Report on 3-D Hydrodynamic Modeling of Falmouth Harbour

Falmouth Cruise Terminal Development

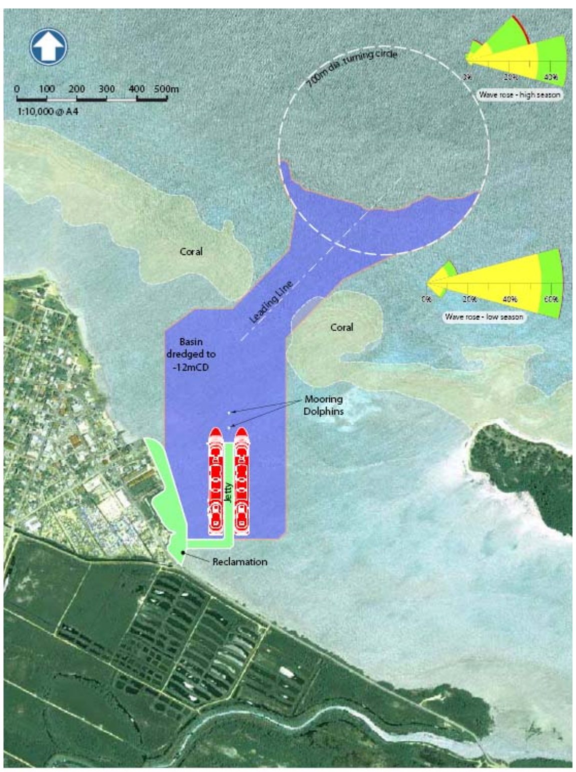
Technological and
Environmental Management
Network Ltd.

Table of Contents   Page

1 PROJECT BACKGROUND

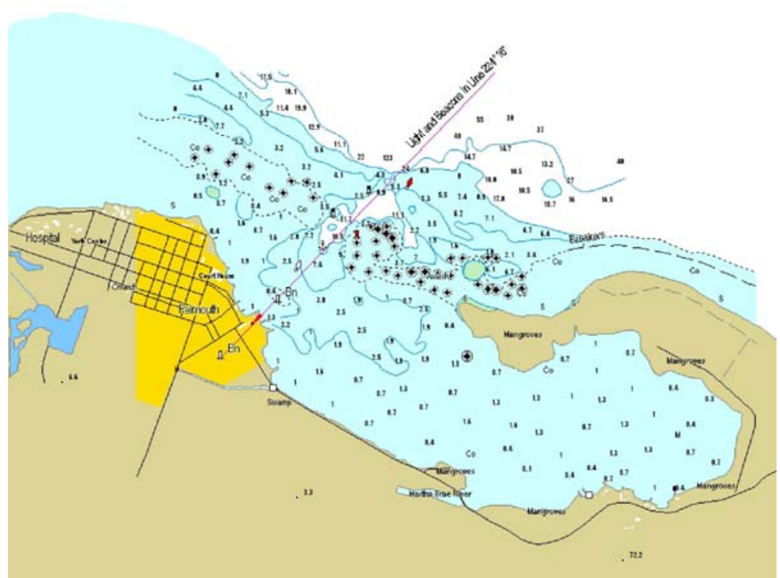
The Port Authority is planning to construct a Cruise Ship facility at Falmouth Harbour, in the parish of Trelawny on the north coast of Jamaica. There is a reef approximately 570m offshore which produces some form of sheltering in the form of wave height reduction. In order to accommodate the expected incoming vessels, it is planned to undertake land filling adjacent to the shoreline and to significantly increase the entrance channel width and depth. As part of the Environmental Impact Assessment, it is necessary to determine how these changes to the seabed will affect nearshore circulation patterns. Of particular interest is the potential impact on the bioluminescent dinoflagellates that inhabit the estuary. It has been found from research that the bioluminescence is affected by river flow from the Martha Brae River, which empties into the bay. Following a rainfall event, there is a noticeable vertical temperature/salinity stratification, which results in the bioluminescence descending to the lower portions of the water column where higher temperatures and salinity remain. It is therefore important to quantify the ways that nearshore circulation patterns would be affected following the construction of the cruise ship facility.

Smith Warner International Ltd. (SWIL) was commissioned to undertake a study of the impact on currents, temperature and salinity for the proposed layout (Option 6), shown below along with the nautical chart of Falmouth Harbour.



Mott MacDonald
233455 Falmouth Cruise Terminal

Figure 8.8
Layout Option 6



In order to evaluate the impacts on the nearshore circulation patterns, the Falmouth estuary was modeled using a 3-dimensional hydrodynamic model. The focus of this investigation was to determine changes to the current and vertical stratification patterns resulting from the new entrance channel.

2 INPUT DATA

Both existing and new, collected data was used as input data to drive the hydrodynamic modeling process. Collected data consisted primarily of bathymetry and tidal information in the study area, as well as details regarding the discharge of the Martha Brae River. A brief description of the methods of data acquisition and results obtained is outlined below.

2.1 BATHYMETRY

A bathymetric survey of the nearshore region was carried out, mapping the topography of the existing seabed. Bathymetric data collection is essential to the prediction of currents and salinity by the hydrodynamic model. The data was collected using a boat to traverse the study area, ensuring that the details of the shallow reef system parallel to the shoreline were captured, as shown in Figure 2.1.

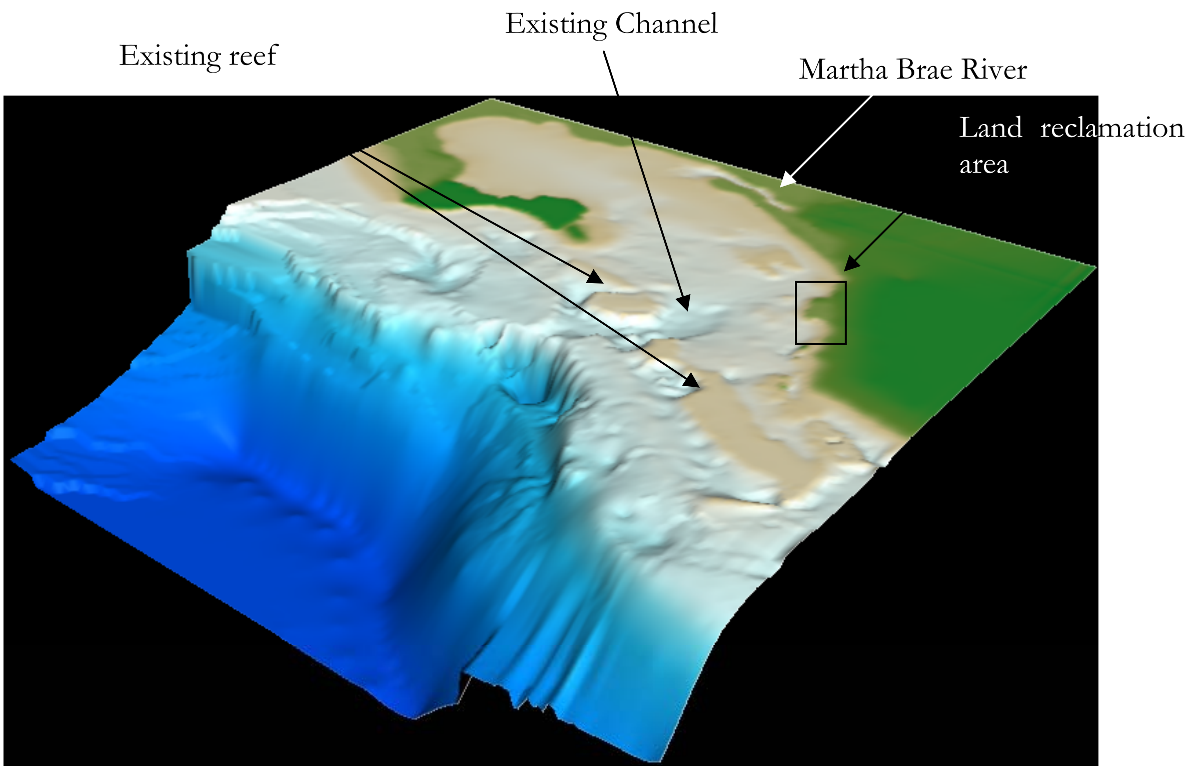


Figure 2.1: 3D image showing existing seabed

The bathymetric data was logged to a hand-held computer at one-second intervals using an Autohelm ST60 depth gauge. Simultaneously, positions were logged using a Trimble GeoXT GPS receiver. Tides and waves were not accounted for in the determination of the water depth, due to minimal tidal fluctuations (0.3m) and wave heights (0.5m) at the time of the survey. The required accuracy for the computations to be carried out does not exceed these levels, making the exclusion of this data acceptable. The quality of the survey data was checked against data from other surveys, and found to be accurate. The results of the bathymetric survey and coastline data are plotted in three-dimensional form in Figure 2.1. The image shows the sharp fall-off beyond the reef, and the existing entrance channel between the reefs.

2.2 TIDE

The tidal data used in the simulations was measured in the nearshore at Silver Sands, Trelawny in 2004. The data was considered appropriate given the relative proximity to the proposed Cruise Ship Pier Development. The simulations were carried out over a neap tide with a minimum tidal range of 0.3m and spring tide with a maximum tidal range of 0.6m (See Figure 2.2).

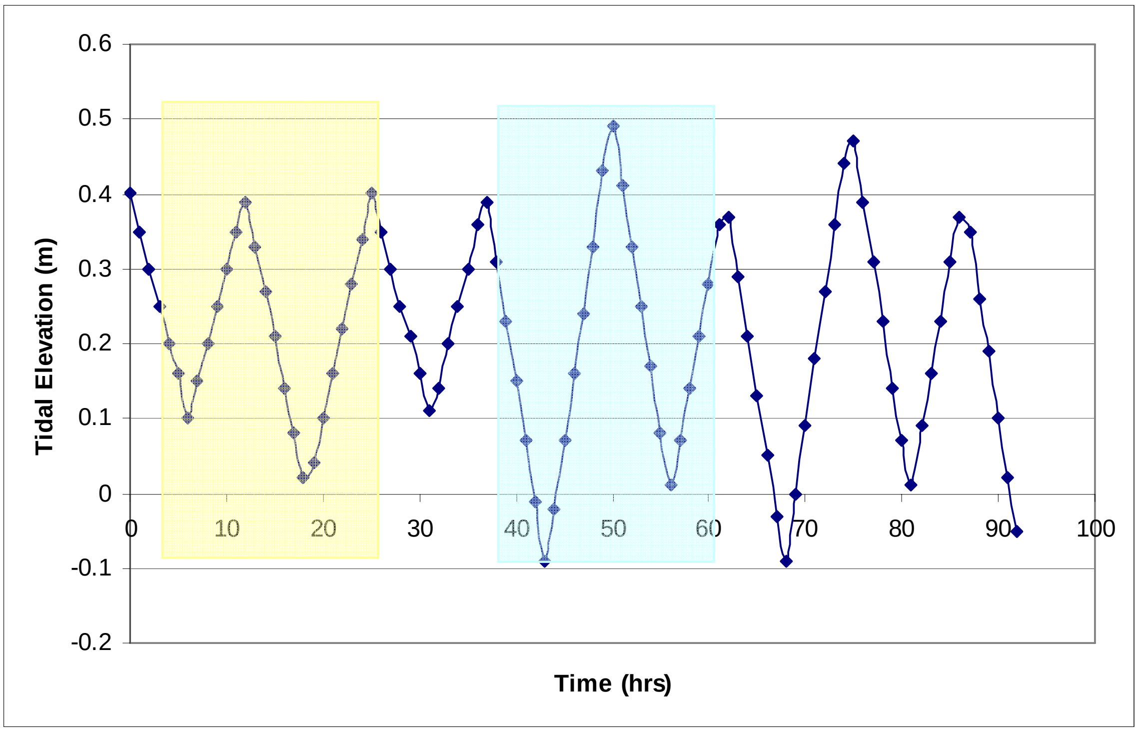


Figure 2.2: Tide Graph

2.3 RIVER FLOW

The flow rates for the Martha Brae River were obtained from the Water Resources Authority. The nearest stream flow gauging station measuring flow of the Martha Brae River is located 2.8 km south of the proposed site of the Falmouth Cruise Ship Pier. The data obtained gave daily flows between 1999 and 2006 with the exception of 2004. A summary of the data showing the annual maximum, mean and minimum daily flows is presented in

Table 2.1

Table 2.1: Annual maximum, mean and minimum daily flows

Year	Maximum (m^3/s)	Mean (m^3/s)	Minimum (m^3/s)
1997	21.00	5.78	2.38
1998	39.62	7.30	2.32
1999	49.64	13.40	2.86
2000	39.24	9.26	1.84
2001	47.91	9.33	3.79
2002	63.39	13.92	2.72
2003	72.56	25.98	4.25
2005	124.38	21.68	6.25
2006	41.88	12.92	5.80
Average	**55.51**	**13.29**	**3.58**

The peak flows in the river for 2002, 2003 and 2005 are all greater than the 1/100yrs flow obtained from WRA (see Table 2.2). The fresh water inputs used for the hydrodynamic model assumed a discharge 20m^3/s, which is representative of flood river flow conditions.

Table 2.2: Discharges for various return periods

Station	1/5 yrs (m^3/s)	1/10 yrs (m^3/s)	1/20 yrs (m^3/s)	1/100 yrs (m^3/s)
Martha Brae	48.62	53.15	56.71	63.06

3 HYDRODYNAMIC MODELING

The hydrodynamic model RMA-10 was used for this project. The model uses a finite element network to define the study area. The flexibility of the RMA-10 model allows 2D and 3D elements to occur within the same model, greatly improving computational efficiency, while not restricting the ability to represent vertical stratification. The primary features of RMA-10 are:

- The solution of the Navier-Stokes equations in three-dimensions;
- The use of the shallow-water and hydrostatic assumptions;
- Coupling of advection and diffusion of temperature, salinity and sediment to the hydrodynamics;
- The inclusion of turbulence in Reynolds stress form;
- Horizontal components of the non-linear terms are included;
- A capacity to include one-dimensional, depth-averaged, laterally-averaged and three-dimensional elements within a single mesh as appropriate;
- No, partial and full-slip conditions can be applied at both lateral boundaries;
- Partial or no slip conditions can be applied at the bed;
- Depth-averaged elements can be made wet and dry during a simulation;
- Vertical turbulence quantities are estimated by either a quadratic parameterization of turbulent exchange or a Mellor-Yamada Level 2 turbulence sub-model.

The development of a suitable oceanographic prediction model requires two main phases. The first is the creation of a 3D hydrodynamic model, which predicts the current patterns and vertical temperature/salinity stratification in the Falmouth Harbour. This requires the creation of two finite element meshes. The first represents the existing seabed contours and the second represents the modified seabed contours shown in Option 6. The second stage is the verification and testing of the model to determine if it is properly representing the circulation patterns.

The driving forces governing flow in Falmouth Harbour include tidal variations, river flow, with secondary forces including wind and density variations in the water column. Available information describing these driving forces were gathered and formatted for input into the hydrodynamic model.

3.1 MESH CONSTRUCTION

The mesh construction exercise involved the construction of two finite element meshes from which comparisons could be made. The first mesh was developed to represent the existing bathymetric and shoreline configuration. The second mesh represents the modified shoreline configuration with the seabed dredged for the proposed cruise ship facility.

