Session 50

# Modeling and computational tools for coral reef management and conservation


**Session chairs**:

James Hendee, jim.hendee@noaa.gov

Elizabeth Drenkard, liz@envsci.rutgers.edu

Mehmet M. Dalkilic, dalkilic@indiana.edu

Allison Allen, allison.allen@noaa.gov

Sean Connolly, sean.connolly@jcu.edu.au

Claudia Johnson, claudia@indiana,edu

Lew Gramer, lew.gramer@noaa.gov

Joan Kleypas, kleypas@ucar.edu

Charles D. Beeker, cbeeker@indiana.edu

Carrie Manfrino, manfrino@reefresearch.org

Peter J. Mumby, p.j.mumby@uq.edu.au

# Agent based modelling as a tool to manage dredging impact on coral spawning

**Caroline Lai, Claus Pedersen**

**Abstract** Turbidity and sedimentation generated by dredging and dredge material disposal can seriously affect coral reproduction during spawning periods. Numerical modelling can be used as a powerful tool to predict and manage the risk of impacts. Dredge plume modelling predicts the plume dispersion and associated turbidity and sedimentation rates, and simultaneous agent based modelling can be used to predict the pathways of released gametes, the interaction between dredge derived turbidity and gametes, and connectivity between reefs on a regional scale. Combined with set tolerance limits, the modelling can be used to predict the level of impacts from a given dredging programme, and scenario type modelling can be used to test different dredge options and optimise the dredging plan to minimize impacts. Taking this a step further, a reliable forecast model may provide the opportunity to make informed proactive and adaptive management decisions for dredging during a spawning period to minimise the impact on the coral gametes. Here we show examples of dredge plume and coral spawn modelling in Western Australia and discuss how the modelling can be used to proactively manage the risks of impacts. The study was carried out using the DHI MIKE Agent Based Modelling (ABM) tool. This integrates hydrodynamic, wave, sediment transport and ABM models to define the dredge plume dispersion and concurrent behaviour of coral larvae in response to the environment. Examples of management measures will be provided and discussed.

**Key words**: agent-based model, coral spawning, dredging impacts, dredge plume, connectivity

Caroline Lai
DHI, Suite 146, Equus Commercial, 580 Hay Street, Perth WA 6000, Australia lai@dhigroup.com

Claus Pedersen
DHI, Level 11, Wisma Perindustrian, Jalan Istiadat, Likas, Sabah 88400, Malaysia clp@dhigroup.com

## Introduction

Many corals in Western Australia release their full year's gametes within a few nights during a mass coral spawning event (Simpson 1985, Rosser and Gilmour 2007). This makes the mass spawning a keystone to demographic changes in coral communities along the West coast of Australia. Any anthropogenic stress to the coral gametes, larvae or juvenile recruits during or immediately after a mass spawning event is likely to have an adverse impact on coral reproduction.

Western Australia's ocean ecosystem is home to several threatened species, and a great number of marine plants and animals that exist nowhere else in the world (Sources: Department of Parks and Wildlife, Government of Western Australia). Besides being an ecologically important marine region, it is also an economically significant region in terms of iron ore and natural gas reserves and production (Geoscience Australia 2015). Western Australia produces more than 90% of the national iron ore and liquefied natural gas (LNG) (Sources: Department of Mines and Petroleum of Western Australia).

Looking at the substantial number of existing navigation channels in morphologically active zones along Western Australia's coastline, with more to come in the near future, it is clear that substantial dredging activities will be required in the future for maintenance of existing navigation channels as well as capital dredging for development of new ports. With a strong desire to protect the rich marine habitats and biodiversity, this has the potential for conflicting interest. It is necessary to understand how dredging activities may lead to adverse ecological impacts on coral, including the propagation through spawning, for future planning and goal setting.

This paper briefly discusses the limitations in "static" regulations of dredging around coral spawning periods, and looks at opportunities to use the latest methods in modelling as a tool to implement site specific adaptive management that may be more effective both from an ecological and a cost perspective.

