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Three Dimensional Hydraulic and Water Quality Modelling of the Red Sea: Challenges and Learnings

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Abstract: The Red Sea is a major international shipping lane linking eastern and southern Asia with the Middle East and Europe. It is also seeing increasing direct and indirect exposure to the aquaculture industry, to which the Sea's relatively warm and clear coastal waters are well suited. As a result, there is a need to develop sufficiently detailed and robust numerical tools to support ongoing decision making and management of the Sea from shipping, commercial and ecological standpoints. Motivated in part by this need, BMT WBM and The Centre for Water Research (CWR) were commissioned to develop a three dimensional hydrodynamic model of the Red Sea, as well as a detailed 'nested' model of a fringing lagoon on the Saudi Arabian shoreline, which was experiencing pressure from proximate aquaculture activities. This paper describes that modelling study.

The Red Sea is approximately 1900 km long by 300 km wide at its widest point. It has maximum and average depths of 2.8 km and 490 m, respectively, with a total surface area of 450,000 km^2. It has fringing coral reef zones (to 50 m depth), deeper coastal shelves (to 600 m depth), main and axial troughs (to greater than 2000 m depth) and joins the Gulf of Aden at its southern end via the Straits of Bab Al Mandab. Due to geothermal activity, deep waters in the axial trough have been found to be above 60^{o}C and have salinities in excess of 300 g/L and as such are known as hot brines.

A nesting approach (low to high resolution) was adopted to focus model resolution in areas of interest whilst obtaining forcing conditions from a low-resolution larger-scale Red Sea model. A model framework based on the three dimensional Estuary, Lake and Coastal Ocean model (ELCOM) was adopted in the nesting approach. The large-scale (Red Sea) model was set up, and calibrated, using an 8km horizontal and variable vertical resolution grid (10m to 500m). The model was forced using sloping tidal boundaries at the eastern extent of the Gulf of Aden, and meteorological data were sourced from a combination of global climate model (GCM) data and locally specific measurements (where needed). Full radiation and thermal budgets were simulated using these data. Model performance was assessed against tidal predictions and measurements along the primary axis of the Sea, and it was shown that well-known amphidromic points were well reproduced. Comparisons of sea surface temperature and salinities were also made to assess model performance.

Results from the Red Sea model were used to produce boundary conditions to force the inner nested model; these included tidal elevation, temperature and salinity. Boundary conditions at the free-surface also adopted a combination of GCM and local meteorological data. The intent of constructing the nested model was to facilitate better understanding of the under pressure lagoon system, which was hypersaline, with particular reference to its exchange with the wider Red Sea. As such, the nested model was variable in both horizontal and vertical grid resolution, with horizontal resolution increased in the area where a field survey identified the occurrence of a complex density driven exchange flow through two relatively narrow lagoon openings. The ELCOM model was also upgraded to provide the capability to simulate a variety of culvert structures that were present in the inner lagoon.

Both models were used to assist in the ongoing management of the lagoon, and the wider Red Sea.

Keywords: *Hydrodynamic modelling, Red Sea, exchange flow*

1. INTRODUCTION

The Red Sea is a major international shipping lane linking eastern and southern Asia with the Middle East and Europe. It is also seeing increasing direct and indirect exposure to the aquaculture industry, to which the Sea's relatively warm and clear coastal waters are well suited. As a result, there is a need to develop sufficiently detailed and robust numerical tools to support ongoing decision making and management of the Sea from shipping, commercial and ecological standpoints. Motivated in part by this need, BMT WBM and The Centre for Water Research (CWR) were commissioned to develop a three dimensional hydrodynamic model of the Red Sea, as well as a detailed 'nested' model of a fringing lagoon on the Saudi Arabian shoreline which was experiencing pressure from proximate aquaculture activities. Although this modelling was supported by a detailed data collection program undertaken by BMT WBM, this paper focuses primarily on the modelling study.

