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Strategic Integrated Marine Science: Dredging

New Knowledge for Better Decisions and Outcomes

WAMSI Dredging Science Node

A Synthesis of Research 2012-2018

April 2019

Acknowledgements

WAMSI Dredging Science Node

The WAMSI Dredging Science Node was a strategic research initiative that evolved in response to uncertainties in the environmental impact assessment and management of large-scale dredging operations and coastal infrastructure developments. Its goal was to enhance capacity within government and the private sector to predict and manage the environmental impacts of dredging in Western Australia, delivered through a combination of reviews, field studies, laboratory experimentation, relationship testing and development of standardised protocols and guidance for impact prediction, monitoring and management.

Funding Sources

The $20 million Dredging Science Node has delivered one of the largest single issue environmental research programs in Australia. This applied research was funded by Woodside Energy, Chevron Australia, BHP Billiton and the WAMSI Partners and designed to provide a significant and meaningful improvement in the certainty around the effects and management of dredging operations in Western Australia. Although focussed on port and coastal development in Western Australia, the outputs are also broadly applicable across Australia and globally.

This remarkable collaboration between industry, government and research has extended beyond the classical funder-provider model. End users of science in regulator and conservation agencies, and consultant and industry groups were actively involved in the governance of the node, to ensure ongoing

Funding and critical data

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Woodside

Chevron

BHP

focus on applicable science and converting the outputs into fit-for-purpose and usable products. The governance structure included clear delineation between end-user focussed scoping and the arms-length research activity to ensure it was independent, unbiased and defensible.

Critically, the trusted across-sector collaboration developed through the WAMSI model has allowed the sharing of hundreds of millions of dollars worth of environmental monitoring data, much of it collected by environmental consultants on behalf of industry. By providing access to this usually confidential data, the industry partners have substantially enhanced WAMSI researchers' ability to determine the real-world impacts of dredging projects and how they can best be managed. Rio Tinto's voluntary data contribution is particularly noteworthy, as it was not one of the funding contributors to the Node.

Legal Notice

Year of Publication

2019

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Front cover image

Atmospherically corrected, colour corrected, pan sharpened satellite image from the United States Geological Survey (USGS) Operational Land Imager (OLI) instrument showing sediment plumes caused by dredging and dredge material placement near Onslow in the Pilbara region of Western Australia (courtesy of Mark Broomhall and Peter Fearns (Curtin University of Technology, Perth, WA).

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Foreword

Dredging is a critical component in developing Western Australia's infrastructure and is essential to the export of commodities like iron ore and LNG.

The combined volume of planned or proposed dredging over recent years is over 200 million m^3 at a cost of some $10 billion. Those volumes are large even by world standards and in some cases the predicted area of impact extends over 1000 km^2.

Noting the obligation to protect and manage Western Australia's marine environment, uncertainties in the prediction and management of dredging impacts has been of long-standing concern to the EPA as well as the wider community.

The environmental impact assessment of dredging in Western Australia is highly problematic for two significant reasons in addition to scale and extent. Dredging in Western Australia generally occurs in sensitive environments about which we know less than we would like – poorly understood ecology and biodiversity which adds further challenges to environmental assessment and environmental management.

Additionally, environmental impact assessment is predictive; we have to be able to predict both the pressures on the environment – that is the result from the physical dredging of the material – as well as predict the response of the environment in space and time.

And at the time this program was proposed, the uncertainty associated with predicting and managing dredging had direct consequences to the approval and regulatory processes required for projects to proceed and succeed.

Such uncertainty can delay the granting of approvals and subsequent investment decisions, which can amount to significant economic costs to the proponent and to the state. Uncertainty can also lead to the imposition of onerous and costly monitoring and management regimes, which might otherwise have been minimised given better predictive confidence.

It is estimated that monitoring and management costs can exceed $100 million on a major dredging program and obviously, the predictive uncertainty has risks to the environment itself.

Six years ago, industry and government saw the value in meeting that challenge through an opportunity to direct environmental offset funds arising from dredging programs executed by Woodside, Chevron and BHP toward a research program to reduce the uncertainties surrounding impacts and management.

A commitment was made to a research program that would reduce the uncertainty associated with assessment and management of dredging and translate new understanding into improved dredging guidelines. The Premier of the day declared the program "a sensible and practical way of using these funds to better protect the environment."

The program had research themes to characterise dredge generated sediments, to characterise and improve the plume dynamic predictions and fate of the plumes, and to define the thresholds and indicators of coral, primary producer and filter feeder response to dredging, as well as the effects on other critical ecological processes.

WAMSI put in place a governing committee to ensure that this research was designed to deliver the outputs in a form that could be directly applied to improve the triple bottom line outcomes of major marine dredging activities in Western Australia.

I am pleased to share with you the success of meeting that commitment. This program has delivered on its promise in full and in a form that has increased the confidence, timeliness and efficiency of the environmental approval and regulatory processes associated with dredging projects.

We have greatly improved the understanding of dredge-related physical pressures and how to better predict and manage and measure those pressures.

We have a much fuller and confident understanding of pressure-response relationships and the associated pathways to recovery for key organisms which will benefit assessments, the setting of appropriate approval conditions, and auditing and compliance.

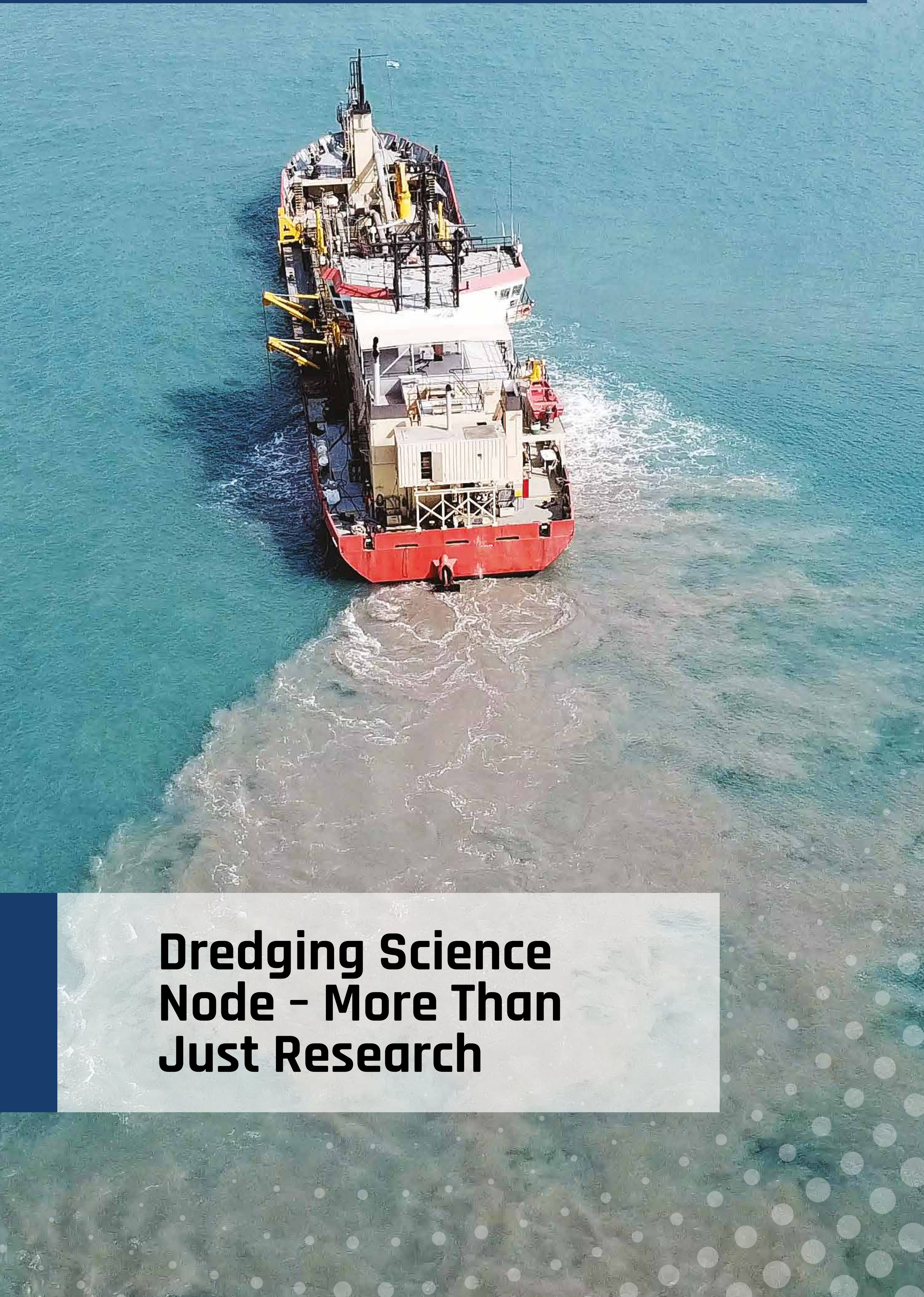
In doing so the WAMSI Dredging Science Node has shown that great and basic science can, through design and intent, deliver practical and substantial means to better protect and manage our environment.

These outcomes are already finding valuable applications in the assessment of current marine dredging proposals in the state and I'm told the same is true in applications in the Mediterranean and elsewhere overseas where environmental managers need to meet similar challenges.

In my 30 years in environmental science and leadership this is the most outstanding example of research program design and intent in the delivery of such a valuable and practical outcome from such excellent science.

It was a great honour to have been one of the WAMSI Governors at the time we developed and approved this program and a greater honour as the Chair of the Dredging Science Advisory Committee and EPA Chairman to receive the fruits of these endeavours.

Dr Tom Hatton PSM FTSE,
Chairman, Environmental Protection Authority



Dredging Science Node – More Than Just Research

Introduction and Context

The Dredging Science Node is one of the world's largest scientific research programs focusing on improving the understanding of the environmental effects of dredging in tropical marine environments.

This Final Synthesis Report 'tells the story' of the Dredging Science Node by reflecting on the historic background leading up to the program, reviews of the final key findings and lessons learnt, and takes a look at the implications of the program's outcome for the future of dredging (and scientific collaboration) in Western Australia.

Importance of dredging in Western Australia

The past decade has seen a rise in port developments across Western Australia in response to rapid economic growth and industrial activities associated with trade, mining and the oil and gas sector. To meet the increasing demands of society and the economy over the next 30 years, navigation infrastructure will continue to be developed, expanded and maintained.

Dredging is carried out at existing and new ports to provide and maintain water depths to enable the safe passage of ships and cargo transfer. The sediment plumes generated by dredging and dredged material disposal can influence areas far beyond the port and into sensitive environments, for which the biodiversity is often poorly documented and the natural tolerances and susceptibilities are often not well understood.

Meanwhile, the level of community concern and public debate about the potential environmental consequences of dredging has been steadily growing across Australia, but the evidence base to address these concerns and inform this debate has been limited.

When things go wrong: the case of Geraldton

The issue first came to prominence in Western Australia (WA) in 2002, when the visible sediment plumes from a capital dredging program at the Port of Geraldton (some 400 km north of Perth) extended over several tens of kilometres along the coast, raising significant government and community concerns about the potential environmental effects.

Unexpectedly, the size and intensity of the turbid plumes from the dredging in this limestone-dominated environment far exceeded model predictions and persisted much longer than what was initially thought.

These concerns were further exacerbated when the duration of the dredging program had to be extended beyond what was initially anticipated to finish the works.

The dredging caused widespread impacts to local seagrass habitats in Champion Bay (40 per cent decline over an area of 1,000 hectares), but there has been substantial recovery in subsequent years.

Despite initial stakeholder concerns, local rock lobster fisheries, migratory humpback whales and resident populations of sea lions and dolphins in the area were not adversely affected.

A conservative response to accommodate uncertainty

Recognising the difficulty of accurately predicting dredging impacts at the initial approval referral stage because of the limited availability of data and great uncertainty, the WA Environmental Protection Authority (EPA) responded in the years following with much stricter and more conservative recommendations for subsequent approvals of new capital dredging projects for port related facilities.

The scale of these facilities and the associated volume of dredging and disposal was large by world standards. In 2011-12 alone, four proposals in the Pilbara[A] had a combined dredging volume of about 130 million m^3.

The predictions of plume dispersal and potential impacts from these large dredging projects were based on a range of conservative assumptions and carried significant uncertainty.

Given the considerable uncertainty about the scale and intensity of potential impacts, proponents were required to conduct comprehensive and often very large environmental monitoring programs during dredging, with an expectation that information collected could be used in reactive management providing surety that environmental impacts did not occur in areas that were not approved at the environmental impact assessment (EIA) stage.

As a result, recent monitoring programs associated with LNG developments in northwest Western Australia rank amongst some of the largest and most expensive marine environmental monitoring efforts ever undertaken worldwide.

The uncertainty associated with predicting and managing dredging also had flow-on effects to the time required for approvals and regulatory processes, sometimes causing considerable delays in the granting of approvals and subsequent final investment decisions for projects to proceed.

While the onerous and costly process provided greater confidence that impacts would be within approved limits, it did little to improve the confidence associated with predicting impacts.

[A] EPA (2013) 2012—13 Annual Report. Environmental Protection Authority (EPA). Perth, Western Australia, 84 pp

Reducing Uncertainty: Demand-Driven Science

Funding and industry data for a large dredging research program

Given the high levels of uncertainty around the prediction of dredging-related pressures and understanding of biological responses to those pressures, proponents of new development projects in Western Australia were required by government, as a condition of approval, to contribute funds for research specifically designed to reduce uncertainty.

The research program was initially established to meet the environmental offset requirements associated with the approvals for three large-scale capital dredging projects in the Pilbara region. The Western Australian Government approved the pooling of these offset funds (totalling $9.5 million of industry investment) to enable a depth and breadth of research work that would not have been possible if each offset was implemented independently and in isolation.

Recognising the critical importance of this issue in WA and the urgent need for it to be addressed, the Western Australian Marine Science Institution (WAMSI) (www.wamsi.org.au) established a Dredging Science Node to strategically respond to the need to improve the capacity within the government and private sector in WA to predict and manage the environmental impacts of dredging.

This research program was carried out by a joint venture consortium of nine research agencies, that collectively co-invested a further $9.5 million in the program, adding significantly more value to the initial industry investment, resulting in a combined total of $19 million.

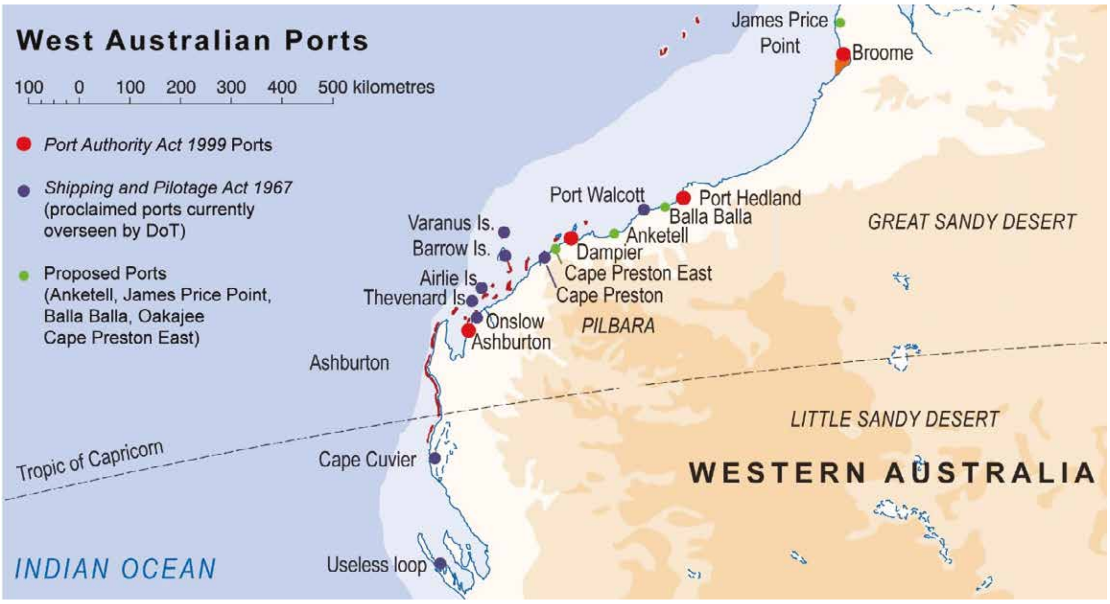
Augmenting the unique opportunity provided by this collaborative research program, the industry partners also agreed to share with the researchers their marine environmental monitoring datasets collected during four large capital dredging projects (Pluto, Cape Lambert, Gorgon and Wheatstone).

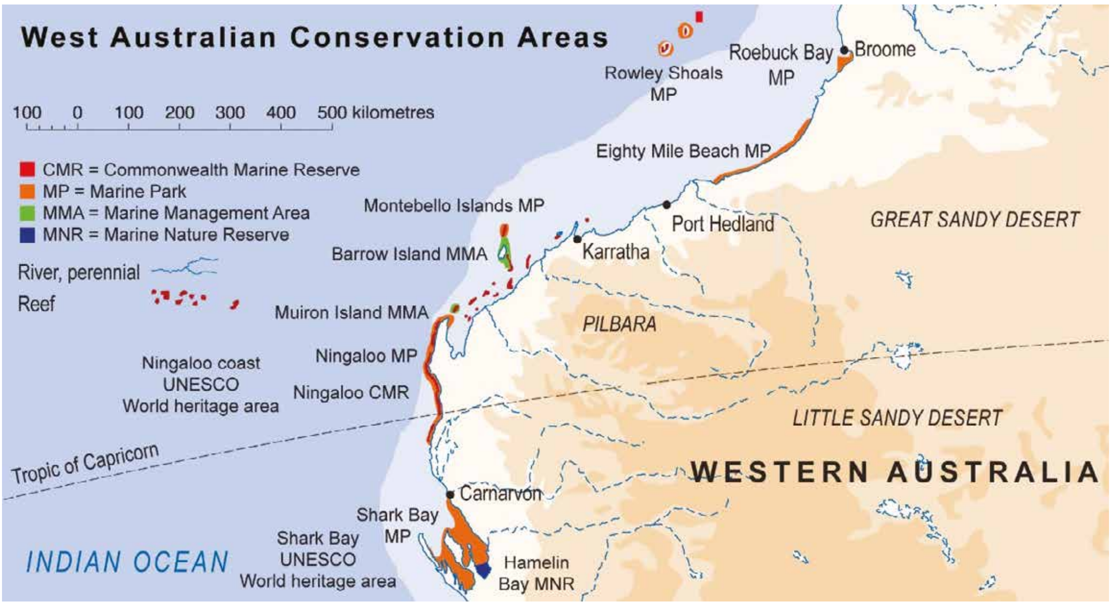
The research program was managed by WAMSI, an independent, not-for-profit agency that was established as a State Major Research Facility. WAMSI was responsible for the governance and coordination of all activities under the different research themes of the Dredging Science Node to ensure that the focus was kept on the strategic priorities and timely delivery of intended outcomes of the program. WAMSI was also responsible for seeking opportunities to add value and integrate research findings, and to foster strategic collaboration between the scientists and end users in government and the private sector.

Focus on tropical northwest Australia

The main focus area of this research program was WA's tropical North West (see maps below), since this is the region with some of the largest recent proposed dredging projects and with the greatest levels of uncertainty in terms of contemporary understanding of biodiversity distribution and environmental resilience to the pressures associated with dredging.

Since 2000, there have been a total of 27 dredging projects in the Pilbara region alone, with a combined total dredging volume of 250 million cubic metres of sediment[A]. The tropical North West region of WA boasts an exceptional marine biodiversity, featuring some of the least disturbed pristine waters in the world (including the World Heritage Areas of Shark Bay, Ningaloo Reef and the Kimberley National Heritage Area) and boasting extensive and diverse coral reefs and sponge gardens, spectacular humpback whale migration and one of the largest remaining dugong populations in the world.





Map of northwestern Australia, showing existing and proposed ports significant conservation areas (SOURCE: Western Australian Ports. 22 January 2018; DoT and Wilson S, Kendrick A, Wilson B (2019) The North-Western Margin of Australia. Chapter 14. Volume II: The Indian Ocean to the Pacific. In: Sheppard, C. (Ed.), World Seas: An environmental Evaluation. 2nd Edition. Academic Press, pp. 303-314.

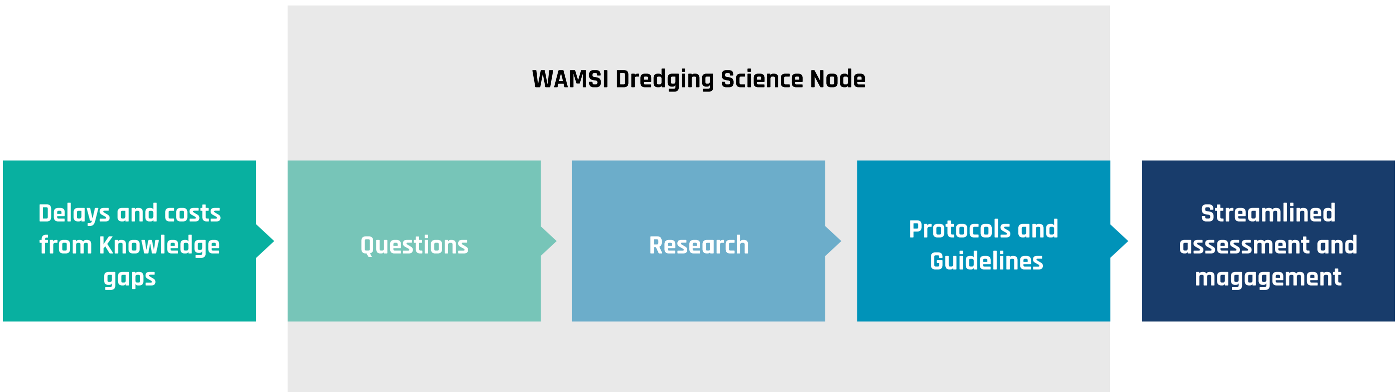
[A] EPA (2013) 2012—13 Annual Report. Environmental Protection Authority (EPA). Perth, Western Australia, 84 pp.

Parts of the region are characterised by particularly strong natural dynamics (due to seasonality, macro-tides, cyclones and floods), which exert their influence on the nearshore habitats and species. This is reflected in the population structure (size and age) of its corals, the ephemeral nature of its seagrasses and the ability of ecosystems and species in these areas to adapt to and cope with relatively high and variable turbidity and low light conditions.

At the same time, this region is also home to a series of busy industrial ports, particularly in the Pilbara region, for the export of mining products (especially iron ore), and oil and liquefied natural gas resources.

Although it would appear that, at least for the moment, most large-scale capital dredging programs in northwest WA have been completed, there is significant merit in learning from the past and reducing uncertainty for the adoption of improved decision making in the future, not only in (Western) Australia, but applicable to any dredging operation around the world.

