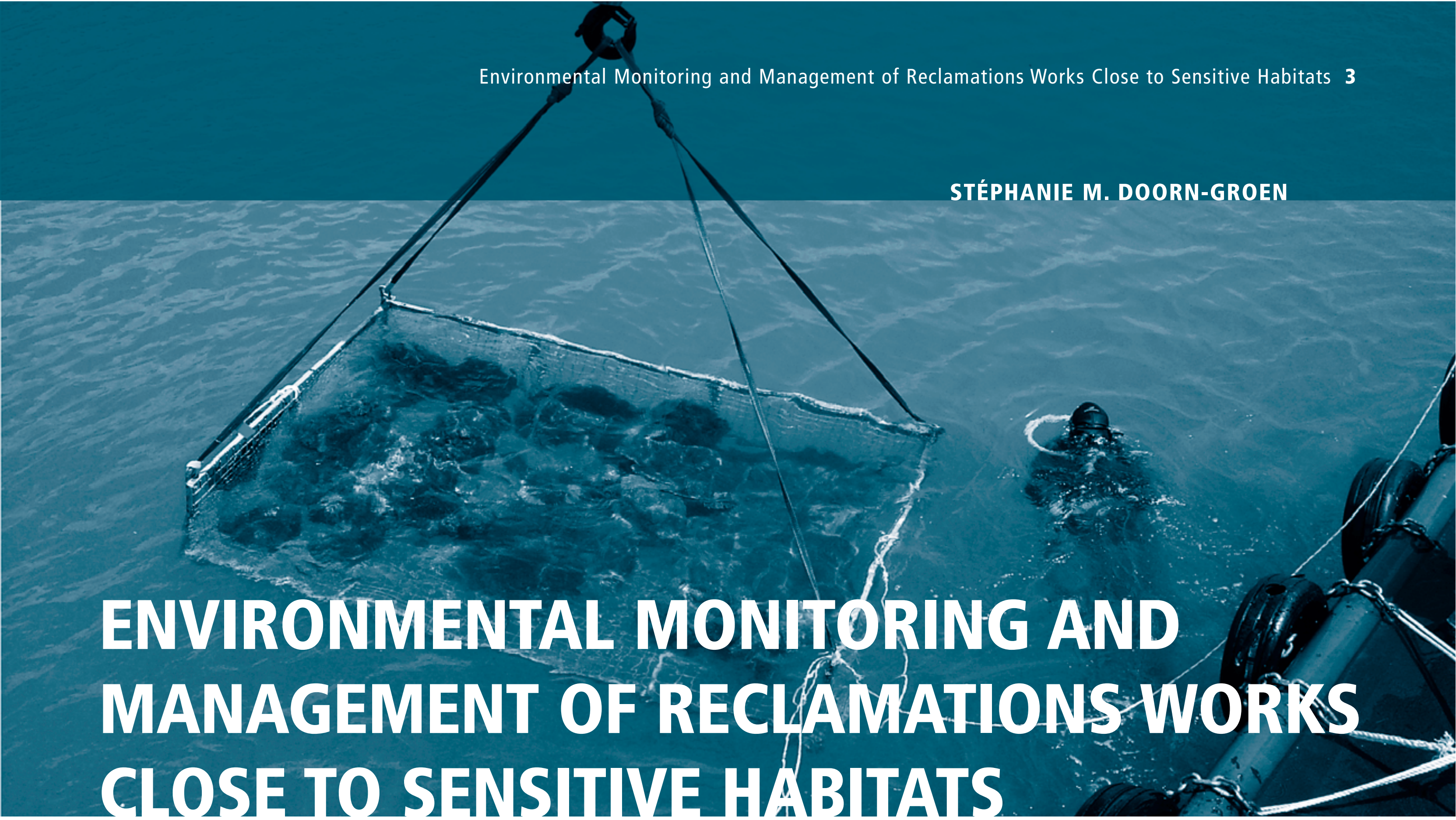


STÉPHANIE M. DOORN-GROEN

ENVIRONMENTAL MONITORING AND MANAGEMENT OF RECLAMATIONS WORKS CLOSE TO SENSITIVE HABITATS

ABSTRACT

Traditional methods for environmental management of marine reclamation works close to sensitive habitats have generally not provided the level of control necessary to ensure preservation of these habitats. Obtaining the level of control necessary to assure authorities and non-governmental organisations (NGOs) of compliance with environmental quality objectives, requires quantifiable compliance targets covering multiple temporal and spatial scales.

Of equal importance to allow feedback of monitoring results into compliance targets and work methods are effective and rapid response mechanisms. This article describes the successful implementation of comprehensive Environmental Monitoring and Management Plans (EMMP), based upon such feedback principles, which allow reclamation activities to proceed in close proximity to Singapore's most important marine habitats under third party scrutiny.

Specific focus is placed on describing the methods utilised to quantify compliance with daily spill budget targets and how such targets and compliances are assessed. To improve reliability, the spill budgets take into account specific habitat tolerance limits for varying magnitudes and durations of sediment loading. Refinements to sediment plume models were undertaken to enhance their ability to hindcast impacts from the contractors' complex reclamation schedules. Methods for segregation of impacts and assessment of cumulative impacts were also integrated into the hindcast procedures. Finally, the article describes the updating of tolerance limits and confirmation of spill budgets via targeted habitat monitoring.

To date, the EMMPs have been able to document compliance of the works to all pre-project environmental quality objectives at a level of reliability that cannot be refuted by third parties. This has minimised the developers' and contractors' exposure to public complaints and liabilities associated with environmental impacts. The EMMPs have thus allowed the reclamation activities to proceed in an efficient manner, whilst ensuring protection of the environment.

The author wishes to acknowledge the important contributions of Thomas M. Foster, Regional Director Southeast Asia, DHI Water & Environment (S) Pte Ltd to this research. This paper was first presented at WODCON XVIII in June 2007 and was published in the conference Proceedings. It is reprinted here in a slightly revised version with permission.

Above, For coral reef areas subject to direct impact, coral relocation is undertaken prior to the start of reclamations works.

INTRODUCTION

The tropical waters in Singapore provide excellent conditions for marine life, owing to relatively constant tropical water temperatures and frequent fresh ocean through flow from both the South China Sea and Melaka Straits. Coral, seagrass and mangrove habitats have been found to be relatively rich in Singapore. The diversity of the coral habitats in Singapore is confirmed by the fact that of the 106 coral genera existing world wide (Veron *et al.* 2000), 55 genera are documented in Singapore waters alone (Tun *et al.* 2004), compared to 13 genera found in the Caribbean. For seagrass habitats, 12 species out of 57 known species are found in Singapore (Waycott *et al.* 2004), whereas 24 out of 54 true and minor mangrove species have been found in Singapore so far (Thomlinson 1999). These numbers document the high diversity of marine habitats in a relatively small environment as Singapore and emphasize the importance of marine habitat conservation in Singapore.

Owing to the confined nature of Singapore waters and the presence of a large number of patch reefs, reclamation and associated dredging activities (in the following referred to generically as reclamation activities), often take place in very close proximity to coral reefs and seagrass areas. In addition, increasing industrial development results in developments also occurring close to sensitive industrial water intakes.

Recognizing the value of these marine habitat and industrial resources, Singapore has established strict Environmental Quality Objectives (EQO) for marine construction activities. In order to document compliance with these EQOs, pro-active Environmental Monitoring and Management Plans (EMMP) based upon feedback monitoring principles are required for marine construction activities to proceed, when these are in close proximity to key environmental receptors.

Introduced in Europe in the 1990s and refined during the EMMP works for the Øresund Link between Denmark and Sweden (Møller 2000) and Bali Turtle Island, Indonesia (Driscoll *et al.* 1997), feedback EMMP provides the level of responsiveness and documentation necessary to assure both authorities and other interest groups that the works meet the EQOs throughout the construction period.

Based upon the strict nature of the EQOs, EMMPs in Singapore are required to establish compliance of the works across multiple temporal and spatial scales:

- Compliance assessment against daily spill budget targets at the work area;
- Real-time monitoring and compliance assessment against response limits, particularly for intakes and reefs in close proximity to the work area;
- Compliance assessment against results of daily hindcast modelling compared to habitat tolerance limits throughout the potential impact area.

The feedback mechanism allows for updating of the spill budget limits, response limits and tolerance limits, based on the results of sedimentation monitoring and habitat monitoring. To ensure the accuracy of the entire system, the performance is confirmed on a daily basis via control monitoring of sediment spill.

This article presents how the various components of the EMMP are established and executed, together with the refinements necessary to ensure a level of responsiveness appropriate to the importance of the receptors.

BASIC COMPONENTS OF THE EMMP

The EMMP is the primary method of control to ensure EQOs relating to marine habitats and other environmental receptors are met. The EMMP is further a tool to:

- detect any unexpected impacts at an early stage,
- establish the response necessary to address such impacts, and
- confirm that appropriate tolerance limits have been adopted.

The feedback approach of the EMMP is pro-active. It links the results of detailed numerical hindcast models of the sediment plumes resulting from reclamation activities with the results from online turbidity and current sensors, daily spill measurements and periodic habitat surveys, and compares these against the spill budget.

The spill budget is the maximum allowable spill (daily, weekly and fortnightly limits are set), which will still ensure (based on the results of sediment plume forecast modelling) that the EQOs are met. As environmental receptors, like corals, have a different tolerance against suspended sediment levels than for example mangroves, individual tolerance limits are defined for each environmental receptor.

The tolerance limits play an important role throughout the project, as the daily spill budget is based on these individual limits. Both tolerance limits and spill budgets are evaluated and updated during the project, based on results of the habitat monitoring campaigns.