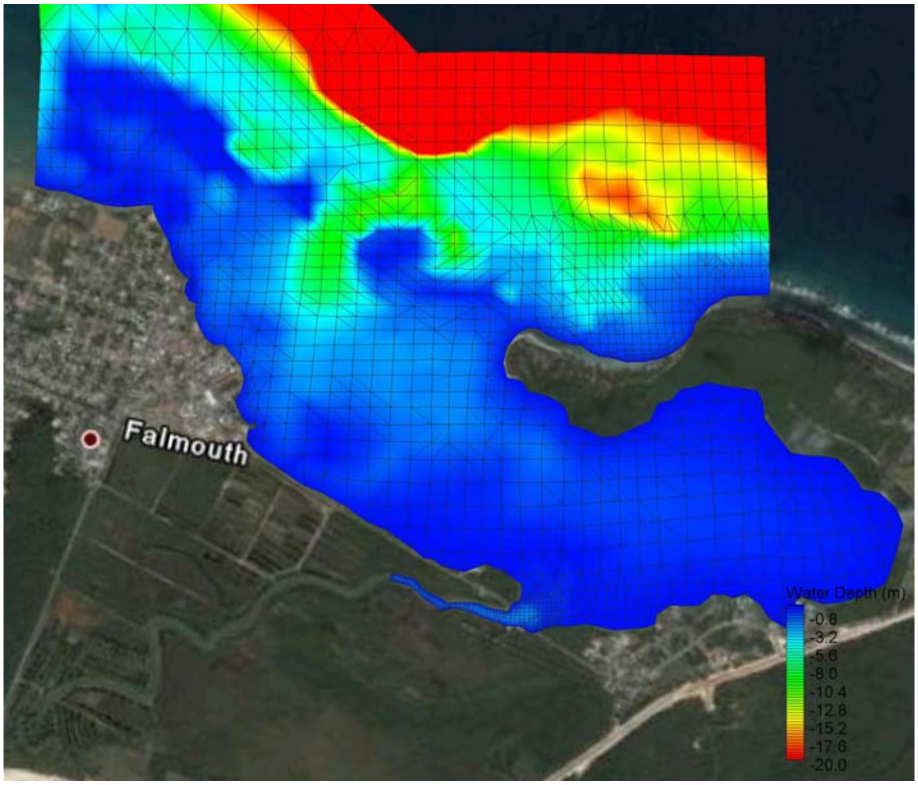


Figure 3.1: Hydrodynamic mesh representing Existing shoreline and seabed

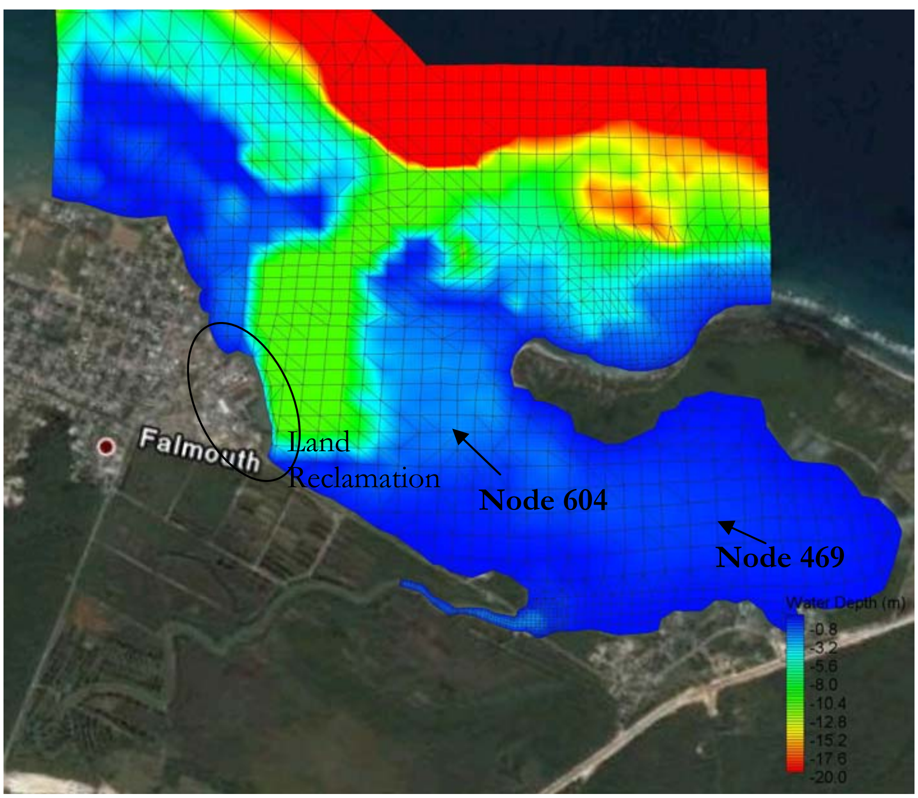


Figure 3.2: Hydrodynamic mesh representing Proposed shoreline and dredged seabed

3.2 MODEL CALIBRATION

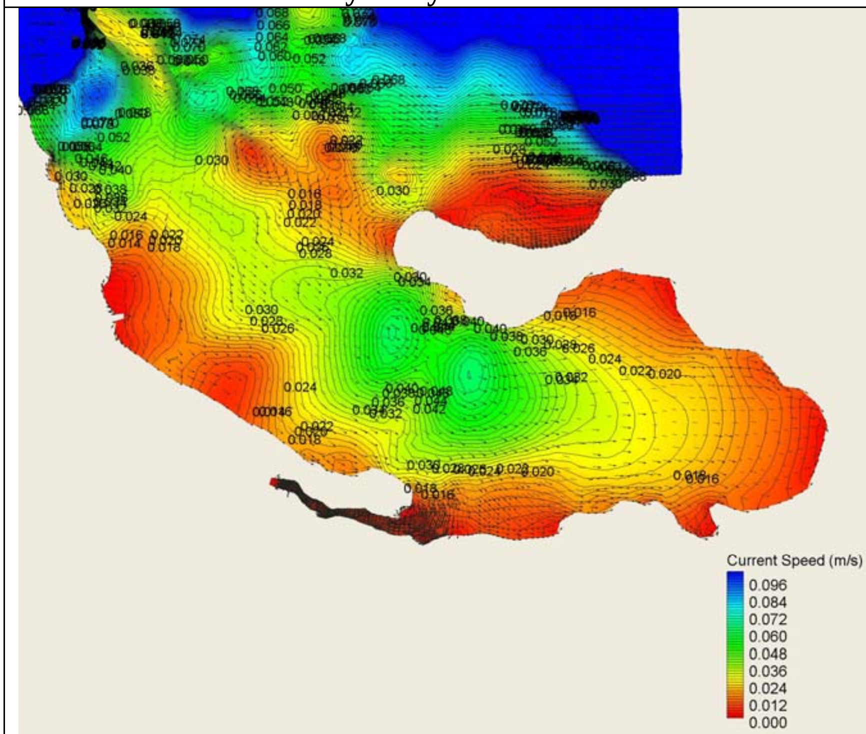
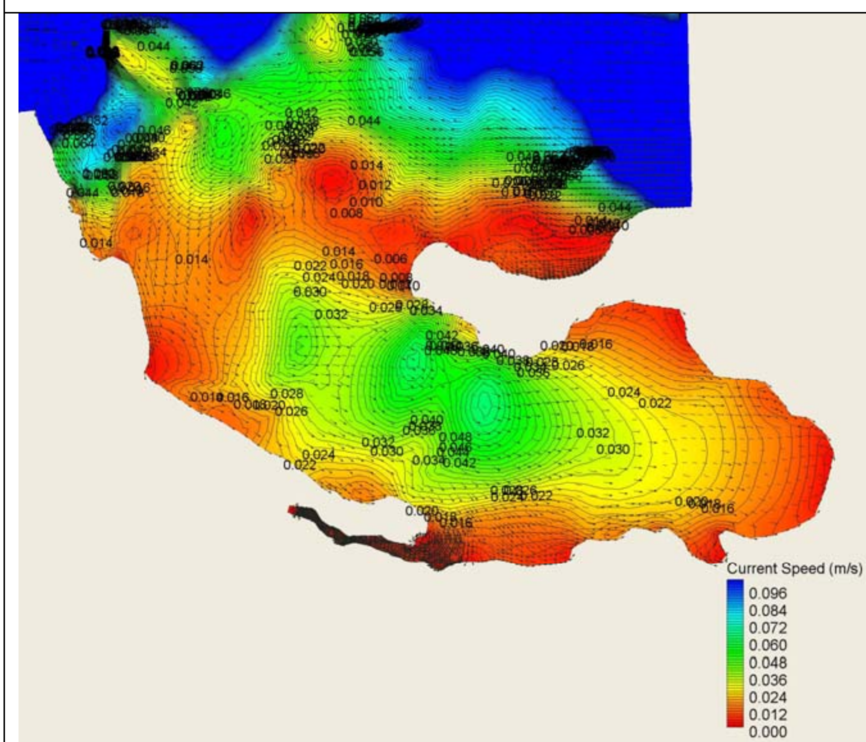
Calibration of the model involved the variation of mixing coefficients in the input data until the results of the simulation represented salinity and temperature variations observed in the field, including a vertical stratification of temperature and salinity. The calibration process was quite lengthy; each time a coefficient was changed the model was required to go through a series of calculations, each taking in excess of 6 hours to re-compute the results.

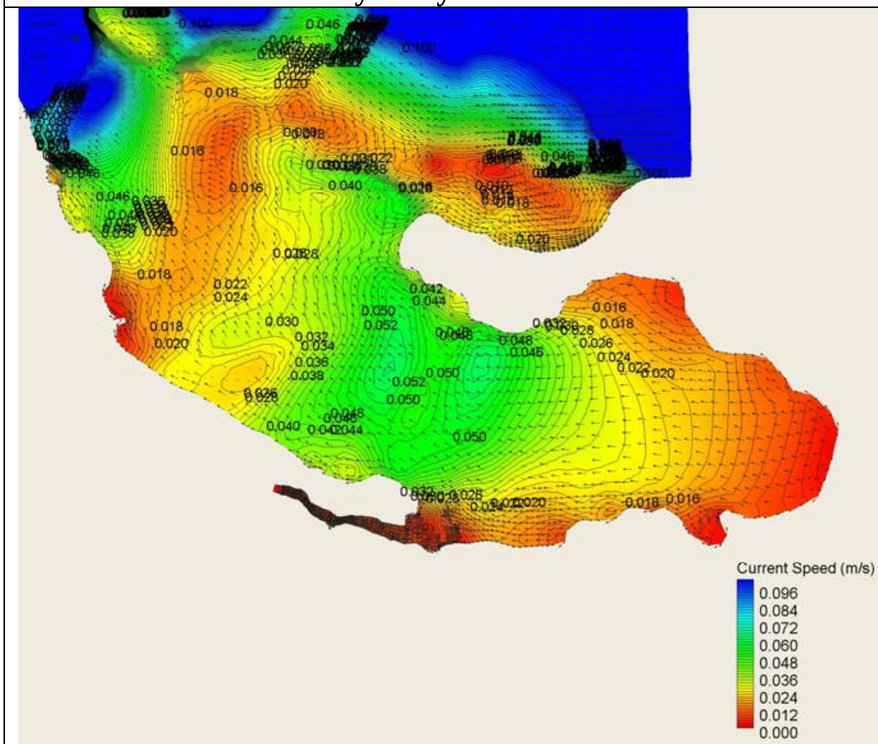
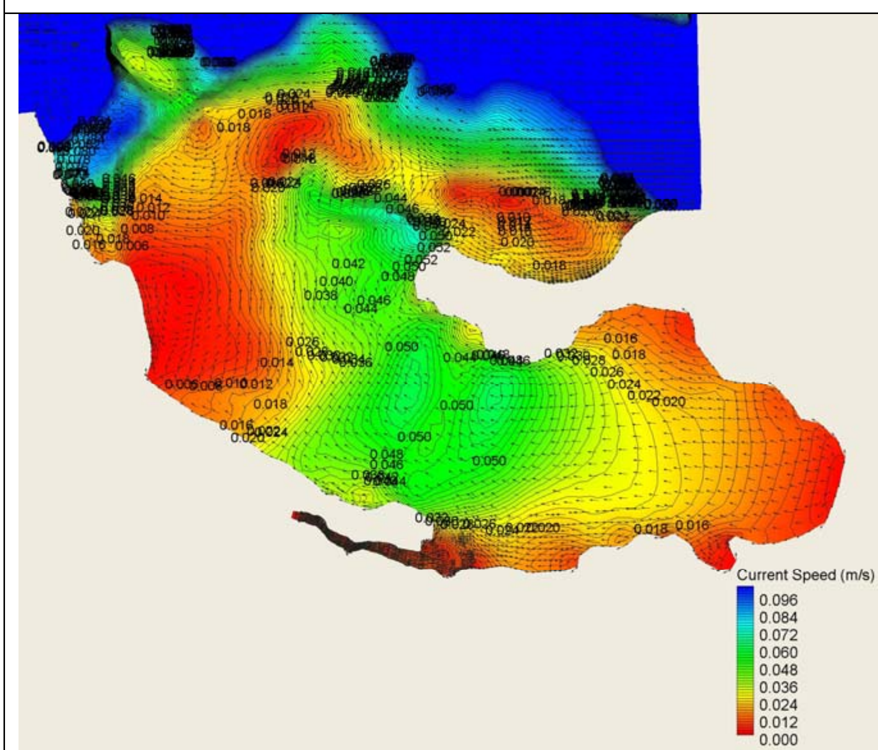
Following calibration, the 3D model was run using the same input parameters, with the exception of the shoreline and seabed input files, which represent the proposed modifications including the land reclamation and the channel dredging.

3.3 MODEL RESULTS

By making detailed comparisons between the model predictions using the existing and proposed shoreline and seabed input files, the magnitude of the impact of the development on salinity, temperature and currents and, in turn, their effect on dinoflagellates can be assessed.

The following plots show the surface current patterns at different stages of the tidal cycle. The spring tide cycle was chosen for use in the model, as this is when the tidal currents are at their strongest and the impacts would be most apparent. The proposed modifications appear to increase the current speeds slightly during the rising tide, and conversely to decrease them during the falling tide. The main area where these changes to current patterns are most visible is adjacent to the shoreline, near the proposed landfill area. A possible explanation for this is that the deeper channel allows the rising tide waters to enter the estuary with greater speed. The modification to the entrance channel would result in the same quantity of water entering the estuary, as this is not a function of depth, but of the tide range. When this water flows out of the estuary during the falling tide, the velocity is decreased because the same volume of water now flows through the deepened channel. In the upper (eastern) portions of the estuary, the current patterns appear to be unchanged.

Falmouth Cruise ship Facility **RMA-10 3D Hydrodynamic Model Results – Surface Velocities**	
 	Existing
 	Proposed
Model – No River flow **Simulation time: Rising Spring Tide**	**Figure 3.3**

Falmouth Cruise ship Facility **RMA-10 3D Hydrodynamic Model Results – Surface Velocity**	
	Existing
	Proposed
Model – No River flow **Simulation time: Spring Falling Tide**	**Figure 3.4**

A detailed comparison was made by evaluating the difference between the predicted current speeds and directions at two nodes, for the entire model simulation. These are shown below, representing Node 494 and 604 in Figures 3.5 and 3.6. The location of these nodes is shown in Figure 3.2. The figures show the current speeds and directions for each time-step in the model simulation as points on the scatter diagram. The distance from the origin represents the current speed, and its direction is plotted from North (Up). If there was no change in the current patterns, then each point representing the *proposed* condition would overly the *Existing* condition point. It can be seen that the predicted currents at both of these nodes do not change significantly as most of the Existing Condition points have been masked by the Proposed Condition points, indicating virtually no change in the current patterns.