2. MODEL SETUP

2.1. Model Framework

A model framework based on the three-dimensional Estuary, Lake and Coastal Ocean Model (ELCOM) model was adopted to focus model resolution in areas of interest (i.e., fringing lagoons), whilst obtaining suitable forcing conditions from a low-resolution larger-scale Red Sea model. ELCOM solves the Reynolds-Averaged Navier-Stokes equations using both hydrostatic and Boussinesq approximations. Solution techniques adopted in ELCOM are described elsewhere (i.e., Hodges 2000, Hodges et al. 2000, Laval et al. 2003, Botelho et al. 2009). ELCOM has been validated in a wide range of studies and was chosen because it is a conservative model with low numerical diffusion. A nesting approach (low to high resolution) was adopted, in which the high-resolution "lagoon-scale" model was forced with tidal elevations, salinities, and temperatures output from the large-scale "Red Sea" model.

2.2. Model Domains and Bathymetry

The large-scale (Red Sea) model domain covered the whole Red Sea and, later in the calibration process, extended to the western part of the Gulf of Aden. The Red Sea domain was discretised with a uniform 8km horizontal and variable vertical resolution grid (10 to 500 m). The lagoon-scale nested model domain was discretised with varying horizontal (200 to 50 m) and vertical (130 to 0.5 m) resolution.

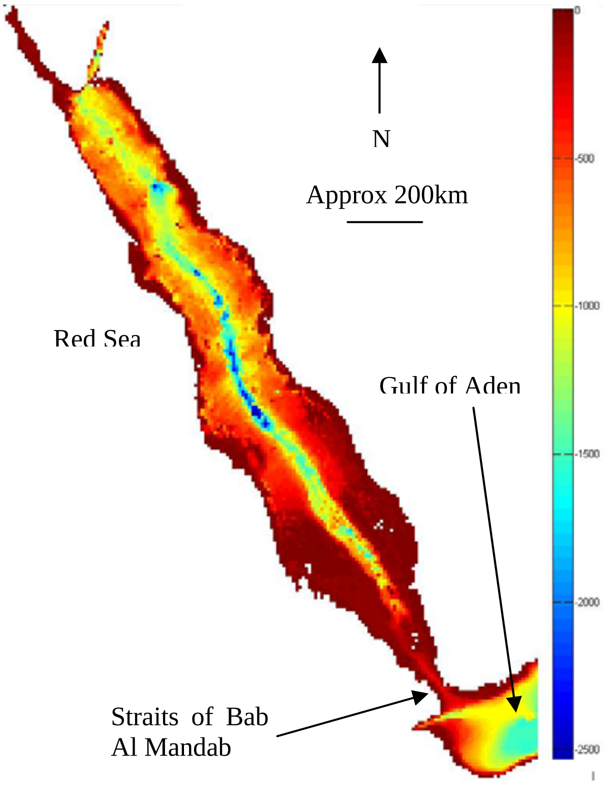

Figure 1. Red Sea bathymetry. Colourbar in metres

Bathymetric data for the Red Sea model were sourced primarily from world digital elevation model (DEM) data owned by BMT WBM. At the broader model scale this data was generally sufficient, however it required improved representation in some key locations. These included the majority of the fringing shallow coral zones, and the Straits of Bab Al Mandab at the southern entrance to the Sea. As the model calibration process evolved, it was found that correctly capturing the bathymetry at the latter location was particularly significant as it acted as a hydraulic control point for exchange between the Gulf of Aden and the entire Red Sea. These additional data were sourced from navigational charts, which were digitised as needed.

Bathymetric data for the nested model were sourced from a combination of the global DEM, local navigational charts, historical field measurements and additional field survey data collected specifically for the modelling study. Model bathymetries are shown in Figure 1 and Figure 2.

Originally, the Red Sea model open tidal boundary was set at the Straits of Bab Al Mandab, which was found to provide relatively poor tidal calibration through the length of the Red Sea. As such, the model boundary was moved to the eastern into the Gulf of Aden, thus allowing tidal hydraulics through the Straits to evolve far from the influence of a forced boundary. This improved the tidal calibration considerably, as is discussed below.