## Management of impacts

Recognising the importance of the mass spawning events, regulators have generally required a stop of turbidity generating activities, which includes dredging and dredge material disposal, from 3 days prior to (or as soon as mass spawning is detected if prior to the predicted time) through 7 days after the mass coral spawning event, unless a peer-reviewed assessment shows that the activities would not significantly impact the functional ecology of local and regional reefs (Ministerial Statement 840, 873 and 930).

This is a potentially costly ~~but~~ and not necessarily the most effective mitigation measure. Dredging activities would be suspended for more than 10 days if the mass spawning event delays. With the potential for two mass coral spawning events in a year, this could easily lead to cost associated with downtime that runs into the 10s of millions of Australian dollars for larger dredging programmes. On the other hand, avoiding dredging 3 days prior to spawning may not be achieved, if the prediction of the spawning event is inaccurate. The 3 days stop of dredging may also not be effective in mitigating risks of impacts if the site is prone to resuspension of dredged material and/or the areas where gametes could settle are affected by sedimentation from dredging prior to the stop of dredging. The risks to coral spawning are site and project specific, which cannot be captured easily in general regulations. Understanding and managing the risks requires detailed information on the dispersion and sedimentation of dredge derived material as well as the pathways and sensitivities of the gametes. Numerical modelling is generally considered a necessary tool in assessing and quantifying these risks.

**Modelling tools and approach**

Predictive modelling for dredge plume dispersion and interaction with coral gametes generally requires the following components:

- A hydrodynamic model that determines the transport of sediments. This may be a two or three dimensional model depending on the site specific requirements.
- A wave model to include the effects of waves on sediment resuspension.
- A sediment transport model that includes the effects of advection/dispersion, settling and resuspension.
- A model for the dispersion and settlement of gametes. An Agent Based Model (ABM) may be applied.

The hydrodynamic model computes the oceanic and tidal flow forcing, which acts as a fundamental component to both the sediment transport and agent based models. The hydrodynamic model needs to be well calibrated and capture all key driving forces for the site, be it the tides, wind/pressure fields, waves or ocean circulations. In tidally dominated areas, it is not uncommon to overlook much weaker, net currents driven by winds or other driving forces.

However, in the near-field excursion zone where-tidal currents are dominant, net currents of just a few cm/s can lead to dredge plumes or coral gametes being transported far beyond the reach of the tidal excursion alone within a few days. If such net currents are not captured in the model, it will be incapable of accurately predicting regional scale sediment dispersion or the connectivity of the reefs in terms of propagation of gametes.

Agent-based models (ABM) have been widely applied to simulate biological and ecological phenomena (Willis 2011). For the assessment of dredge plume impacts on coral spawning and reproduction, the agent based model is used to predict the pathways of released coral gametes/larvae and connectivity between reefs. By running the ABM model concurrent with the dredge plume model it is possible to derive the interaction between turbidity plumes and the coral gametes.

The tolerance of coral gametes to suspended sediments and sedimentation is not well documented and understood. This knowledge gap to some extent prevents an accurate prediction of the impacts from dredging on the propagation of gametes. From a management perspective, this generally leads to a requirement of adopting conservative assumptions which ensure that given objectives in terms of risks of impacts to the spawning can be achieved. This may still be possible without stopping dredging by, for instance, targeting dredge scenarios that separate the plumes from the gametes, and ensure that the potential substrate for settlement are not affected by sedimentation well in advance of the predicted spawning period.

**Model setup**

The complexity of the model setup will both depend on the flexibility of the model and the objectives of the modelling exercise. A model such as the ABM model included in the Mike by DHI software package (MikebyDHI 2011) and built on the ecological modelling module ECOLab has access to all the generic and open equation solver options of ECOlab for customizing the setup. Because of this flexibility, it is the robustness of the understanding of the biological processes that sets the limitations to what can be achieved through the modelling rather than the model itself.

