Improved Dredge Material Management for the Great Barrier Reef Region

APPENDIX B

Water Quality Review and Monitoring Framework

Sinclair Knight Merz Pty Ltd (SKM)

Revision 2.2

10 July 2013

Published by the Great Barrier Reef Marine Park Authority 2013

ISBN 978 1 922126 14 6 (ebook)

National Library of Australia Cataloguing-in-Publication entry

Sinclair Knight Merz (Firm).

Improved dredge material management for the Great Barrier Reef Region / Sinclair Knight Merz Pty Ltd (SKM); Asia-Pacific Applied Science Associates (APASA).

ISBN 978 1 922126 14 6 (ebook)

Dredging spoil--Environmental aspects--Queensland--Great Barrier Reef.
Dredging spoil--Queensland--Great Barrier Reef--Management.
Spoil banks--Environmental aspects--Queensland--Great Barrier Reef.
Spoil banks--Queensland--Great Barrier Reef--Management.
Dredging--Environmental aspects--Queensland--Great Barrier Reef.
Dredging--Risk management--Queensland--Great Barrier Reef.
Water quality management--Queensland--Great Barrier Reef.
Hydrodynamic receptors.

Asia-Pacific Applied Science Associates.
Great Barrier Reef Marine Park Authority.

363.7284

This publication should be cited as:
SKM 2013, *Improved dredge material management for the Great Barrier Reef Region*, Great Barrier Reef Marine Park Authority, Townsville.

Acknowledgement
This report was supported with funding from the Department of Sustainability, Environment, Water, Population, and Communities through the Sustainable Regional Development Program.

Australian Government
Great Barrier Reef Marine Park Authority
Department of Sustainability, Environment, Water, Population and Communities

Requests and enquiries concerning reproduction and rights should be addressed to:

Great Barrier Reef Marine Park Authority
2-68 Flinders Street (PO Box 1379)
Townsville QLD 4810, Australia

Phone: (07) 4750 0700
Fax: (07) 4772 6093
Email: info@gbrmpa.gov.au
www.gbrmpa.gov.au

DOCUMENT HISTORY AND STATUS

Revision	Date issued	Author(s)	Reviewed by	Approved by	Date approved	Revision type
A	26/11/12	T Elsdon	M Huber			Internal draft, not approved
B	28/11/12	T Elsdon M Huber C Bailey	P Morrison			Internal draft, not approved
C	29/11/12	T Elsdon M Huber C Bailey	S Costanzo	M Huber	30/11/12	Internal draft
D	30/11/12	T Elsdon M Huber C Bailey	M Huber	M Huber	30/11/12	Internal draft
0	30/11/12	T Elsdon M Huber C Bailey	M Huber	M Huber	30/11/12	Draft issued to client for comment
1	12/14/12	T Elsdon M Huber C Bailey	M Huber	M Huber	12/14/12	Final issued to Client
1.1	12/20/12	T Elsdon M Huber C Bailey	M Huber	M Huber	12/20/12	Revised Final
2	26/03/13	T Elsdon M Huber C Bailey	M Yeates	M Huber	26/03/13	Revised Final
2.1	28/06/13	T Elsdon M Huber C Bailey	M Yeates	M Yeates	28/06/13	Revised Final
2.2	10/07/13	T Elsdon M Huber C Bailey	M Yeates	M Yeates	10/07/13	Revised Final

CONTENTS

FIGURES

TABLES

ACRONYMS

AIMS	Australian Institute of Marine Science
APASA	Asia-Pacific Applied Science Associates Pty Ltd
ANZECC	Australian and New Zealand Environment Conservation Council
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
BACI	Before-After/Control-Impact
DEEDI	Department of Employment, Economic Development and Innovation
DSEWPaC	Department of Sustainability, Environment, Water, Population and Communities
DO	Dissolved oxygen
DOC	Dissolved organic carbon
EWMA	Exponentially Weighted Moving Average
GBRMPA	Great Barrier Reef Marine Park Authority
GPC	Gladstone Ports Corporation
HPX3	Hay Point berth 3 expansion project
IDF	Intensity-duration-frequency
LNG	Liquefied natural gas
MODIS	Moderate Resolution Imaging Spectroradiometer
MRG	Management Review Group
NQBP	North Queensland Bulk Port Corporation Pty Ltd
NTU	Nephelometric Turbidity Unit
PAR	Photosynthetically active radiation
POTL	Port of Townsville Ltd
QA	Quality Assurance
QC	Quality Control
SAP	Sampling and analysis plan
SCC	Suspended sediment concentration
SKM	Sinclair Knight Merz Pty Ltd
TACC	Technical Advisory and Consultative Committee
TEP	Transitional Environmental Program
TOC	Total organic carbon
TSS	Total suspended solids
WA	Western Australia
WQOs	Water Quality Objectives

GLOSSARY

A priori Decisions, knowledge, or statistical analyses made before an event.

Baseline monitoring Undertaken to establish ambient water quality conditions and variability.

Bed-shear stress Forces exerted by the ocean on bed sediments (at rest). When bed shear stress exceeds the critical shear stress for the bed sediments, the sediments will become transported by the ocean.

Beneficial re-use of dredge material Is the practice of using dredge material for another purpose that provides social, economic or environmental benefits.

Non-beneficial re-use Dredge material placement that does not provide a concurrent benefit, such as disposal at a landfill site or dedicated permanent disposal facility.

Cumulative impacts Impacts resulting from the effects of one or more impacts, and the interactions between those impacts, added to other past, present, and reasonably foreseeable future pressures.

Dredging- Capital Dredging for navigation, to create new or enlarge existing channel, port, marina and boat harbour areas. Dredging for engineering purposes, to create trenches for pipes, cables, immersed tube tunnels, to remove material unsuitable for foundations and to remove overburden for aggregate.

Dredging- Maintenance Dredging to ensure that previously dredged channels, berths or construction works are maintained at their designated dimensions.

Dredge footprint A designated area or areas where dredging operations of bottom sediments are proposed to, or will, occur.

Hydrodynamics The movement (dynamics) of water due to the action of tides, waves, winds and other influences.

Hydrographic The physical and chemical features of the oceans.

Hydrodynamic models Hydrodynamic models are generated by computer softwares. A two-dimensional hydrodynamic model, although useful in many situations, is limited to depth-averaged equations and therefore unable to resolve stratification or vertical gradients. A three-dimensional model can determine the vertical distribution of currents. It provides the most complete solution for any hydrodynamic system including the formulation for the effects of bottom shear stress and surface wind shear stress. A 3D hydrodynamic model is highly recommended as best practice because it provides realistic simulation of the marine environment.

Infauna are benthic organisms that live within the bottom substratum of a body of water, especially within the bottom-most oceanic sediments, rather than on its surface.

Land reclamation When material is used to convert subtidal areas to dry land. Reclamation involves filling, raising and protecting an area that is otherwise periodically or permanently submerged. Land reclamation may also involve constructing perimeter walls or enclosures to limit erosion using dredge rock.

Metocean Referring to the waves, winds and currents conditions that affect offshore operations.

Necrosis is a form of cell injury that results in the premature death of cells in living tissue. Necrosis is caused by factors external to the cell or tissue, such as infection, toxins, or trauma that result in the unregulated digestion of cell components.

Photosynthetically Active Radiation (PAR) The amount of light available for photosynthesis, which is light in the 400 to 700 nanometer wavelength range. PAR changes seasonally and varies depending on the latitude and time of day. Factors that reduce the amount of PAR available to plants include anything that reduces sunlight, such as cloud cover, pollution and sedimentation.

Predictive modelling Used to model predicted sediment plume dispersion based on location-specific threshold values of TSS and sedimentation rate.

Reactive management (in relation to water quality monitoring) Links water quality monitoring to monitoring of ecological responses. The aim of reactive management is to provide for management action to prevent or minimise ecological impact due to reduced water quality through establishing reactive trigger values, determining whether exceedance of those trigger values results from dredging/disposal and implementing management responses accordingly. Reactive management generally requires that water quality monitoring sites are linked to ecological receptor monitoring sites and requires *a priori* specification of trigger values and management response hierarchies.

Multi-tiered reactive management A tiered approach to management allows for a series of management responses ranging from further investigation in the first instance up to, if necessary, the cessation of dredge material placement operations.

Scour changes on the bed of the ocean. The frequent movement of water can lead to a scouring effect.

Sedimentation The deposition or accumulation of sediment either on the seabed or in the water column. Deposition on the seabed is calculated as a probability function of the prevailing bottom stress, local sediment concentration and size class. Sediment that is deposited may subsequently be resuspended into the lower water column if critical levels of bottom stress are exceeded.

Sediment transport The movement of solid particles (sediment), typically due to a combination of the force of gravity acting on the sediment, and the movement of the fluid in which the sediment is entrained. Sediment transport is affected by a range of oceanographic factors including waves, currents and tides.

Sedimentation rate (mg/cm^2/d). The amount of sediment depositing or accumulating on the ocean floor per unit time, in milligrams per square centimetre per day.

Sediment plume spatial extents
For this project spatial extents of sediment plumes associated with dredge material placement are modelled and expressed as median (50th percentile) and 95th percentile contours of a range of values of TSS (mg/L) and sedimentation rate (mg/cm^2/d).

Median (50th percentile) contours represent “average” conditions, for example a 5 mg/L TSS median contour shows locations where 5 mg/L is predicted to occur 50 per cent of the time during the modelling period. Areas enclosed by the contour are predicted to experience TSS concentrations ≥ 5 mg/L more than half the time. Areas outside the contour are predicted to experience 5 mg/L TSS less than half the time during the modelling period.

The 95th percentile contours represent conditions 5 per cent of the time. For example, areas outside the 95th percentile contour for 10 mg/cm^2/d sedimentation rate are predicted to experience sedimentation of this intensity less than 5 per cent of the time during the dredge material placement campaign.

Sediment transport rate For this project sediment transport rates were calculated using a hydrodynamic model applying the influences of large-scale current model predictions, tides and local winds. The influences of these variables on hydrodynamics and sediment transport were incorporated into the model by including vectors (the direction or course followed).

Suspended sediment concentration Total Suspended Solids (TSS) (mg/L)
The concentration of sediment suspended in seawater (not dissolved), expressed in milligrams of dry sediment per litre of water-sediment mixture (mg/L).

Sensitive Receptors (sensitive marine environmental receptors)
Certain key reef marine organisms, habitats and communities are sensitive to dredging and at-sea dredge material placement activities. Coral reefs, seagrass, macroalgal and macroinvertebrate communities are 'sensitive receptors' that occur within the vicinity of Great Barrier Reef Region ports. Impacts can result from both direct effects, for example burial by dredge material and indirect effects such as reductions in light availability to corals or seagrasses due to elevated suspended sediment concentrations in the water column. Reduced health of these sensitive receptors could negatively impact on the world heritage values of the Great Barrier Reef.

Sentinel sites Are located at the boundaries of modelled zones of impact. These are particularly important for large projects, especially if a zone of high impact is predicted, it may be useful to place sensitive receptor monitoring sites within "sentinel sites" at the boundaries of model-predicted zones of influence and impact.

Trailing suction hopper dredger (TSHD) Trails its suction pipe when working, and loads the dredge spoil into one or more hoppers in the vessel. When the hoppers are full, the TSHD sails to a disposal area and either dumps the material through doors in the hull or pumps the material out of the hoppers.

Trigger values In relation to water quality and sensitive environmental receptors. For a given environmental parameter, such as, for example TSS, turbidity or reduced Photosynthetically Active Radiation caused by dredging or dredge material placement; the trigger value is the level in the environment at which, if a Sensitive Receptor is exposed, it would not be resilient to disturbance. Trigger values may also refer to levels of environmental parameters that, if exceeded, require a defined management response during dredging and material placement operations. It is possible to establish trigger values based on the known tolerance of receptors to diminished water quality. For example, one project established light-based triggers for seagrass receptors in the Gladstone region. Minimum light requirements, duration in which seagrass could tolerate light deprivation and the required recovery period from light deprivation was quantitatively established. As coral communities often include many more species than seagrass communities, and coral species differ widely in tolerance to light deprivation and sedimentation, it is more difficult to use known tolerance to set trigger values for coral communities.

Turbidity Turbidity is a measure of the degree to which the water loses its transparency due to the presence of suspended particulates. The more total suspended solids in the water, the higher the turbidity. There are various parameters influencing the cloudiness of the water. Some of these are: sediments, phytoplankton, resuspended sediments from the bottom, waste discharge, algae growth and urban runoff.
Turbidity is measured in NTU: Nephelometric Turbidity Units using a nephelometer, which measures the intensity of light scattered at 90 degrees as a beam of light passes through a water sample.

Zones of Impact Are established through predictive modelling of sediment plumes zones of high impact, moderate impact and influence based on quantitative threshold criteria for the boundary of each zone can be established.

ACKNOWLEDGMENTS

The Department of Sustainability, Environment, Water, Population and Communities (DSEWPaC) funded the work contained within this report and the Great Barrier Reef Marine Park Authority is gratefully acknowledged for commissioning and defining the scope of work and for their assistance during the project.

RELIANCE STATEMENT

This report has been prepared pursuant to the Contract between Sinclair Knight Merz Pty Limited (SKM) and the Great Barrier Reef Marine Park Authority (the Client) dated 18 September 2012 as varied on 21 November 2012, 14 March 2013 and 17 June 2013 (the Contract). The scope of this report and associated services performed by SKM was developed with the Client to meet the specific needs of the project.

In preparing this report, SKM has relied upon, and presumed accurate, information (or confirmation of the absence thereof) provided by the Client and/or other sources including port authorities. Except as otherwise stated in the report, SKM has not attempted to verify the accuracy or completeness of such information. If the information relied upon by SKM as at the date of issue of this report is subsequently determined to be false, inaccurate or incomplete, then it is possible that the accuracy of SKM's observations and conclusions expressed in this report may be affected.

SKM warrant that it has prepared this report in accordance with the usual care and thoroughness of the consulting profession, by reference to applicable standards, guidelines, procedures and practices and information sourced at the date of issue of this report. No other warranty or guarantee, whether expressed or implied, is made as to the data, observations, and findings expressed in this report, to the extent permitted by law except as provided for in the Contract between SKM and the Client.

SKM strongly recommends that this report should be read in full and no excerpts be interpreted as representative of the findings. Except as provided for in the Contract, no responsibility is accepted by SKM for use of any part of this report in any other context.

This report has been prepared on behalf of, SKM's Client, and is subject to, and issued in accordance with, the provisions of the Contract between SKM and the Client. SKM accepts no liability or responsibility whatsoever for any use of, or reliance upon, this report by any third party but this does not affect the obligation on SKM to indemnify the Client in accordance with the terms of the Contract.

SUMMARY

The Great Barrier Reef World Heritage Area (World Heritage Area) has had a rapid increase in the number of proposed new ports and port expansions, which has prompted the Australian and Queensland governments to undertake a strategic assessment to help identify, plan for, and manage existing and emerging risks. This assessment was in part a response to the World Heritage Committee's request to Australia to undertake a strategic assessment of the World Heritage Area and adjacent coastal zone. The Great Barrier Reef Marine Park Authority (GBRMPA) is leading the marine strategic assessment with the primary aim of determining the likely impact of actions on matters of national environmental significance as defined by the *Environment Protection and Biodiversity Conservation Act 1999*, the effectiveness of existing management arrangements, and the need for improved management strategies.

Sinclair Knight Merz (SKM) and Asia-Pacific Applied Science Associates (APASA) were commissioned to complete the 'Improved Dredge Material Management for the Great Barrier Reef Region' project, which encompasses three tasks:

- Task 1. Perform a literature review and cost-benefit analysis that synthesises the available literature on the environmental and financial costs associated with land-based re-use and land-based disposal options for dredge material at six locations (Port of Gladstone, Rosslyn Bay State Boat Harbour, the Port of Hay Point, the Port of Abbot Point, the Port of Townsville, and the Port of Cairns)
- Task 2. Develop a generic water quality monitoring framework that can be applied to developing a water quality monitoring and management program for any dredge material placement site
- Task 3. Identify potential alternative dredge material placement areas within 50 km of the six locations, based on environmental, socioeconomic, and operational considerations, as well as hydrodynamic modelling of bed shear-stress. Within these alternative areas, identify 13 model case sites (two for each port except Gladstone, for which three model cases were identified recognising that the current placement site has no remaining capacity) for hydrodynamic modelling of sediment migration and turbidity plumes, and assessment of risks to environmental values. This study makes no assumption that the alternative areas identified provide intrinsic environmental or socioeconomic benefits compared to the current placement sites, and the forthcoming modelling and risk assessment will consider the current and alternative sites equally.

This report presents the findings of Task 2: a framework for developing water quality monitoring for future dredge material placement projects. Although the framework has been developed specifically in the context of the offshore placement of dredge material, the concepts are applicable to dredging projects generally. The report reviews:

- Methodologies and monitoring parameters for water quality monitoring for dredge material relocation
- Existing information from dredging projects in Queensland and elsewhere in Australia
- Approaches to establishing water quality trigger values for water quality monitoring and management, with a focus on a multi-tier reactive management approach
- Approaches for selecting monitoring sites
- Approaches to establishing reactive management response regimes.

Based on the review, the report presents a framework for developing water quality monitoring programs for dredge material relocation projects and presents recommendations for good practice.

The scope and timeframe for this study did not allow detailed, quantitative development of water quality triggers or management measures at the six locations. Detailed water quality monitoring and management program for dredging projects must be developed on a project-specific basis, on the basis of more comprehensive and detailed environmental impact assessment than permitted by the scope of the present study.

The study reviews monitoring parameters and methodologies available to monitor sediment-related impacts on water quality, including the advantages and disadvantages of different parameters and monitoring methods, and presents recommendations for good practice.

A generic framework for developing and implementing water quality monitoring for the specific purpose of reactive management – i.e. to provide warning of potentially stressful conditions early enough to take management responses to prevent or minimise ecological impacts - is presented. Figure S1 summarises the framework. Although the framework has been developed specifically in the context of the offshore placement of dredge material, the concepts are applicable to dredging projects generally.

As a generic conceptual framework, the framework illustrated in figure S1 cannot be directly applied to individual projects, each of which will have specific aspects that require adaptation of the generic conceptual framework. Steps may be skipped, or their timing altered, in adapting the framework to the specific circumstances of a given project. In many cases monitoring programs will have objectives in addition to reactive management during dredging and dredge material placement operations. In particular, the framework is likely to be adapted on the basis of existing available baseline data and other information regarding the water quality and ecological outcomes of previous projects at the location.

The first step in developing a water quality monitoring program is to determine the data requirements of the program and whether monitoring and/or predictive impact modelling are needed, based on a review and analysis of existing information. In general, water quality monitoring for the purpose of triggering reactive management responses is not required if the proposed project is of shorter duration than established duration thresholds for impact, or the duration is so short that monitoring results cannot realistically lead to management responses.

Water quality monitoring for reactive management may also be unnecessary for maintenance dredging projects that are very similar to previous projects where repeated (minimum three campaigns) water quality monitoring has demonstrated compliance with trigger values and where established ecological monitoring demonstrates no evidence of significant short- or long-term impacts on receptors that can be attributed to dredging and dredge material placement.

It is stressed again that the above discussion on when water quality monitoring may not be required is focused on monitoring for the purpose of identifying declines in water quality early enough to initiate management responses. Water quality monitoring for dredging and dredge material placement projects may be conducted for a variety of other reasons.

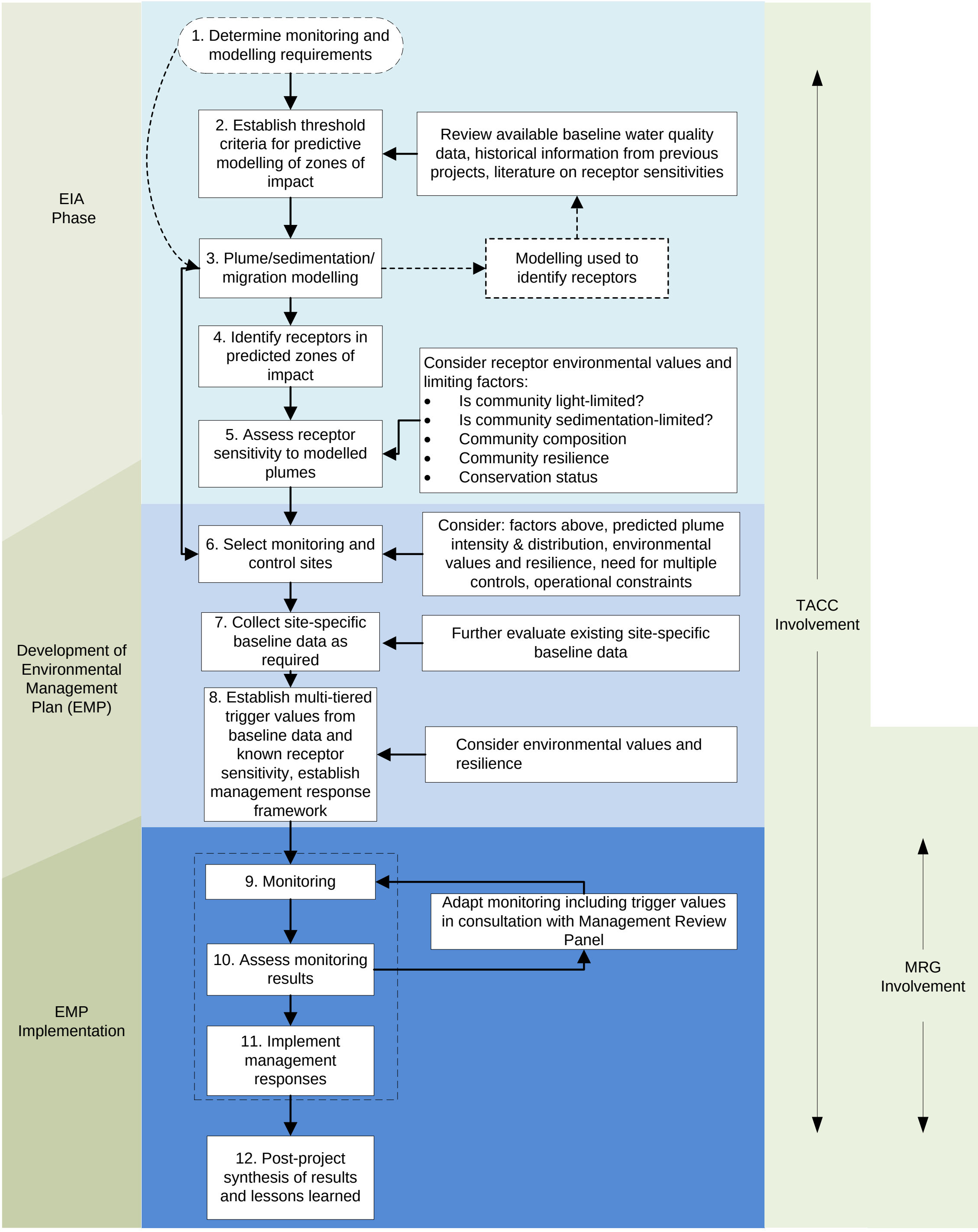

Figure S1. A general framework for developing and implementing water quality monitoring programs for reactive management of dredged material placement.