2.3. Tidal Boundaries

Tidal boundaries were sourced from Admiralty tidal constituents and inhouse software was used to convert these to tidal timeseries. Due to the distance across the open boundary in the Gulf of Aden, a sloping tidal signal was applied from north to south across the span. This slope was derived from tidal constituent data from sites in Yemen (north) and Somalia (south).

Once calibrated (see below) Red Sea model tidal predictions in the region of the fringing lagoon were used to drive the nested model. Again, a sloping tidal boundary running parallel to the shoreline (see Figure 2) was used, with non-tilting tides applied at the north western and south eastern model boundaries.

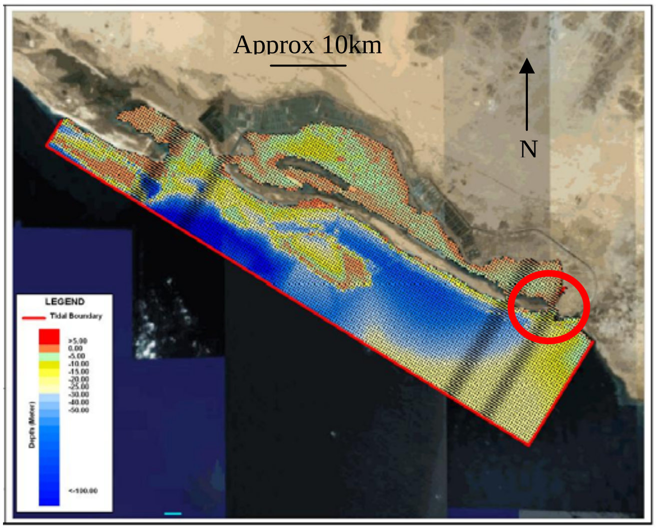

Figure 2. Nested model bathymetry. Red circle shows density current location (section 4). Photo from Google Earth

2.4. Meteorological Forcing

A full heat budget was simulated in both models. Due to the considerable length of the Red Sea and its span of several degrees of latitude and longitude, it was critical to ensure that spatial variations in wind field, radiation (both short and long wave), relative humidity and air temperature were captured and appropriately included in the model. A survey of publicly available meteorological data across the Red Sea found that available information was relatively sparse, and generally of insufficient quality to properly force the Red Sea model. As such, we sourced all meteorological data from an existing high spatial and temporal resolution GCM (NCEP and others). This model provided continuous three hourly wind speed and direction data on a regular grid, as well as six hourly short and longwave radiation. These data had been validated by others (BMT WBM internal report, 2006), and provided a superior data-set for model forcing.

Key features of the data were their continuity (no temporal gaps) and uniform spatial coverage of the model domain. As a consequence, very little effort was expended in deriving and applying the GCM meteorological data to the model, which represented a considerable time and effort saving compared to traditional means of meteorological data collection, collation and processing. Air temperature and relative humidity data were sourced from the sparse on-ground data set, however these data are also being sourced from a GCM for pending (new) model recalibration works. These works (which are not part of this study) will also see the application of individual data records at each GCM node to the model, rather than aggregation of the data to the bands mentioned previously.

2.5. Initial Conditions

Initial temperature and salinity profiles were sourced from the World Ocean Database (http://www.nodc.noaa.gov/) at a number of selected sites within the Red Sea.

2.6. Model Extension

Part of the nested model domain included a lagoon that was connected to the Red Sea via culverts. In order to appropriately capture the influence of these culverts on local hydrodynamics, the full culvert equations for open and gated circular pipes were added to the ELCOM model to support application in this study. These algorithms were those used in other well recognized hydraulic models such as TUFLOW (http://www.tuflow.com/). These routines have now been thoroughly tested and are now included in the standard ELCOM public release version (2.2).

At the time of this study, ELCOM was unable to vary the Coriolis parameter spatially, so we adopted a single mid-latitude value. Due to the relatively low latitudes of the Red Sea (approximately 10 to 30°) the single latitude assumption did not hinder the model skill as shown in the calibration and validation below. The model is now capable of adopting a variable Coriolis parameter, and the subsequent works will exploit this new capability.

