



Part C

Technical Report on the
Outcomes of Additional
Dredge Modelling to
Inform Impact Prediction

Final Environmental Impact Statement/
Response to Submissions on the Environmental
Review and Management Programme for the
Proposed Gorgon Development

GORGON DEVELOPMENT ON BARROW ISLAND
TECHNICAL REPORT ON THE OUTCOMES OF
ADDITIONAL MODELLING TO INFORM
IMPACT PREDICTION

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Executive Summary

Hydrodynamic modelling of sedimentation and turbidity plumes and health criteria, representing potential responses of BPP to these stressors, were used to predict the environmental impacts associated with the proposed Gorgon dredging programme on the east coast of Barrow Island. This impact assessment was presented in the Draft EIS/ERMP for the Gorgon Development. Additional information was provided in the Additional Information Package (AIP) released in October 2005. Since the release of the Draft EIS/ERMP, engineering for the Gorgon Development has progressed the design of the marine facilities and the dredging programme has been refined. Improved meteorological and bathymetric data and the reassessment of the BPP health threshold criteria used to delineate zones of potential impact have necessitated re-modelling the effects of the turbidity and sedimentation associated with the proposed dredging. This report has been written to provide additional information to the EPA to better inform the assessment of the Gorgon Development.

The new meteorological and bathymetric data used within the revised hydrodynamic model has increased the accuracy of impact prediction over that presented in the Draft EIS/ERMP. Design changes for the marine facilities have had little effect on the predicted impacts from dredging and spoil disposal. Reassessment of the BPP health threshold criteria to incorporate cumulative impacts has resulted in a new set of cumulative criteria that are even more conservative than the consecutive criteria modelled in the Draft EIS/ERMP. The additional conservatism has had little effect on the predicted extent of impacts. The Draft EIS/ERMP is considered to be adequately conservative in its assessment of possible impacts relating to dredging and spoil disposal.

Predicted long-term impacts to marine BPP are generally restricted to within 1–2 km of the MOF, LNG access channel and spoil ground, although some turbidity related effects may occur further a field. TSS concentrations are predicted to rarely exceed 25 mg l^{-1} during dredging, even in relatively close proximity to operations. Coarse sediments will accumulate in close proximity to the dredged areas and the spoil ground. Outside of these areas, the sedimentation rate is low in comparison to background levels. Interannual variation in the number of easterly and westerly wind anomalies is predicted to have limited effect of the predicted zones of impact and influence.

Fine particles produced during dredging will be continuously re-suspended and exported from the area through the action of wind, waves and currents. Fine sediments on the seabed are predicted to be removed within 12 weeks. The larger particles at the spoil ground will be relatively stable. The seabed in the spoil ground will be permanently modified, resulting in a change in BPPH.

Hydrodynamic model sensitivity tests indicate that changes in the proportions of fines produced during dredging have a moderate effect of the predicted impact zones. The majority of these impacts will be in close proximity to Barrow Island and the proposed marine facilities and could potentially affect regionally significant coral reefs. Reactive management, such as real time measurement of fines production to inform impact prediction and reducing the amount of fines discharged at any site will aid in the protection of these important BPP communities.

A comparison of the newly developed cumulative BPP criteria with both the previously modelled consecutive criteria presented in the Draft EIS/ERMP and more conservative criteria suggested by the DoE (double cumulative criteria time period) revealed only very small differences in the location and scale of predicted impacts, indicating that both the previously modelled

consecutive criteria in the Draft EIS/ERMP and the newly developed cumulative criteria presented in this report can be considered adequately conservative in their assessment of possible impacts related to dredging and spoil disposal.

Changes to the dredge schedule have the capacity to affect the location of impact zones as a result of changes in the dominant meteorology during dredging. Commencing the dredging operation in October (spanning two summers and one winter, as in the Draft EIS/ERMP) leads to different impact predictions to a start in April (two winters and one summer – this report). These two dredging periods are likely to have the most extreme effects on turbid plumes. Predicted impacts to marine BPP from dredging and spoil disposal tend to occur to the south of operations, particularly in nearshore waters, when dredging starts in April. This is related to the predominance of north and north-easterly events during the winter months. The reverse is true for an October start to operations, when summer 'southerlies' push turbid plumes to the north, resulting in impacts to BPP to the north of operations, particularly on the Lowendal Shelf.

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1 Background

Hydrodynamic modelling and Benthic Primary Producer (BPP) health criteria were used to predict the environmental impacts associated with the proposed dredging programme on the east coast of Barrow Island. This impact assessment was presented in the Draft EIS/ERMP (Chevron, 2005a) for the Gorgon Development. Technical reports that were unavailable at the time of release of the Draft EIS/ERMP, which included field validation studies of the dredge plume modelling, were subsequently released for public comment as an Additional Information Package (AIP) (Chevron, 2005b). The Gorgon Development is currently undergoing formal assessment by the Western Australian Environmental Protection Authority (EPA) and Department of Environment and Heritage (DEH). This technical report comprises the final input into the assessment process.

Since the release of the Draft EIS/ERMP, engineering for the Gorgon Development has progressed the design of the marine facilities and the dredging programme has also been refined. The possibility of delays to the commencement of dredging works has highlighted the need to consider the consequences of changes in the dredge schedule. These changes, improved meteorological and bathymetric data and ongoing examination of the hydrodynamic model's sensitivity to changes in other parameters and assumptions, have necessitated re-modelling the behaviour of the turbidity and sedimentation associated with the proposed dredging.

The re-modelling and preliminary feedback on the BPP health criteria have led to reassessment of the BPP health threshold criteria used to delineate zones of potential impact. In the Draft EIS/ERMP, the prediction of 'high' and 'moderate' impact zones and the 'zone of influence' were based on coral sensitivity criteria derived from published data on coral responses to natural and artificial sedimentation and turbidity stress. However, there are no data for northern Western Australian corals that can be used to accurately predict the response of corals at Barrow Island to turbidity and sedimentation stress. In the absence of directly relevant data, very conservative sensitivity criteria were adopted for impact prediction. These criteria were based on the responses of sensitive coral taxa to persistent sedimentation and turbidity and are detailed in Section 11.3 of the Draft EIS/ERMP (Chevron, 2005). The current assessment examines 'pulse' events as well as the 'consecutive' events described in the Draft EIS/ERMP.

The purpose of this technical report is to update and clarify issues relating to the dredge program predictive modelling, as raised by the Western Australian Department of the Environment (DoE) Marine Branch as part of the Submissions process (submissions received in regard to the Draft EIS/ERMP and Additional Information Package). This report will be published as 'Part C' of the Final EIS/Response to Submissions on the Draft EIS/ERMP document and will therefore be available to submitters and the public (via the Gorgon website).

This technical report examines the sensitivity of the model to changes in the main parameters, examines 'pulse' events as well as the 'press' events described in the Draft EIS/ERMP and presents new baseline water quality data collected since the release of the Draft EIS/ERMP and AIP.

2 Background Data

2.1 Water Quality Data

Background water quality data were collected during the first baseline marine monitoring survey in August/September 2005. This survey was the first of the surveys planned for the Baseline Marine Monitoring Programme (BMMP) for the Gorgon Development. Subject to project approval, the current draft BMMP will be revised to incorporate the latest development plan, dredge scenario and impact predictions. The BMMP would form the basis for the ongoing monitoring programme during construction. The plan will be finalised in consultation with the Western Australian EPA, DoE, CALM and the Commonwealth DEH. Details of the proposed BMMP are contained in the following section. The full data set will be presented in a progress report for the BMMP. A summary of the data are presented below.

Water quality measurements included vertical profiling of the water column and collection of water samples from the surface and bottom for the analysis of Total Suspended Solids (TSS). Water quality measurements were undertaken at 23 sites between Thevenard Island and the Montebello Islands over a period of 14 days (Figure 1). Six sediment trap arrays, each containing six replicate traps, were deployed in and around the proposed dredging and dredge spoil area to provide an indication of the natural (background) level of sediment deposition. Sediment trap arrays were set for 7-9 days over the tidal cycle.

Water quality was profiled using a high accuracy Seabird SBE19 CTD profiler with calibrated YSI sensors. TSS samples were collected in a Niskin sampler. Three litres of seawater from the surface and 0.5 m above the seabed were filtered and washed for subsequent laboratory analysis.

Mean turbidity throughout the vertical profile ranged from 7.69 – 9.79 nephelometric turbidity units (NTU) and was highest at the Double Island moorings and the Barrow Island tide gauge (Appendix A). The majority of water quality sites were located in shallow water, so PAR readings should be treated with caution due to surface reflection. The water column was well mixed, with no apparent haloclines or thermoclines (Appendix A).

TSS concentrations ranged from 2.0 - 5.4 mg l⁻¹ with an overall mean concentration of 3.2 mg l⁻¹. TSS concentrations were highest at Double Island (5.4 mg l⁻¹) and off the south-east coast of Barrow Island (5.3 mg l⁻¹).

Figure 1:
Water Quality Sites



Sedimentation rates off the east coast of Barrow Island ranged from 1.06 to 6.76 mg cm⁻² d⁻¹ with a mean of 4.15 mg cm⁻² d⁻¹. Collected sediment generally comprised less than 10% (by weight) of organic material. Sedimentation rates were lowest on the subtidal pavement reef just south of the proposed LNG channel and highest at the eastern end of the proposed MOF. Sedimentation and TSS concentrations were generally highest in the nearshore waters off the east coast of Barrow Island and lower further offshore.

2.2 Benthic Habitat Mapping

Benthic Habitat mapping was conducted during the August/September 2005 baseline marine monitoring survey to resolve some questions of coral distribution, particularly around the Lowendal Islands. This survey is described in the AIP.

Towed video methods were used to cover large areas of the seabed during the survey. The extent of the video survey of unconfirmed coral habitats on the Lowendal Shelf and along the north-eastern coastline of Barrow Island is shown in Figure 2.

Mapping revealed that there is little coral in the predicted impact area to the south of the Lowendal Islands. The large expanses of 'unconfirmed coral' on the Eastern Lowendal Shelf have been reclassified as limestone pavement supporting variable cover of macroalgae and scattered corals. Unconfirmed coral communities to the north of Double Island, offshore of Ant Point, have been confirmed as an extensive *Acropora* thicket. The 'base' benthic habitat map has been revised to incorporate these changes.

2.3 Baseline Marine Monitoring Programme

It is anticipated that the final BMMP will follow on from the initial survey and will follow the approach and comprise the elements described below.

The baseline studies of coral habitat distribution, coral health and reproduction and water quality proposed in the BMMP will quantify the pre-impact status of the coral communities and waters that may be affected by construction and operation of the marine facilities associated with the Gorgon Development. These baseline data will provide the basis of the ongoing monitoring programme and provide a temporal and spatial reference against which to assess the impacts of dredging and drilling through a Before-After Control and Impact (BACI) design.

Figure 2:
Towed Video Survey Routes



2.3.1 Approach

As suggested by both the DoE and the EPA, the approaches outlined in the proposed BMMP are based on recommendations in EPA Bulletin 1116, Dampier Port Authority – Port Expansion and Dredging Program (EPA, 2003). The proponents of the Dampier dredging project were required to prepare, implement and maintain a number of different coral and water quality monitoring programmes for the duration of the dredging comprising the following key elements:

- Port-wide coral reef field surveys and mapping;
- Coral Health Monitoring Plan (CHMP);
- Coral Habitat Monitoring and Management Plan (CHMMP); and a
- Water Quality Monitoring Plan (WQMP).

Relevant information, techniques and procedures used in the proposed BMMP will be consistent with other coral and water quality monitoring programmes in the region, such as the WA Oil Thevenard Island Region Marine Environmental Monitoring Program and other dredging developments in Australia, such the Nelly Bay Harbour Development on Magnetic Island, Queensland, and the Townsville Port Authority Capital Dredging Works.

2.3.2 Objectives

The broad objectives of the field programme and analyses contained within the proposed BMMP are to:

- Establish a baseline monitoring program, including permanent sites that can continue to be monitored during construction and operations.
- Characterise the baseline (un-impacted/background) status of water quality and coral community health and diversity at each monitoring site against which to compare possible impacts.

2.3.3 Key Elements

The following key elements of the BMMP will be:

- Collect seasonal baseline water quality and coral health data at predicted impact and reference sites prior to dredging.
- Establish remote logging stations to relay 'real time' water quality data.
- Compare field measurements of TSS vs turbidity relationships with laboratory results to calibrate 'real time' data.
- Determine timing of peak in spawning activity for March and October mass coral spawning events.

2.3.4 Relating TSS, Turbidity, Sedimentation and Light Attenuation

TSS concentrations cannot be easily and quickly determined in the field. Transportation to a laboratory and analysis are time-consuming and costly and therefore direct TSS measurement is not practical for reactive monitoring in an area as remote as Barrow Island. Purported TSS loggers measure turbidity and estimate TSS via an algorithm that assumes knowledge of the optical properties of the suspended material.

Turbidity is relatively easy to measure quickly and can also be monitored remotely, as nephelometers can be deployed on moored telemetry buoys. TSS is a measure of the total weight of particles in suspension, and is a direct function of the number, size and specific gravity of the particles. Turbidity is a direct function of the number, surface area, and refractive index of the particles, but is an inverse function of their size. Turbidity (NTU) can only be used as an index of suspended solids concentration if the optical properties of the suspension are understood.

Laboratory tests for deriving a correlation curve between TSS and turbidity must be suspension specific, not just site-specific. If the suspension to be represented is the product of dredging or drilling, in which a sediment suspension is modified by settling, the best way to approximate the suspension is by subjecting sediment samples to a comparable period of settling. The procedure for conducting such a test is described below, and is based on that employed by the United States Environmental Protection Agency (USEPA) and the United States Army Corp of Engineers (USACE). Further details of this methodology can be found in Thackston and Palermo (2000).

In the case of dredging, dredge spoil disposal and drilling, the larger, heavier solids will settle near the source, i.e. close to the dredge cutter head or overflow point from the barge, and only the finer particles will be present at distance from the activity. A laboratory settling column test is proposed to be employed, using material from geotechnical cores obtained from the site of proposed dredging. The material within the geotechnical cores will be ground to a variety of particle sizes and the range of sizes will be similar to those produced by the dredging of hard limestone by a cutter suction dredge during the Geraldton Port Expansion Project. The particle size distribution will be based on samples from the Geraldton hopper barges and subsequently analysed by the CSIRO Division of

Minerals. Grinding of the majority of material to very small sizes for some column tests may also provide some conservatism within correlations.

The ground material is mixed with seawater to a slurry concentration approximating the dredge discharge concentration, based on advice from the dredge manager and contractor regarding cutting and pumping rates for the selected dredge. The slurry is then transferred to a settling column 180 cm high.

As the slurry settles, 50 mL aliquots are taken from sampling ports just below the water surface. Light penetration and sediment settling rates will also be established through the use of light loggers and modified sediment traps within the column.

Linear or non-linear 'lines of best fit' are fitted to the data to derive a relationship between TSS and NTU. The relationships between grain size, sedimentation rates and light attenuation will also be explored. These relationships will be constantly revised using field data collected during construction.

3 Current Development Plan

As the Front End Engineering and Design (FEED) phase of the Gorgon Project progresses, additional work, including modelling of shipping movements and further geotechnical studies, has led to changes to the layout of the marine facilities. These are described fully in Part A of the Final EIS/ Response to Submissions on the ERMP and include:

- Extending the Materials Offloading Facility (MOF) from 325 m to 520 m, with a slight change in orientation. The length of the causeway at Town Point (800 m) remains unchanged.
- Lengthening the dredged access channel to the MOF from the 1.3 km initially modelled to approximately 1.6 km in length. The width (120 m) and depth (6.5 m below chart datum) remain unchanged. The total volume of material dredged at this location will increase from 0.8 Mm³ to 1.1 Mm³. The majority of the dredge spoil from dredging the MOF access channel will be used to construct the MOF and causeway. The duration of dredging remains unchanged at approximately 21 weeks.
- Decrease in the length of the piled LNG jetty from 3.1 km to 2.7 km.
- Dual berth configuration for the tanker turning basin to be dredged to 14 m below chart datum.
- Decrease in volume of material dredged from the LNG channel and ship berths from the initially proposed 7.0 Mm³ to 6.5 Mm³. Although there has been a slight change in orientation, the overall length (~2 km), width (300m) and depth (14 m below chart datum) of the LNG access channel remains unchanged.

4 New Model Input Data

Basic assumptions of the revised model are clarified in the following sections, with particular reference to changes in assumptions previously used in the Draft EIS/ERMP.

4.1 Meteorology

The 3D hydrodynamic model was verified using 3-hourly gridded data from the BOM operational forecast model (LAPS – Limited Area Prediction System). Details of model verification can be found in Part 1 of the AIP (Chevron, 2005b). In the current modelling, LAPS data rather than Barrow Island observations were used to represent the meteorology, as the LAPS data represent the winds over the region far better than the single point Barrow Island. Data for the six year period from 1999 to 2005 were taken as representative of the range of weather patterns around Barrow Island.

Meteorological data for 2001 represents the ‘normal’ meteorology of the area in terms of fewer anomalies to easterly or westerly wind patterns. The year 2000 was chosen to represent a year with more ‘easterly’ anomalies and 2002 to represent the year with more ‘westerly’ anomalies (see Technical Appendix B5 of the Draft EIS/ERMP for further detail). The model runs were conducted on a continuous 16 month time series, with the model starting in April of the appropriate year, i.e. for a ‘normal’ year the model starts in April 2001 and finishes in July 2002.

4.2 Bathymetry

The 3D bathymetric data used in the Draft EIS/ERMP has now been augmented by recently flown LADS data (Laser Airborne Depth Survey). These new data provide high resolution bathymetry for the east coast of Barrow Island that greatly improves the accuracy of the hydrodynamic model in shallow coastal areas.

4.3 Dredge Spoil Ground

The location and layout of the 1500 ha dredge spoil ground remains unchanged since the Draft EIS/ERMP. At its closest point, the spoil ground is approximately 10 km off the east coast of Barrow Island.

Initial dredge plume modelling for the Draft EIS/ERMP did not include the disposal of fine dredged material at the spoil ground, since it was conservatively assumed that 50% of fine particles released during dredging will be released at the cutter head and 50% from the tail water discharge (barge overflow). Consequently, under the previous hydrodynamic model, no fine particles were transported to the spoil ground and they did not contribute to sedimentation and turbidity at this site.

Impacts associated with the disposal of dredged material at the spoil ground in the Draft EIS/ERMP were assessed on the assumption that there would be minimal sedimentation and turbidity beyond the nominal buffer zone that allowed for rock roll, benthic sediment disturbance and a small amount of fines produced during transit and dumping.

However, one possible management response to prolonged exceedance of coral health or water quality criteria during dredging will be to reduce the amount (time) of barge overflow. Reducing the time for which the barges overflow will result in a higher proportion of fines remaining in the barges. These fine particles will be transported to the spoil ground and will contribute to turbidity and sedimentation when dumped at the spoil ground. The revised hydrodynamic model examines the effect of transporting 20% of the fine material generated during dredging to the spoil ground. The remaining 80% is assumed to be liberated equally from the cutter head (40%) and tail water discharge (40%).