Objectives & Expectations



The strategic objective of this research program was to *improve the capacity within the government and private sector to predict and manage the environmental impacts of dredging in tropical regions of Western Australia.*

The outcomes from the research program were to support the EPA's Technical Guidance for the Environmental Impact Assessment of Marine Dredging Proposals and anticipated to include:

- enhanced capacity within the WA government to assess environmental impacts of dredging-related development projects and to set appropriate conditions for such projects, resulting in the delivery of better environmental outcomes;
- better understanding and greater certainty with regards to the cause-effect pathways of dredging-related stressors and the response of sensitive environmental receptors to these stressors, enabling proponents to make predictions with greater confidence than before;
- greater understanding by the community and the EPA of the spatial scales of environmental effects associated with dredging and greater surety of the environmental outcomes; and
- less onerous and more cost-effective monitoring requirements and shorter timelines for environmental assessment processes and regulatory approvals for dredging projects, leading to cost savings for both government and industry.

Research Priorities and Science Plan

Priorities for the research program were identified through a workshop in November 2008, the purpose of which was to:

1. identify key research areas that will improve the capacity of government and the private sector to predict and manage the impacts of dredging on tropical coral communities; and
2. prioritise research needs in order to subsequently allocate resources.

The workshop involving subject matter experts from industry and environmental consultancy companies, WA port authorities, the WA Department of Environment and Conservation, and research scientists from WA universities and publicly funded research agencies (See Acknowledgements). The workshop final report[1] was used as a basis and a guide for development of the Dredging Science Node: Science Plan[2] which included a collation of the key knowledge gaps from an end-user perspective, categorised under a number of key Themes.

The Dredging Science Node: Science Plan provided clear guidance to researchers about the objectives for each component of the program, the key tasks to be undertaken, and the type and form of the information that needed to be generated to make it 'fit for purpose' and readily usable.

In this context, fit for purpose meant that the research program had to deliver practical information to answer specific questions that would directly fit into the policy framework.

The process of developing the science plan was primarily driven by the Node leaders for Policy and Science with input from subject matter experts and end users. The *Dredging Science Node: Science Plan* was formally endorsed by the WAMSI Research and Development committee and the WAMSI Board on advice from a Dredging Science Advisory Committee.

The Dredging Science Node: Science Plan provided the basis for the establishment of expertise-based study teams from the 15 WAMSI partner institutes, who subsequently prepared *science concept plans* for the various research Themes.

These plans considered opportunities for collaboration and co-investments, described the likely team of scientists and their expertise, and provided a brief outline of the intended science with a preliminary budget.

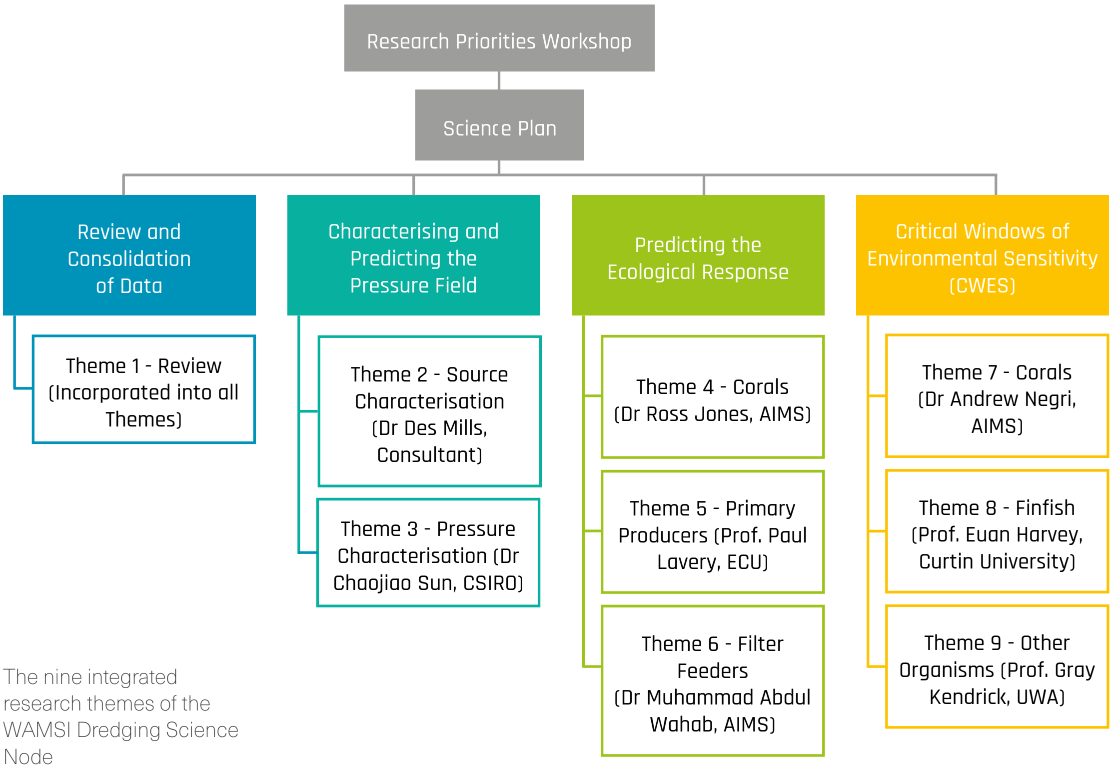
After much discussion between the Node leaders and the scientists, their institutions, the Dredging Science Advisory Committee and the Research and Development Committee, successful teams were then invited to prepare *science project plans*. These contained detailed specifications of the work, including milestones and deliverables and anticipated outputs and outcomes.

After consultation with the Node leaders, the *science project plans* were endorsed by the Dredging Science Advisory Committee and the Research and Development Committee and formed the basis of a legal contract for the work to proceed.

Priorities and plans were further supported and fine-tuned by literature reviews (in each Theme) and in-depth analyses of environmental datasets from previous dredging projects made available by industry.

The final $19m interdisciplinary research program consisted of a series of research Themes under four broad categories delivered through a combination of reviews, field studies and laboratory experiments.

The nine individual Themes were each led by a Theme leader appointed from a university or publicly funded research agency – overall 114 scientists from 26 institutions were involved in the delivery of the Node.



The nine integrated research themes of the WAMSI Dredging Science Node

Review and Consolidation

(Theme 1)
This Theme offered a mechanism for exploring the available data and assessing its relevance for the different Themes and then delivering it to the researchers. The output was via Themes 2–9.

Pressure Field Prediction and Characterisation

(Theme 2 and 3)
Advance our understanding and ability to predict, measure and monitor relevant pressure-field parameters associated with dredge-generated sediments, and allow pressure-field data to be collected in a consistent manner to validate this predictive capacity in laboratory and real-world applications.

Ecological Response Prediction

(Themes 4, 5, 6)
Identify the key pressures impacting on benthic communities and establish quantitative relationships between pressure and response for selected indicator species that are representative of key groups of ecologically important marine organisms relevant to WA.

Derive thresholds and approaches in a form that can be readily transformed into tools and protocols to be used for the prediction, measurement and management in real-world applications.

Critical Ecological Processes and Environmental Windows

(Theme 7, 8, and 9)
Identify the critical ecological processes and windows (e.g. early life stages) in marine biological communities in WA that could be affected by dredging programs, the likely cause-effect pathways, and the significance of those processes at local and regional scales.

Develop field monitoring and evaluation protocols that could guide and target management approaches to minimize disruption to both the critical ecological process and the dredging program.

WAMSI Dredging Science Node Governance and Quality Control

For the management and smooth operation of the Dredging Science Node specific governance arrangements were established to complement the existing WAMSI structure.

The Dredging Science Node was jointly led by two Node leaders. A Node Leader for Science was appointed from the Australian Institute of Marine Science (AIMS) to oversee the scientific research portfolio, ensuring that science outputs and science advice were in forms suitable for reducing uncertainty associated with marine dredging activities, and ensuring the science quality of the research including the production of high quality peer reviewed science publications.

A Node Leader for Policy was appointed from Department of Water and Environmental Regulation (DWER, formerly the Office of the Environmental Protection Authority), to facilitate the development of derived products suitable for adoption by the government and the private sector for EIA and management.

This unique co-leadership arrangement ensured the coherence and practical relevance of the research conducted under the program whilst safeguarding its scientific quality and integrity. As a consequence of this co-leadership, the research work was fit for purpose and aligned with the EPA policy statements.

WAMSI formed a Research and Development Committee with responsibility for the research quality and performance of the Dredging Science Node projects. As part of a QA/QC process the Research and Development committee also commissioned an external, independent scientific review by a two to three person panel for each Theme.

Quality control was maintained through a rigorous system of six monthly reporting and accountability which was embedded in the research agreements, by internal review processes of participating research agencies, by peer-review processes for publication in scientific journals, and by internal reviews of each report or publication by the Node leaders and final approval from the WAMSI CEO.

A Dredging Science Advisory Committee (DSAC) was established to oversee implementation of WAMSI Dredging Science Node, providing advice and, where appropriate, recommendations to other WAMSI committees and the WAMSI Board in relation to dredging research.

The DSAC was chaired by the General Manager of the Office of the Environmental Protection Authority and membership comprised the WAMSI CEO, a Department of Environment and Conservation representative, the Node Leaders and a representative of each of the funding contributors.

The DSAC and WAMSI Board agreed to invite a representative from the Environmental Consultants Association (ECA) of WA in an ‘observer’ capacity and to act as conduit for communication between DSAC and the broader ECA membership.

The key purpose of this committee was to ensure science-management linkages were embedded from the outset and reinforced during execution of the research program.

Report Accessibility and Data Archiving

Each Theme has a final synthesis report which integrates between each Theme's projects and in some cases the multiple sub-projects.

The individual project reports all include an Executive Summary outlining the key science findings, followed by a summary of the management implications as relevant to pre-development surveys, impact prediction and monitoring, and finalised with a summary of key residual knowledge gaps.

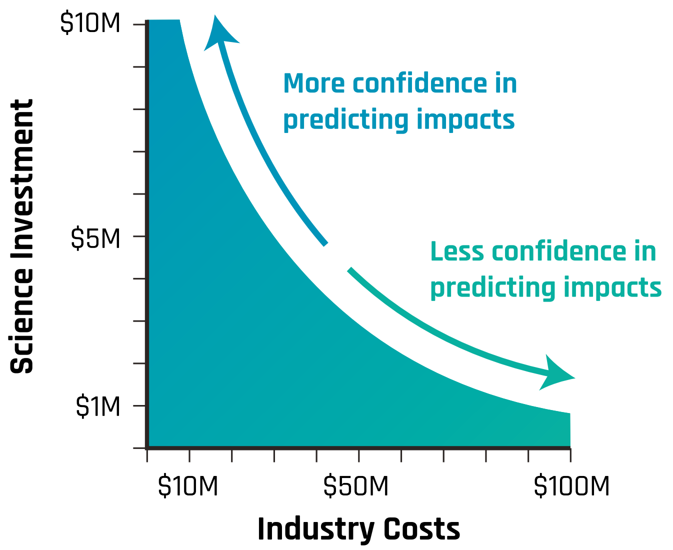
All reports resulting from the Dredging Science Node research program (Appendix I) are available for download from the WAMSI website (www.wamsi.org.au), all of the more than 50 peer reviewed scientific publications (Appendix 2) and five conference proceedings derived from the reports (Appendix 3) have been made publicly available as re-prints.

All raw and derived data (e.g. field-collected datasets, imagery, spatial information, model outputs) developed through projects by WAMSI and its partners have been made publicly available after an 18-month embargo period, and are discoverable through the Australian Ocean Data Network or AODN (https://portal.aodn.org.au).

Reducing Uncertainty – Towards Better Decision Making

Improved Understanding: Benefits to Industry, Regulators and Society

The environmental approval processes associated with several large-scale capital dredging programs in WA over the past two decades involved high-risk decision making within a context wherein facts were uncertain, values in dispute, stakes high and decisions urgent. It was within this context that choices had to be made, despite perhaps limited understanding of the potential environmental consequences on critical and sensitive environments.



The Conceptual Relationship between Knowledge and Regulation

Increased investment in research improves understanding leading to greater confidence in predictions of environmental impact. This in turn reduces the regulatory burden required to provide confidence to decision makers that the environment is being protected.

The end result was what is considered by some to be a highly risk-averse, potentially over-conservative approach to environmental approvals, with a significantly higher level of scrutiny, restrictions, conservative water quality thresholds and onerous (prescriptive) monitoring requirements.

The high level of scrutiny and the large regulatory burden served to improve the confidence (surety) that the outcome would be consistent with what was approved at the EIA level (i.e. that there would be no unexpected environmental effects or long-term damage).

The overall expectation of the Dredging Science Node research program is that it will reduce uncertainty, leading towards better (evidence-based) decision making around dredging programs and ultimately resulting in better environmental protection.

A stock-take of what we knew before and after the Dredging Science Node clearly demonstrates a greatly improved understanding of the potential environmental impacts of dredging in sensitive marine environments, in particular with regard to the cause-effect pathways and tolerance thresholds of sensitive environmental receptors, such as corals, seagrasses and sponges, as well as of their early life histories.

The next challenge is to embed our improved understanding into regulatory policies and decision-making processes to produce positive changes in impact prediction for future capital dredging proposals in WA.

It is the long-term goal and expectation of the Dredging Science Node program that the reduced uncertainty will result in better and faster decision making and more targeted, cost-effective, fit for purpose environmental monitoring and management programs for future dredging projects.

The potential benefits to regulators, industry and society are likely to flow on from the WAMSI Dredging Science Node research program in the coming years.

Potential Benefits From WAMSI DSN

For Regulators

The substantial amount of new scientific information will help to specifically target management efforts to adequately protect the most sensitive environmental receptors and processes from dredging-related stressors. The reduced uncertainty will provide greater confidence in impact predictions and a reduction in the likelihood of unexpected environmental effects, the potential for a streamlining of expectations and development of conditions that are more likely to be less onerous and less restrictive than the previous conservative conditions of approval;

For Industry

The increased (quantitative) understanding of the tolerance thresholds of sensitive habitats and species will provide an evidence base for proponents to better predict potential impacts and reduce the risk of non-compliance and unexpected outcomes. The wealth of uncontested scientific information can also be used to develop more effective and targeted approval conditions and monitoring and management programs;

For Society

The outcome of the Dredging Science Node research program will contribute to an increased confidence that decisions are being based responsibly, accountably, sensibly and most of all empirically on the best available scientific information and are not shaped by beliefs, perceptions and past experiences.

Impact of the Research – Beyond Academia

The Dredging Science Node research program has so far produced 54 scientific papers in international peer-reviewed journals with a combined total of 732 citations (see Google Scholar WAMSI DSN Page) and are cited approximately 97% more than average, after accounting for discipline, year and document types (Web of Science, 21 November 2018). 80% of all publications are in Web of Science Q1 journals. One publication is an ESI Highly cited paper and 30% of the publications are in the top 10% of the Web of Science publication database.

Communicating the Science

114 SCIENTISTS

26 INSTITUTIONS

>70 MEDIA MENTIONS

>60 PRESENTATIONS

WEB PROFILES
LINKEDIN
GOOGLE SCHOLAR

>50 OPEN ACCESS JOURNAL PUBLICATIONS

Delivering Added Value to Economy and Society

Not withstanding the fact that the WAMSI Dredging Science Node was a successful research program in an academic sense with an excellent outcome from a scientific/academic point of view, the merits of this research program extend way beyond the academic world.

Notwithstanding the fact that the WAMSI Dredging Science Node was a successful research program in an academic sense with an excellent outcome from a scientific/academic point of view, the merits of this research program extend way beyond the academic world.

The Dredging Science Node program was an excellent example of strategic and effective use of environmental offset funds and hundreds of millions of dollars' worth of environmental monitoring data, some of which would have otherwise been lost.

In a collaborative world-class marine research program, industry, government and research agencies gave context and purpose to, and transformed data into information used for enhancing the capacity within government and the private sector to predict and manage the environmental impacts of dredging in Western Australia.

The added value of the industry-science-regulator collaboration, effectuated through a joint co-leadership and management of the Dredging Science Node research program by a lead senior scientist from AIMS and a senior management representative from the DWER, has resulted in a strong science synergy within a common focus on practical application that has delivered fit for purpose results.

The program has produced a good return on investment with direct environmental and economic benefits to industry and society.

Research integration across partners has been stimulated by joint research investments in six PhD students (Appendix IV), and the shared use of world class research facilities, resulting in an overall outcome that was evidently more than the sum of the individual research reports and publications. The benefits and win-win spin-offs from the strengthened collaboration and newly formed partnerships are likely to extend well beyond the lifetime of this research program.

The program struck a balance between maintaining scientific rigour versus producing something practical for operational management. This required the application of a certain measure of expert judgment to interpret research findings and translate them into practical and implementable recommendations.

One of the benefits of the role of WAMSI as coordinator and facilitator of the research program has been its position as independent entity and knowledge broker between science institutes, government and industry. This has facilitated communication across sectors and between organisations, helped to preserve the scientific integrity of the independent researchers and avoid conflicts of interest, and prevented a situation whereby industry may be perceived to be influencing the research outputs and the research agenda and direction of independent research agencies.

Shaping Public Perception

Perhaps no other local, marine environmental issue has been subject to more public debate and controversy in Australia over the past decade than the potential environmental impacts of dredging associated with the large-scale construction and expansion projects in the mining, energy and port sectors. It is essential that the public perception in this – often politically sensitive – debate is informed by reliable, unbiased and scientifically sound data, factual information and relevant findings from monitoring and research.

WAMSI has contributed to this process by communicating and disseminating the outputs of its Dredging Science Node research to the public in:

- two WAMSI Research Conferences each attended by >200 participants: 30th March–1st April 2015 and 22nd–23rd November 2017, both at the State Library of Western Australia in Perth (the 60 presentations (with audio) are available from the WAMSI website),
- fully open access journal publications and conference proceedings,
- in newsletters and popular articles,
- and through web-based profiles on LinkedIn and Google Scholar and social media.

There has been significant interest from the media in the Dredging Science Node research findings, as demonstrated by over 73 media mentions to date (2015–2018). There have also been many interactive meetings between regulator and stakeholders on the progress and outcome of the Dredging Science Node research program. WAMSI has also been presenting the Dredging Science Node and its findings annually to the general public at the Perth Science Festival during Science Week since 2016, an event that has been attracting over 17,000 people over the two-day event each year.

Making decisions regarding dredging, especially in the vicinity of sensitive environments, is (and will always be) a highly sensitive and controversial issue, that involves striking a delicate balance between (local) economic interests and broader environmental concerns. The tremendous results achieved by the Dredging Science Node will no doubt inform the public debate and facilitate evidence-based decision-making regarding the environmental considerations for future dredging operations in WA and wider Australia.

Influencing Policy and Common Practice

The outcome of the Dredging Science Node research program is likely to influence future updates of the WA EPA's policy and regulatory approach towards new dredging proposals. This approach is guided by the EPA's Environmental Assessment Guideline for Marine Dredging Proposals and culminates in the environmental conditions of approval established under a Ministerial Statement.

Perhaps the most direct evidence of the impact of the WAMSI Dredging Science Node research is the early adoption of its key findings by other jurisdictions, such as in environmental impact assessment studies, dredging and dredged material disposal management plans and technical consultancy advice on dredging projects elsewhere in Australia and internationally.

This impact is likely to extend far beyond Western Australia, with its application already foreseen in Queensland's Great Barrier Reef, where uncertainty and an incomplete understanding of the potential impacts of dredging is currently causing conflicts.

Key findings from the Dredging Science Node program have also been incorporated in the newly published Maintenance Dredging Strategy for Great Barrier Reef World Heritage Area Ports by the Queensland Government, a dredging management plan for maintenance dredging in Darwin Harbour (INPEX), a series of Sustainable Sediment Management Studies underway at various ports in northern Queensland (commissioned by the North Queensland Bulk Ports Corporation), and in a forthcoming publication by PIANC on Best Practice Guidelines for Dredging and Port Construction near Coastal Plant Habitats, expected to be released mid-2019.

Internationally, known uptake of relevant findings of the Dredging Science Node is already happening in dredging programs in Monaco, South Africa, Kazakhstan and Saudi Arabia.

Economic Returns to Investment

The Dredging Science Node is a key example of the strategic use of environmental offsets. Pooling these funds into a single coordinated research program enabled work on the scale and depth necessary to make substantial inroads into key areas of uncertainty associated with marine dredging projects.

An independent expert economic cost-benefit analysis of three previous WAMSI research projects (on Western Rock Lobster industry-ecosystem interactions, wave impacts on offshore engineering structures, and research supporting management of Ningaloo Marine Park) clearly demonstrated several realised and forecasted economic benefits representing a very good return on the investment made in these WAMSI research programs.

A particular strength of WAMSI and this model of research administration is its capacity to attract partners to undertake focused, single-subject matter programs of collaborative, cross-disciplinary research with practical applications of immediate relevance to society. This type of research is essential for the effective and efficient management of – often very extensive – marine ecosystems subject to multiple uses in WA waters.

To further appreciate the potential economic benefits of the Dredging Science Node program, it is helpful to put the $9.5 million industry investment in the Dredging Science Node research into perspective against other costs associated with dredging operations in the State.

For example, any 'stop dredging' event during large-scale capital dredging programs in WA (e.g. during exceedances of water quality thresholds or coral spawning events) amounts to an average cost of several hundreds of thousands of dollars (up to $1 million) per day per dredging vessel spread.

Detailed geotechnical and bathymetric surveys that are routinely carried out at the start of any large-scale capital dredging programs, typically run into several millions of dollars per project.

Costs for environmental monitoring programs for some of WA's recent dredging programs were in the order of several tens of millions of dollars each ($100 million for the Gorgon project).

Total costs of recent large-scale capital dredging programs in northern Australia were in the order of several hundreds of millions of dollars per program.

Against those numbers, the $9.5 million industry investment for the Dredging Science Node appears relatively insignificant by comparison and yet has yielded a treasure trove of new insights and understanding of direct practical relevance to the environmental management of future dredging programs that is likely to generate long-lasting economic and environmental benefits to industry and society.

Data Sharing – Seizing Unprecedented Opportunities

Unlocking a Goldmine of Data from Past Dredging Projects

Over the last decade there have been a number of large-scale dredging projects in Western Australia. As part of the environmental approval of these projects, the dredging proponents collected considerable amounts of environmental monitoring data for two main purposes: to support the EIA and to support compliance monitoring of the environmental approval conditions (through implementation of dredge management plans).

Purpose for Data Collection

1. **To support the environmental impact assessment**
2. **To support compliance monitoring of the environmental approval conditions (through implementation of dredge management plans**

For the five most recent capital dredging projects in WA, some $250 million dollars was spent by industry on the collection of environmental monitoring data before, during and after dredging. These included data on both the physical environment (e.g. water quality and sediment deposition) as well as the biological environment (e.g. the health of the coral reefs, seagrass beds and other benthic habitats).

There was considered to be great value in learning from these successive dredging projects and applying that knowledge to future projects but, until recently, this has been hampered by the fact that the data were treated as 'commercial in confidence' and hence not available to other proponents and the scientific community.

A corporate commitment to share monitoring datasets can lead to accelerated learning and improvements in impact prediction methodology, greater certainty in decision making and a streamlining of approvals processes and monitoring requirements.

