

Part V: Coastal, Estuarine, and Environmental Problems



Dredging and Reclamation Works for the Øresund Link



Installation of Environmental Monitoring Station, Øresund

INTEGRATED DESIGN OPTIMIZATION FOR A TROPICAL LAND RECLAMATION: BALI TURTLE ISLAND DEVELOPMENT

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Abstract

Bali Turtle Island Development is a major tourism-related coastal development project situated in the SE corner of Bali, Indonesia. The project includes large-scale dredge-and-fill reclamation for the purpose of enlarging the existing natural island of Serangan by 3.7 km². The completed reclamation will include three artificial lagoons, four artificial pocket beaches, six artificial headlands and a causeway/bridge connection to the Balinese mainland.

This paper provides an overview of the development project as a whole, as well as describing the numerous coastal engineering and environmental investigations that have been applied in the optimization of the design. Due to the complex bathymetry and interrelated wave, flow, sedimentological and water quality mechanisms, an integrated approach for design optimization was required. The steps taken for the management of dredging operations in the vicinity of sensitive habitats are also discussed.

Site Description

The study area lies near the shallow Lombok Sill separating the Indian and Pacific Oceans (Fig. 1). Regional tidal forcing is strong and complex, with spring tidal flows in Lombok Strait exceeding 2m/s. Furthermore, net seasonal currents of $\pm 1\text{m/s}$ may be present over the Lombok Sill (Murray and Arief, 1988).

The project site is the existing natural cay of Serangan (post-construction: Turtle Island). Intertidal reef flats extend seaward from Serangan, as well as from the developed beaches

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of Sanur and Tg. Benoa, to the surrounding reef fringe. The reef flats feature a patchy coverage of vegetation, sand and hard material. The existing beach faces are steep (~1:10) and consist of medium to coarse coral sand. The project area has a spring tidal range of almost 3m, and is subjected to some degree of swell wave attack year-round. Coral reefs, seagrass beds and mangroves surround the project site and must not be seriously impacted by the development.

