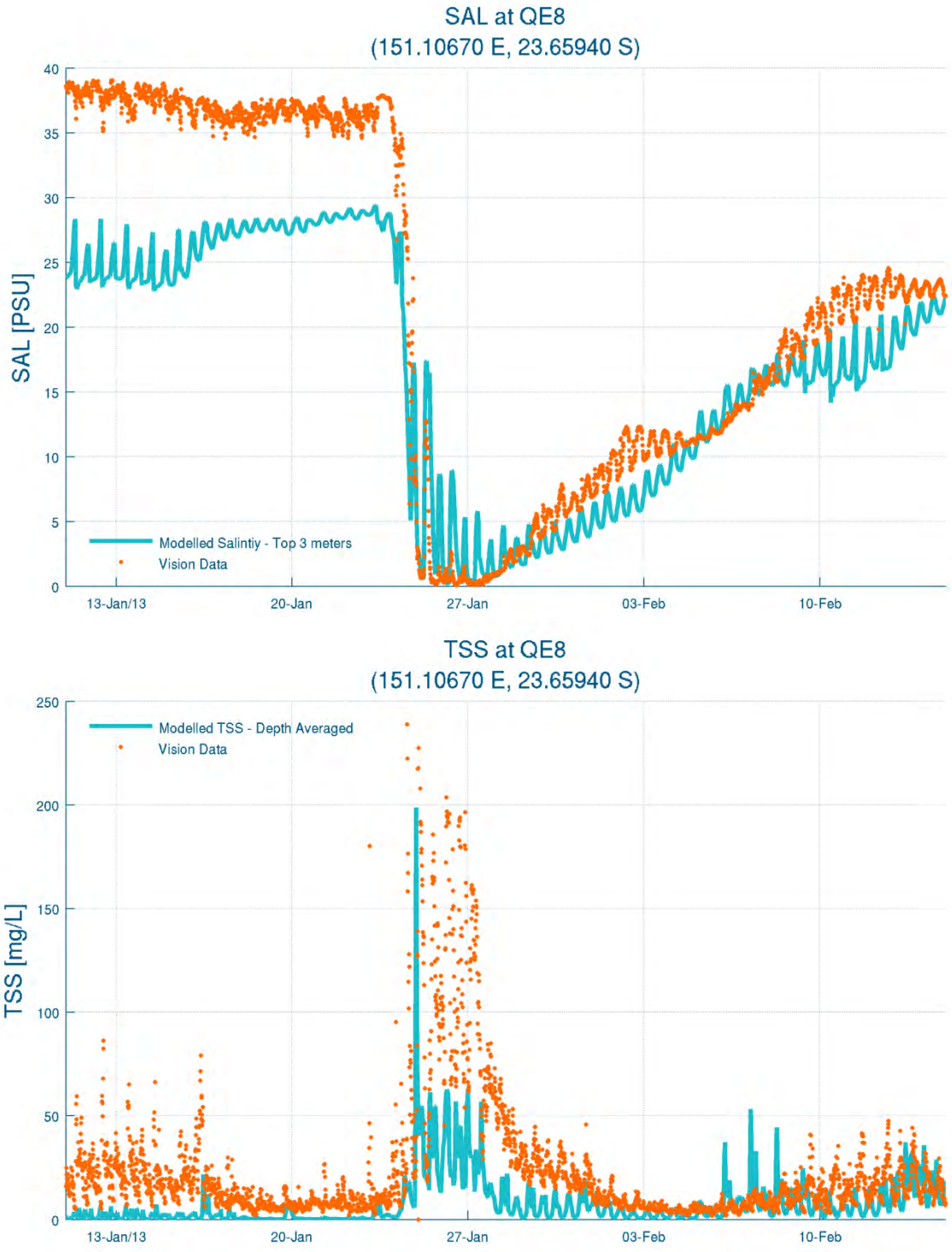


Figure C-19 TSS and Salinity Calibration at Site QE8

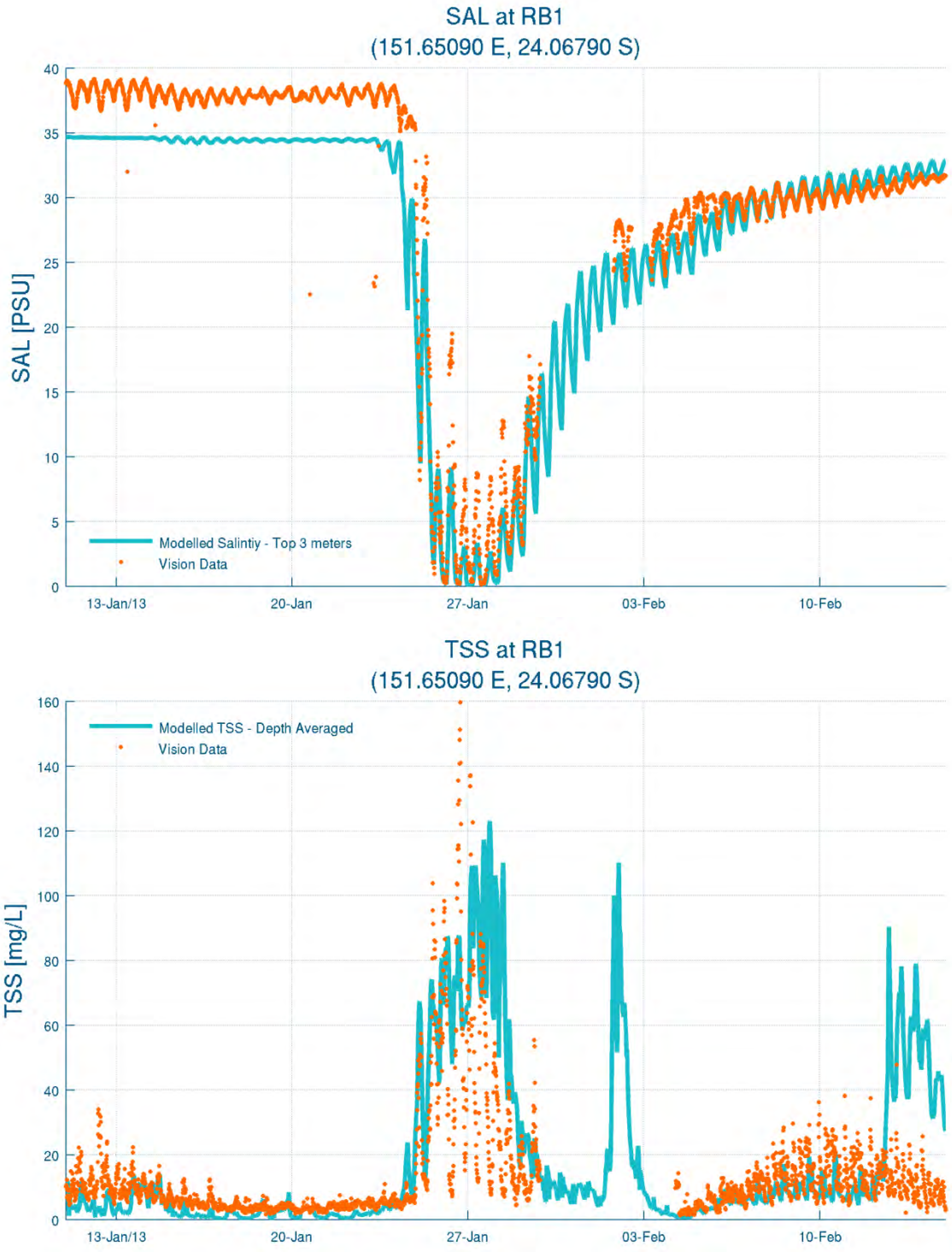


Figure C-20 TSS and Salinity Calibration at Site RB1

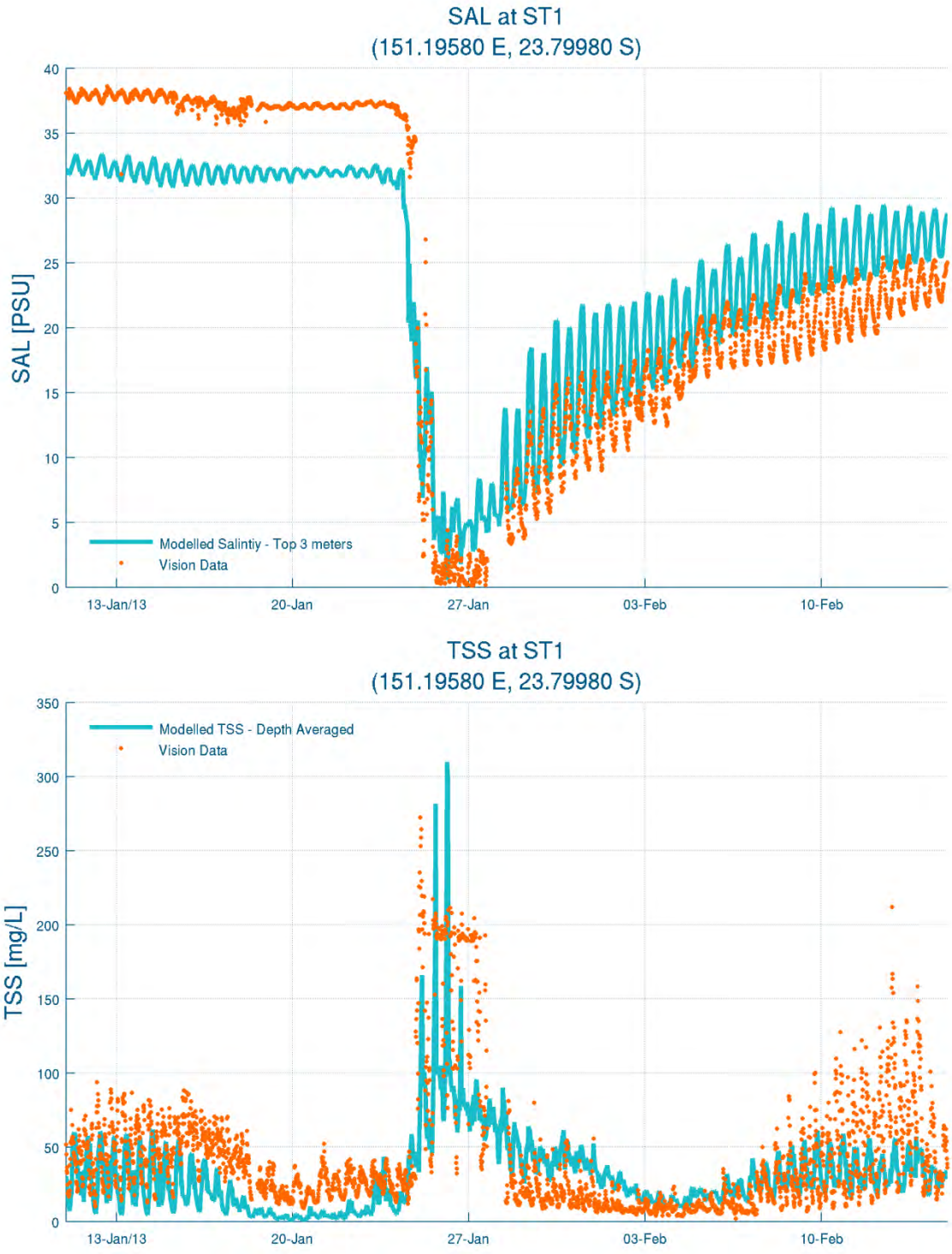


Figure C-21 TSS and Salinity Calibration at Site ST1

Model Scenarios

Six different scenarios were modelled in the assessment of likely causes of coral degradation and to identify potential rehabilitation sites. These scenarios used the same model configuration except for the catchment model inflows and other model boundary conditions. The modelling scenarios included:

(1) January 2013 extreme weather event (existing case) – Used for model calibration and as a base case for impact assessment

(2) January 2013 extreme weather event (future development case)

(3) January 2013 extreme weather event (pre-development case)

(4) January 2011 extreme weather event

(5) A median event for the available rainfall data

(6) 1 in 10 year ARI weather event.

In order to illustrate the high spatial and temporal variation in these 3 dimensional models, percentile plots were generated. These plots show, spatially, the values of certain parameters which are not exceeded n% of the time; where n is the chosen percentile within a 30 day window. The calculations are carried out for a series of 30 day windows (stepping by 10 day increments) throughout the simulation period. The highest set of percentile statistics at each location over all of the 30 day windows is then shown in the final percentile plots.

Different percentiles and depth averaging methods are provided for each parameter according to the significance of the parameter to the relevant sensitive receptor, i.e. corals. A 50th percentile level represents a chronic impact level which is relevant, for example, for characterising sediment deposition rates on coral reefs. A 5th percentile level for salinity represents an acute impact level for the salinity deficit, since the salinity is lower than that level for 5% of the 30 day window. Since corals are more sensitive to shorter duration events for fresh water exposure compared to sediment deposition, there is a focus on acute impacts in the presentation of the salinity results.