Examples of parameters and equations in the ABM template for modelling coral spawning and dispersion include, but are not limited to: timing and duration of mass coral spawning, releasing water depth, number of coral gametes released into the model, dispersion coefficients, drift and settling profiles with initial buoyancy and subsequent settling rate, competency acquisition and loss rates, mortality, habitat quality for settlement, settling characteristics, and sensitivities to various environmental parameters. In areas where information is limited or less robust, conservative assumptions may be applied if these can be defined. In the case where impacts from dredge derived turbid plumes are assessed, some conservative assumptions include:

- Mortality. The population in the water column will reduce due to natural mortality rates, including predation. For an impact assessment, the natural mortality could be excluded as it is not easily quantified. All larvae will remain in the water column for the full simulation period and be subject to potential impacts.
- The competency acquisition rate determines the proportion of the population that becomes competent to settle per day. The competency loss rate determines the proportion of the competent agents that lose settling competence per day. To be conservative, the loss rate could be set as zero and acquisition rate as "1", corresponding to a fully competent population that is subject to potential impacts.
- Threshold limits for impacts are generally considered to be both concentration and time dependent. As the threshold are generally not well documented and understood, it can be assumed that if the coral gametes/larvae interact with a plume that exceeded a conservative threshold at any time, it will be tagged as impacted, regardless of the duration of the exposure.
- Coral larvae require suitable substrate to settle. Not all area within a marine habitat are suitable for settlement. To be conservative, reefs could be defined as suitable habitats for settling.

Output from the ABM model may include parameters related to the status for each defined parameter or process in the model. For each defined output time step and each agent this includes the coordinates and statuses for:

- An indicator whether the agent is still suspended in water column or has settled;
- The origin of the agent (useful for connectivity mapping);
- Where the agent settled, could be a reef ID or location;
- Has the agent been subjected to environmental impact, e.g. a turbid plume above a given tolerance limit?
- Hazard and vulnerability factors are necessary for a risk assessment.

In the case of assessing the risks to coral spawning from dredging, the hazard indices are represented by tolerance limits for turbidity and sedimentation. Combining the set tolerance limits and vulnerability reference, the ABM model is used to predict the risk of impacts from a given dredging programme on a mass spawning event.

**Example from Pilbara**

In a recent example from the Pilbara coastline of Western Australia, a mass coral spawning event was simulated using the agent based model in the Mike by DHI software package.

**Modelling Approach**

The ABM model was developed to record the behaviour and state of coral larvae within the model domain and throughout the simulation period. It recorded the interaction between coral larvae and dredge plumes, and was also applied to derive connectivity amongst reefs. Climatic conditions from historical spawn periods were simulated to achieve a realistic range of climatic scenarios in the models. This was combined with a range of possible dredge and disposal scenarios to produce statistical maps of likely dispersion of gametes and sediment plumes.

Statistical maps of the likely interaction between gametes and dredge plumes were derived from the ABM model and used to identify and optimise dredge and disposal scenarios that could be carried out during the spawn period with a minimized risk of impacts to the gametes. Recognising the limited knowledge on the impacts of sediment and turbidity on gametes, a conservative approach that targeted total separation between the gametes and the dredge plumes was adopted. This eliminated the dependence of the assessment on the tolerance limits of the gametes to suspended sediments and turbidity, and could give regulators added confidence in the assessment.

Figures 1 to 7 illustrate instantaneous, daily output over a 7 day period, from an ABM simulation with spawning over three consecutive days.  The different coloured circles represent gametes released from different reefs, and the concurrent sediment plume is shown in the red/brown colour scale. With the dredging taking place in one location, the dredge plume is focused around this area, while the gametes move up to about 80 km north-eastward over the 7 day period. The figures illustrate interaction between gametes and the dredge plume from Day 2 to Day 5. The gametes not shown moving north-eastward with the net currents have settled on suitable substrate.

Table 1 illustrates an example of the percentage of gametes interacting with the dredge plume for different climatic scenarios (climatic conditions from different years during spawning periods). The percentages shown in Table 1 are for the gametes released over a larger region and are therefore small. The table indicates the origin of the majority of the affected gametes (Reefs A, B and C affected for different climatic scenarios). Releases were simulated from a total of 27 reefs. Similar tables were produced for the individual reefs to show how large a percentage of the gametes released from an individual reef were affected.