4.4 Dredge Log

Additional information on the way the dredging operation will run and the assumptions used in both the current modelling and the Draft EIS/ERMP modelling is presented below.

4.4.1 MOF Access Channel

For the model simulation of the dredging required for the MOF access channel with a Cutter Suction Dredge (CSD) the following assumptions were made:

- A bund wall in the MOF outline will be filled with dredge spoil pumped directly from the CSD.
- The volume of cut and fill is estimated to be 1 Mm³ (Draft EIS/ERMP volume was 0.8 Mm³).
- Geotechnical data indicate the material to be dredged is crystalline limestone with a capping of calcarenite.
- The characteristics of the spoil are anticipated to be similar to that generated at Geraldton (i.e. a high proportion of fines/flour and coarse limestone rubble).
- The rock is believed to be slightly harder on average than that encountered at Geraldton and may create more fines during CSD operations.
- The dredging/reclamation program will run for approximately 18 weeks plus 2 (or more) weeks weather downtime.
- A mean dredge work rate of 84 hours of dredging per week (actual rate will vary depending on hardness of rock).

- The dredge will stop and change teeth every few hours (more frequently in harder rock) and stop for maintenance or refuelling.
- The dredge will start at outer end of the access channel and gradually work towards the shore creating a 6.5m deep channel (LAT).
- There will be shutdowns each 7 to 14 days in harder material and less frequently in softer materials.
- The dredge will refuel every four to six weeks for approximately 2 days.
- It is assumed that 5% of total material cut will be smaller than 75 microns diameter and that the distribution of these particle sizes will be similar to the distribution of particle sizes generated during dredging at Geraldton.
- It is assumed that 40% of these fines will be released at the cutter head and 40% from the 'dewatering' discharge from the MOF. The remaining 20% of fines is assumed to be retained inside the MOF bund.

4.4.2 LNG Access Channel

For the simulation of the dredging of the LNG access channel and turning basin using a Trailer Suction Hopper Dredge (TSHD) and CSD on the eastern side of Barrow Island the following assumptions were made in developing the simulated dredge log.

- The total volume to be dredged is estimated to be 6.5 Mm³.
- Roughly 40% (2.6 Mm³) of the total volume to be dredged in the LNG access channel and turning basin areas is unconsolidated sandy sediment which can be removed by a TSHD.
- The TSHD dredging and disposal cycle period will be approximately 2.5 hrs (based on 90 minutes of dredging, 1 hour of travel to and from spoil ground including 10 minutes for dumping at the spoil ground).
- TSHD's are less weather dependent than CSD's and will be able to deliver about 134 hours production per week which equates to 53 loads per week on average.
- Assuming an average load of 5,000 m³, giving a rate of approx. 250,000 m³ per week, the sands can be removed in approximately 10 to 12 weeks.
- In general, maintenance will be undertaken whilst travelling to and from the spoil grounds but the TSHD will cease operations for two days every 4 to 6 weeks to refuel and undertake major maintenance.

- The TSHD will overflow for the last 60 minutes of the dredging cycle.
- Overflow water will be released under the keel of the TSHD at a depth of approximately 6 m below surface.
- Overflow discharge will be approximately 8 m³/sec (2 x 4 m³ /sec dragheads).
- Fines within the sediments may be released.
- The sands are coarser than the 'rock flour' and the particle size distribution used in this part of the simulation is based on laboratory analyses of field samples taken from the Development area.
- The harder material will be removed by a large CSD pumping directly into one of two self-propelled hopper barges that will transport the material to the spoil ground.
- CSD dredge behaviour and production rates are anticipated to be similar to those for the MOF access channel dredging rates described earlier (effective production of 84 hours/week).
- CSD dredging is anticipated to continue for 48 weeks.
- 40% fines will be generated at the CSD cutter head and 40% released from the hopper barge overflow which will be beneath the keel of the barge, the remaining 20% will be transported to the spoil ground.

4.5 Particle Size

The action of the dredge cutter head creates sediment and the vessel(s) propellers mobilize natural sediments. Fine particles settle more slowly and are deposited in quiescent zones further from the dredging site. Coarse particles settle rapidly close to the source. The major focus in the dredge modelling was on the liberation of fine particles into the water column producing turbidity and some far-field sedimentation. The near-field sedimentation of heavier particles was not modelled as these particles are assumed to settle very close to the dredged areas and as they are too heavy to be resuspended they need not be modelled.

Only particles with a diameter less than 150 µm were included in the hydrodynamic modelling. The range of particle sizes used in modelling the dredging of sands by the TSHD was considerably coarser than the particles used in the modelling the behaviour of 'rock flour' generated by the CSD.

The dumping of material at the spoil ground however was simulated using the full distribution of particle sizes assumed to be in the barge hoppers.

5 Modelling

5.1 Model Sensitivity Tests

The dredge modelling was carried out by Global Environmental Modelling Systems (GEMS) in two steps. Firstly the 3-dimensional ocean circulation of the region from Northwest Cape to north of the Montebello Islands was predicted for 16 months using GCOM3D. Then the total dredge program was simulated over 465 days using DREDGETRAK which simulates the half-hourly behaviour of the dredge(s) based on an estimated dredge log.

Modelling relied on the best available meteorology and bathymetry and model assumptions were based on other recent dredging programs in Western Australia. Where there was uncertainty in model parameters, conservative values were chosen such that the model would tend to overestimate the impact. The 'base case' modelling started in April, with pauses during coral spawning, and extended through two winters (more north-easterly winds) and one summer (more southerly winds). In order to facilitate comparisons with the information presented in the Draft EIS/ERMP, an additional model scenario was run with an October start date.

Modelling predicted the distribution of particles generated by the dredging that caused plumes of TSS and sedimentation on the seabed at hourly intervals over the total dredge program (approximately 465 days). Turbidity and sedimentation data were computed hourly for each 1 m layer of the water column of the study area. The hourly output was analysed to derive periods of exposure to turbidity and/or sedimentation in relation to a prior defined BPP health thresholds.

Model sensitivity tests involved varying key parameters and assumptions and examining the resultant effects on the model output. Changes in model output were assessed by comparison of the size, shape and location of the BPP impact zones.

5.1.1 Scheduling

Dredge plume modelling undertaken for the Draft EIS/ERMP assumed an October start for the dredging of the access channels for the Materials Offloading Facility (MOF) and Liquefied Natural Gas (LNG) loading facilities. The likelihood of a six month delay in commencing the dredging has been addressed by using an April start date for the revised dredging model. The potential ramifications of the rescheduling are discussed in later sections.

5.1.2 Particle Size (Extra Fines)

It is assumed in the hydrodynamic model that under 'normal' operating conditions 5% of total material cut by the CSD will be below 75 µm and that the distribution of these fine particle sizes will be similar to the distribution of particle sizes generated during dredging at Geraldton.

However, the rock to be dredged on the east coast of Barrow Island may be slightly harder on average than that encountered at Geraldton. It is currently unknown whether harder limestone rock will actually decrease the amount of fines produced during dredging, through greater fracturing, or increase the amount of fines due to greater 'crumbling' of the rock.

In the absence of directly relevant data, doubling the amount of fines produced during dredging by the CSD was considered to be a highly conservative scenario that would provide an indication of the sensitivity of the model to increased fines production. It is worth noting that due to the very small size of the fines produced (<75µm) under this scenario, this material is not expected to settle on the seabed and is assumed to contribute only to TSS and not to sedimentation. Resultant outputs are therefore based only on TSS threshold criteria.

5.1.3 Interannual Variation

Variations in the meteorology, especially changes in dominant wind patterns, will produce variations in the spatial and temporal distribution of sediment plumes. Potential interannual variability has been addressed by modelling three separate time periods that represent the likely scale of meteorological scenarios that may occur during dredging.

The meteorological data for 2001 was chosen to represent the 'normal' meteorology of the area, primarily because of fewer anomalies to easterly or westerly wind patterns. The previous year, 2000, was a year with a greater number of 'easterly anomalies' and was chosen to represent a period with more easterly events. The year 2002 displayed more 'westerly anomalies' and the meteorology from this year was chosen to represent a period of more westerly winds on the predicted behaviour of sediment plumes (see Technical Appendix B5 of the Draft EIS/ERMP for further detail).

All model runs included continuous 16 month time series of meteorological data, with the assumption that dredging starts in April of the appropriate year, i.e. for a 'normal' year the modelled dredging began in April 2001 and finished in July 2002.

5.2 Current Model Scenarios and Comparisons

A 'Base Case' model scenario was established using the anticipated scheduling and the newly developed cumulative coral threshold criteria (see Section 7.4.2).

5.2.1 Interannual Variation

Interannual variation was assessed by comparing the 'Base Case' or 'normal' year with 'atypical' years. The three years were:

- A 'normal meteorology' year (April 2001 to July 2002) – 'Base Case'.
- A 'more westerly events' year (April 2002 to July 2003).
- A 'more easterly events' year (April 2000 to July 2001).

5.2.2 Persistence of Sedimentation Loads

The 'Base Case' was continued with 'normal meteorology' for a further 48 weeks to investigate the stability of dredged material that had been deposited on the seabed. This scenario characterises the potential for recovery of physical benthic habitats that have been altered through sediment deposition and accumulation. Recovery of the physical habitats is necessary for recovery of the associated BPP communities.

5.2.3 Double Proportion of Fine Particles

A 'normal meteorology' year (April 2001 to July 2002) that assumes that twice as much fine material (<75 µm) is produced during dredging.

5.2.4 Test of Threshold Conservatism

A 'normal meteorology' year (April 2001 to July 2002) with more conservative cumulative threshold criteria as recommended by the DoE.

5.2.5 Comparison with Draft EIS/ERMP

The modelling presented in the Draft EIS/ERMP was based on dredging starting in October. The prediction of impact zones was based on 'consecutive' BPP health criteria.

Impact zones generated by 'Base Case' modelling using 'consecutive' BPP health criteria were compared with the same zones generated using the new cumulative criteria.

The effects of changes to the dredge schedule were examined by comparing impact zones generated from an October start with the same zones generated from an April start, with both scenarios modelled using 'normal' meteorology.

6 Interpreting the Model

The figures showing the zones of high and moderate impact and the zone of influence should be interpreted on the basis of the following:

- All plots show elevated TSS or sedimentation due to dredging. The 'above background' levels do not include natural turbidity or sedimentation.
- All potential sources of turbidity and sedimentation have been included in the simulations, including direct release by the dredge and suspension due to propeller wash.
- The TSS concentrations represent the highest TSS concentrations within any 1 m depth bin through the water column. The plots therefore show the maximum turbidity and are not 'depth-averaged'.
- It was assumed that particles greater than 150 microns settle quickly, remain within the vicinity of the dredged areas and are not resuspended.
- The behaviour of particles greater than 150 microns liberated during dredging was therefore not simulated in order to focus on the more active, smaller particles.
- Sedimentation impact zones generated from the modelling did not include the impacts in areas adjacent to the dredging areas due to heavier particles. These zones have been estimated on the basis of experience with previous dredging operations (GEMS, pers. comm., 2006) and include a substantial precautionary buffer. The areas receiving particles >150 microns are completely encompassed by the area of deposition of smaller particles.
- The full range of particle sizes expected to be released at the spoil ground was simulated in order to study spoil ground stability over time.
- The model incorporates the best available data for parameters and assumptions, but no model can perfectly simulate the behaviour of water-borne particles in space and time. The output of the model, including the impact zone figures, provide a 'best estimate' of potential impacts from the dredging program. Changes in operation of the dredge, weather patterns or particle characteristics will affect the actual plume behaviour and associated environmental impacts.

7 Impacts to Benthic Primary Producers

7.1 Coral Health Criteria and Other BPP

Conservative coral health criteria were selected to predict the effects of dredging and other construction activities on this component of the ecosystem. Coral reefs are the most highly valued component of the marine ecosystem from many perspectives, principally related to their high ecological diversity, longevity and relative stability in the absence of impacts. The high value of coral communities in the Barrow Island region is reflected in the Indicative Management Plan for the proposed Montebello/Barrow Islands Marine Conservation Reserves where the Barrow Island Marine Park has been established to protect coral communities. This is in contrast with other marine BPP, such as seagrass and macroalgae which have been given no special protection apart from inclusion within the multiple use area of the Marine Management Area (CALM, 2004).

The consequence of the loss of well developed coral assemblages is considered more serious than the loss of other marine BPP as they may take decades to fully recover. Other BPP communities in the impact zones, for example the seagrasses and macroalgae are able to rapidly recolonise disturbed areas.

Cyclone Vance devastated large areas of *Halophila* seagrass meadows in Exmouth Gulf in March 1999. Within eight months of the cyclone, the seagrass had begun to re-establish and by 2001 the areal extent and species richness of the seagrass community had increased greatly. The average seagrass cover increased from 0.15% to 41.9% and biomass values rose to 70 gm⁻², which is capable of supporting a high abundance of juvenile tiger prawns (Loneragan *et al.*, 2003). The re-establishment of seagrass in Exmouth Gulf has been accompanied by increased sightings of Dugong (Loneragan *et al.*, 1998).

Algal turf communities are relatively resilient and have impressive rates of recolonisation when compared with corals. Airoldi (1998) found that algal turf was relatively impervious to disturbance and high rates of vegetative reproduction provided the capability to resist further disturbance and to compete for space against larger macroalgae. During a study on successional patterns on an artificial reef in the Philippines, Pamintuan *et al.* (1994) observed that the initial coloniser of the artificial reef was turf algae which appeared within two weeks of reef establishment. Bailey-Brock (1989) also reported that algal turf species were rapid colonisers, colonizing an artificial reef in Hawaii within 2 weeks. Fabricius and De'ath (2001) reported dead corals being colonised by filamentous turf algae within days in all reef environments, and McVey (1970) recorded the colonization of five species of algae on concrete pipes within 12 hours (Bailey-Brock, 1989).

Succession from turf algae to crustose coralline algae (CCA) assemblages generally occurs within a few months when environmental conditions are suitable (Fabricius & De'ath, 2001). Bailey-Brock (1989) observed in Hawaii that the change from filamentous algae to CCA occurred after two months, and that after a year there was a larger proportion of CCA to fleshy species of algae, with the succession being most conspicuous during the summer months.

Fleshy-macroalgae also rapidly recolonise denuded or new substrates. Experimental studies looking at the recolonisation of *Sargassum*, which is one of the dominant brown macroalgae in the waters around Barrow Island, found that in tropical habitats they recolonise bare substrate in the space of 3-4 months (Ang, 1985). On the Great Barrier Reef, Vuki & Price (1994) found new recruits of *Sargassum* in cleared quadrats three months after the clearing of the substrate, when the substrate was cleared during the reproductive season. The life history characteristics of *Sargassum* promote rapid recolonisation capabilities in this genus. In tropical regions most *Sargassum* species are fertile for five months of the year, generally over summer (Ang, 1985; Vuki & Price, 1994). This long reproductive season coupled with the characteristically high fecundity of marine alga, enables effective recolonisation of cleared or open substrata in marine environments (Paine, 1979). It is anticipated that sedimentation may lead to loss of fleshy thallus, but the plants will regenerate from persistent stipes attached to the underlying rock (Umar *et al.*, 1998).

The invertebrate epifauna associated with marine BPP communities can also recover very rapidly from high magnitude disturbances. Martin-Smith (1994) reported that some taxa were present within 6 hours of complete defaunation and within two weeks, the re-established epifaunal communities were indistinguishable from controls. A study of the recovery rates of copepod assemblages in a temperate seagrass habitat after an anoxic event demonstrated that recolonisation started quickly after the end of the disturbance and within 5 days the abundance and diversity of copepods in the previously disturbed areas had reached an equilibrium with the control plots (Cristoni *et al.*, 2004). These small macrofauna are an important trophic link between the macrophytes and the larger fauna usually associated with them.

Populations of large invertebrate fauna, a significant contributor to coral reef diversity, are also able to recover rapidly after impacts. For example, within 2 years of dredging at Heron Island on the Great Barrier Reef, gastropod numbers had recovered to pre-dredging levels (Catterall *et al.*, 1992). A study of colonization rates of an artificial reef in Hawaii by Bailey-Brock (1989), reported that within two weeks many invertebrates had colonised the substrate, the dominant ones being the rock oysters, tubeworms and encrusting bryozoans. This author also reported that similar invertebrate taxa were among the most frequent recruits in studies on the Great Barrier Reef, the Red Sea and in Hawaii.

Some coral assemblages may recover rapidly from disturbance (Brown *et al.*, 2002). In contrast, some well developed coral assemblages may take years to decades, or longer, to recover fully (Connell *et al.*, 1997). Thus, the protection of coral habitat is of paramount importance in protecting coral reef assemblages. Protection of coral assemblages is considered a conservative means of protecting ecosystem diversity and function because shallow water coral assemblages are generally more sensitive to sedimentation and turbidity.

7.2 Recolonisation and Recovery of Coral Reefs

Coral reefs are affected by the direct impacts of dredging, e.g. removal, and the indirect impacts, such as turbidity and sedimentation stress. Long term studies (~30 years) of coral reef recovery after disturbance have shown that time scales of recovery depend upon the type and scale of damage (Connell *et al.*, 1997). For example, in the shallow subtidal communities on Heron Island, Great Barrier Reef, a long term study of the effects of cyclones showed that when the substrate was not directly affected by disturbance, the time scale of recovery was up to a decade (Connell *et al.*, 1997). In contrast, when the physical environment was directly altered by disturbance recovery was related to the time scale of recovery of the benthic habitat (Connell *et al.*, 1997).

Corals have the ability to compartmentalize sedimentation stress. Philipp and Fabricius (2003) demonstrated that the photosynthetic activity from tissues directly underneath the sediment declined, while the activity in the adjacent clean tissues did not. Furthermore, only colony parts directly exposed to large amounts of sediment died and other parts of the colony remained healthy. If a dredging event damaged but did not kill entire colonies, much of the recovery may be from regrowth of the survivors (Connell *et al.*, 1997). In comparison, if most individuals are killed by an extreme disturbance, recovery will depend almost entirely upon recruitment from elsewhere, and the recovery of the coral assemblage and associated fauna will be slower.

A long term monitoring program of reef flats in Thailand between 1983-2000 (Brown *et al.*, 2002) afforded an opportunity to study the recovery of the reef flat after dredging took place in 1986-1987. The reef flats largely recovered from the dredging impacts in approximately 12 months (Brown *et al.*, 2002). Coral cover and diversity values returned to former levels only 22 months after dredging began (Brown *et al.*, 1990). This was attributed to the fact that the reef flats were dominated by massive coral species, whose morphology exposed only the upper surfaces of the colonies to sedimentation and only the polyps on the upper surface died. The polyps on the shaded edges and sides of the colonies survived and recolonised the upper surface. In addition, the recruitment and survival of juvenile corals was relatively unaffected by dredging activities (Brown *et al.*, 2002).