Appendix D Additional Hydrodynamic Modelling Results

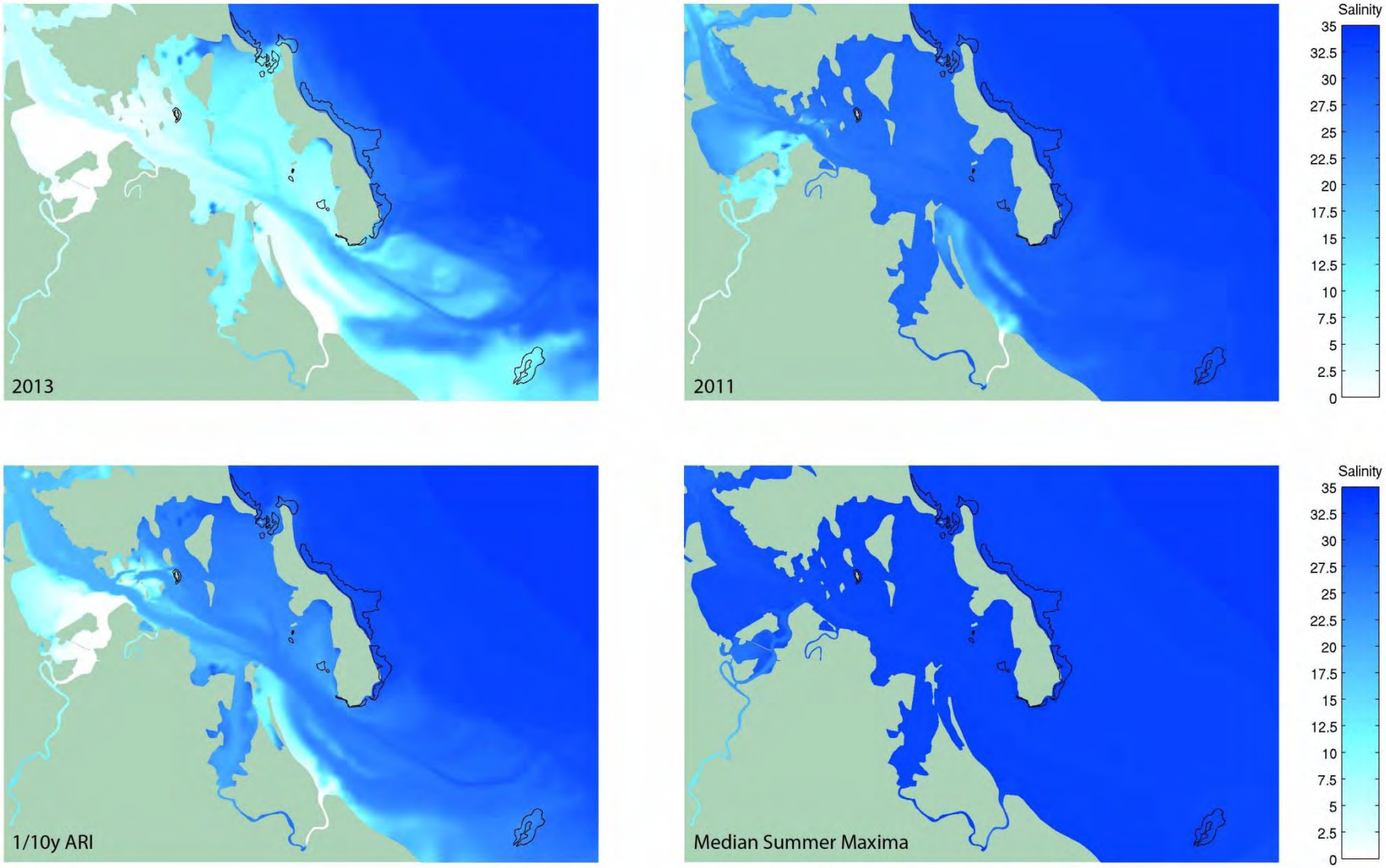


Figure D-1 0th percentile (minimum) salinity under various rainfall scenarios

Appendix E Preliminary Site Selection for Catchment Revegetation

It is widely recognised that terrestrial runoff impacts the condition of marine habitats in the GBR lagoon by reducing water clarity, increasing chlorophyll concentrations, and reducing coral recruitment and diversity (De'ath and Fabricius, 2008). Reducing catchment inputs, such as sediment and nutrients, could improve the condition of marine ecosystems (Wilkinson *et al*., 2015). The Federal and Qld Government Reef Water Quality Protection Plan 2013 to improve GBR water quality is largely focused on reducing sediment and nutrients entering the reef lagoon though improved land management in reef catchments.

Significant clearing for grazing has occurred in the Port Curtis catchment within the Calliope basin and to a lesser extent the Boyne basin. This has included substantial clearing in the upper catchments within eucalypt woodlands on the hills, lowlands and floodplains (Figures E1 to E8). As previously discussed, comparisons between the pre-clearing catchment and the present case show that during extreme events, catchment clearing has resulted in substantially more freshwater, suspended solids and nutrients entrained in floodwaters entering Port Curtis.

Improving tree and surface vegetation cover and reducing surface disturbance by livestock in cleared areas of the catchment to increase rain infiltration into the soil, could reduce runoff, sedimentation and nutrient loading into Port Curtis. Based on the gully management techniques for GBR grazing lands developed by Wilkinson *et al.* (2015), a combination of land-based rehabilitation practices could be applied at cleared, bare and eroded sites, to improve vegetation cover and to reduce runoff. Techniques could include (after Wilkinson *et al.,* 2015):

- Passive gully management such as redistribution of grazing pressure away from erosion prone sites and managing road and fence infrastructure to reduce concentrated surface water runoff
- Low technology revegetation techniques including fencing, seeding to promote high levels of pasture biomass using perennial tussock grasses with large basal areas (for e.g. the native species *Heteropogon contortus* and *Themeda triandra*), fire management to maintain pasture species, weed management (e.g. burning rubbervine in creek lines), and avoiding clearing woody vegetation
- Active gully management such as revegetation, engineering solutions to slow runoff including installation of small sediment trapping structures such as gully ‘stick traps’ in low volume catchments and check-dams with greater runoff volumes, contouring banks to detain and divert runoff, bank re-contouring and gully reshaping to divert runoff and promote natural revegetation.