If it is determined that predictive monitoring of sediment plumes is required, the GBRMPA guidelines for numerical modelling for dredging projects (GBRMPA 2012) encourage the application of the “zones of impact” approach prescribed by the Western Australia Environmental Protection authority (WAEPA 2011). This involves the predictive modelling of zones of high impact, moderate impact, and influence based on quantitative threshold criteria for the boundary of each zone.

For proposed projects involving new ports, dredging and relocation of unprecedented volumes of material, dredging and relocation of unusual material types, or novel dredging and placement methods, knowledge of the potentially affected receptors may not be sufficient to establish impact threshold criteria prior to modelling. It will then be necessary to first model the general spatial distribution of varying levels of TSS and sedimentation, use the results to identify potential receptors, and then proceed to establish threshold criteria for zones of impact and influence. This iterative approach to first identify receptors that might be affected in order to then determine suitable impact thresholds is indicated by the dashed path at the top of figure S1.

The present study considers the implications of placement at hypothetical alternative sites at considerable distance and in different oceanographic settings from the currently used sites. It is therefore an example of a case where the potential receptors were uncertain prior to modelling. The scope of this project did not permit the iterative approach of first using modelling to identify the potentially affected receptors, then establishing thresholds and modelling zones of impact. The project proceeded to the first step, identifying potentially affected receptors on the basis of model predictions of the spatial extent of elevated TSS and sedimentation.

Even when general ecological community types potentially affected by dredge material placement are known, the sensitivity of given community types may vary widely. For example, threshold criteria are often set on the basis of coral receptors because corals are expected to be among the most sediment-sensitive receptors in the World Heritage Area. Corals vary widely in sensitivity to turbidity and sedimentation, however, both among species and as a function of ambient conditions (Erftemeijer et al. 2012; Gilmour et al. 2006). As a result, no generic thresholds will accurately predict turbidity or sedimentation impacts on all coral species or coral communities at all sites. The same is true for other marine communities. Therefore, the development of meaningful impact threshold criteria necessarily requires site-specific information on ambient turbidity and sedimentation regimes and on the species composition of coral communities (Erftemeijer et al. 2012; PIANC 2010) and other receptors.

Once modelling has predicted zones of impact and influence, the next steps in the framework (steps 4 and 5) are to identify receptors in the predicted zones of impact and assess their sensitivity to modelled plumes, taking into account the considerations identified in figure S1. For projects that are similar to previous projects in the area, it will often be possible to identify receptors and their sensitivity during the initial review of available information, and modelling of zones of impact and influence may not be needed.

The report reviews approaches to step 8 in the framework, establishing water quality trigger values for reactive management based on site-specific baseline data. These include:

- Simple percentiles (e.g. 80th, 95th, 99th) of baseline data, or a percentile plus some allowable level above the percentile
- Intensity-duration-frequency (IDF) approaches that consider not only the magnitude of change from baseline levels, but also the duration and frequency of such events
- Control charting, which is a variation of the IDF approach
- Known tolerance thresholds of receptors to reduced light, sedimentation, or other stressors. Tolerance thresholds are generally more applicable to seagrasses than corals because of wide variability in tolerance among coral communities and individual coral species.

SKM recommends that in applying any of the above approaches, the environmental values and resilience of receptors are also considered when setting trigger values.

The report also presents conceptual frameworks for multi-tiered reactive management, commencing with investigative triggers and ramping up to more proactive management responses at higher levels of exceedance.

Finally, the report presents SKM's recommendations for good practice in water quality monitoring programs for dredge material placement, as follows:

Monitoring Methodologies and Parameters

- Except for small projects or routine projects where similar projects have been adequately monitored, multiple methods (vessel-based monitoring, fixed loggers, remote sensing) should be incorporated into the design of monitoring programs
- A robust quality assurance (QA) system including cross-calibration of all monitoring instruments is essential
- Fixed loggers for baseline measurement of water quality should be equipped with sensors capable of recording the full range of natural variability. If baseline monitoring shows that conditions frequently exceed the maximum range of measurement the sensors should be replaced.
- Remote sensing is a complementary monitoring method and should not replace *in situ* measurements, however it is useful for detecting the spatial extent of surface plumes and distinguishing regional climatic influences from sediment plumes related to material placement
- If remote sensing is used, algorithm development and ground truthing should use dredge material plumes, not ambient suspended sediments
- If total suspended solids (TSS) values derived from turbidity measurements are required for model calibration or other purposes, calculation of the turbidity/TSS relationship should be based on actual dredged material rather than ambient suspended sediments
- Photosynthetically active radiation (PAR) is the preferred parameter for monitoring intended to provide warning of potential impacts of increased light attenuation upon light-dependent receptors, followed by turbidity and TSS, which are surrogates for light attenuation. The exception is when there are extensive existing baseline data and/or data on the ecological impacts of turbidity and TSS and baseline data on PAR are not adequate to establish trigger values to warn of potential impending impacts. Monitoring of turbidity and/or TSS may still be required for other purposes such as validating modelling or remote sensing algorithms or to meet approval conditions.

Trigger Values and Management Responses

- Experimental quantification of receptor tolerance thresholds is the preferred approach for setting trigger values, but it is recognised that this is not feasible except for very large projects and with current scientific understanding probably usually not for coral communities
- Where tolerance thresholds are not established, trigger values, at least for large projects, should take into account the ambient regime of variability in duration and frequency of elevated turbidity and sedimentation, as well as the intensity
- Where trigger values are derived from the ambient range of variability (e.g. 80^{th}, 95^{th}, 99^{th} percentiles), consideration should be given to identified environmental values as well as the resilience of monitoring receptors

- Trigger values for light-related impacts should apply only during daylight hours
- If turbidity is the parameter being monitored, it is preferable to express trigger values in nephelometric turbidity units (NTU), rather than measuring turbidity and converting for comparison to a trigger value in mg/L TSS based on a measured turbidity/TSS relationship
- Because of the difficulties in reliably measuring sedimentation, SKM recommends caution in linking operational management responses such as a reduction or termination of material placement directly to sedimentation triggers. Rather, sedimentation triggers should be linked to further water quality and ecological investigations.
- Trigger values for specific seasons will be required when:

  1) A proposed dredging and material placement campaign will span two or more seasons, that is for medium- or long-term campaigns as defined in figure 5 and

  2) There are statistically significant seasonal differences in the 50th, 80th, or 95th percentiles of baseline data for the monitored parameter and/or there are known seasonal differences in receptor sensitivity.

Monitoring Site Selection

- Depending on project size, monitoring designs should consider using multiple reference (control) sites at varying distances from the placement activity
- Sentinel sites at the boundaries of modelled zones of impact should be considered, especially for large projects of long duration.

Need for Water Quality Monitoring in Reactive Management

- Water quality monitoring for reactive management of dredge material placement activities is not necessary if the duration of the activities is less than the duration of stress required to result in impact, or if past monitoring has demonstrated that very similar programs do not result in impact. Monitoring for other purposes may still be required, however.

General Framework

- Technical Advisory and Consultative Committees established for long-term management of maintenance dredging should be involved throughout all three phases of management (Environmental Impact Assessment, Environmental Management Plan Development, and Environmental Management Plan Implementation)
- Management Review Groups should be established and engaged early in the design of the reactive management for capital dredging projects, commencing with the establishment of trigger values and management responses
- There should be a regular cycle of assessing the effectiveness of the monitoring program and adapting it as required
- The final outcomes of reactive management programs for dredge material placement projects should be synthesised and documented to promote continuing improvement in the management of dredge material in the World Heritage Area.

INTRODUCTION

Background

The Australian and Queensland governments are undertaking a strategic assessment of the World Heritage Area and adjacent coastal zone to identify, plan for, and manage risks within the Great Barrier Reef Marine Park (Marine Park) and World Heritage Area and adjacent coastal zone. This assessment is in part a response to the World Heritage Committees' request of Australia to undertake a strategic assessment of future development that could impact on the reef's values, and to enable long-term planning for sustainable development (World Heritage Committee June 2011). GBRMPA is leading the marine components of the strategic assessment, which involve the identification of potential impacts from development; an evaluation of the effectiveness of existing management arrangements; and the development of strategies for improved management to protect the Reef's unique world heritage values.

Queensland's mining and resource sectors are currently in a phase of significant expansion, with a number of new or expanded export facilities proposed along the Queensland coast to meet the needs of the sector. Port expansions have also been proposed to meet the needs of the tourism, naval, and other sectors and economic growth in general. Proposed port expansions often involve significant works within and adjacent to the Marine Park, World Heritage Area and adjacent coastal zone, with projected increases in shipping activities. Port expansion often involves significant capital dredging to create new or deeper shipping channels and/or berth areas. Similarly, the regular maintenance dredging requirements of ports are an important factor in the consideration of improved management of dredge material in the Great Barrier Reef Region.

SKM and APASA have been commissioned by the GBRMPA to provide an independent study on 'Improved Management of Dredge Material for the Great Barrier Reef Region'. This report is the fourth in a series of outputs from the project and presents a review of dredging-related water quality management programs and a suggested framework for the development of future programs.

Purpose

The GBRMPA seeks to improve understanding of the risks, environmental impacts, and future management arrangements associated with the disposal of dredge material in the Great Barrier Reef Region, including port-specific assessments.

The objectives of the project as a whole are to:

- Model bed shear-stress within 50 km of 12 Queensland ports, to indicate broad-scale patterns of sediment transport and related scour, natural deposition, and morphology changes
- Review existing environmental data within a 50 km radius offshore of six locations: the Port of Gladstone, Rosslyn Bay State Boat Harbour, Port of Hay Point, Port of Abbot Point, Port of Townsville, and Port of Cairns (figure 1). One of the six locations, Rosslyn Bay State Boat Harbour, is not a designated port.
- Identify broad alternative dredge material placement areas in the 50 km study area around each location, within which the placement of dredge material appears to represent a low risk of adverse impacts on environmental values. It is stressed that rigorous environmental impact assessment beyond the scope of the present study

must precede any placement of dredge material within the identified alternative areas.

- Identify three model case sites within the alternative area at Gladstone, and two model case sites at the other five locations, (13 sites in total) for further sediment migration and disposal plume modelling and risk assessment, based on a review of environmental, management, socioeconomic, and cultural values
- Conduct hydrodynamic modelling studies and environmental risk assessments, to evaluate risks associated with dredge material placement at the 13 identified model case sites, as well as the currently used placement sites
- Review international and national best practice and examples for the placement of dredge material on land; and conduct a port-specific cost-benefit analysis of land-based re-use and land-based disposal options for dredge material
- Develop a generic water quality monitoring framework that can be applied to developing a water quality monitoring and management program for any dredge material placement site.

This report presents the results of a review of past approaches to developing water quality management programs and trigger values for reactive management, and a framework for developing future water quality monitoring and management programs. The report briefly reviews the outcomes of water quality monitoring and management programs for previous dredging projects; a forthcoming report will provide a more detailed review.

Scope

This report addresses Task 2 of the project and presents a framework for the development of a generic water quality monitoring program that can be applied to any dredge material placement project. The general framework can also be applied to dredging activities. The scope of this report is to:

- Review available water quality data from the six locations (Port of Gladstone, Rosslyn Bay State Boat Harbour, Port of Hay Point, Port of Abbot Point, Port of Townsville, and Port of Cairns)
- Derive indicative threshold values for the six locations to be used in the interpretation of disposal plume modelling in another component of the project
- Conduct a desktop review of water quality monitoring programs for dredging programs in Queensland and elsewhere, including:
    - Approaches to establishing trigger values, focusing on a multi-tier management approach
    - Approaches to selecting monitoring sites
    - Data requirements for establishing water quality triggers and selecting monitoring sites
    - Approaches to management responses to exceedances of trigger values
    - Available monitoring methodologies
- Provide recommendations on best practice in the design and implementation of water quality monitoring programs for dredging projects in the World Heritage Area.

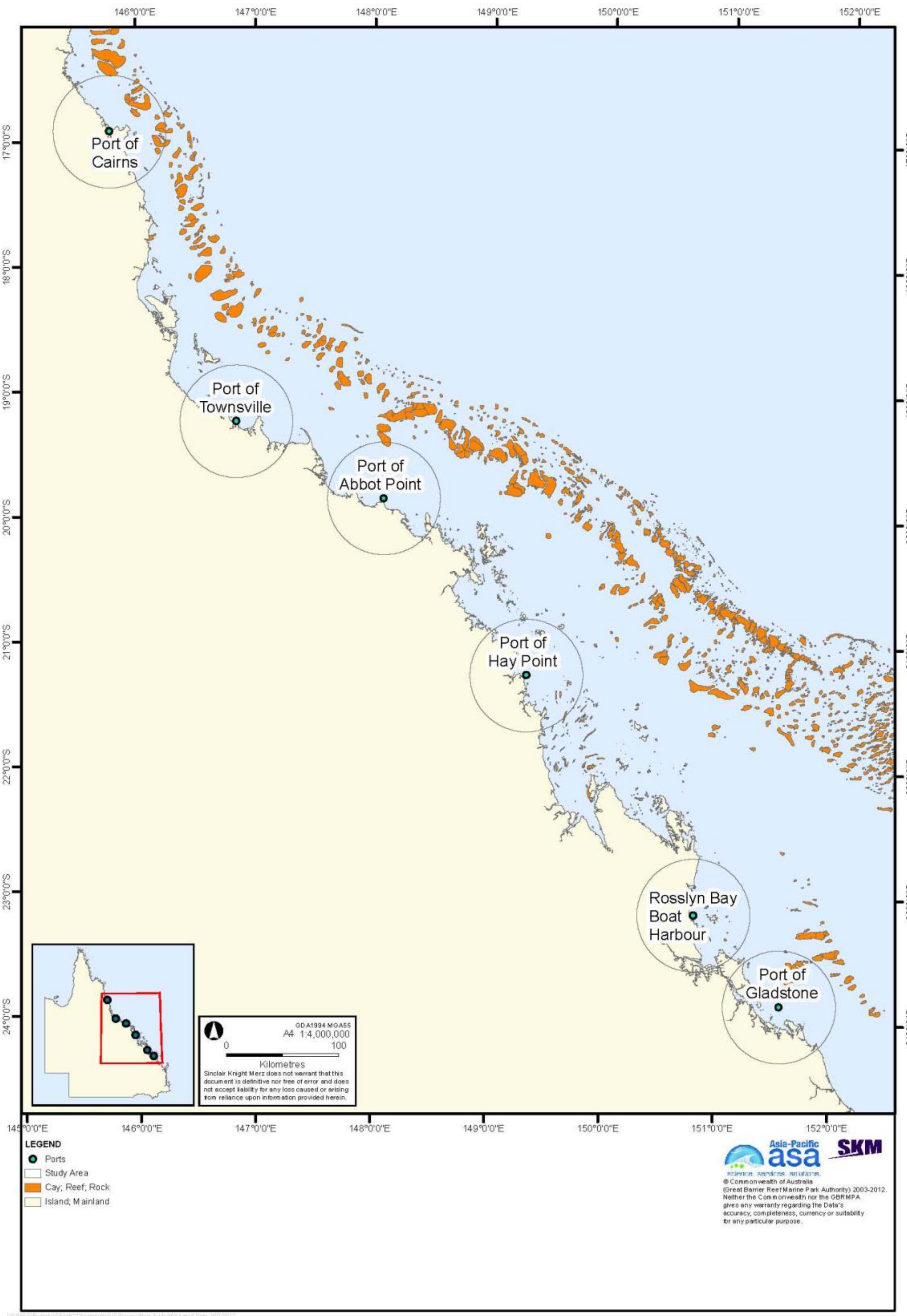

Figure 1. Map of the study area showing the six locations considered.

Because this study is specific to improved management of dredge material in the Great Barrier Reef Region, the scope of the current report was focused on water quality monitoring and management for dredging projects in tropical waters. Approaches used for dredging projects in temperate areas were reviewed only at the conceptual level, and not with respect to ecological receptors.

This report describes aspects of a generic water quality framework that could be applied to dredge material management in the World Heritage Area. Although the framework has been developed specifically in the context of the offshore placement of dredge material, the concepts are applicable to dredging projects generally.

The study was based entirely on previously existing information and data available to SKM, and information about water quality at receptor sites surrounding the alternative model case sites was not necessarily available to determine background levels of turbidity, suspended sediments, sedimentation, or light. The scope of the study did not permit independent statistical analysis of raw water quality data, and the analysis of background turbidity and suspended sediment information is based on statistical data summaries in documents available to SKM. Similarly, no field survey work, new data acquisition, or digitisation of data held in non-digital form was included in the scope of the study.

Modelling of plumes generated by offshore placement of dredge material for two alternative model cases sites at each port, as well as for the placement area in current use, is being conducted as part of the overall project and will be the subject of a forthcoming report. The exception is the Port of Gladstone, for which three alternative model cases, but not the current placement site, are being modelled because dredging programs already approved for Gladstone will consume the entire remaining capacity of the current site. Another forthcoming report will evaluate risks to sensitive receptors on the basis of the modelling results.

METHODS

This report was generated through a desktop review of available information on water quality and water quality management programs for dredge material placement at sea in Queensland and elsewhere in Australia. From these, information relevant to water quality monitoring for improved dredge material management in the World Heritage Area has been summarised, including:

- Parameters used in water quality monitoring, their advantages and disadvantages, and monitoring methodologies
- Available baseline water quality summaries for the six locations
- Approaches used in the development of water quality trigger values for reactive monitoring
- Water quality trigger values used for reactive management during past dredging projects at the six locations and elsewhere
- Results of impact monitoring of sensitive receptors in previous reactive monitoring programs
- Approaches to the development of reactive monitoring programs for dredge material placement programs.

Indicative Water Quality Criteria for Predictive Modelling

The original scope of the study included the development of location-specific threshold values of TSS and sedimentation rate to be used to interpret predictive modelling of sediment plume dispersion. The review of existing water quality information revealed that the available data were not adequate to establish site-specific threshold for impact for reasons including:

- The data were focused on sites selected to monitor dredging rather than dredge material placement
- The data did not provide adequate information on variability (e.g. percentiles)
- There was inadequate information on temporal variability, specifically the duration of periods of elevated turbidity under baseline conditions.

Furthermore, since the modelling was conducted for hypothetical alternative placement sites over large spatial scales, the receptors potentially affected by dredge material placement could not be confidently identified in advance of the modelling. Therefore, threshold criteria for identified levels of impact were not identified.

Framework for Developing Water Quality Monitoring Programs

On the basis of the desktop review and experience in developing and implementing water quality monitoring programs, SKM developed a conceptual framework and identified good practices to guide the development of future monitoring programs for dredge material placement in the World Heritage Area. The framework is focused on monitoring for reactive management, that is, water quality monitoring designed to provide warning of a deterioration in water quality due to dredge material placement that could result in adverse ecological impacts early enough to take management actions to prevent or reduce those impacts. The focus is also on multi-tiered reactive management responses that link water quality monitoring to monitoring of ecological responses.

Study Limitations

The study was based entirely on existing information and data available to SKM. Field surveys and new data acquisition for water quality or sensitive receptors were not included in the scope of the study. Coastal processes and the impact those processes may have on water quality have not been taken into consideration.

OBJECTIVES OF WATER QUALITY MONITORING FOR DREDGE MATERIAL PLACEMENT

Water quality monitoring for dredge material placement activities, and inevitably dredging activities as well, is conducted for a number of different purposes, including:

- Establishing ambient (baseline) water quality conditions and variability
- Establishing expected levels of change from baseline conditions that may result in environmental impacts (impact thresholds) for use in predictive modelling of sediment plumes in environmental impact assessment
- Establishing site-specific trigger values for reactive management of water quality during placement campaigns, exceedance of which results in management responses to avoid impacts on ecological receptors
- Determining whether exceedances of trigger values result from dredge material placement, to inform decisions as to whether additional management measures for material placement are needed
- Determining whether adverse environmental incidents (e.g. harmful algal blooms, fish kills, megafauna mortality or morbidity) are caused by material placement or other factors
- To determine after the fact whether dredge material relocation has resulted in adverse impacts on ecological receptors.

These objectives are clearly interlinked, but often require different approaches to monitoring. For example, baseline monitoring may be conducted not to predict, manage, or assess dredging impacts; instead the purpose may be to set long-term environmental objectives, assess and report on ecosystem health, or assess the effectiveness of broad interventions such as improved catchment management.

When baseline monitoring is conducted to establish thresholds for predictive modelling and impact assessment, it should ideally be designed to reflect broad-scale water quality conditions at the spatial scale over which plume impacts could potentially occur, in advance of modelling such plumes, so as to identify potentially affected receptors. In contrast, baseline monitoring to establish reactive management triggers should focus on specific receptors that modelling indicates are at risk. For new placement sites this adds to the uncertainty involved in predicting impacts, because baseline data from previously monitored sites may not reflect ambient conditions at different receptors that modelling predicts may be influenced by sediment plumes.

Similarly, the requirements of monitoring programs for reactive management (i.e. establishing reactive trigger values, determining whether exceedance of those trigger values result from dredging/disposal, and implementing management responses accordingly) are different from monitoring simply to determine whether dredging has resulted in impacts after the fact. Both reactive management and *post-hoc* impact assessment objectives generally require that water quality monitoring sites are linked to ecological receptor monitoring sites. Reactive management, however, requires *a priori* specification of trigger values and management response hierarchies. Data acquisition, albeit it well-designed, is all that is needed for *post-hoc* impact assessment, should that be the objective of the monitoring program.

It is important to note that the above discussion specifically refers to monitoring changes in water quality due to the placement of dredged material at sea. Water quality monitoring is conducted with a variety of other management objectives, including:

- Protection of human health in relation to recreational uses or seafood consumption
- Protection of human uses of the ecosystem such as fisheries and aquaculture
- Assessment and reporting of long-term trends in ecosystem condition
- Assessment of the effectiveness of environmental policies and management regimes such as the *Reef Water Quality Protection Plan* (the Reef Plan).

The scope of this report is specifically restricted to the objectives of assessing and minimising ecological impacts due to the placement of dredged material at sea.

MONITORING METHODOLOGIES AND PARAMETERS

Data Collection

There are four main methods of collecting water quality data: the collection of physical water samples for chemical or physical analysis at the sampling site or in the laboratory, hand-held or vessel-based water quality probes, fixed *in situ* instrument and data logging packages, and remote sensing (figure 2). Each method has advantages and disadvantages, and a combination of data collection methods is generally required.