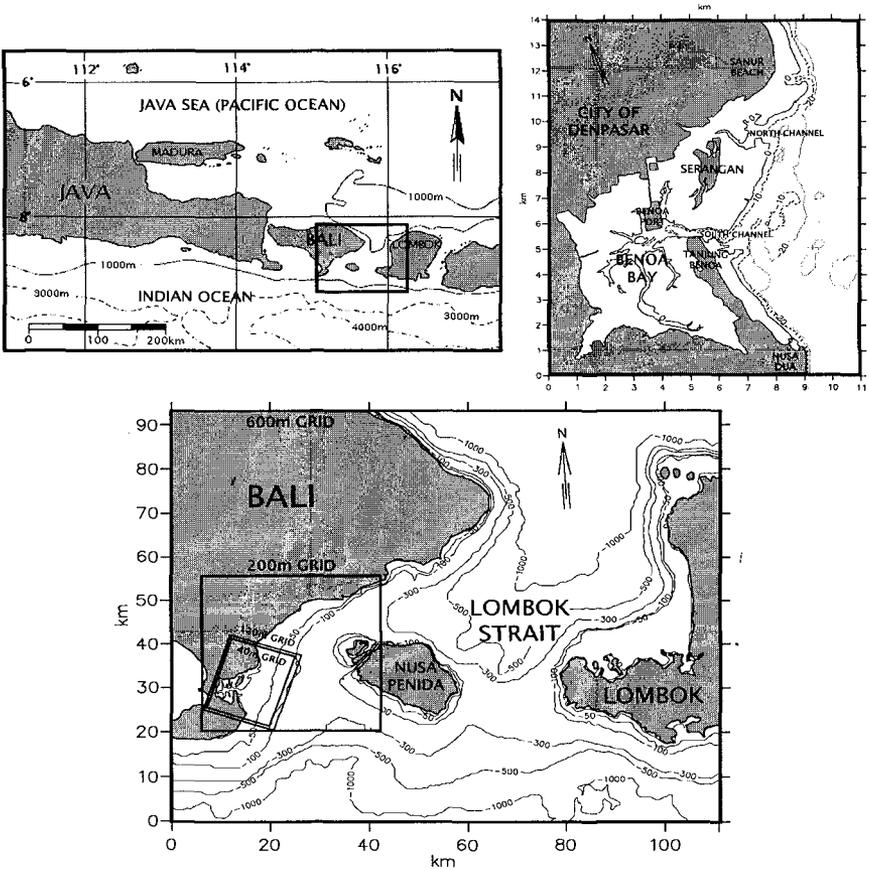


Fig. 1 Geographical references for the study. Top left: The Indonesian Archipelago. Bottom: Bali, Lombok and the Lombok Strait. Top right: The pre-construction study area, the coverage shown is that of the local 40m model domain.

The importance of these ecosystems is not purely aesthetic. The existing beach material consists entirely of eroded coral, and the degradation of the living corals due to increased pollution loading has resulted in a reduction in the natural production of beach material for the area. This fact, in combination with the mining of the reef crest for construction materials (thereby increasing wave exposure) has resulted in erosion problems for the beaches of the area (JICA, 1989). Furthermore, the living reef provides quality sport diving and is considered an essential recreational resource.

Project Description

With the exception of a village lying at the northern tip of the island, Serangan was undeveloped prior to 1996. The Bali Turtle Island Development project aims to establish an up-scale tourist enclave to complement those already existing at Nusa Dua and Sanur Beach. The completed project will include three artificial lagoons, four artificial pocket beaches, six artificial headlands and a causeway/bridge connection to the Balinese mainland (Fig. 2).

Both the dredging and reclamation areas lie within the intertidal zone. Dredging/reclamation activities were initiated in July 1996 and will continue into 1999. A large capacity (~20,000 m³/day) cutter-suction dredger is being used for the work. The total reclamation area is 370ha, and the corresponding dredging volume is 20 million m³. No significant levels of contamination have been found in the borrow material, which typically consists of 20% fine material below 63µm. All dredged material will be utilized for infilling.

The study described in this paper was divided into two phases. The first phase involved the evaluation of 8 proposed design layouts, and the making of recommendations toward the optimization of said layouts with respect to:

- Design conditions (wave, water level & current)
- Impact upon navigation
- Spreading of dredged material
- Water quality / eutrophication
- Revetment stability
- Flushing
- Sediment morphology
- Beach stability

The second phase of the study involved the management of dredging operations, such that the proposed construction activities could be performed without significantly impacting the surrounding ecosystems.

Field Campaign

An intensive survey campaign, including point measurements of water level, current, salinity, suspended and bottom sediments, and numerous water quality parameters was performed. The spatial variation of the wave- and tidally-generated flows was repeatedly

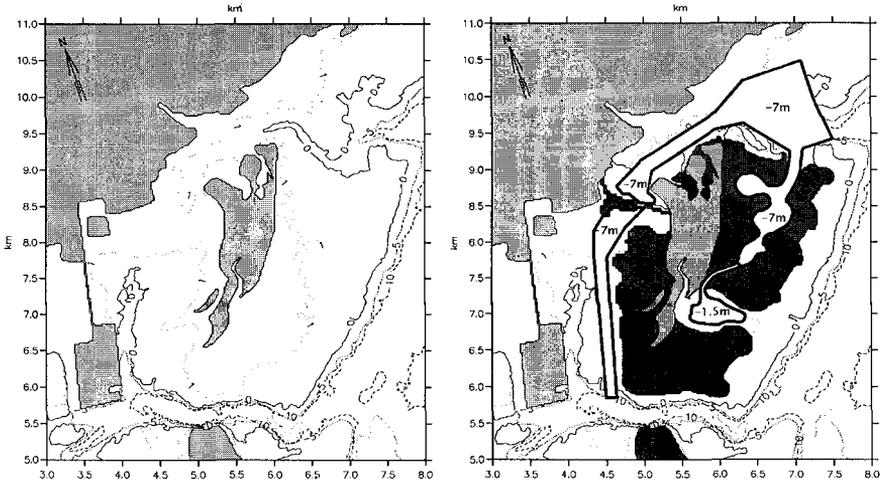


Fig. 2 Detail of the area around Serangan / Turtle Island showing pre-construction (left) and post-construction (right) bathymetry. Reclamation areas are shaded; dredging areas outlined. Depth contours in meters to Port Datum (PD ~ LAT).