3. MODEL CALIBRATION

The models were primarily calibrated to tides, and then (in a more qualitative sense) to the presence and structure of hydrodynamic features specific to each model domain.

3.1. Tides

Tidal data along the Red Sea shoreline were sourced from a combination of measurements and synthetic predictions and compared with model predictions. Comparisons between expected and predicted tidal levels moving from south to north along the Red Sea are shown in Figure 3.

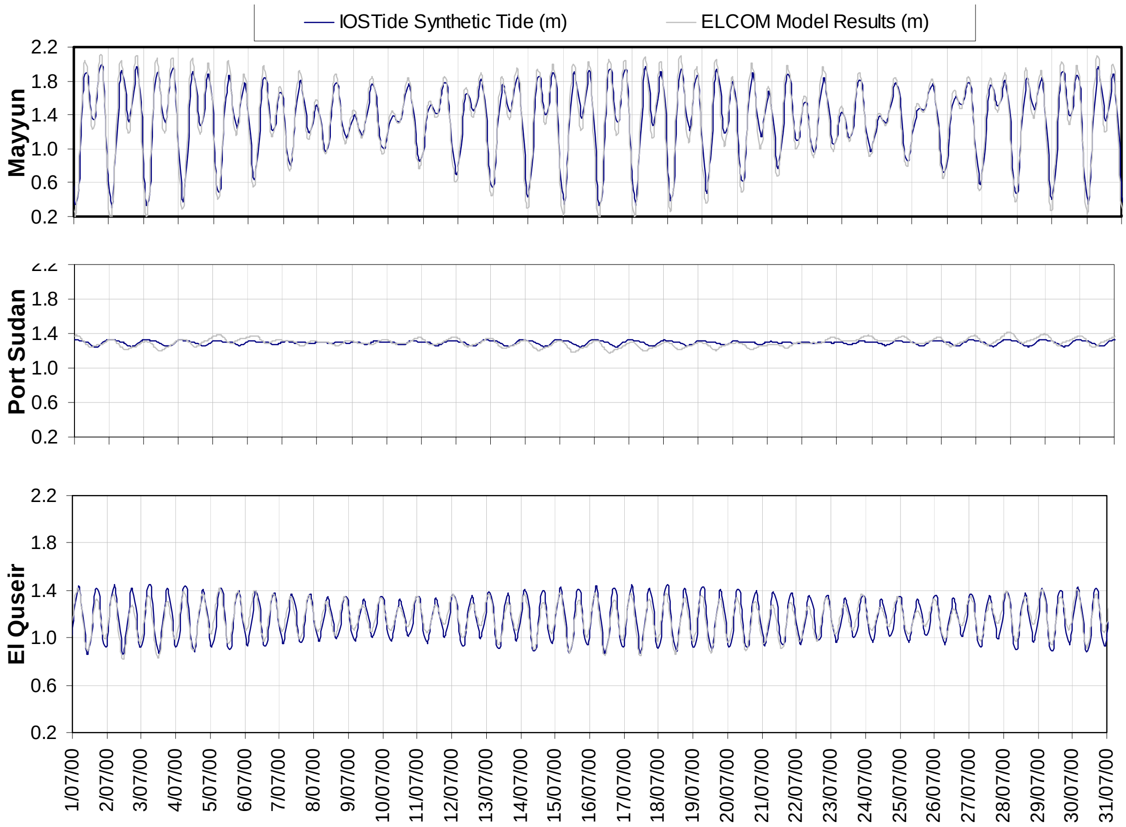

Figure 3. Tidal comparison: Mayyun (south), Port Sudan (midpoint) and El Quseir (north). Y-axis units are in metres above datum