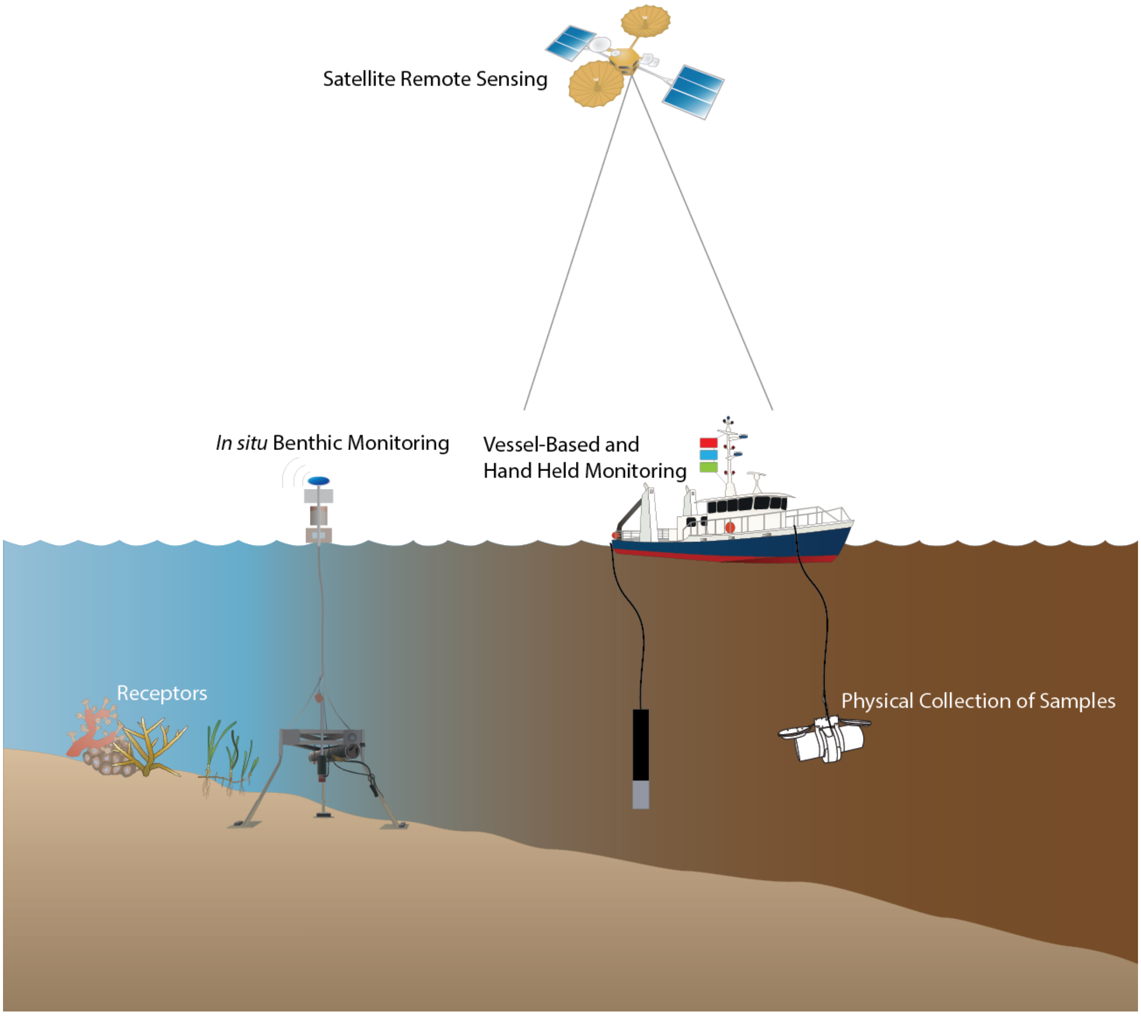

Figure 2. Generic methods for water quality data collection.

Physical water samples are rarely used if water quality data can be collected by other means, but are the only option for some parameters that require physical or chemical analysis, in particular the determination of TSS. A variety of water sampling devices are available that allow sample collection from specific depths, so that a profile of the water column can be derived from samples collected at discrete depths. Physical water samples, however, only provide a snapshot of water quality at a given point in time, and when depth profiles are collected there may be lags between sample collections at different depths. This can be addressed through the selection of sampling apparatus, for example using "rosettes" of multiple sampling bottles that take samples at different times as the rosette is lowered through the water column. Rosettes are typically used to collect depth profiles in the open ocean, at depths of hundreds or thousands of metres. At the relatively shallow depths (tens of metres) at which water quality monitoring occurs in the World Heritage Area, the lag time in collecting water samples at different depths at a site is typically in the order of tens of minutes, which is not usually of concern with respect to monitoring dredge material placement activities.

Hand-held and vessel-based probes are available to measure a variety of water quality parameters, notably including turbidity and light. These probes also allow collection of depth profiles of measured parameters, with the advantages that the data are collected continuously with depth and can be collected on time scales of minutes. Thus, although they technically only provide snapshots in time, use of these probes allows data to be collected from a number of different locations over relatively short time scales in the order of tens of minutes to a few hours. This allows the collection of data in close proximity to moving sources to characterise source levels. It also allows the characterisation of the spatial extent of sediment plumes by collecting profiles along longitudinal and perpendicular transects downstream of a source. Such vessel-based monitoring is also good for characterising water quality at broad spatial scales because multiple sites can be sampled in a short time.

Fixed, *in situ* instrument packages can be fitted with sensors for a range of water quality and oceanographic parameters, including turbidity, light, and sedimentation rate. *In situ* packages are fitted with data loggers that record the monitoring data at specified intervals, typically in the order of every 10 minutes. In some cases the loggers are retrieved at intervals, generally in the order of weeks to a month, to download the data from the loggers. Increasingly, however, the instruments are fitted with buoy-mounted telemetry to transmit data on a daily or even real-time basis. Such systems provide for web-based remote data sharing and monitoring. Data loggers are still used to provide backup for download in the event of telemetry malfunction.

In situ loggers collect data from only one location per logger, so site selection is a critical consideration in their use in monitoring programs. They are usually deployed on the seabed at or near sensitive receptors, to link water quality data to stress, and potential impacts, on the receptors. In this case, loggers only collect data from near the bottom, which can be an advantage or a disadvantage depending on the parameter as discussed further below. It is, however, possible to deploy loggers above the bottom, or at multiple depths, using buoy systems. A recent notable example is the deployment of light sensors both at the surface and at depth to measure the attenuation of surface irradiance (light) during the development of light-based monitoring of seagrass communities for the Western Basin Dredging and Disposal Project at the Port of Gladstone (Chartrand et al. 2012).

Loggers require regular maintenance, generally at fortnightly to monthly intervals, to clean sensors, replace batteries, and/or download data. Retrieval of the loggers for servicing may be done from the surface, or require divers, remotely operated vehicles (ROVs), or acoustic release/subsurface buoys systems depending on depth, metocean conditions, and safety and security considerations. Loggers can also suffer from calibration issues and data may drift when deployed for long times. A robust data QA system (see below) can often allow correction through post-processing of data, especially if data drift is linear and is cross-calibrated with reliable measurements.

Remote sensing based on ocean colour (technically, the reflectance of light of different wavelengths from the ocean as viewed from above) has been used in a number of water quality monitoring programs. The use of remote sensing is discussed in “Ocean Colour”, page 22.

Precision and Accuracy

Variation in water quality data can result from:

- Actual changes in measured parameters, which can result from natural variability, dredge material relocation, or anthropogenic influence other than the relocation project being monitored
- Systematic bias resulting from sample collection and handling, laboratory analysis, instrument calibration, and/or other factors
- Measurement error, meaning how much difference there is among multiple measurements of the same sample using the same methods.

Accuracy refers to the degree of systematic bias. Precision refers to measurement error. Both accuracy and precision are critically important in water quality monitoring, and the goal is always to maximise both accuracy and precision to increase the ability to detect real change. This is critical to increase confidence in a reactive monitoring program's ability to provide early warning of the need for management responses – not only to prevent impacts but also to avoid unnecessary false alarms.

The most important mechanism to maximise precision and accuracy is a documented QA system for all steps in data collection, which will include among a range of measures:

- Selection of appropriate data collection methods
- Suitably trained personnel for sample collection and handling
- Standard operating procedures for sampling and sample handling, storage and transport
- Chain of custody protocols for physical samples
- QC protocols for laboratory (e.g. inter-laboratory comparisons, blind field and laboratory replicates, trip blanks)
- Procedures for instrument servicing and calibration, and maintaining calibration records
- Procedures for cross-calibration of instruments.

The Queensland Monitoring and Sampling Manual (DERM 2010) and Australian Institute of Marine Science (AIMS) Standard Operating Procedure (Devlin & Lourey 2000) provide useful guidance on water quality sampling methods and QA measures.

Data Handling, Storage, Analysis and Reporting

Best practice in water quality monitoring programs is a fully documented system for all steps in data handling, storage, analysis, and reporting that among other things:

- Is agreed in advance among regulators and other key stakeholders
- Defines clear procedures to be followed by all parties
- Securely archives all raw data
- Specifies clear, consistent, and reliable procedures for data file naming, backup, and handover
- Specifies requirements for cross-checking of data entry, processing, and analysis

- Records metadata for data collection (i.e. data collection by whom, what, where, how, when)
- Records metadata for data processing and analysis (i.e. how the raw data were processed or modified, and analysed, and by whom, how, when)
- Defines reporting requirements including what needs to be reported, to whom, and on what time scale
- Provides for permanent data archival, with specified criteria for access to the archived data.

Monitoring Parameters

Water quality monitoring programs, generically, may include measurement of a wide range of parameters. Monitoring for dredging and dredge material relocation projects typically focuses on parameters related to sediment mobilisation.

Light

A primary potential impact addressed by water quality monitoring for dredge material relocation projects is the reduction of available light due to sediment mobilisation into the water column. In the World Heritage Area, hard corals and seagrasses are usually the light-dependent receptors of most concern, but there are many other photosynthetic organisms, including macroalgae, benthic microalgae, giant clams, soft corals and some sponges, ascidians, and other invertebrates that are photosynthetic or have photosynthetic symbionts and are therefore light-dependent. Light is usually monitored as PAR, the spectral band of solar radiation that is used in photosynthesis.

PAR is a direct measure of, rather than a surrogate for, sediment-related light attenuation, the cause of the impact of concern. Light loggers placed on the bottom at sensitive receptors measure the actual light received at the receptor, integrating the effects of elevated turbidity throughout the water column. Instruments to measure PAR underwater were once expensive and sometimes unreliable. The technology has improved, and PAR measurement with fixed loggers or hand-held probes is now essentially as routine as measuring turbidity. Table 1 summarises the advantages and disadvantages of monitoring light.

Table 1. Advantages and disadvantages of monitoring light.

Advantages	Disadvantages
Directly measures the source of potential impact (light attenuation) Can be reliably measured with both fixed and mobile instruments that can be readily inter-calibrated to recognised standards Can be measured in essentially real time, essentially continuously at fixed logger sites (time scale of minutes) Hand-held turbidity probes can rapidly measure the vertical and horizontal extend of turbidity plumes Fixed loggers integrate effects of suspended sediments on light attenuation throughout the water column Measurement technology is now relatively mature and reliable.	Long-term data sets are not as widely available as those for turbidity Relatively short history of use in reactive monitoring Predictive modelling depends on establishing a correlation between TSS and light attenuation; and may differ between ambient and dredging-induced sediments, reducing confidence in model predictions prior to dredging.

Organisms do not use all parts of this spectral range equally; in particular they do not efficiently capture yellow wavelengths, in the middle of the PAR spectrum. This is significant because sediment mobilisation tends to shift the light spectrum toward yellow wavelengths (Petrou et al. 2012). Therefore light quality as well as light quantity may be affected by dredging and dredge material relocation. Changes in the spectral quality of light in the PAR band can also be measured *in situ*, but not as routinely as PAR.

Turbidity

Turbidity is a generic term for water "cloudiness", which can refer to visual perception of whether the water is "dirty" on the surface, underwater visibility, transparency of light, and sometimes water colour. Turbidity is measured with electronic nephelometers that measure the scatter of light from suspended particles, and is expressed in NTU.

Turbidity is used as an indicator of sediment-related light attenuation, the real parameter of interest, but the relationship between turbidity and light attenuation varies widely as a function of the colour, shape and size of the particles. Turbidity may also be used as an indicator of visual plumes, which may be a source of public concern, but again the relationship between measured turbidity and the appearance of the water can vary widely, and water that appears quite cloudy or discoloured to the eye may have relatively low levels of measured turbidity. Turbidity can also be used as an indicator of suspended sediment (or solids) concentration (SSC).

Turbidity in and of itself does not usually directly cause ecological impacts; although very high levels of turbidity can affect the visually mediated behaviour of predators or prey (Meager et al. 2005; Utne-Palm 1999, 2002, 2004; Wilber & Clarke 2001); these are rarely a significant issue in relation to dredging.

Instead, turbidity is used as a surrogate for sediment-related light attenuation, the real parameter of interest, but the relationship between turbidity and light attenuation varies widely as a function of the colour, shape and size of the particles. Nonetheless, turbidity is historically the primary parameter used in water quality monitoring for potential impacts on light-dependent receptors during dredging and dredge material relocation projects. In the past this was largely because turbidity could be measured more reliably and cost-effectively than PAR, but with improvements in technology this advantage is diminishing. Table 2 summarises the advantages and disadvantages of measuring turbidity in dredging projects with respect to impacts on light-dependent receptors.

Table 2. Advantages and disadvantages of monitoring turbidity.

Advantages	Disadvantages
Can be reliably measured with both fixed and mobile instruments that can be readily inter-calibrated to recognised standards Can be measured in essentially real time, essentially continuously at fixed logger sites (time scale of minutes) Hand-held turbidity probes can rapidly measure the vertical and horizontal extend of turbidity plumes Measurement technology is relatively mature and reliable Long-term datasets (albeit sometimes with considerable quality control issues) are generally more available for turbidity than other relevant parameters.	Usually no direct link to ecological impacts Can only be related to direct causal factors (light or suspended sediment concentration) by correlation, or as a surrogate indicator Continuous data loggers can produce transient anomalies from single large particles or fouling debris on the sensor. This is readily addressed through post-processing and Quality Assurance/Quality Control protocols but these need to be agreed in advance Continuous loggers measure only turbidity at the depth of the instrument and not overlying turbid layers in the water column that may reduce light availability Predictive modelling depends on establishing the relationship between TSS and turbidity; these are typically noisy, and may differ between ambient and dredging-induced sediments, reducing confidence in model predictions prior to dredging.

Water clarity as measured by Secchi depth (the depth to which a white or white-and-black disk is visible from the surface) is correlated to turbidity (Davies-Colley & Smith 2001). The Queensland Water Quality Guidelines (DERM 2009) and Marine Park Water Quality Guidelines (GBRMPA 2010) include trigger values for Secchi depth. Measurement of Secchi depth has the advantage of using very inexpensive and reliable equipment and is quickly and easily measured in the field. Measurements are restricted to daylight hours when the sun is relatively high overhead, and as with hand-held or vessel mounted probes can only be collected from one location at a time. Depending on how clear the water is, Secchi depth only reflects clarity in the surface layer, and in many cases will not reflect the existence of deep sediment plumes. Given the widespread availability of reliable turbidity probes, Secchi depth is rarely if ever used in water quality monitoring for dredge material placement projects.

Suspended Sediment Concentration

SSC refers to the amount of particulate material in the water column. SSC is usually measured as TSS by filtering and weighing particulates from physical water samples. Whereas turbidity is a measure of the scattering of light by sediment particles suspended in the water column, TSS measures the actual concentration of particles.

The most important potential impact of TSS in and of itself as a monitoring parameter is the possible impact of suspended sediments on the fertilisation and viability of coral eggs and larvae (Gilmour 1999; Humphrey et al. 2009). In Western Australia this has led to approval conditions requiring monitoring of coral reproductive status and/or the cessation of dredging during likely periods of mass coral spawning (Hanley 2011). Otherwise, ecological effects of suspended sediments such as clogging of fish gills or the feeding apparatus of filter feeders occur only at extremely high TSS concentrations (Au et al. 2004; Norkko et al. 2006; Wilber & Clarke 2001) and are not usually a concern for dredging programs.

The most relevant use of SSC in water quality management for dredging projects is for predictive modelling. The hydrodynamic models in use predict the transport of particles, i.e. the spatial distribution of TSS concentration. Field measurements of TSS are typically made primarily to calibrate and validate models, by determining the relationship between turbidity and TSS. This relationship varies with composition, size, and often concentration of the suspended solids, and there is often considerable error in the turbidity-TSS regression. For this reason, and because sediments mobilised by dredge material relocation usually have different characteristics than ambient suspended sediments, turbidity-TSS regressions under baseline conditions often are not representative of dredging conditions. Good practice in establishing the turbidity-TSS relationship is to analyse it on the basis of the actual sediments to be dredged, for example from core samples, or if possible from actual plumes created by dredge material relocation.

Although TSS is mainly useful in terms of modelling and model validation, some dredging projects have converted baseline data on turbidity into TSS on the basis of the turbidity-TSS regression, derived trigger values for TSS, and then conducted reactive monitoring during dredging by converting monitored turbidity into TSS. This can only introduce error into the measurements. If the actual measurement used for monitoring is turbidity, is better practice to establish trigger values for reactive management on the basis of turbidity, i.e. the actual measured parameter, than to convert to TSS and base trigger values on that. Table 3 summarises the advantages and disadvantages of monitoring suspended sediment concentration.

Table 3. Advantages and disadvantages of monitoring suspended sediment concentration.

Advantages	Disadvantages
Only relevant water-column parameter that can be directly modelled in the water column Can be quantitatively measured with high precision.	Usually no direct link to ecological impacts except at very high concentrations Can only be related to light availability by correlation Requires collection of physical samples – cannot be measured continuously Requires laboratory analysis – introduces lag between sample collection and reporting of results.

It should be noted that laboratory measurements of TSS only measure the fraction of SSC retained on the filter. The pore size of filters used in TSS determination can vary. If TSS measurements are important in a monitoring program, the filter pore size should be consistent and specified in the QA system. Historical data based on TSS measurement using a different, or unknown, filter pore size should be used with some caution.

Ocean Colour

Remote sensing of ocean colour using imagery collected from aircraft or, more commonly, satellites (Moderate Resolution Imaging Spectroradiometer (MODIS) or SeaWiFS) is sometime monitored in dredge material relocation projects. Algorithms based on the relative ocean reflectance in different colour bands can be developed to estimate turbidity or TSS. The spatial resolution of such techniques is generally 250 m to 1 km, depending on the sensors and wavelength bands used. Normally one or two satellite images per day can be captured, which is dependent on the number of satellite overpasses at a given site. SKM's experience in Queensland is that MODIS imagery can capture two images a day at a resolution of 250 m.

Development of the algorithm to estimate TSS or turbidity using ocean colour imagery requires site-specific ground truthing, i.e. direct measurement of turbidity and TSS at the same time that imagery is captured. As noted above, sediments mobilised by dredge material placement usually have different characteristics than ambient sediments, so it is important that ground truthing is done when material placement is underway. Ground truthing and algorithm development usually takes a month or more, so satellite imagery is only useful for projects of relatively long duration. Most of the cost of remote sensing lies in the initial algorithm and ground truthing; once this is complete the imagery can be obtained at relatively low cost. Table 4 summarises the advantages and disadvantages of monitoring ocean colour using satellites.

Table 4. Advantages and disadvantages of monitoring ocean colour from satellites.

Advantages	Disadvantages
Wide synoptic view useful in determining spatial extent of plumes Wide synoptic view can be useful in distinguishing material placement plumes from regional weather-driven events Imagery can be useful in stakeholder communication.	No direct link to ecological impacts – determines turbidity and TSS, themselves surrogates for light attenuation, by correlation Only indicates surface plumes, typically to a maximum depth of 5 m Requires extensive algorithm development and ground truthing – results in a considerable lag between project startup and availability of turbidity/TSS estimates Limited number of images (usually two at most) can be captured per day Not available when there is cloud cover May not be available on some days if satellite passes overhead at an unfavourable angle Usually not useful in areas shallower than approximately 5 m because of difficulty in distinguishing reflected light from the bottom from that due to suspended matter – not generally an issue for dredge material placement but in some cases may limit usefulness of satellite imagery to monitor dredging activities.

Aircraft can also be used for remote sensing of turbidity and TSS, with the same requirements for algorithm development and ground truthing. Aircraft capture a small field of view than satellites, but at higher resolution, and can capture imagery essentially continuously during daylight hours. They can also focus on areas of particular interest. Ongoing image capture from aircraft is expensive, and is generally worthwhile only if a project is particularly sensitive.

Sedimentation

Sedimentation is the settlement of sediment particles to the bottom. Water quality monitoring programs for dredge material placement generally measure the rate of sedimentation per day rather than a total amount of sedimentation. As for light, sedimentation is a direct mode of impact on organisms that are sensitive to sediment settling on them. In the World Heritage Area corals are typically the most sensitive receptors. While seagrass, filter-feeding invertebrate communities, macroalgae communities and other receptors can be adversely affected by sedimentation, the impact thresholds are typically much higher than for corals and not generally of concern except within or in very close proximity to the relocation site.

Corals are subject to natural sedimentation and can clear sediment settling on their surface, but if the sedimentation rate exceeds their clearance capacity, the accumulation of sediment can lead to tissue damage and partial or total mortality of the coral colony. High sedimentation rates can also lead to sub-lethal effects including reduced growth and reproduction, bleaching, and disease (Fabricius et al. 2005; Gilmour et al. 2006). Fine sediments tend to have greater impact on corals than coarse sediments (Weber et al. 2004).

Sedimentation is monitored using either sediment tubes that collect physical samples or electronic sensors mounted on data logger packages. Both methods are plagued with problems. Sediment tubes are placed at monitoring sites over relatively long intervals (typically in the order of a month) and retrieved to weigh the sediment that has settled in the tube, and thus provide only an average rate of deposition over that time interval. The tubes are often affected by fouling or colonisation by animals, which introduces a high degree of variability and/or invalidates the data. Settlement in the tubes may not necessarily reflect actual sedimentation on the bottom if the tubes are elevated above the seabed, or the tubes themselves alter the hydrodynamic micro-environment.

Logger-mounted sedimentation sensors provide continuous measurements of sedimentation rate, however, in SKMs experience they are often unreliable both in operation and with regard to data quality.

Both sediment tubes and electronic sensors measure sediments that have been resuspended from the bottom and re-settled, a natural process. If increases in total sedimentation rates are observed, it is useful to determine whether the change results from natural events or from dredging or dredge material placement, in order to decide what if any management responses are appropriate. Various measurements to distinguish natural sediments for those mobilised by dredging and dredge material placement, and resuspended sediments from newly settled sediments (net sedimentation) have been used with both sediment tubes and electronic sensors. In SKM's experience these are not very reliable.