The results for Node 469, which is located well inside the estuary, show quite small changes between the Existing Condition and Proposed Condition currents. For Node 604, which is located closer to the dredged entrance channel, there is a more noticeable change in the scatter diagram, although the shift does not appear to be significant. A significant shift would appear as an obvious change in the location of the centroid, or in the range of values.

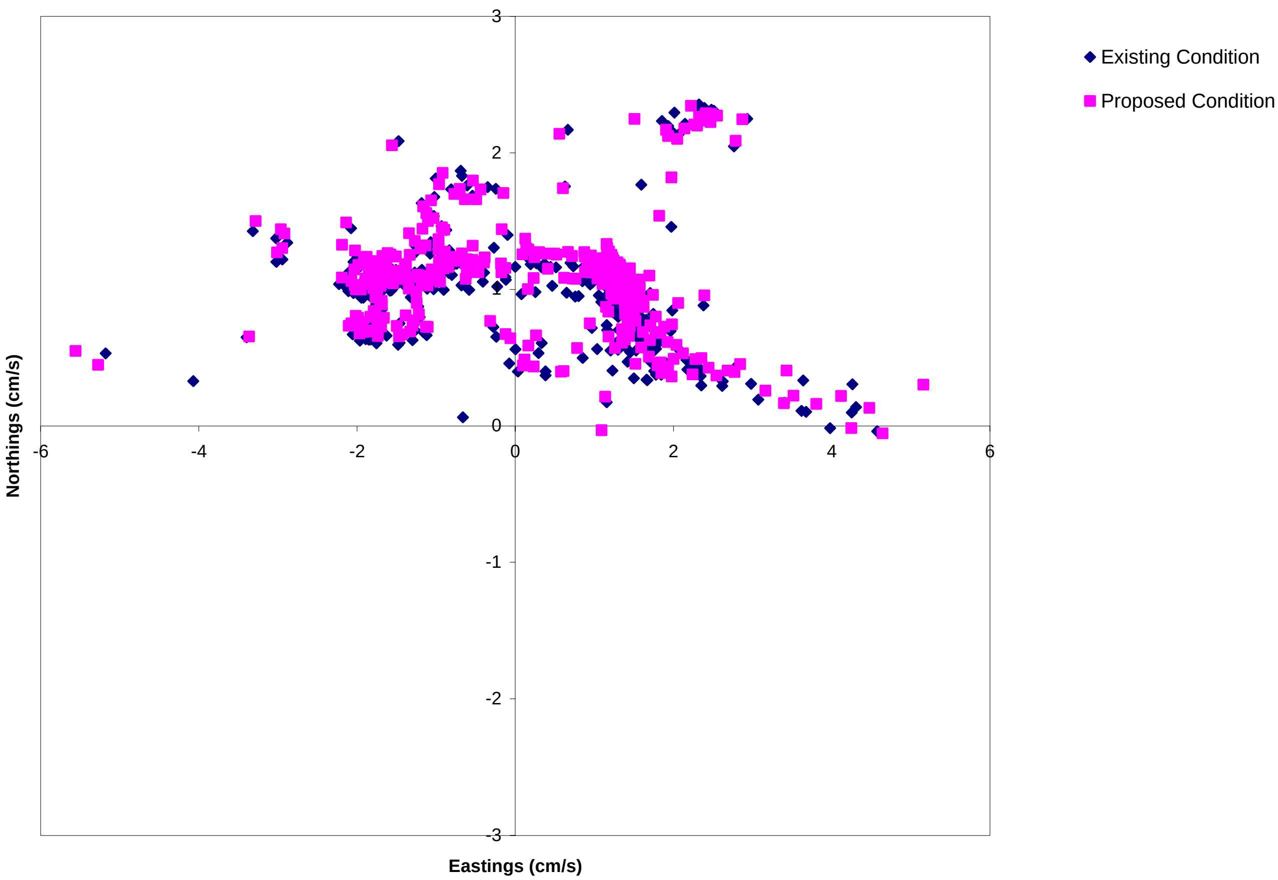


Figure 3.5 Scatter plot showing comparing existing and proposed conditions at Node 469

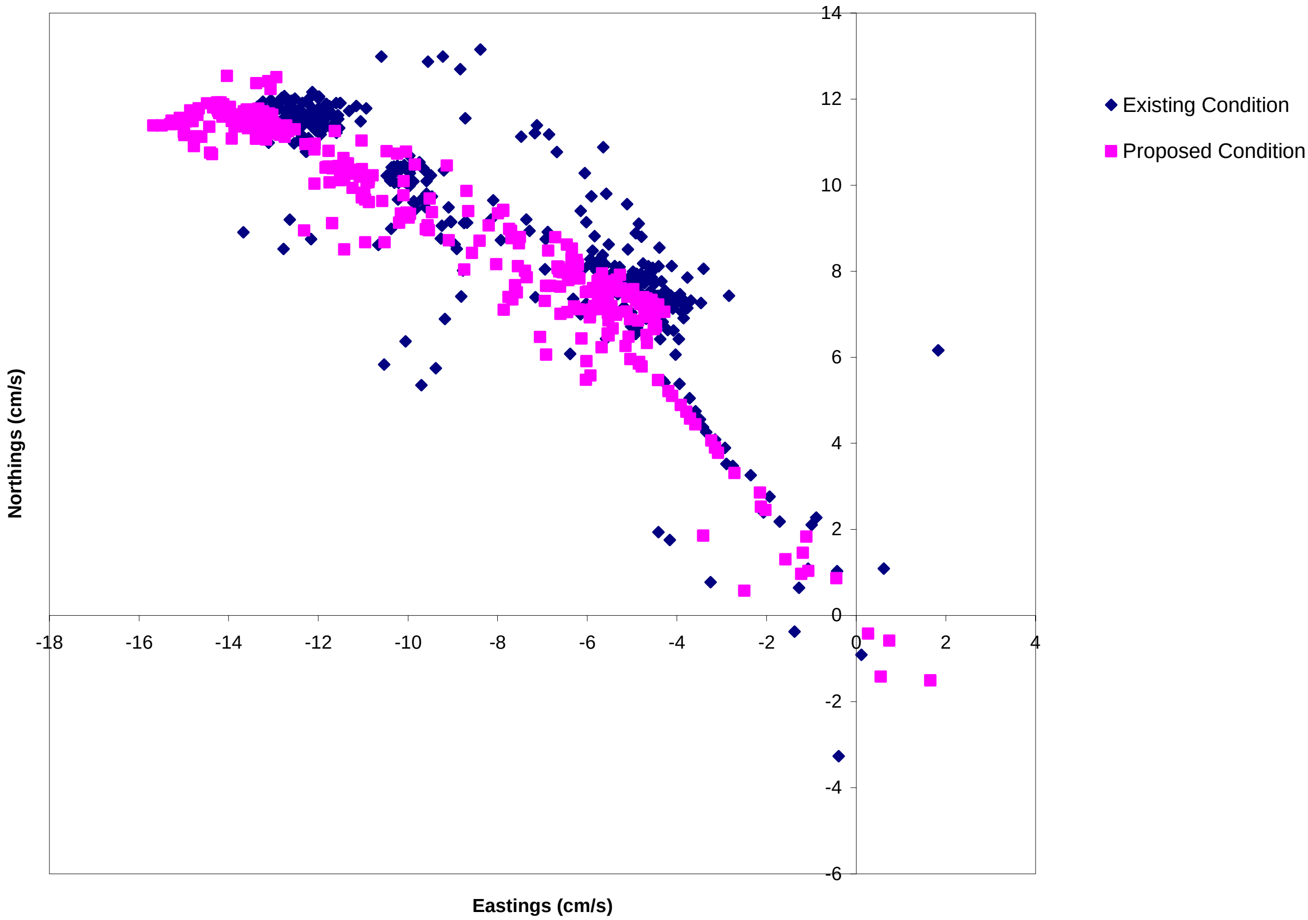
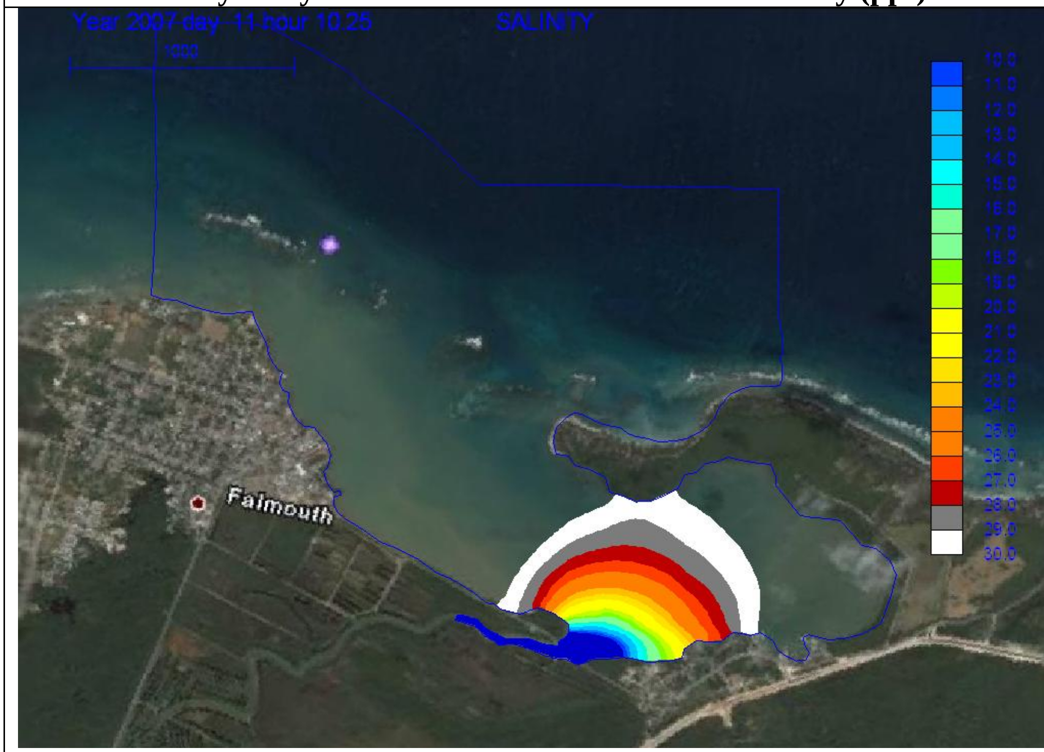


Figure 3.6 Scatter plot showing comparing existing and proposed conditions at Node 604

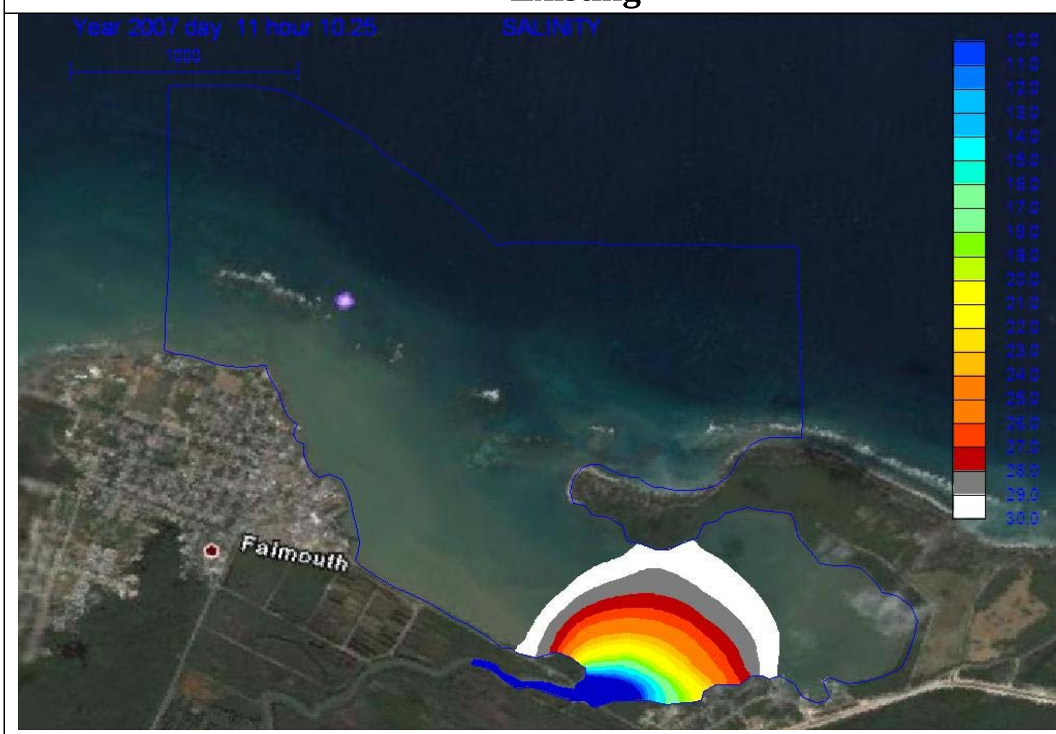
The following plots show contours of the surface salinity at several time intervals following the start of a river flooding event. Each plot shows the results for the existing shoreline and bathymetry and the proposed land reclamation and entrance channel dredging.

The model results consistently indicate that the proposed modifications to the shoreline and seabed result in the fresh river water from the Martha Brae River occupying less of the estuary. The model results indicate that there will be an overall increase in the salinity of the estuary compared to the existing configuration.