Massive species are also resilient to sublethal impacts, such as bleaching. For example, in the Maldives, differential recovery after bleaching led to many reefs being dominated by massive corals such as *Porites* and *Astreopora* (McClanahan, 2000). Branching corals did not recover as well as massive species. After 12 months, branching and encrusting species such as *Acropora*, *Montipora* and *Pocillopora* had started recruiting, suggesting that there may be future changes in the species composition of these reefs (McClanahan, 2000). Acroporids grow rapidly but may not recruit to disturbed areas effectively. Recruitment of *Acropora* four years after widespread mortality in the Western Indian Ocean was low (but increasing) in comparison with faviids (Sheppard and Obura, 2005).

The coral assemblage at Dugong Reef, approximately 5 km south east of Barrow Island was severely affected by a natural stress event in 1991, during which large areas of tabular and branching *Acropora* died. This widespread coral mortality was attributed to water column hypoxia following mass coral spawning in combination with high temperature stress (LeProvost Environmental Consultants, 1992). By 1994, coral recovery in areas of large scale mortality was minimal. This contrasted with a small reef closer to Barrow Island where *Acropora* were similarly affected but a variety of genera, such as *Acropora*, *Porites*, *Pectinia* and *Echinopora* had recruited (Bowman Bishaw Gorham, 1994). Coral habitat mapping for the Gorgon Project in 2005 revealed that sections of Dugong Reef previously dominated by *Acropora* and killed in 1991 and large areas of dead branching *Acropora* on nearby Batman Reef had still not recovered (RPS BBG, unpublished data, 2005).

7.3 Timescales of Recovery

With the exception of well developed coral assemblages, the majority of marine BPP and BPPH within high and moderate impact zones are expected to recover within the first 5 years following dredging. If BPP and BPPH are estimated to take longer than 30 years to recover, they have been identified as loss in the BPPH assessment.

Predicted impacts to marine BPPH in the high impact zone and moderate impact zone are described in Table 1. The concentration of TSS and rate of sedimentation outside of the zone of moderate impact and within the zone of influence is not expected to have a measurable effect on BPP and no impacts are predicted to occur in this zone.

Recovery of non coral BPP, such as macroalgae and seagrass communities within high and moderate impact zones is expected to occur within 2 to 5 years. Coral communities are expected to recover within 5 years in moderate impact zones if reefs are dominated by massive coral species, such as *Porites*.

The highly conservative long term 30 year recovery period allows for a further 25 to 28 year time frame after the initial recolonisation/regrowth of massive coral species for the recovery of populations of rare taxa that might only recruit infrequently.

Table 1: Predicted Impacts to Marine BPPH in the High Impact Zone and Moderate Impact Zone									
Benthic Habitat Type	Key Receptor	Reason for Selection	High Impact Zone			Moderate Impact Zone			
			Predicted effects	Presence in zone	Recovery time frame	Predicted effects	Presence in zone	Recovery time frame	Recovery time frame
Coral communities – more resilient species – Large bomboora	<i>Porites lobata</i>	Large colonies; widespread; important ecologically; resilient but slow growing	High mortality (up to 100%)	Yes (MU 4 & 8)	Permanent loss (>30 yr recovery)	Some mortality (up to 30%)	Yes	Temporary loss, recovery in 2-5 yrs	
Coral communities – more sensitive species – coral thickets	<i>Acropora</i> spp.	Small colonies; large thicket on southern Lowendal Shelf; sensitive but fast growing	High mortality (up to 100%)	No	NA	High mortality (possibly to 100%)	No	NA	
Macroalgae (limestone reef)	<i>Sargassum</i> spp.	Most widespread and abundant genus on hard substrates	High mortality (up to 100%)	Yes (MU 4, 7 & 8)	Temporary loss, recovery in 2-5 yrs	High mortality (possibly to 100%)	Yes	Temporary loss, recovery in 2-5 yrs	
Subtidal reef (low relief) and sand with seagrass	<i>Halophila ovalis</i>	Most abundant and widespread genus; ephemeral	High mortality (up to 100%)	Yes (MU 4, 8, 9, 10 & 11)	Temporary loss, recovery in 2-5 yrs	High mortality (possibly to 100%)	Yes	Temporary loss, recovery in 2-5 yrs	

7.4 Sedimentation and Turbidity Threshold Criteria

7.4.1 Consecutive Criteria

High turbidity and sedimentation stress over extended periods has been shown to have detrimental effects on corals and other BPP. The literature reports the effects of persistent stress, or 'press' impacts rather than intermittent or 'pulse' impacts.

Preliminary modelling suggested that persistent plumes are predicted to last for weeks in close proximity to dredging operations, rather than short pulses of a few days. The greatest effects of sedimentation and elevated TSS on corals are likely to be due to a continuous reduction in the light climate and/or continuous sediment deposition because the corals have no recovery time to remove sediments or to photosynthesise. The effects of continuous stress were represented by threshold criteria comprising elevated TSS or sedimentation over a number of consecutive days in the Draft EIS/ERMP.

Impacts of increased and persistent sedimentation and suspended solid concentrations on corals and other BPP were assessed by setting highly conservative threshold criteria for coral responses to 'press' stressors and using these to predict the range of effects due to the proposed dredging and drilling programs. Both the length of time corals are exposed to increased suspended sediment loads and the amount of suspended and deposited sediment were assumed to affect the severity of the impacts to any coral or marine BPP. The criteria incorporate a high level of conservatism to account for possible additive effects of increased TSS and sedimentation events that occur together. A detailed description of the previously modelled consecutive coral threshold criteria can be found in Section 11.3.1 of the Draft EIS/ERMP and are provided in Table 2.

However, pulses of elevated TSS or sedimentation every few days may have cumulative effects on corals and other BPP if there is not sufficient 'recovery' time between the pulses. Following the release of the Draft EIS/ERMP and the AIP, concern was raised over the potential cumulative impacts of TSS and sedimentation to corals and other marine BPP that would not be accounted for using consecutive criteria. In order to resolve this issue, cumulative coral health threshold criteria that take into account both the intensity and duration of stressors over given time periods have been developed and are described [below](#).

7.4.2 Cumulative Criteria

Cumulative threshold criteria have been designed to account for the intensity and duration of the sediment plume within a longer 'rolling' time period. By design, previously modelled consecutive criteria will be contained within the new cumulative criteria. For example, consecutive coral health threshold criteria modelled in the Draft EIS/ERMP, e.g. the zone of high impact due to acute stress of $\geq 25 \text{ mg cm}^{-2} \text{ d}^{-1}$ of sediment above background levels for five consecutive days is encompassed by the new and more conservative cumulative coral health threshold criterion of $\geq 25 \text{ mg cm}^{-2} \text{ d}^{-1}$ above background for any five days in a 15 day period. The five days of exceedance within the 15 day period may or may not be consecutive, but regardless of whether they are consecutive or cumulative will trigger, the high impact criterion.

While there is very limited relevant literature on cumulative effects the cumulative criteria are based on a one third exposure time vs two thirds recovery time to allow for a minimum recovery time between pulse events. This was based on the available published material, including laboratory and field observations. Great Barrier Reef corals exposed to high sediment loads ($79\text{-}234 \text{ mg cm}^{-2}$) for 24 hours needed 36 to 48 h to recover (Philipp and Fabricius, 2003). Studies on sediment rejection by 22 species of Australian scleractinian corals by Stafford-Smith (1993) showed that most species cleared a 200 mg cm^{-2} dose of sediment within 2 days (48 h) and that fine sediment ($<250 \mu\text{m}$) was removed faster than coarse sediment ($>500 \mu\text{m}$).

The cumulative levels set for this assessment are considered to be highly conservative since other research suggests corals can withstand prolonged periods of sedimentation and turbidity. For example, Rogers (1983) showed that *Acropora cervicornis*, *Montastraea anularis* and *Diploria stitigosa* survived extreme sedimentation at $200 \text{ mg cm}^{-2} \text{ d}^{-1}$ for 45 continuous days without extensive damage. In another experiment, complete shading of a coral reef by Rogers (1979) to simulate extreme turbidity revealed that 9 out of 10 coral species showed few deleterious effects after three weeks of darkness, with only *A. cervicornis* showing extensive bleaching after 21 days.

Consistent with the consecutive criteria in the Draft EIS/ERMP, the cumulative effects of increased TSS on corals are assumed to be dominated by daytime effects and the coral health threshold criteria are based on a TSS concentration above background which

exceeds set values for at least half of the daylight hours (6 out of 12 hours) in any day. The zone of influence represents TSS concentrations of 2 mg l^{-1} above background in any hourly period at any depth during the entire dredging programme.

Sedimentation may affect the feeding efficiency of corals at night and the cumulative threshold criteria are therefore based on a daily load (24 h) to account for possible smothering, abrasion, energetic depletion and reduced feeding efficiency during the day and night. Sedimentation impact criteria are based on daily sedimentation rates as presented in Table 2. Cumulative impact criteria represent specified daily sediment loads for a specific number of days in a

defined period, e.g. for 5 days in a 'rolling' 15 day period. The zone of influence represents sedimentation $\geq 1 \text{ mg cm}^{-2}$ above background at any time during the entire dredging programme.

As a conservative measure, the sedimentation criteria assume that all material that settles will accumulate and does not account for re-suspension.

Details of cumulative coral health threshold criteria are contained in Table 2. Previously modelled consecutive coral health threshold criteria are also provided for comparative purposes. For a detailed description of the derivation of concentration thresholds, see Section 11.3.1 of the Draft EIS/ERMP.

Table 2:
Cumulative and Consecutive Coral Health Threshold Criteria

Zone of High Impact			
Variable	Timeframe	Concentration	Time (consecutive days)
TSS	Short	$\geq 25 \text{ mg l}^{-1}$	5
	Medium	$\geq 10 \text{ mg l}^{-1}$	20
	Long	$\geq 5 \text{ mg l}^{-1}$	80
Sedimentation	Short	$\geq 25 \text{ mg cm}^{-2} \text{ d}^{-1}$	5
	Medium	$\geq 10 \text{ mg cm}^{-2} \text{ d}^{-1}$	20
	Long	$\geq 5 \text{ mg cm}^{-2} \text{ d}^{-1}$	40
Zone of Moderate Impact			
Variable	Timeframe	Concentration	Time (cumulative days)
TSS	Short	$\geq 25 \text{ mg l}^{-1}$	5 in 15
	Medium	$\geq 10 \text{ mg l}^{-1}$	20 in 60
	Long	$\geq 5 \text{ mg l}^{-1}$	80 in 240
Sedimentation	Daily	$\geq 100 \text{ mg cm}^{-2} \text{ d}^{-1}$	1
	Short	$\geq 25 \text{ mg cm}^{-2} \text{ d}^{-1}$	5 in 15
	Medium	$\geq 10 \text{ mg cm}^{-2} \text{ d}^{-1}$	20 in 60
	Long	$\geq 5 \text{ mg cm}^{-2} \text{ d}^{-1}$	40 in 120
Zone of Moderate Impact			
Variable	Timeframe	Concentration	Time (consecutive days)
TSS	Short	$\geq 25 \text{ mg l}^{-1}$	2
	Medium	$\geq 10 \text{ mg l}^{-1}$	7
	Long	$\geq 5 \text{ mg l}^{-1}$	20
Sedimentation	Short	$\geq 25 \text{ mg cm}^{-2} \text{ d}^{-1}$	2
	Medium	$\geq 10 \text{ mg cm}^{-2} \text{ d}^{-1}$	7
	Long	$\geq 5 \text{ mg cm}^{-2} \text{ d}^{-1}$	20

Table 2:
Cumulative and Consecutive Coral Health Threshold Criteria (continued)

Zone of Moderate Impact (continued)			
Variable	Timeframe	Concentration	Time (cumulative days)
TSS	Short	$\geq 25 \text{ mg l}^{-1}$	2 in 6
	Medium	$\geq 10 \text{ mg l}^{-1}$	7 in 21
	Long	$\geq 5 \text{ mg l}^{-1}$	20 in 60
Sedimentation	Daily	$\geq 50 \text{ mg cm}^{-2} \text{ d}^{-1}$	1
	Short	$\geq 25 \text{ mg cm}^{-2} \text{ d}^{-1}$	2 in 6
	Medium	$\geq 10 \text{ mg cm}^{-2} \text{ d}^{-1}$	7 in 21
	Long	$\geq 5 \text{ mg cm}^{-2} \text{ d}^{-1}$	
Zone of Influence			
Variable	Concentration		Time
TSS	$\geq 2 \text{ mg l}^{-1}$		In any daylight period
Sedimentation	$\geq 1 \text{ mg cm}^{-2}$		During any 24 hr period

7.5 Zones of Impact

Consistent with the impact assessments in the Draft EIS/ERMP, two zones of differing levels of impact and one zone of influence were established. These zones were defined on the basis of both sediment load and exposure time above background levels, taking into account published values for acute (short-term), medium-term and chronic (long-term) responses to both sedimentation and elevated total suspended solids (TSS). See Section 11.3.1 of the Draft EIS/ERMP for further detail. The same approach has been undertaken for this assessment using the cumulative criteria and the updated model assumptions for each model scenario. Three zones have been delineated:

- The 'zone of high impact' with possible high to total mortality of corals, macroalgae and seagrasses.
- The 'zone of moderate impact' with potential for significant losses of sensitive coral species and macrophytes, and partial loss of resilient species.
- The 'visible plume and extent of sedimentation' where turbid water plumes and/or sedimentation will occur, but are not expected to have a measurable impact upon benthic primary producers.

The predicted impacts to the main BPP communities within the two impact zones are presented with expected recovery times in Table 1. Conservatism built into each criterion and the definition of each zone means that a range of potential impact levels are plausible within each zone. For example, in the high impact zone, effects may range from total mortality of all corals to mortality of specific coral taxa, mortality of individual colonies or partial death of colonies. The impact assessment assumes total loss of all BPP in the high impact zone.

These zones of impact and influence have been plotted over the revised Development Plan and the regional benthic habitat database to indicate which benthic habitats lay within each impact zone.

8 Model Results

The results of the hydrodynamic modelling and analyses of the model output to determine zones of impact based on BPP health criteria are presented in the following sections. Sections 8.1 to 8.7 describe the results of the tests of the model's sensitivity to changes in key parameters and the effect of different model scenarios on the size and shape of the impact zones. The environmental impacts to BPPH, associated with the 'Base Case', are described in section 8.8.

8.1 Interannual Variation

8.1.1 'Normal' Meteorology

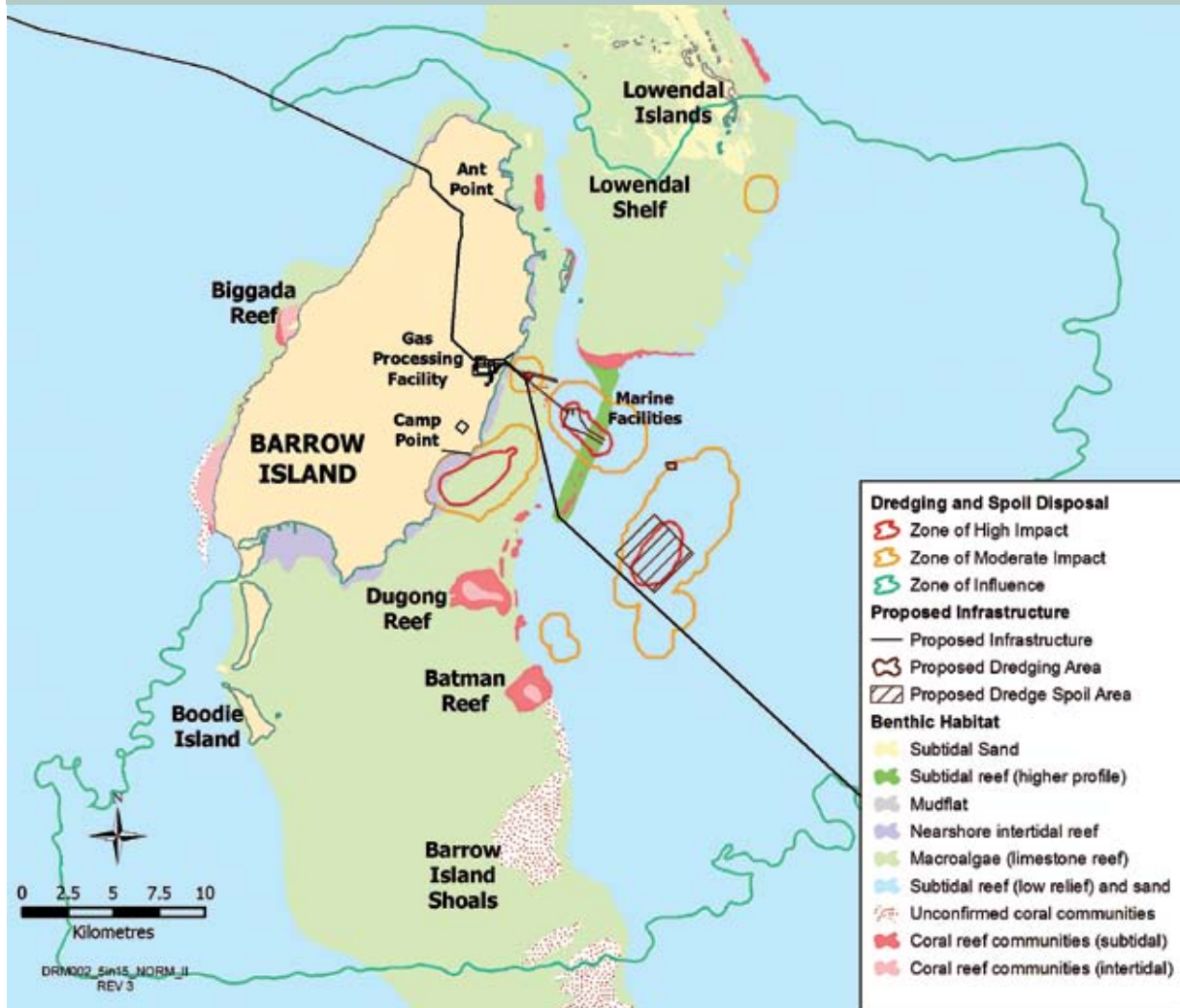
The 'normal' meteorology scenario (Figures 3 & 4) represents the areas of seabed most likely to be influenced by TSS and sedimentation from the proposed Development. This scenario is considered to be the 'Base Case'. Zones of high impact, moderate impact and influence have been delineated based on the standard cumulative coral sensitivity criteria and hydrodynamic modelling described in previous sections.

High impact zones are generally restricted to the vicinity of the MOF and extend up to a maximum of approximately 1 km from the proposed LNG access channel, turning basin and spoil ground (Figure 4). An additional high impact zone is predicted to occur close to the island near Shark Beach, south of Camp Point (Figure 4). This is due to persistent and elevated TSS concentrations in the area as a result of local circulation patterns.