One advantage of sediment tubes is that they collect an actual sample of the settled sediment. As noted above, dredge material often has different characteristics than ambient sediments, such as particle size distribution and chemical composition (particularly calcium carbonate content in reef environments). Analysis of sediment collected in sediment tubes can therefore be useful in distinguishing natural sedimentation from that resulting from dredge material placement. Table 5 summarises the advantages and disadvantages of monitoring sedimentation.

Table 5. Advantages and disadvantages of sedimentation.

Advantages	Disadvantages
Measures the direct source of impact If monitored with sediment tubes, collected sediments can be used to distinguish ambient sediments from dredge material.	Data variability is often high, and data quality often low Difficult to distinguish settlement of resuspended sediments from net sedimentation

Sedimentation is an important potential source of impact, particularly on corals, so despite the measurement difficulties sedimentation monitoring is likely to be an important component of water quality monitoring for some dredge material placement projects in the World Heritage Area. This is especially true for large capital dredging projects, or if new placement sites are used for which impacts of material placement have not previously been monitored. SKM does not, however, recommend using sedimentation rate monitoring to trigger direct operational responses (e.g. a reduction or cessation of material placement). SKM recommends instead that sedimentation rate are used to trigger investigative responses, for example, the collection of settlement sediment to determine whether increased sedimentation is from dredge material or ecological monitoring for coral stress indicators, sediment build-up on coral colonies, or coral tissue necrosis/partial mortality.

Other Parameters

It may be useful or necessary to monitor a variety of other parameters using physical samples, hand-held probes, or fixed loggers. These include:

- Water depth
- Temperature and salinity
- pH
- Dissolved oxygen
- Total organic carbon or dissolved organic carbon
- Nutrients
- Metals or other potentially toxic substances.

Physico-chemical parameters can be useful in interpreting changes in parameters used for reactive monitoring, for example changes in water depth due to tides and waves can be used to interpret observed variation in light or turbidity levels, and salinity can reflect freshwater runoff events. The need to monitor parameters such as dissolved oxygen, organic carbon, nutrients, and metals or other toxic substances is generally determined through sediment quality assessment. The present study does not consider monitoring necessitated by the chemical nature of the sediments being relocated.

WATER QUALITY MONITORING FRAMEWORK

The overarching framework for water quality monitoring in Australia is the National Water Quality Management Strategy (NWQMS). Water quality monitoring and reporting in the Marine Park uses a hierarchical set of guidelines from national to local levels (table 6) that have been developed in accordance with the NWQMS. The development of guidelines at local, state, and national levels has followed a consistent conceptual framework. For metals, pesticides, and other toxicants, guidelines have been developed on the basis of ecotoxicology data. In general, the ANZECC/ARMCANZ (2000) trigger values for toxicants apply, with the exception that Marine Park guidelines have been developed for a suite of synthetic pesticides.

For turbidity, TSS, dissolved oxygen, nutrients and other naturally variable physico-chemical parameters, guideline values were developed at local and state levels in the context of natural long-term variability. The guidelines were developed on the basis of long-term datasets from reference sites considered least affected by post-European development. An overriding principle throughout the hierarchy of table 6 is that monitoring and reporting should always be based on the most locally-specific available guidelines. Thus, ANZECC/ARMCANZ (2000) guideline values for a parameter are not applied if there are Queensland, Marine Park, or catchment guidelines for the parameter.

All of the guidelines listed in table 6 provide trigger values based on upstream-to-downstream or inshore-to-offshore classifications of ecosystem type, recognising the natural difference in water quality and sensitivity among different categories of water bodies. The water body classifications of the Queensland and Marine Park guidelines overlap, but have been integrated so that the Queensland guidelines for Enclosed Coastal systems have been adopted in the Marine Park guidelines, effectively integrating the two sets of guidelines.

Table 6. Hierarchy of published water quality guidelines that applies in the World Heritage Area.

Level	Guidelines	Ecosystem Classification
National	Australian and New Zealand Guidelines for Fresh and Marine Water Quality. ANZECC/ARMCANZ (2000)	Upland River to Marine
Queensland	Queensland Water Quality Guidelines 2009 (DERM 2009)	Upland streams, freshwater lakes to Open coastal, mid-shelf & offshore
Marine Park	Water Quality Guidelines for the Great Barrier Reef Marine Park, Revised Edition 2010 (GBRMPA 2010)	Enclosed coastal to Offshore
Local	Individual catchment Environmental Values and Water Quality Objectives (various) developed under the *Environmental Protection (Water) Policy 1997*	Upland streams, freshwater lakes to Open coastal, mid-shelf & offshore

The water quality guidelines listed in table 6 were designed primarily to assess long-term changes in water quality, with a particular focus on establishing management objectives, assessing and reporting on ecosystem health in relation to the objectives, and measuring the effectiveness of management interventions such as the Reef Plan. The guidelines are generally defined at much broader spatial scales than are appropriate to individual dredge material placement sites, with the exception of catchment Water Quality Objectives (WQOs) in some cases, and smooth out seasonal variability so that the guidelines are not necessarily appropriate for application to activities that are completed in a single wet or dry season. The guidelines themselves acknowledge that locally specific data collection and development of site-specific guidelines should be conducted for individual activities with potential impacts on water quality. Therefore, the guidelines in table 6 are not directly applicable to the monitoring and management of changes in water quality in relation to dredge material placement projects. They do, however, establish the important principles that guidelines (or in the context of this report, trigger values for management responses) should be based on natural variability, as well as on site-specific baseline data.

General Framework for Water Quality Monitoring for Reactive Management

Figure 3 presents a general conceptual framework for developing and implementing water quality monitoring programs for reactive management of dredged material placement in the Marine Park and World Heritage Area. Although the framework has been developed specifically in the context of the offshore placement of dredge material, the concepts are applicable to dredging projects generally.

The framework represented in figure 3 is structured around three overlapping phases of environmental impact assessment and management that are typically associated with dredge material placement: environmental impact assessment, the development of an environmental management plan (EMP) including a monitoring plan, and EMP implementation including monitoring and management responses as required on the basis of monitoring results. The framework is consistent with the National Assessment Guidelines for Dredging (NAGD; Commonwealth of Australia 2009), and encompasses the final two steps in the NAGD Assessment Framework (Commonwealth of Australia 2009, page 9), namely to *Assess potential impacts on the environment at the loading and disposal sites*, and to *Identify monitoring and management measures to control or mitigate impacts at loading and disposal sites*. The latter step, of course, implies that the monitoring and management measures will not only be identified but also implemented, which is made clear in the Staged Disposal Site Monitoring Framework of the NAGD (Commonwealth of Australia 2009, page 25). The NAGD Staged Disposal Monitoring Framework includes elements aimed at assessing potential impacts resulting from contamination of the dredged material by toxic substances. This report, including the framework depicted in figure 3, assumes that dredge material has already been assessed to be suitable for unconfined ocean disposal in accordance with the NAGD with respect to contamination by toxicants. The framework developed herein focuses on changes to water quality and potential ecological impacts in the context of sediment mobilisation.

Figure 3 presents a generic conceptual framework that can be applied not only to dredge material placement, but also to dredging. As a generic framework, however, it cannot be directly applied to individual projects without adaptation. Every project has specific aspects that need to be taken into account in its monitoring program. The nature of available baseline data, information on sensitive receptors including their current status and impacts of previous projects, volume and type of material, project duration and seasonality, and indeed all the considerations represented in figure 3 will be project-specific. The framework is intended to be adapted to the individual circumstances of any single project. As noted in “Approaches to Developing Water Quality Trigger Values”, page 39, for example, the review of available information conducted to inform step 2, the establishment of threshold criteria for predictive modelling, may also provide for the identification of monitoring sites and data gaps so that site-specific monitoring commences from the EIA phase rather than during EMP development as shown in the framework. Similarly, information already available may render some steps in the framework, for example collection of additional site-specific baseline data, unnecessary.

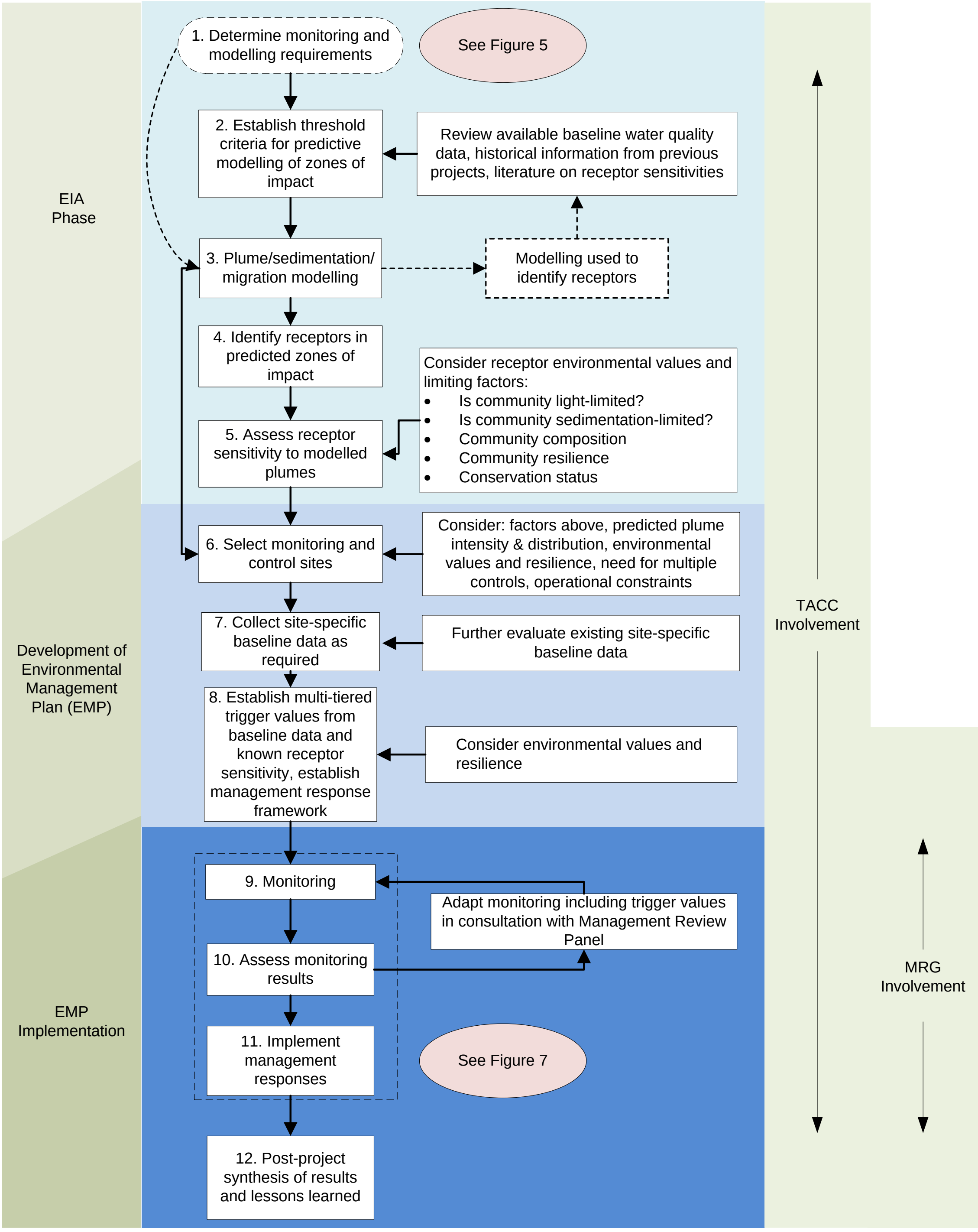

Figure 3. A general framework for developing and implementing water quality monitoring programs for reactive management of dredged material placement.

Two key components of any monitoring framework have been omitted from figure 3 because of the specific focus of the present study on managing potential impacts of dredge material placement. These two components are:

- **Clearly define goals and objectives for monitoring and management.** The goals of water quality monitoring for dredge material placement are clear: to detect deterioration of water quality conditions that result from placement activities in time to take management actions to prevent or minimise adverse ecological impacts.

- **Establish a clear conceptual model of modes of impact and ecological responses**. In the context of managing potential impacts of dredge material placement, the conceptual model for the water quality monitoring framework described herein is clearly the potential for placement to mobilise sediments, with resultant impacts due to reduction of the quantity and/or quality of available light, as well as increased sedimentation (figure 4).

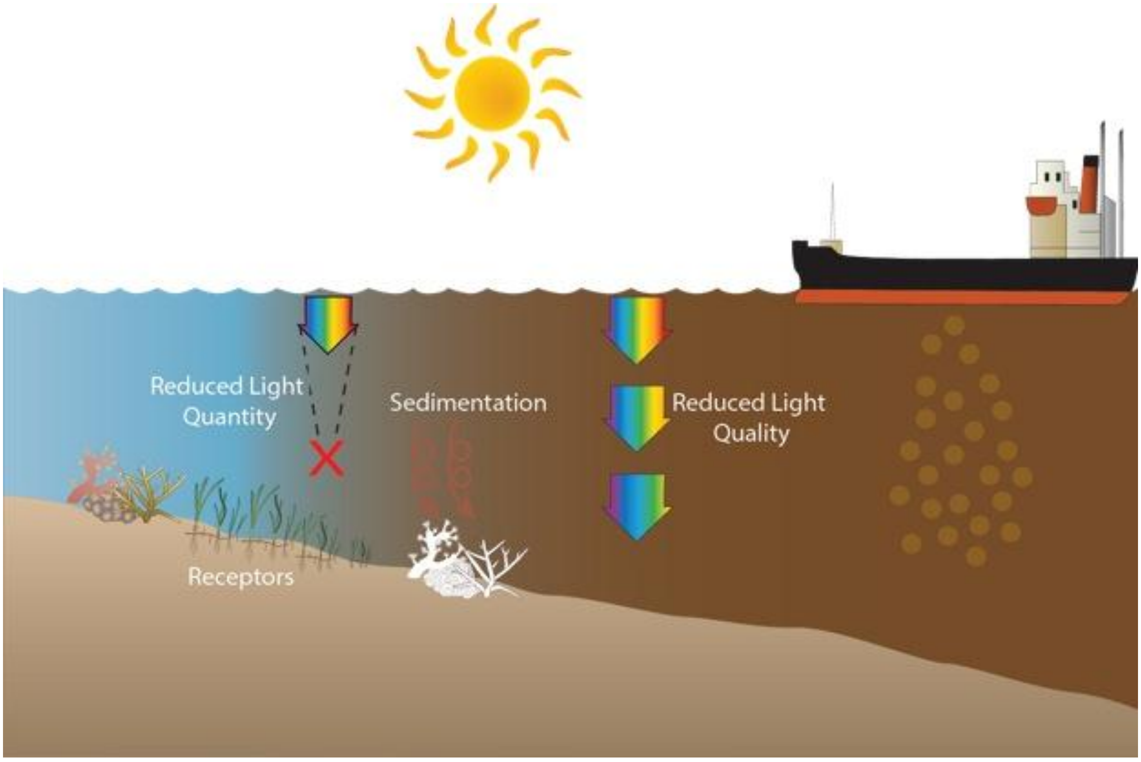

Figure 4. Conceptual model of potential impacts from dredge material placement.

Monitoring and Data Requirements

Given clear objectives and a conceptual framework, which is generally true for dredge material placement projects, the first step in developing a water quality monitoring program is to determine the data requirements of the program and whether monitoring and/or predictive impact modelling are needed. Figure 5 shows a conceptual decision tree for determining these requirements.

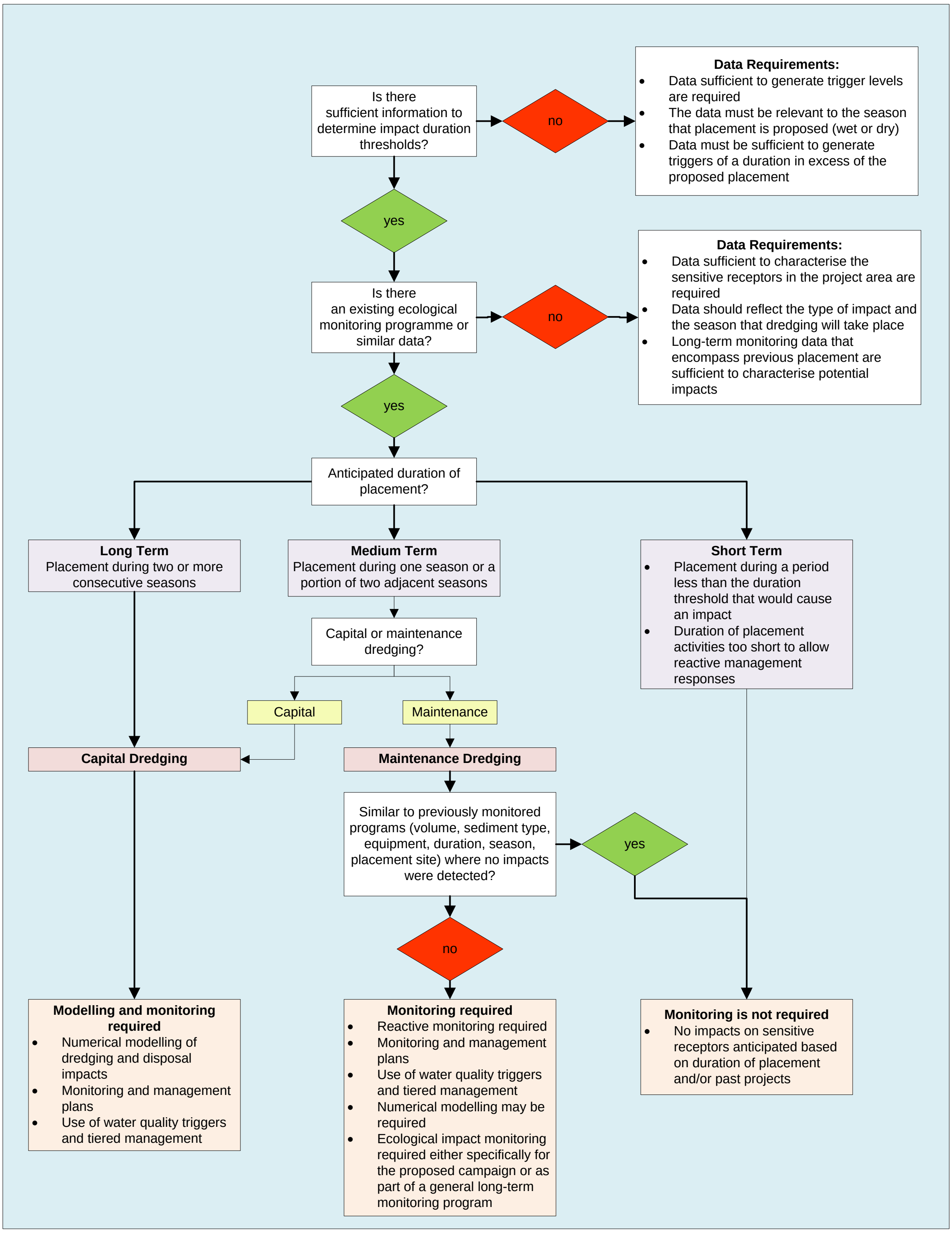

Figure 5. Decision process for determining need for monitoring and modelling to support reactive management, including data requirements. Decision steps are to be made by or in close consultation with the TACC or MRG for the project. Monitoring for purposes other than reactive management may still be required.

The decision process begins with evaluating whether there is sufficient information available to characterise the time scales at which impacts on sensitive receptors will occur. If there is not sufficient information available, baseline surveys and monitoring of water quality and ecological receptors are required. For existing dredge material placement sites in the World Heritage Area there is generally a considerable body of knowledge from past placement campaigns that is sufficient to characterise the time scales on which impacts are likely to occur.

The time scales on which impacts are expected to occur are then compared to the duration of the proposed dredging campaign. If the campaign will be shorter than the time needed to cause impact (or in the case of very short campaigns where there would not be sufficient time for management responses to water quality monitoring results), then water quality monitoring may not necessary.

If placement is proposed to take place for longer than the time needed to cause impacts to receptors, further evaluation is necessary. The decision framework in figure 5 assumes water quality monitoring, and predictive modelling of the associated sediment plumes, will be needed for material placement in capital dredging projects. This is because capital dredging generally involves large quantities of material, with the particle size distribution and other characteristics of the material likely to vary considerably from one project to another.

Maintenance dredging in the World Heritage Area, by contrast, often involves the repeated placement of:

- Similar volumes of material
- Similar types of material
- Placement at the same site
- Placement during a similar season
- For many Queensland ports, similar or even the same dredging and placement plant.

For proposed maintenance dredging campaigns that essentially repeat previous dredging campaigns, and if water quality and ecological impact monitoring have shown that previous campaigns have not had significant impacts on receptors, water quality monitoring for reactive management is not needed. SKM does not recommend that monitoring of only one similar previous campaign would make water quality monitoring unnecessary, and recommends that at least three previous campaigns have been monitored without evidence of significant ecological impact. SKM also recommends in these instances that the proposed campaign does not involve a larger volume of material than the maximum volume of the previously monitored campaigns. In addition, it would be prudent to implement contingency plans to either immediately institute water quality monitoring, or cease placement, if climatic conditions during placement move beyond the range observed in previous campaigns.

It is stressed that the focus of the decision tree depicted in figure 5 is on monitoring for reactive management, that is, to identify declines in water quality early enough to initiate management responses. Water quality monitoring for dredging and dredge material placement projects may be conducted for a variety of other reasons.

Predictive Impact Modelling

The decision process in figure 5 will generally conclude that hydrodynamic modelling of sediment plumes is required for capital dredging projects and the placement of dredge material, whether capital or maintenance, in new placement sites.

The GBRMPA has released guidelines for hydrodynamic modelling for dredging projects in the Marine Park (GBRMPA 2012). The guidelines encourage the use of a zonation scheme for predicting the distribution of impact that has been developed for the environmental assessment of dredging projects in Western Australia (WA; WAEPA 2011). The WA approach calls for hydrodynamic modelling to be conducted so as to predict the spatial extent of:

- A zone of high impact, within which impacts on benthic communities are predicted to be irreversible, meaning that the communities will lack the capacity to return to their pre-impact state within five years
- A zone of moderate impact, within which impacts on benthic communities are predicted to be sub-lethal, and/or recovery from impact is expected to occur within five years
- A zone of influence, within which changes in water quality are expected, but the changes are not expected to result in impacts on benthic communities.

Modelling of zones of impact necessarily requires establishing quantitative water quality criteria for impact thresholds, usually as ranges of TSS and sedimentation that will lead to moderate or high impact as defined above, with some lower bound to the zone of influence reflecting levels of detectible change. There are no established procedures for developing threshold criteria for modelling the zones of impact and influence using the WAEPA (2011) approach. Information that can support the establishment of impact threshold criteria includes:

- Scientific literature on receptor sensitivity
- Baseline data on ambient water quality conditions
- Historical information on outcomes of water quality and ecological monitoring for previous projects in the area
- Available information on receptor community species composition.