This figure shows that the model is reliably reproducing large scale tidal water levels within the Red Sea, with high tides and low tides generally within 5-10% of expected values. The model also captures the oscillatory and semi-diurnal characteristics of the tides in the Red Sea adequately, as well as the spatial distribution of the tidal range. For example, the predicted tidal ranges at Mayyun and El Quseir are of the order of 1.8m and 0.6m respectively, with this range decreasing to only 0.1m and 0.2m at Port Sudan in the 'middle' reaches of the Red Sea, where quasi-amphidromic conditions exist. Reproducing the global seiching motion so as to provide accurate tidal boundaries for the nested model was a key feature for successful modelling of the fringing lagoon, which is located near the amphidromic point

Relevant tidal elevation boundaries were extracted from the Red Sea model and used to drive the nested model. The nested model performance was then assessed against data collected as part of the field program associated with this study. An example of this comparison is shown in Figure 4, which demonstrates adequate model performance.

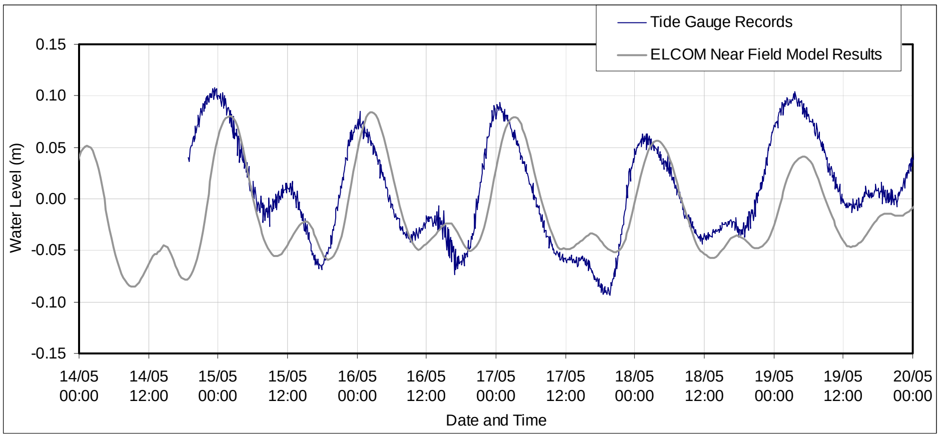

Figure 4. Nested model tidal calibration example.

3.2. Hydrodynamic features

Sea surface temperature data from NASA were sourced (http://www.nasa.gov/) to compare with the Red Sea model predictions. An example for April is shown in Figure 5. The comparisons were generally favorable, however the model generally under-predicted sea surface temperatures in the summer months. Sensitivity analysis (not shown) indicated that the specification of relative humidity at a single and relatively distant point is a major source of error in the predictions. The subsequent phase of works will extract these data from a GCM, and it is anticipated that the model will soon be improved in this regard.