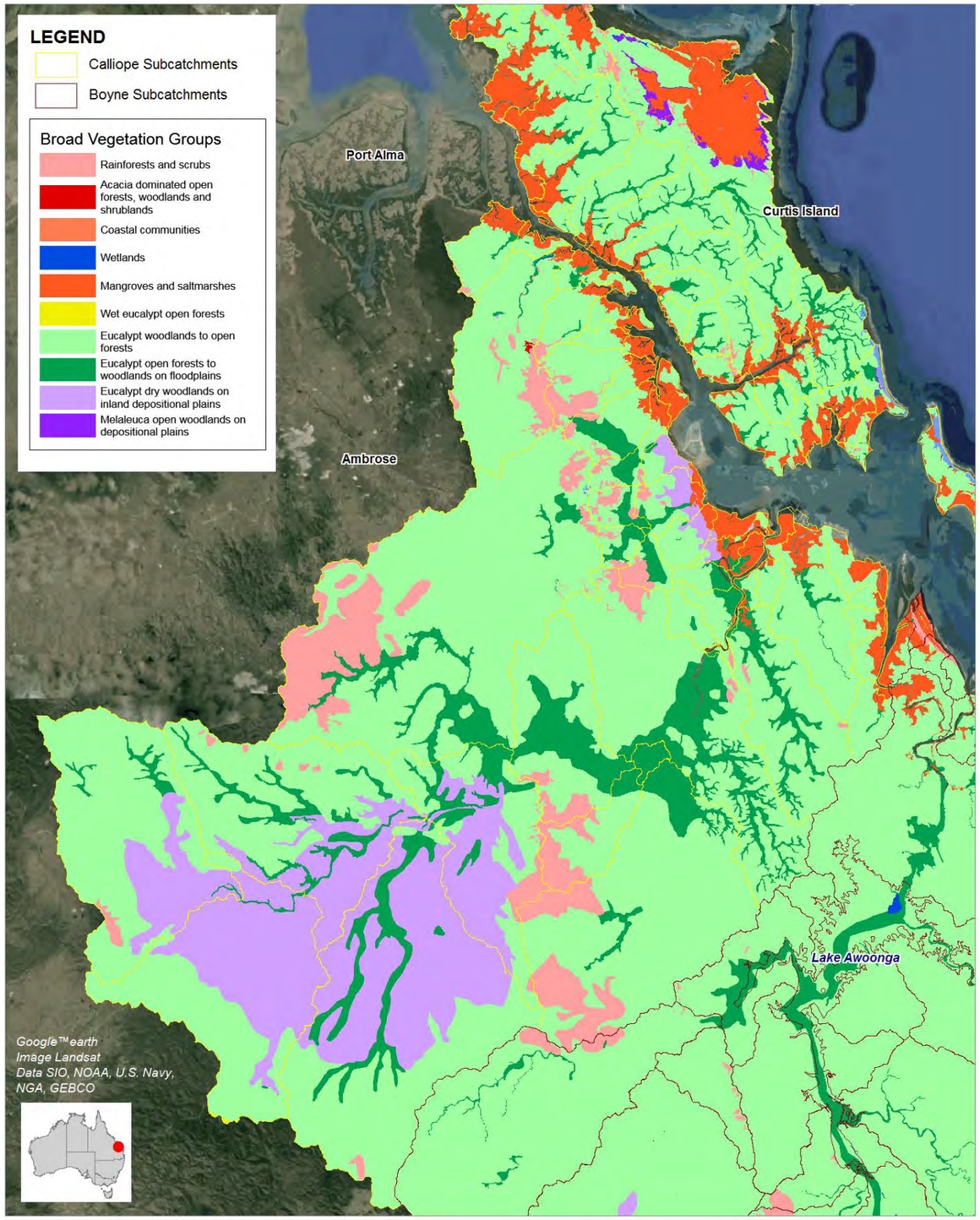
Identifying runoff and erosion sources in the catchment are essential to target management actions to reduce overland flow and improve water quality for the benefit of downstream marine habitats. Given the extensive scale of clearing in the Calliope and Boyne catchments across various land parcels, the following section demonstrates how broad investigation sites may be identified for further detailed assessment to improve land condition for downstream water quality.

The following data sources were reviewed to identify potential bare ground within eroding gullies and overgrazed pastures within the Calliope and Boyne catchments which have the potential to be revegetated or managed to improve ground infiltration to reduce runoff and improve water quality:

- Current and historical aerial imagery (2004-2015)
- Bare ground index (Fractional land cover product from DSITI/TERN)
- 2013 Preclear and Remnant Regional Ecosystem Mapping (V9.0)
- EHP regrowth benefits metric (http://environment.ehp.qld.gov.au/regrowth-benefits/).

Based on the data review, 10 cleared and potentially eroded investigation areas with rehabilitation potential were identified as examples of the types of landscapes that could be improved for marine habitat benefit (refer Figures E2 and E4). Given that Awoonga Dam regulates water flow and quality from the Boyne catchment, site selection was focused on the Calliope basin. Sites were also selected based on their proximity to drainage channels to ensure rehabilitation strategies would have the most likely direct benefit for water quality.

With the addition of other metrics contained within the regrowth benefits tool, rehabilitation interventions could be targeted in areas to maximise co-benefits to biodiversity and carbon storage. Once sites have been prioritised for more detailed assessment, landholder negotiations and field inspections would be required to assess landuse, site condition in terms of soil stability and terrain, and the feasibility of land rehabilitation practices to improve runoff conditions and downstream water quality.