The WAEPA (2011) guidelines state that the spatial scale of modelling should extend across the entire zone of influence. Since the zone of influence is an output of the model this requires a reasonably foreseeable extent of influence to be assumed, at least in the first iteration of modelling. A decision that predictive modelling is required implies that there is unacceptable uncertainly regarding the outcomes of proposed dredge material placement. This may be due to the nature or volume of the material, the placement method, or the proposed use of a new placement site. This uncertainty often limits the ability to set threshold criteria based on ambient water quality data or the outcomes of past projects because, almost by definition, at least some aspects of the proposed project are novel. To the extent that threshold criteria are based on ambient water quality data, for example, the data should be representative of the areas of impact and influence, but data are usually available for areas affected by past projects, not proposed ones with novel aspects. Nonetheless, SKM considers the use of available data on ambient conditions in establishing impact criteria for predictive modelling to be good practice.

For some proposed projects there may be so much uncertainty regarding the receptors that could be affected by dredge material placement that it is not feasible to establish scientifically valid impact threshold criteria before modelling of sediment dispersion from the placement site. This may be the case for new ports, dredging and relocation of unprecedented volumes of material, dredging and relocation of unusual material types, or proposals involving novel dredging and relocation methods. In such cases, it will be necessary to conduct hydrodynamic modelling in iterations, with a first round of modelling to predict the general spatial distribution of varying levels of TSS and sedimentation. This would be followed by the identification of ecological receptors influenced by different levels of TSS and sedimentation. It may even be necessary to conduct field surveys if the habitat and community types in the area are not sufficiently known to confidently identify receptor types. Once potentially affected receptors have been identified, the establishment of impact thresholds and prediction of zones of impact and influence can proceed, consistent with the WA approach and therefore the GBRMPA modelling guidelines. This iterative approach to first identify receptors that might be affected in order to then determine suitable impact thresholds is indicated by the dashed path at the top of figure 3.

Review of Ambient Water Quality at the Six Locations

SKM reviewed available water quality data for the six locations to determine whether it is possible to determine scientifically valid specific impact thresholds for TSS and sedimentation for use in this study. As noted in "General Framework for Water Quality Monitoring for Reactive Management", page 26, the overarching Queensland and GBRMPA water guidelines, and WQOs established for individual catchments, do not provide a basis to establish site-specific ambient conditions for individual receptors. Most available baseline data was for turbidity, however dredge material transport models predict TSS. Therefore, the study also reviewed measured relationships between turbidity and TSS at each location.

Port of Gladstone

Extensive baseline water quality monitoring was conducted during environmental impact assessment and environmental management plan development for the Western Basin Dredging and Disposal Project; including the deployment of in-situ turbidity loggers at ten sites (GHD 2009a). These ten sites were all within Gladstone Harbour and not representative of the open coastal waters of the lagoon, nor of the expected potential receptors north-west of the alternative model cases identified in a previous output of this project (SKM APASA 2013), including the north-east coast of Curtis Island and reef to the north of Model Case 1 (see SKM APASA 2013).

The Water Quality Management Plan for the Western Basin Dredging and Disposal Project does establish trigger values (table 7) for two monitoring sites north-west of the current placement site, in areas where past surveys have observed seagrass communities. The trigger values were based on 80^{th} and 95^{th} percentiles of baseline monitoring data collected by fixed loggers.

Table 7. Reporting trigger values developed for Western Basin Dredging and Disposal Project placement site from ambient water quality data.

Site	Wet season based on 80^{th} percentile		Wet season based on 95^{th} percentile		Dry season based on 80^{th} percentile		Dry season based on 95^{th} percentile	
	Turbidity (NTU)	TSS (mg/L)	Turbidity (NTU)	TSS (mg/L)	Turbidity (NTU)	TSS (mg/L)	Turbidity (NTU)	TSS (mg/L)
SGM1	4	4	7	8	2	2	5	6
SGM2	6	7	7	8	4	4	5	6

The TSS values in table 7 are derived from the turbidity-TSS relationship adopted by the project (GHD 2009a), which was:

- $TSS = 1.12 * NTU$ for turbidity ≤ 7 NTU
- $TSS = 3.68 * NTU – 17.92$ for turbidity > 7 NTU.

The above relationship was derived using a combination of ambient data and data collected during dredging. Visual examination of TSS-NTU plots indicates that the relationship may be different between ambient and dredging conditions, increasing the uncertainty associated with conversion of turbidity data to TSS.

After reviewing the available data, SKM has concluded that they are not adequate to establish threshold impact criteria for modelling because they are not adequately representative of the spatial extent of the area potentially affected by dredge material placement at the alternative model cases, and the conversion of the data to TSS for modelling purposes is uncertain. Baseline data on sedimentation in the model study area for the Port of Gladstone were not available.

Rosslyn Bay State Boat Harbour

Baseline turbidity monitoring at two key receptors near the Rosslyn Bay State Boat Harbour placement site, Bluff Rock and Wreck Point, reported 80th percentiles for turbidity of 28.6 and 20.90 NTU, as shown in table 8. These values were converted to TSS values of 42.9 and 31.4 mg/L, respectively, using a conversion of TSS = NTU * 1.5 established during dredging in 2006 (GHD 2007). Data provided to SKM by the Department of Transport and Main Roads indicate 90th percentile values of 38.3 NTU (57.5 mg/L) for Bluff Rock and 44.1 NTU (66.2 mg/L) at Wreck Point, which are considerable increases over the 80th percentiles (table 8). No data for more distant receptors potentially affected by material placement at the alternative model case sites identified by SKM APASA (2013) were available.

Table 8. Baseline turbidity and TSS at Rosslyn Bay State Boat Harbour

Site	80th percentile		90th percentile	
	Turbidity (NTU)	TSS (mg/L)	Turbidity (NTU)	TSS (mg/L)
Bluff Rock	28.6	42.9	38.3	57.5
Wreck Point	20.9	31.4	44.1	66.2

Port of Hay Point

Spot measurements of turbidity conducted on two days in December 1992 at the placement site used prior to 2005 inshore of the currently used site found an increase in turbidity with depth (table 9); no percentiles were provided.

Table 9. Results of spot measurements of turbidity in December 1992 at the inshore placement area used prior to 2005 at Hay Point (WBM 2004)

Depth range	Mean turbidity (NTU)	Turbidity range (NTU
Less than 5 m	14	10 to 18
5 to 10 m	16	12 to 23
Greater than 10 m	49	20 to 86

PCQ (2005) reported the 50th and 80th percentiles of turbidity recorded over one month in April and May 2005 at three sites in the Hay Point area, including two fringing coral reef sites, Victor Islet and Round Top Island, and the current dredge material placement site (table 10). SKM derived the TSS values in table 10 using the measured relationship of TSS = 2.2 * NTU reported by Trimarchi & Keane (2007). Although 80th percentile values during the monitoring period were not particularly high, they were more than double the median (50th percentile) values, indicating considerable variability over the one-month monitoring period.

Table 10. Baseline turbidity and TSS at the Port of Hay Point in April and May 2005 (PCQ 2005).

Site	50th percentile		80th percentile	
	Turbidity (NTU)	TSS (mg/L)	Turbidity (NTU)	TSS (mg/L)
Victor Islet	4	8	10	22
Round Top Island	3	6	8	17
Current placement site	2	5	5	11

Longer-term (several months to years) monitoring at five fringing reef sites in the Hay Point region, incorporating intermittent baseline (non-dredging) periods from 2005 to 2010, demonstrated a high degree of spatial variation in turbidity at scales of kilometres to tens of kilometres (table 11; BMA 2010). SKM derived the TSS values in table 11 from a measured turbidity to TSS relationship of TSS = 1.95 * NTU.

Table 11. Baseline turbidity and TSS measured over variable periods between 2005 and 2010 (BMA 2010).

Site	95th percentile		99th percentile	
	Turbidity (NTU)	TSS (mg/L)	Turbidity (NTU)	TSS (mg/L)
Hay Reef (coastal)	43	84	79	154
Dudgeon Reef (coastal)	89	174	166	324
Victor Islet (inshore island)	232	452	521	1016
Round Top Island (inshore island)	28	55	86	168
Slade Islet (inshore island)	17	33	58	113

Given the high vertical and spatial variability of turbidity data from the Hay Point area it was not feasible to use the available data to develop port-specific impact threshold criteria for use in the modelling.

Port of Abbot Point

There are limited historical water quality data for the marine environment in the Abbot Point region. Baseline water quality monitoring of eight sites in the Abbot Point area was conducted from April 2008 to June 2009 (GHD 2009b). Three of these sites were close to shore in the immediate vicinity of the working port, and of limited relevance to modelling potential impacts for the alternative placement sites identified by SKM APASA (2013). Two sites were relatively far offshore, in similar depths to the identified model case sites.

The assessment (GHD 2009b) found no consistent relationship between TSS and turbidity, the observed relationship at individual sites varying from TSS = 0.48 * NTU at one offshore site to the northwest to TSS = 2.42 * NTU at an inshore site. The relationship approximated TSS = 2 * NTU at five of the eight monitoring sites.

GHD (2009b) did not report percentiles of turbidity or TSS except for the median. NQBP (2012, in draft, unpublished), however, reported 80th and 95th percentiles, as well as the median, for TSS derived from the turbidity data (table 12). SKM derived the turbidity values in table 12 by back-converting to turbidity using the reported turbidity/TSS regressions for each site. Three coastal sites, where sensitive receptors are more likely to occur, had 80th percentile TSS concentrations of 15.7, 35.2, and 53.4 mg/L, and 95th percentiles of 64.3, 118.8, and 208.5 mg/L. This again demonstrates the high spatial variability of ambient water quality common in inshore areas in the World Heritage Area. It should be noted in particular that turbidity was higher at coastal sites than offshore.

Table 12. Baseline turbidity and TSS at the Port of Abbot Point.

Site	Median		80th percentile		95th percentile	
	Turbidity (NTU)	TSS (mg/L)	Turbidity (NTU)	TSS (mg/L)	Turbidity (NTU)	TSS (mg/L)
Deepwater west	2	1.2	6	2.7	17	7.9
Deepwater east	1	1.2	2	2.4	4	4.7
Coastal west	2	5.7	6	15.7	27	64.3
Coastal middle	5	9.1	18	35.2	61	118.8
Coastal east	9	20.3	23	53.4	90	208.5

Port of Townsville

Water quality in the Townsville study area has been surveyed biannually since 2004 at 12 sites, with the furthest site approximately 1500 m offshore in Cleveland Bay (GHD 2009c). This site is situated in an area of seagrass meadows at 6 m depth. In addition to spot measurements, water quality at this site was monitored continuously with a fixed logger from September 2008 to February 2009. Median turbidity in the logger measurements was 23 NTU, with an 80th percentile of 57 NTU and a 95th percentile of 109 NTU (table 13). Although (GHD 2009c) reported that there was a positive relationship between SSC and turbidity, they did not report the quantitative relationship and the turbidity data could not be converted into TSS to establish threshold criteria for modelling.

Table 13. Baseline turbidity at the Port of Townsville.

Site	Turbidity (NTU)		
	Median	80th percentile	95th percentile
1500 m offshore	23	57	109

Port of Cairns

Worley Parsons (2010) summarise information regarding turbidity and SSC in the Cairns study area (table 14) but do not report summary statistics that could be used to establish port-specific thresholds for impact modelling.

Table 14 Summary of baseline turbidity at the Port of Cairns.

Area	Range	Range
	TSS mg/L	Turbidity (NTU)

Area	Range TSS mg/L	Range Turbidity (NTU)
Trinity Inlet/Trinity	20 to 200	70
Port Entrance	Less than or equal to 400	NR
Marlin Jetty	30 to 50*	NR
Esplanade mud banks	1000 to 2000	NR
Spoil Ground	420 to 430	NR
Inner Port	NR	18 to 30*

NR: Not Reported
*Reduced mean concentration

Predictive Modelling of Sediment Plume Dispersion and Long-Term Migration

The original scope of the present study included attempting to establish port-specific threshold criteria for predictive modelling of zones of impact, but the data available were not adequate for this purpose. Reasons for this included:

- The data were focused on sites selected to monitor dredging rather than dredge material placement
- The data did not provide adequate information on variability (e.g. percentiles)
- There was inadequate information on temporal variability, specifically the duration of periods of elevated turbidity under baseline conditions.

This outcome reflects the fact that previous baseline water quality programs were often conducted for specific purposes other than establishing impact modelling criteria. It should not be interpreted as a shortcoming of previous monitoring programs, which were designed to achieve specific objectives.

Even if available data were adequate to establish impact thresholds in relation to currently used material placement sites, the present study considers the implications of hypothetical placement at alternative sites at considerable distance and in different oceanographic settings from the currently used sites. This study thus represented the situation described in “Predictive Impact Modelling”, p 30, where the potentially affected receptors could not be predicted well enough to establish quantitative impact thresholds to define zones of impact and influence. For the purposes of EIA for a specific project, this would call for an iterative approach to modelling, first using model predictions to identify which receptors are potentially affected and then setting thresholds based on those receptors and available data through further modelling and/or model interpretation. The scope of this project did not permit this iterative approach, and instead modelling proceeded to the first step, the identification of potentially affected receptors.

Even within specific receptor types (e.g. coral, seagrass), sensitivities can vary widely. For example, threshold criteria are often set on the basis of coral receptors because corals are expected to be among the most sediment-sensitive receptors in the World Heritage Area. Corals and coral communities, however, have widely varying sensitivity to sediment-related impacts. Relatively undisturbed offshore reefs are typically exposed to TSS concentrations of 10 mg/L or less and sedimentation rates of 10 $mg/cm^2/d$ (Rogers 1990); inshore reefs are regularly exposed to higher levels of TSS and sedimentation (Gilmour et al. 2006). Reported tolerances of coral communities to chronic TSS concentrations range from < 10 mg/L for offshore communities in clear waters to > 100 mg/L for some nearshore reefs (Erftemeijer et al. 2012). There is even greater variation in measured tolerances of individual coral species, TSS concentrations of < 30 mg/L to as high as 1000 mg/L TSS over exposures of several weeks, and sedimentation rates ranging from < 10 $mg/cm^2/d$ to > 400 $mg/cm^2/d$ (Erftemeijer et al. 2012). Thus, current knowledge does not provide a quantitative basis for predicting impacts at the species level (PIANC 2010). Similarly, the duration of exposure to elevated sediment levels ranges from days to weeks for elevated TSS and from < 24 hours to four weeks for sedimentation (Erftemeijer et al. 2012). Inshore coral communities generally experience more turbid conditions, and have higher tolerance to elevated turbidity, TSS, and sedimentation, than communities in clear offshore waters (Erftemeijer et al. 2012; Gilmour et al. 2006).

Given this wide variety in coral tolerances, the development of meaningful impact threshold criteria necessarily requires site-specific information on ambient turbidity and sedimentation regimes and on the species composition of coral community receptors (Erftemeijer et al. 2012; PIANC 2010). No generic threshold values can accurately predict turbidity or sedimentation impacts on all coral species or coral communities at all sites. Generic thresholds are even more problematic for other receptors such as seagrass and filter-feeding macroinvertebrate communities. For EIA of specific projects, site-specific thresholds for individual receptor types will need to be established for predictive impact modelling. These may need to incorporate considerations of seasonal susceptibility to impact, as described in “Seasonal Trigger Values” p. 44.

Therefore, the approach used in modelling in this project, which is consistent with figure 3, was to generate quantitative predictions of spatial extent of a range of TSS and sedimentation levels to support the identification of potentially affected receptors, and subsequent first-order risk assessment.

Identification of Receptors and Monitoring Sites for Baseline Data Collection

Modelling is used to identify sensitive receptors both to help establish impact criteria and then to assess the spatial distribution of different zones of impact. In Western Australia, defined levels of mortality of corals or other receptors may be accepted within the zones of high and moderate impact. Whether such impacts are acceptable in the World Heritage Area is a matter of environmental management policy and beyond the scope of this study. For projects that are similar to previous projects in the area, it will often be possible to identify receptors and their sensitivity during the initial review of available information, and modelling of zones of impact and influence may not be needed.

Site Selection and Design

Sites for compliance monitoring are then selected based on the locations of sensitive receptors in relation to predicted zones of impact. An important step in site selection is to assess the relative sensitivity of receptors to identify those most at risk of impact and hence most in need of monitoring to provide early warning of the need for management responses. To a large extent, such sites will be identified by their location in relation to predicted zones of impact. It is also important to consider the inherent sensitivities of receptors. For example, receptors that already experience limitation by light availability or high ambient sedimentation are likely to be more vulnerable to the effects of dredge material placement. Because sensitivity to sediment-related impacts varies markedly among species, the community composition of receptors also needs to be considered on the basis of ecological baseline surveys. Sites may also be selected for monitoring due to a particularly high environmental value, for example tourism or research sites.

Control Sites and Beyond BACI – Multiple Controls

A common experimental design in environmental impact monitoring is the Before-After/Control-Impact (BACI) design, which compares the pattern of change before and after a potentially impacting human activity between potentially impacted sites and control sites considered to be outside the of potential impact. BACI designs are not usually used *per se* in water quality monitoring for dredge material placement projects, because the disturbance to water quality will be transient and unlikely to persist after completion of the project, and because the primary objective is to detect deteriorated water quality in time to take management action. Water quality sites are, however, usually placed at or near ecological monitoring sites to link water quality to ecological changes, and the BACI design is commonly used for ecological monitoring. Furthermore, the concepts of BACI designs do apply to water quality monitoring.

Given the significant spatial and temporal variability in water quality conditions in the six study areas, comparison of changes in water quality between two sites in relation to material placement activities can be difficult to interpret. Differences between the sites could reflect the influence of material placement, simple natural variation, or a combination of both. The best way to reduce this ambiguity is to establish multiple control sites, such that should any natural changes unrelated to the impact occur at a control site, they will be detectible through comparison among the control sites (Underwood 1991). This use of multiple controls is known as a “Beyond-BACI” design. Beyond-BACI designs do not eliminate the possibility that natural variation will occur at impact and not control sites, but do reduce the likelihood of natural variability being interpreted as impact. Having multiple impact sites and multiple control sites provides the highest probability of detecting changes unrelated to impacts, for example from weather conditions and naturally occurring events. The use of multiple reference sites adds complexity and expense to monitoring programs and is typically only suitable for monitoring of large placement projects of long duration.

The most important role of reference sites in water quality monitoring for dredge material placement is not as controls for before-after comparisons, but rather to help determine whether or not observed changes in water quality reflect natural variation or the effects of material placement. This cannot be done reliably simply on the basis of deviation from long-term baseline conditions at the impact sites. Comparison between impact and reference sites to evaluate whether reduced water quality at the impact sites is attributable to dredging or dredge material placement will also consider prevailing weather and oceanographic conditions, the nature and location of current dredging and material placement activities, and other factors. The rationale for this approach comes from literature on the detection of ecological impacts (e.g. Downes et al. 2002; Quinn & Keough 2002; Underwood 1997). Here again it is important to have multiple reference sites, at varying distance from the placement site, to allow for the possibility that sediment plumes extend further than expected from the placement site so that sites considered to be reference sites are in fact affected by material placement. SKM has not recommended the number of reference sites that should be used for monitoring programs, because this will depend on the scale of the project and its likely impact.

Sentinel Sites

For large projects, especially if a zone of high impact is predicted, it may be useful to augment sensitive receptor monitoring sites with “sentinel sites” at the boundaries of model-predicted zones of influence and impact. In cases where the Zone of High Impact has allowable loss of corals, monitoring is often done on the edge of that zone, as a method of tracking water quality within the Zone of Moderate Impact. The monitoring of sentinel sites can give an early indication of deviation from predicted plume extent, especially if *in situ* loggers are telemetered so that real time data is obtained. Care must be taken when establishing sentinel sites, particularly in deploying loggers at similar depths to receptor sites. Chevron's Gorgon project provides an example of the use of sentinel sites being used. The monitoring program for the Gorgon Project deployed nine telemetered loggers at the boundary of the predicted Zone of Moderate Impact and Zone of Influence to provide real-time information monitoring of the extent of dredging and material placement plumes.

Approaches to Developing Water Quality Trigger Values

Once impact and reference sites have been established, baseline data should be collected for the purpose of setting site-specific trigger values for reactive management. Trigger values are only required for the impact monitoring sites, but it is useful to also have baseline data from the reference sites to characterise natural variability and confirm that the selected reference sites are comparable to the impact sites under baseline conditions.

The development of water quality trigger values requires adequate, site-specific baseline data. Inadequate baseline data often results in trigger values for which there is considerable uncertainty as to whether the trigger values adequately reflect ambient conditions at the monitoring sites. This in turn may limit the effectiveness of the water quality management program in providing adequate warning of potential impact or guiding management responses.

The conceptual framework in figure 3 indicates that collection of site-specific baseline data for the development of trigger values occurs at step 7, during EMP development. For some projects the review of available information that feeds into step 2, establishment of criteria for predictive modelling, may allow the identification of monitoring sites with a high degree of confidence, so that the collection of site-specific baseline data can commence early in the EIA phase. Conversely, the review of information at step 2 may conclude that existing site-specific baseline data are adequate to develop trigger values, in which case further baseline monitoring at step 7 may not be necessary. In either case, however, the existing baseline data should be further reviewed at step 7 in light of the results of modelling and the assessment of receptor sensitivity in the preceding steps.

Trigger values should ideally reflect the sensitivity of the receptors, so that exceedances trigger appropriate management responses when they are needed without resulting in repeated "false alarms" where the trigger values are exceeded without resulting in significant ecological stress.

As previously noted, setting trigger values needs to be done in the context of the ambient conditions prevailing at a given receptor. This is usually done on the basis that the tolerance of ecological communities depends upon both the magnitude (intensity) of a given stressor and the duration over which the stressful conditions persist (figure 6).

SKM has reviewed approaches taken to establishing water quality trigger values for reactive management in a number of dredging projects (Appendix A). The review included both dredging and dredge material placement activities, as monitoring programs usually do not explicitly distinguish the two activities in the design of monitoring programs.

Projects generally established trigger values for allowable increases in turbidity or TSS for a certain duration. However, some projects have instead established light-based criteria for minimum levels of PAR for a given duration. A number of different approaches have been used to establish the criteria for turbidity, TSS, and PAR.