The zones of moderate impact associated with dredging on the east coast of Barrow Island generally surround the zones of high impact indicating a cline of TSS concentrations and sedimentation rates. The moderate impact zone extends a further 1 km from the high impact zone around the MOF and up to a further 2 km from the high impact zone around the LNG loading facilities and turbid plume south of Camp Point (Figure 4). The moderate impact zone around the spoil ground is also predicted to spread further north-east and south than the high impact zone with an additional zone of moderate impacts predicted to occur to the north of Batman Reef and another just south of the Lowendal Islands on the eastern Lowendal Shelf (Figure 4).

The zone of influence, where transient and very low levels of TSS and sedimentation may occur during dredging, stretches for up to 40 km from the dredging and spoil disposal locations (Figure 3). The levels of TSS and sedimentation in this zone are very low and are not expected to have a measurable impact on marine BPP or their habitats.

Figure 3:
The Anticipated Area of Impact (Base Case) Associated with Dredging and Spoil Disposal Under 'Normal' Meteorology



No regionally significant coral assemblages or well developed assemblages of sensitive *Acropora* corals are predicted to be affected by dredging under the 'Base Case' scenario. The scattered *Porites* bomboora within the high impact areas around the MOF and LNG channel may be severely affected and if they suffer total mortality would take more than 30 years to recover. Scattered coral communities on nearshore pavement, such as *Turbinaria*, may suffer effects ranging from bleaching of individual colonies to partial mortality (<30%) of some individuals in moderate impact zones. The main BPP seabed communities in the high and moderate impact zones, macroalgae dominated pavement and seagrass dominated sand, will recover relatively rapidly, (<5 years) in areas not permanently modified following the cessation of dredging activities.

8.1.2 'More Easterly Events' Scenario

The impact zones generated under the 'more easterly events' meteorology scenario (Figure 5) represent the areas of seabed most likely to be influenced by TSS and sedimentation if dredging is undertaken during a period of more easterly wind anomalies (more easterly winds than in an average year).

In general, easterly winds tend to push turbid plumes closer to Barrow Island, exacerbating impacts in nearshore waters. High impact zones are predicted to occur in similar locations to those under 'normal' meteorological conditions, with the exception of an additional, but small, high impact zone south-east of the spoil ground and another larger high impact zone south of the MOF (Figures 3 & 5).

Figure 4:

A Detailed View of the Anticipated Area of Impact Near the Proposed Marine Facilities Under the 'Normal' Meteorology (Base Case) Scenario

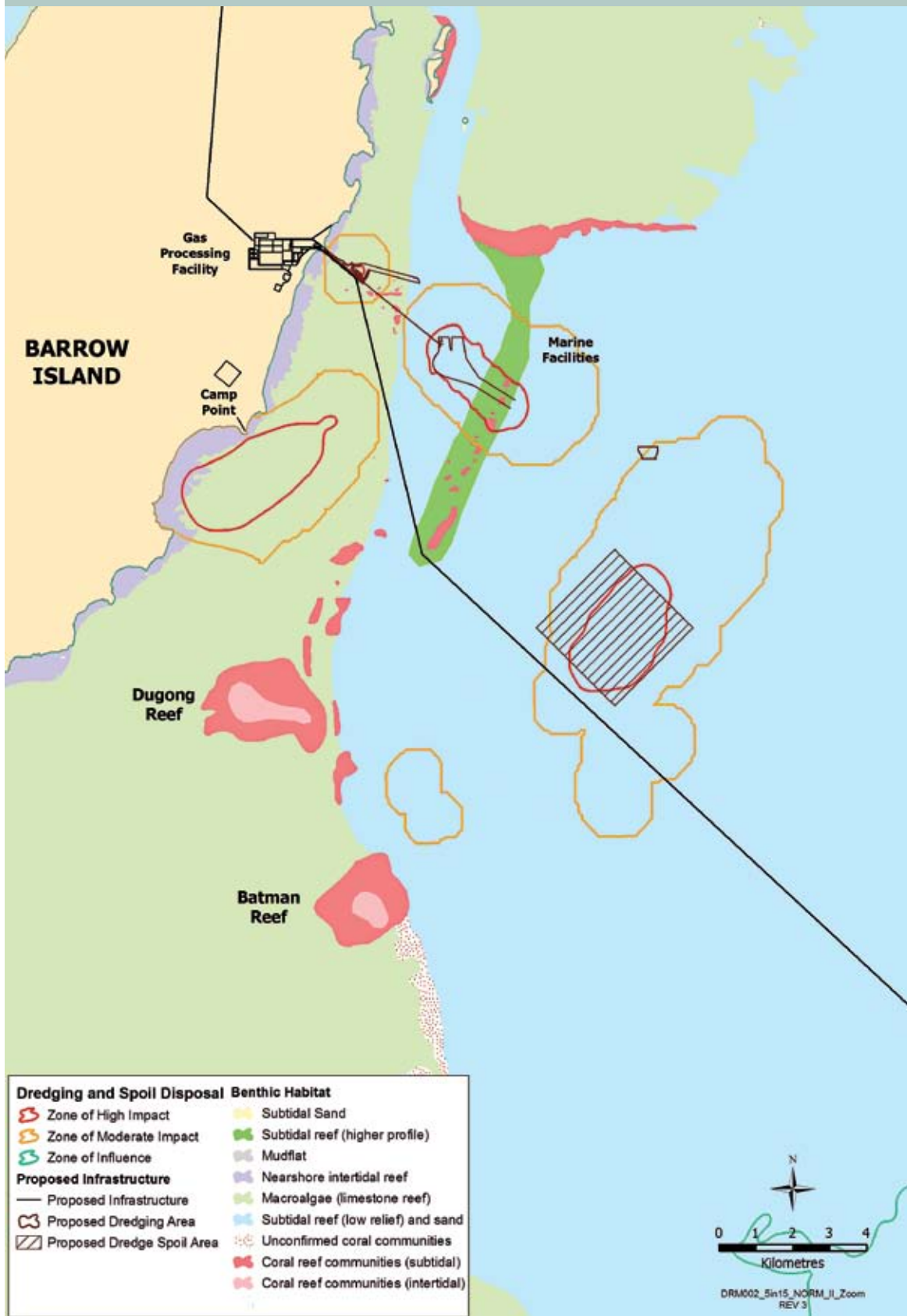
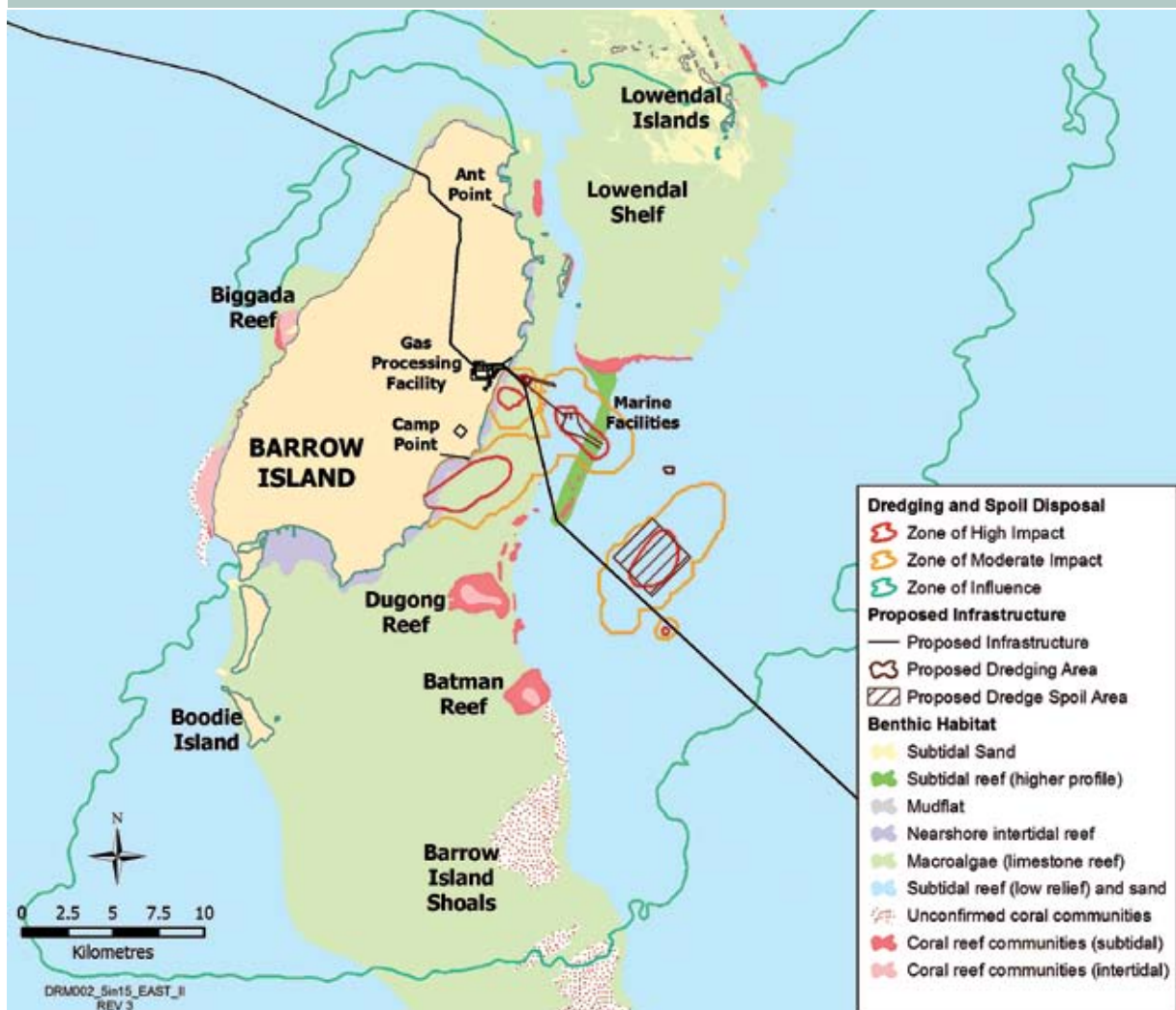


Figure 5:

The Anticipated Area of Impact Associated with Dredging and Spoil Disposal During 'More Easterly Events'



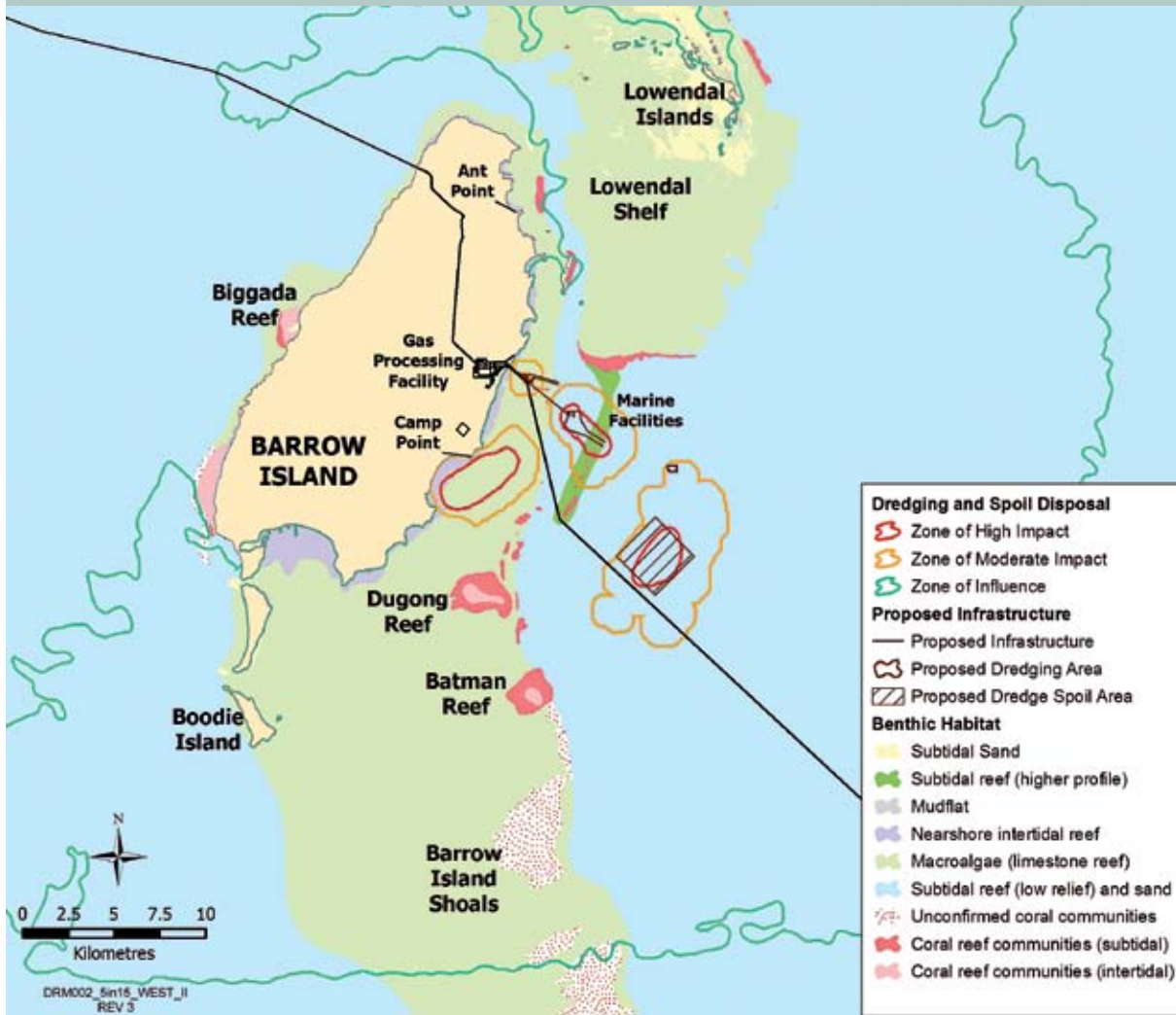
Moderate impact zones are also similar to those produced under 'normal' meteorological conditions, although they tend to be slightly larger with separate moderate impact zones 'joining' in nearshore waters to create larger zones of moderate impact (Figure 5). No moderate impacts on the Lowendal Shelf are predicated with more easterly winds.

Easterly wind anomalies tend to restrict the movement of the zone of influence to the west of Barrow Island, possibly due to enhancing dilution of the plume to $<2 \text{ mgL}^{-1}$. However this zone extends further to the north of the island than under 'normal' meteorological conditions (Figures 3 & 5). No impacts to BPP within the zone of influence are expected.

No regionally significant coral assemblages or known areas of sensitive *Acropora* corals are predicted to be affected by dredging during a 'more easterly events' period. *Porites bombora* within the high impact areas around the MOF and LNG channel will be similarly affected under this scenario as under the 'normal' scenario. The larger moderate impact zones in nearshore waters may include a greater number of scattered coral communities on nearshore pavement, such as *Turbinaria*, but does not include well developed *Acropora* communities. Impacts to corals in the moderate impact zone, apart from well developed *Acropora* thickets, are considered a short term impact as these corals will rapidly recolonise affected areas.

Figure 6:

The Anticipated Area of Impact Associated with Dredging and Spoil Disposal During 'More Westerly Events'



8.1.3 'More Westerly Events' Scenario

The 'more westerly events' meteorology scenario (Figure 6) represents the areas of seabed most likely to be influenced by TSS and sedimentation if dredging is undertaken during a period with more westerly wind anomalies.

Overall, more westerly wind anomalies have only a small effect on turbid water plumes compared to the 'normal' meteorology scenario. High impact zones are predicted to be very similar to those under 'normal' meteorological conditions and moderate impact zones, whilst showing small differences, are also of a very similar scale to those in a 'normal' year (Figures 3 & 6). During more 'westerly events', there is the

possibility that a greater number of *Porites bombora* will suffer moderate impacts as this zone stretches further south along the high profile subtidal reef than under the 'normal' meteorological scenario. The effects on *Porites* colonies in this zone would range from bleaching of individual colonies to partial (<30%) mortality of individual *bombora*. Small colonies of more sensitive coral species are likely to suffer very high mortality in this zone, although this is considered to be a short term impact as these corals will rapidly recolonise affected areas. No regionally significant coral assemblages or known areas of sensitive *Acropora* corals are known to occur in either the high or moderate impact zones under this scenario.

The zone of influence under the ‘more westerly’ scenario is also very similar to that predicted under ‘normal’ conditions, although it tends to extend further to the west and south (Figures 3 & 6). Marine BPP in this zone are unlikely to suffer any measurable effects due to dredging.

8.2 TSS Pulses and Sediment Accumulation

In order to explore any possible impacts to marine BPP from large spikes in TSS concentrations or the accumulation of sediment during the proposed dredging programme the behaviour and intensity of sediment plumes at selected sites were plotted (Figures 8 & 9). Details of the four locations for which time series plots have been presented are detailed in Table 3 and Figure 7.

Maximum daily TSS (mg l^{-1}) and on bottom sediment load (mg cm^{-2}) above background at each site is presented graphically for the 66 weeks of the proposed dredging programme (Figures 8 & 9).

At each site, TSS is predicted to vary markedly over short temporal scales, primarily due to the strong currents and tides in the waters offshore of the east coast of Barrow Island which rapidly dilute and disperse the turbid plumes. TSS is rarely expected to exceed 25 mg l^{-1} and no long term, persistent turbid pulses or very high levels of TSS are predicted to occur, even at sites close to dredging operations, e.g. Town Point Reef (Figure 8). Cumulative coral health threshold criteria at this site are ‘triggered’ by low levels of TSS for long periods, rather than short, high TSS pulses over several days.

Elevated TSS at Dugong Reef and on the Southern Lowendal Shelf is predicted to occur as a result of dredging and spoil disposal operations, although not a level that is predicted to have a measurable effect on local marine BPP. TSS at these sites is not expected to

exceed two or three times background levels on more than a small number of occasions. Further north, close to the Lowendal Islands, turbid plumes are expected to occur sporadically throughout the proposed dredging programme (Figure 8).

The time series sedimentation plots (Figure 9) show the daily accumulated sediment load at each of the modelled locations over the dredging programme. Rises in the graph indicate sediment settling on the seabed and contributing to on bottom sediment load. Declines in the time series plot indicate that a greater proportion of sediment is resuspended during that 24 hour period, reducing overall on bottom sediment load.

Very low levels of sedimentation are expected to occur in areas more than several hundred metres to 1 km from dredging and spoil disposal operations. Larger, heavier particles will tend to settle very close to dredging operations and will not resuspend under normal conditions. Fine material is predicted to continually settle and then resuspend, slowly diluting and dispersing into deeper, offshore waters.

Only very low levels of fine sediment are anticipated to accumulate on the seabed at the modelled locations, and then only at three of the four sites (Figure 9). The predicted levels of sediment accumulation at each site are far below those that are expected to have a negative effect on marine BPP. No large ‘pulses’ of sedimentation are predicted to occur under normal meteorological conditions (Figure 9).

8.3 Stability of Dredged Material

The 3-D hydrodynamic model was run for a further 48 weeks after the cessation of dredging to track the movement of particles liberated during dredging and spoil disposal. The model run was based on a ‘normal’ meteorology year (2001 start) and ‘snapshots’ of bottom sediment load (mg cm^{-2}) were output quarterly, starting immediately after dredging finished.