**Table 1** Example of daily probability of interaction of coral larvae and dredge plume for different climatic scenarios. The letter indicates the main reef source for affected gametes

| Climatic scenario | Day 1 | Day 2 | Day 3 | Day 4 | Day 5 |
|---|---|---|---|---|---|
| Sce1 | | | | | A 1% |
| Sce2 | | | | | B 1% |
| Sce3 | | A 3% | A 4% | A 4% | A 1% |
| Sce4 | | | A 2% | A 2% | A 2% |
| Sce5 | | | | | C 5% |
| Sce6 | | | B 3% | B 2% | B 2% |

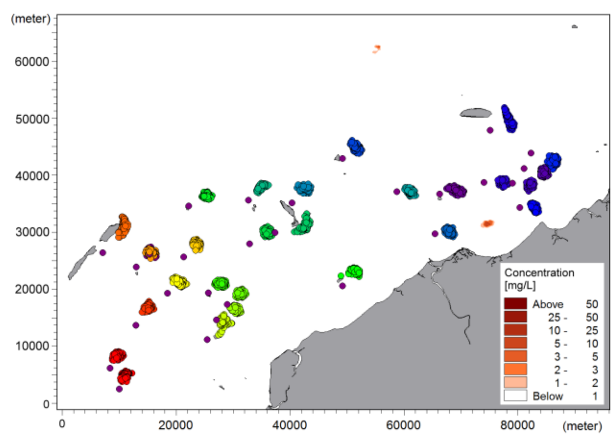


**Fig. 1** Example output showing coral gametes/larvae and distribution of suspended sediments (brown plume) one day after the initial coral spawning