Percentiles of Baseline Data

Trigger values for a number of projects have been set on the basis of natural variability in the intensity of a stressor, without taking into account the typical duration of periods of elevated turbidity or TSS under ambient conditions. The trigger value for the Hay Point Coal Terminal Expansion Project, Phase 3, for example, used the 80th percentile

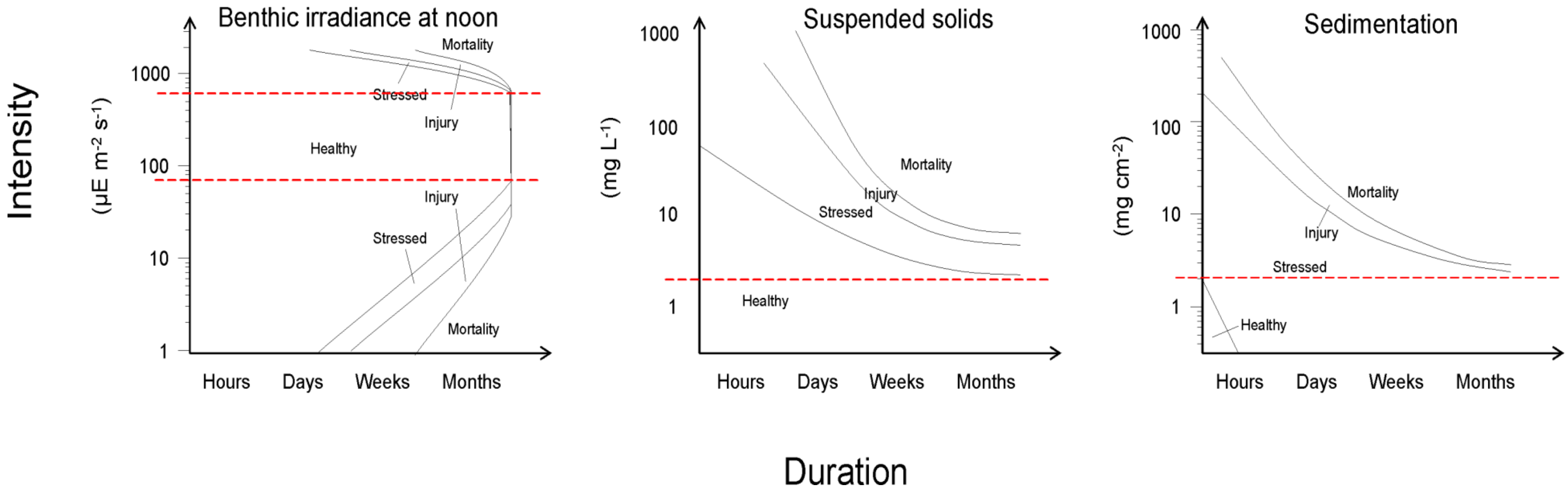

Figure 6. Conceptual diagrams showing levels of impact as a function of the intensity and duration of the stressing agent (modified from De'Ath & Fabricius 2008).

of baseline turbidity at the compliance site plus 100 NTU. For 2012 maintenance dredging at Rosslyn Bay State Boat Harbour an investigative trigger value of the 80th percentile of baseline turbidity data is proposed.

Intensity-Frequency-Duration Criteria

McArthur et al. (2004) proposed the development of multiple trigger values based on an IDF framework. This uses the conceptual relationship between the intensity and duration of stress shown in figure 6, and also recognises that stresses of a given frequency and duration that might be tolerable can stress organisms if frequently repeated. The IDF approach proposed by MacArthur et al. (2002) also incorporates the idea that an ecological community at a given site can tolerate the ambient IDF regime, or the community would not occur at the site. Thus, it is assumed that appropriate trigger values can be derived from the IDF regime reflected in baseline data. Several projects reviewed by SKM adopted trigger values based on different stressor levels (e.g. 80th, 95th, and 99th percentiles of baseline data) occurring for different durations and/or with different frequencies. It is not clear to what extent the values, except for the intensity values, were derived from analysis of the ambient IDF regime, as opposed to scientific judgement. In some cases, different intensity trigger values were not applied to changes in water quality conditions over different periods of time, but rather to trigger different levels of management response. The Western Basin Dredging and Disposal Project at the Port of Gladstone, for example, has site-specific turbidity triggers based on 80th, 95th, and 99th percentiles of baseline data that correspond to internal alert (Level 1), external reporting (Level 2), and action (Level 3) responses.

SKM regards it as good practice to establish trigger values on an IDF basis, so as to take into account that acute stress can have impacts on short time scales, whereas lower levels of stress can cause impact if they persist for a long time and/or occur frequently.

Control Charting

One approach to developing trigger values in an IDF context is control charting. A challenge for dredging-related water quality monitoring designs is to apply appropriate statistical tools to rapidly identify a change in water quality conditions which may be caused by dredging. For this aim to be achieved, data need to be rapidly assessed for signs of a change beyond pre-determined levels where environmental impacts are considered to be likely. Control charts assist in the identification of a deviation in an environmental parameter that is beyond what might otherwise be expected, by plotting through time a measure with reference to its expected value. Control chart methods provide a basis to identify environmental impacts at individual sites quickly, triggering an ‘alarm bell’ worthy of further investigation and allowing corrective actions to be taken (Anderson &Thompson 2004). However, this early warning function needs also to be balanced with the potential for false triggering when there is in fact no harm being done, in order to provide an effective tool for managers (Environmetrics Australia 2007a). Control charts can be used to monitor environmental variables before, during and after a development activity with the potential to cause environmental impacts (e.g. Schipper et al. 1998), with their application extending beyond and originating outside of environmental monitoring, in monitoring other stochastic processes such as manufacturing and financial risk (Anderson & Thompson 2004).

A control chart approach was developed by Environmetrics Australia (2007a, b) for application to water quality monitoring for dredging at the Port of Melbourne in Victoria. They discussed the importance of achieving a balance between the risk that trivial environmental effects trigger a cessation of dredging when there is no reason for concern (Type I risk) and that an environmentally significant impact goes undetected

(Type II risk). The ANZECC/ARMCANZ 2000 water quality guidelines advocate a risk-based approach to water quality monitoring, with balancing of the two types of risk a salient objective for any monitoring program. Environmetrics Australia (2007a) discussed the Exponentially Weighted Moving Average (EWMA) chart as a means of balancing these risks, by weighting the contribution of present and previous data to the analysis. Such an approach was applied by the Gladstone Ports Corporation (GPC) to the Western Basin Dredging and Disposal Project in Gladstone, with Internal Alert and External Reporting Trigger Levels established based on application of a 6 hourly EWMA to raw background turbidity levels (GPC 2011). Their approach to calculation of the EWMA used a 60:40 weighting system, where the mean turbidity for the most recent 6 hours comprised 60 per cent of the EWMA value, and the mean turbidity for the 6 hours previous to that comprised 40 per cent of the EWMA. The Internal Alert Level Trigger Level (requiring an internal investigation within 24 h) was applied to the 80^{th} percentile of the 6 h EWMA, with the External Reporting Trigger Level (requiring notification to regulators and formal investigation) applied to the 95^{th} percentile for the 6 h EWMA. Control charting is typically used in large, long-term projects, as the process can be time consuming and expensive. Control charting may not be applicable to small, routine dredge material placement projects.

Known Tolerance Thresholds

In some cases it is possible to establish trigger values based on the known tolerance of receptors to diminished water quality. Light-based triggers for seagrass receptors for monitoring by the Western Basin Dredging and Disposal Project (Gladstone), for example, were developed through field and laboratory experiments that quantitatively established the minimum light requirements of the seagrass receptors, the duration for which they could tolerate light deprivation, and the required recovery period from light deprivation. Trigger values based on known tolerance thresholds provide the highest degree of certainty in water quality management. In most cases, unfortunately, such reliable quantitative information is not available, and establishing tolerance thresholds requires extensive research over a long period of time. The use of known tolerance thresholds is generally only feasible for major, long-term projects. Knowledge of tolerance thresholds is improving, however, and absolute trigger values based on tolerance thresholds is likely to become more common in the future. At present, known tolerance thresholds are most applicable to seagrass receptors. Because coral communities often include many more species than seagrass communities, and coral species differ widely in tolerance to light deprivation and sedimentation (Erftemeijer et al. 2012), it is more difficult to use known tolerance to set trigger values for coral communities.

Environmental Value and Receptor Resilience

SKM recommends that, in addition to baseline conditions, identified environmental values are considered in setting trigger values. A higher degree of precaution may be appropriate for receptors identified to have high environmental value.

Resilience is another factor that should be taken into account in setting trigger values. The assumption that ecological communities are able to tolerate the baseline conditions measured over a few months or years prior to a project commencing may not be valid if the communities are under stress from longer-term declines in water quality. Another consideration in evaluating resilience is the connectivity of isolated receptors to distant larval sources. Recovery of communities may be delayed if they have poor connectivity.

Seasonal Trigger Values

Given the marked climatic seasonality that prevails in the Great Barrier Reef Region, ambient regimes of light climate, turbidity, and sedimentation often also vary significantly from season to season. In addition, the ecological sensitivity of receptors may vary seasonally. For example, Chartrand et al. (2012) showed that the seagrass *Zostera capricorni* in the Gladstone area is sensitive to light deprivation only during the dry, or active growing season from July to June. The seagrass is not sensitive to reduced light availability from February to June, when it undergoes a senescent period of drawing upon stored energy reserves rather than active photosynthesis in response to wet season conditions. Natural seasonal cycles of sensitivity are likely to often be linked to seasonal climatic cycles.

Consistent with the conceptual decision framework illustrated in figure 5 for determining whether monitoring and predictive modelling are necessary, SKM considers that seasonal trigger values will be required when:

1) A proposed dredging and material placement campaign will span two or more seasons, that is for medium- or long-term campaigns as defined in figure 5, and
2) There are statistically significant seasonal differences in the 50^{th}, 80^{th}, or 95^{th} percentiles of baseline data for the monitored parameter and/or there are known seasonal differences in receptor sensitivity.

Reactive Management

As previously stated, SKM's view is that the primary objective of water quality monitoring for dredge material placement projects is to provide for management action to prevent or minimise ecological impact due to reduced water quality, i.e. to provide for reactive management.

Tiered Response Approach

Tiered response approaches are often used to track water quality in relation to ecological stress. A tiered approach allows for a series of management responses ranging from further investigation in the first instance up to, if necessary, the cessation of placement operations. An example of a tiered response approach is shown in figure 7. When a trigger value is exceeded, the initial response is to investigate the cause of the exceedance, first whether the data are reliable and then whether the exceedance is due to the material placement activities. If the trigger is a false trigger resulting from data quality issues, no further action is required except investigation of whether improvements in data collection and QA are needed.

If the data are reliable, the next step is to investigate whether the observed exceedance can be attributed to dredging and dredge material placement activities. Information considered in the investigation may include:

- Recent weather and oceanographic conditions
- Location of dredging and material placement activities in relation to the monitoring site recording the exceedance
- Nature of recent dredging and placement activities in relation to the onset of exceedance conditions
- Water quality measured at reference sites relative to impact sites
- Remote sensing imagery of turbidity plumes

- Physical and chemical characteristics of settled sediment collected from sediment tubes.

A conclusion that exceedance of trigger values may be caused by dredging and material placement will not necessarily immediate ecological response monitoring or management actions to alter the current project activities. Other factors to be considered by the TACC or MRG in deciding the appropriate level of response include:

- Forecast changes in weather or tides than are expected to reduce natural background turbidity
- Remaining project duration – if near completion project it may be preferable to finish the project instead of extending it over a longer duration
- Imminent planned changed in project operations, for example if changes in the dredging footprint or nature of material dredged are expected in the next few days.

When ecological monitoring is conducted as a management response to water quality exceedances, it is often also multi-tiered, with initial rapid assessment for stress indicators leading to more extensive monitoring to assess impact and the need for management measures for the placement activities if monitoring indicates that impacts are likely to occur.

It may be appropriate, especially for large projects, to nest the response approach depicted in figure 7 in a hierarchy of increasingly restrictive management responses depending on the severity of the water quality exceedance. Figure 8 shows a conceptual framework for such a hierarchy, where exceedances are identified at Levels 1, 2, and 3 by increasing severity of the intensity or duration exceedance. Each level of exceedance triggers a management response as conceptually illustrated in figure 7, with more proactive management responses at each level. The three levels might be reached sequentially, with management responses ramping up. Alternatively, a higher level exceedance could immediately trigger more vigorous responses.

Similar to the sequentially ramp up through exceedance levels, sites may sequentially ramp down to lower levels of exceedance. For example, a site would drop from a Level 3 to a Level 2 exceedance, and then Level 1, as water quality conditions improve.

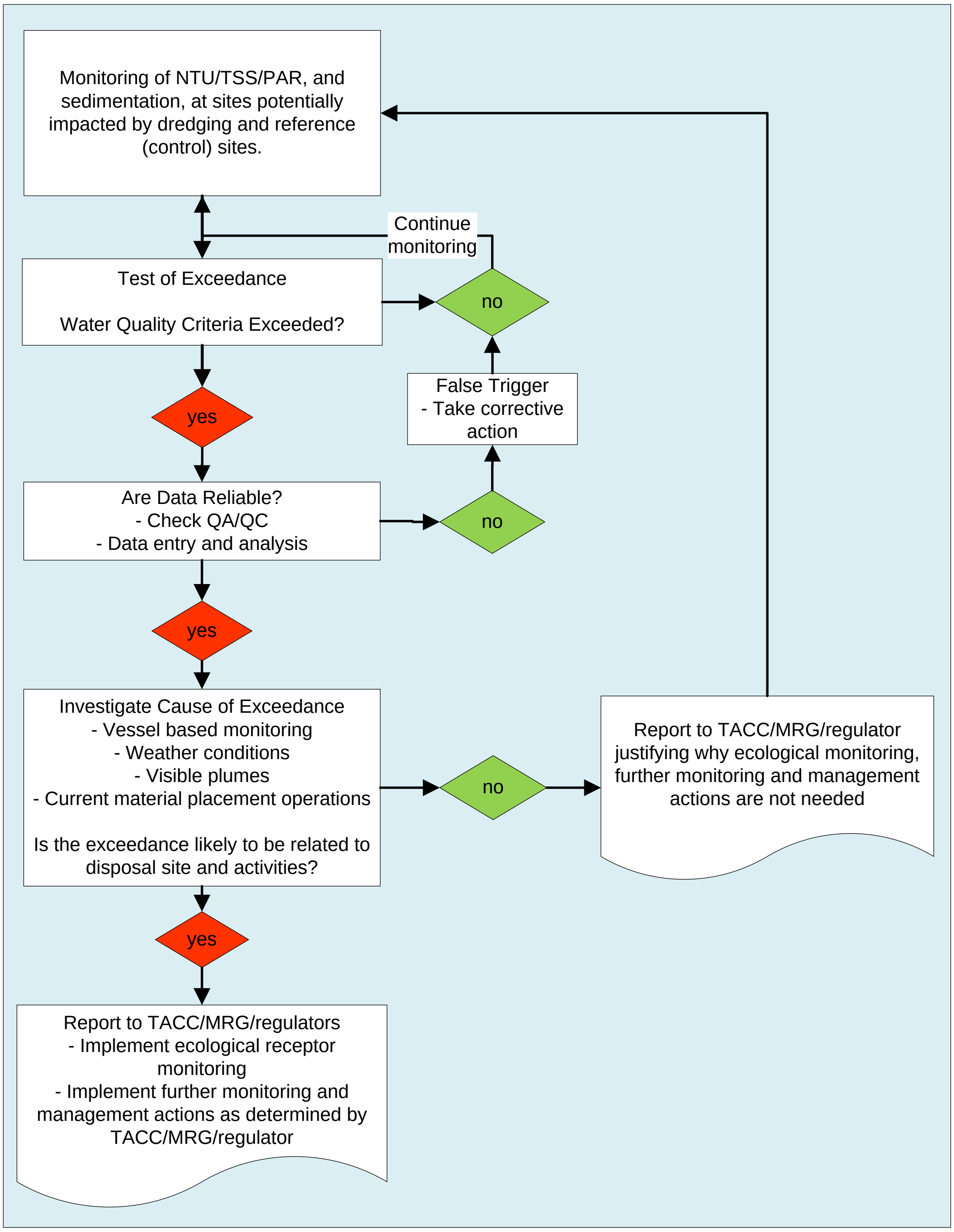

Figure 7. Tiered response approach to initial exceedance of investigative water quality trigger. Decision steps are to be made by or in close consultation with the TACC or MRG for the project.

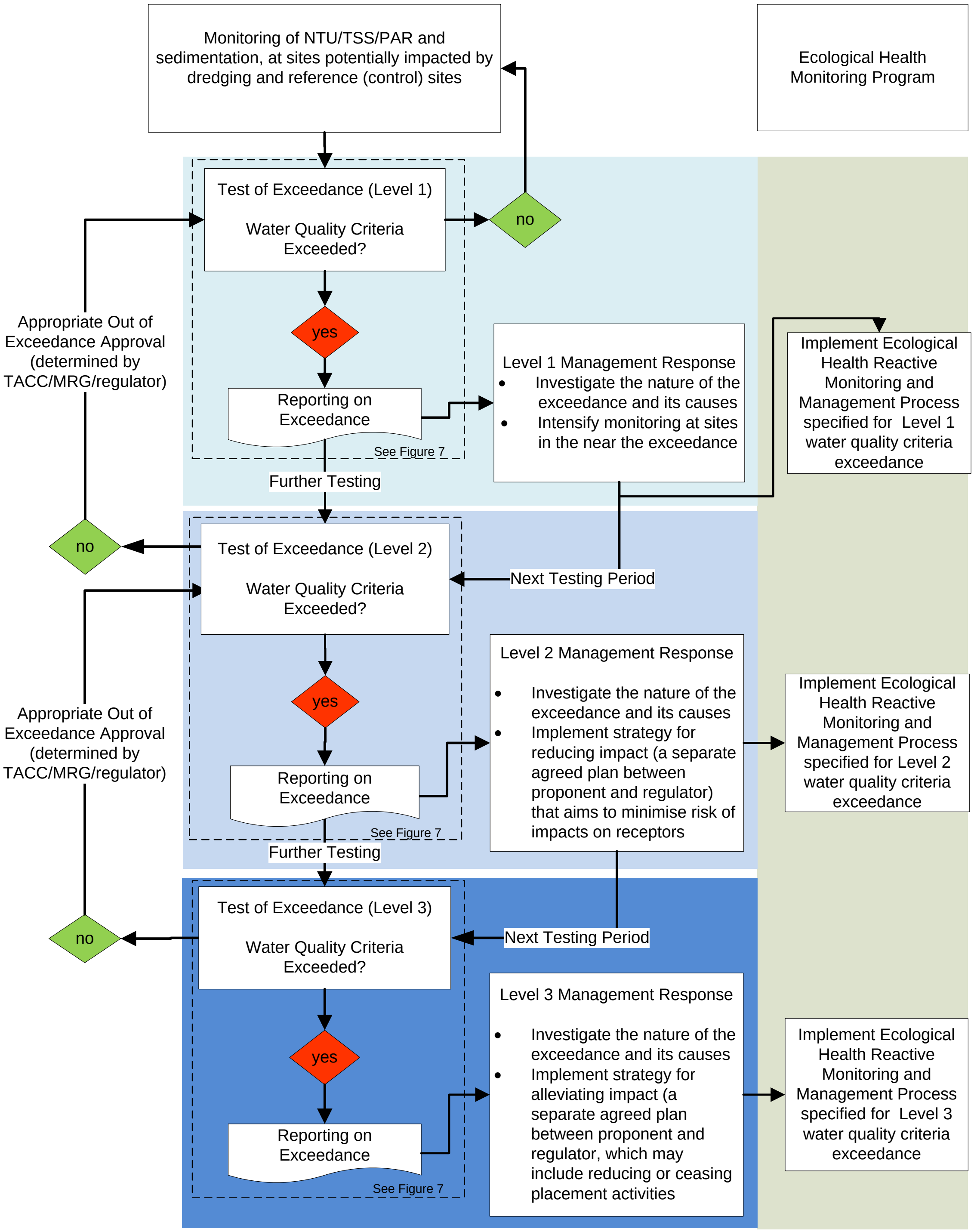

Figure 8. Conceptual flow diagram of a generic tiered management approach to reactive monitoring for locations in the World Heritage Area. Decision steps and identification of appropriate management responses are to be made by or in close consultation with the TACC or MRG for the project.

Advisory and Management Review Panels

Most dredge material placement projects establish some form of committee or panel to advise on or make decisions on management responses. These panels may take different forms in different jurisdictions. Panels may be formed to make recommendations to the project proponent, or to provide recommendations to regulators. In Queensland, such panels generally take two forms. Most ports that conduct regular maintenance dredging have a standing Technical Advisory and Consultative Committee (TACC). The NAGD (Commonwealth of Australia 2009) require that a TACC is established to support long-term management in order for a long-term Sea Dumping Permit for maintenance dredging to be granted. Long-term Sea Dumping Permits allow for multiple maintenance dredging campaigns to be conducted during the duration of the permit. Capital dredging projects usually establish a Management Review Group (MRG). TACCs and MRGs are typically comprised of:

- Representatives of responsible regulatory agencies
- The port authority or other project proponent
- Independent scientists.

In the case of capital dredging the MRG also often includes a representative of the dredging contractor and possibly an independent dredging specialist. Technical personnel involved in implementing monitoring programs are also often involved, though not necessarily as members of the panel.

The primary roles of a technical advisory panel are to make recommendations about monitoring practices and procedures, to review and accept the trigger values adopted, to determine whether water quality exceedances are related to the placement activities, to review reporting on monitoring outcomes, responses of receptors, and to decide when the reactive management program needs to be adapted and/or approve requests for modification of the program by the proponent.

In the case of maintenance dredging conducted under a long-term Sea Dumping Permit, the TACC will be involved in multiple dredging and dredge material placement campaigns, and thus in all three phases (EIA, EMP Development, EMP Implementation) of the framework depicted in figure 3. Ports in the World Heritage Area that conduct regular maintenance dredging have been granted a series of long-term permits, so TACC involvement at all three phases will not be limited to the duration of an individual permit.

MRGs for capital dredging projects are often established and have their initial meeting after final approval of the EMP for the project. SKM considers it good practice, however, for the MRG to be engaged earlier, at the stage of finalising trigger values and the management response framework in the EMP Development phase. Benefits of this earlier involvement include:

- The identification and resolution of differing views on how trigger values should be established and applied may reduce subsequent debate on the appropriateness of the trigger values and management response framework when the commencement of dredging and material placement operations is imminent, and/or after exceedances of the trigger values occur
- The development of a common understanding of the overall approach of the monitoring program, and the basis for establishing trigger values and management responses, can facilitate adaptation of the monitoring program if required. The adaptation required can be considered without revisiting the original design of the program.

A key part of the overall framework shown in figure 3 is continual adaptation of the monitoring program in light of experience. For example, monitoring programs sometimes experience recurring exceedances of water quality triggers without signs of stress or impact being detected in ecological health monitoring. In such cases it may be appropriate to relax the trigger values. Conversely, the detection of stress or impact on receptors in the absence of water quality exceedances, if the stress/impact is potentially attributable to placement activities, indicate that more stringent triggers and/or other management responses are required.

Another key aspect of improving the management of dredge material in the World Heritage Area is to capture and document the results and lessons from dredge material placement projects, to provide for continuous improvement in monitoring and reactive management.