Table 3:
Location of Sites for Times Series Plots

Sites – Time Series Plots	Site Number	Easting	Northing
Town Point Subtidal Pavement Reef (South)	1	344225	7694674
Southern Lowendal Shelf Reef	2	345479	7700574
Dugong Reef	3	340179	7687827
Lowendal Islands Patch Reef	4	354578	7709154

Four 'snapshots' of bottom sediment load were output from the model, corresponding to the periods immediately following the cessation of dredging (week 0) and at 12, 24 and 48 week intervals after dredging (Figures 10, 11, 12 & 13, respectively).

It is important to note that the near-field sedimentation from larger, heavier particles (>150 µm) was not modelled, except at the spoil ground, as these particles are assumed to remain within the vicinity of the dredged areas. It is anticipated that this coarse material will be restricted to within several hundred metres of dredged channels and will only be mobilised in extreme weather conditions, such as during cyclones.

In practice this meant that for the dredging of the MOF, turning basin and access channel only particles of diameter less than 150 µm were included in the particle distribution. However, the dumping of material at the

spoil ground was simulated using the full distribution of particle sizes assumed to be pumped into the hopper barges. As a conservative measure, it was also assumed that 20% of fines produced during dredging would be transported to the spoil ground.

At the cessation of dredging (week 0) the hydrodynamic model predicted that the bottom sediment load at the spoil ground will be in the order of 100 to 10,000 mg cm⁻² (Figure 10). Thin veneers of sediment are expected to have accumulated on the seabed (1 to 20 mg cm⁻²) directly to the east and south-east of the LNG access channel and in patches to the south-west of the dredging and dredge spoil sites towards Boodie Island (Figure 10). Sediment load on the seabed beyond the spoil ground is very low (maximum of 20 mg cm⁻²) and is not predicted to have any measurable effect on marine BPP or BPPH.

Figure 7:

The Location of the Four Individual Sites Modelled to Produce Time Series Plots of TSS and Sedimentation

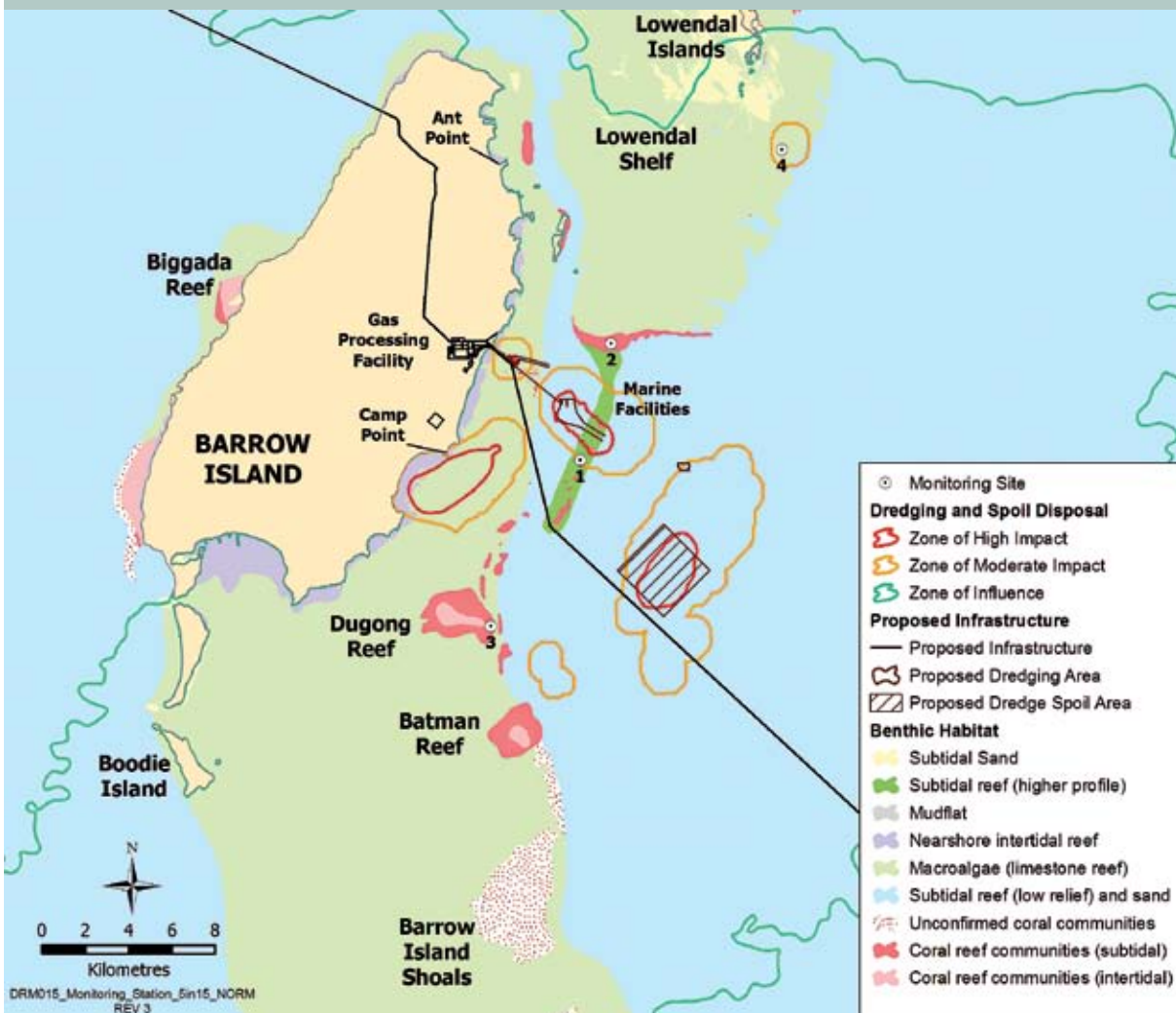


Figure 8:

Time Series Plots of Predicted TSS at Four Sites Under 'Normal' Meteorological Conditions

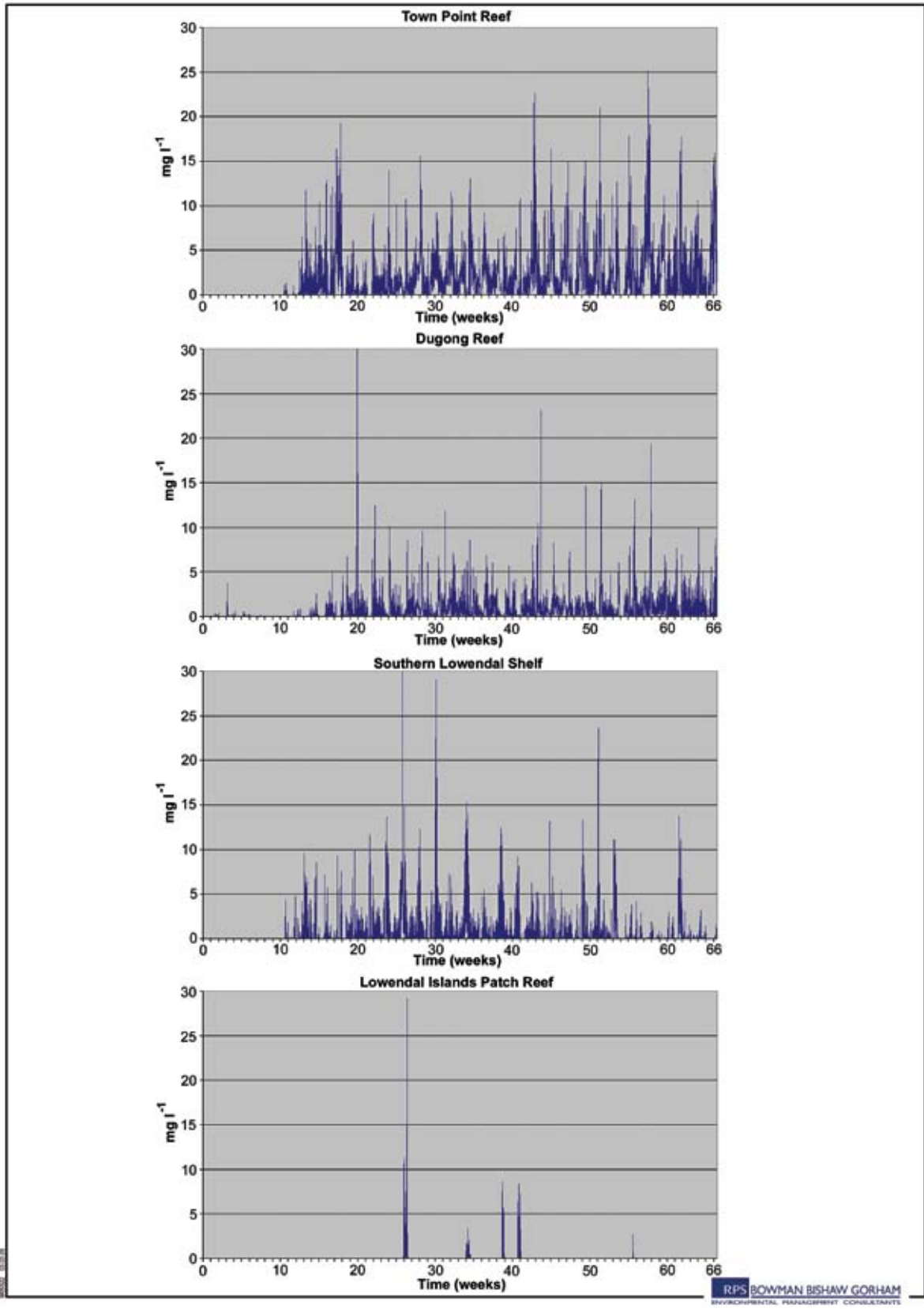


Figure 9:

Time Series Plots of Predicted Sedimentation at Three Sites Under 'Normal' Meteorological Conditions

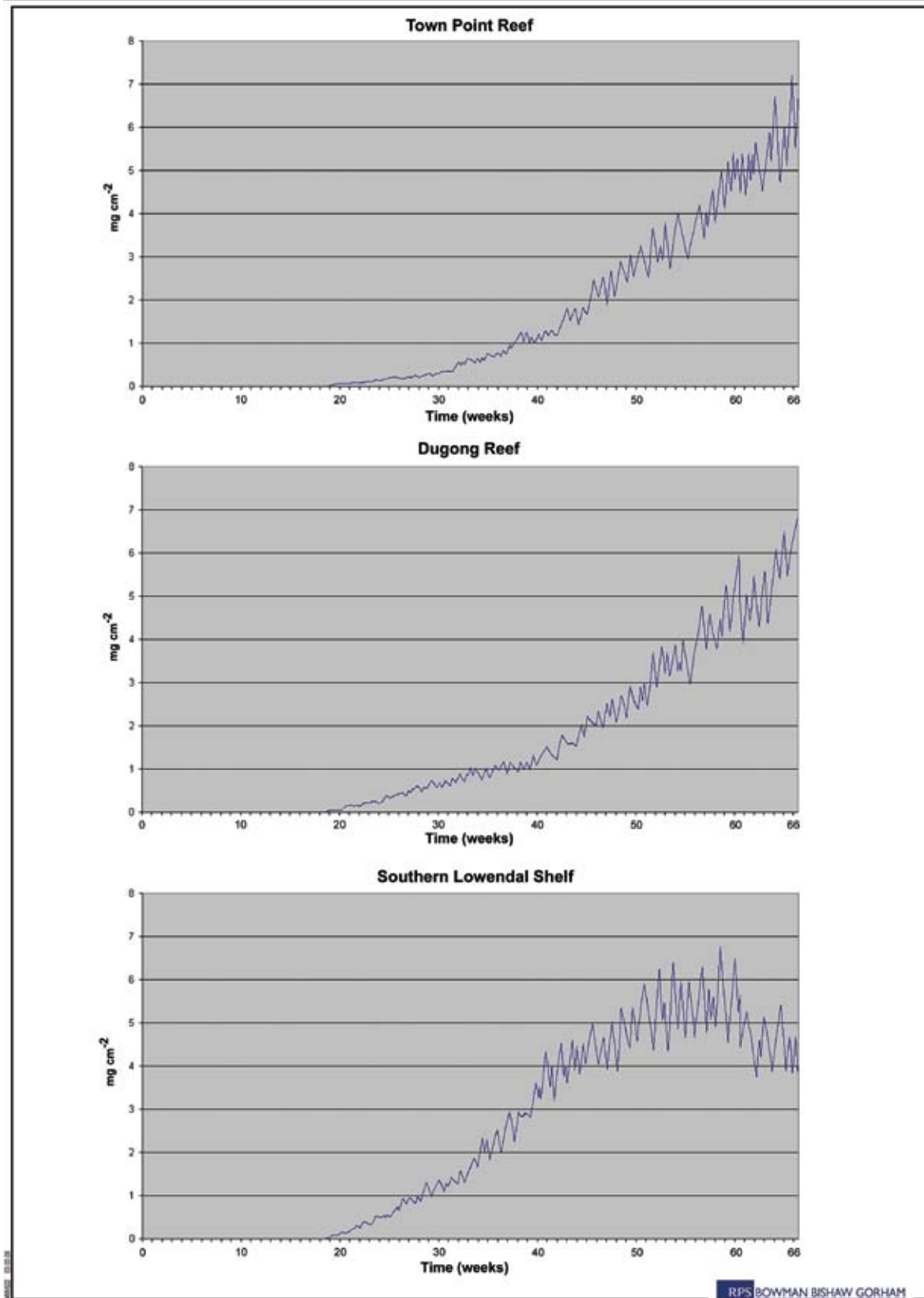
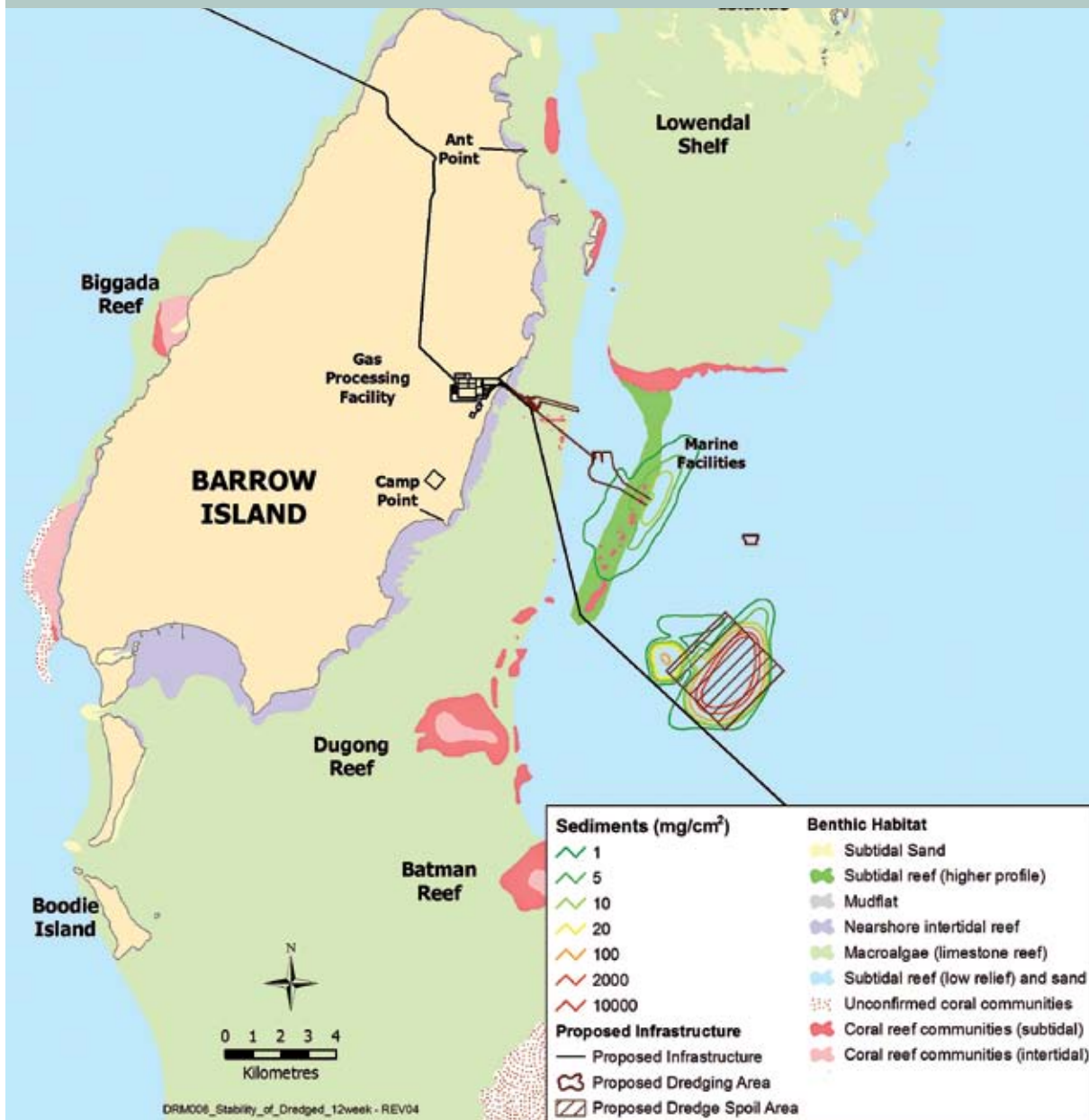


Figure 10:
The Anticipated On Bottom Sediment Load at the End of Dredging (0 Weeks)



Figure 11:

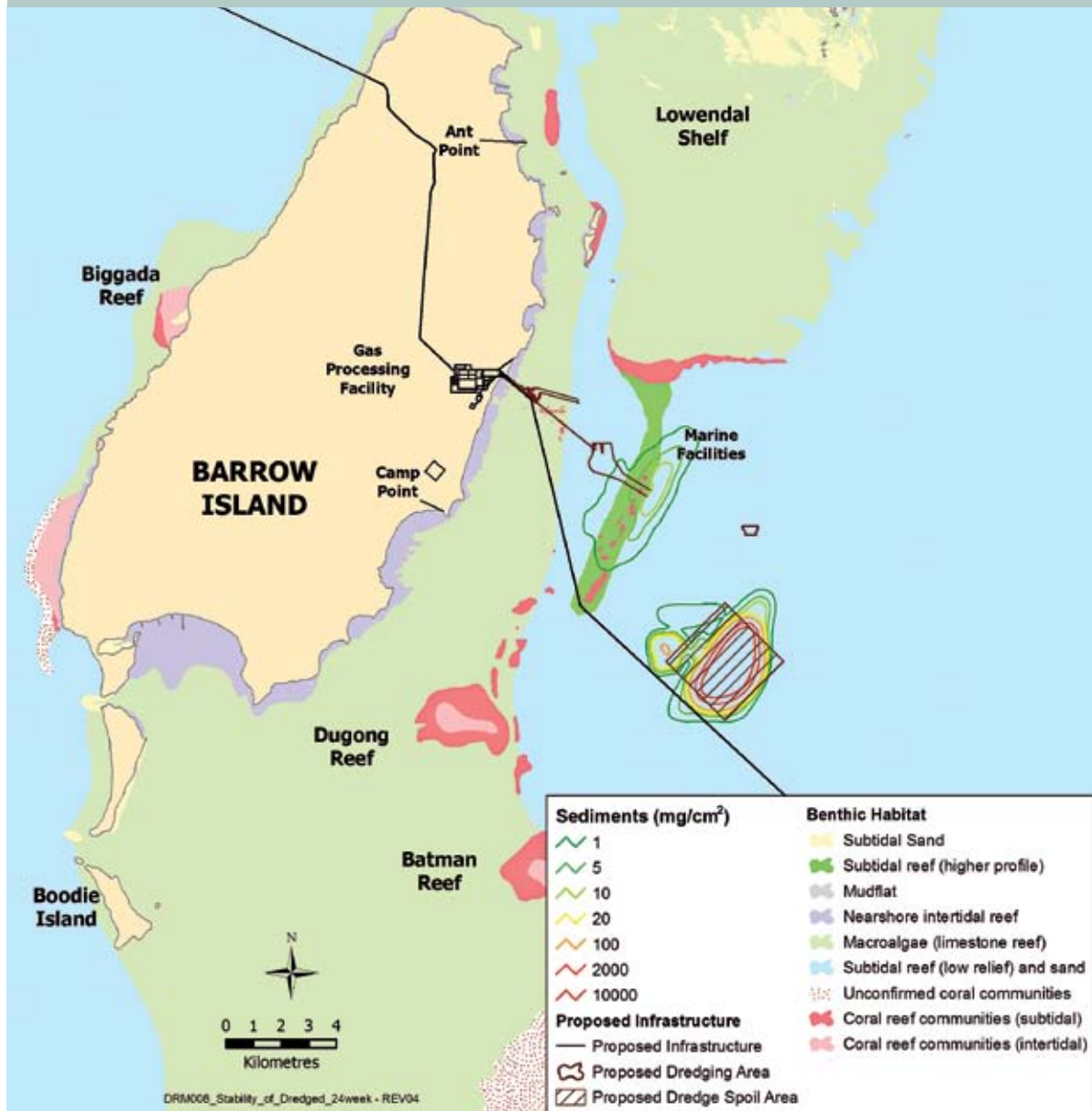
The Anticipated On Bottom Sediment Load 12 Weeks After the End of Dredging



The hydrodynamic model predicts that the spoil ground will be stable with only small movements of material around the periphery of the site over the 48 weeks following dredging. The fine sediment that accumulates on the seabed at the eastern end of the dredged LNG access channel will also persist at approximately 1-10 mg cm⁻². This area of deposited sediments only slightly decreases in size over 48 weeks (Figures 10 to 13). This sediment load is predicted to have no measurable impacts to marine BPP although increased turbidity in the area may reduce the recovery rate of impacted BPP in close proximity.