Since 2010, approval conditions in Western Australia require that proponents make environmental monitoring data publicly available. While that in itself is a major step forward, it still left two underlying issues. Firstly, there was no capacity within government to collate and analyse these data so the ability to value add to the existing knowledge base was limited. Secondly, there remained a large amount of valuable data collected pre-2010 that could be of enormous value.

A desktop exercise identified past, present and future (pending approval) dredging projects in tropical northwest Australia and evaluated the potential of any available monitoring datasets, ancillary studies and other relevant information[3].

From these, four large-scale capital dredging projects in the Pilbara region were identified, including the 'Pluto' project at Burrup Peninsula (Woodside), Cape Lambert A and B projects (Rio Tinto), the 'Gorgon' project at Barrow Island (Chevron), and the 'Wheatstone' project at Onslow (Chevron).

The respective proponent companies were approached individually to negotiate access to these data. These negotiations were complex, requiring considerable time and effort, with multiple levels of approval within each company, partly due to fear of potential legal implications (i.e. the potential for post-project discovery of non-compliance issues and associated issues of liability and indemnity), but all companies eventually agreed. Data sharing agreements were developed between WAMSI and the respective companies to govern the use of the datasets for relevant research activities.

This constituted an unprecedented breakthrough, as environmental monitoring data of this detail and scale had never been made publicly available before in Western Australia. Access to these valuable monitoring datasets enabled the scientists to turn data into information for use in many different individual projects and themes, and provided an immense source of detailed information that would feed into improving the ability to predict and manage the effects of dredging.

Benefits of Data Sharing

The sharing of monitoring data by industry with scientists enabled the re-use of existing data and extract information to be re-analysed in different ways to improve our understanding of pressure-response relationships associated with dredging.

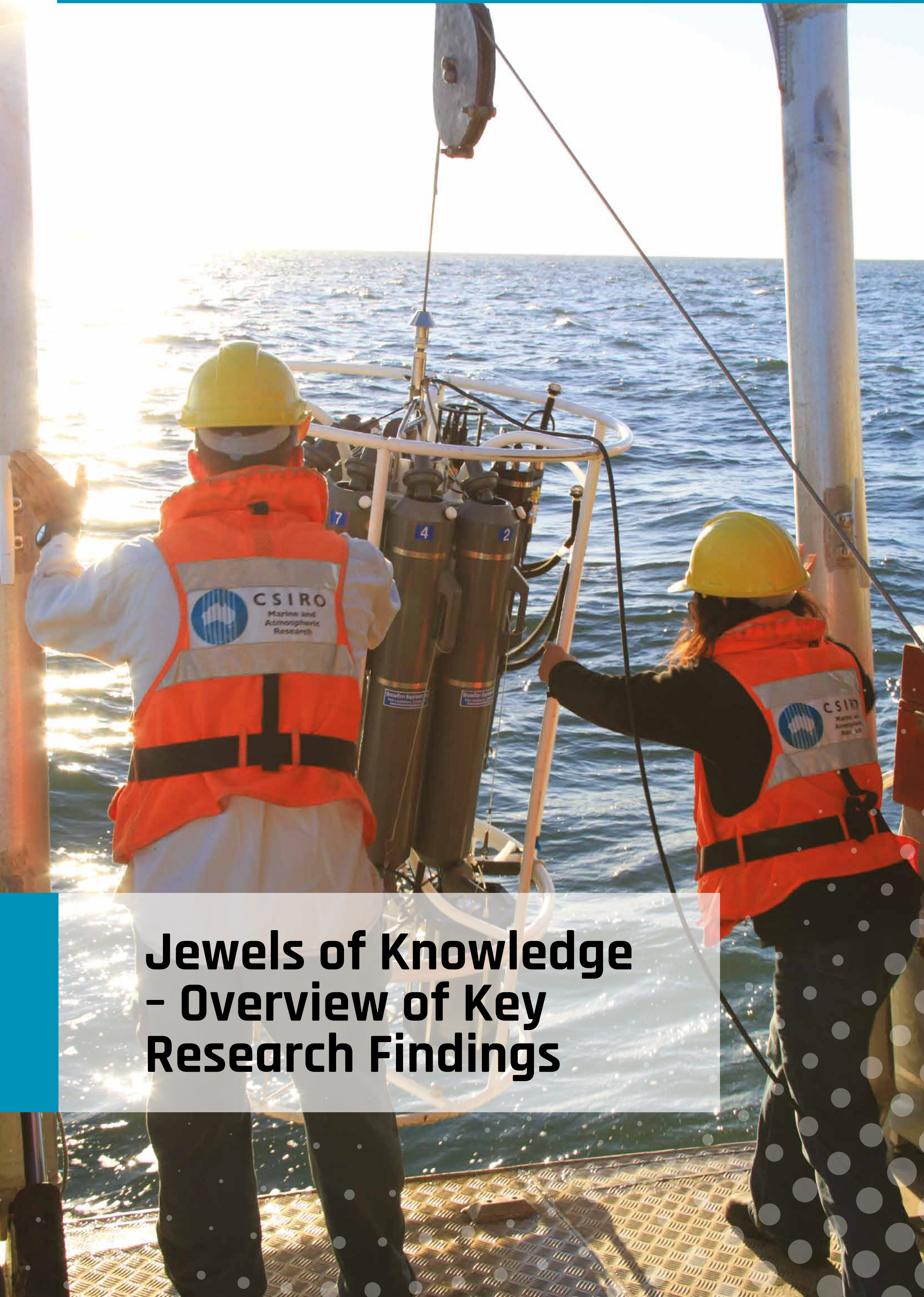
Without the WAMSI-brokered data sharing agreement, these datasets might never have been used for anything else, kept under lock of confidentiality and eventually would likely have been lost. This offered a golden opportunity for scientists to have access to a wealth of field data they would have never been able to collect on such a scale by themselves in individual research projects.

Through the Dredging Science Node research program, the data sharing enabled these previous dredging projects to contribute to an increase in knowledge and understanding for application in future dredging projects.

The improved access and availability of industry should serve to avoid duplication of data gathering through coordination across member organisations and industry partnerships, optimisation of application of marine science data (Australia-wide), enhance transparency, improve public trust, influence public perception and support evidence-based decision making.

The WAMSI Dredging Science Node has clearly demonstrated far-reaching benefits from the sharing of industry data with scientists, which supports its adoption in regulatory policy as a new standard practice.

Initial fears within industry of the potential risk of misuse of the data by opponents or competitors, or potential for post-dredging discovery of evidence of non-compliance have been proven to be unfounded. All data acquired from industry have now been stored centrally on the Pawsey database system. Access is governed through WAMSI under conditions of the data sharing agreements.



Jewels of Knowledge – Overview of Key Research Findings

Analysis of Industry Data

Learning from environmental data collected during past dredging projects

A huge set of detailed water quality and biological monitoring data from the four major capital dredging projects were analysed, offering a unique opportunity to look back and see what organisms are exposed to during those dredging operations and to inform realistic conditions for use in experimental studies[3].

Water Quality Data

Water quality data made available from the projects comprised a total of 8.5 million individual readings of water column turbidity and benthic light, collected over a combined total of 85,433 days of observation from 111 sites[3].

These data included measurements made at locations that varied from a few hundred metres away from the dredging (heavily influenced by plumes) to more distant reference sites located tens of kilometres away (unlikely to be influenced by plumes)[3].

In some cases, the datasets included extended baseline pre-dredging periods, allowing detailed study to better understand how the intensity, duration and frequency of turbidity events caused by dredging differ from natural turbidity events associated with river plumes, storms and cyclones.

Supplementary studies provided information on sediment particle size distribution in the water column, changes in light quality and quantity underneath plumes, and changes in seabed composition before and after dredging.

Additional data included daily dredging logs from the two-year Wheatstone project near Onslow, specifying day-to-day activities of dredging equipment and progress of dredging and placement[11].

Biological Data

Biological data included information on the abundance, health and distribution of corals, seagrasses and filter feeders before, during and after the dredging at multiple different locations at various distances from the dredging (including reference sites[3]).

The biological data also comprised a remarkable 'tagged coral' monitoring program dataset from the Gorgon project at Barrow Island. This was the largest tagged coral study of its kind anywhere in the world to date, with 50–70 representative coral colonies at 26 monitoring sites photographed every two weeks for the duration of the two year dredging project, resulting in some 17,700 photographic images available for analysis.

Other biological studies included assessments of the reproductive status of different coral species to identify peak spawning windows to temporarily suspend (or relocate) dredging activities during that period.

The information derived from these data was highly significant as it showed just what corals, seagrasses and filter feeders experience *in situ* during natural and dredging-associated turbidity events.

Analysis of temporal patterns showed high variability both during dredging and natural resuspension events, highlighting the need to use appropriate metrics and time scales in manipulative experimental studies and when establishing thresholds and triggers for impact prediction and management of dredging operations[9].

Changes in spectral quality of the light under the plumes were also identified in the data, which is significant as not all wavelengths are of equal value for photosynthesis[12].

Turbid plumes changed underwater light to less photosynthetically useful yellow and green wavelengths. For corals the implications of this loss of light quality is currently under investigation in studies that directly stemmed from this discovery.

Analysis of spatial patterns showed a marked improvement of water quality with increasing distance from the dredging activity[13]. Although intuitive, this provided evidence supporting the use of spatially-based zonation schemes to manage dredging projects, as introduced by the EPA in Western Australia (and now also adopted elsewhere in Australia).

Perhaps the most significant outcome from the analysis of the industry-supplied data was that it enabled the research team to identify and describe the actual pressure fields in terms of turbidity, underwater light and sediment deposition dynamics as it happened during real (large-scale) dredging programs over multiple temporal scales and at different distances from dredging.

This effectively defined the 'hazard' associated with dredging activities and was critically important for contextualising the results of past studies[12, 14]. This was then used to develop environmentally relevant and realistic exposure scenarios and regimes for the laboratory-based studies to examine the physiological response of corals[15], sponges[16] and seagrasses [17, 18, 19, 20] and hence assess the 'risk' of that hazard to affect them.

The industry-supplied data also enabled the development of a detailed hind-cast model for the entire Wheatstone dredging project, further enhancing the predictive capability to reliably characterise the pressure fields associated with dredging[11].

The industry-supplied environmental data were critical to providing genuine insight into things that would not have been possible without these data (e.g. plume characterisation). It enabled things that otherwise would not have happened (e.g. hind-cast modelling), extended observations vastly beyond ongoing efforts (field research), and led to insights into things that needed to be done (design of lab experiments).

Feeding into the design and execution of experiments

The synergy in approach between the different themes, how the research work was structured around the central topic of dredging science, clearly benefitted the consistency in outcome, effectiveness and relevance of this research program.

All themes started with a review of the available data and literature, which helped to fine-tune and focus on the most critical research priorities and inform subsequent experiments with realistic exposure scenarios, timeframes, species and sediment types that are relevant to dredging operations in northwest WA.

The findings of all individual research activities were subsequently interpreted and translated with reference to the practical reality of the management of dredging operations through frequent interactions between the lead scientists, the regulator and industry representatives. These aspects together constituted a unique and unprecedented approach to ensure relevance of science to management and regulation, and hence to the benefit of the WA community.

Characterising and Predicting the Pressure Field

Understanding and estimating the generation and release of sediments

When soil and rock material is disturbed by marine dredging activities some of it is released as particles into the water column and transported away from the source by currents, giving rise to plumes of fine suspended sediment. The estimation or model prediction of dredge-related turbidity plumes has been challenging and a significant cause of uncertainty in the context of environmental impact assessment, particularly for large capital dredging projects at locations with little or no previous dredging history.

Due to the high costs and logistical complexity of conducting preliminary dredging trials and extensive geotechnical surveys prior to approvals, information available during the environmental impact assessment phase is typically incomplete. This often leads to the use of untested assumptions about dredging equipment and methodology, 'typical' composition of dredged material, local conditions, substrate characteristics and their interaction to estimate likely source term values.

There is a lack of consistency in the approaches to estimate source terms, often incomplete or unclear estimates of overflow (arguably the greatest contributor to far-field plumes) as a source of fines, and no common approach for estimating source rates for propeller wash[21, 22].

The Dredging Science Node produced two cutting-edge reviews of available literature and monitoring reports on the process of sediment particle generation and release by different types of dredgers, and approaches to estimating dredge source terms.

Both reviews[21, 22] have proven instrumental in improving our understanding and ability to quantify and predict the (near-field) suspended sediment source rates and characteristics for input into sediment transport models that simulate the extent, intensity and duration of (far-field) dredge plumes.

Dredge plumes generated by trailing suction hopper dredgers, particularly through the hopper overflow, are relatively well studied. Laboratory, field and numerical modelling investigations have shown that sediment concentration and particle size distribution in the plume produced by overflow depends primarily on the sediment production rate, sediment concentration and particle-size characteristics of the inputs to the hopper, dimensions of the hopper, and the configuration and control of the loading and overflow systems.

There is reasonable understanding on turbidity generation by cutter suction dredgers, but there is need for more field data to derive empirical resuspension factor values for large cutter heads[21].

There is still a general lack of data and limited understanding of propeller-induced turbidity (especially relevant in areas with limited under-keel clearance), natural resuspension of seabed sediments, release of fines from disposal areas (and associated timescales), and their contribution to far-field plume generation. Consolidation of dredged material after placement is also poorly understood.

Predicting and measuring dredge plume dynamics and fate

Remote sensing information from satellite imagery can be used to provide data on suspended sediment patterns and dynamics over large areas and in near-real time, assist in tracking of dredging plumes and provide evidence of resuspension due to storms and cyclones[23].

A cutting edge review of optical remote sensing for dredge plume modelling was produced that included a theoretical background introduction into water optics (how to interpret water quality from visual observations from space) and an overview of all relevant remote sensing products and algorithms[23].

Mathematical algorithms are designed to convert spectral data into suspended sediment concentrations and may be 'tuned' to the local conditions for improved accuracy.

There was no understanding of the expected accuracy of the more than 70 published MODIS and Landsat total suspended solids (TSS) algorithms if they were to be applied in northwest Australian waters of unknown optical characteristics.

A combination of field measurements and tank-based tests were used to measure relevant optical and physical parameters required for algorithm development and tuning[24].

As a key outcome from this work, we now have a reliable TSS algorithm, exhaustively tested against field measurements, for the interpretation of remote sensing imagery from northwest Australian waters (suited for both turbid inshore and offshore marine waters)[24].

Field work undertaken in the Pilbara region during the Wheatstone dredging campaign provided valuable information on dredge plume characteristics, established relationships between turbidity and TSS. It also examined the 3D structure of dredging plumes in shallow waters and provided estimates of the in situ settling velocity[11].

Historical data were used to identify anomalous TSS events linked to storms, enhanced river outflow and resuspension at dredge material disposal grounds[23].

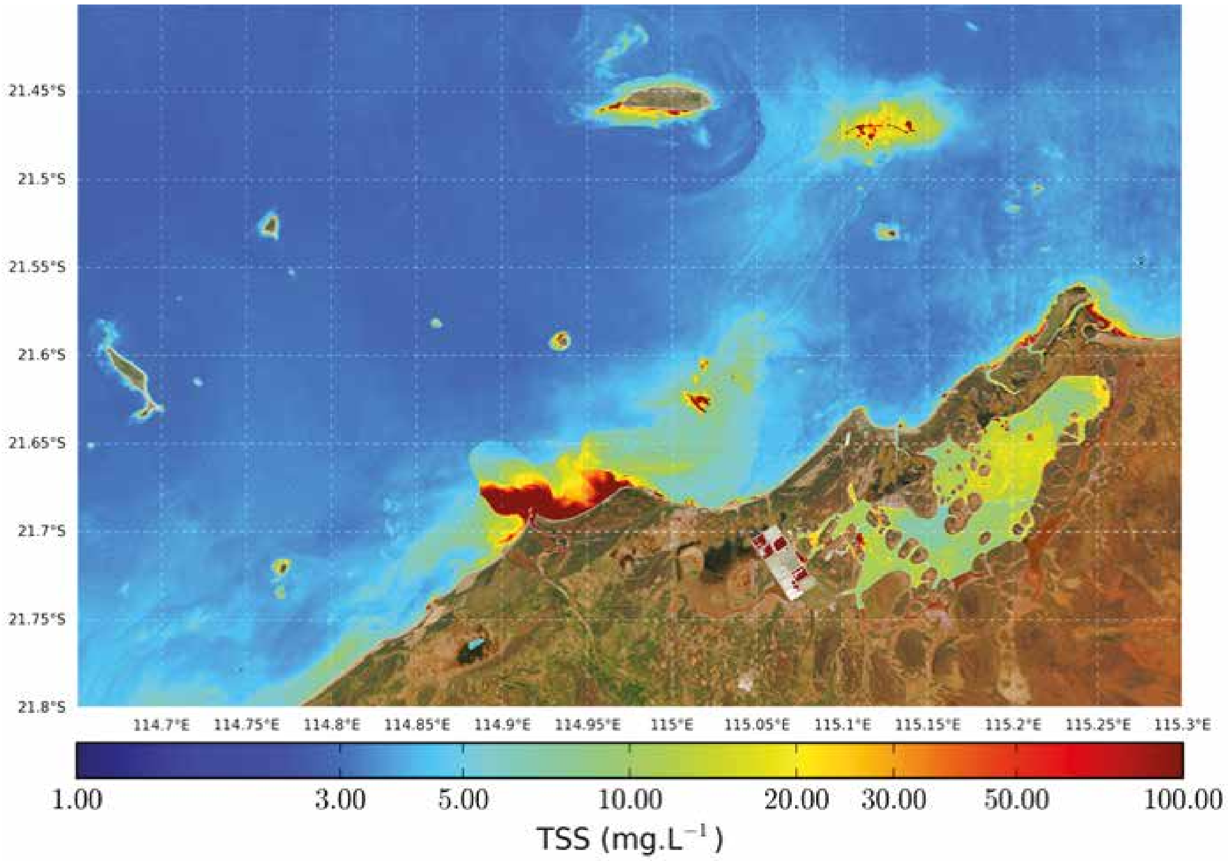
The validity of a recently published empirical source term model approach was tested for over 22,000 separate dredge plumes across eight different operational modes used during the Wheatstone dredging campaign[11].

Experimental work in the laboratory and field on sediment transport across canopies of seagrass vegetation and coral reefs demonstrated and quantified how such canopies reduce flow velocity and resuspension, resulting in significantly lower TSS concentrations and higher deposition (especially of heavier sediment fractions) within such areas[25]. Further study is required to apply this to fine (cohesive) sediments for practical application in models for the improved prediction of dispersal and impact of dredge plumes[25].

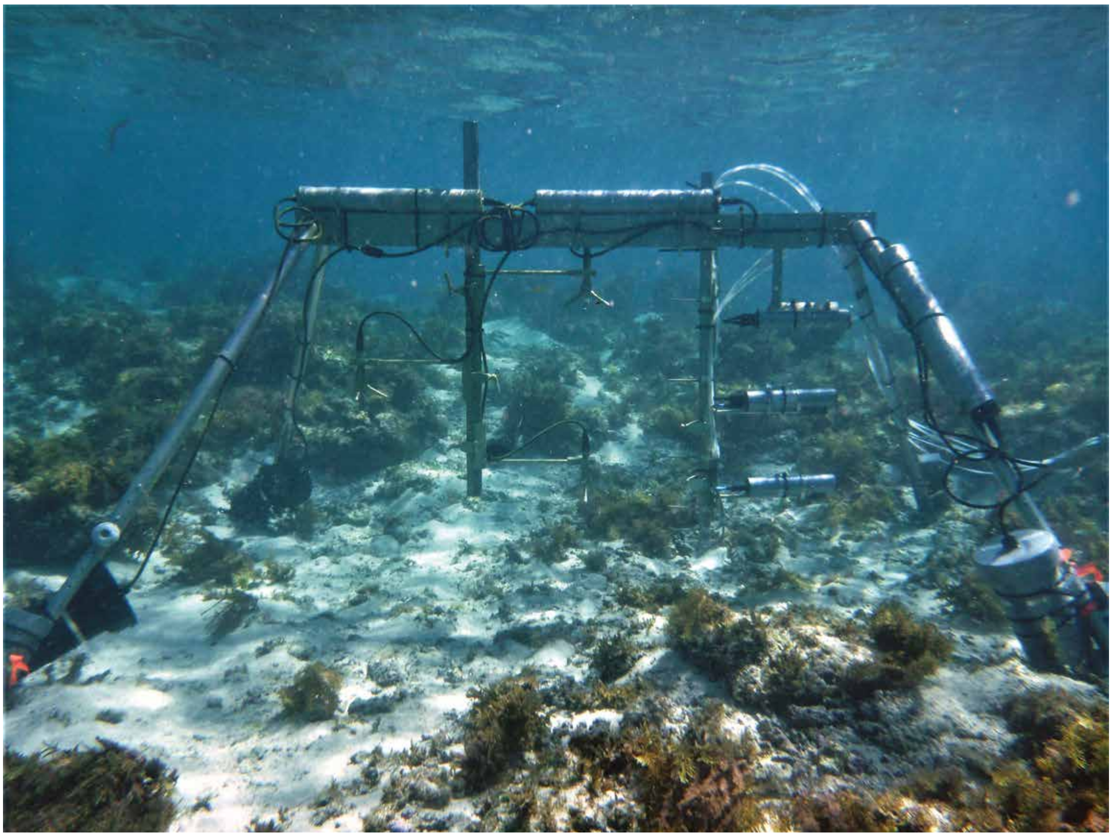
A hydrodynamic and sediment modelling study enabled researchers to conduct hind-cast modelling of the dredging plumes associated with a large-scale dredging project in the Pilbara (Wheatstone), with the benefit of access to all the collected field data to calibrate and validate the model predictions[11].

This hind-cast modelling, a rare and unique opportunity, offered insight into which of the modelling processes and parameters are most important, difficult to assess or interdependent.

Modelling of ambient (natural) background TSS dynamics (calibrated and validated against field measurements) enables proponents to better establish the magnitude of the dredging impact relative to that of natural processes, especially in naturally high TSS environments. It also allows for direct comparison between model output and monitoring data.



Satellite image of the Wheatstone dredging project in the Pilbara region of northwest Australia on 23 May 2014 from a Landsat 8 derived TSS map. The images show the dredge material placement site located east of Thevenard Island, dredging of a channel and flooding of the Ashburton River. The TSS maps are derived using a generic set of algorithms thus the TSS values are indicative only [23].



WAMSI DSN Theme 3.3

An instrument platform on the reef at Ningaloo measuring water flow at different depths. The project was associated developing new transport formulations to better predict how sediment moves over complex surfaces such as reefs.

For reliable background TSS predictions, it is necessary to collect baseline data on seabed sediment composition. Modelling of dredging plumes should preferably be done in 3D, as the vertical distribution of TSS is often highly variable, which can affect predictions of benthic light availability[11].

The hind-cast model was also used to improve the estimation of source terms and calculate ecologically relevant pressure fields.

The results of this testing demonstrated that the empirical model is a reasonable approach to the estimation of (temporarily and spatially variable) source terms, though it is sensitive to the duration of the dredging and placement phases of the dredging cycle and was less reliable in shallow nearshore areas[11]. Propeller wash can also produce considerable resuspension but is often neglected as a source term in modelling studies.