The main components of Feedback EMMPs, as implemented in Singapore are:

i) Environmental Baseline
Feedback variables are identified, instrumented and monitored for a statistically significant period prior to construction, which is typically in the order of 3 to 6 months. Variables monitored include all key environmental receptors such as corals reefs, seagrass beds, mangroves, turbidity, water quality, currents and sedimentation. This phase also includes the confirmation of the environmental quality objectives for the project and environmental tolerance limits. If compensatory works are required, such as coral relocation from direct impact areas, this is also undertaken at this stage of the EMMP.

ii) Elaboration of work plans
The appointed reclamation contractor elaborates a work plan, specifying the distribution of the work in time and space, procedures and equipment.

iii) Assessment of work plans
The effect of performing the work plan on the environment is assessed through the use of numerical sediment plume forecast modelling.

vi) Revision of work plans
If the forecasted impact resulting from implementation of the work plan leads to unacceptable effects, i.e. violation of EQOs, the work plan is revised and reassessed. Once the work plan is finalised a final EMMP specification document is drawn up that specifies the detailed execution, response and management process for the EMMP. In particular, the final EMMP specification includes a spill budget (for each phase of the reclamation), which is the limiting amount of spill that will still result in the EQOs being met and against which the day-to-day control of the reclamation work can be assessed.

v) Construction phase
Reclamation commences.

Stéphanie M. Doorn-Groen receiving an IADC Award for young authors from Constantijn Dolmans, Secretary General of IADC.

IADC AWARD 2007
PRESENTED AT WODCON XVIII,
ORLANDO, FLORIDA, USA
MAY 27-JUNE 1, 2007

An IADC Best Paper Award was presented to Stéphanie M. Doorn-Groen, Manager Engineering Services at DHI Singapore, who has been based in Southeast Asia since May 2002 and joined DHI Singapore in January 2004. She graduated in 2000 with a BSc (Civil Engineering) from the Polytechnic The Hague, the Netherlands and in 2002 with a MSc (Civil Engineering Management & Geotechnology) from South Bank University London, UK. Her previous experience was as a geotechnical adviser for Fugro Onshore Geotechnical bv, as a superintendent and technical employee for the dredging company Van Oord bv and for Municipal Works, Ports, Design & Construct, Rotterdam, the Netherlands.

Each year at selected conferences, the International Association of Dredging Companies grants awards for the best papers written by younger authors. In each case the Conference Paper Committee is asked to recommend a prizewinner whose paper makes a significant contribution to the literature on dredging and related fields. The purpose of the IADC Award is "to stimulate the promotion of new ideas and encourage younger men and women in the dredging industry". The winner of an IADC Award receives Euros 1000 and a certificate of recognition and the paper may then be published in *Terra et Aqua*.

vi) Compliance monitoring
Monitoring of daily compliance variables against the pre-determined sediment spill limits (spill budget). If daily compliance limits are violated, mitigation actions are established and implemented. If no violations of limits occur, reclamation work and daily monitoring continue. Compliance monitoring is reported on a daily basis and to ensure the level of responsiveness, reporting is required a maximum of 45 hours in arrears of any reclamation activity.

vii) Control monitoring
Monitoring of real time measurements and comparison to response limits, such as online turbidity data or weekly sedimentation data. If no violations of limits occur, work and control monitoring continue. Control monitoring is reported to the time scale of the monitoring activity (daily or weekly).

viii) Spill hindcast
Spill hindcast documents the impact of the reclamation progress on the environment remote to the work site. The spill hindcast is based upon realized production schedules, composition of fill material and actual tide conditions. The assessment is made through the use of numerical sediment plume hindcast modelling, with the hindcast updated every day. Reporting of the hindcast is made a maximum of three days in arrears of the actual progress of the reclamation works so that remote impacts are captured prior to them becoming significant.

ix) Habitat monitoring
Monitoring of biological habitat feedback variables is performed to an appropriate time schedule for the anticipated response rates. This is typically once every three months for coral reefs, seagrass beds and mangrove areas.

x) Evaluation of construction phase
Based on the results of the biological monitoring of feedback variables and the results of the numerical spill hindcast modelling of the realized construction process, the temporal and spatial impacts of the construction phase are assessed. If EQOs are violated, mitigation actions are established, assessed and undertaken. On the basis of the realized impacts, environmental criteria (tolerance limits) and compliance criteria (spill budgets) for the next construction phase are updated (the feedback loop).

xi) Next construction phase
The construction and monitoring process returns to task v) for each major stage of the reclamation and the process is repeated until reclamation is complete.

xii) Completion of construction
An environmental audit is produced at the end of the construction period as formal documentation of the impacts realised during the construction phase. This is based upon the result of the compliance, control, habitat and support monitoring together with the results of the hindcast modelling of impacts. The environmental audit is based on a final habitat survey usually carried out three months after the end of construction.

The main advantages of this approach to EMMPs are:

- Compliance measurements are targeted in the sediment plume resulting from dredging and reclamation activities, as close as possible to the source of spill at the given time of measurement. This provides a much more accurate measurement of suspended sediment spill than can be achieved via fixed turbidity sensor stations, which often lie outside the sediment plume for individual dredging or reclamation operations.
- Numerical sediment plume forecast models allow assessment of changes to the spill budget for variations in complex reclamation schedules and varying tide and ocean current conditions, thereby ensuring the spill budget is the most appropriate for the given stage of the works given the specific equipment to be utilized and timing of the activity.
- The hindcast model documents the spatial distribution of impacts at all

the receptor sites in the vicinity of the reclamation site with far broader spatial scale and finer temporal resolution than can be achieved via habitat monitoring in isolation.
- The hindcast model keeps a running balance of the cumulative sedimentation impact levels based on actual production provided by the reclamation contractor. Increasing levels of sedimentation can be detected at an early stage and mitigating measures can be applied, if necessary.
- The combined use of daily spill compliance monitoring, control monitoring and hindcast modelling allows the EMMP to respond rapidly and reliably to different temporal impact scales (from for example, short term exceedences resulting from, for example, unexpected events, to long-term trends resulting from, for example, deterioration in the quality of fill material).
- The feedback loop ensures that tolerance limits and resultant spill budgets are consistent with the specific sensitivity of the environmental receptors in the impact area.

ENVIRONMENTAL QUALITY OBJECTIVES

In order to set EQOs for a project, it is essential that a classification scale is adopted to define the scale of impacts that may be allowed at a given environmental receptor. The following scale of impact classifications has been adopted for several projects in Singapore:
- *No impact:* Changes are significantly below physical detection level and below the reliability of numerical models, so that no change to the quality or functionality of the receptor will occur.
- *Slight impact:* Changes can be resolved by numerical sediment plume models, but are difficult to detect in the field as they are associated with changes that cause stress, not mortality, to marine ecosystems. Slight impacts may be recoverable once the stress factor has been removed.
- *Minor impact:* Changes can be resolved by the numerical models and are likely to be detected in the field as localized mortalities, but to a spatial scale that is unlikely to have any secondary consequences.
- *Moderate impact:* Changes can be resolved by the numerical models and are detectable in the field. Moderate impacts are expected to be locally significant.
- *Major impact:* Changes are detectable in the field and are likely to be related to complete habitat loss. Major impacts are likely to have secondary influences on other ecosystems.

The task of defining EQOs rests with the authorities and is made on an area by area, habitat by habitat basis. For reclamation projects in Singapore, "Slight Impact" is typically allowed in the area immediately adjacent to (within 500 m) of the work area, whilst "No Impact" is required for all environmental receptors remote from the work area. For coral reef areas subject to direct impact (i.e. under the reclamation profile), it is presently common practice in Singapore to compensate for the habitat loss by undertaking a coral relocation exercise prior to start of reclamation works.

TOLERANCE LIMITS AND ENVIRONMENTAL QUALITY OBJECTIVES

The linkage between project EQOs and spill budget depends on the method of reclamation and on the tolerance limits of the various environmental receptors, which in turn depends upon the pre-project external stress levels on the ecosystem. In Singapore, initial tolerance limits for the most sensitive marine habitats (corals and seagrass) have been established based upon extensive literature review and DHI's experience from similar projects in the South East Asia region.

These tolerance limits have then been refined over the course of several projects in Singapore, based upon the results of project specific habitat monitoring. Presently, these limits, as presented below, are believed to be the most relevant set of tolerance data available for coral reefs and seagrass beds subject to incremental reclamation impacts on top of elevated external (non-project related) stress levels.

Coral tolerance to suspended sediments

In simplified terms, as hard corals are dependent on symbiotic photosynthesizing *zooxanthellae* for their nutrient supply and survival, they are sensitive to increased turbidity levels as the reduction in light penetration through the water column adversely affects the photosynthesis process. Perhaps more seriously, elevated sedimentation levels can clog the corals' respiratory and feeding system, whilst also causing complete light extinction to the impacted area of the colony.

The level of sensitivity depends on the characteristics of the corals, with plate corals like *Pachyseris* sp. proving the most sensitive to increased sedimentation and least sensitive to reduction in light penetration. Conversely, branching corals such as *Acropora* sp. show the opposite sensitivity trend. Clearly, other impacts such as degradation of substrate impacting attachment of coralline larvae are also important to the overall impact level experienced by a reef. However, the present state of the art cannot quantify such details, which are therefore captured via the habitat monitoring component of the EMMP rather than via the tolerance limits. Background levels vary from region to region and are very site specific. Research from the Barrier Reef (Harriot *et al.* 1988) indicates that these corals are tolerant to levels of suspended sediments up to 4 mg/l (absolute concentration). However, studies in Hong Kong have shown tolerance levels up to 10 mg/l. Extensive monitoring data from multiple projects in Singapore (where changes in reef health, measured as a function of live hard coral cover and diversity, has been compared to measured and predicted suspended sediment and sedimentation levels), has allowed the development of an coral tolerance matrix for excess (above background) suspended sediment concentrations, see Table I.