Title:
Calliope Basin Preclear Broad Vegetation Groups

Figure: **E1**

Rev: **A**

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Approx. Scale

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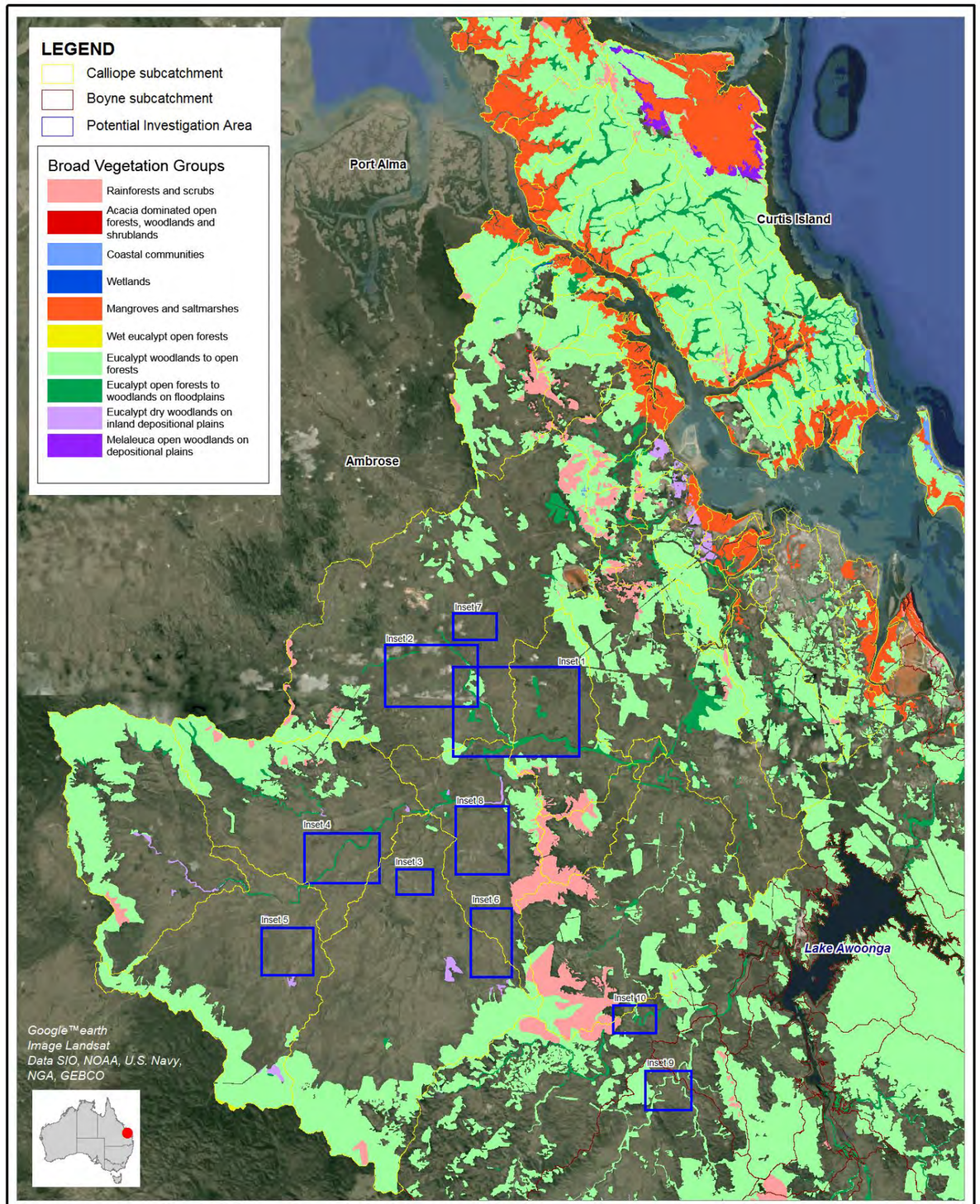

Title:
Calliope Basin Remnant Broad Vegetation Groups

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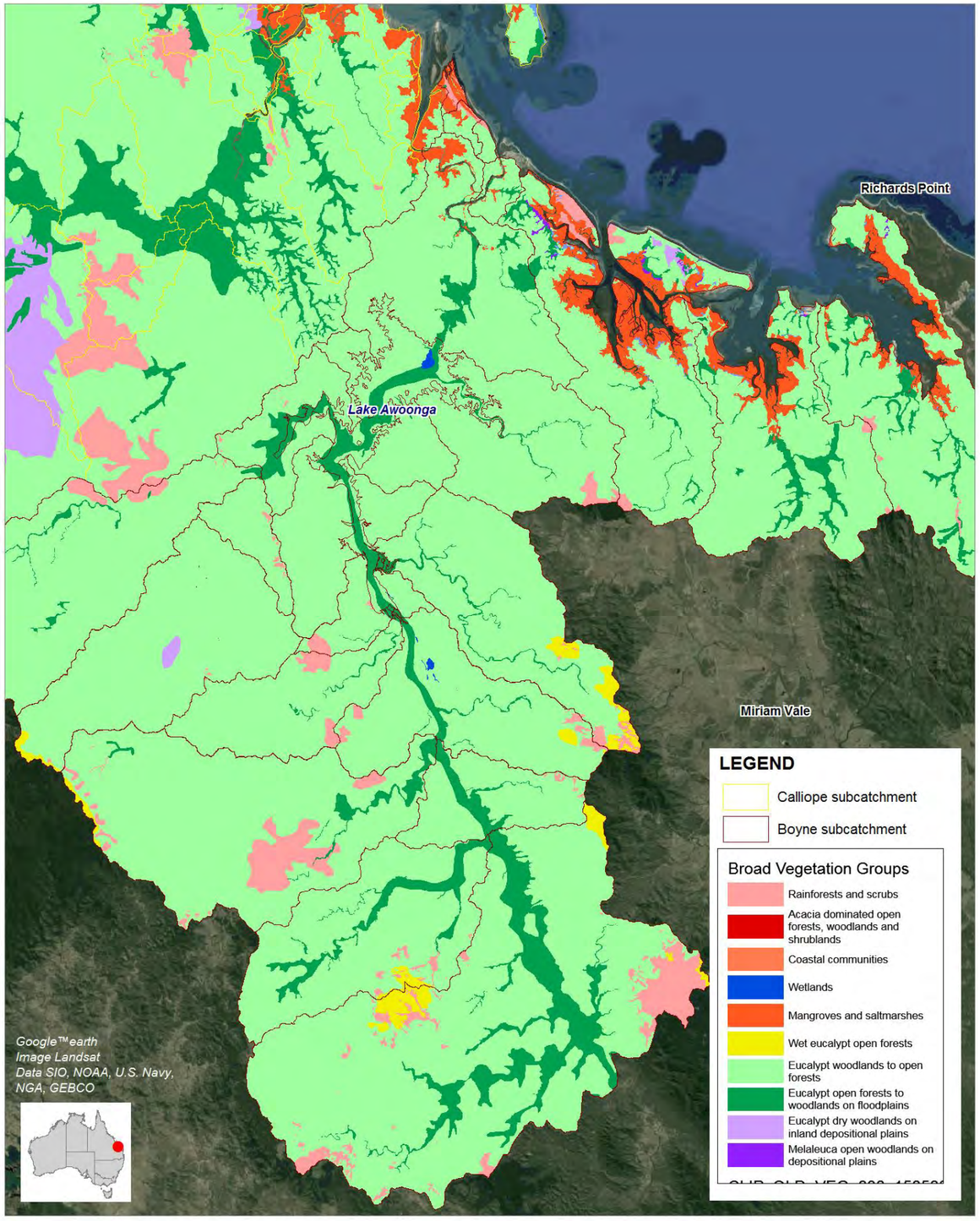