measured in transects with a vessel-mounted ADCP. Fig. 3 shows the coverage of the ADCP transects, as well as the locations of CTD and suspended sediment profiling. The measurement locations for fresh water inflow / nutrient loadings are also shown.

Numerical Wave Modelling

Waves generated locally due to winds over Lombok Straits were determined using the simple hindcasting model PWAVE (after Hawkes, 1988). The offshore swell wave climate was determined from acquired global spectral ocean wave modelling data (Clancy et al., 1986), verified against satellite measurements, and then transformed to five locations just outside the reef using the parameterized wave action model MIKE21 NSW (after Holthuisen et al., 1989). Detailed local wave simulations were performed using the same model. The wave transformations occurring on the reef slope and reef flats were tuned in the numerical model to be consistent with the physical modelling results discussed below, as well as with nearby field measurements (Sulaiman et al., 1994, see Fig. 3).

Physical Wave Modelling

An undistorted 1:40 scale 3D physical model was created for the purposes of (a) providing calibration data for numerical modelling of wave transformations across the reef slope, crest

and flats, (b) providing design wave data for the development frontage, and (c) optimizing revetment design with respect to overtopping and stability. This portion of the study is described in an accompanying ICCE '98 paper (Jensen et al., 1998).

Hydrodynamic Modelling

Regional and local high-resolution hydrodynamic modelling was performed in 2DH using the model system MIKE21 HD (Abbott et al., 1981; Warren and Bach, 1992). A regional tidal model, driven by tidal constituents and supported by predictions from a global tidal model (Eanes and Bettadpur, 1995), was established. The regional model, in which net seasonal flows were also present, included a dynamic nesting of two Cartesian model domains of 600m and 200m resolution (Fig. 1). An M_2 constituent co-amplitude plot from a tide-only regional model simulation is shown in Fig. 5. It is seen that there is a strong attenuation of the semidiurnal signal from south to north in the Lombok Straits.

The results of the regional tidal model were then used to provide boundary conditions to drive a local hydrodynamic model, which consists of a second pair of dynamically nested Cartesian grids with resolutions of 120m and 40m (Fig. 1). An excellent calibration was achieved through comparison with the ADCP transects and stationary profiles (Fig. 6).

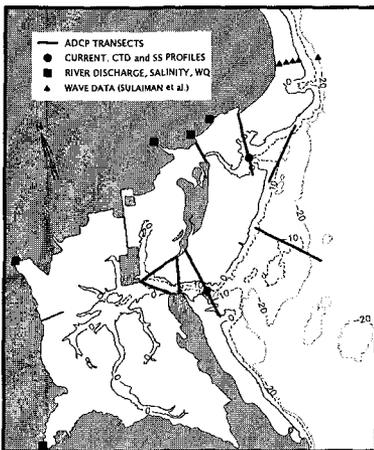


Fig. 3 (left) Coverage of local field campaign. Extensive grab, suspended and water quality sampling omitted for brevity.

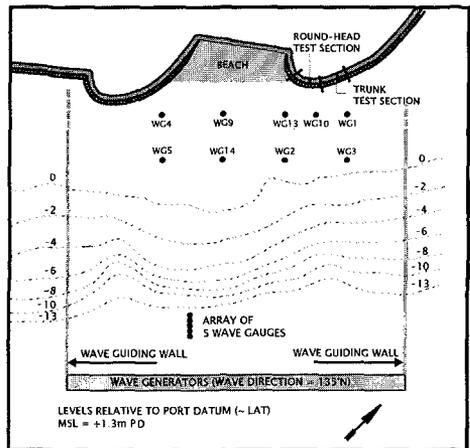


Fig. 4 (right) Setup of the 3D physical model, which covers a 1200m x 1200m section of the seaward face of the design.