This table is found to be applicable for the elevated background turbidity levels common in Singapore and the typical Singapore reef morphology, which is dominated by the more resilient massive corals and plate corals, as shown in Figure 1.

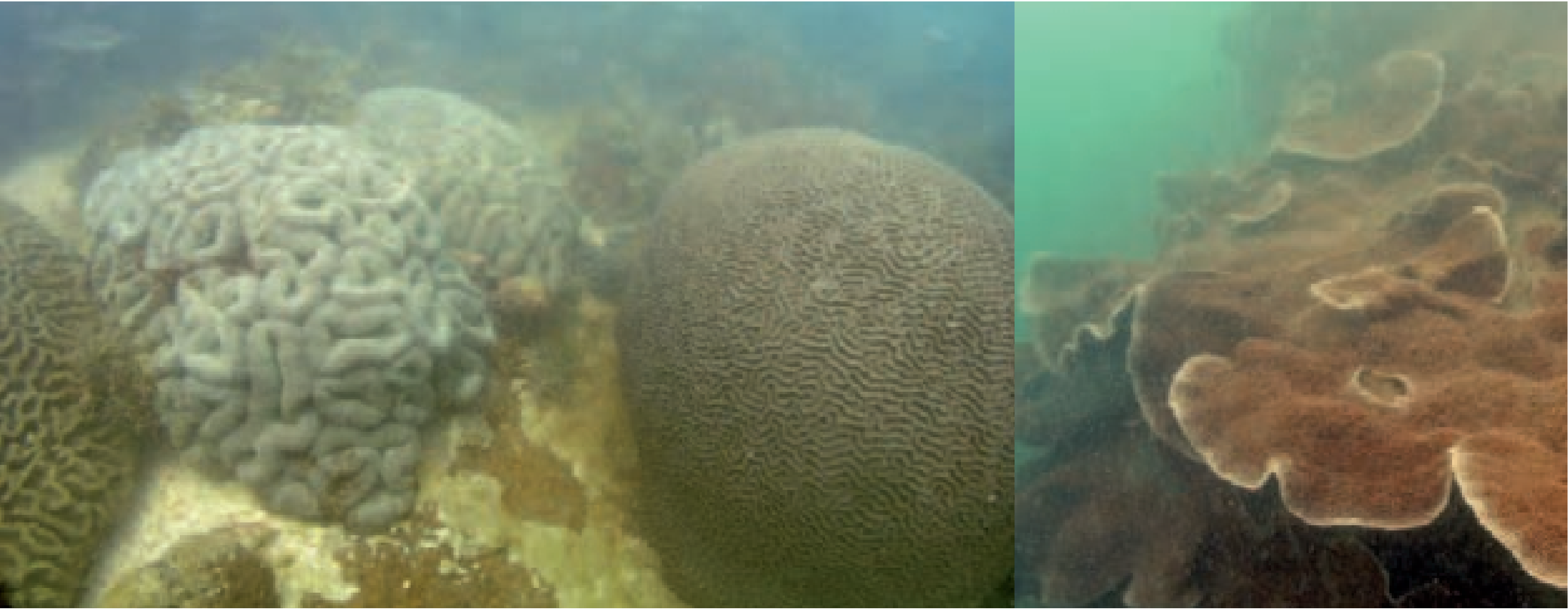


Figure 1. Typical coral habitats in Singapore.

Coral tolerance to sedimentation

Coral sensitivities to sedimentation are determined largely by the particle-trapping properties of the colony and the ability of individual polyps to reject settled materials (Figure 2). Horizontal plate-like colonies and massive growth forms present large stable surfaces for the interception and retention of settling solids. Conversely, vertical plates and upright branching forms are less likely to retain sediments.

A threshold (absolute) value of 0.1 kg/m^2/day has previously been adopted as the critical value for corals in Environmental Impact Assessments in Hong Kong. However, monitoring data from Singapore indicates that an incremental value of 0.05 kg/m^2/day is more appropriate for the type of coral habitats and existing stress levels in Singapore waters. Based on these Singapore data sets, the tolerance limits presented in Table II are found to be relevant for sedimentation impact on corals for reefs with naturally high background sedimentation levels, assuming a net deposition density of 400 kg/m^3.

Table I. Impact severity matrix for suspended sediments on corals in environments with high background concentrations

Severity	Definition (excess concentration)
No Impact	Excess Suspended Sediment Concentration > 5 mg/l for less than 5% of the time
Slight Impact	Excess Suspended Sediment Concentration > 5 mg/l for less than 20% of the time Excess Suspended Sediment Concentration > 10 mg/l for less than 5% of the time
Minor Impact	Excess Suspended Sediment Concentration > 5 mg/l for more than 20% of the time Excess Suspended Sediment Concentration > 10 mg/l for less than 20% of the time
Moderate Impact	Excess Suspended Sediment Concentration > 10 mg/l for more than 20% of the time Excess Suspended Sediment Concentration > 25 mg/l for more than 5% of the time
Major Impact	Excess Suspended Sediment Concentration > 25 mg/l for more than 20% of the time Excess Suspended Sediment Concentration > 100 mg/l for more than 1% of the time

Table II. Impact severity matrix for sedimentation impact on corals

Severity	Definition (excess sedimentation)
No Impact	Sedimentation < 0.05 kg/m^2/day (<1.7 mm/14 day)
Slight Impact	Sedimentation < 0.1 kg/m^2/day (<3.5 mm/14 day)
Minor Impact	Sedimentation < 0.2 kg/m^2/day (<7.0 mm/14 day)
Moderate Impact	Sedimentation < 0.5 kg/m^2/day (<17.5 mm/14 day)
Major Impact	Sedimentation > 0.5 kg/m^2/day (>17.5 mm/14 day)

Seagrass tolerance to suspended sediments

Productivity of seagrass can be limited owing to reduced light penetration resulting from the presence of algal blooms and suspended sediments. Seagrass requirements for light penetration have been well described by multiple authors, with the habitat being confined to water depths where light levels are above 10% to 15% of surface irradiance. For the normal tidal range experienced in the Singapore area, these figures concur well with observations within Singapore waters, which indicates that seagrass are generally limited to seabed areas shallower than –1 m CD. At low tide, many seagrass beds in the Singapore area are exposed (Figure 3), indicating a possible adaptation to, and higher tolerance to a high level of excess suspended sediments. For deeper beds, the tolerance is lower, but given the natural background variability in

Figure 2. Sedimentation impact on corals and expulsion of sediment via mucus generation.

suspended sediment load in the Singapore area, it is reasonable to assume that the outer limits of the seagrass are well adapted (in terms of water depth) to short-term fluctuations in the background concentration of 5 to 10 mg/l, such that excess loadings higher than 5 mg/l will be required to stimulate a noticeable habitat change. These findings, coupled with monitoring experience from the SE Asia region, result in the proposed impact severity matrix presented in Table III.

Table III. Impact severity matrix for suspended sediment impact on Seagrass in high background environments

Severity	Definition (excess concentrations)
No Impact	Excess Suspended Sediment Concentration > 5 mg/l for less than 20% of the time
Slight Impact	Excess Suspended Sediment Concentration > 5 mg/l for more than 20% of the time Excess Suspended Sediment Concentration > 10 mg/l for less than 20% of the time
Minor Impact	Excess Suspended Sediment Concentration > 25 mg/l for less than 5% of the time
Moderate Impact	Excess Suspended Sediment Concentration > 25 mg/l for more than 20% of the time Excess Suspended Sediment Concentration > 75 mg/l for less than 1% of the time
Major Impact	Excess Suspended Sediment Concentration > 75mg/l for more than 20% of the time

Seagrass tolerance to sedimentation

The growth rates of seagrass are high. Growth in the order of 1 to 2 cm per day has been recorded for example for *Thalassia* sp. (Durate *et al.* 1999) whilst growth rates in the order of 0.6 cm per day have been recorded for *Enhalus* sp. in Malaysia. Therefore, the short-term survival of seagrass beds, which depends on anaerobic performance, will only be impacted in the case of very high sedimentation rates. Such critical sedimentation rates will normally only occur very close to a reclamation site. Based on experience in the SE Asia region, the following impact severity matrix is presented for sedimentation impact on seagrass (see Table IV). Other impacts resulting from increased sedimentation, such as change in composition of substrate, are clearly also important to the overall impact levels experienced by a seagrass bed, but such detailed impacts are difficult to quantify and are therefore captured via the habitat monitoring component of the EMMP.

Table IV. Impact severity matrix for sedimentation impact on Seagrass in high background environments

Severity	Definition (Excess sedimentation)
No Impact	Sedimentation < 0.1 kg/m^2/day (<0.25 mm/day)
Slight Impact	Sedimentation < 0.25 kg/m^2/day (<0.63 mm/day)
Minor Impact	Sedimentation < 0.5 kg/m^2/day (<1.25 mm/day)
Moderate Impact	Sedimentation < 1.0 kg/m^2/day (<2.5 mm/day)
Major Impact	Sedimentation > 1.0 kg/m^2/day (>2.5 mm/day)

Figure 3. Typical seagrass habitat in Singapore.