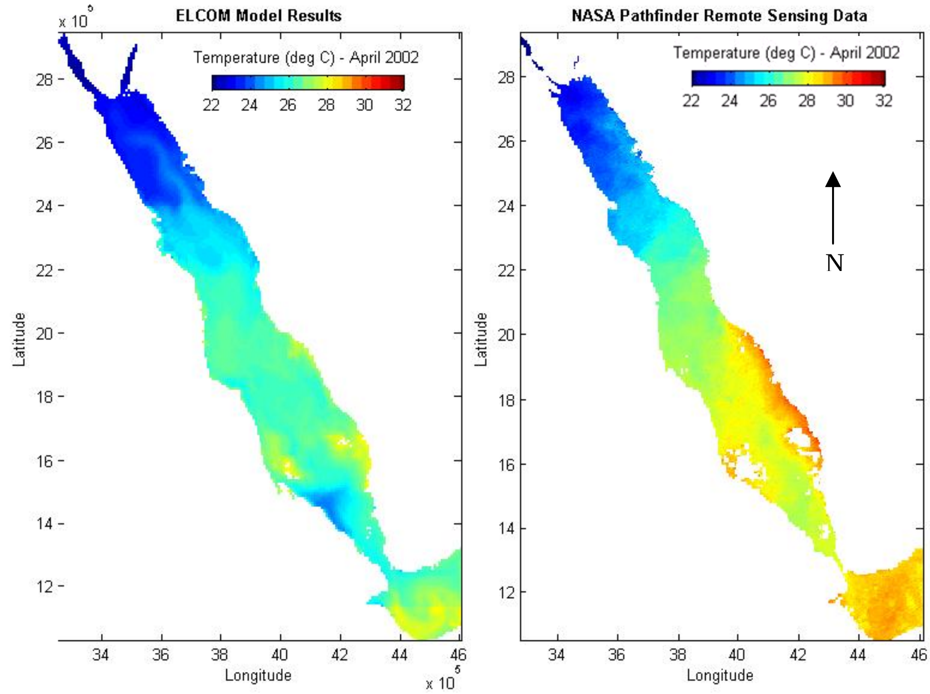

Figure 5. Example sea surface temperature comparison.

Although not the primary focus of the current study, the ELCOM model also predicted the cyclonic 'C1' eddy observed in the southwestern part of the Gulf of Aden (as reported in Bower & Fratantoni, 2002), as shown in Figure 6. Speeds of 0.5 to 1.5m/s were predicted at the surface due to this eddy. This is a major feature predicted by the model, and provides certainty in the model's predictive capability.

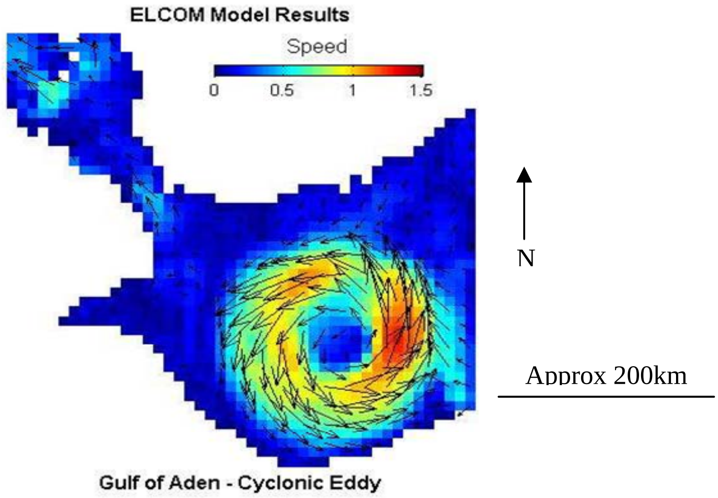

Figure 6. Cyclonic eddy prediction. Left hand figure is sourced from Bower & Fratantoni, 2002. Units on right hand figure are metres per second

4. MODEL APPLICATION

This modelling study saw the construction and execution of two three-dimensional models of varying spatial extents and resolution. These were used in combination to provide an improved understanding of the fringing lagoon with regards to a variety of matters. One key item of interest was the model's ability to reproduce density currents which were observed to be exiting the lagoon at its south eastern end on an ebbing tide (see Figure 2). These currents are strong underflows as the density difference between the (saltier) inner lagoon and adjacent Red Sea can be up to 10 psu.

To investigate this, acoustic Doppler current meter (ADCP) measurements were conducted across the exit channel, and representative data are shown in Figure 7. The colour scale represents current speed, with the range being from zero to 1 m/s (purple to red). The dense underflow (heading in a direction out of the page) is clearly visible as the green area, which is characterized by velocities of approximately 0.5 m/s, through the area that is approximately 10 metres deep. It is circled for clarity.