One of the key points emphasised in the Dredging Science Node was the significance of sediment deposition leading to smothering on adult and juvenile corals and hence defining zones of high impact[13, 26, 27, 12].

Spatial and temporal patterns in water quality and deposition during recent dredging projects

Analysis of spatial and temporal patterns in one of the world's largest available water quality datasets from four previous large-scale dredging projects in northwest Australia revealed that during dredging – within 500 m from the dredger – suspended sediment concentrations could reach >100 mg L^{-1} over several hours. In less turbid conditions (tens of mg L^{-1}) suspended sediment concentrations could persist over several days, but over longer periods (weeks to months) were <10 mg L^{-1} on average[13].

During turbidity events, corals sometimes experienced very low light or 'twilight' periods near the dredging for weeks.

Tides, weather conditions (sea breezes), seasonality and distance from dredging all affected spatial patterns in the observed water quality data.

It is essential that baseline datasets capture as much of the natural variability in water quality as possible before the start of dredging[13].

Dredging creates high suspended sediment concentrations in a low energy water column where the ambient hydrodynamics are insufficient to keep the sediment load in suspension. The sediments then settle out and deposition rates could exceed those during natural resuspension events and which nearby organisms are physiologically adapted to[12].

Images of coral taken during the capital dredging projects frequently showed smothering of corals by sediment.

From the time sequence of images it was also noted that if the sediments were not removed by resuspension or self-cleaning, then the underlying tissues eventually died[26].

Coral morphology was highly influential in terms of the smothering susceptibility with branching species showing no smothering even very close to the dredging activity, but encrusting and hemispherical (boulder like) corals very susceptible with sediments pooling in hollows on the surface[26].

The problem is there are no instruments capable of routinely measuring actual sediment deposition at the required scales (mg cm^{2} day^{-1})[12].

In the absence of suitable instrumentation, sediment deposition has frequently been estimated using sediment traps which are small cylindrical tubes that collect settling sediment.

There are many known problems associated with these devices. They suffer from resuspension limitation and deposition bias, and can grossly overestimate sediment deposition, particularly in energetic environments which are characteristic of most reefs[27].

To try to estimate deposition fields around dredging, a simple statistical turbidity model was tested to estimate sediment deposition (through 'reverse' modelling, also termed 'overburden' modelling), but this approach was not found to be useful in some circumstances, as it relies on sufficient turbidity events during the baseline period to allow training of the model[28].

Development of a 'new' sensor to monitor sediment deposition in reef environments

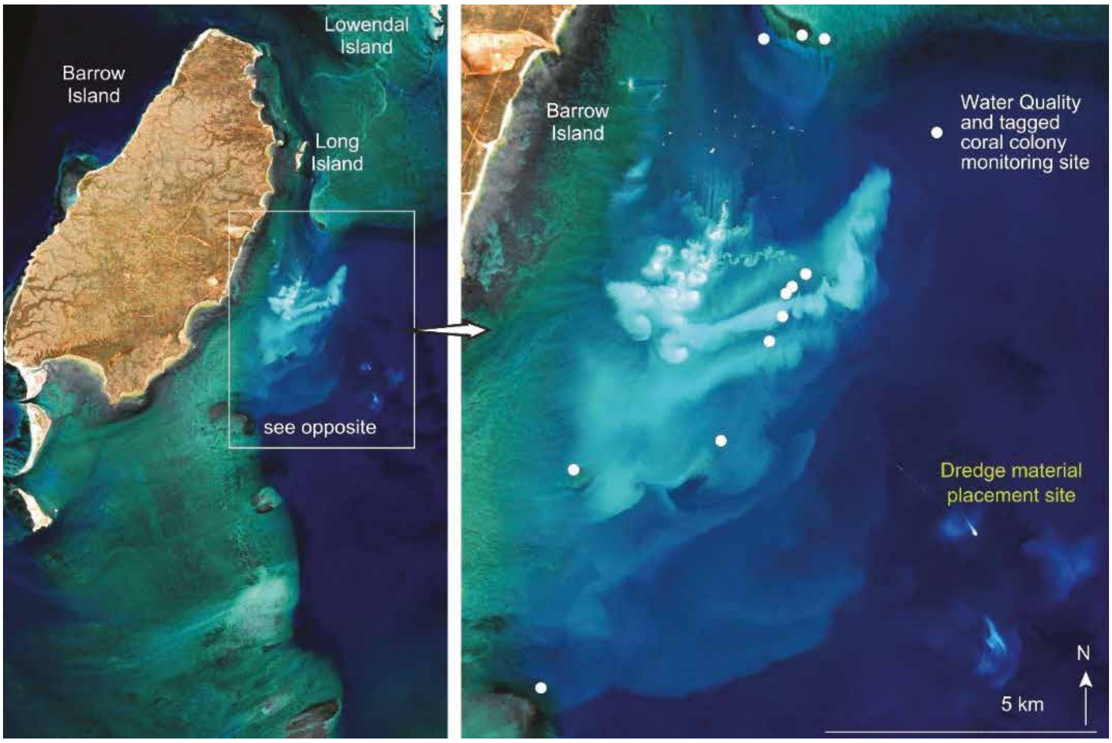
In a more successful attempt, an earlier version of a (low-cost) sediment 'deposition sensor' for use in coral reef environments was re-designed to increase the number of measurement points and increase its surface complexity so that it more closely resembles a coral surface[27].

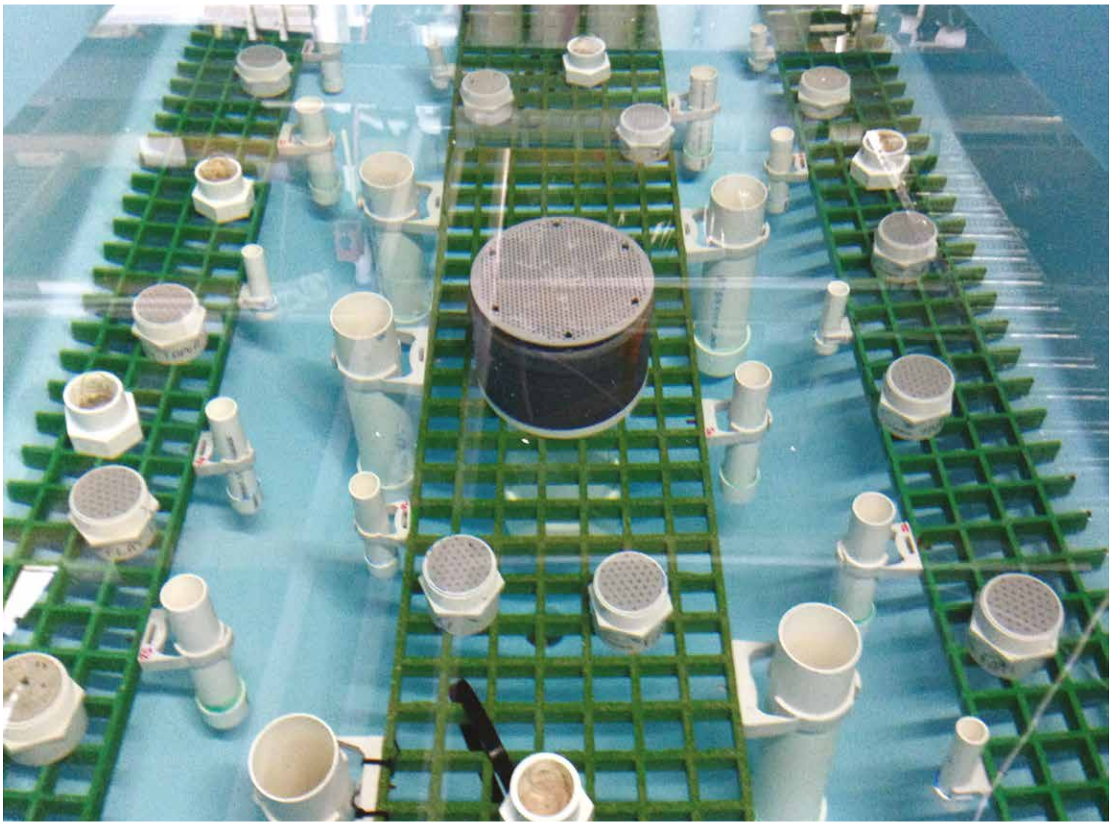
The new sensor was calibrated and tested in the lab and then deployed alongside sediment traps in the turbid nearshore Great Barrier Reef.

The lab-based trials demonstrated that conventional sediment traps overestimate sediment deposition by up to ten times (depending on the flow and wind conditions) confirming other reports that some of the trap-based sedimentation may simply be an artefact of the trapping process.

Field deployment of the sensor provided some of the first measurements of deposition rates on reefs over appropriate scale[27].

The new, affordable deposition sensor needs site-specific calibration (as with nephelometers) and is being further tested and used to monitor sediment deposition in dredging projects in the Great Barrier Reef region.





Top:

WAMSI DSN Theme 1

Satellite image of a dredging plume at Barrow Island, from the Japan Aerospace Exploration Agency (JAXA) Advanced Land Observing Satellite (ALOS) taken on 29/08/2010.

Bottom:

WAMSI DSN Theme 4.4

A sediment deposition sensor (centre of the image) being tested against sediment traps and SedPods in a 1500L tank at the Australian Institute of Marine Science (AIMS) Sea Simulator (SeaSim)

Predicting the Ecological Response

Defining thresholds and indicators of coral response to dredging-related pressures

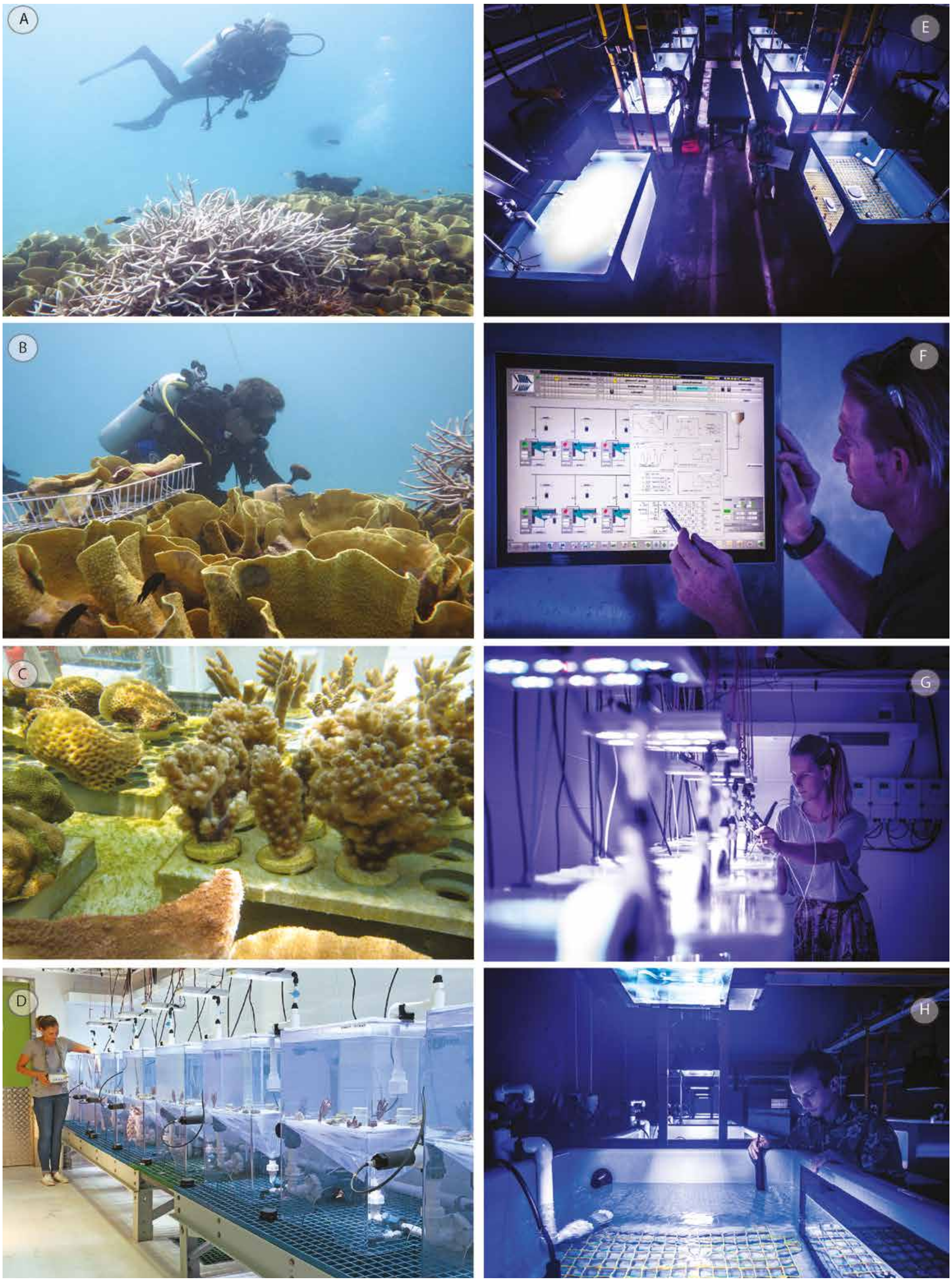
Corals can be impacted by dredging operations through three primary cause-effect pathways: light reduction, increased suspended sediment concentrations, and sediment deposition (smothering)[12].

These pressures can act either alone or in combination, which can obscure or confound attempts to relate the various pressures to the biological responses and to define exposure conditions above which effects could occur (i.e. derive guideline values).

A comprehensive literature review of research papers was conducted and it was noted that there was a large disconnect between conditions used in laboratory based experimental studies and the conditions measured *in situ* during dredging.

The studies indicate sediments are a risk to corals but cannot be used to adequately assess the hazard and reliably define zones of high impact[12].

The literature review and monitoring observations from previous dredging operations were used to guide a set of laboratory based, manipulative studies designed to explore the three primary cause-effect pathways on corals[15].



WAMSI DSN Theme 4 Final Report

Field collection of corals and subsequent laboratory based experiments in the National Sea Simulator (SeaSim, Australian Institute of Marine Science (AIMS) Townsville).

Manipulative experiments were conducted in aquaria at the AIMS National Sea Simulator (SeaSim, Townsville, Queensland), a world-class marine research aquarium facility for tropical marine organisms in which scientists can conduct cutting-edge research not previously possible in Australia.

WA boasts a total of 361 species of hard corals, of which 240 species occur in the inshore/offshore Pilbara region (65% of which also occur in the Great Barrier Reef)[29]. Eight of these species, representing common and widely distributed species with varying morphologies (branching, encrusting, foliose, massive etc.) and sediment rejection strategies/adaptations, were selected for the experiments[29].

Experiments on the effects of elevated SSC revealed no negative impacts on any of the corals at any sediment concentrations, as long as light levels were still sufficient and no sediments had settled on and smothered the corals)[15].

The implications are that it is the light attenuation properties of the suspended sediment that is more important to corals than the concentration of suspended sediment particles for predicting impacts.

Experiments on the chronic effects of long-term low light exposure revealed that the crustose coralline algae – which are important for settlement of new coral recruits – were more sensitive to low light conditions than adult/juvenile corals[15].

Overall, corals could adapt to a 3-fold decrease in light levels, and a combination of 10 mg L^{-1} and 2.3 mol photons m^{-2} day^{-1} over a 42-day period was tolerated by most corals.

No impacts of low light are expected if total benthic light availability is >4 mol photons $m^{-2}d^{-1}$.

In the absence of sedimentation, if daily light levels are maintained at >2.2 mol photons $m^{-2}d^{-1}$ and SSCs remain below 10 mg L^{-1}, there may only be sub-lethal effects without mortality[15].

Experiments on the effects of sediment deposition confirmed field observations[26] that branching corals are very capable of self-cleaning relative to foliose and massive corals[15].

Sediment smothering resulted in partial bleaching and tissue mortality (lesion formation), but if sediments were removed (by currents) bleached areas regained pigmentation over weeks and there was rapid regrowth/reparation of lesions.

Smothering was never observed on branching species, even under extreme levels of sedimentation.

There was no significant difference in sediment rejection ability of corals between fine silt and coarse silt at deposition rates of <20 mg cm^{-2} day^{-1}.

Under a slight flow of <3 m s^{-1} corals were capable of removing all sediment up to 20 mg cm^{-2} day^{-1} (all species tested), up to 40 mg cm^{-2} day^{-1} (massive corals) and up to 235 mg cm^{-2} day^{-1} (branching corals).

Once corals were smothered, bleaching occurred within 4 days, but there was no colony mortality even after 6 weeks[15].

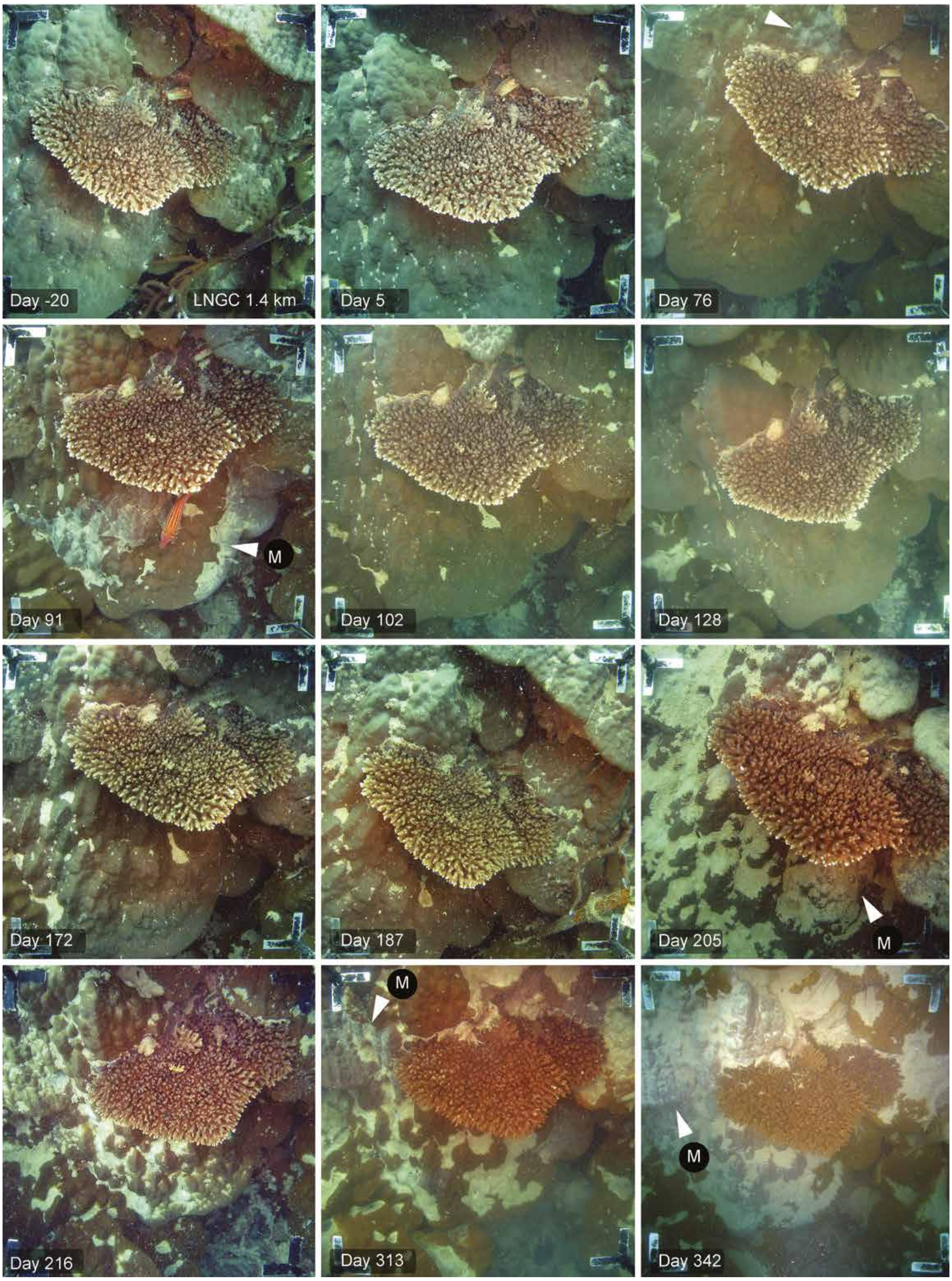
Evaluation of observations of water quality and coral health in the Pilbara region during previous dredging programs revealed that low to moderate reductions in available light caused by suspended sediment reduced the incidence of coral bleaching, consequently reducing coral mortality especially for branching corals.

This was however not true when sediment loads were high and increased mortality due to severe low light periods outweighed the reduced mortality from bleaching[26].

Experiments on the interaction between sedimentation and bleaching revealed that bleached corals are less capable of removing sediment from their surfaces, resulting in a 3–4 fold sediment accumulation compared to non-bleached corals.

Repeated deposition resulted in a three–fold increase in remaining sediments regardless of bleaching status, indicating reduction in self-cleaning abilities with time[26].

This confirmed the need to monitor water temperature during dredging programs to take into consideration marine heat waves, which – as part of a multiple lines of evidence



WAMSI DSN Project 4.9

Time series of images collected during a large scale capital dredging project, showing the distance from dredging activities (km) and days from the start of dredging. The images show the superior sediment clearing abilities of branching (tabulate) morphology of the tabulate *Acropora* species compared to underlying massive, hemispherical morphology of the *Porites* spp which becomes smothered with fine sediments.

approach – may assist in evaluating whether some observed coral impacts are attributable to (or have been exacerbated by) causes other than dredging.

A demographic study of over 730 coral colonies near the port of Dampier revealed that fast-growing branching corals (e.g. *Acropora*) have the capacity for the most rapid recovery from disturbances, while massive Porites colonies showed a much slower recovery[30].

Acropora millepora was the most affected by recruitment failure (causing uncertainty in their recovery projections following severe disturbance).

Recovery within five years (based on confidence intervals) was only likely when impacts on live coral cover of *Acropora* and *Turbinaria* were <15%. Predicted recovery periods (based on average cover) were otherwise in the order of 14 to 18 years.

When impacts are severe, Acropora and Turbinaria corals are unlikely to recover even after 20 years[30].

Some 17,700 photographic images of tagged coral colonies taken during the 530 day capital dredging (Gorgon) project at Barrow Island were used as part of a 'forensic' investigation of cause-effect pathways and the susceptibility of different coral growth forms and to assess the likely cause of any partial or whole colony mortality.

Patterns of mortality were examined at different distances from the dredging activities (200 m to 30 km away) and also the water quality analyses (light and suspended sediment concentrations)[26].

The study revealed the significance of sediment deposition as a primary cause-effect pathway associated with mortality with some (encrusting, massive and foliose) coral morphologies and the comparative resilience of other (branching) corals. Light reduction was found to be more associated with mortality in branching (*Acropora*) coral colonies[26].

When the field measurements of the pressure fields for the well-studied Barrow Island project were combined with *in situ* observations of the health of the corals an interesting picture emerged.