Mangrove tolerance to suspended sediments and sedimentation

Mangroves can be considered to be very tolerant to the range of suspended sediment loads that may be generated from dredging and reclamation activities. Of the various mangrove species, those with pneumatophore root systems are the most sensitive to sedimentation (Thampanya *et al.* 2002), but even mangroves with pneumatophore root systems are only likely to be stressed when prolonged sedimentation reach levels from 10 cm up to 30 cm. This level of sedimentation is unlikely to occur outside the work area, and mangroves are thus not considered as sensitive receptors. Never-the-less, as EQOs are normally specified for mangrove areas, they are normally included in the habitat monitoring campaigns for reclamation EMMP in Singapore. Figure 4 presents a typical mangrove habitat in Singapore area.

Figure 4. Typical mangrove habitat in Singapore: Avicennia pneumatophore system (foreground) and Rhizophora stilt root system (background).

Visual impact and detection limits

In the turbid environments that are found around Singapore, low concentration sediment plumes in the surface of the water column are generally not visible (based upon results of remote sensing analysis) if the excess concentration above background does not exceed 5 mg/l. A realistic measurable visual detection limit for non-recreational areas (in the Singapore high background turbidity context) would be a reoccurring plume present for 30-40 minutes per 12 hour daylight period, i.e. an exceedence of about 5% per day, whilst for recreation areas a limit of 2.5% exceedence proves to be appropriate.

Intake tolerance limits to suspended sediments

For many industrial intakes the absolute tolerance limit to suspended sediments is not known by the operators. In such cases, the most practical method for establishing a tolerance limit is to carry out statistical analysis on long-term background suspended sediment data from the immediate area of the intake. It is then possible to carry out a test for *no statistical change* (at a confidence limit agreed with the operator) for the various time scales of interest (daily, weekly, monthly and 6 monthly tests are normally considered in Singapore).

DAILY COMPLIANCE MONITORING

Based on the EQOs, spill budgets are defined for each stage of the reclamation works. The spill budgets are updated as work progresses and feedback information confirms their applicability or indicates a relaxation or tightening is warranted.

The contractor's compliance to the daily spill budget is assessed on a daily basis against daily spill budget targets and on a weekly basis against weekly and fortnightly spill budget targets. Typically, the fortnightly spill budget is 60% of the daily spill budget, reflecting the ability of most receptors to cope with higher levels of stress if they are short-term or intermittent in nature. Daily compliance to spill budget targets must be established within a time frame which will allow response before any non-compliance will pose a threat to the environment. Therefore, daily compliance monitoring requires strict daily procedures for data delivery from the contractor, to ensure daily spill calculations, laboratory analysis daily compliance analysis and reporting can be carried out in a timely manner.

On daily basis the contractor supplies:

- Realised dredging volumes per dredger for every single trip, including location and method;
- Start and end time of dredging cycle, including delays;
- Realised reclamation volumes per dredger for every single trip, including location and method;
- Start and end time of reclamation cycle, including delays;
- Representative sediment samples from each load to be analyzed for fine contents by an external laboratory.

In addition to the data provided by the contractor, suspended sediment samples are taken in the main plume discharge of the reclamation site (either as suspended sediment samples (TSS) or sediment flux measurements using acoustic backscatter technology). The location and the time of the sampling reflect the reclamation activities of the contractor and the samples are analysed for TSS by an external laboratory.

This analysis provides a second method of control and serves as a validation for the spill calculation and performance of the numerical hindcast models. Based upon the fines content of the fill and dredge material and method of reclamation an empirical estimate of the total spill is made, for each reclamation/dredging operation over the preceding 24 hr period. The resultant total can then be compared to the spill budget

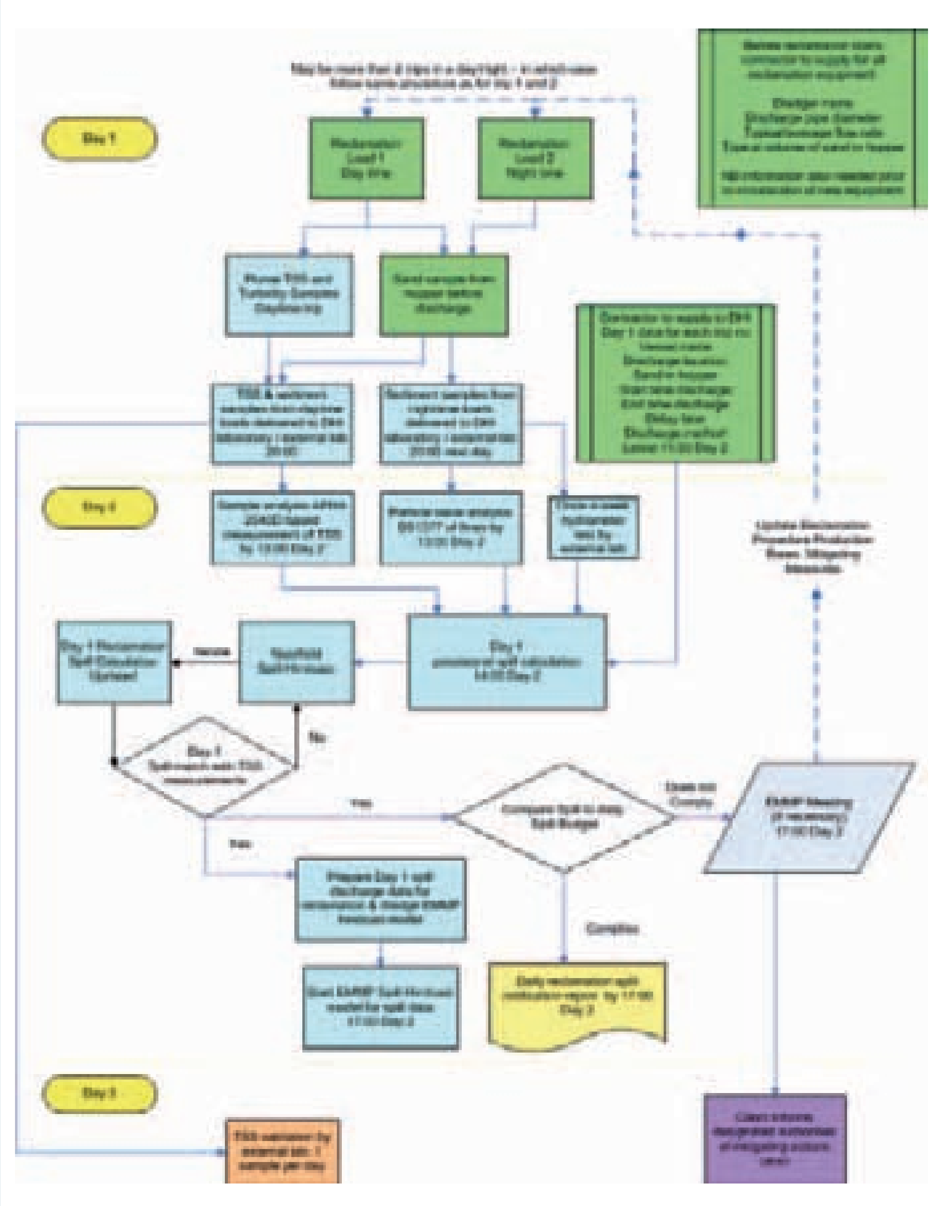


Figure 5. Daily operating procedure for daily compliance monitoring.

on the level of compliance established for the 24 hr period. A typical example is shown below for rainbowing operations.

Spill of fines leaving immediate dredging area = Load volume * fines % * 25%

Although it is recognised that the specific spill is dependent on many factors such as the prevailing water depth and current speed, this simple empirical formula has proved to be a reliable method for estimation of spill for sand placement in the typical range of physical conditions encountered in Singapore.

Validation of the spill calculation is subsequently provided by the TSS or sediment flux measurements in the plume. However, for the purpose of the daily compliance monitoring a simple, yet reliable, empirical formulation is required to meet the reporting time scale.

Figure 5 presents a general flowchart of the complex daily operating procedures required to establish compliance with spill budget targets to a time frame which will allow response before any non-compliance will pose a threat to the environment, which has been defined as a maximum of 45 hrs in arrears of any activity on site.

Figure 6 presents an example of the daily spill calculations over a period of five months based on the empirical methods described above and validated by the control sampling in the sediment plume. This figure indicates that the daily spill budget was exceeded for a period in April. Mitigating measures were introduced and subsequently the spill budget was achieved for the remainder of the reclamation work.

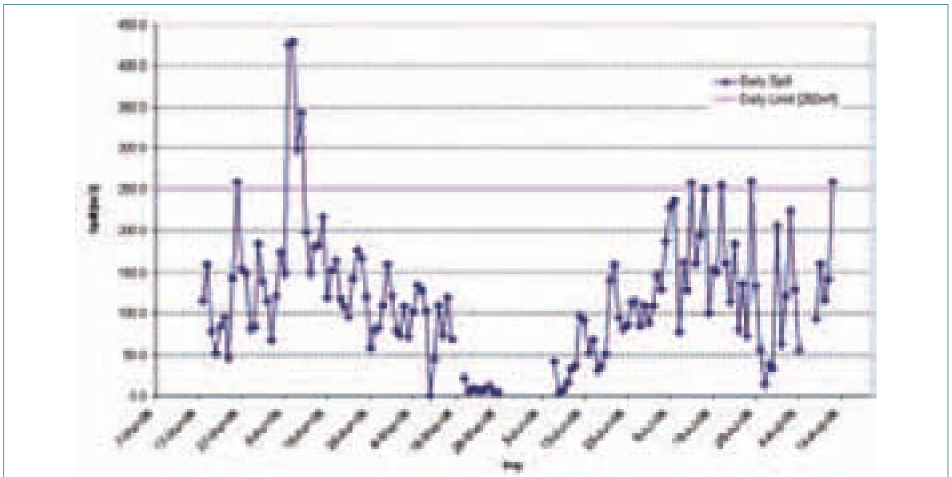


Figure 6. Spill results from reclamation operations.