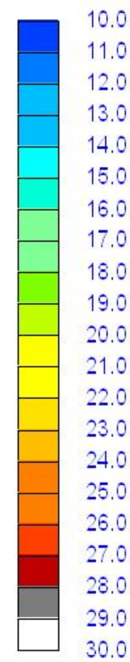
Falmouth Cruise ship Facility
RMA-10 3D Hydrodynamic Model Results – Surface Salinity (ppt)



Existing

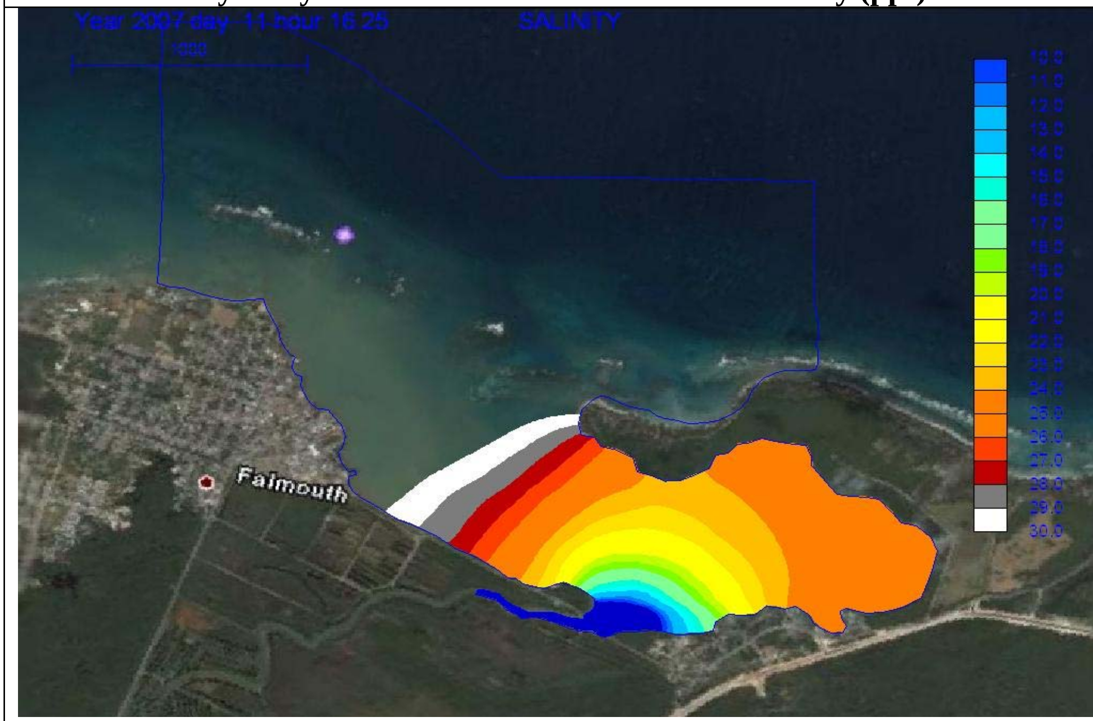


Proposed

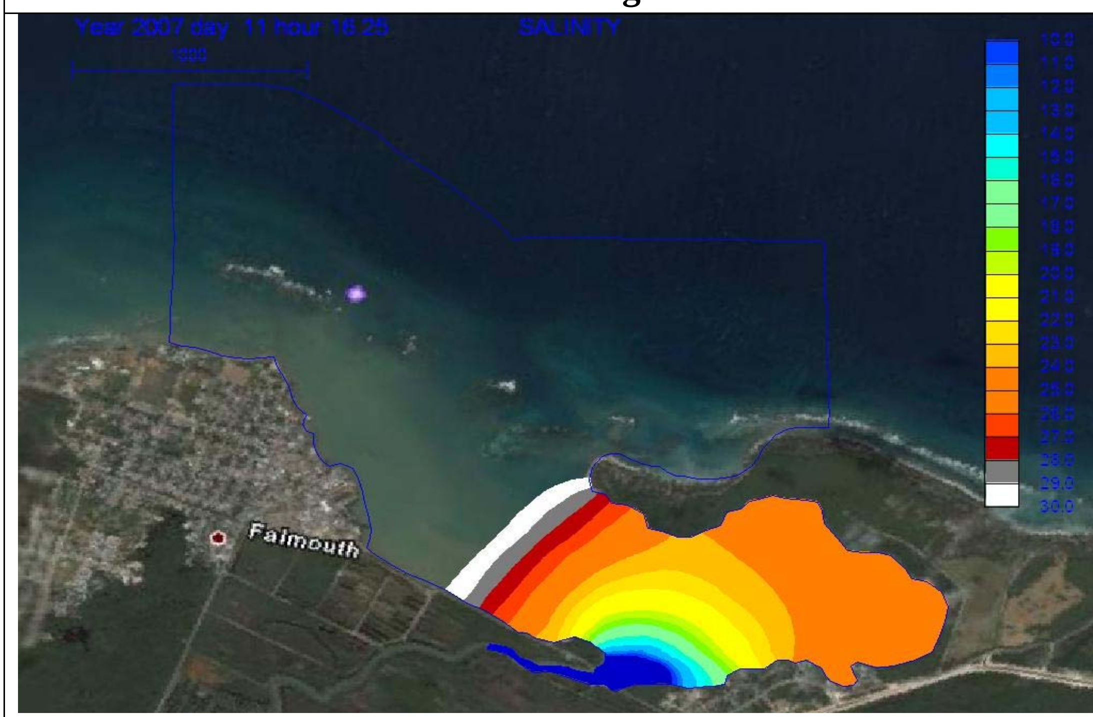


Model – River flow – 20 m^3/s **Simulation time: 6 hours** **Figure 3.7**

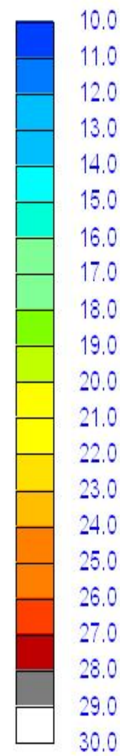
Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Surface Salinity (ppt)



Existing

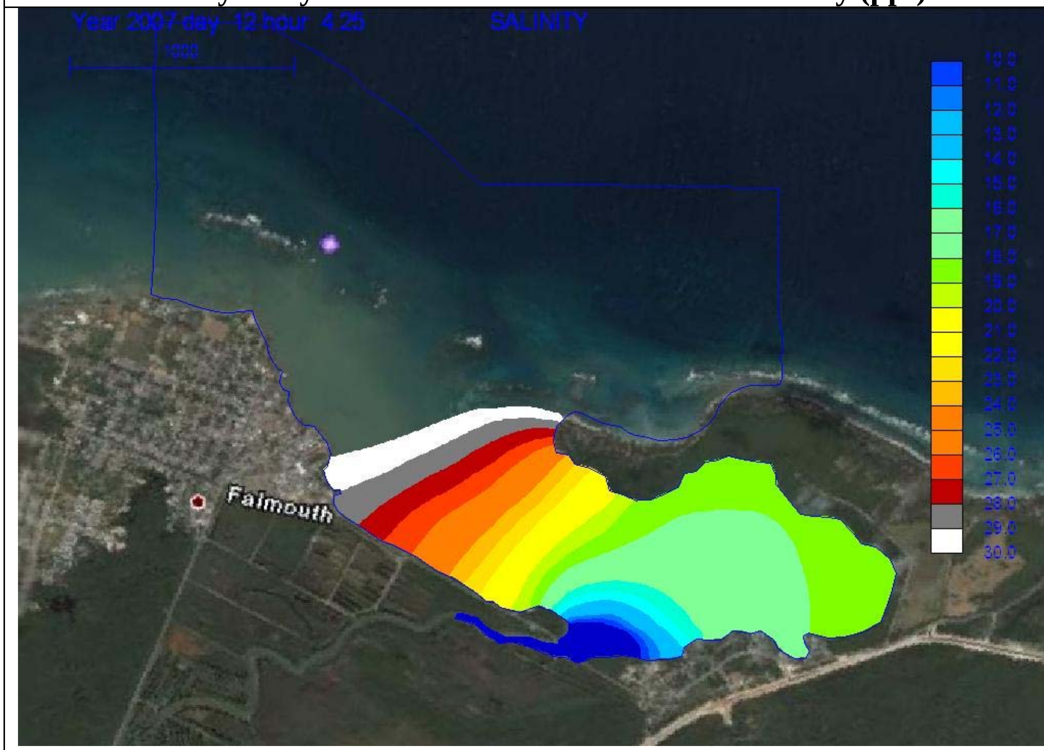


Proposed

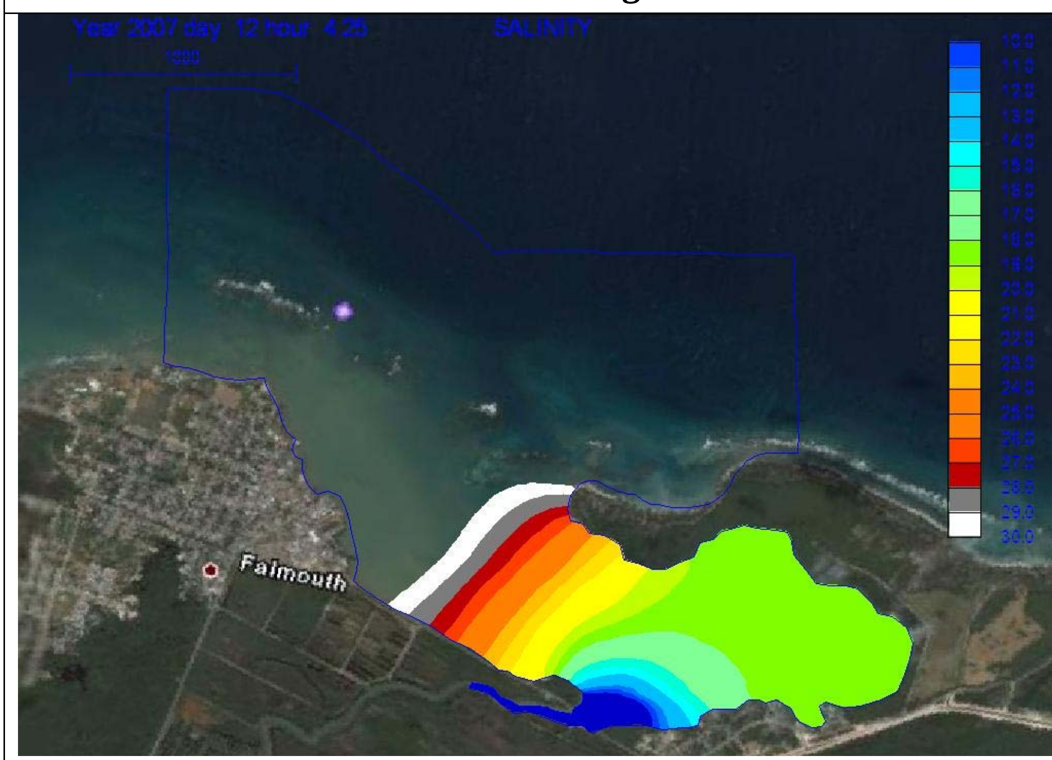


Model – River flow – 20 m^3/s **Simulation time: 12 hours** **Figure 3.8**

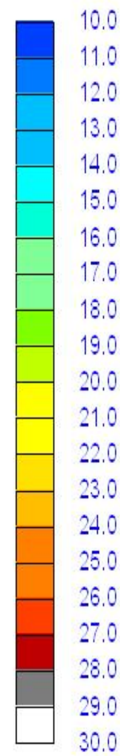
Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Surface Salinity (ppt)



Existing

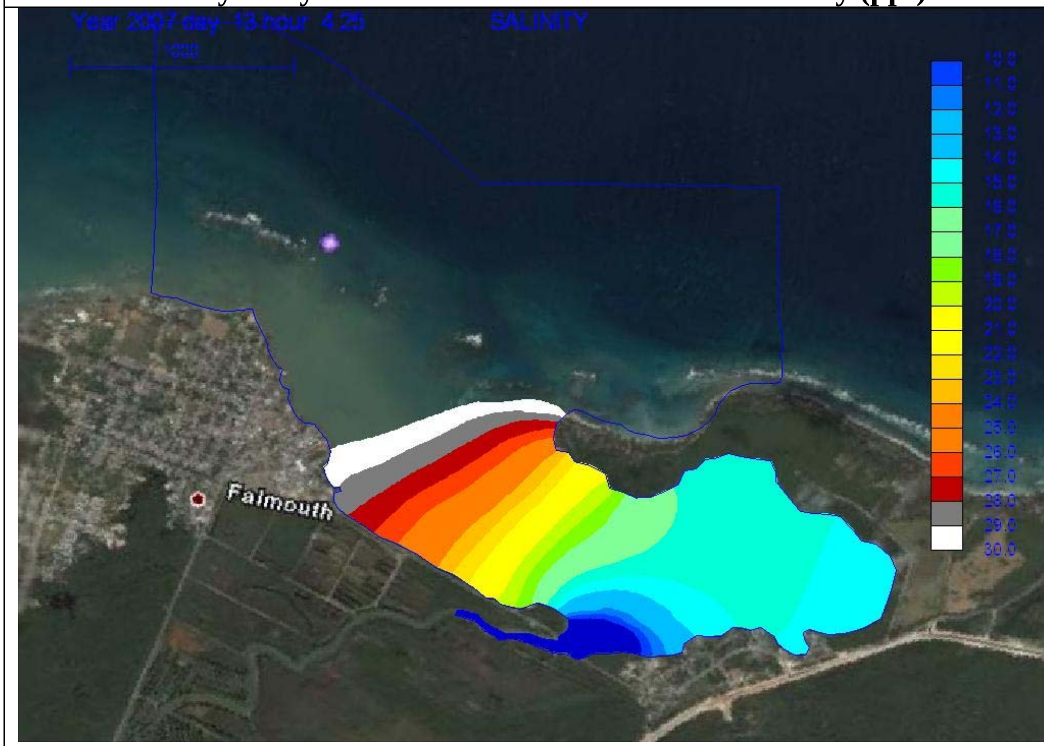


Proposed

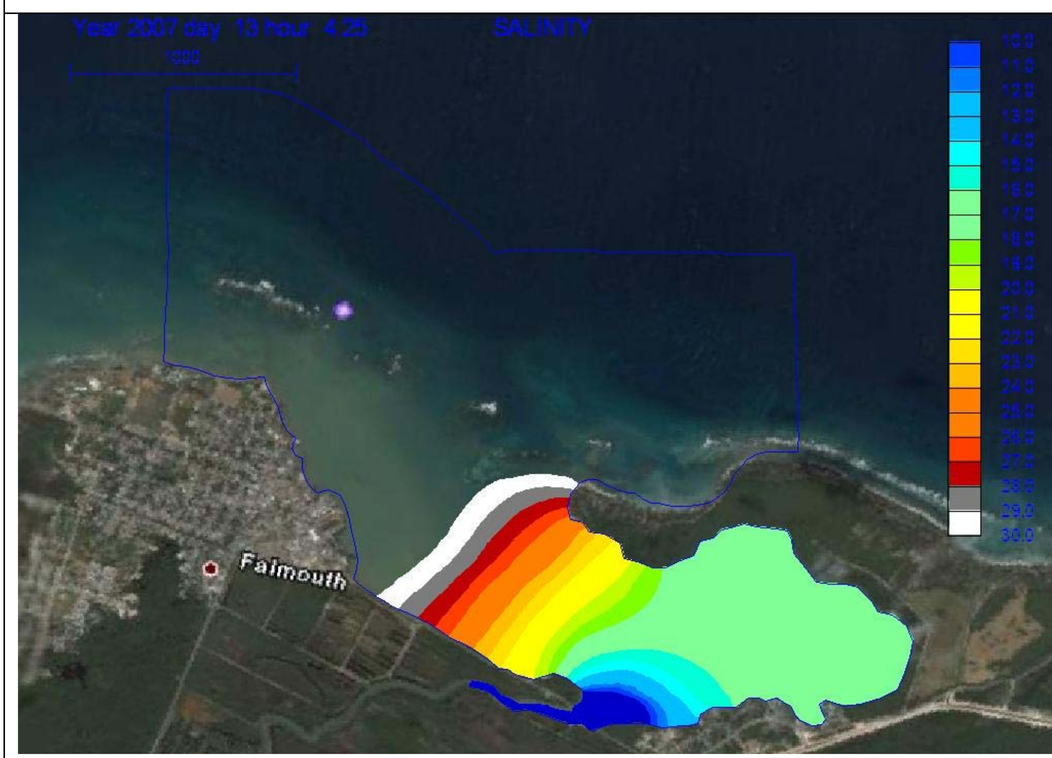


Model – River flow – 20 m^3/s	Simulation time: 24 hours	Figure 3.9

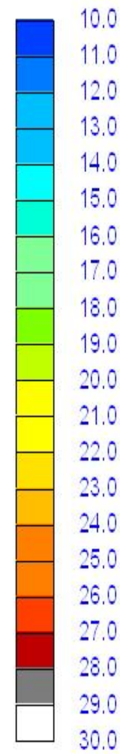
Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Surface Salinity (ppt)