Outcomes of Reactive Monitoring in Dredging and Dredge Material Placement Projects

SKM conducted a desktop review of the outcomes of water quality and reactive management programs, including both the extent of trigger value exceedances and the results of ecological monitoring of the receptors (Appendix B). The review found that the majority of projects developed multiple trigger values for TSS or turbidity graded from minor to severe. The derived trigger values, and way they were applied, differed substantially among projects. Most monitoring programs attempted to integrate some aspects of intensity, duration, or frequency of elevated TSS or turbidity into the trigger values. Most of the trigger values for the dredging programs reviewed assumed that corals suffer mortality as a result of short-term, but very high turbidity. It is important to note that few projects have examined the effects of long-term mortality as a result of chronic impacts from sustained levels of lower turbidity.

Although a number of projects reported multiple exceedances of water quality trigger values, ecological monitoring generally indicated no more than minor impacts.

Water quality trigger levels were exceeded on multiple occasions during the Port of Hay Point capital dredging project in 2006. A review of the monitoring program showed that the magnitude and/or duration of periods of high turbidity at the receptor monitoring sites increased during dredging (Trimarchi & Keane, 2007). The Environmental Impact Statement predicted a potential be a loss of up to 16 per cent coral cover at the impact sites. Coral monitoring during dredging did show partial mortality of a significant number of coral colonies due to sedimentation (Trimarchi & Keane, 2007). Post-dredging coral surveys, however, found that hard coral cover at the impact sites had declined by no more than one per cent, less than at one of the control sites (Trimarchi & Keane, 2007). Thus, anticipated impacts from dredging operations were over-estimated despite multiple exceedances of water quality triggers and monitoring found dredging had minimal impacts on nearby sensitive receptors.

Exceedances at the Port of Hay Point during dredging operations for the Hay Point Expansion Phase 3 project in 2010 and 2011 reported all exceedances of the water quality trigger level coincided with strong winds during periods when the dredge was unable to operate (BMA 2012).There were was slight declines in live coral cover between the baseline and post-dredging surveys at both the impact and control site, but the pattern of decline did not differ between impact and control (BMA 2012). The main change in benthic communities observed before and after dredging at the receptor sites was a large increase in macroalgal cover at both impact and control sites. This was attributed to the effects of Tropical Cyclone Ului, which passed through the area shortly before the baseline surveys were conducted in 2010, as well as flooding in early 2011 (BMA 2012).

Hanley (2011) describes how the management triggers for turbidity specified in approval conditions for environmental monitoring programs of with 12 dredging projects in the Pilbara region have become increasingly comprehensive, prescriptive, and strict. Hanley's (2011) view of these past projects was that thresholds may be set too low on short time scales, given there were often multiple water quality exceedances in the absence of detectible coral mortality. Conversely, water quality monitoring for the Gorgon LNG project (Western Australia), which did result in net coral mortality, suggests that trigger values for the Gorgon project were set too high.

One other exception to the review's finding that ecological impacts have been minor or undetectable for most of the dredging projects reviewed is the Dampier dredging program of 2004. Significant dredging-induced mortality occurred at one monitoring site (Blakeway 2005) during the dredging program. Blakeway (2005) concluded that this coral mortality probably resulted from acute sedimentation caused by propeller wash from one of the dredging vessels. Water quality monitoring would be neither likely to detect nor able to provide warning to trigger a management response to this mode of impact.

RECOMMENDATIONS FOR GOOD PRACTICE

On the basis of this study and experience in the design and implementation of water quality and reactive management projects dredging and dredge material relocation projects, SKM has developed a number of recommendations for good practice, not all of which are explicitly stated in the foregoing text.

Monitoring Methodologies and Parameters

- Except for small projects or routine projects where similar projects have been adequately monitored, multiple methods (vessel-based monitoring, fixed loggers, remote sensing) should be incorporated into the design of monitoring programs
- A robust QA system including cross-calibration of all monitoring instruments is essential
- Fixed loggers for baseline measurement of water quality should be equipped with sensors capable of recording the full range of natural variability. If baseline monitoring shows that conditions frequently exceed the maximum range of measurement the sensors should be replaced.
- Remote sensing is a complementary monitoring method and should not replace *in situ* measurements, however it is useful for detecting the spatial extent of surface plumes and distinguishing regional climatic influences from sediment plumes related to material placement
- If remote sensing is used, algorithm development and ground truthing should use dredge material plumes, not ambient suspended sediments
- If TSS values derived from turbidity measurements are required for model calibration or other purposes, calculation of the turbidity/TSS relationship should be based on actual dredged material rather than ambient suspended sediments
- Photosynthetically active radiation (PAR) is the preferred parameter for monitoring intended to provide warning of potential impacts of increased light attenuation upon light-dependent receptors, followed by turbidity and total suspended solids (TSS), which are surrogates for light attenuation. The exception is when there are extensive existing baseline data and/or data on the ecological impacts of turbidity and TSS and baseline data on PAR are not adequate to establish trigger values to warn of potential impending impacts. Monitoring of turbidity and/or TSS may still be required for other purposes such as validating modelling or remote sensing algorithms or to meet approval conditions.

Trigger Values and Management Responses

- Experimental quantification of receptor tolerance thresholds is the preferred approach for setting trigger values, but it is recognised that this is not feasible except for very large projects and with current scientific understanding probably usually not for coral communities
- Where tolerance thresholds are not established, trigger values, at least for large projects, should take into account the ambient regime of variability in duration and frequency of elevated turbidity and sedimentation, as well as the intensity
- Where trigger values are derived from the ambient range of variability (e.g. 80^{th}, 95^{th}, 99^{th} percentiles) consideration should be given to identified environmental values as well as the resilience of monitoring receptors
- Trigger values for light-related impacts should apply only during daylight hours
- If turbidity is the parameter being monitored, it is preferable to express trigger values in nephelometric turbidity units (NTU), rather than measuring turbidity and

converting for comparison to a trigger value in mg/L TSS based on a measured turbidity/TSS relationship

- Because of the difficulties in reliably measuring sedimentation, SKM recommends caution in linking operational management responses such as a reduction or termination of material placement directly to sedimentation triggers. Rather, sedimentation triggers should be linked to further water quality and ecological investigations.
- Trigger values for specific seasons will be required when:
    1) A proposed dredging and material placement campaign will span two or more seasons, that is for medium- or long-term campaigns as defined in figure 5 and
    2) There are statistically significant seasonal differences in the 50th, 80th, or 95th percentiles of baseline data for the monitored parameter and/or there are known seasonal differences in receptor sensitivity.

Monitoring Site Selection

- Depending on project size, monitoring designs should consider using multiple reference (control) sites at varying distances from the placement activity
- Sentinel sites at the boundaries of modelled zones of impact should be considered, especially for large projects of long duration.

Need for Water Quality Monitoring in Reactive Management

- Water quality monitoring for reactive management of dredge material placement activities is not necessary if the duration of the activities is less than the duration of stress required to result in impact, or if past monitoring has demonstrated that very similar programs do not result in impact. Monitoring for other purposes may still be required, however.

General Framework

- Technical Advisory and Consultative Committees established for long-term management of maintenance dredging should be involved throughout all three phases of management (Environmental Impact Assessment, Environmental Management Plan Development, and Environmental Management Plan Implementation)
- Management Review Groups should be established and engaged early in the design of the reactive management for capital dredging projects, commencing with the establishment of trigger values and management responses
- There should be a regular cycle of assessing the effectiveness of the monitoring program and adapting it as required
- The final outcomes of reactive management programs for dredge material placement projects should be synthesised and documented to promote continuing improvement in the management of dredge material in the World Heritage Area.

REFERENCES

Alquezar, R. & Boyd, W., 2008, ‘Dredge Related Impacts and Ecosystem Recovery: a One Year Follow-Up Study’, Report to Fitzroy Basin Association and Queensland Transport, August 2008.

Anderson M. J. & Thompson, A. A. 2004, ‘Multivariate control charts for ecological and environmental monitoring’, *Ecological Applications* 14(6), 1921-1935.

ANZECC/ARMCANZ 2000, *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*, Australian and New Zealand Environment and Conservation Council, Agricultural and Resource Management Council of Australia and New Zealand. Canberra.

Au, D. W. T., Pollino, C. A., Wu, R. S. S., Shin, P. K. S., Lau, S. T. & Tang, J. Y., 2004, ‘Chronic effects of suspended solids on gill structure, osmoregulation, growth, and triiodothyronine in juvenile green grouper Epinephelus coioides’, *Marine Ecology Progress Series* 266, 255–264.

Aurecon 2011, *Western Basin Dredge and Disposal (Onshore and Offshore) Project Water Quality Management Plan*, Gladstone Ports Corporation. Brisbane, Queensland.

Blakeway, D. R. 2005, ‘Patterns of mortality from natural and anthropogenic influences in Dampier corals: 2004 cyclone and dredging impacts’, in *Corals of the Dampier Harbour: their Survival and Reproduction During the Dredging Programs of 2004,* Stoddart J., Stoddart S. E. (eds),MScience, Perth, Western Australia.

BMA 2010, *Environmental Management Plan (Marine Ecology) for Dredging and Dredged Material Disposal, Hay Point Coal Terminal Expansion Phase 3 (HPX3), Revision 3, May 2010*. BHP Billiton Mitsubishi Alliance, Brisbane.

BMA 2011, *Environmental Management Plan (Marine Ecology) for Dredging and Dredged Material Disposal, Hay Point Coal Terminal Expansion Phase 3 (HPX3), Revision 5.1 March 2011*. BM Alliance Coal Operations Pty Ltd.

BMA 2012, ‘Annual Ecological Monitoring Summary Report – 2011, Hay Point Coal Terminal Expansion Phase 3, Revision 2’, BM Alliance Coal Operations Pty Ltd.

BMT WBM 2011, ‘Dredge Plume Measurements at Port of Cairns August 2011’, Report to Ports North.

Chartrand, K., Rasheed M. & Sankey T., 2008. ‘Deepwater seagrass dynamics in Hay Point - Measuring variabiltiy and monitoring impacts of capital dredging’, Department of Primary Industries and Fisheries. Report to the Ports Corporation of Queensland.

Chartrand, K. M., Ralph, P. J., Petrou, K. & Rasheed, M.A. 2012, *Development of a Light-based Seagrass Management Approach for the Gladstone Western Basin Dredging Program,* DAFF Publication, Fisheries Queensland, Cairns.

Commonwealth of Australia 2009, *National Assessment Guidelines for Dredging*, Department of the Environment, Water, Heritage and the Arts (ed), Canberra Australia.

Davies-Colley, R. J. & Smith, D. G. 2001. ‘Turbidity, suspended sediment, and water clarity: review’, *Journal of the American Water Resources Association* 37(5),1085-1101.

De'ath, G & Fabricius, KE. 2008, 'Water quality of the Great Barrier Reef: distributions, effects on reef biota and trigger values for conservation of ecosystem health'. Final Report to the Great Barrier Reef Marine Park Authority. Australian Institute of Marine Science, Townsville. 100 pp.

DERM 2009, *Queensland Water Quality Guidelines, Version 3*, Queensland Department of Environment and Resource Management.

DERM 2010, *Monitoring and Sampling Manual 2009. Version 2, September 2010*, Queensland Department of Environment and Resource Management.

Devlin, M. J. & Lourey, M. J. 2000, *Water Quality – Field and Analytical Procedures*, *Long-term Monitoring of the Great Barrier Reef, Standard Operational Procedure Number 6*, Australian Institute of Marine Science, Townsville.

Downes, B. J., Barmuta, L. A., Fairweather, P. G., Faith, D. P., Keough, M. J., Lake, P. S., Mapstone, B. D. & Quinn, G. P. 2002, *Monitoring Ecological Impacts: Concepts and Practice in Flowing Waters*, Vol. Cambridge University Press, Cambridge.

DTMR, 2010, *Final Environmental Report, QT12-124 Rosslyn Bay Boat Harbour Maintenance Dredging*, Queensland Department of Transport and Main Roads.

DTMR 2012, *Environmental Management Plan (Dredging), Rosslyn Bay Boat Harbour*, Department of Transport and Main Roads.

Environmentrics Australia (2007a). 'Statistical aspects of turbidity monitoring – control charting', Report to Port of Melbourne Corporation.

Environmetrics Australia (2007b). 'Statistical aspects of turbidity monitoring – setting environmental limits', Report to Port of Melbourne Corporation.

Erftemeijer, P.L.A., Riegl, B., Hoeksema, B.W., Todd, P.A. 2012, 'Environmental impacts of dredging and other sediment disturbances on corals: a review'. *Marine Pollution Bulletin* 64: 1737-1765.

Fabricius, K., E. 2005, 'Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis', *Marine Pollution Bulletin* 50,125-146.

GBRMPA 2010. *Water Quality Guidelines for the Great Barrier Reef Marine Park. Revised Edition 2010*. Great Barrier Reef Marine Park Authority, Townsville.

GBRMPA 2012.*The Use of Hydrodynamic Numerical Modelling for Dredging Projects in the Great Barrier Reef Marine Park*. GBRMPA External Guideline. http://www.gbrmpa.gov.au/__data/assets/pdf_file/0018/26532/Guidelines-on-Hydrodynamics-Modelling-15-Aug-2012.pdf

GHD 2002, 'Cityport Turbidity Monitoring – Final Report', Report to the Department of Defence, June 2000.

GHD 2007, 'Report for Rosslyn Bay Boat Harbour maintenance dredging, report on dredging outcomes, January 2007', Report to Department of Transport and Main Roads.

GHD 2009a, 'Report for Western Basin Dredging and Disposal Project, Water quality report', October 2009, Report to Gladstone Port Corporation.

(http://www.westernbasinportdevelopment.com.au/media/pdf/EIS%20Appendix%20Q.pdf.

GHD 2009b, 'Baseline Water Quality Assessment - Final Report, Abbot Point Environmental Monitoring', Report to North Queensland Bulk Ports Corporation Limited.

GHD 2009c, 'Townsville Marine Precinct Project Environmental Impact Statement. Appendix J Water and sediment quality assessment, Report to Port of Townsville Ltd.

GHD 2012, 'Abbot Point, terminal 0, Terminal 2 and Terminal 3 Capital Dredging Draft Environmental Report (EPBC 2011/6213/GBRMPA G34897.1)', Report to North Queensland Bulk Ports Corporation, September 2012. DRAFT, UNPUBLISHED.

Gilmour J.1999, 'Experimental investigations into the effects of suspended sediment on fertilisation, larval survival and settlement in a scleractinian coral'. *Marine Biology* 135: 451-462.

Gilmour, J. P., Cooper, T. F., Fabricius, K. E. & Smith, L. D. 2006, 'Early warning indicators of change in the condition of corals and coral communities in response to key anthropogenic stressors in the Pilbara, Western Australia'. Environmental Protection Authority. Western Australia.

GPC 2011, *Port of Gladstone Western Basin Strategic Dredging and Disposal Project, Water Quality Management Plan*, Gladstone Ports Corporation, http://www.westernbasinportdevelopment.com.au/media/pdf/Water%20Quality%20Management%20Plans.pdf.

Grech, A. & Marsh, H. 2007, 'Prioritising areas for dugong conservation in a marine protected area using a spatially explicit population model', *Applied GIS* 3(2), 1-14.

Hanley, J. R. 2011, 'Environmental monitoring programs on recent capital dredging projects in the Pilbara (2003-10): a review', *APPEA Journal*, 273-293.

Humphrey, C., Weber, M., Lott, C., Cooper, T., & Fabricius, K. 2009, 'Effects of suspended sediments, dissolved inorganic nutrients and salinity on fertilisation and embryo development in the coral Acropora millepora (Ehrenberg, 1834)', *Coral Reefs* 27, 837–850.

McArthur, C., Ferry, R., & Proni, J. 2004, 'Development of guidelines for dredging material disposal based on abiotic determinants of coral reef community structure', Proceedings of the *Third Specialty Conference on Dredging and Dredged Material Disposal*.

McKenna, S. A. & Rasheed, M. A. 2011, 'Port of Abbot Point long-term seagrass monitoring: update report 2008-2011', DEEDI Publication, Fisheries Queensland, Cairns.

Meager, J. J. Domenici, P. Shingles, A. & Utne-Palm, A. C. 2005, 'Escape responses in juvenile Atlantic cod (Gadus morhua): the effect of turbidity and predator velocity', *Journal of Experimental Biology*, 209, 4174-4184.

MScience 2009, 'Dampier marine services facility - water quality impacts of the Pluto program in an area of intensive dredging', MScience Report MSA142R2.

Neil K.M., Stafford, H., Rose, C. & Thomas, R. 2003, ‘Flora and Fauna Survey: Cairns Port Authority Ocean Disposal Site’, CRC Reef Research Centre and Queensland Department of Primary Industries, Report to the Cairns Port Authority.

NQBP 2012. *Abbot Point, Terminal 0, Terminal 2 and Terminal 3 Capital Dredging Draft Public Environment Report (EPBC 2011/6213/GBRMPA G34897.1)*. In draft, unpublished.

Norkko, A., Rosenberg, R., Thrush, S.F., & Whitlatch, R. B. 2006, ‘Scale- and intensity-dependent disturbance determines the magnitude of opportunistic response’, *Journal of Experimental Marine Biology and Ecology*. 330, 195-207.

PCQ 2005, *Port of Hay Point Apron Area and Departure Path Capital Dredging, Draft Environmental Impact Statement,* Ports Corporation of Queensland.

Petrou, K., Ralph, P.J., Molina-Balari, E. & Chartrand, K.M. 2012, ‘Shifts in the spectral quality of light: the effects of dredging on the optical properties of Gladstone Harbour’, Appendix II in Chartrand, K. M., Ralph, P. J., Petrou, K. & Rasheed, M.A. 2012, *Development of a Light-based Seagrass Management Approach for the Gladstone Western Basin Dredging Program,* DAFF Publication, Fisheries Queensland, Cairns.

PIANC 2010. ‘Dredging and Port Construction Around Coral Reefs’, PIANC Report No. 108, World Association for Waterborne Transport Infrastructure.

Quinn, G. P., & Keough, M. J. 2002, ‘Experimental design and data analysis for biologists’, Vol. Cambridge University Press, Cambridge.

Rasheed, M. A. Taylor, H. A., Coles, R. G. & McKenzie, L. J. 2007, ‘Coastal seagrass habitats at risk from human activity in the Great Barrier Reef World Heritage Area: review of areas to be targeted for monitoring’. DPI&F Publication PR07-2971 (DPI Cairns). pp. 43.

Reason, C., Chartrand, K and Rasheed, M. 2011 ‘Long-term seagrass monitoring in Cairns Harbour and Trinity Inlet September 2011’, DEEDI report for Ports North.

Rogers, C. S. 1990, ‘Responses of coral reefs and reef organisms to sedimentation’, *Marine Ecology Progress Series* 62, 185-202.

Schipper, M., den Hartog, J., Meelis, E. 1998, ‘Sequential analysis of environmental monitoring data: optimal SPRTs’, *Environmetrics* 8(1), 29-41.

Sea Research 2012, ‘The impact of dredge spoil dumping on fringing coral reefs around Facing Island’, Report to Gladstone Ports Corporation.

SKM APASA 2013, ‘Improved dredge material management for the Great Barrier Reef Region. Identification of alternative sites for the placement of dredge material at sea: report to Great Barrier Reef Marine Park Authority’, Unpublished report.

Stafford-Smith, M. G., Kaly, U. L. & Choat, J. H. 1994, ‘Reactive Monitoring (Short term Reponses) of Coral Species’, in *Townsville Port Authority Capital Dredging Works 1993: Environmental Monitoring Program*, Benson LJ, PM Goldsworthy, IR Butler & J Oliver (eds),. Townsville Port Authority, Townsville, November 1994.

Stoddart, J. 2011, ‘The Pluto LNG project: dredging in a busy harbour surrounded by a proposed marine protected area’, Paper presented at the *PIANC Australian Dredge Workshop 'Environmental Approvals and Management'*, Perth, Western Australia, 26-27 September 2011.

Stoddart, J, & Anstee, S. 2005, 'Water quality, plume modelling and tracking before and during dredging in Mermaid Sound, Dampier, Western Australia', in *Corals of the Dampier Harbour: their survival and reproduction during the dredging programs of 2004*, Stoddart J, Stoddart SE (eds),. MScience, Perth, Western Australia.

Stoddart, J. A. & Stoddart, S. E. 2005, *Corals of the Dampier Harbour: their Survival and Reproduction during the Dredge Programs of 2004*, Vol. MScience Perth, Western Australia.

Tennyson, A. 2011, Port Headland RGP5 dredge monitoring: resilience of coral communities to natural and dredge-related elevations in turbidity, Paper presented at the *PIANC Australian Dredge Workshop 'Environmental Approvals and Management'*, Perth, Western Australia, 26-27 September 2011.

Thomas, R., Unsworth, R.K.F. & Rasheed, M.A. 2010, *Seagrasses of Port Curtis and Rodds Bay and Long Term Seagrass Monitoring, November 2009*, Department of Employment, Economic Development and Innovation.

Trimarchi, S. & Keane, J. 2007, *Port of Hay Point Apron Areas and Departure Path Capital Dredging Project, Environmental Review, EcoPorts Monograph Series No. 24*, Ports Corporation of Queensland Ltd.

Underwood, A. J. 1991, 'Beyond BACI: Experimental designs for detecting human environmental impacts on temporal variation in natural populations', *Australian Journal of Marine and Freshwater Research* 42, 569-587.

Underwood, A. J. 1997, *Experiments in Ecology: their Logical Design and Interpretation Using Analysis of Variance*, Vol. Cambridge University Press, Cambridge.

Utne-Palm, A. C. 1999, 'The effect of prey mobility, prey contrast, turbidity and spectral composition on the reaction distance of *Gobiusculus flavescens* to its planktonic prey', *Journal of Fish Biology* 54(6), 1244-1258.

Utne-Palm, A. C. 2002, 'Visual feeding of fish in a turbid environment: physical and behavioural aspects', *Marine and Freshwater Behaviour and Physiology*. 35(1-2), 111-128.

Utne-Palm, A. C. 2004, 'Effects of larvae ontogeny, turbidity, and turbulence on prey attack rate and swimming activity of Atlantic herring larvae', *Journal of Experimental Marine Biology and Ecology*. 310(2), 147-161.

Vision Environment 2012, 'WBDDP water quality monitoring', Report to the Gladstone Ports Corporation.

WAEPA 2011, *Environmental Assessment Guideline for Marine Dredging Proposals*, Environmental Assessment Guidelines EAG 7, Western Australia Environmental Protection Authority, Perth.

WBM 2004, 'Spoil ground site selection Port of Hay Point', Report to Ports Corporation of Queensland.