The water level gradients and strong tidal flow velocities in the Lombok Strait are seen to have a significant influence on the project area, even inshore of the reef crest. As a result of the strong attenuation of the tidal signal from south to north, at times which would normally be considered "high water slack" there exists a significant offshore forcing which drives a northward flow both on the reef flats and in the channel between Turtle Island and the Balinese mainland. A complimentary offshore gradient exists toward south during "low water slack". However, this southward forcing is inconsequential in the pre-construction layout as the area is largely dry at low water. The result is a tidally-forced net northward drift which, although small, has a large influence on the flushing response of the design layouts. This net drift is eliminated in the channel west of Turtle Island in the design layouts, as a deep channel will be present there even at LAT. However, net northward flows will still be present on the seaward side of the island and can be used to enhance the flushing response of the design. It can thus be concluded that a comprehensive regional modelling approach is essential for resolving the local flow conditions in this complex area.

Additional sensitivity tests performed with the local hydrodynamic model showed that wave-induced circulation was also significant on the reef flats. Waves effect the nearshore hydrodynamics by continuously pumping water shoreward over the reef crest due to the breaking and corresponding setup which occurs on the reef slope. The result is a net flow of water onto the reef flats from offshore, which in turn drives a return flow seaward through the North and South Channels. As this circulation is forced primarily by the cross-shore gradient in momentum transfer due to wave breaking, it is present even for waves of normal incidence. This mechanism, also observed during the field campaign, is clearly of great significance in the spreading of dredging spill during the construction phase.

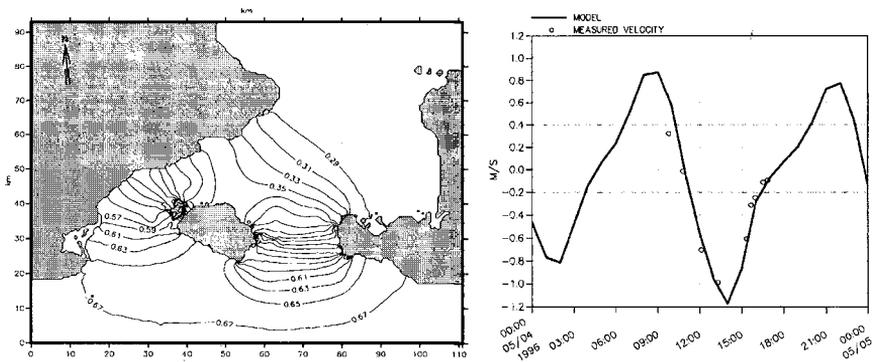


Fig. 5 (left) Co-amplitude map extracted from the regional tidal model for the principle semidiurnal constituent M_2 . Contours in meters.

Fig. 6 (right) Comparison of current speed from local hydrodynamic model vs. depth-average of measured current profiles in South Channel during spring tide.

Flushing Modelling

The water quality in any semi-enclosed area is a function of the pollutant load and the time required for the resident water to be exchanged with unpolluted water from outside. For unchanged pollution loadings, the flushing response of a given layout relative to pre-construction provides a reliable indication of whether water quality problems are to be expected for the design. Two-dimensional advection-dispersion modelling was performed in the local nested 120m/40m model areas to evaluate the impact of various designs on the flushing regime. The model applied was MIKE21 AD (Ekebjerg and Justesen, 1991), which is coupled with the local hydrodynamic model discussed above. The dispersion coefficients applied in the model were verified by accurately reproducing the dynamic salinity distribution in Benoa Bay and the waters surrounding Serangan, balancing the measured fresh water inflow with the mixing processes occurring throughout the area.