Effects of the dredging on SSCs and reductions in light had largely dissipated by 20 km away from the dredging. Smothering of corals by sediment had largely dissipated by 3 km (or <1 km for heavy smothering)[26].

The analyses of the field data also showed a distinct association between the production of (multiple) thick sheets of mucus by massive *Porites* coral colonies and proximity to dredging activities, observations of which increased tenfold during dredging compared to baseline[31].

This observation was confirmed in laboratory-based manipulative experiments under aquarium conditions where exposure to sediments induced mucus sheet formation.

These results suggest the development of mucus sheet formation (easily quantifiable in % of surface and % of colonies) is a potential early warning indicator of stress caused by sediment exposure for massive *Porites* coral colonies[31].

The laboratory-based experiments and field-based measurements and observations provided a consistent, coherent story and simplified the identification of the cause-effect pathways.

The overall conclusion for corals from the field observations and the experimental studies, was that it is light attenuation and sediment deposition leading to smothering that are the key cause effects pathways that define zones of high impact (mortality).

Susceptibility is very much driven by colony morphology, with flatter encrusting corals and corals with surface indents (hollows where sediments can accumulate) being susceptible to sedimentation.

In branching species, which can easily remove sediments, it is likely to be light attenuation that is the key cause-effect pathway.

Impacts from turbidity and light were found to be best assessed over 14-day time periods (running means), whereas longer times scales (e.g. 60 days) were better for predicting, assessing and evaluating the chronic effects from deposition[26].

Defining thresholds and indicators of the response of seagrasses to dredging-related pressures

Seagrasses are primarily impacted by dredging operations by a reduction in daily light availability (through light attenuation by suspended sediment).

Three of the eleven seagrass species that are dominant in the northwest of WA were identified as high priority for research and selected for the experimental studies: two colonising species (*Halophila ovalis, Halodule uninervis*) and one persistent species (*Cymodocea serrulata*)[32].

As different seagrass species have different life history strategies and potentials to resist and recover from disturbance, the magnitude, duration and frequency of stress they can cope with and recover from will vary among species[33].

Diver-operated still camera photographs taken within one metre of the sea bed proved to be the most effective means of detecting and surveying seagrass during pre-development surveys. Due to considerable turbidity in large areas of the Pilbara, satellite or airborne remote sensing methods as well as remotely deployed video or still camera methods are considered less suitable for detecting seagrass in this region[34].

There has been a view, presented in many of the environmental impact assessment documents on developments in the north-west of WA, that many of the seagrass meadows in this region are highly transitory and so probably have mechanisms (most likely seed banks) to aid recovery[35].

This has led to the view that they would likely recover rapidly from dredging impacts and need not be considered within impact assessments.

The lack of measurements and field data to support (or reject) these perceptions were the main focus of the field-based seagrass research within the Dredging Science Node[33, 34].

Field sampling found very low numbers of viable seeds in the sediments, suggesting that seed banks may play a less significant role than previously thought, with recovery relying more on vegetative propagation[33, 34].

A detailed genetic study of *Halophila ovalis* revealed that there are high levels of connectivity among sites within 2–5 km and low to moderate levels of connectivity over larger distances[36].

Seagrass populations in northwest WA indeed appear to be opportunistic and resilient to environmental perturbations, which occur regularly in this region (especially storms and cyclones).

The species composition and temporal patterns of abundance and distribution of seagrasses in northwest Australia are highly dynamic and highly variable, often seasonal, dying off over certain periods of the year and subsequently re-establishing[34].

These unpredictable temporal dynamics pose a challenge to the choice of timing for pre-development baseline surveys.

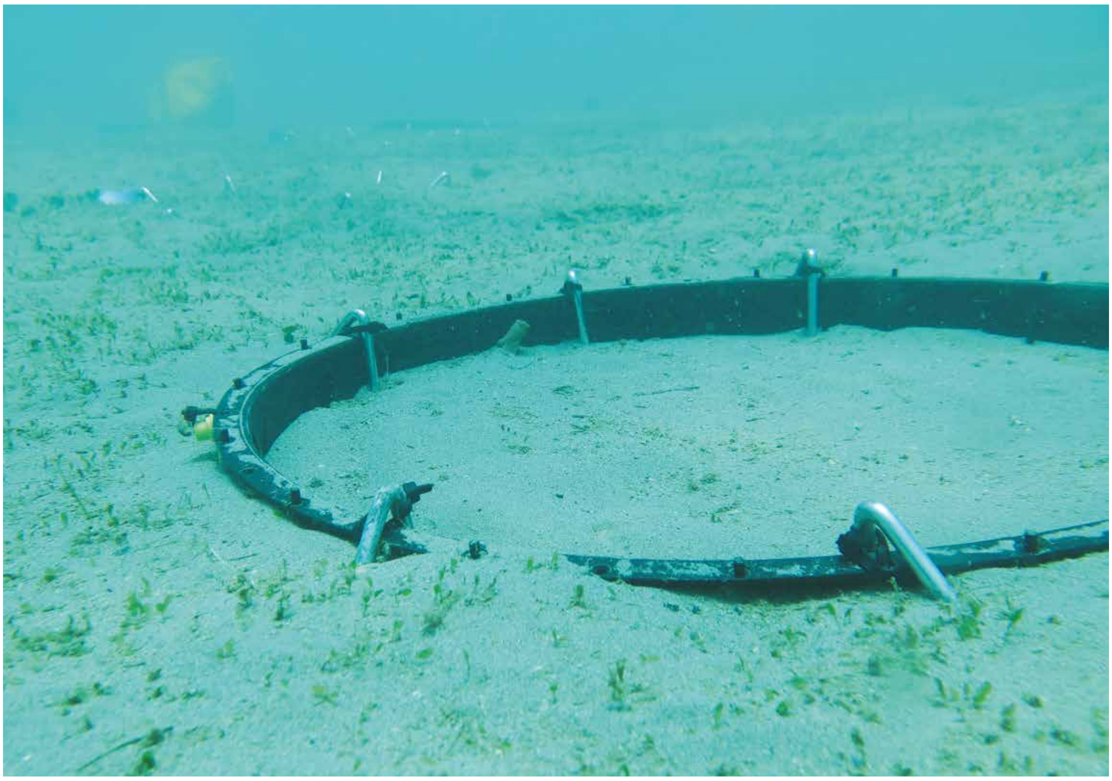
Field experiments to determine the mechanisms and rates of seagrass recovery following disturbances revealed that it takes 2–3 months for small (0.5 m^2) cleared patches in seagrass meadows to fully recover through vegetative growth[33].

Field surveys provided a set of baseline light data that characterise sites supporting seagrass assemblages[34].

Total daily light availability at a site known to support seagrass for most of the year ranged from about 3 to 11 mol photons $m^{-2}d^{-1}$.

Light reduction experiments revealed a significant decrease in biomass of *Cymodocea serrulata* after 9 weeks at light intensities <2.3 mol photons $m^{-2}d^{-1}$.

Halodule uninervis, with its faster growth rate and smaller carbohydrate storage, was more sensitive to low light than the slower-growing *C. serrulata*[17].



Top:

WAMSI DSN Project 5.3

A seagrass (*Halophila ovalis*) meadow at Thevenard Isand (Pilbara Region, Western Australia). *H. ovalis* was the most ubiquitous species in the ecological surveys of Theme 5 and used in the laboratory based studies examining tolerance to light reduction and burial.

Bottom:

WAMSI DSN Project 5.4

Photographs of a long-term, field-based, manipulative, seagrass clearance and recovery experiment at Thevenard Island investigating the capacity, duration and mechanisms of recovery of seagrass from a severe localised disturbance, and in particular, whether seagrass recovery is by vegetative regrowth from rhizome extension (i.e. asexual) or via recruitment from seeds (i.e. sexual).

Several potential indicators of physiological stress in seagrass plants when affected by light reduction were identified for future studies.

Recovery of seagrass (through vegetative growth) following cessation of the light reduction treatments was rapid (within 2-3 months) for *Halophila ovalis* and *Halodule uninervis*.

Vegetative regrowth appears to be the primary mechanism for recovery from disturbance in these seagrasses, although seed banks (along with immigration of plant fragments from elsewhere) may play a significant role in recovery where seagrass loss has occurred over much larger areas[33].

A second experiment addressed the question whether the impacts of dredging can be reduced by altering the frequency of dredging activities, by subjecting seagrass plants in mesocosm aquaria to different treatments that delivered approximately the same total light availability over a two-week period but with different patterns of delivery (including different numbers of high, moderate and low light days)[18].

There was greater potential for recovery in plants that received frequently intervening periods of moderate/high light during extended periods of low light. Ten days of continuous low light was more detrimental than five days of continuous low light, even if over a two week period plants received the same total amount of light[18].

The findings of these experiments were translated into impact thresholds for benthic light availability for the three most common seagrass species (and for mixed meadows) in the North West. These thresholds can be used in impact prediction and assessment of planned and future dredging projects[6].

Sediment deposition experiments showed that burial by up to 40 mm of inorganic sediments for 14 weeks in ambient light had no effect on either of the two seagrass species tested (*Halodule uninervis* and *Cymodocea serrulata*). *Halodule uninervis* even endured up to 70 mm for 14 weeks without any significant effects[19].

When the same experiments were repeated with organically enriched sediments (>4%) under dredge-simulated conditions of severe

Daily water quality and seagrass health monitoring of aquaculture tanks in the seagrass research facility, The University of Western Australia light reduction (<2 mol photons $m^{-2}day^{-1}$) for 6 weeks, burial by 40 mm or more caused significant reduction in shoot density in both species, revealing a potential synergistic effect of low light and burial stress (but only when the added organic matter was present) [20].

It is, however, unlikely that seagrasses will experience such rapid and deep burial and organic enrichment that they were subjected to in these experiments and so it is concluded that sediment deposition is unlikely to present a significant pressure field for seagrasses during dredging (except in very close vicinity of excavation and disposal areas).

Defining thresholds and indicators of responses of sponges to dredging-related pressures

Sponge gardens are very common in WA waters and are especially dominant and extensive in deeper water.

Sponges are critically important to ecosystem functioning due to their remarkable ability to filter large volumes of water, improving water quality, and providing a habitat to a range of motile and sessile invertebrate and vertebrate species[7].

The ecological significance of sponges in WA is increasingly being recognised and a component of the Dredging Science Node was about improving the knowledge base and creating a comprehensive database of sponge biodiversity for their management and conservation [37, 38].

Analyses of large databases showed the Pilbara and Kimberley areas have >1,400 species and morphospecies (a group of organisms regarded as a taxonomic species solely on the basis of sharing a distinctive morphology) and a high level of endemism (45% to Australia, 22% to northwest WA)[39].

WAMSI DSN Project 6.3

Mixed filter feeder community near Onslow (Pilbara coast, Western Australia) showing sponges and soft and hard corals with different growth morphologies.

The sponge species diversity far exceeds the diversity of, for example, hard coral species found in the Great Barrier Reef (n= 405) confirming WA as globally important for sponge biodiversity conservation.

Part of the sponge theme, associated with the diversity assessment, involved the production of a 166-page colour photograph catalogue intended as a field guide for future studies in the area, to aid and assist in field identifications and improve standardisation of data with respect to sponge functional morphology[38].

Some sponges are heterotrophic, relying solely on particulate organic matter for their nutrition. Other sponge species are phototrophic, living in symbiosis with photosynthetic cyanobacteria embedded in their tissue, and are confined to illuminated shallow waters where they often occur interspersed with corals.

Prior to the WAMSI Dredging Science Node research, remarkably little was known about the ecology of these sponge gardens and their susceptibility to dredging-related pressures[40].

A critical global literature review of over 900 scientific articles, reports and student theses revealed that there can be both positive and negative effects of sediments on sponges[40].

Natural adaptations of sponges to a life with sediments include sediment incorporation into their tissue (skeleton reinforcement), forming sediment crusts (providing shade, camouflage and shelter from grazers and desiccation), ability to anchor in soft sediments (sometimes partially embedded), and passive or active cleaning mechanisms (including self-cleaning surfaces, mucus production and tissue sloughing)[40].

Nevertheless, there is a range of ways in which high doses of sediments can negatively affect sponges (and other filter feeders), including increased energy cost and maintenance needs due to shading (relevant for phototrophic sponge species), clogging, tissue smothering, reduced reproduction success, settlement and growth.

Dr Mari-Carmen Pineda works on a DSN sponge project in the Australian Institute for Marine Science (AIMS) National Sea Simulator (SeaSim) facility.

The review assisted in the identification of key research gaps, test species and realistic exposure scenarios from dredging and informed the subsequent laboratory based experiments[40].

Six sponge species were selected for the laboratory-based experiments, reflecting common species with different functional morphologies and nutritional modes[39].

Experiments on the effects of five different light levels on three phototrophic and two heterotrophic sponge species showed considerable resilience to light reduction in four out of the five sponge species tested[16].

Only one of the phototrophic species, *Cliona foliascens* (typically absent from naturally turbid areas), was significantly impacted at the lowest light level (<0.8 mol photons $m^{-2}d^{-1}$) after 28 days, causing bleaching followed by mortality.

Another phototrophic species, *Cliona orientalis*, bleached but totally recovered after 14 days under natural light conditions, while a third phototrophic species, *Cymbastela coralliophila*, was not affected by the treatments at all.

At higher light levels (>0.8 mol photons $m^{-2}d^{-1}$), all species survived and/or recovered within 14 days from stress encountered during treatments.

None of the heterotrophic species were affected by any of the light reduction treatments[16].

Experiments to test the effect of TSS on five sponge species revealed a general resilience of most sponges to high loads of suspended sediments (up to 100 mg L^{-1}) for 14 days[16].

At exposure to SSC's >30 mg L^{-1} for 28 days, many sponges reduced in size, had fewer energy reserves, and (some) bleached. This indicates that exposure to high SSC for extended periods (28 days) can have negative effects on feeding behaviour and growth of sponges. However, most sponges recovered 14 days following cessation of the experimental treatments. Only two phototrophic species, Cliona foliascens and *Carteriospongia foliascens*, exhibited necrosis and mortality when exposed to >30 mg L^{-1}.

These results were corroborated by findings from the field, which demonstrated that three sponge species (*Cliona sp., C. stipitata* and *Stylissa flabelliformis*) persisted throughout one of the recent (two year) dredging programs[16, 41].

Experiments to test the effects of sediment smothering on sponges demonstrated a high resilience of all sponges tested to high levels of sediment deposition (50 mg $cm^{-2}d^{-1}$) or acute sediment smothering for as long as 30 days without causing mortality (though causing reduction in growth rates and some partial necrosis in massive, encrusting and horizontal cup morphologies)[16].

When both stressors (turbidity and smothering) were combined, mortality was accelerated and increased in the two tested phototrophic sponge species, but only at the highest turbidity scenario (70 mg L^{-1}), while the other species all survived.

These results suggest that most sponges possess mechanisms or adaptations to effectively deal with dredging-related pressures, at least in the short term.

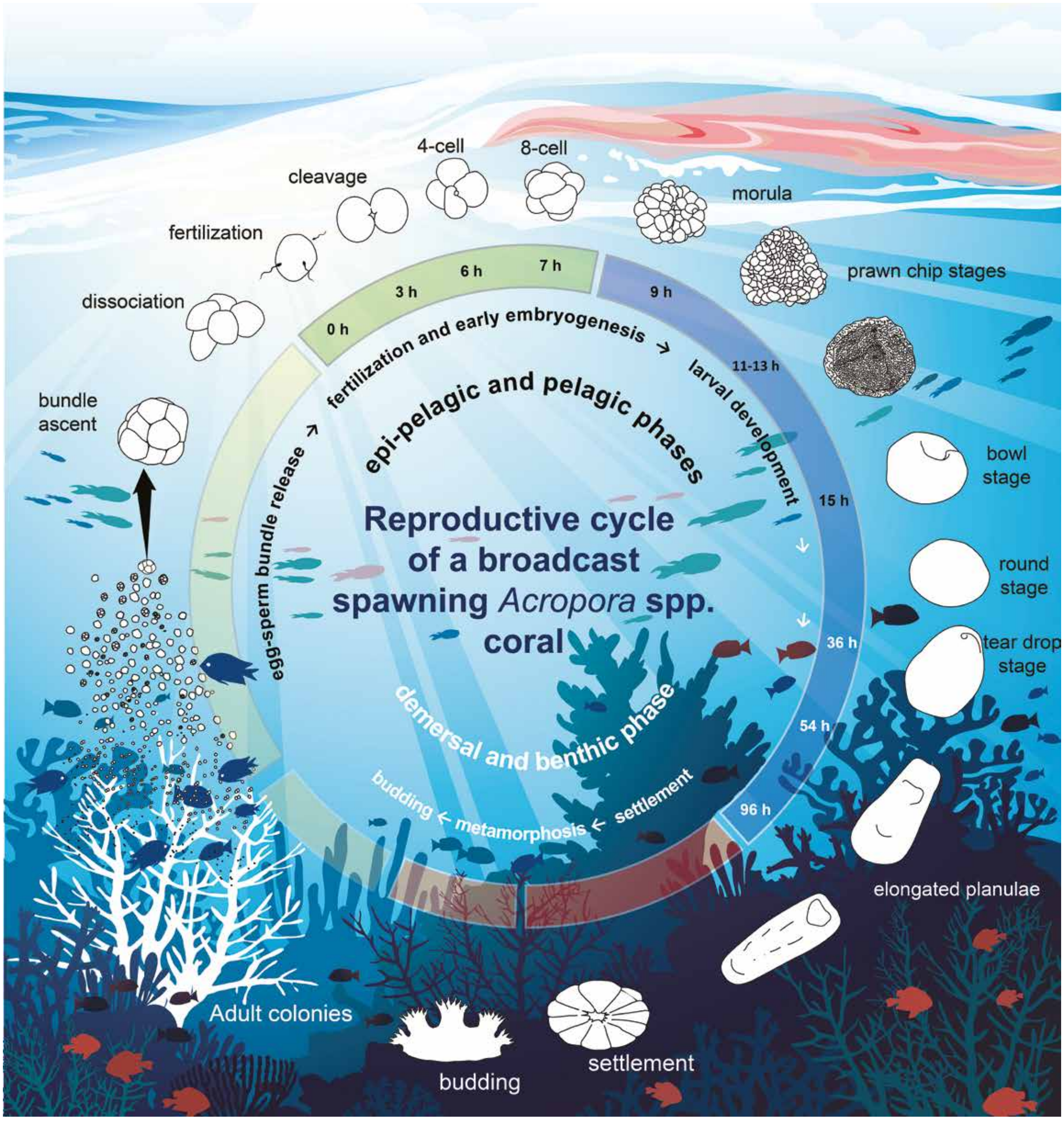
However, these tolerance mechanisms come at a cost (depletion of energy reserves, reduced sponge health), suggesting that longer-term exposure to such extreme sediment disturbance conditions is likely to result in mortality[16].

Phototrophic sponges have been reported from clear water localities in the offshore Pilbara bioregion and Dampier Archipelago, but they are rarely encountered in the relatively turbid (nearshore) environment of Onslow.

Comparison of video survey data of sponge (and other filter feeder) communities in the Onslow area before and after a large-scale dredging program revealed no significant changes for filter feeders before and after dredging, suggesting that the many sponge species encountered here are well adapted to high turbidity (from regular cyclone exposure and river floods)[41].

Critical Windows Of Environmental Sensitivity (CWES)

In Western Australia, critical windows of environmental sensitivity (CWES) are defined as periods of increased environmental sensitivity during which time dredging may be required to be restricted or ceased temporarily.



WAMSI DSN Theme 7 Final report.

Stylized depiction of the reproductive life-cycle of a broadcast spawning hard coral (*Acropora* spp.). The effects of sediments were examined at mutiple stages from egg-sperm bundles through to settlement in Theme 7.3.

In Western Australia, critical windows have thus far only been applied to protect mass coral spawning events.

This theme of the Dredging Science Node program looked more specifically at the science underpinning the critical windows approach for corals in WA and investigated whether other organisms may also benefit from a similar approach to protect particularly sensitive stages of their life cycle during certain parts of the year.

Effects of dredging-related pressures on critical ecological processes for coral

The release of suspended sediments by dredging activities may impact on potentially sensitive and ecologically important events such as coral spawning.

A general (global) literature review of 46 studies on the effects of sediments on the reproductive cycle of corals revealed insight in the causal pathways and modes of action and effects and seemed to support the view that early life stages are more sensitive and more vulnerable than adult corals[14].

However, it was evident that there were large gaps in our knowledge and limited understanding of the effects of sediments on the success of the early life phases of corals.

As a consequence, regulators have been adopting a precautionary approach requiring shutdowns of dredging during spawning events, unless proponents can demonstrate that dredge plumes will not impact on spawning corals.

The review highlighted the need to establish dose-response relationships (based on an understanding of cause-effect pathways), use statistical metrics such as EC_{10} and EC_{50} values for establishment of sediment effect thresholds, and suitably-sized sediment particles (with consideration of organic and inorganic chemical contents) when conducting experiments. The review documented key knowledge gaps to assess dredging risk and identified priorities for future research[14].

A separate review on coral reproduction in Western Australia revealed that – although coral mass spawning is reasonably predictable – there is considerable variation between species and locations in the timing of spawning and the degree of synchrony[42].

Coral reef habitats in WA are characterised by widely contrasting environments and across a considerably long north-south latitudinal gradient, both of which influence the patterns and timing of coral reproduction.

Mass coral spawning events (the synchronised release of gametes by corals for external fertilisation), which are potentially sensitive to sediment disturbances (such as dredging), are critically important to the maintenance and resilience of coral reefs (including their recovery after disturbances).

Across WA, mass spawning occurs most commonly in March and/or April, but may also include a significant spawning event in October-November in more northern areas.

Some species sometimes show split spawning. The presence of mature testes and/or eggs (pigmented) in adult corals, or larvae, followed by their subsequent disappearance, is the best basis for making strong inferences about the timing of spawning.

The review offered practical guidelines on a standardised sampling strategy and methodology for monitoring of coral spawning in WA[42].

The two reviews fed into the design of a series of experiments to better understand how sediments can affect the four main (broad) life phases: egg bundle rise, fertilisation, larval development and settlement[43].

Experiments were done in the AIMS National Sea Simulator to validate the mechanisms and determine pressure-response relationships to identify thresholds for application in modelling risk and to help assess the potential suitability of a CWES.

Top:

WAMSI DSN Theme 7

Microscopy image showing sediments sticking to an egg-sperm bundle (diameter 1-2 mm) recently released from a hard coral *Acropora nasuta*. Sediment attachment reduced the ascent of these otherwise buoyant bundles to the sea surface where fertilisation occurs.

Bottom:

WAMSI DSN Theme 7

Coral sperm (blue) bound to fine sediment grains are incapable of fertilising eggs.