Weber, M., Fabricius, K. E., Lott, C. & DeBeer, D. 2004, 'Effects of sedimentation by contrasting sediment types on the photophysiology of corals', *Tenth International Coral Reef Symposium*, Okinawa, Japan, 28

Wilber, D. H., & Clarke, D. G. 2001, ‘Biological effects of suspended sediments: a review of suspended sediment impacts on fish and shellfish with relation to dredging activities in estuaries’, *North American Journal of Fisheries Management* 21, 855-875.

Worley Parsons 2010, *Cairns Port Long Term Management Plan, Dredging and Dredge Spoil Management May 2010*. Report to Far North Queensland Ports Corporation.

APPENDIX A SUMMARY OF WATER QUALITY TRIGGER VALUES IN PAST AND PROPOSED DREDGING AND DREDGE MATERIAL PLACEMENT PROJECTS

Project	Trigger Value	Program Specifications
Port of Hay Point Apron Areas and Departure Path Capital Dredging Project (QLD)	100 NTU	Trigger values set at 100 NTU over a continuous period of six hours at two fringing reefs.
Hay Point Coal Terminal Expansion Phase 3 (QLD)	110 NTU (derived as 80th percentile of baseline turbidity at the compliance site plus 100 NTU)	Trigger value of 110 NTU based on a 6 hour daily median during daylight hours as a daily trigger, the occurrence of 4 daily triggers within any 7 day period constituted an exceedance.
Western Basin Dredging and Disposal Project (QLD)	Level 1 – 80th percentile (NTU) Level 2 – 95th percentile (NTU) Level 3 – 99th percentile (NTU)	Site -specific turbidity trigger values with different levels of reporting ranging from 2 to 46 NTU (dry season) averages over 6 hours. Level 1 and Level 2 triggers internal and external reporting triggers and a Level 3 action trigger when eight continuous values (48 hours) exceed the trigger value.
	PAR less than 6 $mol/m^2/d$	Light-based trigger values established for seagrass sites based on a two-week moving average. Light-based triggers only apply during the period of active seagrass growth.
Townsville Marine Precinct Project (QLD)	109 NTU	Trigger values used were based on ANZECC/ARMCANZ and QWQG Central coast guidelines. More specific criteria of consecutive minutes above 109 NTU and the number of times incidences that were allowed per week (10 and 20 minute exceedances), as well as number of incidences allowed during the dredging project (30 minute to 12 hour exceedance).
Cairns CityPort Dredging Project (QLD)	35 NTU	A threshold of 35 NTU was set for waters around seagrass receptors, outside of this receptor areas a threshold of ambient plus 100 per cent was adopted as a management trigger based on a period of greater than 6 hours.
Rosslyn Bay State Boat Harbour Maintenance Dredging (QLD)	42.9 mg/L at Bluff Rock (80th percentile) 31.4 mg/L at Wreck Point (80th percentile)	Proposed trigger value for 2012 maintenance dredging is the 80th percentile of baseline measurements.
Port of Dampier Dredging Project (WA)	10 mg/L (offshore) 35 mg/L (inshore)	Frequency of exceedances of 10 mg/L TSS (offshore) and 35 mg/L TSS (inshore) for various durations (hrs) in a period of a month, depending on impact zone.
Fremantle Harbour Dredging Program (WA)	PAR	Water quality triggers based on minimum light requirement for seagrasses and corals for boundaries of

Project	Trigger Value	Program Specifications
		zones of Loss, Effect and Influence. Tiered management responses based on trigger levels with no reduction in coral or seagrass cover in zone of Influence.
Pluto LNG Dredging Program (WA)	95^{th} percentile (NTU)	Exceedances of 95^{th} percentiles for intensity, duration and frequency of SSC (derived from the baseline data) for different zones.
Cape Lambert – Port B (WA)	Level 1 80^{th} percentile (NTU) Level 2 95^{th} percentile (NTU) Level 3 99^{th} percentile (NTU)	Exceedances of NTU from potentially impacted sites versus reference sites at different percentiles of water quality tested over a frequency of exceeding daily values for 14 days in 21 day duration. Management responses of Level 1, 2, and 3 include: exceedance of Level 1 meant reducing dredging, Level 2 meant relocating the dredge, and Level 3 meant reducing dredging further.
Port Hedland RGPS (WA)	80^{th} percentile (NTU) 95^{th} percentile (NTU)	Exceedances of 80^{th} and 95^{th} percentiles of background turbidity data (expressed as NTU levels), with the percentile chosen depending on tide, season and impact zone.
Gorgon Project (WA)	25 mg/L TSS for 2 in 6 days 10 mg/L TSS for 7 in 21 days 5 mg/L for 20 in 60 days	TSS triggers represent short-term, medium-term and long-term water quality criteria. These criteria were applied to the Zone of Moderate Impact and Zone of Influence. For the sake of ongoing monitoring of *in situ* loggers a TSS/NTU conversion was used.
Wheatstone Project (WA)	NTU to be confirmed, project in approval stage.	Exceedance of NTU at varying levels for different periods of time (expressed as a fraction of days above NTU values depending on management zone); trigger values being derived from data on Gorgon Project coral morality.

APPENDIX B OUTCOMES OF MONITORING PREVIOUS DREDGING AND DREDGE MATERIAL PLACEMENT PROJECTS

Port of Gladstone

The objective of the Water Quality Management Plan for the Gladstone Harbour Western Basin Dredging and Disposal Project is to manage the impacts of turbidity generated by dredging and disposal activities at the reclamation area and at the material placement area. It is a reactive monitoring program with the purpose of managing impacts from dredging and material placement activities on sensitive receptors surrounding the project area. The Port of Gladstone contains extensive seagrass communities that are likely to be of regional significance, providing food for local and transiting animals (Thomas et al. 2010) The Gladstone region is of low to medium conservation value for dugongs (Grech & Marsh 2007) and dugongs are resident in areas adjacent to port activities (Thomas et al. 2010).

The program manages water quality within zones of predicted high, medium and low impact, and includes the monitoring of seagrass and sensitive areas (Aurecon 2011). There are six compliance sites and fourteen supplementary sites surrounding the dredging footprint, reclamation discharge, and material placement site. Water quality triggers are based on background data and predicted sediment plume loading. Water quality trigger values are site-specific and have been developed with Level 1 and Level 2 triggers being internal and external reporting triggers, respectively, while exceedances of a Level 3 trigger requires a management response.

The main performance indicator of the monitoring program is no exceedance of the External Reporting Trigger Level in the low to no impact zone due to sediment suspension associated with dredging or material placement (Aurecon 2011). Exceedances of the External Reporting Trigger Level have occurred, for example in August and September 2012, however, during these months there was a Transitional Environmental Program (TEP) in place that allowed short-term temporary continual exceedances to occur in order to accelerate completion of bund wall construction. Completion of the bund wall was a priority because it was expected to reduce turbid discharges from the reclamation area. While the TEP is in place, a fourteen day rolling average for benthic PAR at three seagrass sites was implemented (Vision Environment 2012).

Seagrass communities within Port Curtis and Rodds Bay have been monitored by the Department of Employment, Economic Development and Innovation (DEEDI) as part of the annual seagrass monitoring program since 2002. The 2009 annual report of this monitoring program found that the broad distribution of seagrass meadows in 2009 was similar to 2002. The total area of seagrass meadows declined by approximately 1500 hectares between 2002 and 2009 (Thomas et al. 2010). A 10 per cent decline in meadow area was observed at Quoin Island and Rodds Bay but not over the total survey area. Thomas et al. (2010) postulated that the drivers of long-term seagrass change in Gladstone are climatic conditions (elevated rainfall, river flow, elevated water temperature, cyclone Hamish), but noted that this was difficult to confirm. Seagrass meadows in close proximity to port operations or vulnerable to high anthropogenic stress did not significantly decrease, therefore Thomas et al. (2010) concluded that the overall reduction in the area of seagrass meadows was not due to port operations and human impacts.

Surveys in February and March 2011 reported seagrass cover as the lowest since the program began in 2002, which was attributed to increased turbidity due to extreme rainfall and flooding events of 2010/2011 (GPC 2011). July 2011 saw a small improvement in seagrass cover and biomass, indicating the onset of recovery. There were, however, still some sites within the port with the lowest recorded seagrass cover.

To date, there have been no measured impacts from port-related activities and seagrass meadows appear to be resilient to port operations. With increased port activities and more extreme climatic events there have been concerns about the vulnerability of the meadows. To supplement regular monitoring of seagrass meadows in the port, Chart and et al. (2012) conducted a two-year study to develop a light-based management approach to monitoring Gladstone seagrasses during dredging and material placement operations for the Western Basin Dredging and Disposal Project, based on the intensity and duration of reduced light availability.

Coral surveys of the fringing reefs within the impact zone were conducted before dredging and in June 2012 to monitor short-term impacts associated with the dredging operations associated with the Western Basin Dredging and Disposal Project (Sea Research 2012). The study found that hard and soft coral cover was similar between the baseline and post-dredging surveys, and that the benthic community had not been impacted by port activities over the twelve months (Sea Research 2012).

Rosslyn Bay State Boat Harbour

Water quality monitoring of dredging operations and dredge material placement at Rosslyn Bay in 2006 and 2009 found that turbidity from dredging and dredge material placement did not impinge on the fringing coral reefs of Wreck Point, Bluff Rock or the Keppel Islands (DTMR 2010). Monitoring in 2009 showed:

- Increased levels of turbidity associated with the disposal were contained primarily within 100 m of the DMPA
- Turbidity mirrored the control site in most cases within 1000 m from the DMPA
- A few cases where transects were extended more than 1000 m showed difference between control and impact sites of < 1 NTU
- No turbidity plumes reached sensitive receptors.

The 2009 monitoring program concluded that sensitive receptors were not impacted by dredging and disposal activities for dredging volumes of up to 31,000 cubic metres, and turbidity associated with the placement of the material in 2009 was actually less than the turbidity recorded during baseline monitoring prior dredging (DTMR 2010). DTMR (2010) concluded that no impacts on benthic communities were expected in areas that the turbidity plume did not actually reach. Modelling of turbidity plumes generated by a 120,000 m^3 campaign predicted a small potential for the plume to reach Bluff Rock in the worst-case, peak spring ebb tidal flow (DTMR 2012). The modelling also predicted that Wreck Point and Bluff Rock were still the receptors most likely to be influenced by turbidity plumes during the larger campaign. The fringing reefs of Great Keppel Island are 15 kilometres away from the dredging footprint, and previous modelling and water quality monitoring suggest that these receptors are too far away to be impacted by project works (DTMR 2010; DTMR 2012).

Alquezar & Boyd (2008) surveyed infauna communities at Wreck Point and Bluff Rock one week prior to the 2006 maintenance dredging campaign, two weeks post-dredging and one year post-dredging. They also surveyed Monkey Point on Great Keppel Island, approximately 15 km south-east of the dredge material placement site, as an intended control site. There were significant declines in infauna abundance and species diversity at Wreck Point and Bluff Rock two weeks post-dredging, but not at Monkey Point. One year after dredging, infauna abundance and diversity at Wreck Point and Bluff Rock had significantly recovered, though not to pre-dredging levels. Infauna community structure did not change between the pre- and one year post-dredging surveys at Bluff Rock or Monkey Point, though there was some change in community structure at Wreck Point (Alquezar & Boyd 2008). Alquezar & Boyd (2008) conducted coral surveys at both Bluff Rock and Monkey Point one week before dredging. No significant post-dredging change in coral cover was observed at Monkey Point, indicating no impact from dredging there; bad weather prevented post-dredging coral surveys at Bluff Rock.

It should be noted that the Monkey Point site treated by Alquezar & Boyd (2008) as a control site is not representative of the two impact sites, Bluff Rock and Wreck Point. Bluff Rock and Wreck Point lie in the nutrient-rich and relatively turbid coastal strip downstream of the Fitzroy River discharge into Keppel Bay. Benthic communities surveyed at Bluff Rock were dominated by sand, macroalgae and the hard coral *Pavona cactus*. Monkey Point lies well offshore and the benthic community surveyed there is dominated by hard corals (*Acropora formosa*). SKM's opinion is that given the very different environmental settings of the impact (Bluff Rock/Wreck Point) and control (Monkey Point) sites, the conclusion that the observed changes in infauna communities at the impact sites resulted from dredging rather than natural processes is highly suspect, especially since turbidity plumes were not observed to extend to the impact sites.

Port of Hay Point

Water quality trigger levels were exceeded on multiple occasions during the Port of Hay Point capital dredging project in 2006. A review of the monitoring program showed that the magnitude and/or duration of periods of high turbidity at the receptor monitoring sites increased during dredging (Trimarchi & Keane, 2007). The Environmental Impact Statement predicted that there would potentially be a loss of coral cover of up to 16 per cent at the receptor sites, leading to an approved loss of 20 per cent as a performance indicator in the EMP. Coral monitoring during dredging did show partial mortality of a significant number of coral colonies due to sedimentation (Trimarchi & Keane, 2007). Post-dredging coral surveys, however, found that hard coral cover at the impact sites had declined by no more than one per cent, less than at one of the control sites (Trimarchi & Keane, 2007). Thus, anticipated impacts from dredging operations were over-estimated despite multiple exceedances of water quality triggers and monitoring found dredging had minimal impacts on nearby sensitive receptors.

Water quality during dredging and dredge material placement operations for the Hay Point Coal Terminal Expansion Project (HPX3) in 2010 and 2011 used a water quality trigger value (based on a 6 hour rolling median) of 110 NTU. The trigger value was exceeded on multiple occasions, but only during periods of strong winds when dredging operations were unable to continue (BMA 2012). No relationship was found between dredging and high turbidity at the monitored impact site (Hay Reef). Satellite imagery showed that TSS concentrations increased regionally during periods of high wind and no defined plumes could be detected during dredging.

The reactive coral monitoring program for the HPX3 project was based on exceedance of the water quality trigger level for turbidity (6 h rolling median of 110 NTU during daylight hours) and associated management response. Key performance indicators of the program were percentage cover of corals and coral health and mortality compared to three levels of trigger values (Level 1: < 5 per cent net detectable mortality; Level 2: 5–10 per cent net detectable mortality; Level 3: > 10 per cent net detectable mortality). Reactive coral monitoring was never required because the water quality trigger value for turbidity was never exceeded while dredging and disposal was in progress (BMA 2012).

There were was a slight decline in live coral cover between the baseline and post-dredging surveys at both the impact and control site, but the pattern of decline did not differ between impact and control (BMA 2012). He main change in benthic communities observed before and after dredging at the receptor sites was a large increase in macroalgal cover at both impact and control sites. This was attributed to the effects of Tropical Cyclone Ului, which passed through the area shortly before the baseline surveys were conducted in 2010, as well as flooding in early 2011 (BMA 2012).

Chartrand et al. (2008) show that deepwater seagrass communities at Hay Point are highly variable in space in time, with a dramatic decline in seagrass abundance and distribution observed between pre-dredging baseline surveys in July 2004 and December 2005, likely as a result of a seasonal pattern of senescence during the wet summer months and recruitment in the dry winter. Turbidity from the 2006 capital dredging and material placement campaign is likely to have prevented the seasonal recruitment in 2006, but recruitment was observed during the next winter after dredging (Chartrand et al. 2008). Surveys in 2010 found patchy seagrass cover at both offshore and inshore sites, including sites in the material placement area used for the 2006 capital dredging (BMA 2011). Quarterly surveys during 2011 were inconclusive regarding possible impacts of dredging, because seagrass was not observed at any impact or control sites during surveys in February, April, or July 2011(BMA 2012). Scattered, low-density seagrass communities reappeared in the October 2011 survey (BMA 2012). There was no evidence for dredging or dredge material placement impacts on deepwater seagrass communities, except possibly the direct impacts of disposal at the material placement itself (BMA 2012). SKM has subsequently observed deepwater seagrass within the HPX3 material placement site, the first time seagrass has been observed there in surveys since 2004.

Port of Abbot Point

Baseline surveys of coastal and deepwater seagrass communities at Abbot Point since 2005 show that seagrass meadows in the Abbot Point area are highly variable, both seasonally and in response to climatic events such as floods (GHD 2012, McKenna & Rasheed 2011). Water quality monitoring indicates that seagrasses can persist through periods of very high turbidity (GHD 2012). McKenna and Rasheed (2011), however, note that natural climatic stressors and future port expansion make seagrasses in the area more vulnerable. No water quality or ecological monitoring data during periods of active dredging and dredge material placement are available to SKM, so the ecological outcomes of monitoring and reactive management during dredging could not be evaluated.

Port of Townsville

Reactive coral monitoring implemented during the 1993 capital dredging project at Magnetic Island included direct observations of sub-lethal stress and partial mortality of corals at a range of sites around the sensitive receptor, Magnetic Island (Stafford-Smith et al. 1994). The program detected very small increases in partial mortality, bleaching and sediment deposits on coral tissue, on time scales of once or twice per week. No coral colonies died from dredging-related causes at the principal impact locations, and partial mortality was < 10 per cent (Stafford-Smith et al. 1994).

The proposed water quality trigger values for dredging for the Townsville Marine Precinct Project are based on the 95th percentile of baseline data at a Cleveland Bay seagrass community monitoring site that regularly experiences high turbidity (GHD 2009c). A series of trigger values based on duration and frequency of 109 NTU turbidity, ranging from a 60 occurrences of 109 NTU for more than ten minutes constituting a trigger to a single occurrence of 109 NTU for more than 12 hours being a trigger.

Port of Cairns

BMT WBM (2011) monitored the extent of the turbidity plume from maintenance dredging at the Port of Cairns to verify the results of monitoring in 1990 showing that background turbidity levels were reached within 700 m and 1000 m of the entrance channel and material placement area, respectively. The 2011 dredging plume was reported to extend 650–700 m west of the channel, and 150–200 m east of the channel. BMT WBM (2011) concluded that dredging plumes were mostly contained within the channel confines due to tidal flow.

Reactive monitoring of water quality during the Cairns CityPort dredging project by GHD (2002) using deployed nephelometer instruments adopted a trigger value of 35 NTU when sediment plumes intersected seagrass beds. In these instances, a trigger value of ambient (outside the influence of the dredge plume) plus 100 per cent for periods greater than 6 hours was adopted. Despite the dredge plume intersecting the seagrass beds on several occasions during dredging, none of the monitoring sites experienced conditions above the trigger value (GHD 2002). The highest increases in turbidity were associated with natural tidal movement and not related to dredging operations (GHD 2002).

Neil et al. (2003) surveyed the Cairns material placement site in April and May 2003 to assess whether dredge material placement had impacted benthic flora and fauna within and adjacent to the site. Results from the survey were:

- All areas sampled (impact and control sites) had a similar habitat with flat, open soft-sediment seabed
- Benthic fauna dominated the sites, with corals and seagrass uncommon and sparsely distributed
- Sites to the north of the placement area and sites within the placement area had similar assemblages compared to sites to the south of the placement area
- A number of factors could be responsible for the differences in assemblages between the impact and northern sites, and the southern reference sites
- The findings suggested that dredge material at the placement area is acting to change the structure of benthic assemblages at the dredge material placement area and northern off-site area (downstream) compared to the southern sites.

Neil et al. (2003) concluded that the impact of dredge material placement on benthic assemblages was minor and only affected taxa that occurred in low numbers.

Seagrass monitoring has identified the Cairns region as one of the four regions of the World Heritage Area facing the highest level of risk to seagrass communities from anthropogenic impacts (Rasheed et al. 2007). Reason et al. (2011) also concluded that seagrass communities in Cairns and Trinity Inlet were in a vulnerable condition compared to the long-term average. Some seagrass meadows showed signs of recovery in 2011 compared to 2010, however, the majority of meadows remained at their lowest distribution and second lowest density since monitoring began in 2001. Reason et al. 2011 suggested that large declines in seagrasses were likely associated with climatic factors (extreme rainfall and flooding of 2010/2011) as in other areas along the Queensland coast, and that port-related activities were unlikely to have had significant impact on seagrasses in the Cairns area.

Port of Dampier (Western Australia)

Water quality trigger values for the 2004 Dampier dredging project were 10 mg/L TSS (offshore) and 35 mg/L TSS (inshore) for various durations (hours) per month, depending on impact zone defined in the project's approval conditions. Coral communities in the 'Zone of High Impact' and 'Zone of Moderate Impact' were subjected to TSS concentrations well above background for weeks at a time, or to very intense events of a few days (maximum of 75 mg/L at impact sites versus 24 mg/L at reference sites; Stoddart & Anstee 2005; Stoddart & Stoddart 2005).

Coral mortality showed that, though some coral mortality occurred, in general it was not attributable to dredging-related activities. Natural causes such as cyclone and heavy rainfall events and attendant reduced salinity, thermal bleaching, and seasonal overgrowth by algae (*Sargassum* sp.) *w*ere found to be the main causes of coral mortality (Stoddart & Stoddart 2005). Only one site experienced coral mortality that could be attributed to dredging. This site was within a few hundred metres of intense dredging and propeller wash from constant repositioning of a trailer hopper suction dredge, depositing large amounts of sediment directly onto the corals (Blakeway 2005). Unfortunately, access to the site was restricted due to safety concerns and extremely poor visibility during the initial dredging, and as a result there were no reliable water quality data available immediately prior to the observed coral mortality. Available monitoring data suggested that TSS concentrations during these events may have exceeded 60 mg/L (Stoddart & Anstee 2005). Most coral communities within the permitted 'Zone of High Impact' and 'Zone of Moderate Impact' did not suffer any reduction in live coral cover during the dredging program. It was concluded that the water quality trigger values used in this program were clearly below levels that would cause detectable mortality.

One other exception to the review's finding that ecological impacts have been minor or undetectable for most of the dredging projects reviewed is the Dampier dredging program of 2004. Significant dredging-induced mortality occurred at one monitoring site (Blakeway 2005) during the dredging program. Blakeway (2005) concluded that this coral mortality probably resulted from acute sedimentation caused by propeller wash from one of the dredging vessels. Water quality monitoring would be neither likely to detect nor able to provide warning to trigger a management response to this mode of impact.

Mermaid Sound (Western Australia)

Coral communities appear not to have suffered any reduction in live coral cover during the Pluto LNG dredging program (MScience 2009), even though water quality trigger values were exceeded as many as 60 times (Stoddart 2011). These observations demonstrated that the water quality trigger values applied in the Pluto LNG project substantially underestimated the levels of suspended sediment and sedimentation required to cause detectable mortality.

Port Hedland (Western Australia)

The Port Hedland RGP5 monitoring program showed that the water quality trigger values, which were based on the 80th percentile of baseline data, were overly conservative. They were reached as a result of both natural variability (since 80th percentile turbidity levels are expected to be reached 20 per cent of the time naturally) and dredging-related sediment mobilisation, but with no impacts on coral health were detected. Despite turbidity at the impact site reaching 15 NTU for periods of up to six weeks, compared to a median of 6 NTU during the baseline period, and rarely falling below 5 NTU throughout the dredging program, there were no detectable impacts on coral health at the impact site relative to the reference site (Tennyson 2011).