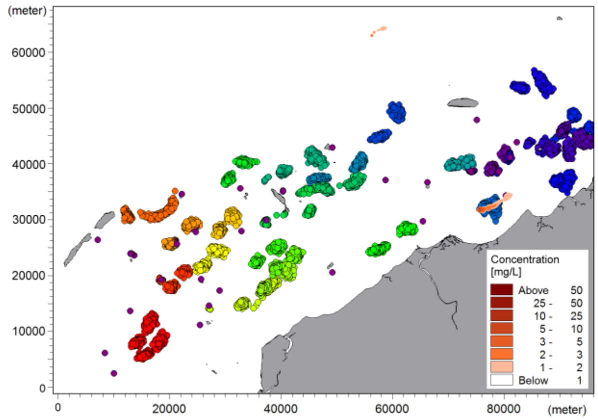


**Fig. 2** Two days after initial coral spawning

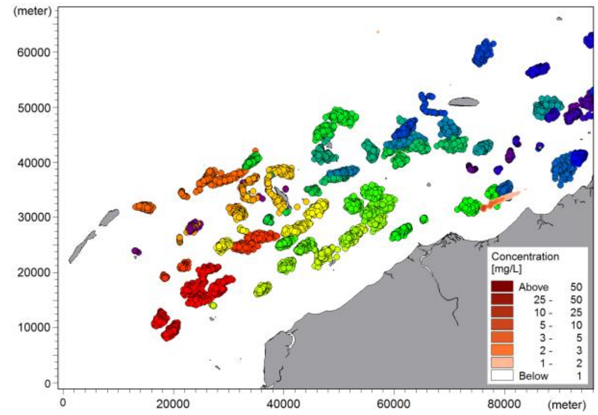


**Fig. 3** Three days after initial coral spawning

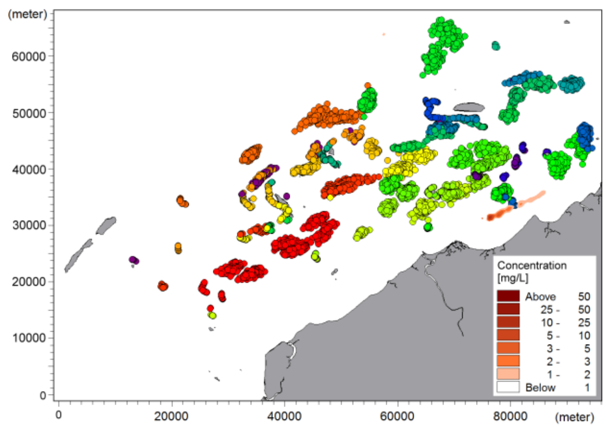


**Fig. 4** Four days after the initial coral spawning

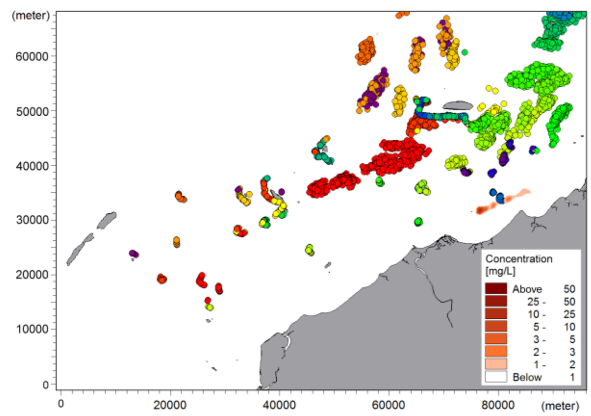


**Fig. 5** Five days after initial coral spawning

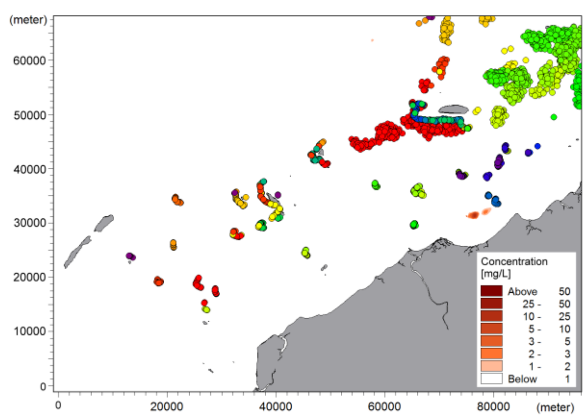


**Fig. 6** Six days after the initial coral spawning

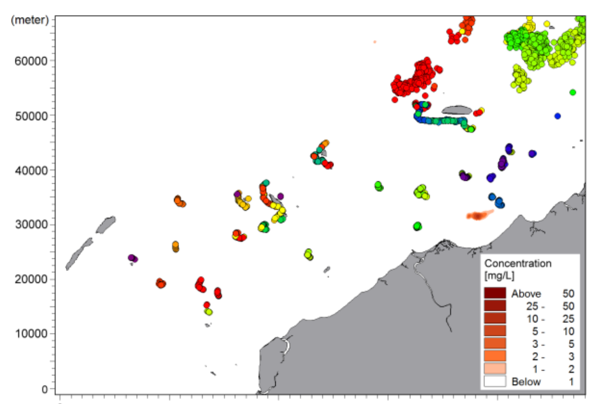


**Fig. 7** Seven days after initial coral spawning

The assessment was carried out for a matrix of dredge/disposal scenarios combined with climatic scenarios. Table 2 shows the cumulative percentages of released gametes that have been exposed to the dredge plumes over the assessment period for a subset of simulations covering six dredge scenarios and four climatic scenarios (2010 to 2013). Some dredge scenarios such as Scenario 3, were predicted to interact with a substantial proportion of the gametes released regionally. This was due to the dredging and/or disposal causing persistent plumes in the main pathway of the gametes. By relocating the dredging and disposal, it was possible to reduce that to a very low percentage of the gametes affected, as for instance in Dredge Scenario 2. The variability in results for the different climatic scenarios was limited, suggesting robustness of the predicted outcome.

**Table 2** Examples of cumulative percentages of interaction between coral larvae and dredge plumes during the first five days following mass coral spawning initiation for matrix of dredge and climatic scenarios

| Dredge scenario | 2010 | 2011 | 2012 | 2013 | Average |
|---|---|---|---|---|---|
| Sce1 | 3% | - | 1% | 1% | 1.3% |
| Sce2 | 1% | - | 1% | - | 0.5% |
| Sce3 | 20% | 14% | 12% | 7% | 13.3% |
| Sce4 | 3% | 2% | 6% | 2% | 3.3% |
| Sce5 | 4% | 1% | 5% | - | 2.5% |
| Sce6 | 6% | 6% | 7% | 3% | 5.5% |

*Sedimentation*

In addition to the assessment of the interaction between gametes and suspended sediment plumes, the sedimentation on areas with substrate suitable for settlement was also modelled and quantified based on a similar approach for the matrix of dredge and climatic scenarios. The dredge plume models were in this case run for more than a month in advance of the predicted spawn period to include the effects of resuspension and sedimentation of previously spilled material. The modelling demonstrated that for dredge scenarios that would separate the coral gametes from the dredge plumes, the sedimentation risks on suitable substrates (mainly the existing reef areas) were negligible. The risk from normal dredge scenarios was also very low due to adaptive management measures in place to achieve the established environmental protection objectives for the project.