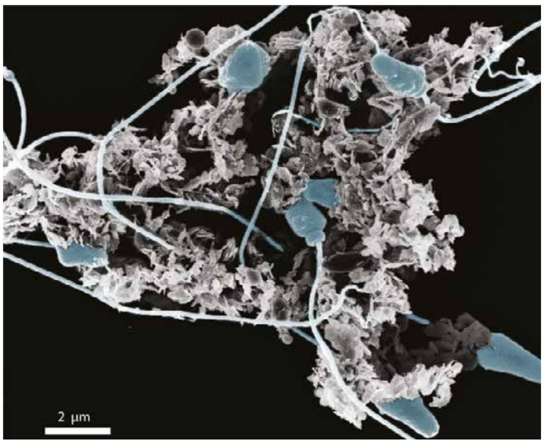
Experiments on the effects of sediment on egg release revealed that 'ballasting' of egg-sperm bundles by collisions with and adherence of sediment particles affects their ability to rise, leading to a reduction in sperm-egg encounters at the water surface and ultimately the likelihood of fertilisation[43].

The SSC-ballasting thresholds decreased with larger grain sizes and in deeper waters. For colonies spawning from 15m depth, coarse-silt SSCs of 35 mg L^{-1} and 87 mg L^{-1} resulted in a 10% and 50% decrease in egg-sperm encounters. From shallower (5 metres depth), the EC_{10} occurred at an SSC of 106 mg L^{-1}.

Experiments on the effects of sediment on fertilisation revealed that high SSCs can remove sperm from the water's surface during coral spawning events, reducing the window for fertilisation with potential flow-on effects for recruitment[43].

The lowest thresholds for sediments to affect egg-sperm encounter rates is 35 mg L^{-1}, which is probably only restricted to sites very close to dredging operations.

Effects on fertilisation success were associated with the sperm entanglement and knockout from the water column.



A considerable (>45%) decrease in sperm concentrations at the water surface was recorded in the presence of siliciclastic sediment and a >20% decrease for carbonate sediment.

Organic clay-rich sediments inhibited fertilisation by 10% at an SSC as low as 2.5 mg L^{-1}, with clear binding of the mineral clay to sperm[43].

Experiments on the effects of sediment on embryo and larval development identified a novel adaptation in which embryos form a mucous coating which protects the developing embryos (cocooning) until they are capable of swimming, at which point they use cilia beating movements to break free.

Embryo cocooning occurred at suspended sediment concentrations of >35 mg L^{-1} (EC_{10}), but larvae were able to escape and continue development unhindered.

The study concluded that embryo and larval development are comparatively insensitive to elevated SSCs, with the lowest threshold for inhibition of normal development of coral larvae being at 300 mg L^{-1}[43]. Experiments on the effects of sediment on larval settlement revealed that sediment deposition had a very strong direct impact on settlement success, while light attenuation had little effect.

Thresholds for deposited sediments were similar for a range of sediment types, with EC_{10} values ranging from 0.9 to 16 mg cm^{-2}.

Clearly, the settlement life history stage is the most sensitive phase to sediment.

Deposited sediments also caused deterioration in the quality and health of crustose calcareous red algae, which are a powerful settlement inducer for corals, and therefore could have indirect flow-on effects on coral settlement success.

This research discovered many different cause-effect pathways which have not been described previously introducing a plethora of new terms (bundle ballasting, sperm dropout and limitation and cocooning).

Overall, some stages were found to be sensitive (i.e. fertilization), very sensitive (i.e. settlement) and others were quite insensitive (embryogenesis and larval development).

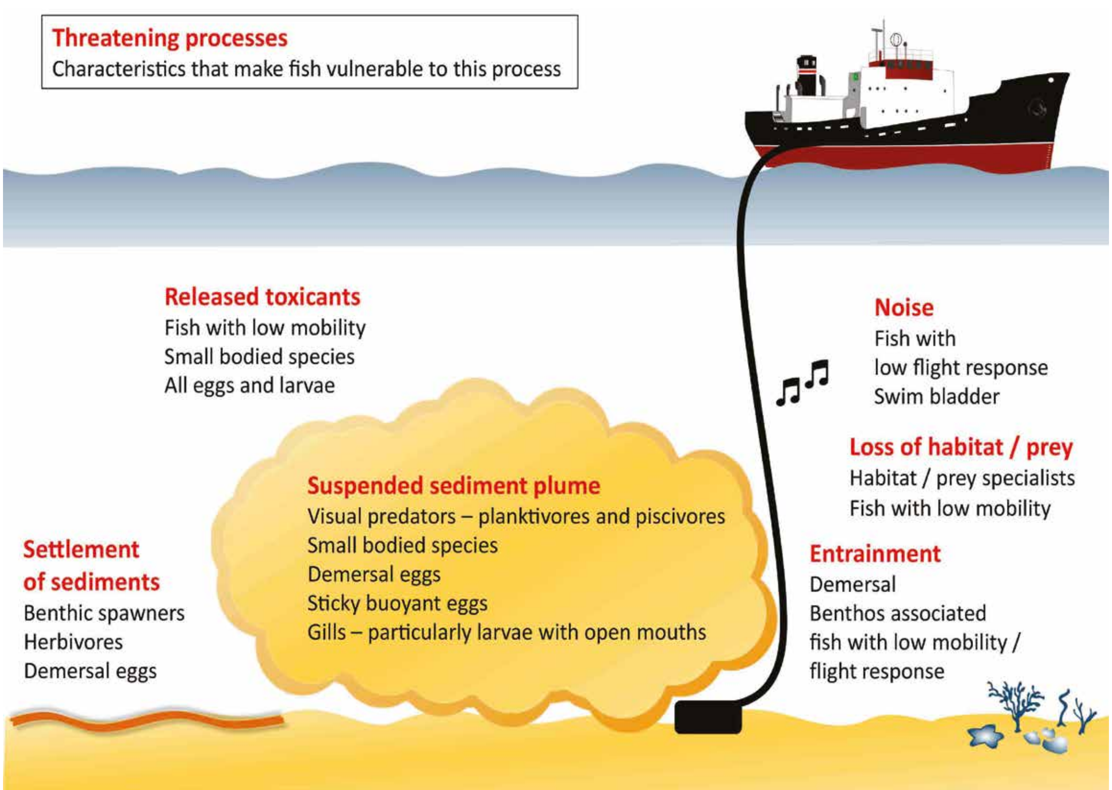
Importantly these stages were tested against environmentally realistic exposure concentrations derived from the analyses of water quality in several large-scale dredging programs. The research derived dose-response relationships for use in management[43].

A major portion of this part of the Dredging Science Node research program focused on informing and evaluating the coral spawning critical window of environmental sensitivity approach used by regulators in Western Australia[14].

The introduction of spawning windows in various dredging approvals and its evolution over the last 20 years was examined closely. The window was undoubtedly introduced out of precautionary concern (lots of unknowns) and originally no dredging was allowed during a predicted coral spawning window.

It is believed that enough information is now available to manage dredging over the spawning window using thresholds and spatially based plans that take into account the geographical separation of dredging plumes and spawning corals (and hence the likelihood of interaction at different stages of the pelagic phase)[8].

There is a caveat to this however. Given the aversion of the larvae to settling on sediment covered surfaces, dredging in the days or



WAMSI DSN Theme 8

A schematic diagram of categories of potential effects of dredging on fish.

weeks before spawning could have already created conditions that are sub-optimal for larval settlement. And similarly, resuming dredging after the window may also create conditions that are unfavourable for the survival of the newly settled recruits.

The window was originally introduced to protect the very early life-history, i.e. when the gametes are in the water column[14].

Using the derived thresholds in conjunction with spatial separation described previously, there is probably greater surety of successful fertilisation and embryogenesis happening. The question still remains whether ultimately this results in successful recruitment into the next generation, which is the ultimate test of the efficacy of the window. Nevertheless, managing water quality around coral spawning will maximize the chances of fertilisation and embryogenesis and maximise the possibility of this8.

Effects of dredging-related pressures on critical ecological processes for finfish

Finfish are ecologically and culturally significant components of all marine environments.

In WA, there are many fish species of critical importance both ecologically and socially, for recreational and commercial fisheries. Some species (e.g. whale shark, sawfish) are particularly important for biodiversity conservation.

Effects of dredging on finfish are not as well understood as for coral reef and seagrass communities, and important cause-effect pathways remain largely unresolved.

Consequently, it is difficult to make confident predictions as to the extent and severity of impacts of any given dredging activity on local finfish populations.

As there is little information on the critical periods in the fishes' lifecycles or preferential spawning locations in the northwest of WA, it is difficult to avoid important times or areas and adds uncertainty to impact prediction and management.

A critical review (which included a workshop with scientific experts) was conducted to assess the current state of knowledge regarding the effects of dredging-related pressure on key finfish reproductive processes generally, and to collate current knowledge of the key ecological windows around spawning and recruitment for Western Australian fish species9.

This knowledge would be used to determine the effects of dredging and dredge-generated sediments on reproductive processes of key (tropical) finfish in northwest WA and apply this information to identify critical thresholds and environmental windows, and to develop a prioritisation tool for vulnerability assessment.

Dredging can potentially affect finfishes and their reproductive process in six ways: habitat loss, hydraulic entrainment, release of chemical contaminants, sedimentation, suspended sediment and underwater noise.

The majority of scientific articles on the effects of dredging on fish is biased toward examining the effects of suspended sediments. Some 430 papers described the effects of suspended sediments on fish, whereas 136 articles considered the effects of contaminated sediments, 35 on the effects of underwater noise and 24 on the effects of hydraulic entrainment[9]. There was generally a paucity of direct field measurements of the effects of dredging on fish.

Elevated suspended sediment concentrations can induce behavioural changes such as area avoidance and prey switching, and is known to inhibit foraging success of planktivorous and drift feeding fish species by reducing the visual acuity and reactive distance.

Increased exposure of fish to high suspended sediment levels can cause damage to gill tissue (especially in larval fish).

Dredging of contaminated sediments (including acid-sulphate soils) can have greater negative impacts on fish.

Entrainment rates of eggs, embryos and larvae are generally thought to represent a small proportion of total fish production, with fish eggs being most vulnerable. Entrainment rates of adult fishes appear to be relatively low.

Noise effects from dredging activities on fish are limited (worse for fish species that use their swim bladder for hearing), and although potentially causing behavioural changes and physiological stress, no lethal effects were recorded[9].

Spatial variation in sediment sensitivity and general lack of biological information for most marine fish species complicates the process of determining appropriate thresholds for suspended sediments.

From the available information it appears that, although tolerances were highly variable, the types of observed responses were similar and allowed for deriving some generic ecological quality guidelines.

Spawning times were available for 60 species and the durations of spawning for 58 species. Less is known about larval duration and recruitment timing and duration.

This represents only a small portion of the total fish diversity of Western Australia (estimates of which range from about 2,000 to 4,000 species)[9].

For the vast majority of fish species, very little information exists on their reproductive biology (or even their general ecology).

For those species for which data are available, the peak spawning period seems to be between October and April, although at any given time of the year, at least 20% of fish species in WA waters are spawning.

There are some distinct latitudinal gradients in spawning times for certain species. These patterns and data gaps indicate that there is need for location-specific research into the reproductive biology of key fish species to inform impact studies of planned dredging operations.

Given a significant overlap of spawning activities by different fish species between October and April (in northwest WA), there may be merit in avoiding or minimising dredging near critical habitats during this time to mitigate potential impacts on fish. Such an environmental window may also have a spatial component, such as aggregation sites for mating and/or spawning[9].

Given the high level of fish species diversity, it would be best to first consider a prioritisation exercise to rank species based on their economic and societal value (or particular concern for conservation), and their vulnerability to dredging pressures, based on biological aspects such as their reproductive strategies, degree of habitat specificity and distributions.

This combination of community values and vulnerability attributes enabled the ranking and identification of 13 indicator species that are both valuable (for fisheries, conservation and ecology) and susceptible to dredging, and represent a range of life history types, habitats and values.

Similar types of prioritisation exercises could be applied in future dredging projects to obtain a more location-specific short-list of indicator species.

Further (location-specific) research should then ideally be undertaken into the reproductive biology of these key species to inform dredging management and impact assessment studies during the pre-development stage[9].

Effects of dredging-related pressures on critical ecological processes for other organisms

The potential validity of considering a critical windows of environmental sensitivity approach for marine organisms other than corals or fish, i.e. invertebrates, seagrasses and macroalgae, was also investigated under the Dredging Science Node program[10].

Marine invertebrates encompass a huge diversity of organisms, including (besides corals) sponges, sea squirts, sea stars, sea cucumbers, sea urchins, molluscs, polychaete worms, cnidarians and crustaceans (shrimps, crabs and lobsters), and they exhibit a broad range of feeding habits and reproductive strategies.

Of greatest importance among these are the habitat-forming groups, but some individual species can be particularly important for economic reasons (e.g. fisheries) or conservation.

Filter feeders, in particular, are a highly diverse and economically important group that provide food and shelter for other organisms and provide habitat for recreationally and commercially important fish species.

They also have incredible capacities to filter seawater and as such improve water quality by reducing turbidity, allowing more light to reach the seabed for photosynthetic organisms such as seagrasses.

Seagrasses and macroalgae are also critically important, providing habitat, nursery grounds, food and shelter and other ecological services to many marine organisms of economic, ecological and conservation importance, including fish, juvenile prawns, crabs, sea turtles and dugongs[10].

Prior to the Dredging Science Node, knowledge about the reproductive cycles and timing for most tropical marine organisms of the northwest of WA was sketchy and unconsolidated (including unpublished information and grey literature).

It was further realised that transferring and applying information from other locations to northwest WA can have significant limitations and risks.

For many species, the actual period of ecological sensitivity remained unrecognised/unknown and hence unmanaged.

Contemporary knowledge of critical environmental windows of sensitivity was collated and consolidated for a range of marine biota in WA, informed by expert knowledge and opinion through sequential workshops with relevant subject matter experts[10].

The vulnerability of invertebrate species depends on their reproductive strategy (single episode, multiple or protracted events throughout the year).

Many larval invertebrate species have difficulty attaching to substrata covered in a layer of fine sediment. Reducing turbidity generation around neap tides in autumn would benefit invertebrates.

There is some evidence that many invertebrates associated with coral reefs tend to spawn synchronously with corals, suggesting that they would be protected by the same window as corals.

Seagrasses can be grouped in three broad categories: colonising, persistent and opportunistic.

Colonising seagrass species (e.g. *Halophila* spp., *Halodule* spp.) have a limited resistance to dredging disturbance but have the ability to recover quickly. They tend to demonstrate a high level of spatial and temporal variability.

In the Kimberley, dredging during the dry season would place the greatest pressure on these species, as during this period the plants rely on the higher light levels to stimulate germination of seed banks, plant growth, meadow development and flowering.

There is insufficient knowledge on these species in the Pilbara to identify a meaningful window[10].

Persistent seagrass species (e.g. *Posidonia* spp.) are more resilient to dredging disturbance but take much longer to recover. Reducing dredging pressure during the summer months would benefit these plants to increase flowering and fruiting success and allow carbohydrate reserves to be built up and stored for winter survival.

Opportunistic seagrass species would benefit most from avoidance of dredging during the warmer months (*Zostera* spp.) and Austral autumn (*Amphibolis* spp.)[10].

Environmental windows for macroalgae should account for plant phenology.

Phenology of *Sargassum* spp. in temperate WA is characterised by spring-summer growth with reproduction in late summer, followed by senescence in early autumn.

In kelp (*Ecklonia radiata*), production of spores occurs from early summer to autumn with a peak in April, while winter is the season of slowest growth and dislodgement due to storms.

Based on a vulnerability assessment for major WA macroalgal genera and the known timing of their reproduction and recruitment, dredging would pose the lowest risk during August-September[10].

Locally relevant information on life history characteristics and ecologically sensitive periods that would inform management decisions is lacking in a range of species of invertebrates, seagrasses and macroalgae that are known to be ecologically significant in WA.

For large dredging programs, the key (ecologically significant) indicator species in the areas potentially influenced by the dredging should be identified and subject to further baseline studies to identify their timing and duration of sensitive life phases. Such studies could also be used to determine whether the environmental windows may have a spatial component, for example specific spawning aggregations or substrate types for larval settlement.

In temperate waters, many marine organisms exhibit an increased vulnerability to dredging pressures during the late spring to early autumn period (October–April).

The wet season in the Kimberley is considered to be the period when dredging-related pressures are likely to be the least detrimental to opportunistic seagrasses, but within the Pilbara region, this is less clear and here, there is a degree of opportunism built in to their reproductive strategies that allows them to cope with the episodic and irregular nature of the climatic regime in the region.

In conclusion, developing meaningful CWES for marine organisms other than corals or fish requires location-specific knowledge of the timing of sensitive periods in the life histories of key habitat-forming organisms.

Given the wide variety of organisms considered, and the fact that their sensitive periods varied widely across different times of the year, the review found no 'generic' environmental window ('one shoe fits all') that would afford protection across the range of taxa considered.

Emerging 'New' Insights (Cutting Through All Themes)

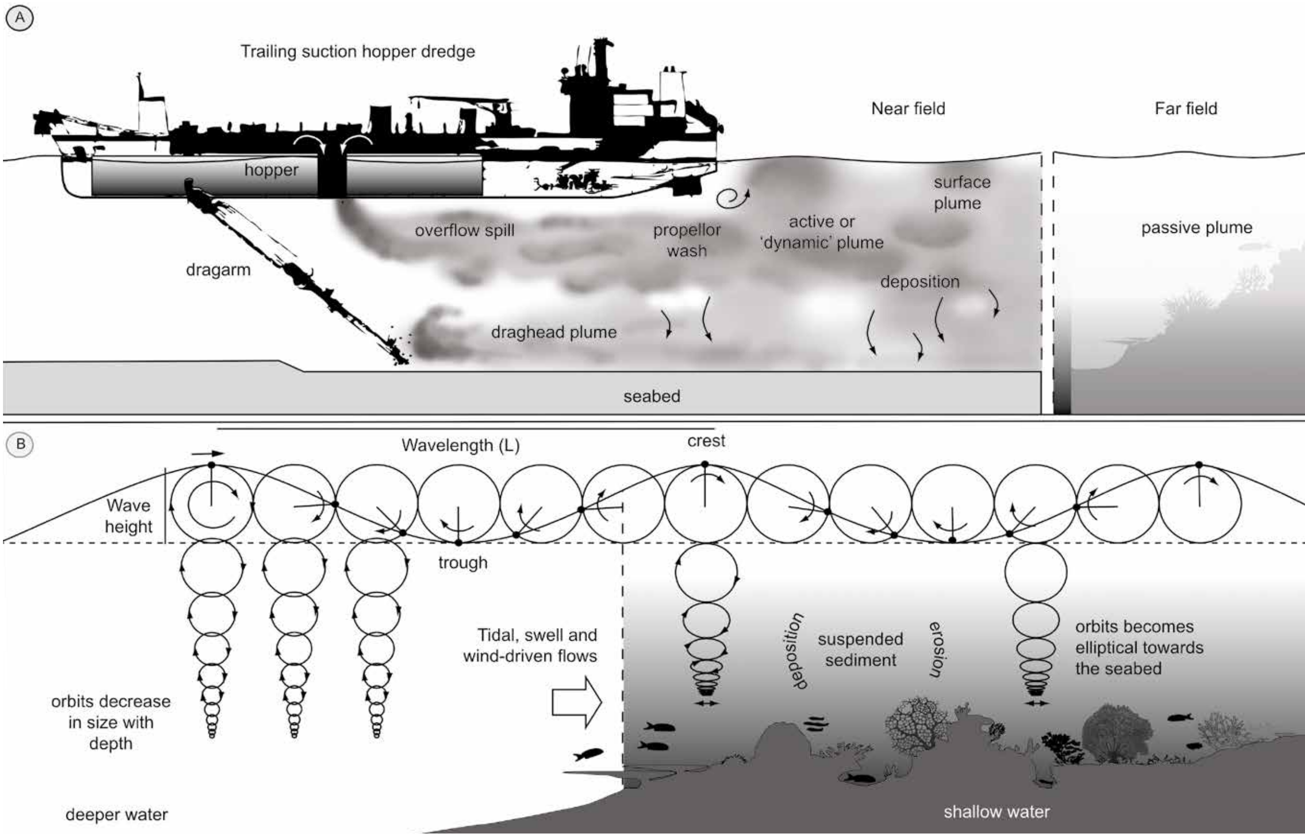
Much of the WAMSI research suggests that the most significant environmental impacts from dredging-associated stressors (whether on corals, seagrasses or sponges) in northwest WA only occur close to the dredging activities.

Oversimplifications can be dangerous and each dredging project will be fundamentally different, but some observations are offered from the 1.5 year long (7.6 Mm3) Barrow Island capital dredging project where an extraordinary amount of information was collected along a clear gradient away from the dredging3, 26.

Visible turbid plumes extended for up to 30 km[13] but the distance at which there was a 90% reduction of water quality effects (from maximum near to the dredging, referred to as the effect distance ED_{10}) was 20 km for both elevated SSCs and a reduction in underwater light[26]. For sediment deposition, measured using sediment deposition sensors, the ED_{10} was 15 km, and for measurable changes in seabed clay and silt content after dredging (from sediments dropping out of suspension) was 5 km.

WAMSI DSN Theme 4

(A) Stylized representations of current and wave-induced turbidity generation in the shallow reef environment and (B) plume generation by a trailing suction hopper dredge, the most commonly used of the hydraulic dredges for soft sediments. Turbidity is generated at the drag-head and at the surface if sediment-laden water inside the hopper is allowed to discharge (overflow). This can occur from the ship's sides but more recently through a vertical shaft inside the hopper, exiting below water level.



Similar analyses for biological responses showed effects were even closer still, with the ED_{10} for mucus sheet formation in massive *Porites* spp. (which is a useful bioindicator of sediment exposure[31]) was 3 km away[26].

Smothering of corals by sediment (the build-up of pools of loose sediment on the surface that could not be removed by self-cleaning) had also mostly (90%) dissipated by 3 km (or ~0.5 km for a 50% dissipation)[26].

Noting the caveats associated with oversimplification, the results show that despite dredging plumes being visually quite spectacular, and even visible from space, the distance at which corals can be affected is perhaps an order of magnitude less than distances travelled by the plumes.

These numbers allow some conceptualisation of the scale of possible effects in the context of cloudy plumes and the zone of influence[26].

Underwater light (as daily light integral), is a very relevant pressure parameter for seagrasses, phototrophic sponges and certain coral morphologies. For corals it was found to be more relevant than suspended sediments.

Rates of sediment deposition that result in smothering of corals was also found to be a very important parameter for defining zones of high impact[26].

Light levels are increasingly being monitored in dredging projects around seagrass beds (when thresholds are understood) but rarely during dredging operations around sponge gardens or reefs (due to a lack of knowledge on critical thresholds).

Based on the findings from the manipulative experiments, it is now possible to define quantitative threshold values for all of these groups in WA waters, and it would therefore be relevant to include monitoring of light and consider light availability during impact predictions (at the EIA stage) in future dredging operations in WA.

The spectral changes in light under dredge plumes identified during the Node are presently difficult to evaluate[12]. Unquestionably, a decrease in available light is most significant for photoautotrophs but under chronic light starvation but it seems reasonable to assume that the loss of the 'usefulness' of any remaining light may have physiological consequences. Work is ongoing to evaluate the significance of this.