Title:
Boyne Basin Preclear Broad Vegetation Groups

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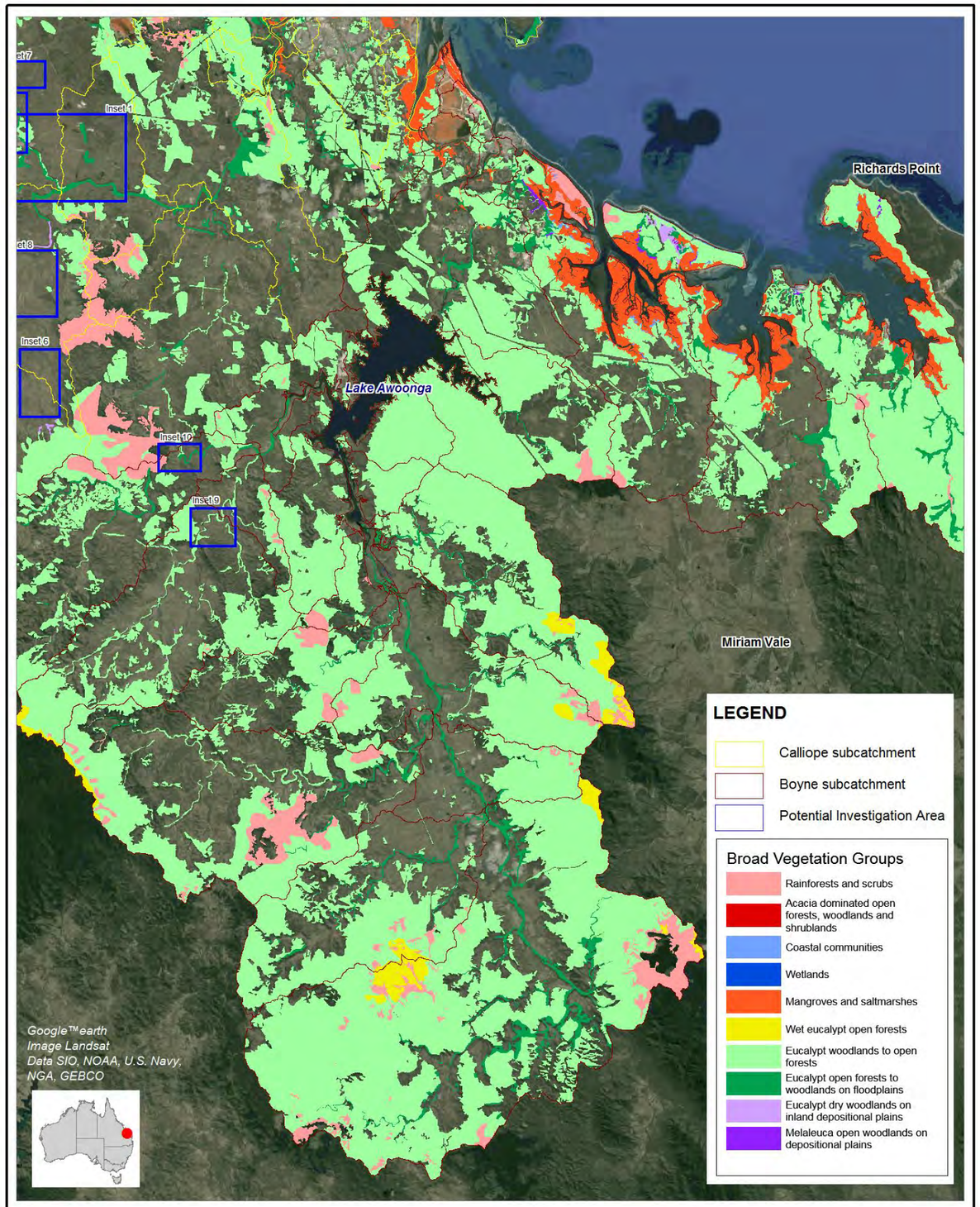

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Boyne Basin Remnant Broad Vegetation Groups

Figure: **E4**

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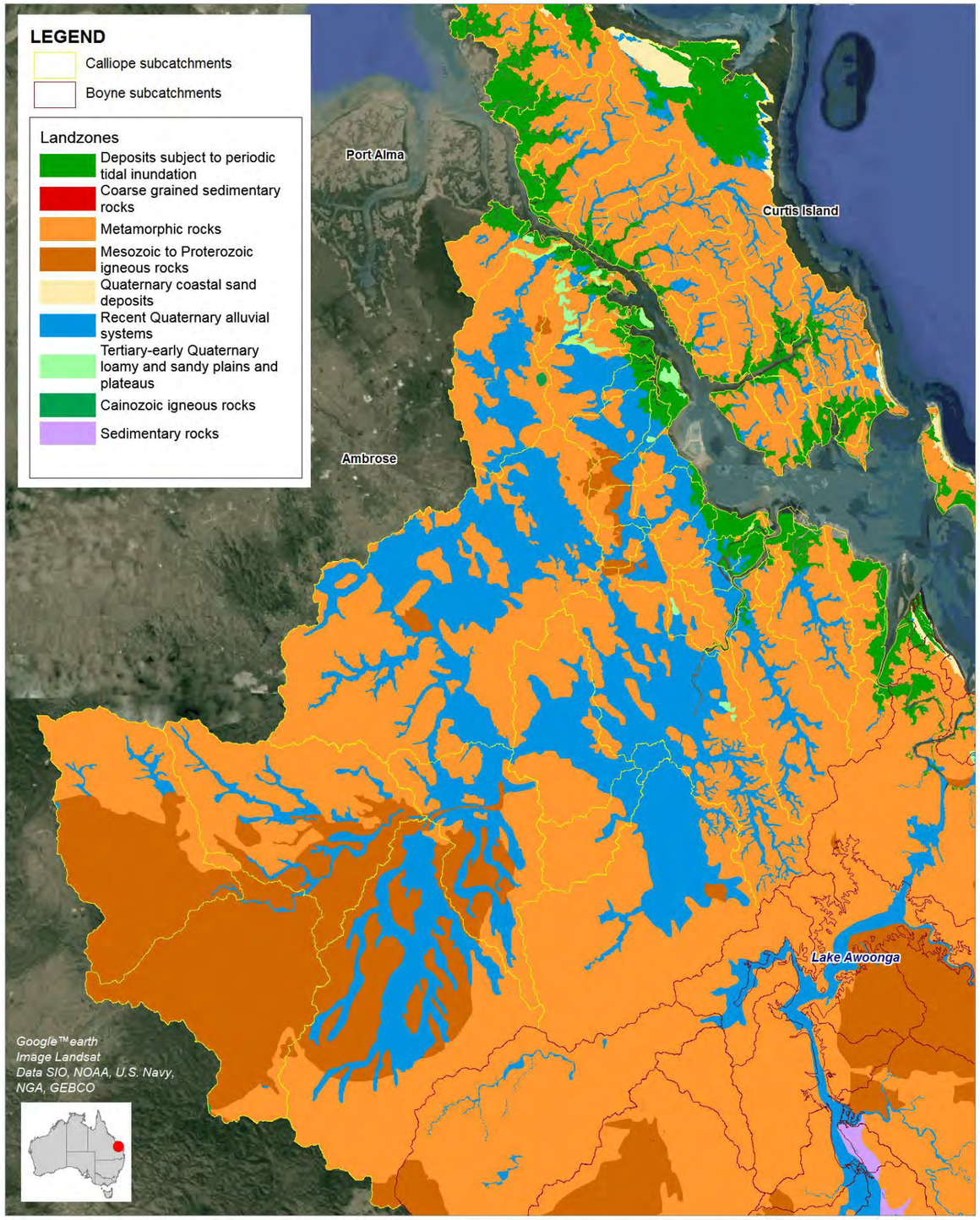