Existing

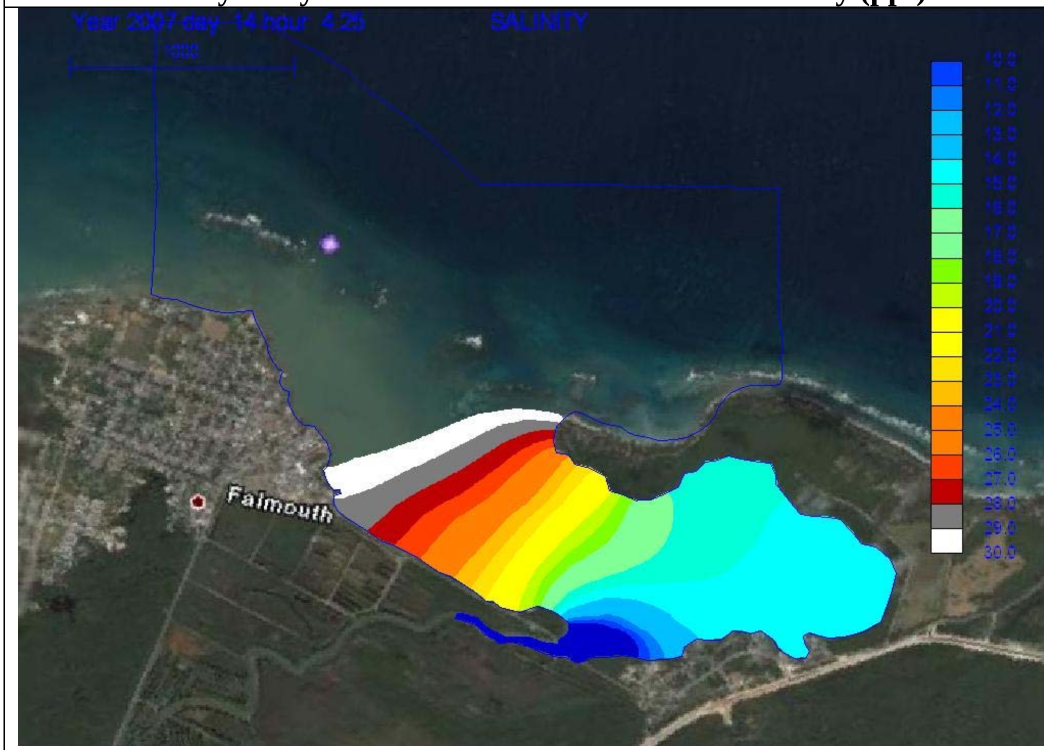


Proposed

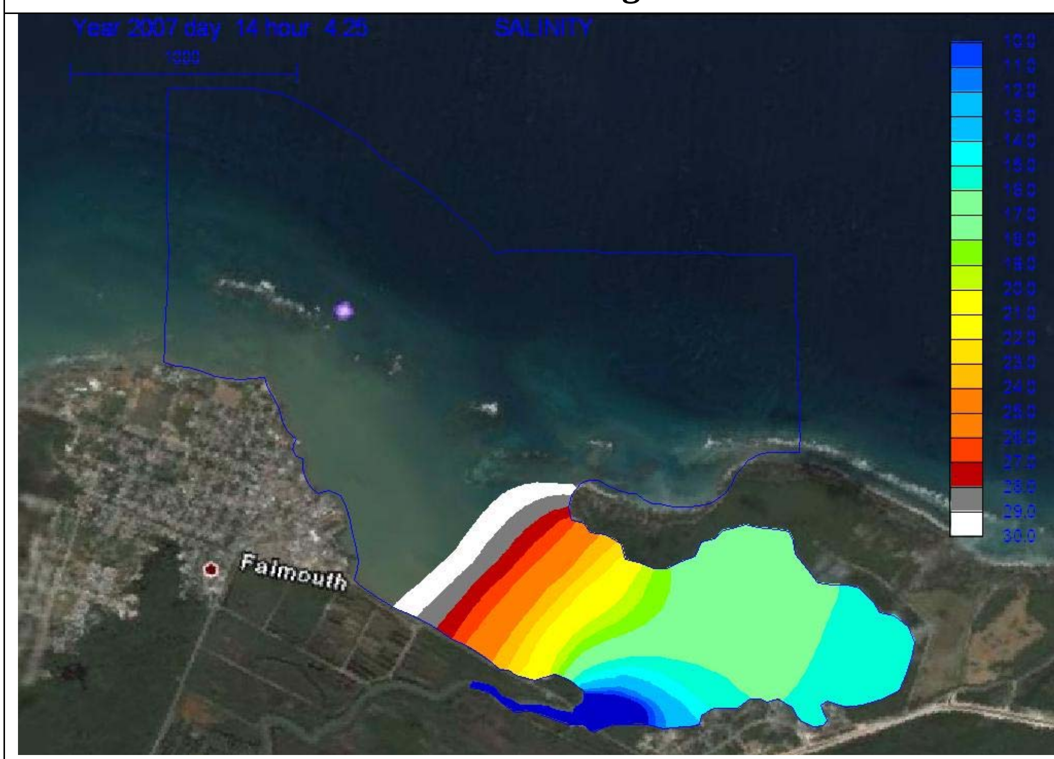


Model – River flow – 20 m^3/s	Simulation time: 48 hours	Figure 3.10

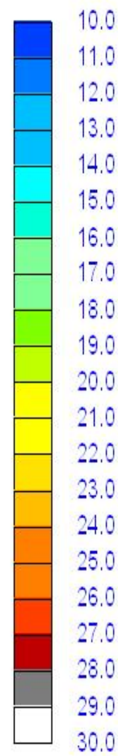
Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Surface Salinity (ppt)



Existing



Proposed



Model – River flow – 20 m^3/s **Simulation time: 72 hours** **Figure 3.11**

In order to properly determine the nature of the changes in the salinity within the estuary, it was necessary to examine the 3D modeling results. Figure 3.12 following shows the locations where detailed comparisons of the existing and proposed configurations were made. Four cross-sections, or "slices", were made through the model to examine the way in which the stratification within the water column may be affected.

These are vertical cross-sections through the water column, and show the mixing and stratification of the fresh water from the Martha Brae River as it flows into the estuary and as the tide brings sea water upstream.

The plots show contour lines of salinity along four section lines A-A to D-D, as indicated in Figure 3.12. Pairs of plots are shown together, each section representing the Existing and Proposed Condition. Each pair represents a different time-step within the simulation. A vertical distortion has been introduced into the plots as the sections are less than 2 metres deep, but several hundred metres in length. This distortion allows the vertical stratification to be more easily observed.

The salinity profiles indicate vertical stratification after the first few hours of the flood condition. The stratification appears to be strongest close to the mouth of the Martha Brae, at Section A-A, and appears to be less noticeable along the northern shoreline at Section D-D.

The comparison of salinity profiles across the estuary indicate the general trend of increasing salinity, or a more rapid return to non-flood conditions following a storm event.

Plots of temperature stratification are also presented. The model does predict some vertical stratification, although it is less noticeable than the salinity stratification. Comparisons of the results using the existing and proposed water depth and shoreline configurations show only very small changes to the temperature profiles.

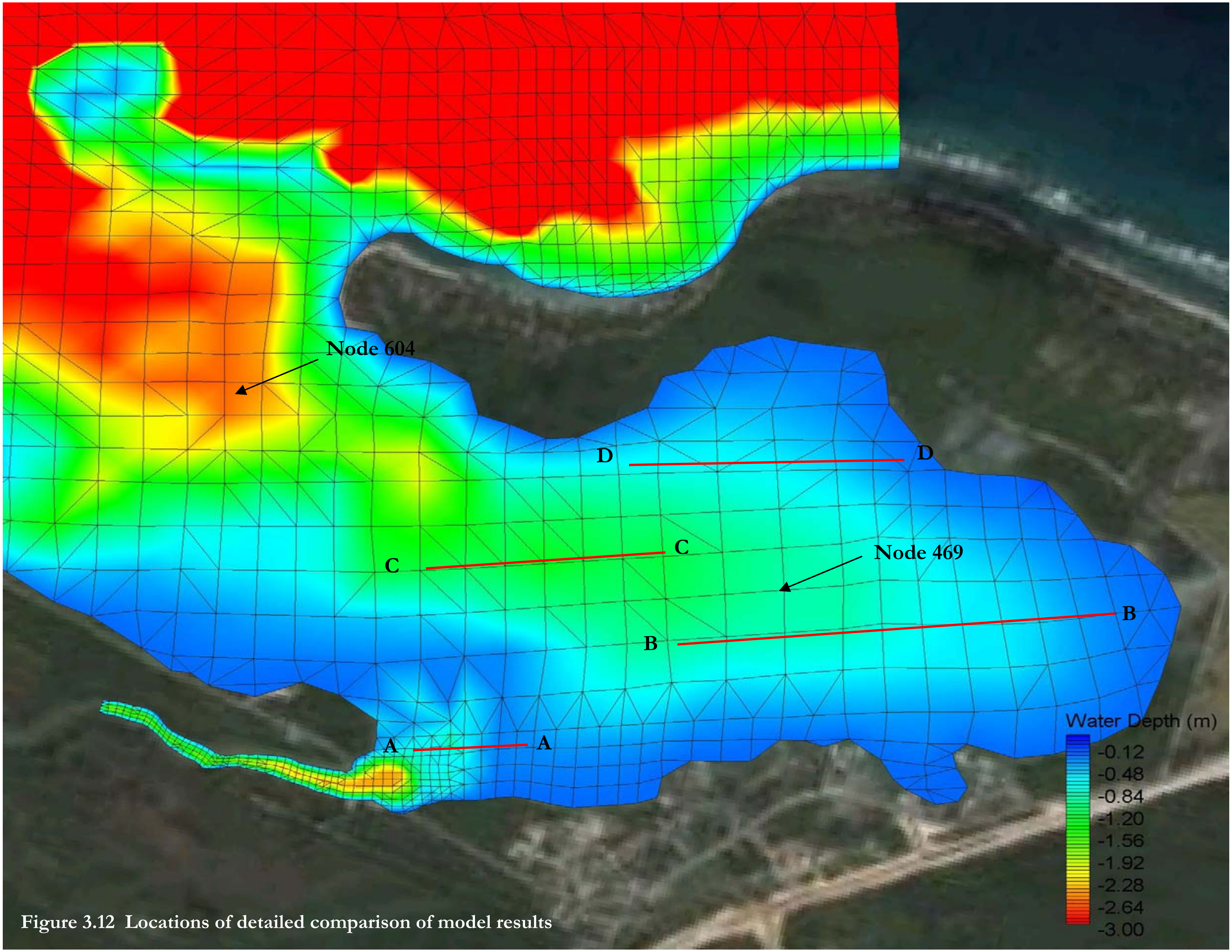
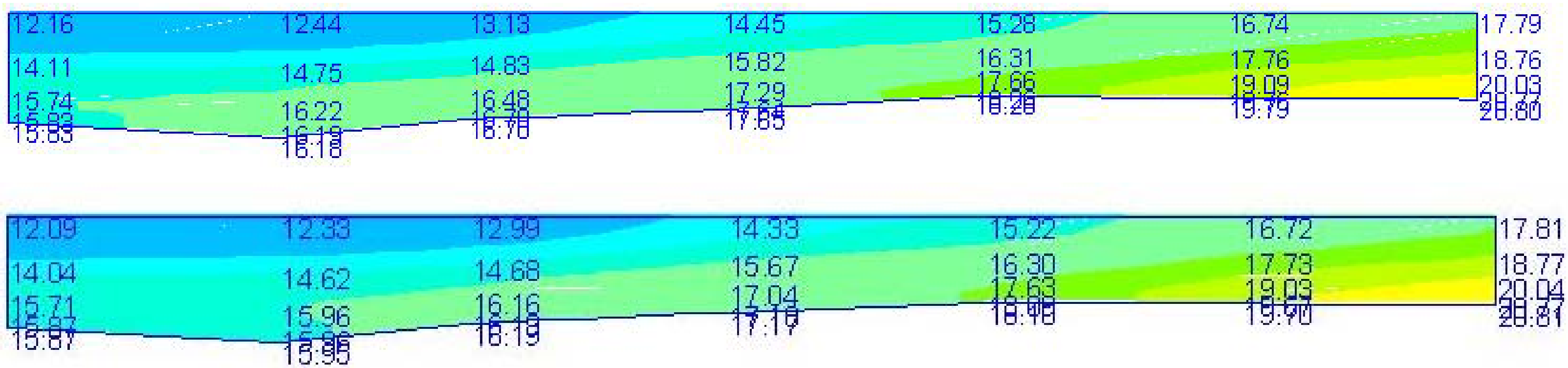
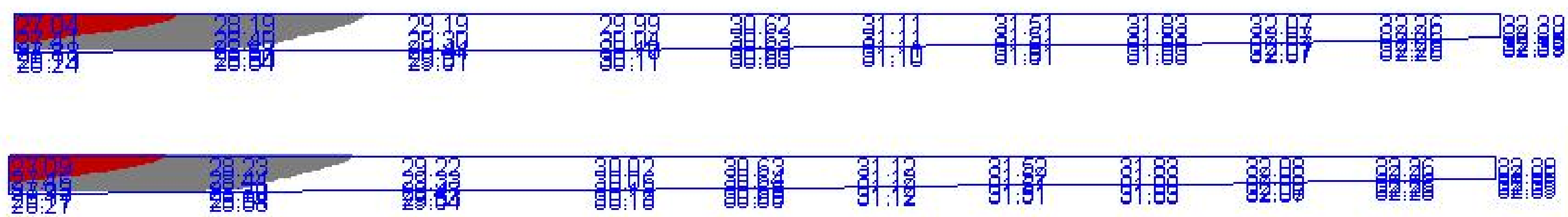


Figure 3.12 Locations of detailed comparison of model results

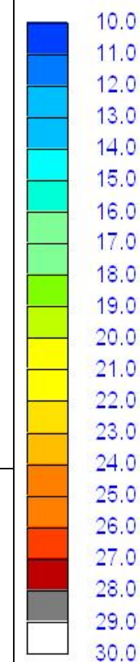
Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Salinity (ppt)



Section A-A



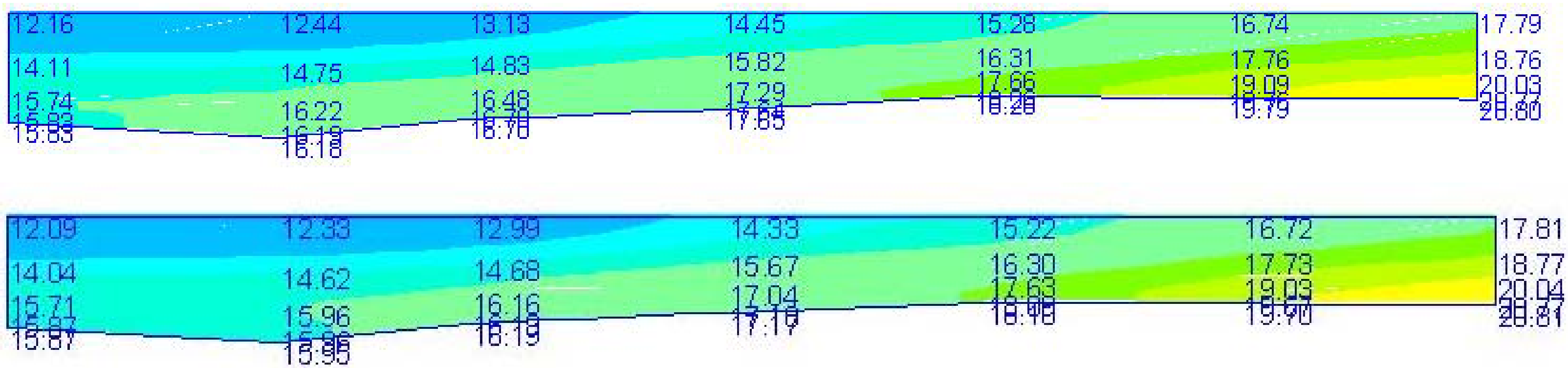
Section B-B



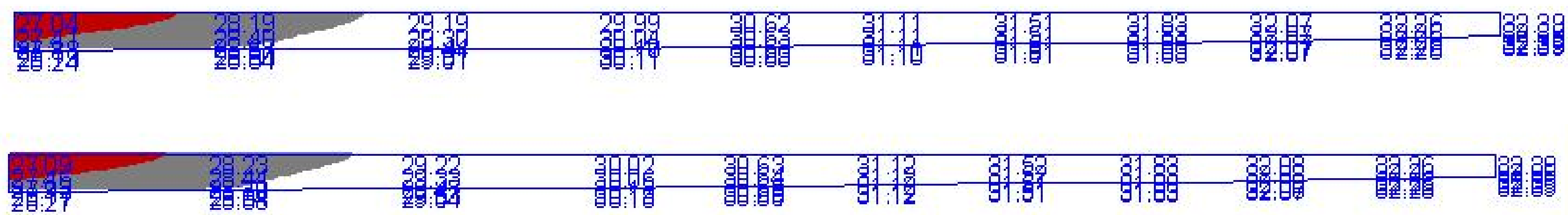
Model – River flow – 20 m^3/s
Simulation time: 6 hours