The flushing simulations were performed by initializing the calibrated advection-dispersion model with a conservative "tracer" concentration of unity in all areas inshore of the reef fringe. The remaining offshore areas, as well as the offshore boundary conditions, were set to a concentration of zero. The time required for the tracer concentration to be reduced in a given area then gives an indication of the water residence time for a given layout. Fig. 7 shows the tracer concentration remaining after 3 days for

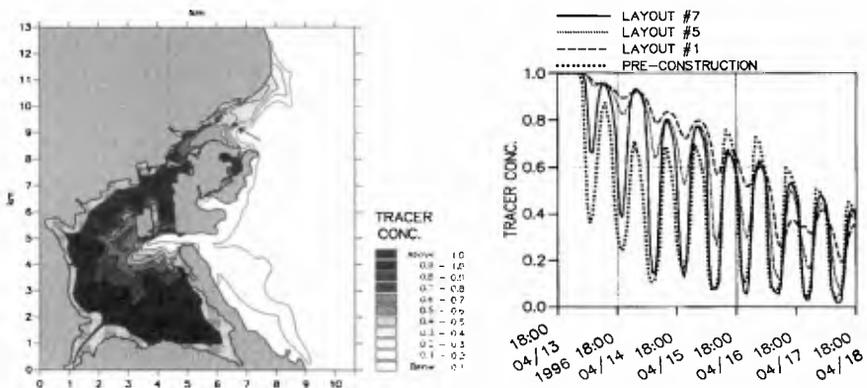


Fig. 7 (left) Sample flushing results: map of tracer concentration at mean high water after 3 simulation days from advection-dispersion model. Darker areas imply longer retention times. Shaded edges of Benoa Bay denote dried water points.

Fig. 8 (right) Extracted time series of tracer concentrations from the same location (marked in Fig. 7) in the primary borrow area for 3 design layouts as well as pre-construction.

the final layout. Fig. 8 shows extracted time series of tracer concentrations at a point in the primary borrow area, clearly indicating that at this location Layout #7 provides the best flushing, responding comparably to pre-construction.

Eutrophication Modelling

In addition to the flushing evaluation, a full 2D eutrophication model was established to gauge the effect of both the proposed development and increased loadings due to future population growth on the water quality around Turtle Island. The model applied was MIKE21 EU (Bach et al., 1990), which is also coupled with the previously established hydrodynamic model.

The eutrophication model describes the condition in the model area by using a number of state variables including carbon, nitrogen and phosphorus in phytoplankton, zooplankton, detritus and benthic vegetation and, with regard to nitrogen and phosphorus, also the dissolved form in the water. The model describes the seasonal and spatial variations of the interrelated state variables. The effect of dredging plumes was included by inputting construction-induced suspended sediment plumes calculated via the mud transport modelling described below.

Modelling of Littoral Processes

The longshore sediment budget for the study area was calculated using the process-based 1D model LITDRIFT (Deigaard et al., 1988), valid for arbitrary profile shapes. Wave transformations over the reef were calibrated versus the physical modelling results and field measurements (Sulaiman et al., 1994). Sediment recharge requirements were calculated for the pocket beaches fronting the development using the combined results of LITDRIFT, the 2D sediment transport model MIKE21 ST (Deigaard et al., 1986) and the 1D profile development model LITPROF (Hedegaard et al., 1991).

Not surprisingly, waves and water levels were found to be equally dominant factors in the longshore transport climate. Transport was found to be negligible for water levels below MSL (+1.3m PD). An excerpt of the four years' hindcast longshore transport rates is shown in Fig. 9, plotted along with the mean water level variation for the same period. The longshore transport as plotted is for the swell component of the wave climate only, which induces a drift which is almost exclusively northward. A separate transport calculation was made for the waves generated locally by winds over Lombok Strait, which contribute a smaller but significant net southerly drift.