Title:
Calliope Basin Preclear Land Zones

Figure: **E5**

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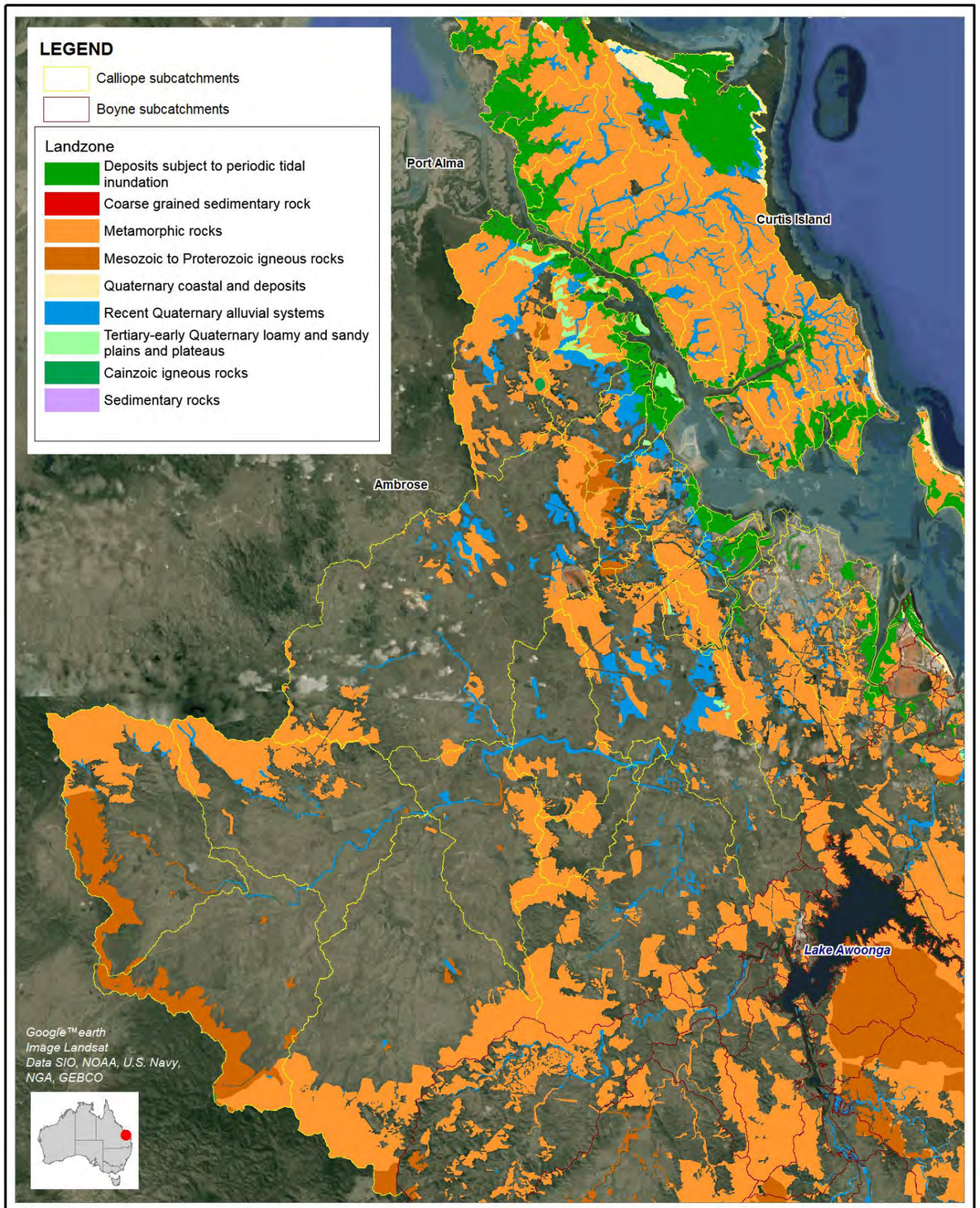

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Calliope Basin Remnant Land Zones