Figure 3.13

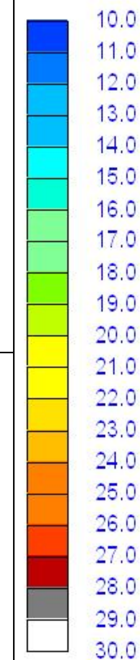
Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Salinity (ppt)



Section A-A



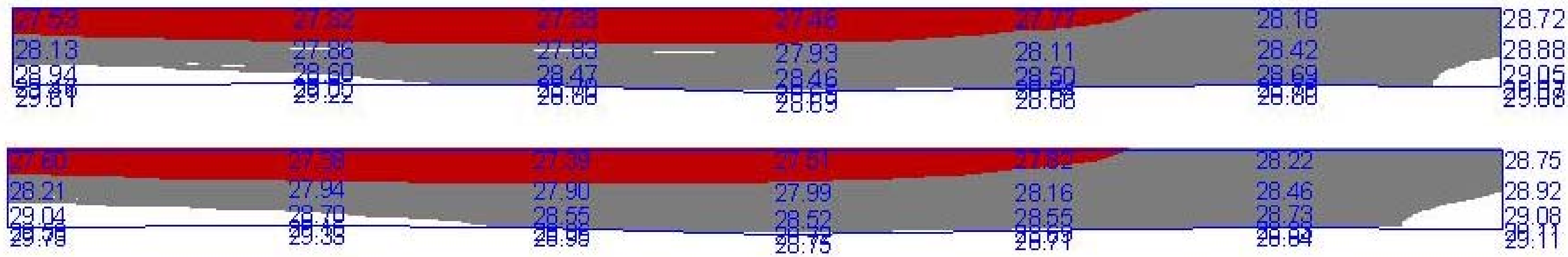
Section B-B



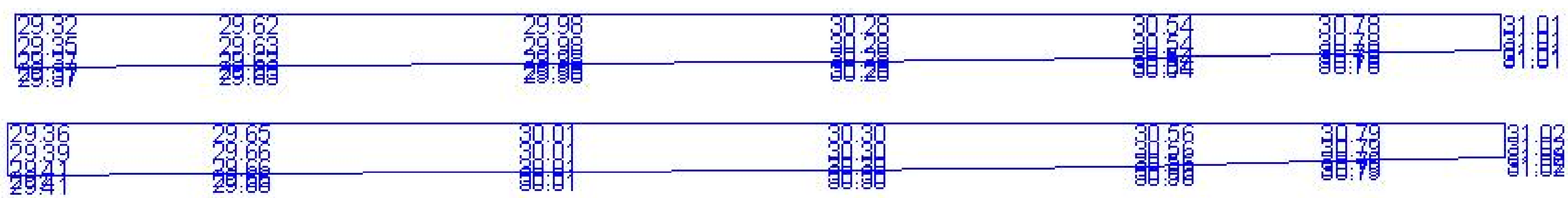
Model – River flow – 20 m^3/s
Simulation time: 6 hours

Figure 3.14

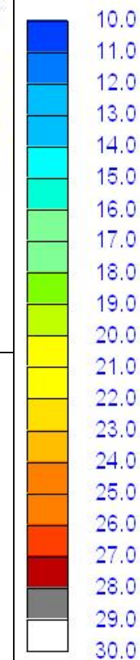
Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Salinity (ppt)



Section C-C



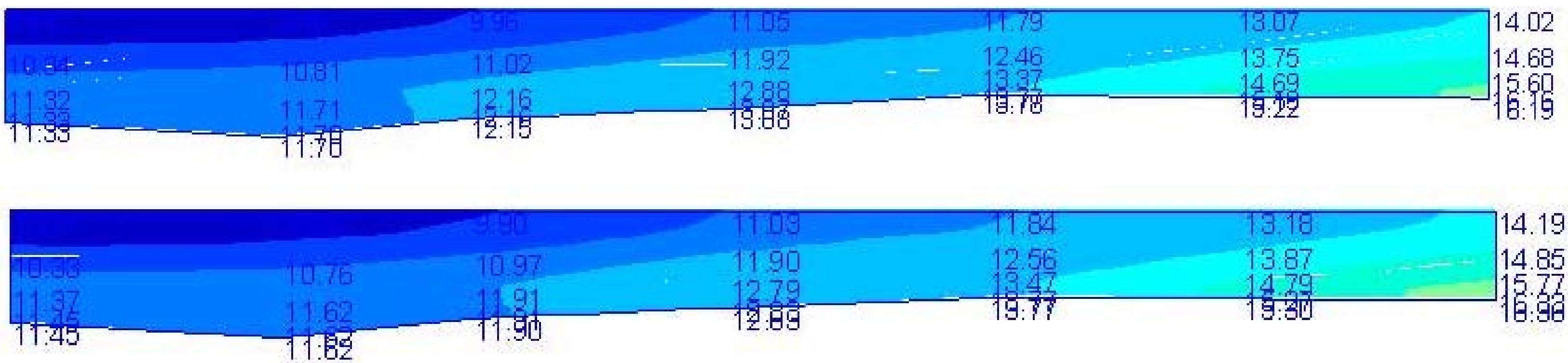
Section D-D



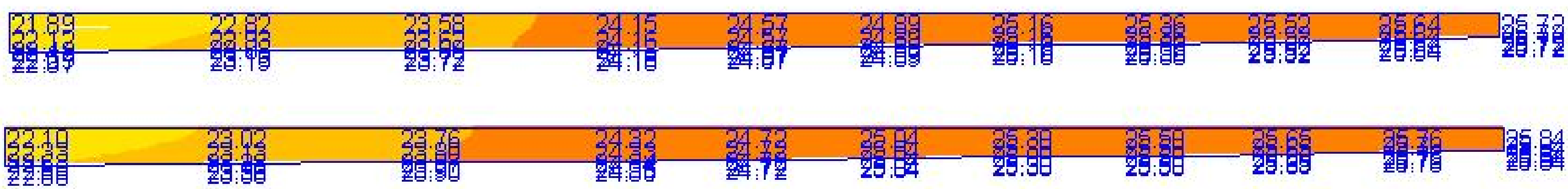
Model – River flow – 20 m^3/s
Simulation time: 6 hours

Figure 3.15

Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Salinity (ppt)



Section A-A

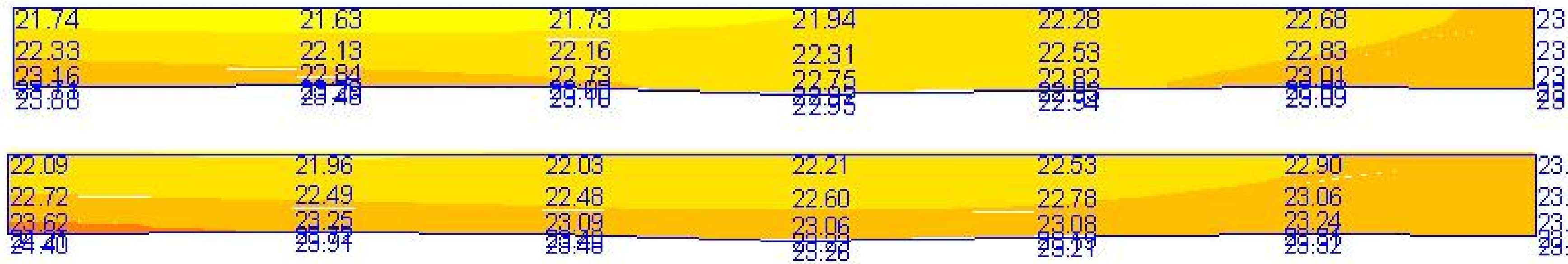


Section B-B

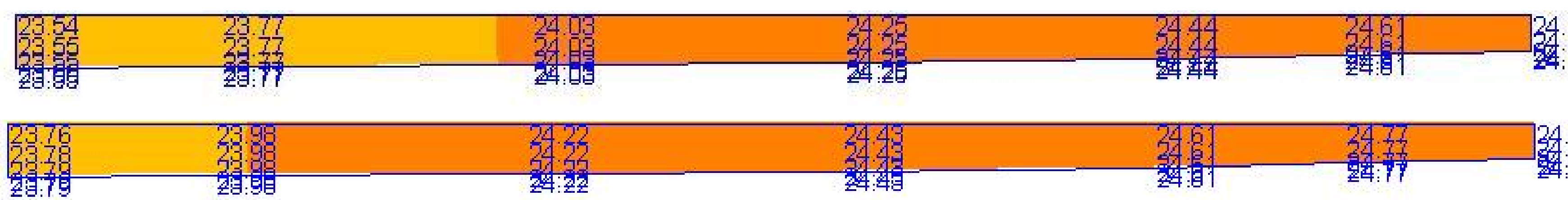
Model – River flow – 20 m^3/s
Simulation time: 12 hours

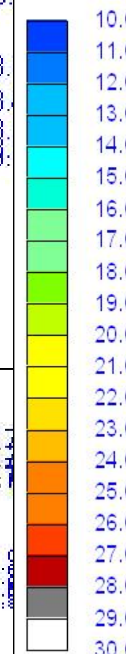
Figure 3.16

Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Salinity (ppt)



Section C-C



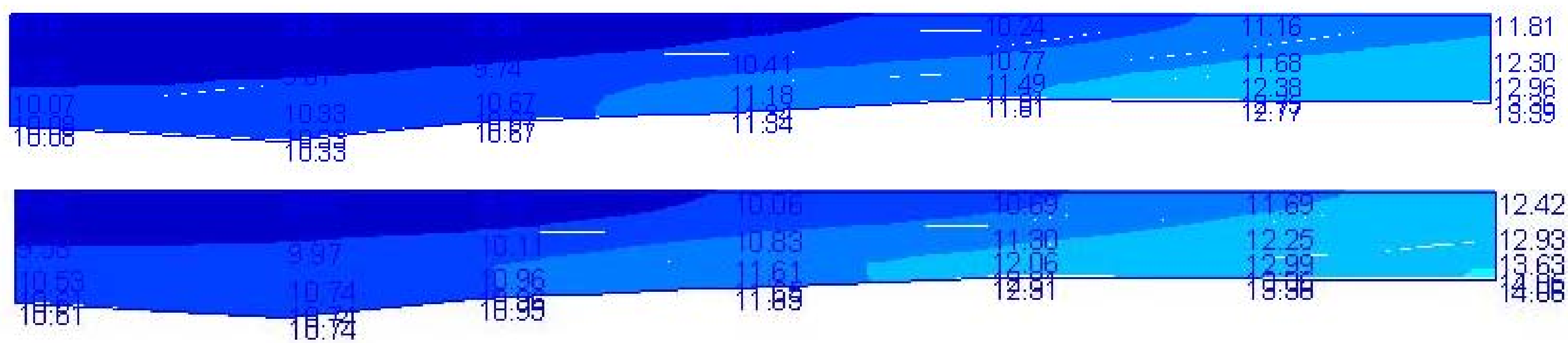


Section D-D

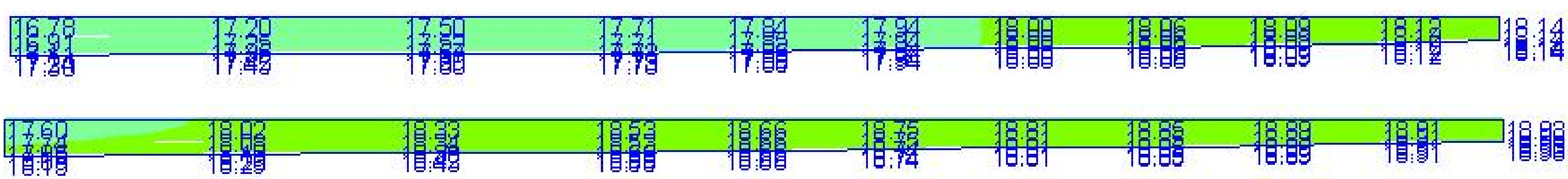
Model – River flow – 20 m^3/s
Simulation time:12 hours

Figure 3.17

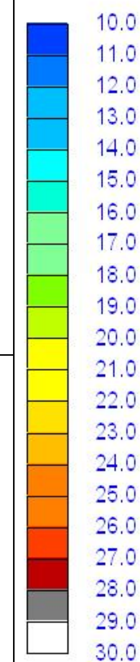
Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Salinity (ppt)



Section A-A



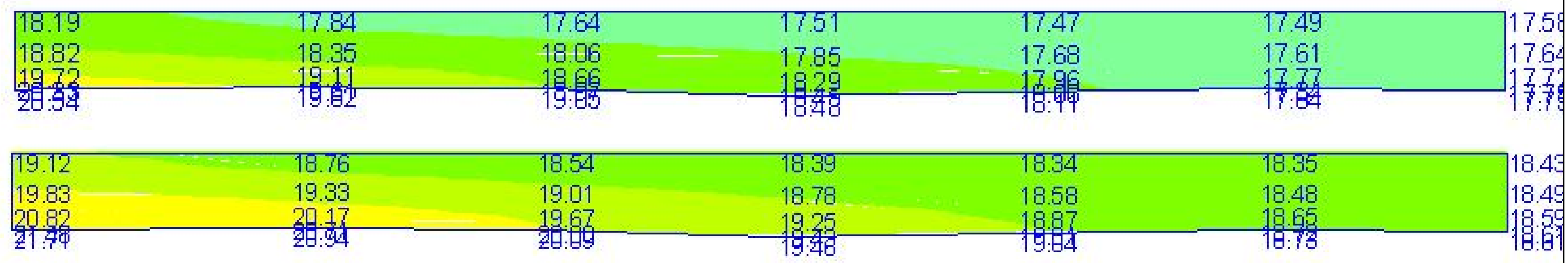
Section B-B



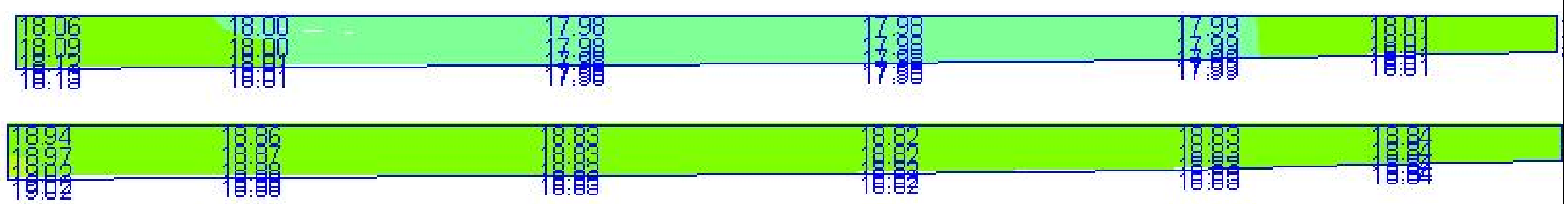
Model – River flow – 20 m^3/s
Simulation time: 24 hours