While the spoil ground is considered a loss of BPPH under the BPPH assessment due to permanent habitat modification, it is expected that turf and macroalgae will colonise the spoil ground rapidly (2-5 years), with the establishment of a diverse macroalgae community in the longer term.

Figure 12:
The Anticipated On Bottom Sediment Load 24 Weeks After the End of Dredging



8.4 Greater Contribution of Fines

The 'Base Case' modelling assumes the proportion of fine particles generated during dredging of hard limestone at Barrow Island will be similar to the proportion generated at Geraldton. It is possible, however, that the limestone at Barrow Island is harder.

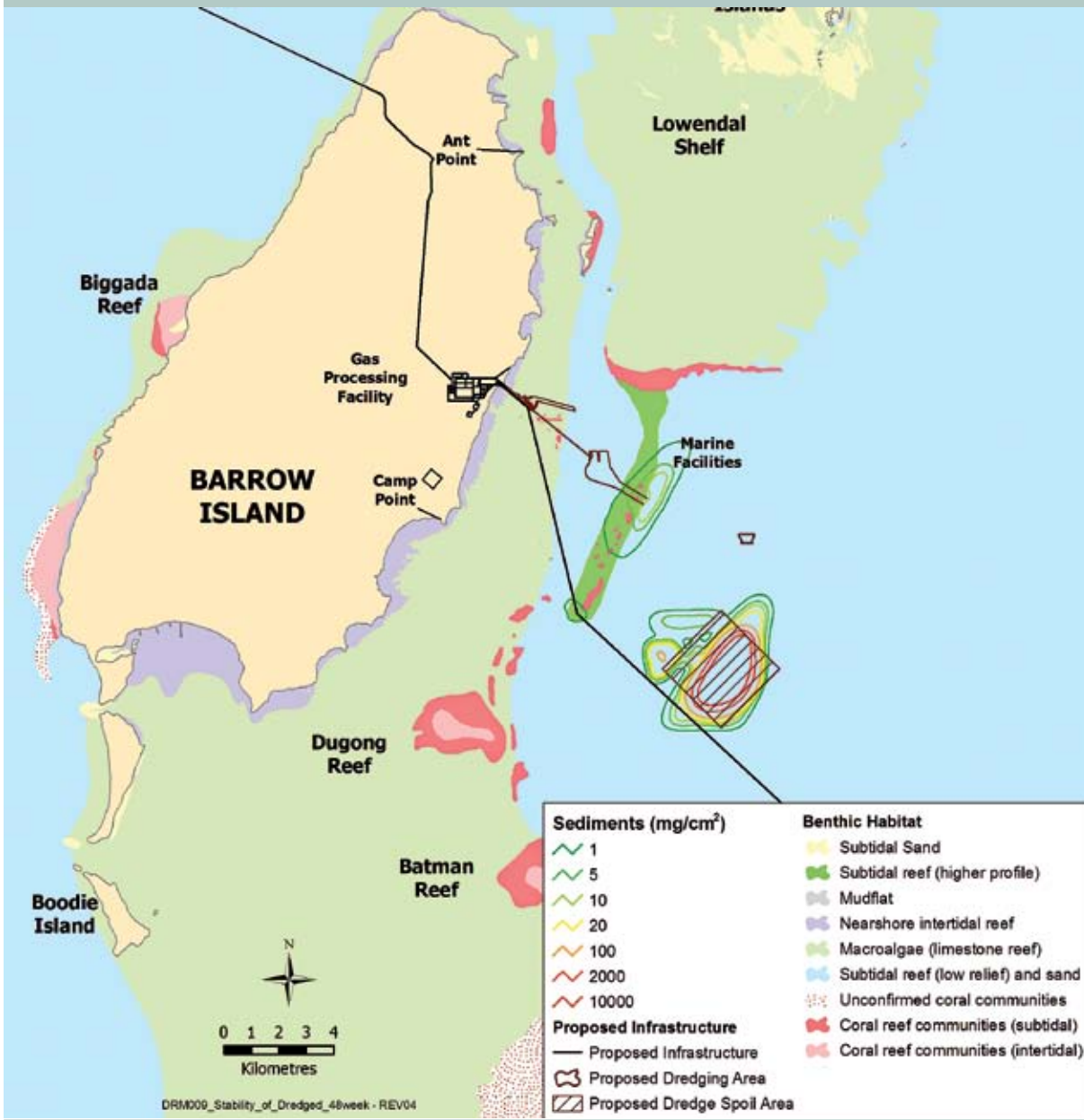
It is currently unknown how the hardness of the limestone will affect the amount of fines produced during dredging. If dredging the limestone at Barrow Island produces a higher proportion of fines, this will increase the mass of fine particles and create larger turbid plumes. Doubling the proportion of fines produced was considered to be a highly conservative

test of the effects of this parameter on the model results in the absence of directly relevant data. Due to the very small size of the fines produced (<75µm), this material is not expected to settle on the seabed and is thus assumed to contribute only to TSS and not to sedimentation.

The 'double fines' scenario was modelled using a 'normal' meteorology year and the zones of impact and influence derived using the standard cumulative threshold criteria described in previous sections. Impact zones under the 'double fines' scenario were plotted over the zones for the 'Base Case' scenario for comparative purposes (Figure 14).

Figure 13:

The Anticipated On Bottom Sediment Load 48 Weeks After the End of Dredging

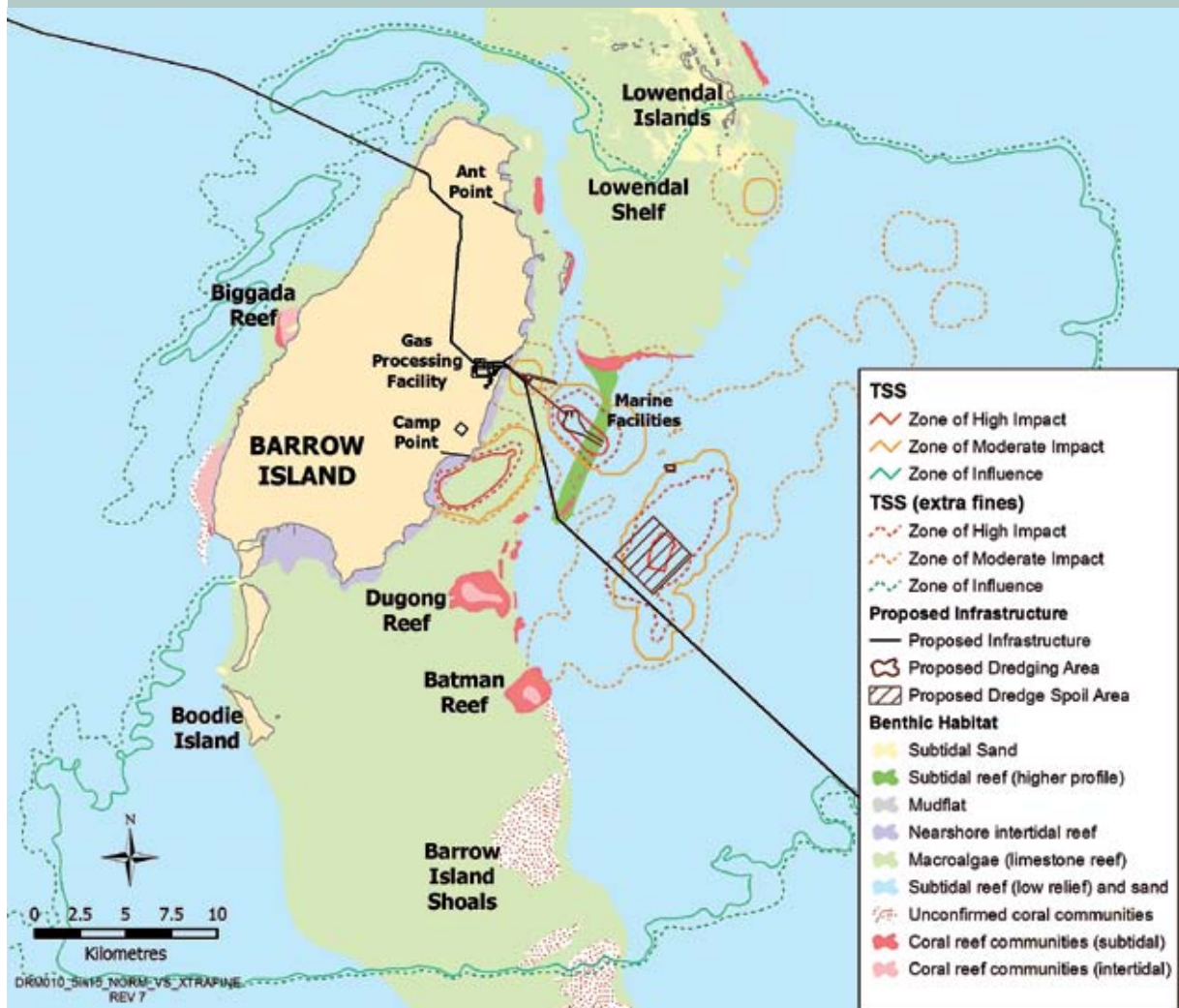


The zone of high impact produced from extra fines tends to extend the zones produced under normal particle size and volume predictions. The zone of high impact around the LNG channel from extra fines is approximately double that under the anticipated fines production. The predicted high impact zone from extra fines around the spoil ground is also much larger than that under normal conditions, covering approximately twice the area of the spoil ground, running in a general north-east, south-west direction (Figure 14). While the areas of high and moderate impacts are much larger, the zone of high impacts from turbidity associated with doubling the fines production during dredging, does not affect any regionally significant coral assemblages.

The 'double fines' moderate impact zone is appreciably larger than that under the 'Base Case' encompassing most of the area around the proposed marine facilities including a large area offshore and to the north of the spoil ground (Figure 14). Under this highly conservative scenario, moderate impacts to marine BPP from elevated TSS are predicted to occur on the southern and eastern margins of the Lowendal Shelf and possibly as far south as Batman Reef. This may have serious effects on the well-developed Acroporid assemblages in these areas.

Figure 14:

The Area of Impact (TSS) Predicted to Occur Under Base Case Assumptions (Solid Lines) and if Double the Amount of Fines are Produced During Dredging and Spoil Disposal (Dashed Line)



Potential impacts under this 'double fines' scenario should be considered to be a significant overestimate of impacts from turbidity related stress, with levels set artificially high to test the sensitivity of the model to changes in basic assumptions. Real time monitoring of fines production during dredging operations will allow the model assumptions to be tested, the results of which will enable spatial and temporal differences in the turbid plumes due to fines production to be effectively managed. Management responses will be detailed in the Dredging Management Plan.

The visible plume under both normal and extra fines conditions are of a similar magnitude, with double the amount of fines producing only a marginally larger zone of influence (Figure 14).

8.5 Double 'Rolling' Time Period

Zones of impact generated using the cumulative coral health threshold criteria represent areas affected by a series of 'pulses' of high TSS or sedimentation. The closer the 'pulses' are together, or the shorter the time period within which they occur, the greater the stress on the corals and other BPP. The cumulative criteria set a threshold of a certain number of days of high TSS or sedimentation within a given 'rolling' time period. The cumulative criteria are explained in detail in Section 7.4.2.

At the suggestion of the DoE and EPASU, the 'rolling' time period was doubled to test the effects on the impact zones. The longer 'rolling' period results in significantly more conservative criteria than those originally proposed and on which the base case is modelled. It should be noted that these criteria are not based on the published literature and are only be

used to gauge the sensitivity of the model to changes in threshold limits. They should be considered in this context to be a significant overestimate of possible impacts to marine BPP from dredging activities.

A summary of the more conservative cumulative threshold criteria for the sensitivity analysis is presented in Table 4. The zones of impact under the double 'rolling' time during a 'normal' meteorology year were overlaid on the base case scenario for comparative purposes (Figure 15).

The zones of high impact near the marine facilities produced from doubling the 'rolling' time period are the same, or very similar, to those produced using the standard cumulative criteria (Figure 15).

However, the predicted high impact zone around the spoil ground is larger than under the base case, covering approximately twice the area of the spoil ground, with a new small high impact zone approximately 2 km south of the spoil ground (Figure 15).

The moderate impact zones around the MOF and spoil ground are significantly larger than that under 'standard' modelling conditions, but only slightly larger around the LNG channel, the impact zone south of Camp Point and on the eastern Lowendal Shelf. The moderate impact zone around the spoil ground is also significantly larger (Figure 15). No regionally significant coral assemblages would be affected within the moderate impact zone.

Table 4:
'Double Rolling Time Period' Cumulative Coral Health Threshold Criteria

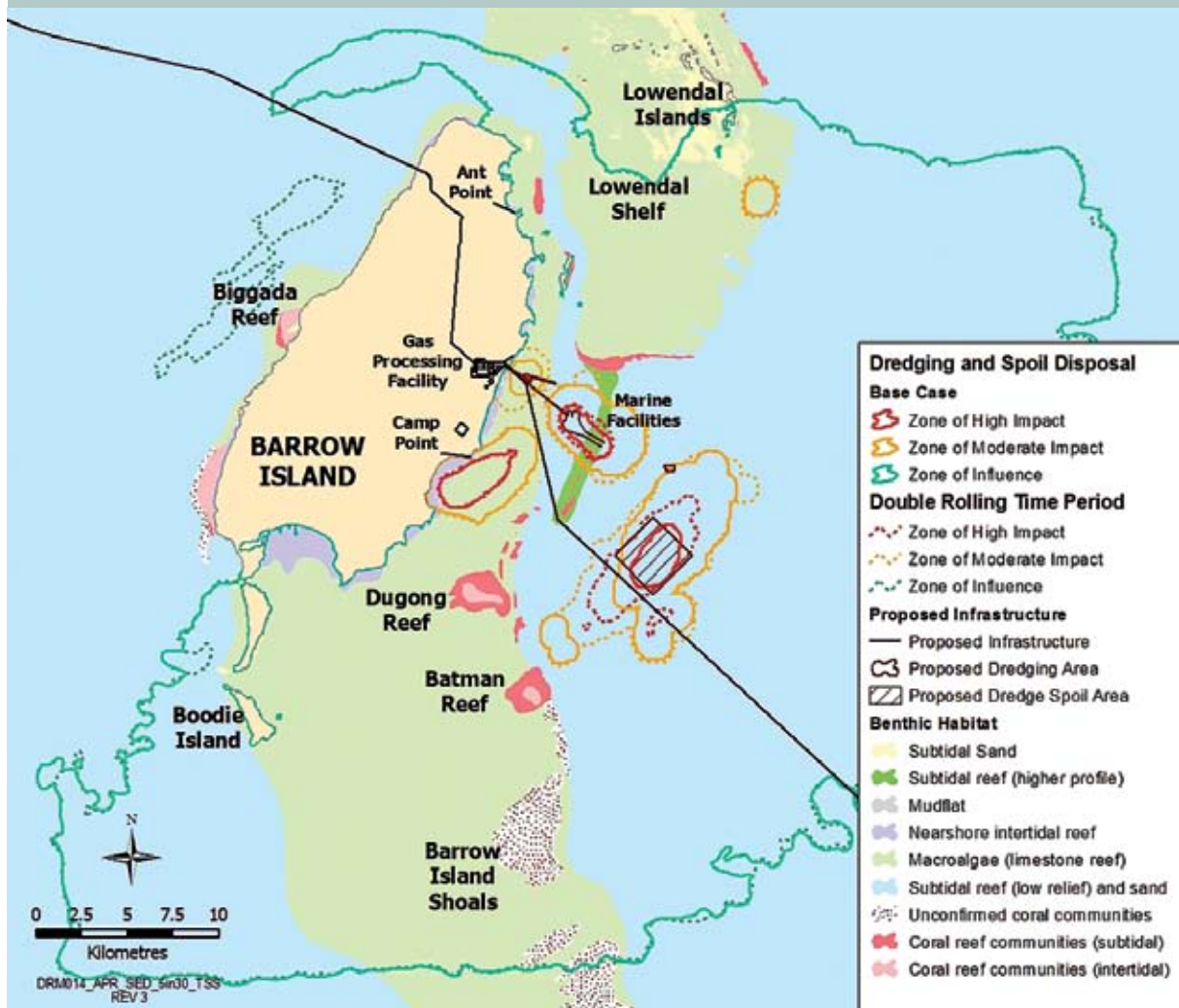
Zone of High Impact			
Variable	Timeframe	Concentration	Time (cumulative days)
TSS	Short	$\geq 25 \text{ mg l}^{-1}$	5 in 30
	Medium	$\geq 10 \text{ mg l}^{-1}$	20 in 120
	Long	$\geq 5 \text{ mg l}^{-1}$	80 in 480
Sedimentation	Daily	$\geq 100 \text{ mg cm}^{-2} \text{ d}^{-1}$	1
	Short	$\geq 25 \text{ mg cm}^{-2} \text{ d}^{-1}$	5 in 30
	Medium	$\geq 10 \text{ mg cm}^{-2} \text{ d}^{-1}$	20 in 120
	Long	$\geq 5 \text{ mg cm}^{-2} \text{ d}^{-1}$	40 in 240

Zone of Moderate Impact			
Variable	Timeframe	Concentration	Time (cumulative days)
TSS	Short	$\geq 25 \text{ mg l}^{-1}$	2 in 12
	Medium	$\geq 10 \text{ mg l}^{-1}$	7 in 63
	Long	$\geq 5 \text{ mg l}^{-1}$	20 in 180
Sedimentation	Daily	$\geq 50 \text{ mg cm}^{-2} \text{ d}^{-1}$	1
	Short	$\geq 25 \text{ mg cm}^{-2} \text{ d}^{-1}$	2 in 12
	Medium	$\geq 10 \text{ mg cm}^{-2} \text{ d}^{-1}$	7 in 63
	Long	$\geq 5 \text{ mg cm}^{-2} \text{ d}^{-1}$	20 in 180

Zone of Influence		
Variable	Concentration	Time
TSS	$\geq 2 \text{ mg l}^{-1}$	In any daylight period
Sedimentation	$\geq 1 \text{ mg cm}^{-2}$	During any 24 hr period

Figure 15:

The Area of Impact Predicted to Occur Under 'Base Case' Assumptions (Solid Lines) and the Cumulative Criteria 'Rolling' Time Period is Doubled (Dashed Line)



The zone of influence under both normal and double the rolling time period criteria are of a similar magnitude, with the double criteria producing only a marginally larger zone of influence with an extra zone on the west coast of the island, offshore from Biggada Reef (Figures 3 & 15). Turbidity at this concentration will not affect BPP within the Barrow Island Marine Park.