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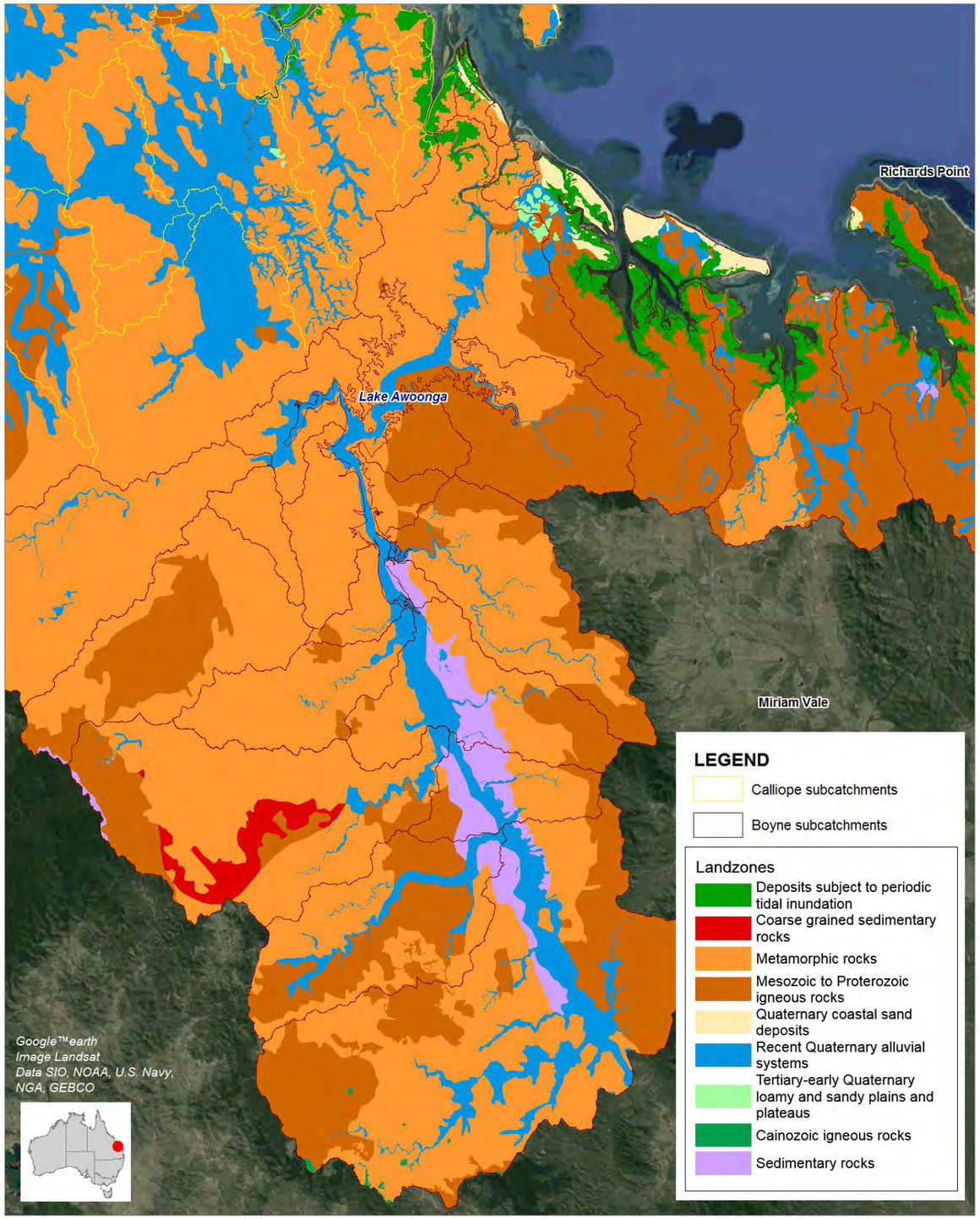

Title:
Boyne Basin Preclear Land Zones

Figure: **E7**

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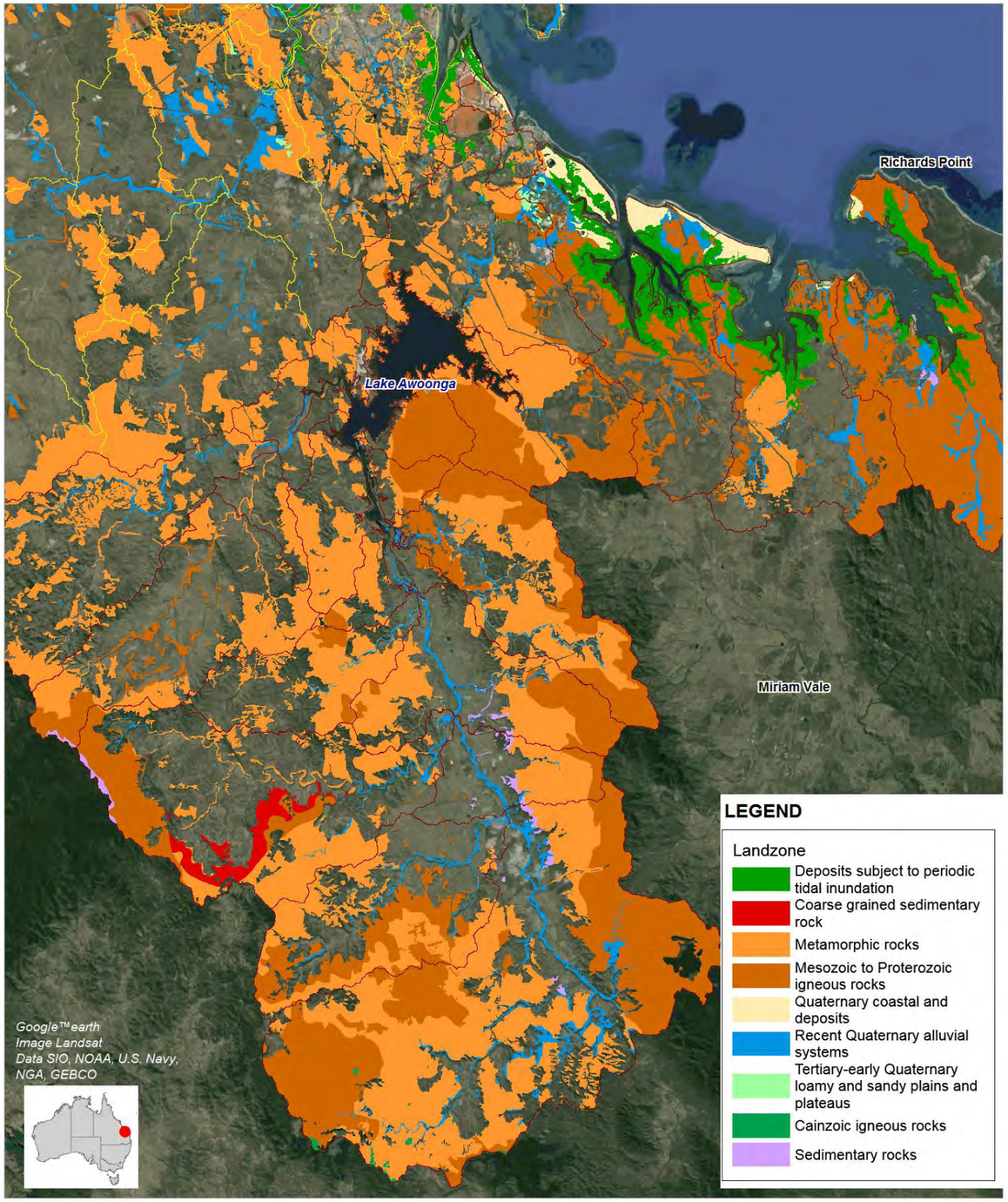

Title:
Boyne Basin Remnant Land Zones

Figure: **E8**

Rev: **A**

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0km 15 30
Approx. Scale

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