Figure 3.18

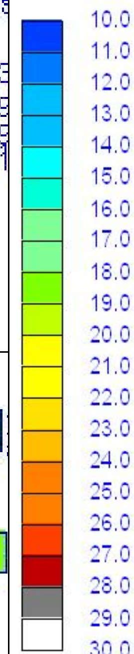
Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Salinity (ppt)



Section C-C



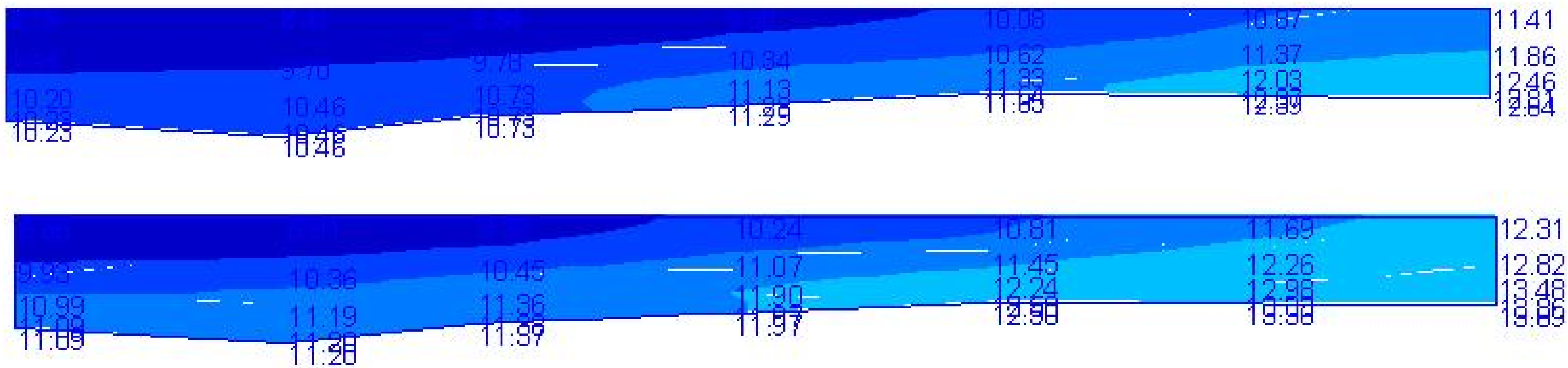
Section D-D



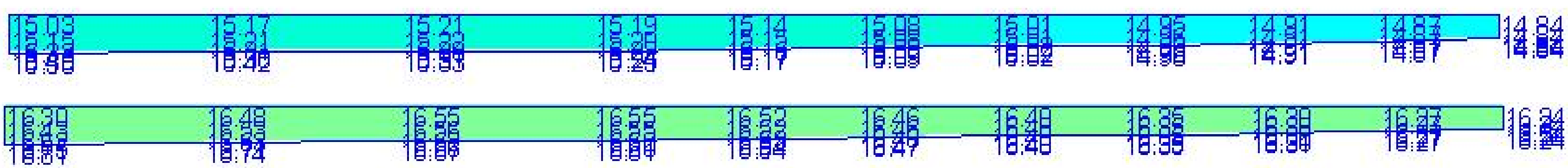
Model – River flow – 20 m^3/s
Simulation time:24 hours

Figure 3.19

Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Salinity (ppt)



Section A-A



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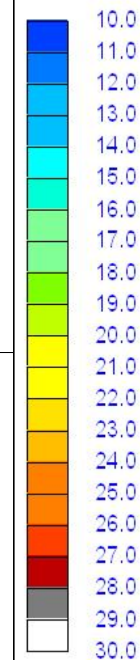
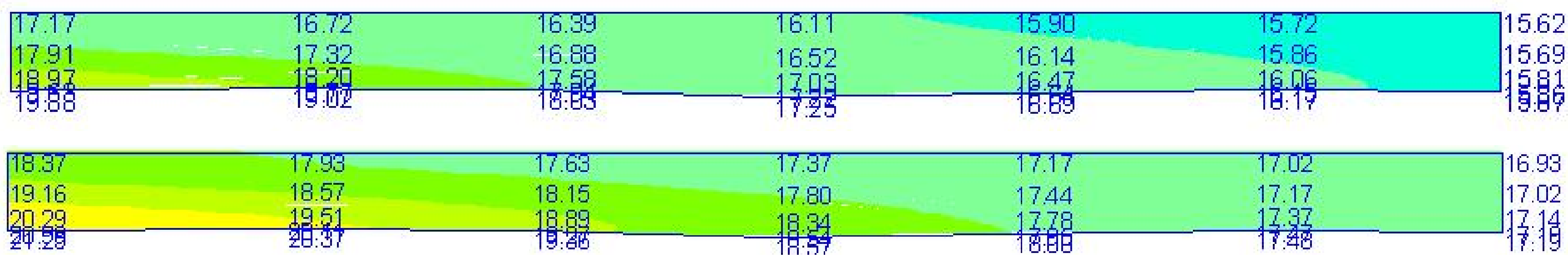


Model – River flow – 20 m^3/s
Simulation time: 48 hours

Figure 3.20

Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Salinity (ppt)



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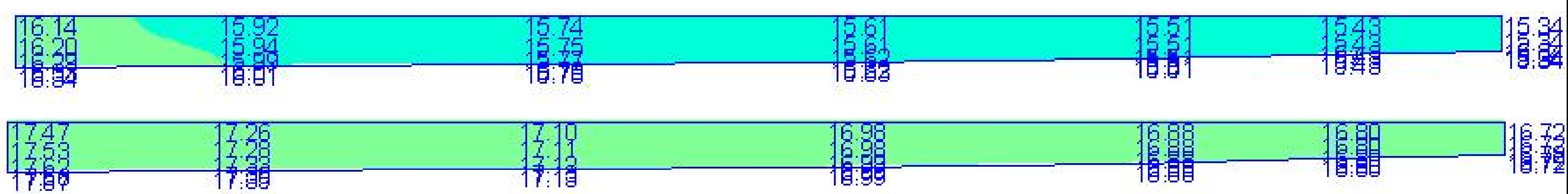
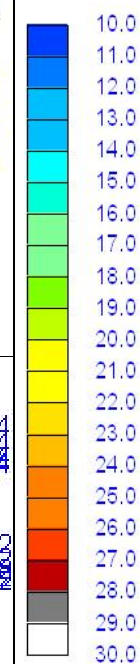


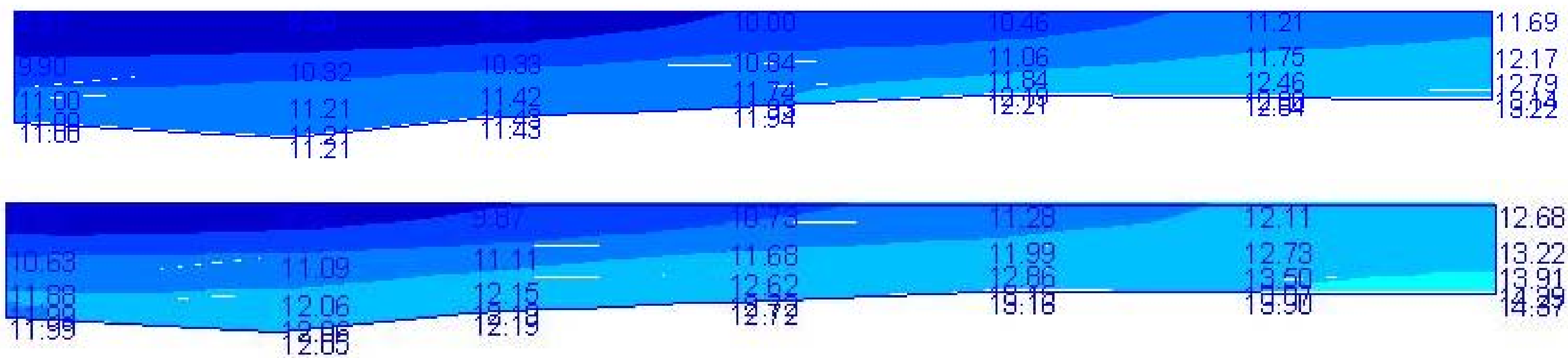
Section D-D



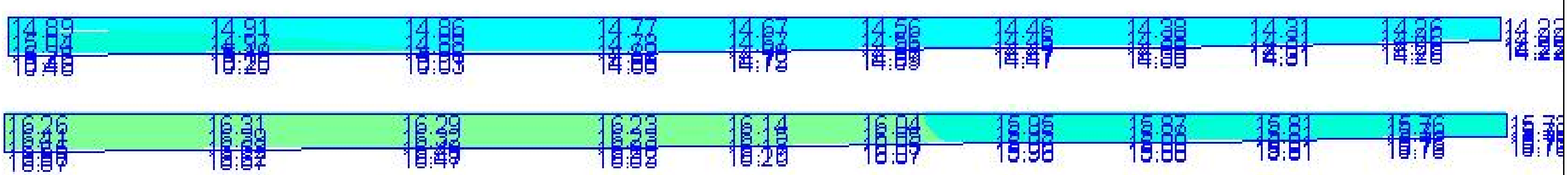
Model – River flow – 20 m^3/s
Simulation time 48hours

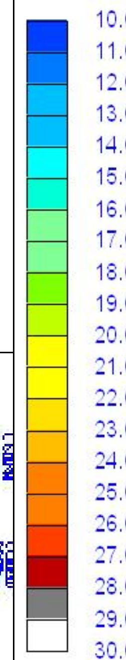
Figure 3.21

Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Salinity (ppt)



Section A-A



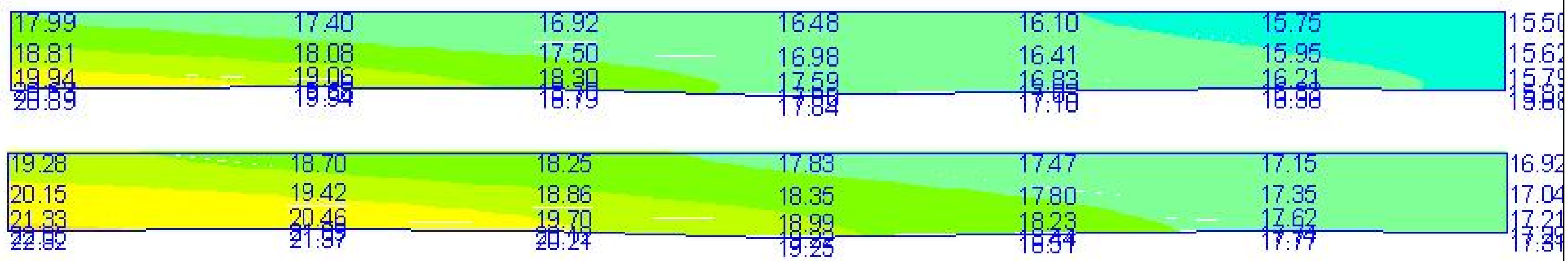


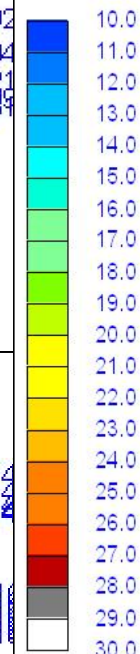
Section B-B

Model – River flow – 20 m^3/s
Simulation time: 72 hours

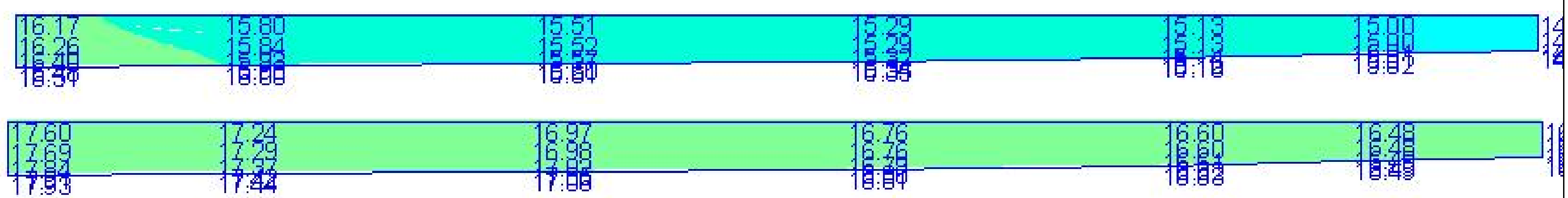
Figure 3.22

Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Salinity (ppt)





Section C-C

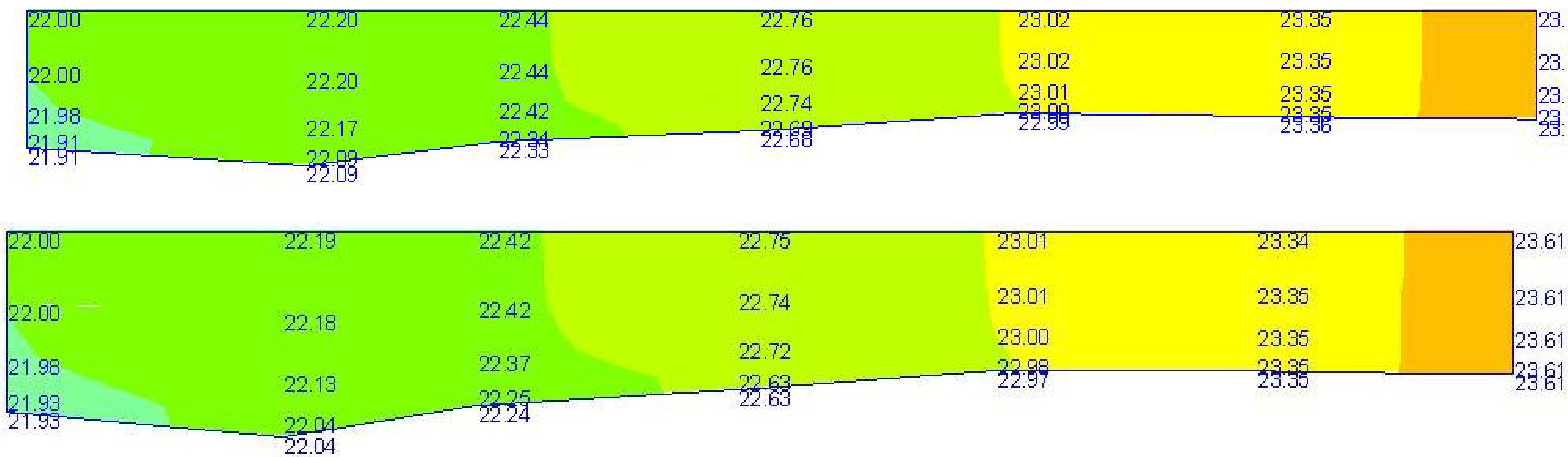


Section D-D

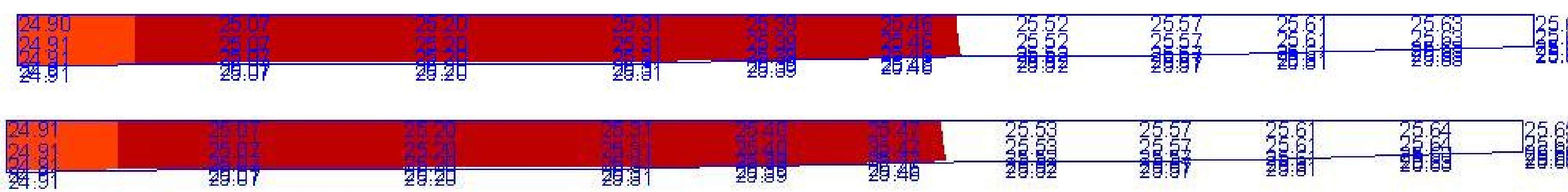
Model – River flow – 20 m^3/s
Simulation time 72 hours