Doubling the time period had only a minor effect on the extent and type of environmental impacts, confirming that the standard cumulative criteria used for the 'base case' are sufficiently conservative.

8.6 Consecutive vs Cumulative Criteria

Following the release of the Draft EIS/ERMP, concern was raised over the potential cumulative impacts due to 'pulses' of TSS and sedimentation to corals and other marine BPP that would not be accounted for

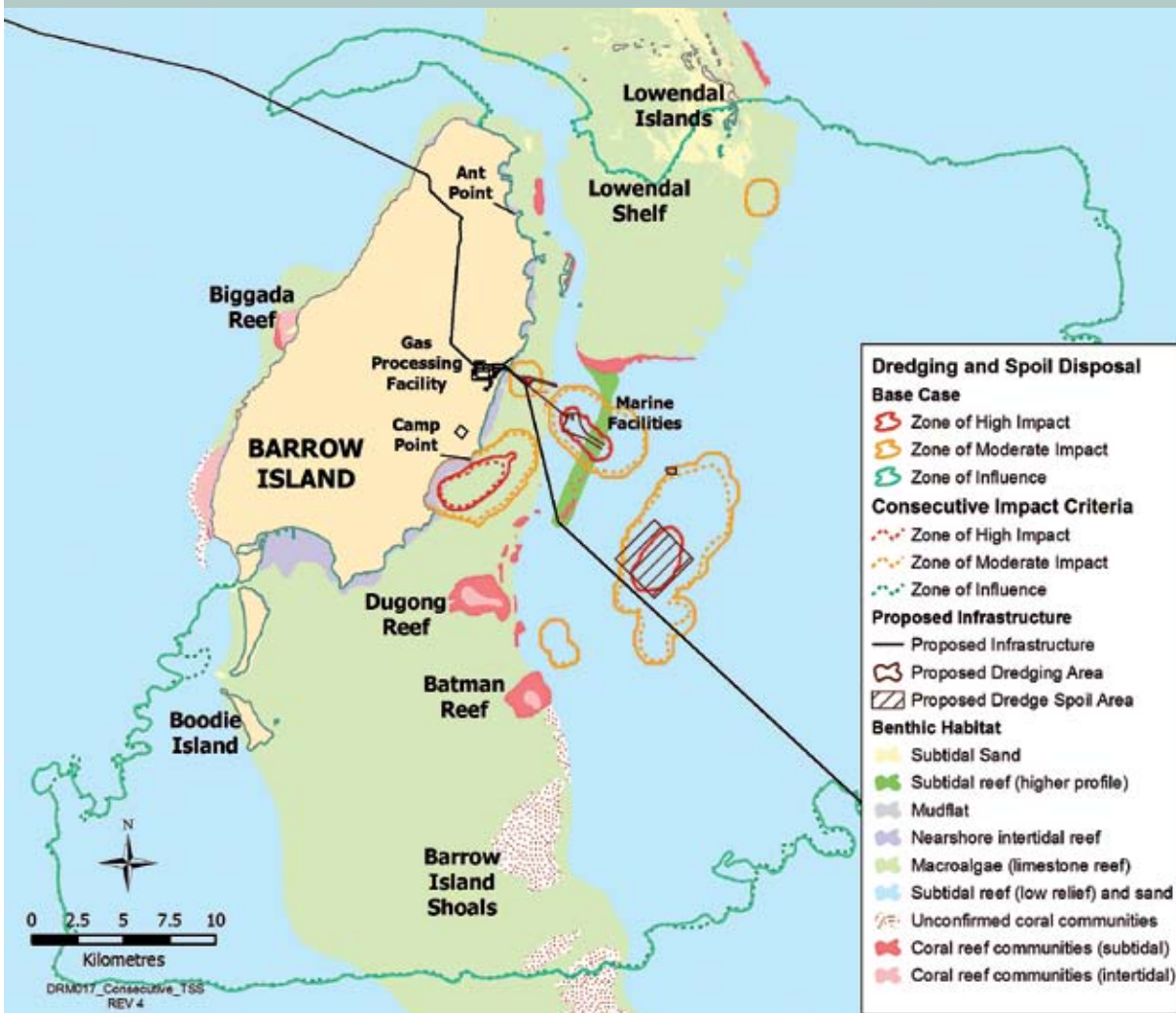
using 'press' consecutive criteria. In order to resolve this issue, cumulative coral health threshold criteria that take into account both the intensity and duration of stressors over given time periods have been developed and used to derive impact zones (see Section 7.4.2).

Comparison of the previously modelled consecutive coral criteria and the newly developed cumulative coral threshold criteria facilitates comparison of the current impact assessment with that provided in the Draft EIS/ERMP. It also provides a sensitivity analysis of the new cumulative criteria in relation to their ability to predict potential impacts that were not identified using the consecutive criteria.

The cumulative criteria are based on time periods and concentrations defining the consecutive coral threshold criteria and are therefore more conservative

Figure 16:

The Area of Impact Predicted to Occur Under 'Base Case' Assumptions (Solid Lines) and if the Consecutive Criteria Used in the Draft EIS/ERMP are Employed (Dashed Line)



than the consecutive criteria. Thus, cumulative impacts predicted within any model scenario will always be larger than those predicted under the consecutive criteria. The scale of that difference provides an indication of the sensitivity of the impact assessment to using these different types of criteria for predicting impact zones.

Zones of impact derived using the cumulative and consecutive criteria during a year of 'normal' meteorology are shown in Figure 16.

Overall, there were only slight differences in the impact and influence zones produced by the cumulative (base case) and consecutive criteria. This indicates that impacts to BPP from dredging and spoil disposal are generally the result of elevated and persistent TSS and sedimentation levels which occur for several consecutive days, rather than a series of 'pulse' events.

Under both the consecutive criteria scenario and the base case (cumulative) criteria scenario, no regionally significant coral assemblages or well-developed *Acropora* assemblages are predicted to be affected by dredging.

8.7 Seasonal Variation

Dredge plume modelling presented in the Draft EIS/ERMP was based on the expected schedule at that time commencing in October. From October, the 16 month dredging programme extended through two summers, which are dominated by southerly winds, and one winter, with predominantly north-easterly winds. The overall result of this scenario was that sediment plumes displayed a tendency to be driven north from the dredging locations by the predominantly southerly flow. Possible impacts to marine BPP were predicted to occur almost exclusively in close proximity to dredging operations or to the north of operations,

with potential impacts some distance onto the Lowendal Shelf (See Figure 11-5).

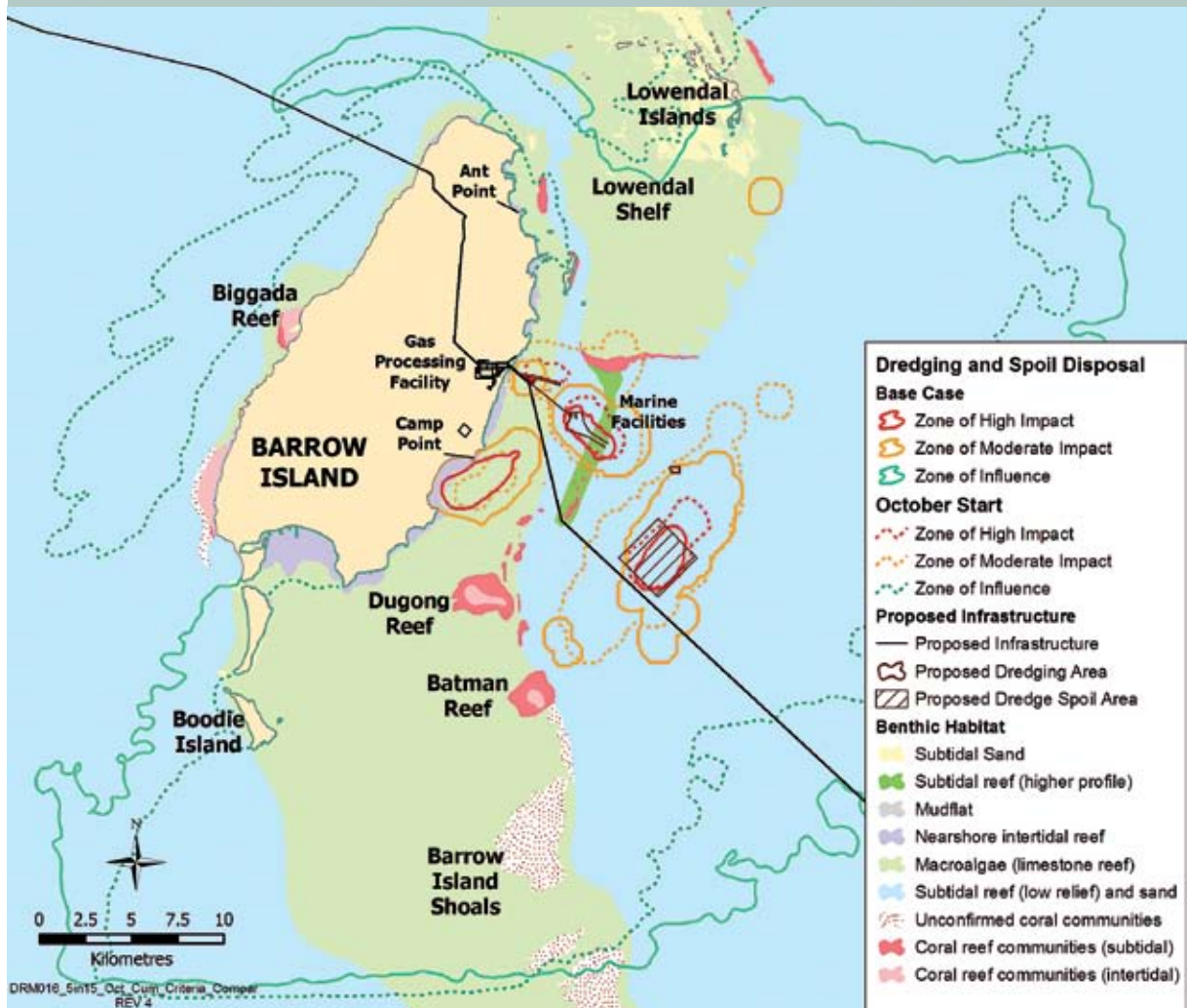
The schedule has since been revisited to account for probable delays and an April start date has been assumed for this revised dredging assessment. The consequence of starting the proposed 16 month dredging programme in April is that dredging will take place over two winters and only one summer, in contrast to the two summer and one winter previously modelled. This results in a significant change in the dominant wind patterns during dredging from the previously southerly dominated pattern to a north-easterly pattern. This change means that the two schedule scenarios that are likely to have the greatest differences in predicted impacts have now been modelled.

To test the sensitivity of the impact prediction to changes in the dredging schedule, both the April start (Base Case) and October start scenarios have been modelled for a 'normal' meteorology year and standard cumulative coral threshold criteria. The October start scenario (dashed line) has been overlaid on the April base case scenario (solid line) in Figure 17. Zones of impact derived from the October start modelling are not directly comparable with the Draft EIS/ERMP zones (Sections 11.3 & 11.4) as the new model incorporates changes to the development plan, spoil ground, meteorology, bathymetry and distribution of particles.

Under both schedule scenarios, the main impacts to marine BPP are in close proximity to dredging operations (Figure 17). However, the predominance of

Figure 17:

A Comparison of the Predicted Areas of Impact from Dredging and Spoil Disposal if Dredging Starts in April (Base Case – Solid Line) and October (Dashed Line)



southerly winds after an October start tend to push sediment plumes further north in nearshore waters, which results in larger and more northerly zones of high and moderate impacts around the MOF, LNG channel and spoil ground. The high impact zone south of the proposed marine facilities at Camp Point is not present under the October start scenario (Figure 17).

The northward flow following the October schedule scenario causes a large zone of moderate impact to form over the east coast marine facilities and extend up onto the southern Lowendal Shelf (Figure 17). Moderate impacts in nearshore waters south of Camp point are reduced from those predicted for an April start and no impacts to the eastern Lowendal Shelf are anticipated. The moderate impact zone surrounding the spoil ground extends further northeast under the October start scenario (Figure 17).

The moderate impact zone under the October start scenario covers part of the regionally significant *Acropora* community on the south western corner of the Lowendal Shelf. Potentially high mortality in this area would lead to long-term impacts to a regionally significant BPP assemblage. This would increase the residual risk of unacceptable impacts.

8.8 BPPH calculations

8.8.1 Background

Benthic primary producer habitats comprise both benthic primary producer communities and the substrates that support these communities. Examples of benthic primary producer habitats in the Pilbara region include coral reefs, seagrass meadows, macroalgae beds and mangrove forests as well as the intertidal and subtidal substrates that support them. Benthic primary producers are important as they are a key source of energy (primary production) in marine ecosystems, provide substrate and shelter for other marine organisms and increase substrate stability (EPA 2004).

The EPA has developed a Guidance Statement aimed at protecting benthic primary producer habitat (EPA 2004). This Statement specifically applies to development proposals that may result in removal or destruction of, or damage to, benthic primary producer habitats. The guidelines provide for the protection and maintenance of ecosystem integrity by applying a risk-based environmental protection framework which includes quantitative cumulative loss thresholds (EPA 2004).

Consistent with the EPA guidance (EPA 2004), unavoidable impacts to benthic primary producer habitats have been assessed as either 'permanent loss' or 'temporary change'. A thirty year recovery period has been selected as the basis for distinguishing between permanent loss of BPPH and temporary damage to BPPH. 'Permanent loss' indicates loss of the functionality of the benthic primary producer habitat such that it is no longer able to support the same benthic primary producer communities or that the damage to the BPP community persists for greater than 30 years, e.g. *Porites bombora* in high impact zones. A permanent change in the substrate type is also treated as benthic primary producer habitat loss, although there is frequently a mitigating shift to another benthic primary producer habitat type, such as that predicted to occur at the spoil ground.

'Temporary damage' to benthic primary producer habitat indicates temporary or sublethal impacts that may reduce or remove the current standing crop of benthic primary producers, but that the substrate will retain its ecological function as benthic primary producer habitat and the benthic primary producer communities are predicted to recover fully within 30 years. Full recovery indicates the recovery of the biomass of BPP and the full diversity of marine life associated with the original BPP community. Macroalgae dominated limestone reefs, subtidal limestone reef platforms with macroalgae and scattered corals and reef platform/sand with scattered seagrass within high and moderate impacts zones are considered to be temporarily affected as full recovery of these communities is anticipated within five years of the disturbance.

Impacts to benthic primary producer habitats from the proposed Development are expected to comprise direct loss by removal (dredged areas) or burial (infrastructure, dredge spoil) and temporary damage (anchor scars, sedimentation, increased turbidity). Most of the damaged areas are expected to recover fully during the post-construction period when water quality and sedimentation return to within their natural range. Much of the permanent loss of benthic primary producer habitat will be offset by colonisation of new hard substrates created by the Development, for example the causeway, jetty piles and dredge spoil ground.

Direct and permanent removal of BPPH by excavation or replacement by infrastructure, permanent modification of BPPH type and loss of BPP communities that

may take greater than 30 years to recover have been assessed as loss against the cumulative loss threshold criteria (EPA 2004). Impacts due to temporary loss from sedimentation, direct disturbance (anchoring), and turbidity have been assessed as damage from which full recovery is predicted within 30 years. Sedimentation and turbidity (TSS) impacts are considered as loss only if they lead to total mortality of a BPP assemblage or serious damage to a BPPH that would not recover within 30 years, e.g. death of an extensive *Acropora* thicket or large *Porites* bomбора.

8.8.2 Revised BPPH Assessment

The assessment of impacts to BPPH in this section provides an update of the BPPH assessment conducted for the Draft EIS/ERMP to incorporate changes to the development plan, new model input data, the revised dredging schedule and the new cumulative threshold criteria. The assessment is based on the revised marine benthic habitat map as described in the Additional Information Package and shown in all figures in this report. Only the management units for which there have been changes since the Draft EIS/ERMP assessment have been re-assessed. The original BPPH assessment can be found in Sections 11.3 & 11.4 of the Draft EIS/ERMP.

Seven of the east coast management units defined in the Draft EIS/ERMP (Section 11.4) are predicted to suffer impacts to BPPH, based on the results of the revised hydrodynamic dredge plume model and the existing HDD plume model. These management units 3, 4, 7, 8, 9, 10, and 11. A summary of the area of different benthic primary producer habitat types within these seven management units and the total cumulative losses of each benthic primary producer habitat expected in each unit, including permanent and temporary change is presented in Table 5.

Predicted losses and damage within each management unit are described in the following.