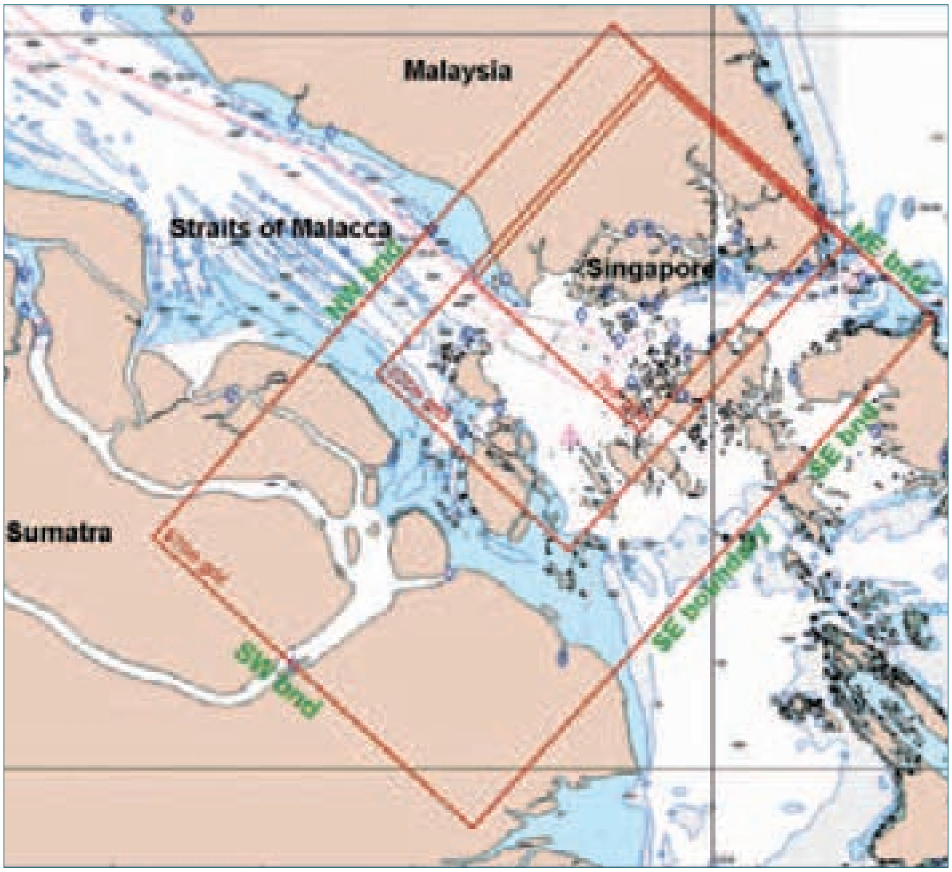


Figure 7. DHI's Singapore Straits regional 675 m grid model with nested intermediate 225 m grid and local 75 m grid sub-domain models.

DAILY HINDCAST MODELLING

Based upon the information provided by the contractor in terms of time and location of activities and the calculated spill, daily spill hindcast simulations are run in order to establish the temporal and spatial impacts of the sediment plumes released from the work area.

Hydrodynamic model setup and performance

The daily hindcast modelling is based upon DHI's extensively verified 675/225/75/25 m MIKE 21 nested grid hydrodynamic model of the Singapore Straits, which was developed in 2001 and is being continuously refined on the basis of daily real time current measurements.

Figure 7 shows the overall regional model grid coverage utilised for EMMP projects in the Singapore area, whilst Figure 8 presents an example of the model performance which meets relevant international standards such as UK Foundation for Water Research Publication Ref FR0374 *"A framework for marine and estuarine model specification in the UK"*. The 25 m Model resolution is adopted in the specific area of reclamation to ensure all relevant local hydrodynamic factors, which may affect the plume transport and dispersion are resolved.

Bathymetric survey data are taken directly from digital navigation charts, supplemented by project specific survey data, which is updated on a weekly basis for reclamation progress in the specific project areas.

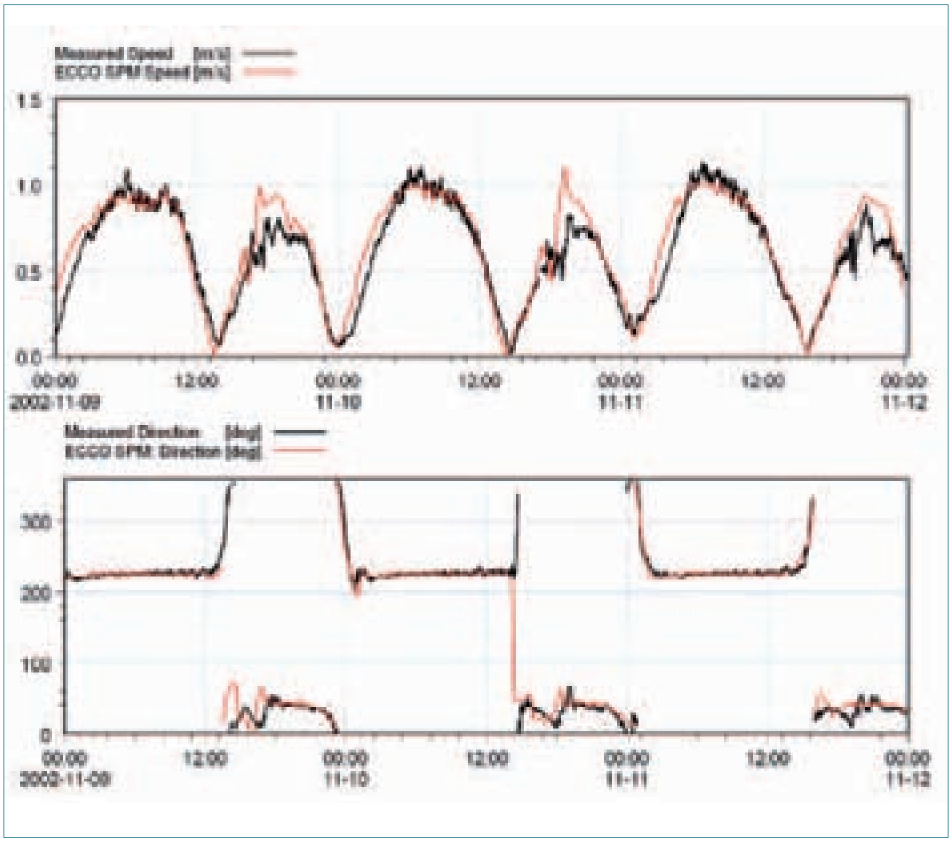


Figure 8. Example performance of DHI's Singapore Straits current forecast model. RMS error on current speed at presented validation point = 0.09 m/s.

Sediment plume model set-up and performance

Calibration and validation of DHI's sediment plume hindcast model for Singapore waters has been carried out over the course of several projects. A typical example of the model performance is provided in Figure 9. Throughout the course of the EMMP, the performance of the model is verified on a daily basis, either by direct TSS measurements within the sediment plume or via sediment flux transects through the plume.

Critical shear stress for erosion and deposition

A vital factor to the performance of the model in terms of documenting impacts on coral reef habitats is the parameterisation of the critical shear stress for erosion and deposition over the reef areas. The complex morphology of coral reefs on both micro and macro scales, leads to an increased tendency for deposition to occur and a reduced tendency for re-suspension. Extensive testing and comparison to sediment trap data collected on a weekly basis has been undertaken, leading to the following conclusions concerning average critical shear stress parameters for deposition and re-suspension of fines over coral reef areas in Singapore:

- Critical shear stress for deposition of fine material over coral reef: 0.6 N/m^2
- Critical shear stress for re-suspension of initial deposits over coral reef: 1.5 N/m^2

Figure 10 presents the example maps of critical shear stress in South-West Singapore, whilst Table V presents an example of model performance against measured sediment trap data.