For dredging near coral reefs, sediment deposition is a very significant pressure parameter and for certain morphologies sediment smothering from high levels of deposition is likely to determine the zone of high mortality.

Measurement of sediment deposition at appropriate scales is very difficult, a point which has been emphasised multiple times within Theme 4 (see [27, 28, 12, 5]).

The development of novel deposition sensors in the Node has led to instruments that are currently being tested in some dredging programs on Australia's east coast. However, until relating pressure-response relationships have been resolved, using elevated suspended sediment concentrations as a proxy for high levels of sediment deposition is the only viable option, and this is discussed at length in Project 4.9[26].

Suspended sediment concentrations over various running time intervals (for up to 30 days) that could be used to estimate zones of effect were derived, based on detailed laboratory[15] and field measurements[26]. However, as these are proxy measurements there remains a degrees of uncertainty associated with them, which was built into the analysis. Most (but not all) early life history stages of corals, fishes, invertebrates and seagrasses were found to be more sensitive to increased levels of turbidity and deposition than adult stages.

Most (but not all) early life history stages of corals, fishes, invertebrates and seagrasses were found to be more sensitive to increased levels of turbidity and deposition than adult stages. Where there is marked spawning synchronicity (such as for many corals and some reef-dwelling invertebrates), there appears merit to consider an environmental window approach to dredging.

The WAMSI research findings provide a sufficiently detailed evidence base to justify a threshold approach in northwest WA to more strictly manage turbidity and deposition from dredging during this sensitive time period for corals.

It would make sense to do this only at sites that are within close proximity to the dredger, rather than implement a complete shutdown of all dredging activities, as done previously[8].

Adopting a similar generic 'windows' approach to avoid impacts on early life history stages of other groups of organisms (e.g. fishes, seagrasses, sponges and other invertebrates) is not practical, owing to the vast diversity of species, and highly variable reproductive timing, strategies and sensitivities among those groups in northwest WA[9].

The preferred approach in this case would be to first select species that are of key importance to the (local) economy or conservation in the area of concern, and then conduct a targeted risk assessment (where necessary supplemented by new research) to evaluate potential merits of adopting a window of heightened caution during the most sensitive period for these target species at sites near the dredging activity.

Most experiments were concentrated on a few selected key species. This brings to question how representative the findings of these experiments are for the entire group they were selected to represent. However, the selection process of indicator species for use in the experiments was done very systematically[29, 32, 39] and with caution, making sure that the choice of species represented common species of the region, included different growth forms or feeding strategies, and focused on the keystone (habitat-forming) species.

Virtually all of the species ultimately chosen had very wide distributions across the Indo-West Pacific and across the east and west coast of Australia.

Nevertheless, interpretation of the experimental results should be done with caution especially when translating their implications for other species or other growth forms.

For corals, the gross morphology (i.e. branching, encrusting, foliose or massive) was found to be much more important in determining the sensitivity to light reduction and sediment smothering than species (taxonomy)[26].

Similarly, there is the danger of generalisation. For example, it would be tempting to conclude that (apart from a few sensitive phototrophic species) nearly all sponges are tolerant of high sediment disturbances and thus of no concern during dredging operations.

While this may be true for the naturally turbid nearshore waters of the Pilbara region in WA, where phototrophic sponges are rare, it may prove unlikely to apply in relatively clear water environments such as many parts of the Great Barrier Reef, where over 75% of all sponges are phototrophic.

Perhaps the greatest challenge in the northwest region of WA (and many other coastal environments containing reefs) remains the ability to detect significant changes and attribute them to the impact of dredging activities in a region that is naturally highly variable and turbid due to regular natural disturbances arising from cyclones, river plumes and wind-driven resuspension (exacerbated by frequent coral bleaching).

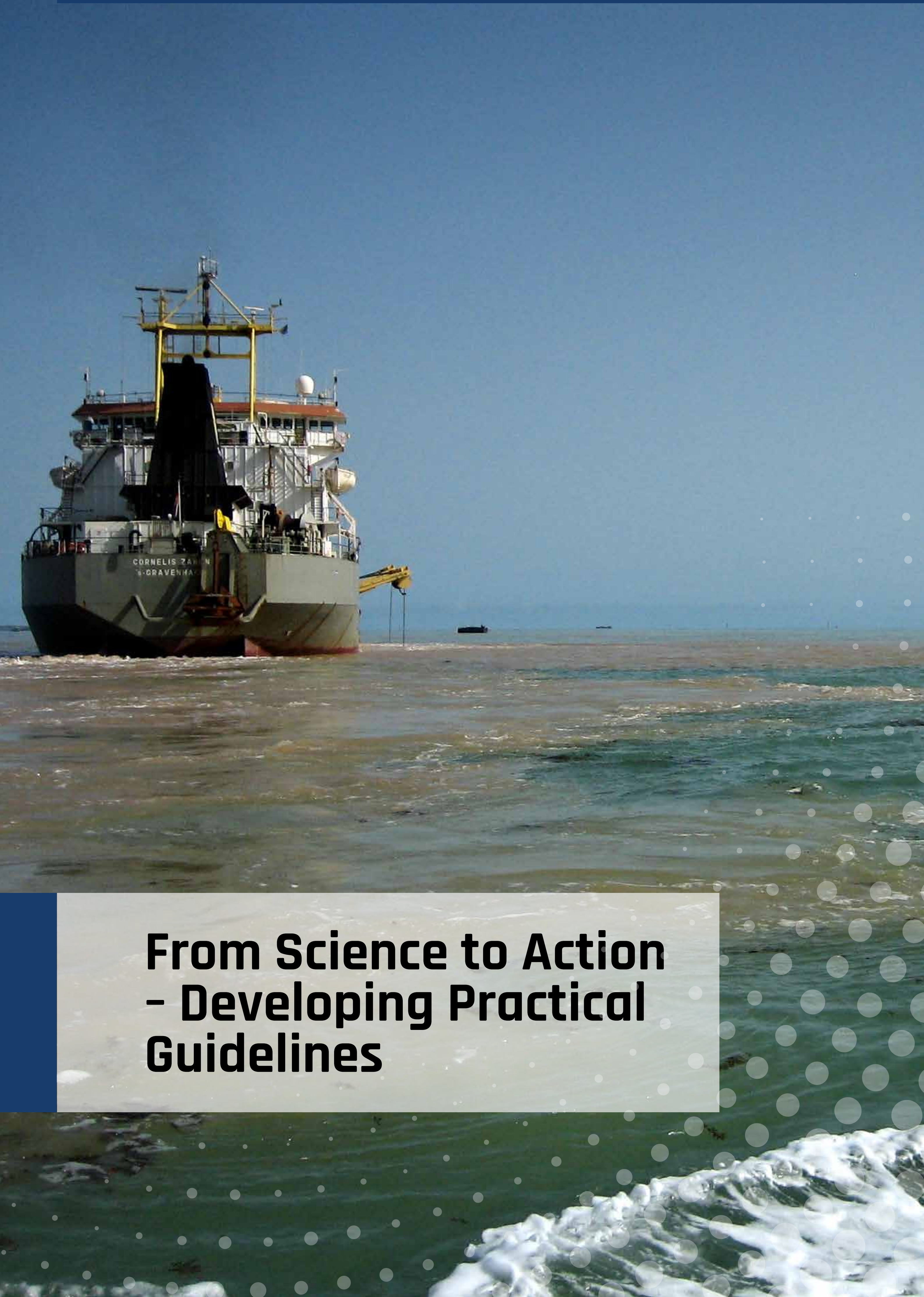
The identification of the most relevant cause and effect pathways and derivation of dose response thresholds associated with many of the Dredging Science Node projects was very much about impact prediction at the EIA stage and triggers for managing dredging projects to remain complaint with EIA predictions.

The time frames considered were over weeks and months. One of the longer-term legacies of dredging may appear to be a local build-up of readily resuspendable fine sediments[12].

Regular maintenance dredging and ship propeller-wash associated with active ports may also result in a further siltification of the environment.

Over longer timeframes (multiple years to decades), different and more subtle sets of cause-effect pathways may become more relevant, which might include effects on larval supply and recruitment failure, and their effects on populations[12].

It may, however, prove difficult to distinguish some of these effects from the consequences of port activities and associated industrial development in coastal environments near sensitive receptors, suggesting the need for monitoring programs around working ports close to sensitive habitats.



From Science to Action – Developing Practical Guidelines

Pathway To Adoption

The fruitful and open collaboration between the experts, scientists, environmental regulators and industry representatives involved in the program has led to a rich source of scientific information that has greatly increased our understanding of the main cause-effect pathways of dredging-related stressors and the response of sensitive environmental receptors to these stressors in the North West region of Western Australia.

As a final step, it is now critical that this information is translated into practice to ensure that the acquired knowledge will contribute to improved impact prediction, more efficient decision making and cost-effective environmental management and monitoring of dredging operations in WA.

To facilitate the use of the research findings of the Dredging Science Node to improve and inform the environmental impact assessment and management of dredging projects, WAMSI implemented a number of initiatives:

- **Theme synthesis reports:** WAMSI and lead scientists of the various partner research agencies have produced theme synthesis reports that summarise and integrate the research findings for each of the themes of the Dredging Science Node program in a form that will enable the important elements and implications to be understood by a broader audience of decision makers[3, 4, 5, 6, 7, 8, 9, 10].

  On the basis of research findings under the various themes, scientists proposed a range of considerations for predicting and minimising the environmental impacts of dredging.

  Modelling guidelines: WAMSI scientists are currently working on the preparation of best practice guidelines for the numerical modelling of dredging plumes.

  It is anticipated that these guidelines will improve the capability of proponents and their consultants to predict the potential environmental impacts of dredging proposals, increase the confidence of regulators in these predictions, increase the clarity for proponents and modellers on what is required, offer guidance to translate model output into ecologically relevant pressure fields, and improve consistency in reporting.

  To support the production of these guidelines, the scientists have consulted with international specialists in this field (including experts from Deltares, Svasek Hydraulics, Van Oord, DHI, RPS and BMT).

- **Guidelines for monitoring of coral spawning:** As part of the research into the sensitivity of early life stages of corals to dredging-related pressures, practical guidelines[42] have been drafted outlining a standardised and consistent sampling strategy and methodology for the monitoring of coral spawning, to inform dredging management when a mass spawning event of corals is imminent.

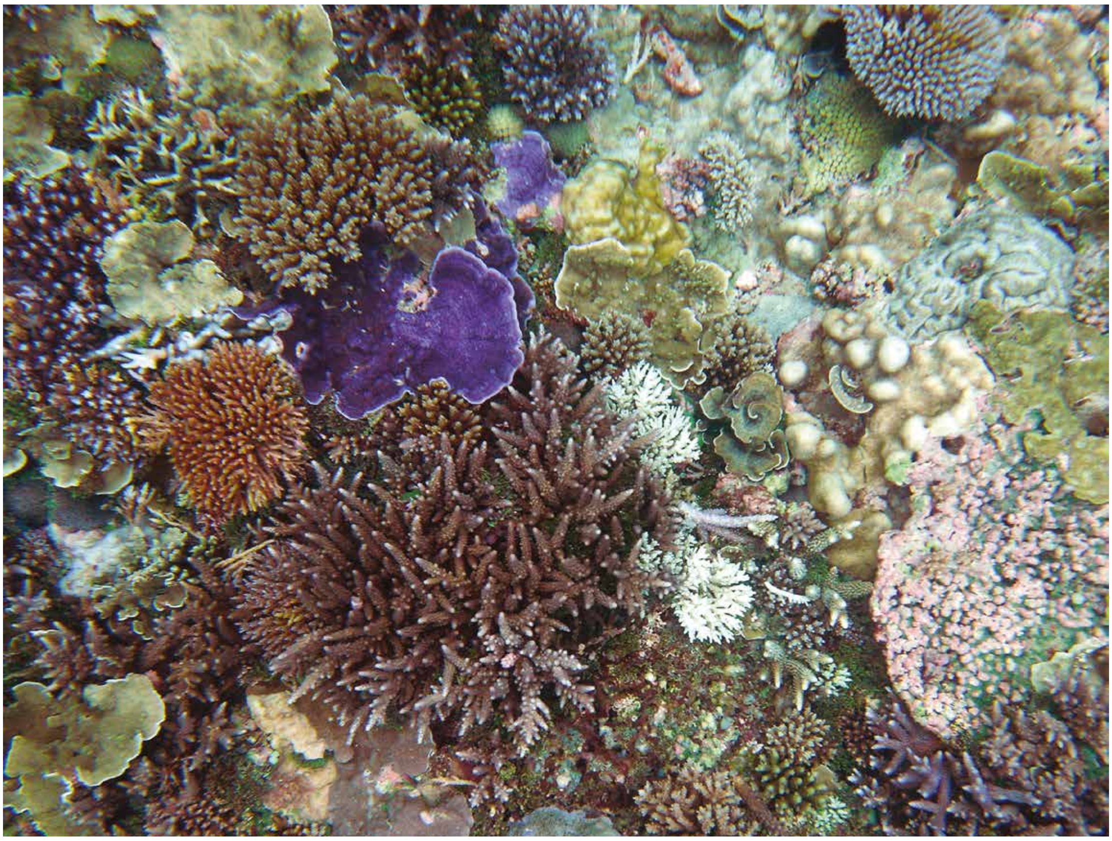
- **Data/model accessibility:** Making the information, including technical reports, scientific papers, data and models more accessible on the WAMSI and Pawsey websites to increase the likelihood that the findings and conclusions of the program will be taken up by practitioners, consultants and proponents involved in impact assessment, approvals and adaptive management of dredging projects.
- **Compendium of dredging science for management:** The Dredging Science Node was designed from the outset to provide directly relevant information for the impact assessment and management of dredging in northwest WA.

  The scientific publications and technical reports are comprehensive and are structured in such a way as to provide guidance to end users.

A key component of the compendium will be a revision of the EPA's Technical Guidance to include the relevant scientific findings from the Node that will assist proponents and regulators to better and more efficiently assess and manage large scale dredging projects.

Although it is focused on large-scale capital dredging in northwest WA, the information will also be directly applicable to maintenance dredging and other turbidity-generating activities and can be adapted for use elsewhere in Australia and internationally.

DWER will involve key stakeholders to further consolidate the research findings and combine this with the practical experience of proponents, regulators and environmental consultants to provide both scientifically-defensible and practical guidance and advice.



Practical Application and Adaptive Management

The ultimate purpose of uptake and practical application of the Dredging Science Node findings in future dredging programs is to offer guidance to proponents who are encouraged to apply this as part of their environmental impact assessment and dredge management planning.

It is anticipated that by adopting such guidance, proponents and regulators will have confidence that decision making is based on the best available information.

It is important that 'continued learning' from environmental monitoring during dredging is incorporated as part of an adaptive management cycle to facilitate further improvement and reduce any remaining uncertainty to close the loop between prediction and reality.

What Next? – Lessons Learnt and Future Outlook

Ingredients for Success

Key ingredients underpinning the success of the WAMSI-led Dredging Science Node research program include the commitment of funds and sharing of data by industry, in conjunction with the commitment and provision of substantial matching funds by key research organisations.

Other important ingredients include the structured and thorough science planning and prioritisation process[1] and alignment of the *Dredging Science Node: Science Plan*[2] to the policy framework for managing dredging, and the researchers' commitment to provide the practical, solution-orientated and fit-for-purpose research.

The involvement of senior end users from both the regulator and industry on a Dredging Science Advisory Committee (DSAC), the oversight and influence from the WAMSI Research and Development committee, and the secondment of the Node Leader for Science Node (Dr Ross Jones) from the Australian Institute of Marine Science (AIMS), and the Node Leader for Policy (Dr Ray Masini) from the Department of Water and Environmental Regulation (DWER), was important to ensure the coherence and practical relevance of the research whilst safeguarding its scientific quality and integrity.

The success story of the Dredging Science Node as a demand-driven, science-regulator-industry collaborative approach to research focused on the delivery of relevant outcomes that are fit for purpose, can be repeated in other important and emerging issues in marine science in Western Australia. For example, the approach could be extended to research on decommissioning of disused offshore oil and gas infrastructure, risks and impacts of underwater (marine) noise and fate of hydrocarbons in oil spills, aquaculture and sustainable fisheries management, and marine biosecurity risks and mitigation strategies.

This will require targeted co-investments and genuine and effective marine science collaborations led by science end users from industry and government of a similar nature to the one successfully implemented for the WAMSI Dredging Science Node. Some of these are currently being considered and followed up by WAMSI under the *Blueprint for Marine Science*.

As the successful outcome of the Dredging Science Node research program has demonstrated, a meaningful and intentional collaboration between knowledge providers and end users – if followed through consistently and from beginning (research prioritisation and planning) to end (synthesis and uptake) – can be applied to any particular science program to improve the societal relevance of the research outcome and influence policy and common practice. Such collaboration can encourage fit-for-purpose deliverables that can contribute to cost-saving solutions and thereby increase the impact of the research beyond academia.

Residual Knowledge Gaps

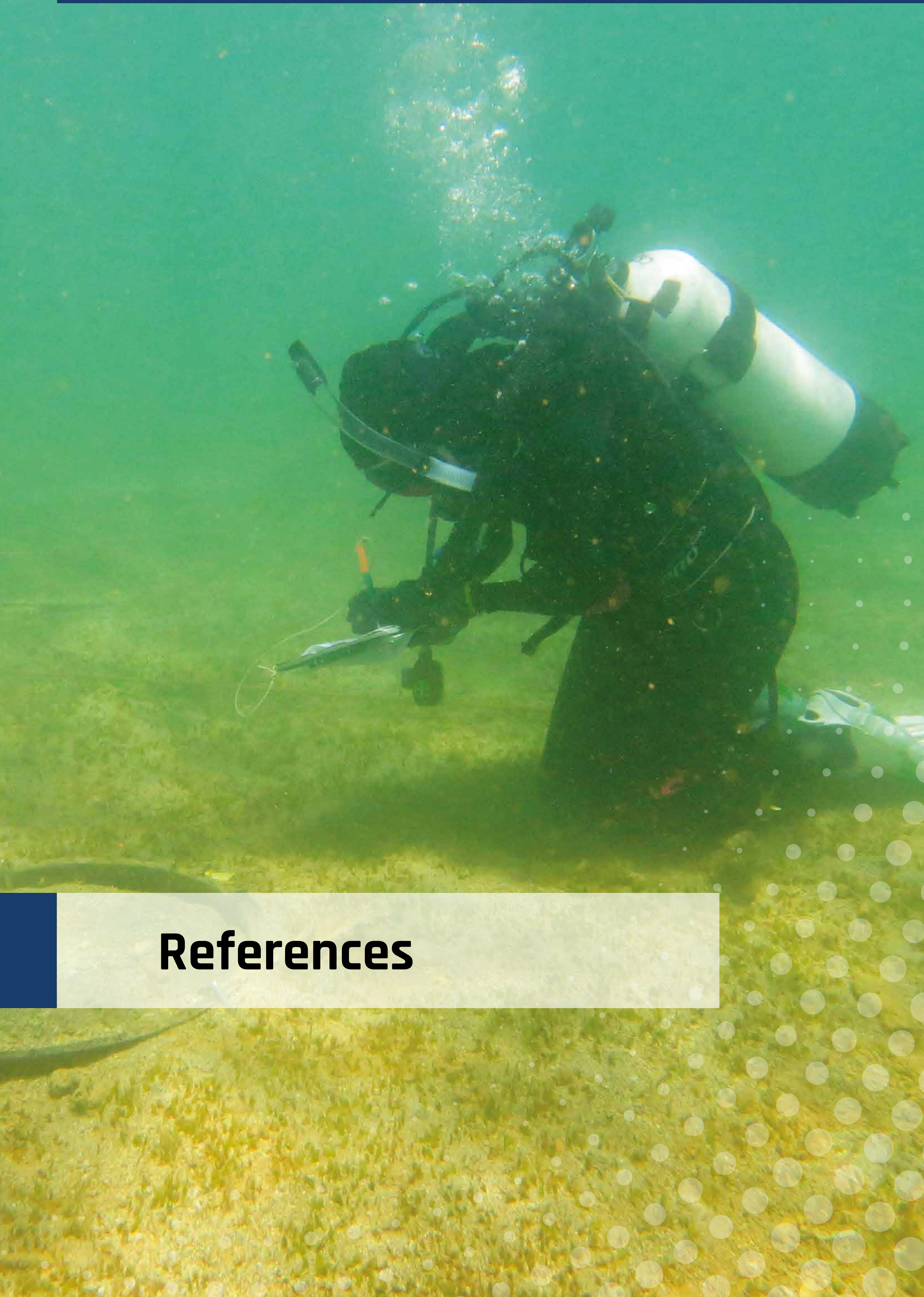
There is still more work to be done to address some of the residual knowledge gaps around environmental aspects of dredging that could not be addressed during the WAMSI-led Dredging Science Node. One of those gaps is the social aspect, such as understanding the factors that shape public perception around dredging, the role of media and politics in influencing decision making around dredging (including socio-economic and environmental trade-offs), and the socio-economic consequences of regulatory conservatism surrounding environmental policy and legislation around dredging.

Other major critical research gaps still to be addressed include: uncertainty around the fate and behaviour of dredged material at disposal grounds; cumulative and synergistic effects (e.g. of climate change, pollution, fisheries, land-use practices or repeated/ongoing dredging at the same location) that affect the scale and magnitude of dredging impacts on the environment; feasibility of beneficial re-use of dredged material; and cost-effectiveness of mitigating measures commonly applied to dredging operations (e.g. silt curtains, spawning windows, overflow restrictions) to minimise or prevent environmental impacts.

Targeted research on some of these issues could potentially be funded with additional offset moneys already pledged and committed as part of approvals for planned new dredging and port construction projects in WA, once they do go ahead.

Proof of Concept

Eventually, the real success and benefits of the Dredging Science Node may only come to light once its findings and recommendations are put to the test by implementing them in a real-world pilot case study: the next big dredging job in Western Australia.



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Abdul Wahab M, Gomez O, Bryce M, Fromont J (2017) Photo catalogue of marine benthic diversity off Onslow (Pilbara region of Western Australia). Report of Theme 6 - Project 6.3.1. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, . Perth, Western Australia,. 176 pp.

[39] Report of Theme 6 - Project 6.2
Fromont J, Abdul Wahab MA, Gomez O, Ekins M, Grol M, Hooper J (2017) Sponges of the north west of Western Australia: biogeography and considerations for dredging related research. Report of Theme 6 - Project 6.2. Prepared for the Dredging Science Node, Western Australian Marine Science Institution. Perth, Western Australia. 73 pp.

[40] Report of Theme 6 - Project 6.1
Schönberg C (2016) Effects of dredging on filter feeder communities, with a focus on sponges. Report of Theme 6 - Project 6.1. Prepared for the Dredging Science Node, Western Australian Marine Science Institution. Perth, Western Australia. 139 pp.

[41] Report of Theme 6 - Project 6.3
Abdul Wahab M, Fromont J, Gomez O, Fisher R, Jones R (2017) Comparisons of benthic filter feeder communities before and after a large-scale capital dredging program. Report of Theme 6 - Project 6.3. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, . Perth, Western Australia. 67 pp.