Management Unit 3 – South of Lowendal Islands

Benthic primary producer habitats around the Lowendal Islands (MU3 – Figure 18), to the north-east of Barrow Island, include macroalgae dominated reefs, seagrass communities and sparse coral assemblages. Management unit 3 lies within the multiple use area of the Barrow Island Marine Management Area and has a cumulative loss threshold of 2%. The revised dredge plume modelling indicates that a small plume of elevated TSS may persist in the vicinity of the

Lowendal Islands. This is predicted to have moderate impacts on BPPH. There are no known areas of BPPH in this management unit that would take longer than 30 years to recover. These impacts are considered acceptable.

Management Units 4, 7 & 8 – East Coast Barrow Island

The main coastal components of the proposed Development are concentrated in the mid-east coast of Barrow Island at Town Point and include the causeway, MOF, dredged shipping channels, open-pile jetty and domestic gas pipeline. Revised dredge plume modelling predicts impacts from dredging and spoil disposal to BPPH in four of the existing management units (MU4, 7, 8 & 9) established within the Barrow Island Port Area (Figure 18). Management unit 9 is included in the subsequent section.

These management units lie within the Barrow Island Port Area, designated by the *Shipping and Pilotage Act 1967* and vested under the *Marine and Harbours Act 1981*. Under the benthic primary producer habitat Guidance Statement (EPA 2004), a port may be classified as a Development Area (Category E) with a cumulative loss threshold of 10%. The whole port area represents a higher management level at which the significance of the predicted cumulative benthic primary producer habitat losses can be assessed.

The port management units encompass a large proportion of the benthic habitats along the east coast of Barrow Island. They include nearshore reef platform adjacent to the east coast of Barrow Island, the southern Lowendal Shelf, the reef ridge running south from the Shelf and areas of deeper sand veneers over pavement reef (Figure 18).

Permanent loss within these management units is associated with proposed construction of the solid causeway and MOF, the dredged access channel for the MOF, domestic gas pipeline (30 m disturbance corridor), open-piled jetty (18 m disturbance corridor), dredged tanker turning/loading basin, dredged shipping channel and optical fibre cable (10 m corridor). Benthic primary producer habitats within the high and moderate impact zones are predicted to be temporarily damaged unless the zones include BPPH that may not recover to the same pre-disturbance benthic primary producer communities within 30 years. The predicted areas of moderate impact under the 'base case' do not include any benthic primary producer habitats that would take greater than 30 years to recover.

Permanent loss of coral BPPH is predicted to be greater than the CLT in MU4 and MU8 (Table 5). Scattered large *Porites* bombora on the rocky ridge running south from the Lowendal Shelf may take longer than 30 years to fully recover and are assessed as permanent loss. While these losses exceed the CLT (10%), they are considered sustainable as not all of the corals are long-lived *Porites* bombora and the affected *Porites* bombora are the smallest of those in the area. There are much better developed *Porites* bombora fields to the north and to the south of the dredge area that are not predicted to be affected. The physical structure of these bombora will continue to provide complex habitat for the faunal assemblages currently inhabiting the area.

Sedimentation and elevated TSS concentrations are predicted to cause temporary loss of BPPH in all of the port area management units (Table 5). The largest temporary losses are predicted for the management units adjacent the dredging sites. These areas will recover their function as BPPH when excess sediment and TSS have been reduced to the level that the substrates regain their ability to support the same benthic primary producer communities. Current modelling indicates that sediment deposits will only persist in the immediate vicinity of the dredged areas. In areas beyond the potential permanent sediment accumulation zone, all of the damaged benthic primary producer habitats supporting macrophytes on the east coast are predicted to fully recover in less than 30 years.

Management Units 9, 10 & 11 – Spoil Ground

The benthic primary producer habitats within the dredge spoil management units are characterised by deep sandy seabed with occasional emergent pavement reef which supports scattered seagrass meadows dominated by *Halophila*. The whole of this area is conservatively assumed to be capable of supporting seagrass and is considered as seagrass BPPH. The disposal of boulders and rubble at this site will lead to a change in the substrate type from sandy seabed to boulder reef. This is expected to be a permanent change to the characteristics of the benthic primary producer habitat in the area.

Management unit 9 covers the area within the Barrow Island port limits that would be affected by the spoil ground and the small area of additional dredging for the offshore part of the shipping channel (Figure 18). Management units 10 and 11 encompass the

area outside the Barrow Island port limits, which is proposed for the disposal of dredged material from the MOF access channel and LNG shipping turning basin and channel (Figure 18).

Management unit 9 lies within the Barrow Island port limits and has a cumulative loss threshold of 10%. Management unit 10 lies within the Marine Conservation Reserve boundary and has a cumulative loss threshold of 2%. Management unit 11 is outside the reserve and as a general coastal area has a cumulative loss threshold of 5%.

The proposed dredge spoil area, the offshore area to be dredged for the shipping channel and the domgas pipeline will permanently modify approximately 4, 5 and 11% of the seabed in management units 9, 10 and 11 respectively (Figure 18, Table 5). While the losses exceed the BPPH guidance cumulative threshold levels for the later two management units, they do not represent a threat to the ecological integrity of the surrounding benthic primary producer habitat or to the conservation values of the Barrow Island Marine Conservation Area. Macroalgae and small corals are expected to colonise parts of the spoil ground within 2-5 years and the area will regain function as benthic primary producer habitat. However, seagrasses are unlikely to successfully colonise the area and there will be a permanent shift in benthic primary producer community type. The area to be lost is a very small proportion of this habitat type in the waters off the east coast of Barrow Island and there are no other significant developments in the area.

The spoil ground is predicted to become macroalgae dominated benthic primary producer habitat and will support a diverse assemblage of associated fauna. The local biodiversity is expected to increase due to creation of a new habitat type in the area without affecting the persistence of ephemeral seagrasses in the general area. The permanent loss of the *Halophila* is not expected to effect local populations of turtles or dugong as these animals are highly mobile and forage over large areas, the small areas to be modified are expected to be less productive than shallower sandy areas and this BPPH type is very well represented in the region. No ecosystem function effects are anticipated as a result of the changes to the benthic habitats in these management units.

Table 5: (continued)

BPPH Assessment Under Revised Dredge Plume Modelling and Prediction of Impact Zones using Cumulative Impact Criteria

Benthic Primary Producer Habitat Type	Total area of BPPH before disturbance (ha)	Percentage of temporary BPPH change	Percentage of permanent BPPH loss	CLT ¹
Management Unit 3				
Macroalgae-dominated intertidal limestone reef platform	0	-	-	2%
Subtidal limestone reef platform with macroalgae and scattered corals	2425	10	0	2%
Reef platform/sand with scattered seagrass	1219	3	0	2%
Coral habitats	5	<1	0	2%
Management Unit 4				
Macroalgae-dominated intertidal limestone reef platform	435	9	<1	10%
Subtidal limestone reef platform with macroalgae and scattered corals	2690	11	<2	10%
Reef platform/sand with scattered seagrass	982	15	<1	10%
Coral habitats	157	22	11	10%
Management Unit 7				
Macroalgae-dominated intertidal limestone reef platform	509	56	0	10%
Subtidal limestone reef platform with macroalgae and scattered corals	4032	40	<1	10%
Reef platform/sand with scattered seagrass	331	6	<2	10%
Coral habitats	175	0	0	10%
Management Unit 8				
Macroalgae-dominated intertidal limestone reef platform	0	-	-	10%
Subtidal limestone reef platform with macroalgae and scattered corals	724	38	4	10%
Reef platform/sand with scattered seagrass	3424	24	4	10%
Coral habitats	61	4	21	10%
Management Unit 9				
Macroalgae-dominated intertidal limestone reef platform	0	-	-	10%
Subtidal limestone reef platform with macroalgae and scattered corals	0	-	-	10%

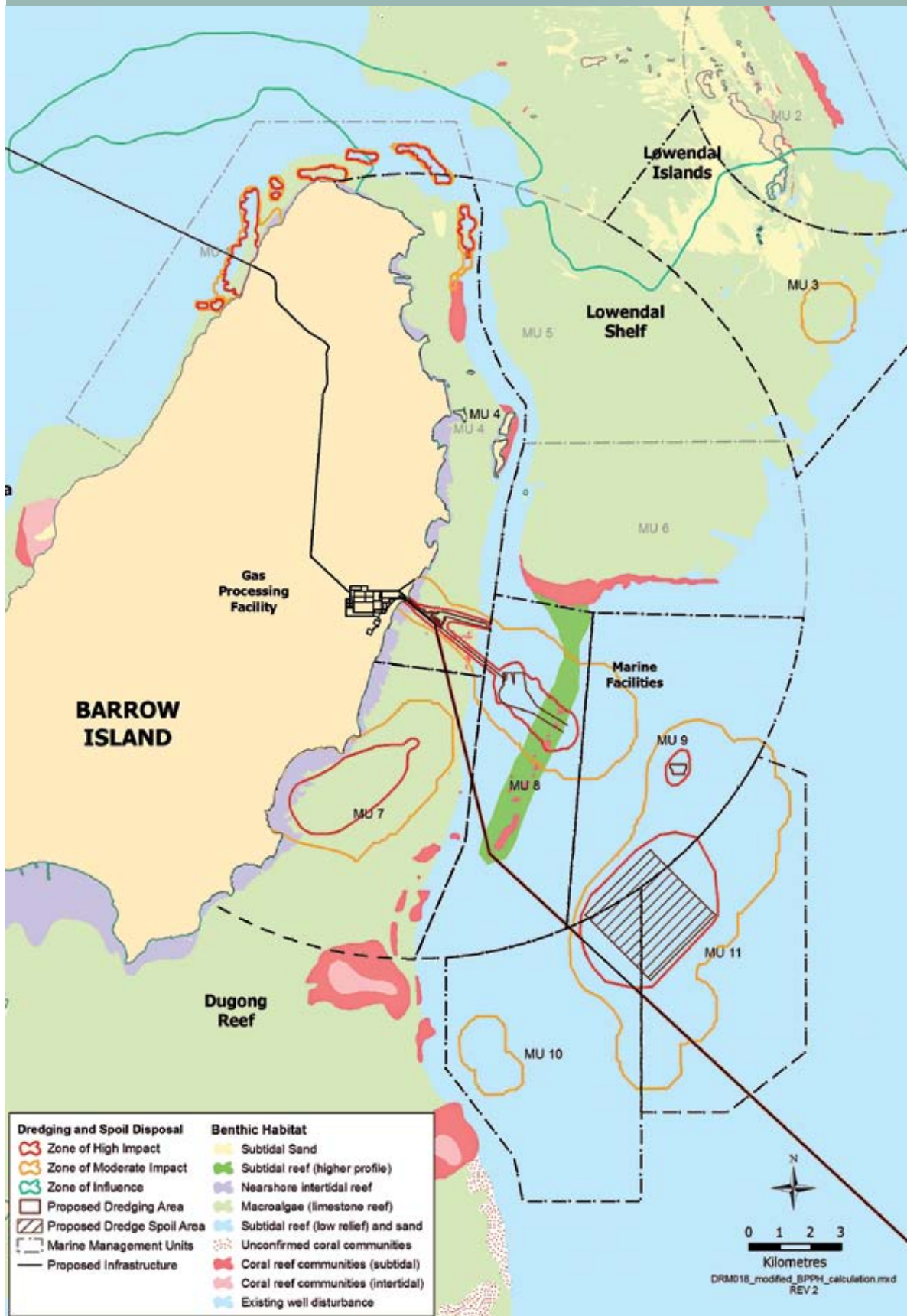
Table 5: (continued)

BPPH Assessment Under Revised Dredge Plume Modelling and Prediction of Impact Zones using Cumulative Impact Criteria

Benthic Primary Producer Habitat Type	Total area of BPPH before disturbance (ha)	Percentage of temporary BPPH change	Percentage of permanent BPPH loss	CLT ¹
Reef platform/sand with scattered seagrass	4941	37	4	10%
Coral habitats	0	-	-	10%
Management Unit 10				
Macroalgae-dominated intertidal limestone reef platform	0	-	-	2%
Subtidal limestone reef platform with macroalgae and scattered corals	0	-	-	2%
Reef platform/sand with scattered seagrass	4923	20	5	2%
Coral habitats	0	-	-	2%
Management Unit 11				
Macroalgae-dominated intertidal limestone reef platform	0	-	-	5%
Subtidal limestone reef platform with macroalgae and scattered corals	0	-	-	5%
Reef platform/sand with scattered seagrass	4760	42	11	5%
Coral habitats	0	-	-	5%

¹Cumulative loss threshold (EPA 2004)

Figure 18:
BPPH Management Units and 'Base Case' Impact Zones



9 References

Airoldi, L. (1998). Roles of disturbance, sediment stress, and substratum retention on spatial dominance in algal turf. *Ecology* **79**(8), 2759-2770.

Ang Jr., P.O. (1985). Studies on the recruitment of *Sargassum spp* (Fucales: Phaeophyta) in Balibago, Calatagan, Philippines. *Journal of Experimental Marine Biology and Ecology* (**91**), 293-301.

Bailey-Brock, J.H. (1989). Fouling community development on an artificial reef in Hawaiian waters. *Bulletin of Marine Science* **44**(2), 580-591.

Bowman, Bishaw, Gorham (1994). Survey of the coral community condition at Dugong Reef, Barrow Island, February, 1994. Unpublished report (RI3217) to West Australian Petroleum Pty Ltd (WAPET), Perth, WA.

Brown, B.E., Clarke, K.R. and Warwick, R.M. (2002). Serial patterns of biodiversity change in corals across shallow reef flats in Ko Puket, Thailand, due to the effects of local (sedimentation) and regional (climatic) perturbations. *Marine Biology* **141**, 21-29.

Brown, B.E., Le Tissier, M.D.A., Scoffin, T.P. and Tudhope, A.W. (1990). Evaluation of the environmental impact of dredging on intertidal coral reefs at Ko Phuket, Thailand, using ecological and physiological parameters. *Marine Ecology Progress Series* **65**, 273-281.

CALM. (2004). *Indicative Management Plan for the Proposed Montebello/Barrow Islands Marine Conservation Reserves*. Department of Conservation and Land Management, Fremantle, Western Australia

Catterall, C.P., Poiner, I.R. and Kerr, J. (1992). Impact of dredging on the volute *Cymbiolacca pulchra* and its environment at Heron Island, Great Barrier Reef, Australia. Research Publication (Great Barrier Reef Marine Park Authority) No. 17.

Chevron Australia. (2005a). Draft Environmental Impact Statement/Environmental Review and Management Programme for the Proposed Gorgon Development: Main Report. pp 818

Chevron Australia. (2005b). Draft Environmental Impact Statement/Environmental Review and Management Programme for the Proposed Gorgon Development: Additional Information Package.

Connell, J.H., Hughes, T.P. and Wallace, C.C. (1997). A 30-year study of coral abundance, recruitment, and disturbance at several scales in space and time. *Ecological Monographs* **67(4)**, 461-488.

Cristoni, C., Colangelo, M.A. and Ceccherelli, V.U. (2004). Spatial scale and meiobenthic copepod recolonisation: testing the effect of disturbance size in a seagrass habitat. *Journal of Experimental Marine Biology and Ecology* **298**, 49-70.

Environmental Protection Authority (EPA). (2003). Dampier Port Authority - Port Expansion and Dredging Program. Report and recommendations of the Environmental Protection Authority. Environmental Protection Authority, Perth, WA.

Environment Protection Authority (EPA). 2004. Benthic Primary Producer Habitat Protection for Western Australia's Marine Environment – Guidance Statement No. 29. Environmental Protection Authority, Perth, WA.

Fabricius, K. and De'ath, G. (2001). Environmental factors associated with the spatial distribution of crustose coralline algae on the Great Barrier Reef. *Coral Reefs* **19**, 303-309.

LeProvost Environmental Consultants. (1992). Dugong well coral monitoring programme report on pre- and post-drilling surveys. Unpublished report (R377) to West Australian Petroleum Pty Ltd (WAPET), Perth, WA.

Loneragan, N., Kenyon, R., Crocos, P., Ward, R., Lehnert, S., Hayward, M., Arnold, S., Barnard, R., Bravington, M., Burford, M., Caputi, N., Kangas, M., McCulloch, R., Penn, J., Sellars, M., Manson, F., Harch, B., Ye, Y., Toscas, P., and Grewe, P. (2003). Developing Techniques for Enhancing Prawn Fisheries with a Focus on Brown Tiger Prawns (*Panaeus esulentus*) in Exmouth Gulf. FRDC Project 1999/222 Final Report.

Loneragan, N., Kenyon, R., Staples, D.J., Poiner, I.R., and Conacher, C.A. (1998). The influence of seagrass type on the distribution and abundance of postlarval and juvenile tiger prawns in the western Gulf of Carpentaria, Australia *Journal of Experimental Marine Biology and Ecology* **228**, 175-196.

Martin-Smith, K.M. (1994). Short-term dynamics of tropical macroalgal epifauna: Patterns and processes in recolonisation of *Sargassum fiissifolium*. *Marine Ecology Progress Series* **110(2-3)**, 177-185.

McClanahan, T.R. (2000). Bleaching damage and recovery potential of Maldivian coral reefs. *Marine Pollution Bulletin* **40(7)**, 587-597.

McVey, J.P. (1970). Fishery ecology of the Pokai artificial reef. University of Hawaii, Honolulu, PhD Dissertation. 268pp

Paine, R.T. (1979). Disaster, catastrophe and local persistence of the sea palm *Postelsia palmaeformis*. *Science* **205**, 685-687

Pamintuan, I.S., Alino, P.M., Gomez, E.D. and Rollon, R.N. (1994). Early successional patterns of invertebrates in artificial reefs established at clear and silty areas in Bolinao, Pangasinan, Northern Philippines. *Bulletin of Marine Science* **55(2-3)**, 867-877.

Philipp, E. and Fabricius, K. (2003). Photophysiological stress in scleractinian corals in response to short-term sedimentation. *Journal of Experimental Marine Biology and Ecology* **287**, 57-78.

Rogers, C. (1979). The effect of shading on coral reef structure and function. *Journal of Experimental Marine Biology and Ecology* **41**, 269-288.

Rogers, C.S. (1983). Sublethal and lethal effects of sediments applied to common Caribbean reef corals in the field. *Marine Pollution Bulletin* **14**, 378-382.

Sheppard, C. and Obura, D. (2005). Corals and reefs of Cosmoledo and Aldabra atolls: Extent of damage, assemblage shifts and recovery following the severe mortality of 1988. *Journal of Natural History* **39(2)**, 103-121.

Stafford-Smith, M.G. (1993). Sediment-rejection efficiency of 22 species of Australian scleractinian corals. *Marine Biology* **115**, 229–243.

Thackston, E. L., and Palermo, M. R. (2000). Improved methods for correlating turbidity and suspended solids for monitoring. *DOER Technical Notes Collection (ERDC TN-DOER-E8)*. U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Umar, M.J., McCook, L.J. and Price, I.R. (1998). Effects of sediment deposition on the seaweed *Sargassum* on a fringing coral reef. *Coral Reefs* **17**, 169-177.

Vuki, V.C. and Price, I.R. (1994). Seasonal changes in the *Sargassum* populations on a fringing coral reef, Magnetic Island, Great Barrier Reef region, Australia. *Aquatic Botany* **48**, 153-166.