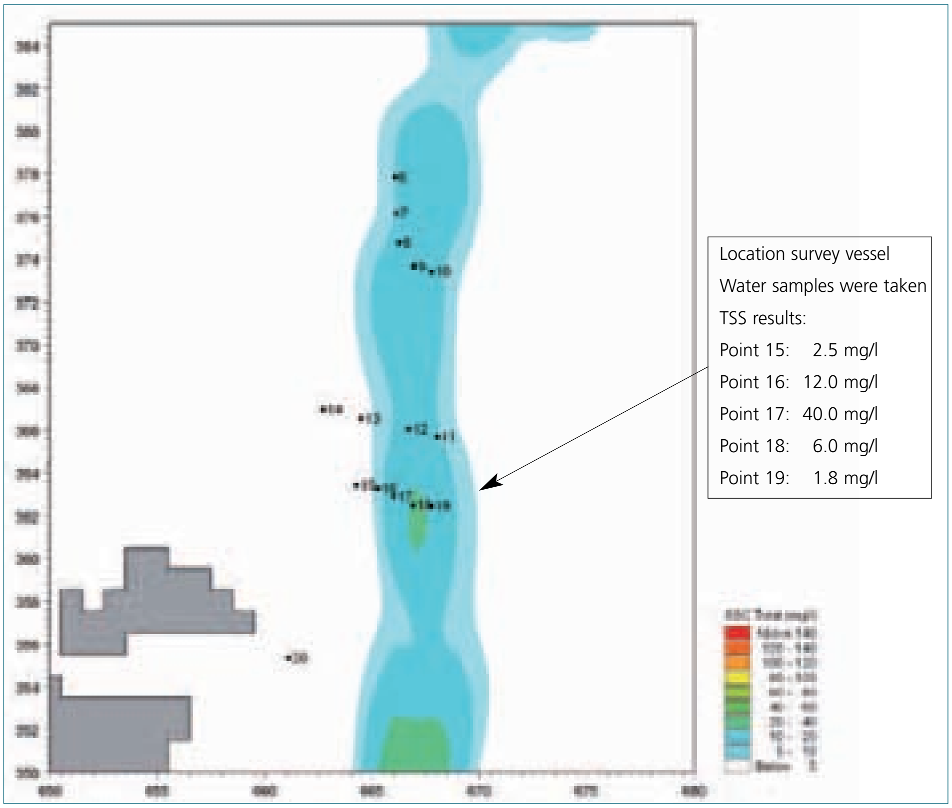
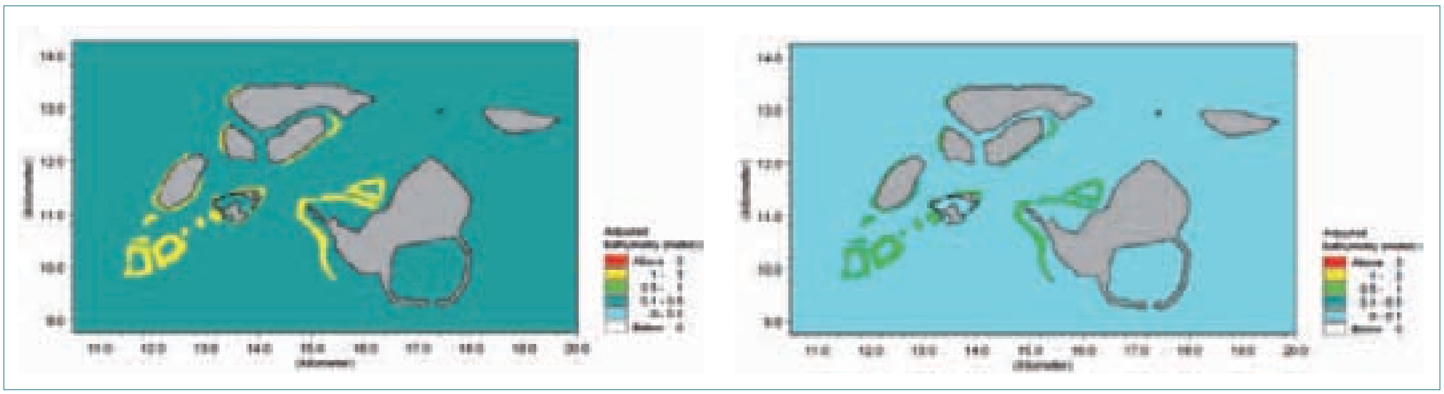


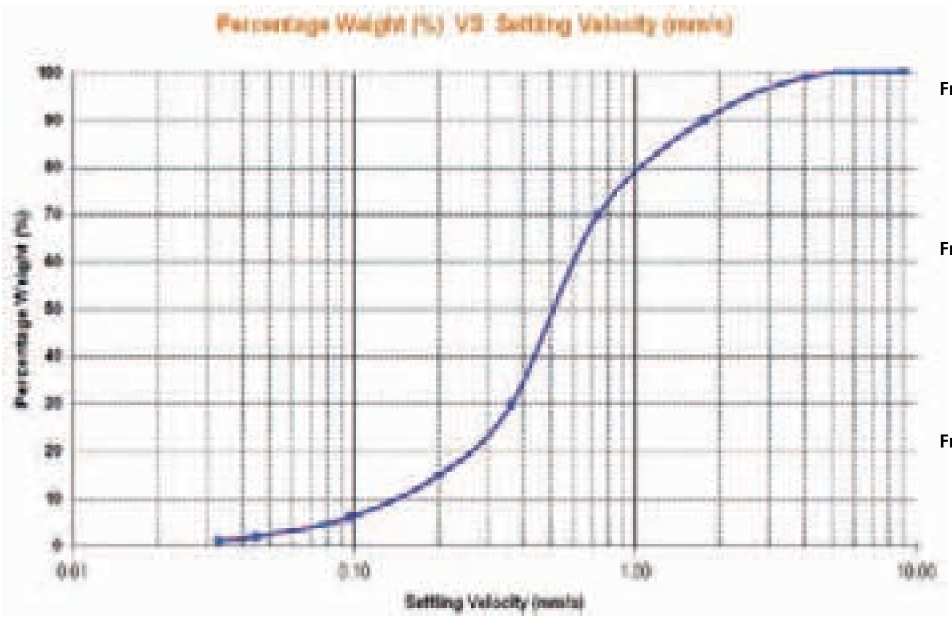
Figure 9. Location and magnitude of the sediment plume predicted by DHI's hindcast model and the location of the survey vessel during plume transects.

Table V. Example of model performance measured against reef sedimentation data

Measured incremental sedimentation $Kg/m^2/day$	Predicted incremental sedimentation without adjustment of critical shear stress parameters	Predicted incremental sedimentation with adjustment of critical shear stress parameters
0.02	< 0.01	0.04
0.04	< 0.01	0.04

Figure 10. Maps of critical shear stress for erosion (left) and deposition (right) covering SW Singapore for sediment released from dredging and reclamation operations.





Fraction 1 60% contribution
Representative fall velocity v = 0.00075 m/s
Coarse fines: settles quickly outside the work area

Fraction 2 36% contribution
Representative fall velocity v = 0.00027 m/s
Medium fines: can be transported large distances during spring tide, prime case of remote sedimentation

Fraction 3 4% contribution
Representative fall velocity v = 0.000067 m/s
Fine fines: regularly transported large distances, generally will not settle out, contributing to suspended sediment impacts

Figure 11. Example sediment fall velocity distribution from Owen Tube test of fine material content of reclamation fill.

Sediment settling velocity

In order to reliably simulate the transport and fate of the fine material released from dredging and reclamation activities, it also proves necessary to divide the sediment spill into a number of sediment fractions. After testing of various options, 6 fractions (3 for reclamation fill and 3 for dredge material) have been found to provide a generally consistent compromise between model reliability and computational time, which is critical to the reporting schedule.

In order to establish the characteristics of the 6 sediment fractions, fall velocity testing of the fine material present in the reclamation and dredge material is carried out on a regular basis via Owen tube tests. Fall velocity characteristics are typically updated on a monthly basis (separately for reclamation fill and dredged material), or when the daily control measurements in the sediment plume indicate a necessity for updating. An example of the Owen tube test results is provided in Figure 11.

Execution of daily hindcast

Based on the contractor's activity information and calculated spill, the numerical spill hindcast is carried out on a daily basis for the actual reclamation operations. The result of the daily EMMP hindcast model are validated against the daily control samples taken in the sediment plumes originating from the reclamation.

The daily hindcast is processed to allow direct comparison to the EQOs with the following key outputs:

- Time series and tabulation of excess suspended sediment concentration at the various environmental receptors;
- Maps of exceedences of 5, 10 and 25 mg/l excess concentration;
- Animations of concentration maps.

UPDATING OF TOLERANCE LIMITS AND SPILL BUDGET

As the spill budget is dependent on the tolerance limits of the various environmental receptors, it is critical that the reliability of these limits is confirmed at an early stage of the construction works, with continuous refinement carried out throughout the construction period. The tolerance limits are confirmed (or refined) based upon the results of quarterly habitat monitoring of key environmental indicators compared to the results of the sediment plume hindcast and sedimentation monitoring.

Habitat monitoring

Quarterly control habitat monitoring surveys are carried out to establish the status of the various marine habitats near the development site. The choice of survey locations is based upon three criteria:

- Importance and/or sensitivity of the habitat;
- Expected level of impact (based upon the sediment plume forecast); and
- Control stations outside the potential impact area (based upon the sediment plume forecast).

For each survey station key indicators are identified and the survey sites laid out to facilitate exact replicate surveys.

Coral habitat monitoring

Coral surveys are primarily carried out using the Line Intercept Transect (LIT) method, as shown in Figure 12, which is recommended by the Global Coral Reef Monitoring Network (English *et al.* 1997, Hill *et al.* 2004) for quantification of the percentage cover of reef building corals, coral diversity, as well as other benthic life forms. The LIT methodology, which provides a good method for identification of mortalities of larger reef areas, is supplemented by exact repeat surveys of selected individual colonies,

Figure 12. LIT Coral habitat survey in Singapore.

which is required to establish changes in stress levels or partial mortalities of colonies lying off the transect line.

Example results from a repeat LIT survey close to the reclamation site at station CR07 are presented in Table VI. The LIT surveys indicate no significant change in reef characteristics as illustrated by the plot in Figure 13.

For the exact repeat colony monitoring at the same site, 50% of the colonies showed some form of improvement in life form characteristics. 30% showed no change and 2 colonies (20%) were noted to have declined as a result of physical damage not directly attributable to the reclamation works.

The sediment loading from the reclamation works at this site over the monitoring period is tabulated in Table VII. Comparison with the coral tolerance limits presented in Table I and Table II indicates that the sediment loading falls in the No Impact category. This is consistent with the recoded LIT and exact repeat results confirming, in this case, the applicability of the tolerance limits (at the No Impact level). Tolerance limits were therefore not updated and spill budget limits for the period after August 2006 were not adjusted.

Seagrass monitoring

Parameters used to assess the health of the seagrass areas include seagrass spatial distribution and composition, seagrass percent cover, seagrass diversity and evenness, seagrass biomass, sediment level and composition.

Measures Analysis of Variance on Ranks, which is commonly used for comparison between two datasets, is used for the statistical analysis of sediment level and seagrass cover for comparison of the baseline and repeat surveys. Figure 14 shows an example from a seagrass bed close to the reclamation site. The mean seagrass cover documents a general increase between the baseline and the first Repeat Survey, but a decrease of approximately 20% documented between the first and second repeat.