The seaward reclamation limit of the completed project lies within 200m of the fringe of the surrounding reef, whereas the pre-construction beachface on Serangan was approximately 2km from the reef fringe. The reef flats act to dissipate wave energy through bed friction, enhanced by the locally irregular and vegetated bed. The post-construction beach face thus

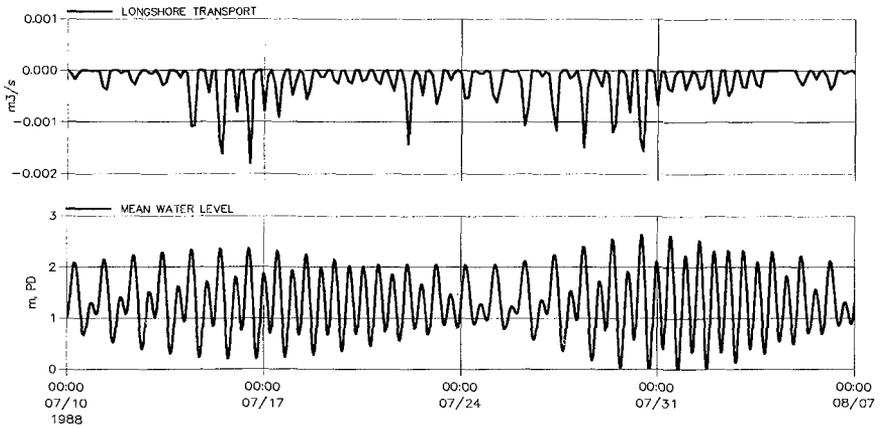


Fig. 9 One-month excerpt from the 4 years' calculated longshore transport climate on the seaward face of Serangan (pre-construction, negative northward), along with the simultaneous mean water level.

feels a significantly stronger local wave climate than was present on Serangan prior to construction. This is illustrated in Fig. 10, which compares the profiles, wave attenuation and net sediment transport calculated via LITDRIFT for pre- and post-construction profiles extracted across the seaward face of Serangan. This increase in net annual longshore drift demands both a rotation of the post-construction beaches and an increase in compartmentalization through the introduction of protective headlands in order to keep fill losses and seasonal beach rotations within acceptable limits.

Feedback Monitoring of Construction Activities

The scale of the dredging operations required for Turtle Island, in combination with the high content of fines in the borrow material and close proximity of sensitive habitats, dictates that the construction activities must be carefully managed to avoid serious environmental impact. Tools normally used for such a situation include (a) spill fate modelling performed prior to construction, or (b) biological monitoring of the status of the habitats during the construction process. The novel approach of *feedback monitoring* (Grey and Jensen, 1993; Bach et al., 1997) has been applied in the present study. On the simplest level, feedback monitoring can be described as an orchestrated joint application of spill fate modelling and biological monitoring. The strategy embraces four components:

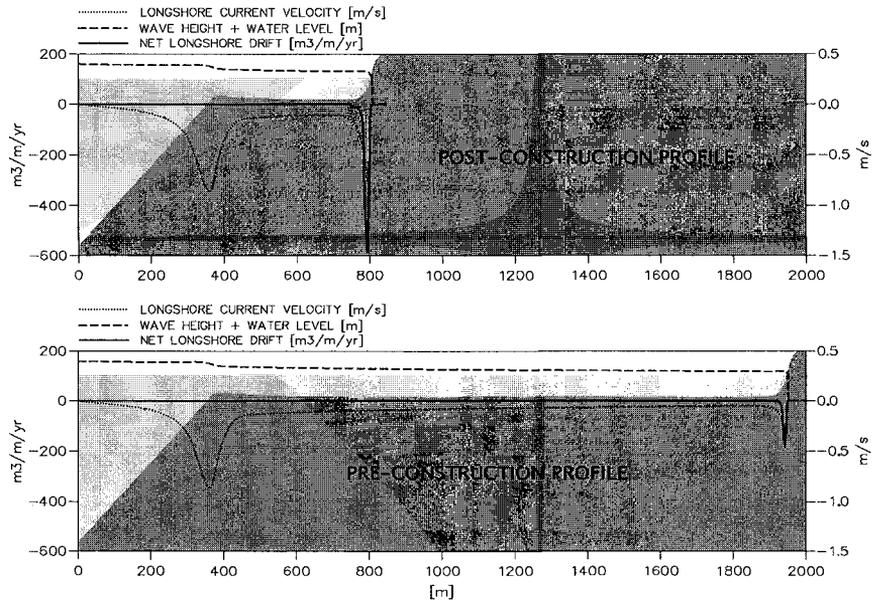


Fig. 10 Comparison of pre- and post-construction profiles, wave attenuation and net longshore drift. Wave height and water level shown are instantaneous values (offshore: $H_{rms} = 1.5m$, $T_z = 6s$, $dir = 145^\circ$, $WL = +2.5m$ PD), whereas the net longshore drift shown is the annual rate. While the greatest transport potential is seen to lie just offshore of the reef crest, this portion of the profile has been rendered inactive in the model due to the lack of mobile sediment in these areas.

- 1) Careful planning using numerical models to avoid unnecessary environmental damage by forecasting the effects of possible sediment spills. This is performed at the planning stage of the project.
- 2) Medium-term spill forecast modelling throughout the construction process, such that the potential environmental impact can be assessed on the basis of detailed dredging schedules for the forecast period. This allows the formulation and testing of mitigating actions if the predicted impact exceeds certain pre-defined limits.
- 3) On-site monitoring of selected key species and variables -- in the case of Turtle Island seagrasses, corals and mangroves -- to provide a direct indication of the impact upon the habitats and to provide feedback based on the impact criterion used in processing the results of the spill forecast modelling.

- 4) Updating the net environmental impact assessment by performing numerical model hindcasts on the basis of the *actual* achieved dredging schedule (as opposed to the predicted schedule assumed in 2 above) and the results of the biological monitoring of the selected species.

Feedback monitoring is in many ways a union stronger than the sum of its parts. Initial spill forecasting can be used to more efficiently design the scope of the biological monitoring so that energy can be focused on the areas of most likely impact. Furthermore, as numerical spill fate modelling greatly increases the understanding of the local sedimentation processes, the results of the spill hindcasting allow for a much more definitive interpretation of the results of the biological monitoring.

The application of feedback monitoring to Turtle Island is described in detail elsewhere (Driscoll et al., 1997), but is summarized here. A two-month repeat cycle was prescribed for the Turtle Island feedback monitoring. Thus, every two months the contractor provided a detailed plan of upcoming dredging operations (dredger locations and schedules, as well as outlet pipe locations and settling pond configurations). This information was combined with tidal predictions and typical seasonal values of wind, offshore net flows, and waves to produce a 2-month forecast of dredging spill to evaluate the impact of upcoming construction tasks. Parallel data was provided by the contractor documenting the actual realized dredging operations achieved in the prior two months. This historical information was merged with the available hydrographic data to construct a detailed 2 month hindcast of the most recent dredging operations. Two-monthly biological monitoring campaigns were then performed, with the hindcast results being utilized for the purpose of verifying causality in any observed impact to the habitats.

Spill fate modelling was performed using the Eulerian 2D model MIKE21 MT (Johnsen and Warren, 1993, with subsequent improvements) which describes cohesive sediment transport processes under combined current and waves. The spill model was coupled with the previously established local hydrodynamic and wave models, so that the effects of wave-generated currents and setup were included both with regard to physical forcing and sedimentation. The model was calibrated based upon daily measurements of suspended sediment concentrations at fixed stations throughout the area. Output consisted of time-varying maps of suspended concentration and net deposition/erosion. These outputs were then processed to provide maps of parameters useful for quantifying biological impacts, such as light attenuation at the seabed due to plume shading, daily exceedances of threshold deposition rates, etc. This approach allows for the proper consideration of environmentally positive steps such as timing high-spill activities during hours of darkness, when plume shading has no effect on light-sensitive organisms. A comparison of % light reduction at the bed is given in Fig. 11 for two spill hindcast periods, showing the improved environmental loading in the latter period.