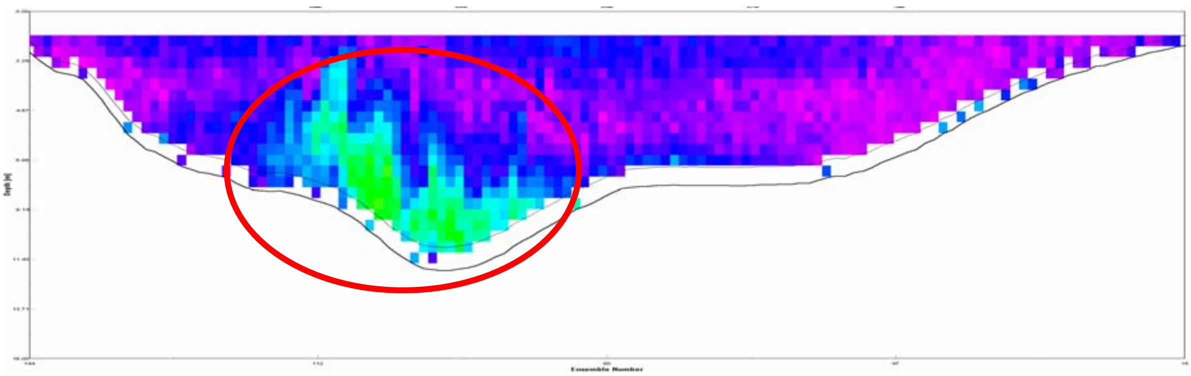

Figure 7. ADCP field data at lagoon exit. The bottom contour offset is the approximate zone of bed penetration of the ADCP beams.

Figure 8 shows the nested model's prediction for these gravity flows. The figure shows a vertical curtain cut through the model domain in a west-east direction across the exit circled in Figure 2. The left hand panel shows velocity, and the right hand panel shows salinity. The figure shows that the model clearly predicts the saline discharge at depth, and at approximately the same exit velocity as shown in Figure 7.

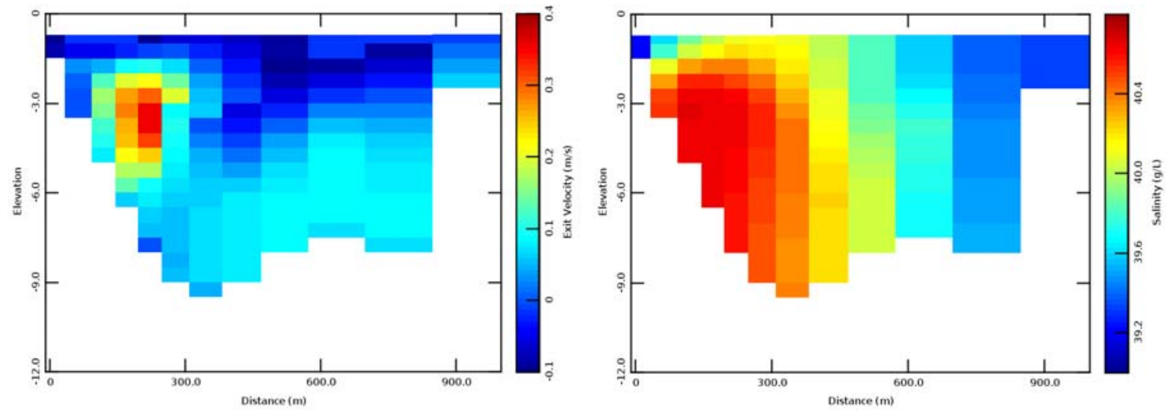

Figure 8. Density current exiting the fringing lagoon: model bottom layer data.

A range of other model scenarios were set up and executed in order to logically and rationally inform the management of the system. These are not reported here due to space constraints.

5. CONCLUSIONS AND FUTURE WORK

A one-way nesting model framework was established to represent the circulation in the wider area of the Red Sea and flow patterns in areas of interest, aiming at providing an improved understanding of hydrodynamic and water quality processes of a saltier local fringing lagoon on the shoreline of the Red Sea. Several challenges were met throughout the study, especially with regards to setup, forcing, calibration and validation of the Red Sea model. Since this study, further works have been commissioned by the client to revisit and improve the Red Sea model calibration, and to use this model to examine further issues around the wider Red Sea area and also the area around the aquaculture operations. Works on this model improvement are imminent, and future papers are intended to be prepared at an appropriate time documenting the performance of the new and improved models.

6. ACKNOWLEDGEMENTS

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