*Reef connectivity*

The Ministerial guidance around coral spawning states that the dredging cannot "significantly impact the functional ecology of local and regional reefs" (Ministerial Statement 840, 873 and 930). To ascertain the implications of this requirement, it is necessary to understand the local and regional reef connectivity. This involves understanding where the gametes are recruited from for a given reef – are they mostly recruited locally from the same or neighbouring reefs, or is the propagation derived from a wider region? And how would affecting the gametes in one area impact the local and regional recruitment?

Based on a well calibrated hydrodynamic model and appropriate representation and assumptions for the spawning and life cycle of gametes, an assessment of reef connectivity can be carried out by running the ABM model together with a reef habitat map and realistic assumptions on the competency and settling of larvae.

For the example from the Pilbara, reef connectivity was studied by simulating the release of particles at all modelled reefs simultaneously over 3 consecutive days to emulate a mass spawning event. This was done for all the historical mass spawning events with sufficient environmental data available, and the model was run with the actual climatic data from the respective spawning events to emulate the likely dispersion of the gametes as realistically as possible. Rather than trying to tie the number of particles released at each reef into the size, health or species composition, a fixed number of particles sufficient to provide a sound statistical basis for the assessment was released at each reef. This was used to produce a connectivity map to answer the questions:

1) Where are the gametes released from Reef X likely to end up?
2) Where are the gametes settling on Reef X likely to originate from?

Question 2 only considers the dispersion and likely pathways. A more complete answer to the question would require an assessment of the relative release in terms of numbers and competency from each reef area.

For this simplistic connectivity mapping, the opportunity to settle was correlated to particles passing over a reef after an initial period in the water column when they were assumed to have become competent for settling. This allowed the production of connectivity maps showing both where particles from a given reef would go, and where particles passing over a given reef originated from. The exercise was repeated for a significant number of climatic scenarios, which allowed a more robust statistical assessment. A simplistic example for 5 reefs (A to E) is shown in Table 3. Agents settled within the parent reef were not taken into account in this example.

With the limited number of reefs included in this example, their relative positioning in respect of the net currents is key to the findings. In the simplified example, Reefs A and B have a smaller exchange of particles, but otherwise receive particles from Reef E only, so they could be said to be highly dependent on Reef E as a donor, and impacting Reef E would affect Reefs A and B severely if these were the only donor reefs.

**Table 3** Examples of reef connectivity among five reefs averaged over 4 years

| Reef | From A | From B | From C | From D | From E |
|---|---|---|---|---|---|
| To A | - | 6% | | | 23% |
| To B | 6% | - | | | 28% |
| To C | 73% | 31% | - | 12% | 19% |
| To D | 21% | 13 % | 98% | - | 30% |
| To E | | 50% | 2% | 88% | - |

Whereas the entire exercise for the Pilbara example applied the conservative approach of ensuring minimal interaction between dredge plumes and gametes, the assessment of the reef connectivity further demonstrates that there was a fairly wide connectivity across the region.

**ABM as a forecasting tool**

The previously described approach and examples were based on statistical approaches to predict the risk of given impacts.

In cases where the climatic drivers for the modelling favour a reliable forecast model for currents, it is possible to use a forecast model as a supplementary or replacement tool to the statistical approach. The ABM model coupled with a forecast hydrodynamic model can provide more detailed information on likely impacts from a given programme under the actual coming climatic conditions. This information may be used to adapt the dredging programme to either reduce the risk of impacts or potentially provide greater flexibility in the allowable dredging activities if the confidence in the predictions is sufficiently high.

In DHI's experience for the Pilbara coastline, where wind and pressure driven net currents in many areas play a key role in the transport and dispersion of both dredge plumes and coral gametes, a fairly good forecast can be achieved within the typical climatic forecast period of about 8 days.

Fig. **2** and Fig. **3** show some examples of comparison between realized and forecasted current and wave data for eight days. The current model in this case captured the right trends in the current directions, though the forecast is clearly more accurate within the first few days of the forecast period.