The corresponding sediment loading from the reclamation works at this site over the monitoring period is tabulated in Table VIII. This indicates the seagrass bed lie in the No-Impact zone, though a moderate decrease

Table VI. Comparison of mean percent cover and standard deviation for the major benthic categories at CR07

Major Category	Baseline August-05		Repeat Survey 1 May-06		Repeat Survey 2 August-06	
	Mean Cover (%)	STDEV	Mean Cover (%)	STDEV	Mean Cover (%)	STDEV
Hard Coral	24.66	8.73	26.87	6.95	26.61	8.45
Dead Coral	0.28	0.31	0.38	0.53	1.01	0.78
Soft Coral	1.34	1.46	0.86	0.58	0.75	0.40
Sponge	2.55	2.19	3.84	2.19	3.66	2.39
Other Fauna	16.13	4.35	14.10	8.28	13.44	9.46
Algae	19.93	8.01	27.87	8.76	30.36	12.86
Rubble	32.72	16.21	21.86	8.62	22.02	9.51
Rock	0.00	0.00	0.00	0.00	0.00	0.00
Silt	0.00	0.00	1.94	2.50	1.63	2.16
Sand	2.39	1.76	2.28	1.61	0.52	0.83
Other	0.00	0.00	0.00	0.00	0.00	0.00

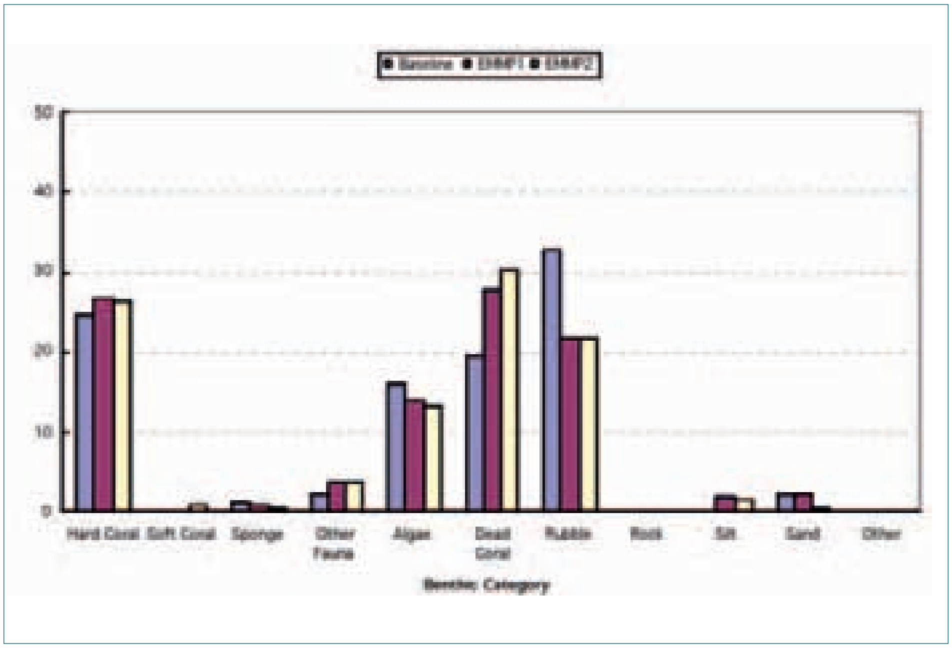


Figure 13. Changes in the mean percentage cover of the major benthic categories.

in cover was identified by the habitat monitoring. In this case the hindcast models are conclusive in confirming that there is no direct flow of sediment from the reclamation area to this seagrass site, such that it can be firmly concluded that the decrease in seagrass cover is not attributable to the reclamation works. Tolerance limits were therefore not updated and spill budget limits for the period after August 2006 were not adjusted. The ability to isolate impacts from a development project from other third part or regional impacts is a major advantage of the feedback EMMP system adopted in Singapore.

Sedimentation monitoring

Sediment traps are deployed on the reef crest, close to the LIT monitoring sites. These measurements document sedimentation levels along the reef area, which is used in part to validate the results of the sediment plume hindcast models (incremental sedimentation above background values) and in part to confirm tolerance limits. Sediment traps function as a measuring device for sedimentation on the reef area and are deployed in three replicates; each consisting of three cylindrical small tubes attached together. The theory and dimension of the sediment trap follows those recommended in the Survey Manual for Tropical Marine Resources (English *et al,* 1997). See Figure 15 for an impression of the sediment traps deployed.

To function reliably in the high sedimentation environment present in Singapore, sediment traps are recovered every fortnight. As a result of the large number of traps deployed in Singapore, ease of underwater service is important. This has lead DHI to develop a single point of attachment system that is operated by the single Allen screw seen in Figure 15. This system reduces the underwater service time by approximately 50%, improves the reliability of the data by reducing sediment loss during recovery and also reduces expenditures associated with cable ties and other consumables by approximately 50%.

Table VII. Summary of percentage exceedence of suspended sediment and sedimentation loading over the coral reef monitoring site CR07 presented in Table VI

Date	March 2006	April 2006	May 2006	June 2006	July 2006	August 2006
% Exceedence 5 mg/l	< 5%	< 5%	< 5%	< 5%	< 5%	< 5%
Nett sedimentation kg/m^2/day	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05

Table VIII. Summary of sedimentation loading over the seagrass monitoring sites presented in Figure 14

Date	March 2006	April 2006	May 2006	June 2006	July 2006	August 2006
Nett sedimentation kg/m^2/day	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1

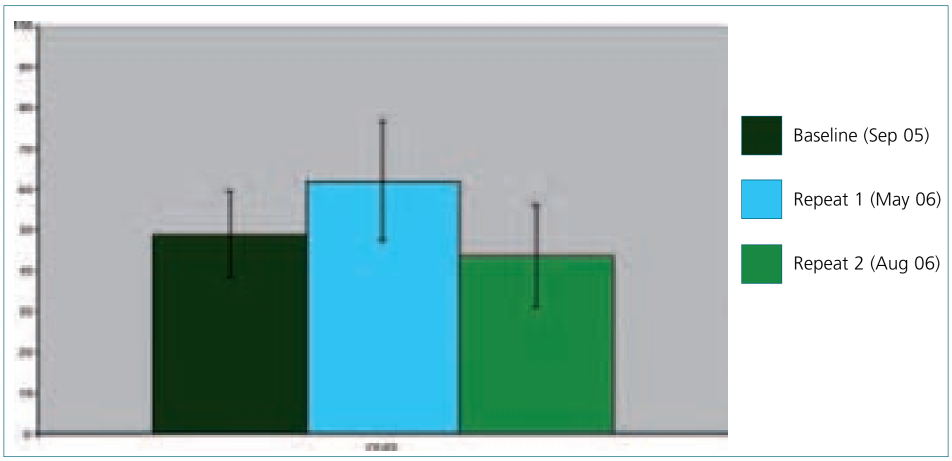
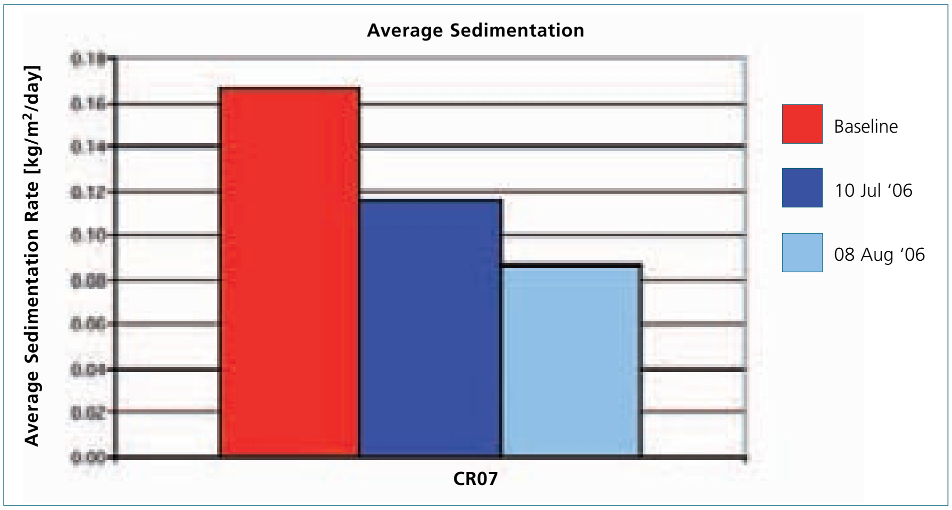


Figure 14. Comparison of mean seagrass cover along transect CY03.

Figure 16 presents an example of the absolute sedimentation rates close to the work area at the same reef monitoring presented in Table VI. This shows an average declining sedimentation rate between 0.08~0.11 kg/m^2/day after baseline. The results presented in the figure indicate that no sedimentation impact at station CR07 during July and August falls within the No Impact limits. These results are consistent with the results of the sediment plume hindcast and habitat surveys (see Table VI for details of change in live coral cover at CR07) and fall within the EQOs for the project.