The complimentary biological monitoring took the form of two-monthly surveys covering 5 to 6 stations each for coral, seagrass and mangroves. For each habitat, the focus was placed on the detailed monitoring of quantifiable variables rather than qualitative observations. For corals, variables included % coral coverage along fixed transects, recolonization rates, and measured growth rates of resident and transplanted specimens for the dominant species *Acropora sp.* Table 1 below shows the change in observed coral growth rates between two survey campaigns. These time periods may be compared directly to the spill hindcast periods shown in Fig. 11. A strong correlation is seen between modelled loading and observed impact. It should be noted that, while temporary reductions in growth rates were observed in the corals, the loadings were found to be sub-lethal.

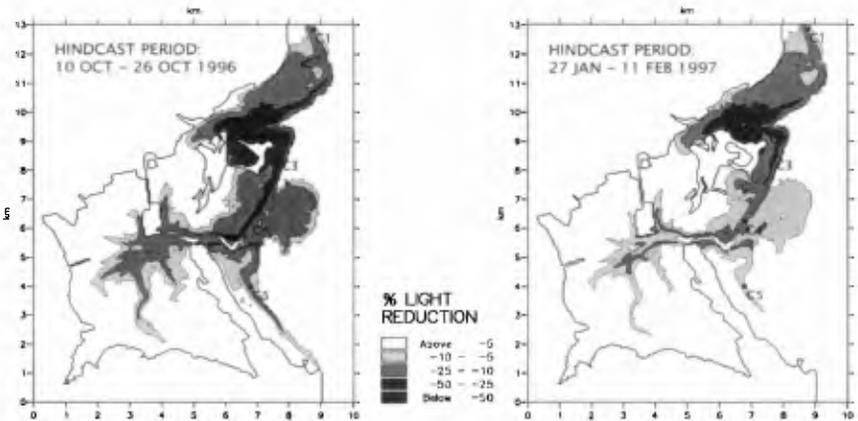


Fig. 11 Results from two spill hindcast periods shown in terms of % light reduction at the bed. Depths > 20m are not plotted. Coral monitoring stations C1 through C5 also shown.

Period	Max. growth rate of <i>Acropora sp.</i> (mm/month)*				
	station C1	station C3	station C4	Station C5	mean
Oct 96 - Dec 96	3.9	2.3	2.7	4.9	3.5
Dec 96 - Feb 97	5.5	7.6	8.5	8.7	7.6

Table 1 Measured coral growth rates, based upon the results of the Oct. 1996, Dec. 1996 and Feb. 1997 biological monitoring surveys. (Station C2 omitted due to insufficient data coverage).

Summary of Conclusions

The integrated hydraulic and environmental design evaluation for the Bali Turtle Island Development project resulted in (a) a detailed description of the complex physical and biological environment surrounding the site, (b) an accurate description of how the development will impact that environment, and (c) recommended modifications to improve the design in light of these findings. A summary of the conclusions is presented in the following:

The preliminary revetment design was found to be inadequate with respect to both the overtopping and stability criteria. Larger stone sizes and increases in revetment crest height and width were recommended.

The optimized development was shown to have a beneficial effect on navigation, slightly reducing the peak tidal current velocities in the South Channel. No areas of notable current intensification due to the development were found, with the exception of the channel beneath the causeway bridge which will see typical spring flows of 0.9m/s. Net tidal circulations were found to exist around Turtle Island. This tidal forcing has been utilized to optimize the flushing response of the design.

The flushing response around Turtle Island was optimized such that the final design shows either no change or a modest improvement in residence time for much of the area relative to pre-construction.

Due to the presence of the shallow reef flats between the reclamation and the reef crest, the wave climate and resulting littoral transport at the beach face was shown to be dominated by the water level. Waves attacking during water level below MSL produced negligible transport due to nearly complete attenuation over the reef crest and reef flat. Beach material losses for the optimized layout were within acceptable limits.

Feedback monitoring of the dredging operations was initiated to safeguard the habitats during the construction phase.

The results of the performed study have proven the benefits of integrating state of the art numerical modelling tools, supported by physical modelling and biological monitoring, for both the hydraulic / environmental optimization of the design and for feedback monitoring of the actual construction sequence.

Acknowledgement

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