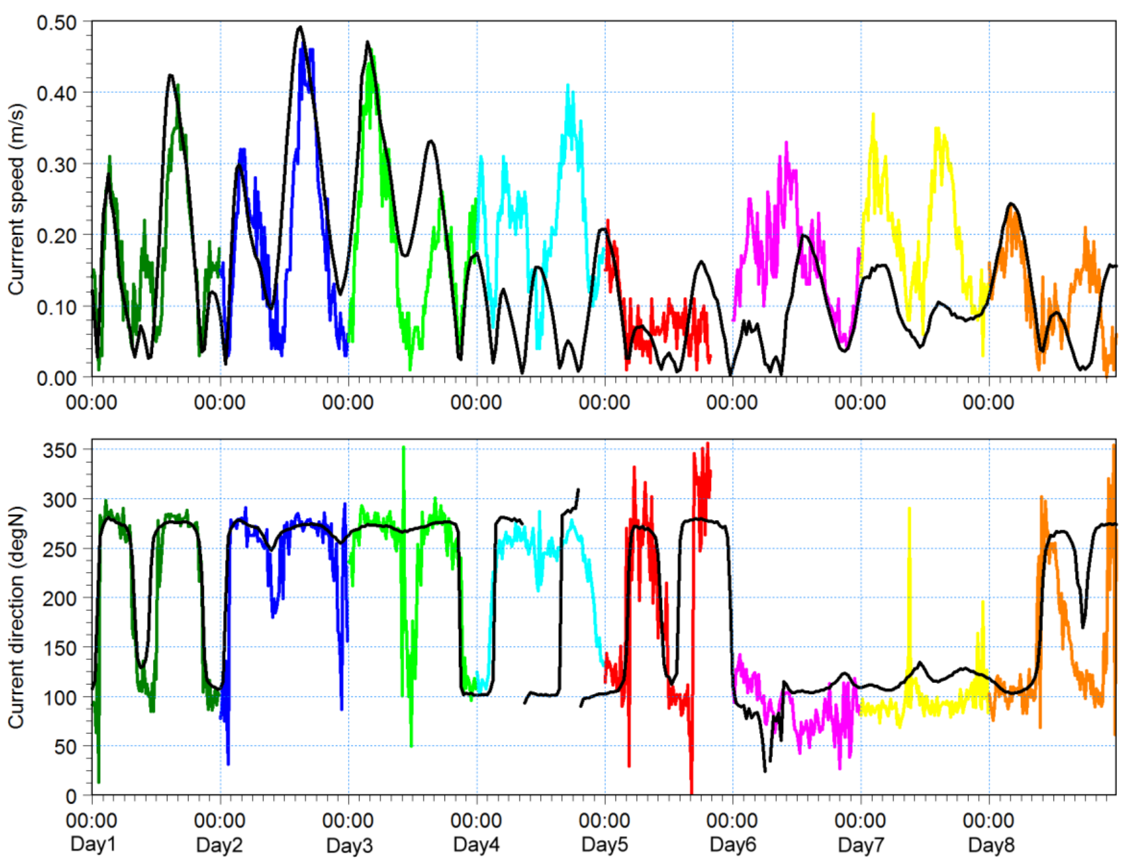


**Fig. 2** Comparison of realized and forecasted current speed (top) and direction (bottom). Black line = forecasted output, colour line = eight days of realized data.