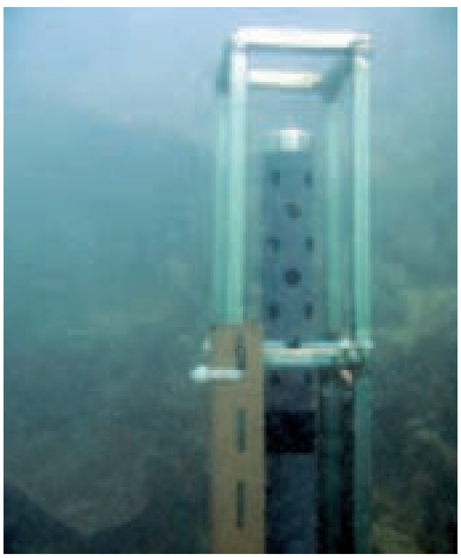
Figure 15. Three sedimentation traps are fixed at each site located on the reef slope close to the coral LIT sites. The height of the trap from the reef surface to the opening is 35 cm. The sediment traps are held vertically by angle-bars hammered deep into the ground in an area of dead coral.
The actual dimension of the sediment trap is: height 15 cm and Ø 5 cm.

Figure 16. Average sedimentation rates at station CR07.



Online turbidity sensors

Online turbidity sensors are deployed at key environmental receptors (coral reefs and intakes) in close proximity to the reclamation area in order to provide an initial response mechanism to any transients in suspended sediment concentrations and to provide supplementary validation data for the sediment plume hindcast models.
The instruments are vertically secured to a platform deployed on the seabed, and held approximately 1 metre above the seabed. Data recorded is transformed from NTU to TSS via site-specific validation curves, which are updated on a weekly basis based on measurements taken during instrument servicing. The data is transmitted to a Data Information System that is used to disseminate all EMMP related data to the authorities and contractors.



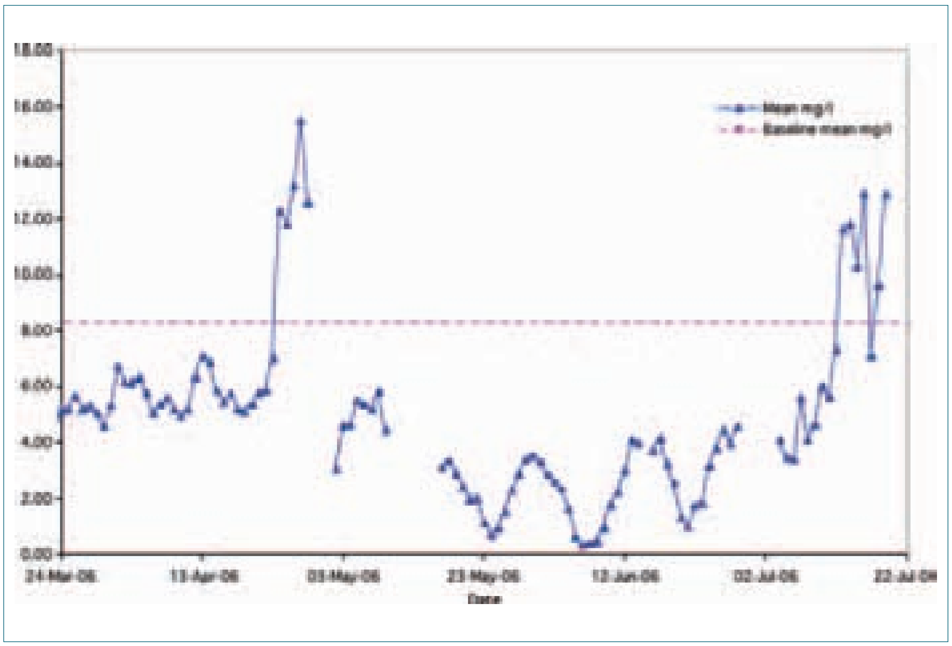


Figure 17. Left: deployed YSI turbidity sensor. Right: Time series of turbidity measurements.

Figure 18. A noise meter, built into a switch box.

Figure 19. An Acoustic Doppler Current Profiler mounted on a stainless steel frame and about to be deployed on the seabed.

Figure 17 presents a typical picture of the online sensor and an example of mean turbidity levels. The increase in turbidity levels observed in this example above the baseline mean results from sensor fouling, which is a significant problem in Singapore waters owing to high rates of algae growth, despite automatic sensor cleaning and weekly equipment service.

As the turbidity measurements provide only a second level of EMMP response the reliability of the overall EMMP is not influenced by this fouling problem, which would otherwise be critical to management plans reliant purely on static monitoring.

Other online instrumentation used for control monitoring include, for example, noise meters (Figure 18) and Acoustic Doppler Current Profilers (ADCP) (Figure 19). Noise meters are generally deployed at receptor sites (residential buildings and/or work sites) to document noise levels from the construction. ADCPs are deployed on the seabed for current and wave measurements.

CONCLUSION

The feedback approach to the Environmental Monitoring and Management of reclamation works summarised in Figure 20, which has been adopted in Singapore, provides a practical and reliable method for the pro-active management of potential environmental impacts resulting from reclamation works.

The responsiveness of the system allows unexpected impacts to be mitigated prior to them becoming a serious threat to the environment. Importantly, the level of documentation provided ensures that developers and contractors are not exposed to unwarranted claims concerning environmental degradation as the EMMP approach allows full segregation of project impacts from other third party disturbances.

In order to obtain the level of reliability and responsiveness required to meet strict EQOs relating to marine habitats and other environmental receptors in Singapore, several enhancements to various components of the EMMP have had to be realised. These include empirical methods for estimation of spill based upon sediment characteristics and type of operation, adapting sediment plume models to cater for complex dredging and reclamation schedules, plus specific adjustment of settling and re-suspension characteristics to cater for the complexities of reef morphology.

The performance of the feedback EMMP in terms of meeting EQOs has been verified by habitat monitoring which also confirm adopted tolerance limits for corals and seagrass in high background suspended sediment and sedimentation environments such as those encountered in Singapore.

The EMMP techniques presented here have also been successfully adopted for the environmental management of other dredging and reclamation projects in the region, including Bintulu and Kota Kinabalu, Malaysia and previously mentioned Bali Turtle Island, Indonesia. The EMMP techniques are thus becoming accepted best practice methodologies in the South East Asia Region.

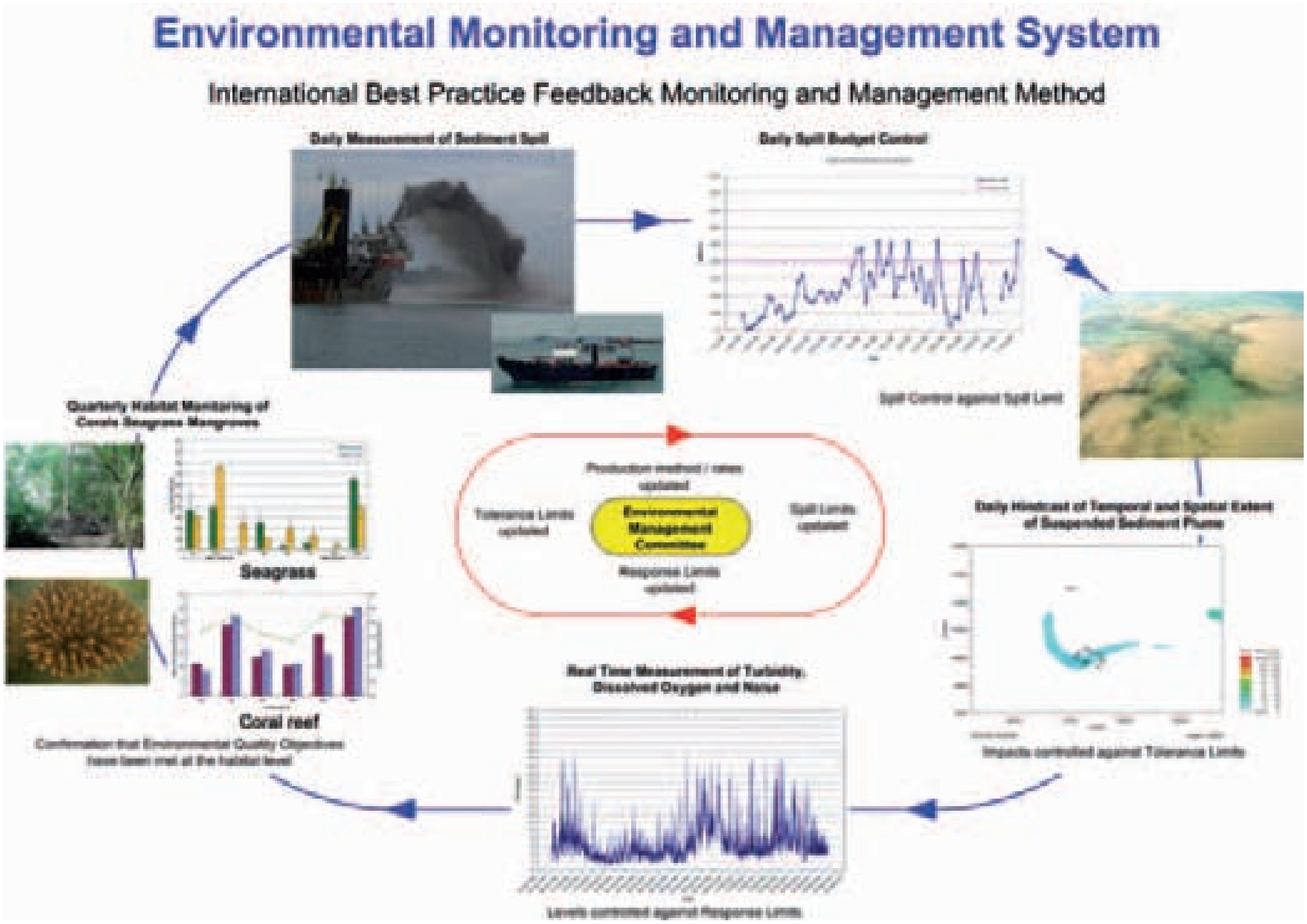


Figure 20. Summary of the prime components of feedback EMMP adopted in Singapore.

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