[42] Report of Theme 7 - Project 7.2
Gilmour J, Speed C, Babcock R (2017) Coral reproduction in Western Australia. Report of Theme 7 - Project 7.2. Prepared for the Dredging Science Node, Western Australian Marine Science Institution. Perth, Western Australia. 85 pp.

[43] Report of Theme 7 - Projects 7.3 to 7.5
Ricardo G, Jones R, Negri A (2017) Effects of sediments on the reproductive cycle of corals: Experimental studies. Report of Theme 7 - Projects 7.3 to 7.5. Prepared for the Dredging Science Node, Western Australian Marine Science Institution. Perth, Western Australia. 35 pp.

Acknowledgements

Governance Structure

'Research Priorities' workshop

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Theme 2 - **Team Leader: Des Mills** (Ind.) • Hans Kemps (EPA) • Ray Masini (EPA)

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Theme 5 - **Team Leader: Paul Lavery** (ECU) • Matthew Adams (UQ) • Paul Armstrong (ECU) • Douglas Bearham (CSIRO) • Ed Biffin (UA) • Louise Bruce (UWA) • David Callaghan (UQ) • Richard Evans (DBCA) • Ming Feng (CSIRO) • Marco Ghisalberti (UWA) • Renee Gruber (UWA) • Mick Haywood (CSIRO) • Udhi Hernawan (ECU) • Matthew Hipsey (UWA) • Renae Hovey (UWA) • Gary Kendrick (UWA) • Ryan Lowe (UWA) • Hector Lozano-Montes (CSIRO) • Paul Maxwell (HW) • Roisin McCallum (ECU) • James McLaughlin (CSIRO) • Kathryn McMahon (ECU) • Nick Mortimer (CSIRO) • Katherine O'Brien (UQ) • Marji Puotinen (AIMS) • Leonardo Ruiz-Montoya (UWA) • John Statton (UWA) • Simone Strydom (ECU) • Kor-jent van Dijk (UA) • Mat Vanderklift (CSIRO) • Michelle Waycott (DEWNR)

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External Review Committee members

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Committee members

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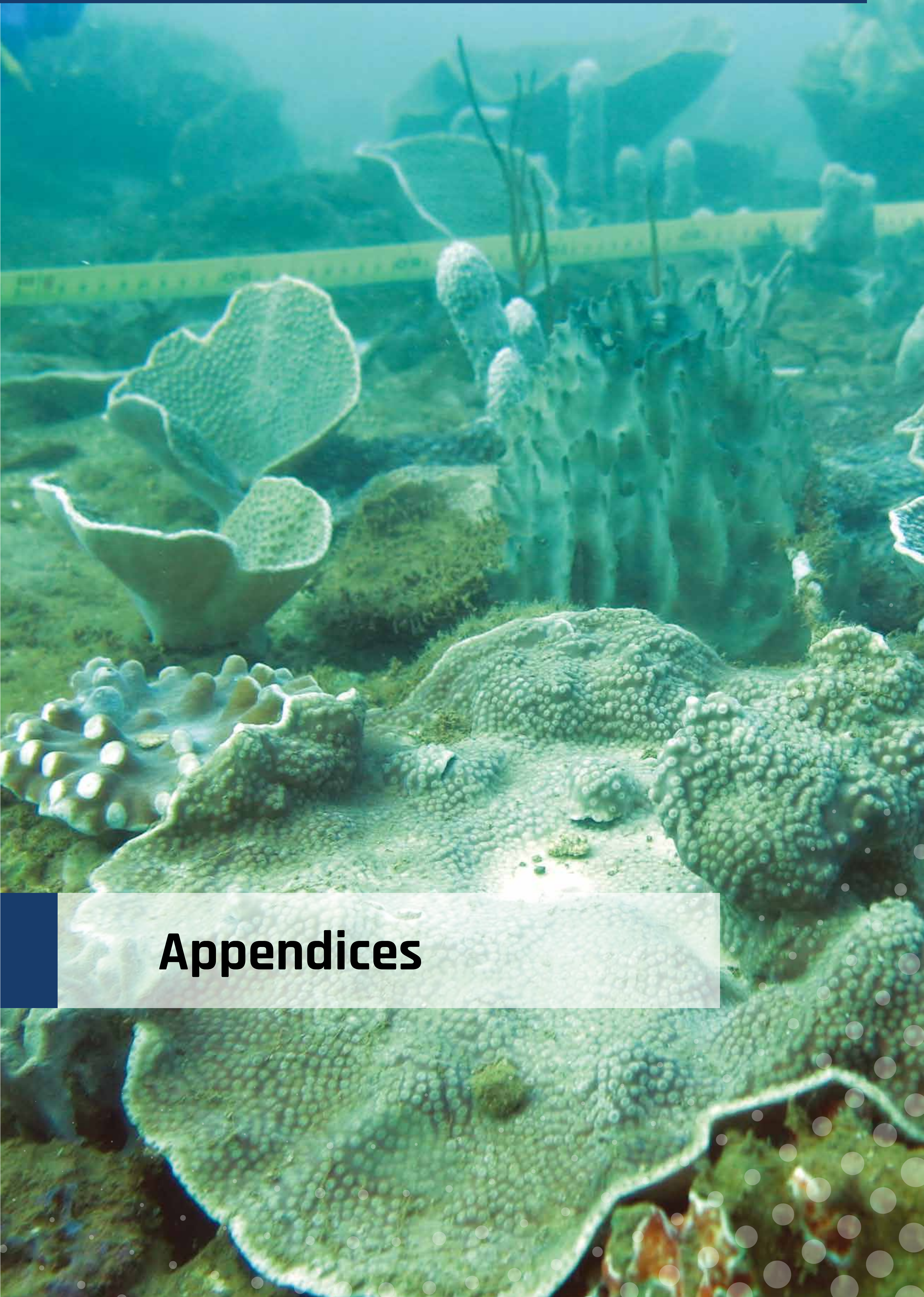
Image Credits

Muhammad Azmi Abdul Wahab, Steve Clarke, Jane Fromont, Oliver Gomez, Kathryn McMahon, Christian Miller, Gerard Ricardo, Christine Schönberg, John Statton, Amelia Wenger, AIMS, CSIRO, Curtin University, ECU, Landsat, SeaSim, UWA, WA Museum

Appendices



Appendix I - Dredging Science Node Reports

Research Priorities Workshop	Lavery P, McMahon K (2009) Research priorities for improving the capacity to manage dredging impacts on tropical coral communities in Western Australia. Prepared for the Western Australian Marine Science Institution (WAMSI), Workshop Discussion and Outcomes. Tradewinds Hotel, Fremantle, Perth, Western Australia. 24th-25th November 2008, 65 pp
Science Plan	Masini R, Jones R, Sim C (2011) Western Australian Marine Science Institution (WAMSI) Dredging Science Node: Science Plan. WAMSI, Perth, Western Australia, 23 pp

Category 1 – Analysis of Industry Data

Objective: To better understand the pressure gradients and range of measured biological responses associated with dredging in a range of biophysical settings

Theme 1

Theme 1 Final Report	Jones R, Twomey L (2019) Review and consolidation of environmental monitoring data collected by industry. Theme 1 Final Report. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 16 pp

Category 2 – Characterising and Predicting the Pressure Field

Objective: To better predict, measure and monitor relevant pressure-field parameters associated with dredge-generated sediments

Themes 2 and 3

Theme 2 and 3 Final Report	Sun C, Branson P (2019) WAMSI Dredging Science Node Theme 3 Synthesis report: Predicting and measuring the characteristics of sediments generated by dredging and dredge plume dynamics and fate. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 23 pp
Project 2.1	Mills D, Kemps H (2016) Generation and release of sediments by hydraulic dredging: a review. Report of Theme 2 - Project 2.1. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 97 pp
Project 2.2	Kemp H, Masini R (2017) Estimating dredge source terms – a review of contemporary practice in the context of Environmental Impact Assessment in Western Australia. Report of Theme 2 - Project 2.2. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 29 pp

Project 3.1.1	Fearns P, Broomhall M, Dorji P (2017) Optical remote sensing for dredge plume monitoring: a review. Report of Theme 3 - Project 3.1.1. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 46 pp
Project 3.1.2	Lowe R, Ghisalberti M (2016) Sediment transport processes within coral reef and vegetated coastal ecosystems: a review. Report of Theme 3 - Project 3.1.2. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 27 pp
Project 3.1.3	Sun C, Shimizu K, Symonds G (2016) Numerical modelling of dredge plumes: a review. Report of Theme 3 - Project 3.1.3. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 55 pp
Project 3.2.1	Fearns P, Dorji P, Broomhall M, Branson P, Mortimer N (2019a) Plume Characterization – Remote sensing. Report of Theme 3 - Project 3.2.1. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 57 pp
Project 3.2.2	Fearns P, Dorji P, M B, Branson P, Mortimer N (2019b) Plume Characterization – Laboratory Studies. Report of Theme 3 - Project 3.2.2. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 57 pp
Project 3.3	Lowe R, Ghisalberti M, Pomeroy A, Cuttler M, Bowyer C (2019) Sediment transport processes over benthic ecosystems. Report of Theme 3 - Project 3.3. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 99 pp
Project 3.4	Sun C, Branson P (2019) Numerical modelling of dredge plumes Report of Theme 3 - Project 3.4. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 84 pp

Category 3 — Predicting the Ecological Response

Objective: To establish quantitative relationships between pressure and response for key groups of ecologically important organisms

Theme 4

Theme 4 Final Report	Jones R, Fisher R, Bessell-Browne P, Negri A, Duckworth A (2019) WAMSI Dredging Science Node Theme 4 Synthesis report: Defining thresholds and indicators of coral response to dredging-related pressures. Theme 4 Final Synthesis Report. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 36 pp

Project 4.1	Jones R, Bessell-Browne P, Fisher R, Klonowski W, Slivkoff M (2017a) Assessing the impacts of sediments from dredging on corals. Report of Theme 4 - Project 4.1. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 33 pp
Project 4.2	Fisher R, Stark C, Ridd P, Jones R (2017) Effects of dredging and dredging related activities on water quality: Spatial and temporal patterns. Report of Theme 4 - Project 4.2. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia., 106 pp
Project 4.3	Stark C, Whinney J, Ridd P, Jones R (2017) Estimating sediment deposition fields around dredging activities. Report of Theme 4 - Project 4.3. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 26 pp
Project 4.4	Whinney J, Jones R, Duckworth A, Ridd P (2016) Continuous in situ monitoring of sediment deposition in shallow benthic environments. Report of Theme 4 - Project 4.4. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 25 pp
Project 4.5	Jones R (2016) Corals of the north west of Western Australia: biogeography and considerations for dredging-related research. Report of Theme 4 - Project 4.5. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 31 pp
Project 4.6	Jones R, Duckworth A, Bessell-Browne P, Fisher R, Giofre N, Negri A (2019) Laboratory-based studies examining the effects of sediments on corals: Executive summary and management implications. Report of Theme 4 - Project 4.6. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 78 pp
Project 4.7	Babcock R, Gilmour J, Thomson D (2017) Measurement and modelling of key demographic processes in corals of the Dampier Archipelago. Report of Theme 4 - Project 4.7. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 43 pp
Project 4.8	Bessell-Browne P, Fisher R, Duckworth A, Jones R (2017) Mucous sheet production in Porites spp. and links to sediment. Report of Theme 4 - Project 4.8. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 25 pp
Project 4.9	Fisher R, Jones R, Bessell-Browne P (2019) Effects of dredging and dredging related activities on water quality: Impacts on coral mortality and threshold development. Report of Theme 4 - Project 4.9. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 94 pp

Theme 5

Theme 5 Final Report	Lavery P, MacMahon K, Statton J, Vanderklift M, Strydom S, Kendrick G (2019) WAMSI Dredging Science Node Theme 5 Synthesis Report: Defining thresholds and indicators of primary producer response to dredging-related pressures. Theme 5 Final Synthesis Report. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 32 pp
Project 5.1.1	McMahon K, Lavery P, McCallum R, Hernawan U (2017a) Current state of knowledge regarding the effects of dredging-related ‘pressure’ on seagrasses. Report of Theme 5 - Project 5.1.1. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 64 pp
Project 5.1.2	McMahon K, Statton J, Lavery P (2017b) Seagrasses of the north west of Western Australia: biogeography and considerations for dredging-related research. Report of Theme 5 - Project 5.1.2. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 39 pp
Project 5.2	McMahon K, Hernawan U, van Dijk K, Waycott M, Biffin E, Evans R, Lavery P (2017) Genetic variability within seagrass of the north west of Western Australia. Report of Theme 5 - Project 5.2. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australi, 41 pp
Project 5.3	Vanderklift M, Bearham D, Haywood M, Lozano-Montes H, McCallum R, Mc Laughlin J, McMahon K, Mortimer N, Lavery P (2017a) Natural dynamics: understanding natural dynamics of seagrasses of the north west of Western Australia. Report of Theme 5 - Project 5.3. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 55 pp
Project 5.4	Vanderklift M, Bearham D, Haywood M, McCallum R, McLaughlin J, McMahon K, Mortimer N, Lavery P (2017b) Recovery mechanisms: understanding mechanisms of seagrass recovery following disturbance. Report of Theme 5 - Project 5.4. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 25 pp
Project 5.5.1	Statton J, McMahon KM, Armstrong P, Strydom S, McCallum R, Kendrick GA, Lavery PS (2017a) Determining light stress bio-indicators and thresholds for a tropical multi-species seagrass assemblage. Report of Theme 5 - Project 5.5.1. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 50 pp
Project 5.5.2	Statton J, McMahon KM, McCallum R, Kendrick GA, Lavery PS (2017c) Sediment burial stress response, bio-indicators and thresholds for a tropical multi-species seagrass assemblage. Report of Theme 5 - Project 5.5.2. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 38 pp

Project 5.5.3	Statton J, McMahon KM, McCallum R, Kendrick GA, Lavery PS (2017b) Response and recovery of a mixed tropical seagrass assemblage to variation in the frequency and magnitude of light deprivation. Report of Theme 5 - Project 5.5.3. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 55 pp
Project 5.5.4	Statton J, McMahon KM, McCallum R, M VB, Kendrick GA, Lavery PS (2017d) Response of a mixed tropical seagrass assemblage to burial by inorganic and organic sediments under low light. Report of Theme 5 - Project 5.5.4. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 28 pp

Theme 6

Theme 6 Final Report	Abdul Wahab MA, Fromont Jane, Pineda Mari-Carmen, Strehlow B, Duckworth A , Jones R, Webster N (2019) WAMSI Dredging Science Node Theme 6 Synthesis report: Defining thresholds and indicators of filter feeder responses to dredging-related pressures. Theme 6 Final Synthesis Report. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 26 pp
Project 6.1	Schönberg C (2016) Effects of dredging on filter feeder communities, with a focus on sponges. Report of Theme 6 - Project 6.1. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 139 pp
Project 6.2	Fromont J, Abdul Wahab MA, Gomez O, Ekins M, Grol M, Hooper J (2017) Sponges of the north west of Western Australia: biogeography and considerations for dredging related research. Report of Theme 6 - Project 6.2. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 73 pp
Project 6.3	Wahab MA, Fromont J, Gomez O, Fisher R, R J (2017) Comparisons of benthic filter feeder communities before and after a large-scale capital dredging program. Report of Theme 6 - Project 6.3. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 67 pp
Project 6.3.1	Abdul Wahab M, Gomez O, Bryce M, Fromont J (2019) Photo catalogue of marine benthic diversity off Onslow (Pilbara region of Western Australia). Report of Theme 6 - Project 6.3.1. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 176 pp
Project 6.4	Pineda M-C, Strehlow B, Duckworth A, Webster N (2017) Effects of dredging-related stressors on sponges: laboratory experiments. Report of Theme 6 - Project 6.4. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 157 pp

Category 4 – Critical Windows Of Environmental Sensitivity (CWES)

Objective: To identify the critical ecological processes in marine communities in that could be affected by dredging programs

Theme 7

Theme 7 Final Report	Negri A, Ricardo G, Jones R (2019) Effects of dredging-related pressures on critical ecological processes for corals | Synthesis Report. Theme 7 Final Synthesis Report. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 23 pp
Project 7.1	Jones R, Ricardo G, Negri A (2017b) Effects of sediments on the reproductive cycle of corals. Report of Theme 7 - Project 7.1. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 35 pp
Project 7.2	Gilmour J, Speed C, Babcock R (2017) Coral reproduction in Western Australia. Report of Theme 7 - Project 7.2. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 85 pp
Project 7.3, 7.4, 7.5	Ricardo G, Jones R, Negri A (2017) Effects of sediments on the reproductive cycle of corals: Experimental studies. Report of Theme 7 - Projects 7.3 to 7.5. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 35 pp

Theme 8

Project 8.1, 8.2	Harvey E, Wenger A, Saunders B, Newman S, Wilson S, Travers M, Browne N, Rawson C, Clarke D, Hobbs JP, Mcilwain J, Evans R, Erftemeijer P, Mclean D, Depczynski M (2016) Effects of dredging-related pressures on critical ecological processes for finfish: a review and possible management strategies. Report of Theme 8 - Projects 8.1 & 8.2. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 91 pp

Theme 9

Theme 9 Final Report	Short J, Fraser M, McLean D, Kendrick G, Byrne M, Caley J, Clarke D, Davis A, Erftemeijer P, Field S, Gustin-Craig S, Huisman J, Keesing J, Keough M, Lavery P, Masini R, McMahon K, Mergersen K, Rasheed M, Statton J, Stoddart J, Wu P (2017) Effects of dredging-related pressures on critical ecological processes for organisms other than fish or coral. Theme 9 Final Synthesis Report. Prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 47 pp

Appendix II Dredging Science Node Peer-Reviewed Journal Articles

Abdul Wahab M, Fromont J, Gomez O, Fisher R, Jones R (2017) Comparisons of benthic filter feeder communities before and after a large-scale capital dredging program. Marine Pollution Bulletin 122:176-193. https://doi.org/10.1016/j.marpolbul.2017.06.041

Adams M, Hovey R, Hipsey M, Bruce L, Ghisalberti M, Lowe R, Gruber R, Ruiz-Montoya L, Maxwell P, Callaghan D (2016) Feedback between sediment and light for seagrass: Where is it important? Limnology and Oceanography 61:1937-1955. https://doi.org/10.1002/lno.10319

Bessell-Browne P, Fisher R, Duckworth A, Jones R (2017) Mucous sheet production in Porites: an effective bioindicator of sediment related pressures. Ecological Indicators 77:276-285. http://dx.doi.org/10.1016/j.ecolind.2017.02.023

Bessell-Browne P, Negri A, Fisher R, Clode P, Jones R (2017) Cumulative impacts: thermally bleached corals have reduced capacity to clear deposited sediment Scientific Reports 7:2716. https://doi.org/10.1038/s41598-017-02810-0

Bessell-Browne P, Negri A, Fisher R, Clode P, Jones R (2017) Impacts of light limitation on corals and crustose coralline algae. Scientific Reports 7:1 1553https://doi.org/10.1038/s41598-017-11783-z

Bessell-Browne P, Negri AP, Fisher R, Clode PL, Duckworth A, Jones R (2017) Impacts of turbidity on corals: The relative importance of light limitation and suspended sediments. Marine Pollution Bulletin 117:161-170. http://dx.doi.org/10.1016/j.marpolbul.2017.01.050

Cuttler M, Lowe R, Falter J, Buscombe D (2017) Estimating the settling velocity of bioclastic sediment using common grain-size analysis techniques. Sedimentology 64:987-1004. https://doi.org/10.1111/sed.12338

Dorji P, Fearns P (2016) A Quantitative Comparison of Total Suspended Sediment Algorithms: A Case Study of the Last Decade for MODIS and Landsat-Based Sensors. Remote Sensing 8:32. https://doi.org/10.3390/rs8100810

Dorji P, Fearns P (2017) Impact of the spatial resolution of satellite remote sensing sensors in the quantification of total suspended sediment concentration: A case study in turbid waters of Northern Western Australia. PLoS One 12(4): :e0175042. https://doi.org/10.1371/journal.pone.0175042

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Appendix III Dredging Science Node Conference Proceedings

Branson P, Sun C (2017) WAMSI Dredging Science Node: Plume modelling uncertainty - hydrodynamics [online]. In: Australasian Coasts & Ports 2017: Working with Nature. Barton, ACT: Engineers Australia, PIANC Australia and Institute of Professional Engineers New Zealand. Proc Coasts & Ports 2017 Conference. 21-23 June 2017, Cairns, Australia

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Wu P, Mengersen K, McMahon K, Kendrick GA, Caley J (2015) Predicting the temporal response of seagrass meadows to dredging using Dynamic Bayesian Networks. Proc MODSIM2015 21st International Congress on Modelling and Simulation: ProceedingsModelling and Simulation Society of Australia and New Zealand

Appendix IV Dredging Science Node PhD Completions

Bessell-Browne P (2017) **Lethal and sublethal impacts of dredge related stressors on corals**. Doctor of Philosophy, 199 pp. Centre for Microscopy, Characterisation and Analysis, School of Biological Sciences, The University of Western Australia, Perth, Western Australia. **PhD Supervisors**: Dr Ross Jones (AIMS), Dr Andrew Negri (AIMS), Dr Peta Clode (UWA)

Dorji P (2017) **Satellite remote sensing algorithm development to estimate total suspended sediment concentration for highly turbid waters of Western Australia**. Doctor of Philosophy, School of Applied Physics, Faculty of Science and Engineering Curtin University, Perth, Western Australia. **PhD Supervisors**: Dr Peter Fearns (Curtin)

Ricardo G (2017) **The impacts of dredging on the early life history stages of coral**. Doctor of Philosophy, 222 pp. Centre for Microscopy, Characterisation and Analysis, School of Biological Sciences, The University of Western Australia, Perth, Western Australia. **PhD Supervisors**: Dr Andrew Negri (AIMS), Dr Ross Jones (AIMS), Dr Peta Clode (UWA)

Strehlow B (2017) **The effects of sediments on marine sponges**. Doctor of Philosophy, pp. Centre for Microscopy, Characterisation and Analysis, School of Biological Sciences, The University of Western Australia, Perth, Western Australia. **PhD Supervisors**: Dr Nicole Webster (AIMS), Dr Alan Duckworth (AIMS), Dr Peta Clode (UWA), Dr Michael Renton (UWA), Dr Gary Kendrick (UWA)

Strydom S (2017) **Investigating the effects of changes in light quality on different life history stages of seagrasses**. Doctor of Philosophy, pp. School of Science, Edith Cowan University, Perth, Western Australia. **PhD Supervisors**: Dr Kathryn McMahon (EDU), Dr Paul Lavery (ECU), Dr John Statton (UWA), Dr Gary Kendrick (UWA)

Stark C (2016) **Spatial and temporal water quality changes during a large scale dredging operation**. Doctor of Philosophy, 189 pp. College of Science and Engineering, James Cook University, Townsville, Queensland. **PhD Supervisors**: Dr Peter Ridd (JCU), Dr Ross Jones (AIMS), Dr James Whinney (JCU), Dr Ron White (JCU)

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