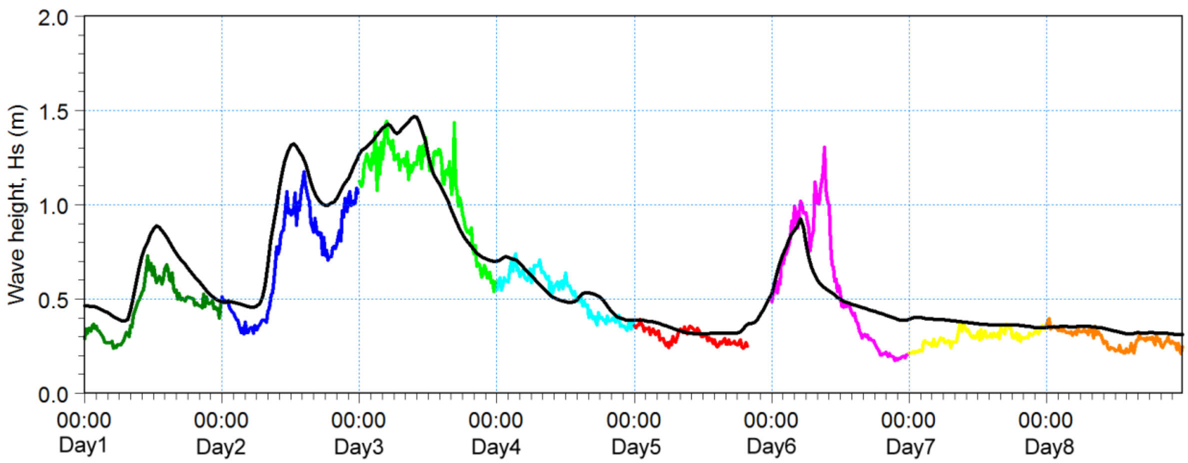


**Fig. 3** Comparison of realized and forecasted wave height. Black line= forecasted output, colour line = eight days of realized data

**Related work**

DHI MIKE Agent Based Modelling (ABM) tool was used to investigate the movement and habitat use of bull sharks with observation data from acoustic tagging of sharks in a semi-enclosed ecosystem in Australia (Mortensen 2012).

## Discussion

Understanding the dynamics of local ambient background conditions, including spatial and temporal variability of winds, waves, currents, turbidity and sedimentation is a key to reliable agent based modelling.

The ABM model can be used to predict the interaction between coral larvae and dredge/disposal plumes, either statistically based on hindcasting of past mass coral events or in forecast mode for future events. The hindcast option has great potential to be used in the planning phase for projects to optimise the dredging activities during predicted coral spawn periods to minimise the risk of impacts, while the forecast option may be used as a supplement to this to further adapt and optimise the operations during construction.

The ABM model can further be applied to establish and assess the vulnerability of inter-reef linkages on both a local and regional scale. This may further be used to assess and address risks to coral spawning from dredging campaigns and balance the often opposing needs for development and environmental protection.


## Acknowledgement

Special thanks to Michael Potthoff who builds the ABM module in both MIKE 2011 and 2014 versions, Karin Cooper for help with the ABM model setup, and the project team members Amy Ling, Hasmida Binti Hamza, Jennifer Chong and Mariaster Binti Ham.


## References


Geoscience Australia (2015) Australian atlas of minerals resources, mines & processing centres, Australia's Identified Mineral Resources. Retrieved from **http://www.australianminesatlas.gov.au/aimr/commodity/iron_ore.html**

Mikeby DHI (2011) ECOLab User Guide. Introduction. Ministerial Statement 840 (2010). Statement that a proposal may be implemented (pursuant to the provisions of the Environmental Protection Act 1986). Cape lambert Port B development – Shire of Roebourne. Condition 8-9 on page 9

Ministerial Statement 873 (2011) Statement that a proposal may be implemented (pursuant to the provisions of the Environmental Protection Act 1986). Wheatstone Development – Gas processing, export facilities and infrastructure. Shire of Ashburton and Roebourne. Condition 6.11 on page 9 and Condition 8-18 on page 19

Ministerial Statement 930 (2013) Statement that a proposal may be implemented (pursuant to the provisions of the Environmental Protection Act 1986). Anketell Point Port development, Antonymyre, Shire of Roebourne. Condition 8-11 on page 10

Mortensen JB (2012) Agent-based modelling of short-term juvenile bull shark movement in a semi-enclosed Gold Coast estuary. Griffith University

Rosser NL and Gilmour JP (2007) New insights into patterns of coral spawning on Western Australian reefs. Coral Reefs 27: 345-349

Simpson CJ (1985) Mass Spawning of Scleractinian Corals in the Dampier Archipelago and the implications for management of Coral Reefs in Western Australia. Department of Conservation and Environment, Perth, Western Australia, Bulletin 244

Willis J (2011) Modelling swimming aquatic animals in hydrodynamic models. Ecological Modelling 222: 3869-3887