Figure 3.23

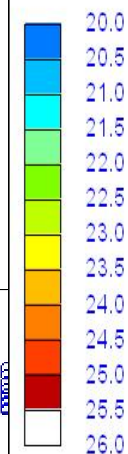
Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results –Temperature (deg. C)



Section A-A



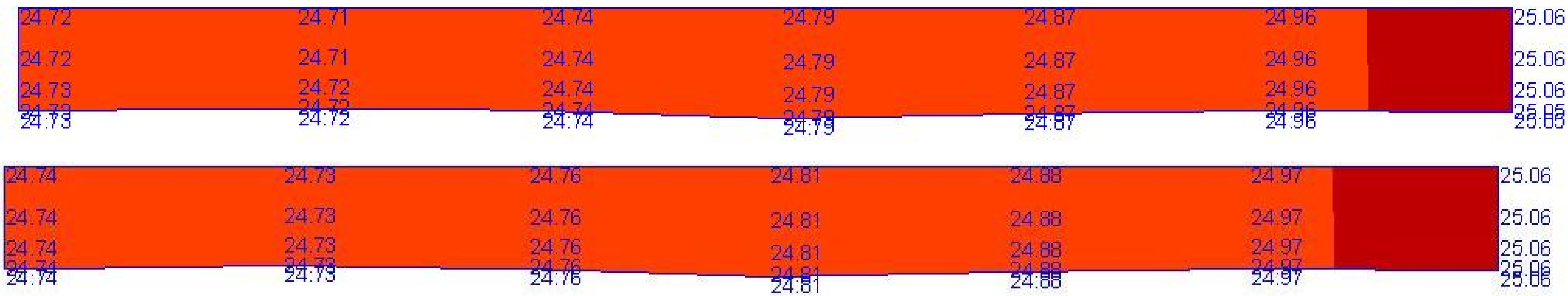
Section B-B



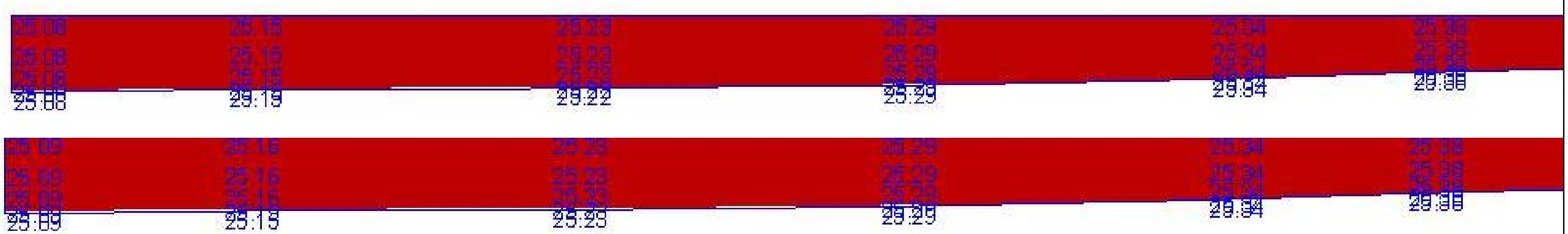
Model – River flow – 20 m^3/s
Simulation time: 6 hours

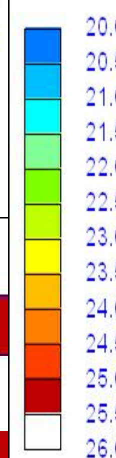
Figure 3.24

Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Temperature (deg. C)



Section C-C



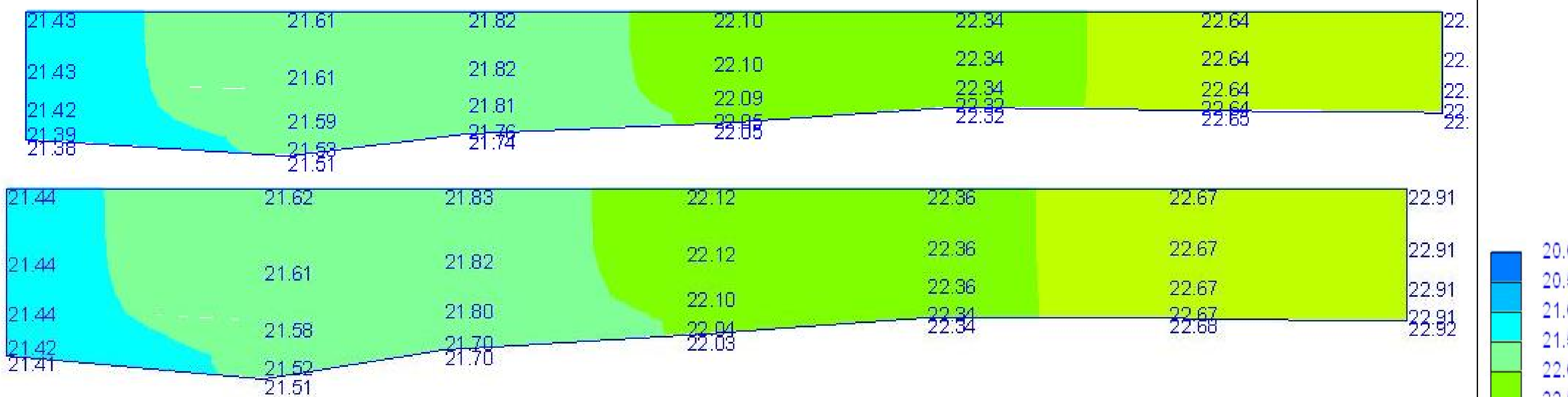


Section D-D

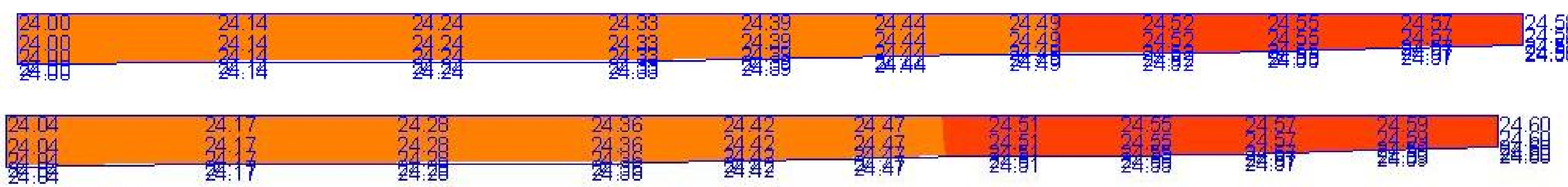
Model – River flow – 20 m^3/s
Simulation time: 6 hours

Figure 3.25

Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Temperature (deg. C)



Section A-A

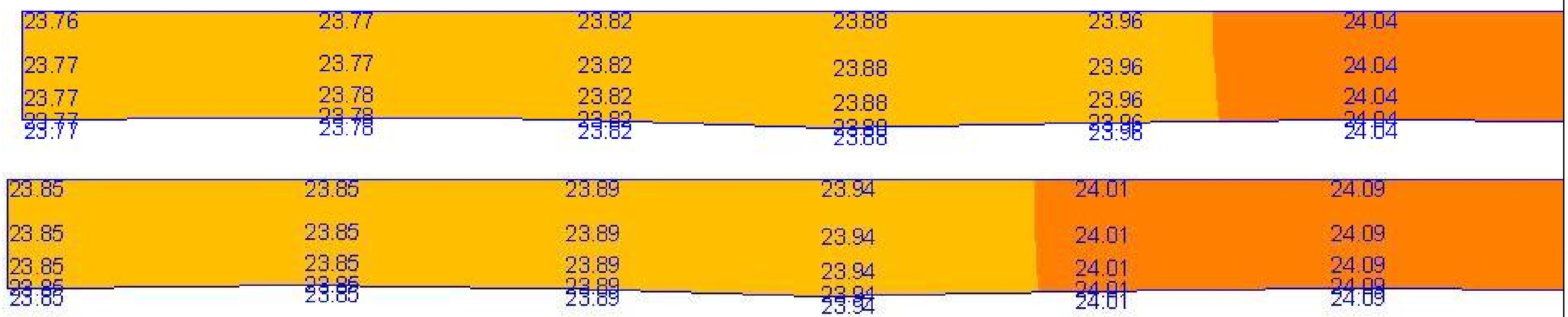


Section B-B

Model – River flow – 20 m^3/s
Simulation time: 12 hours

Figure 3.26

Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Temperature (deg. C)



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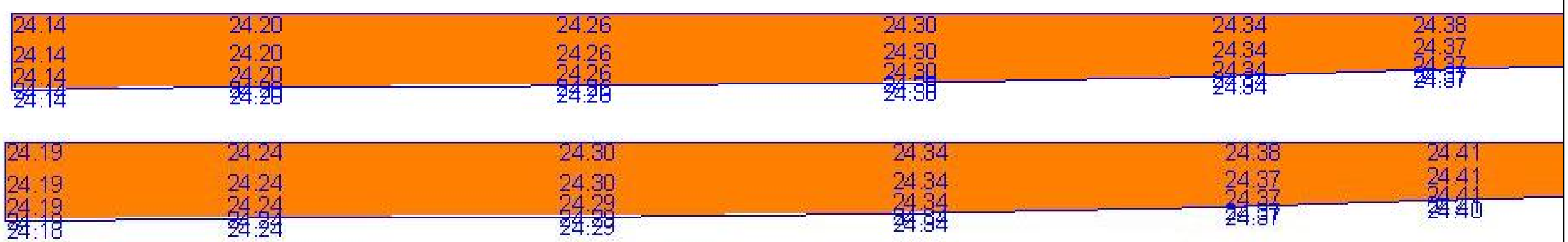
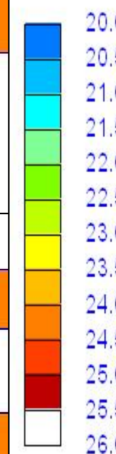


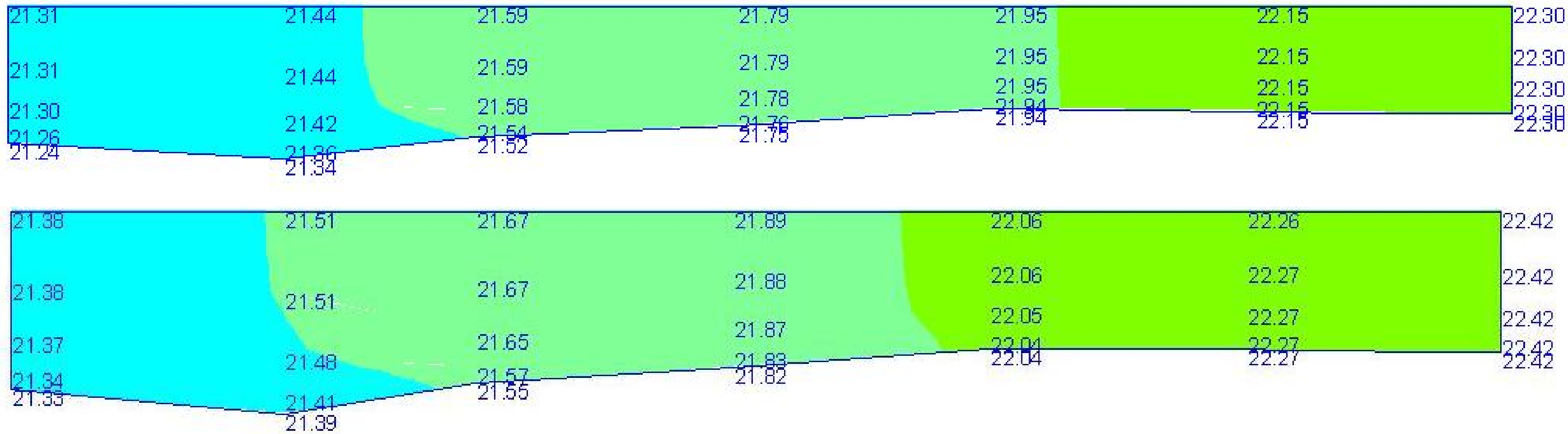


Section D-D

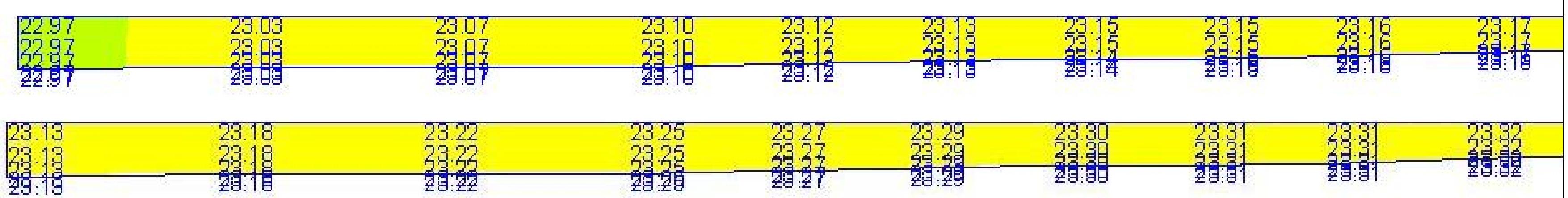
Model – River flow – 20 m^3/s
Simulation time:12 hours

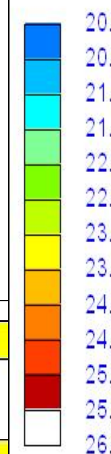
Figure 3.27

Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Temperature (deg. C)



Section A-A



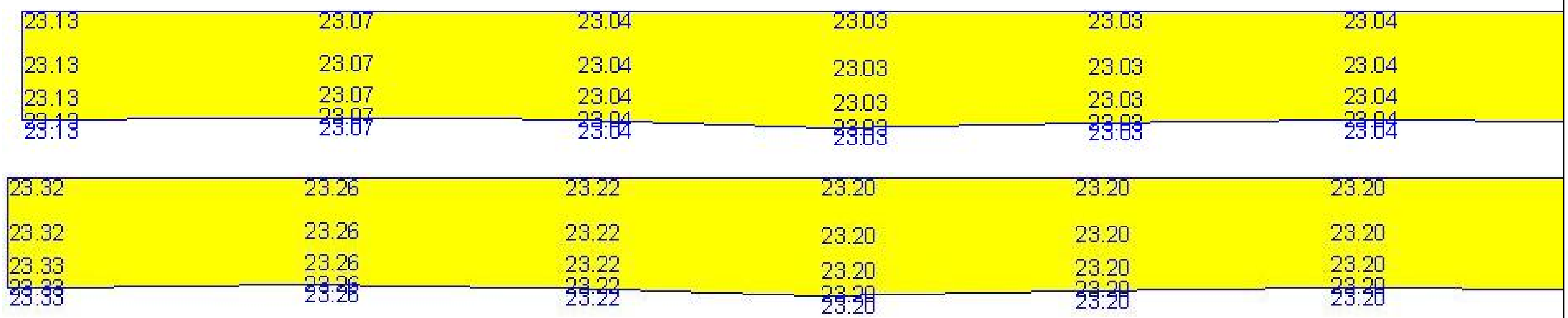


Section B-B

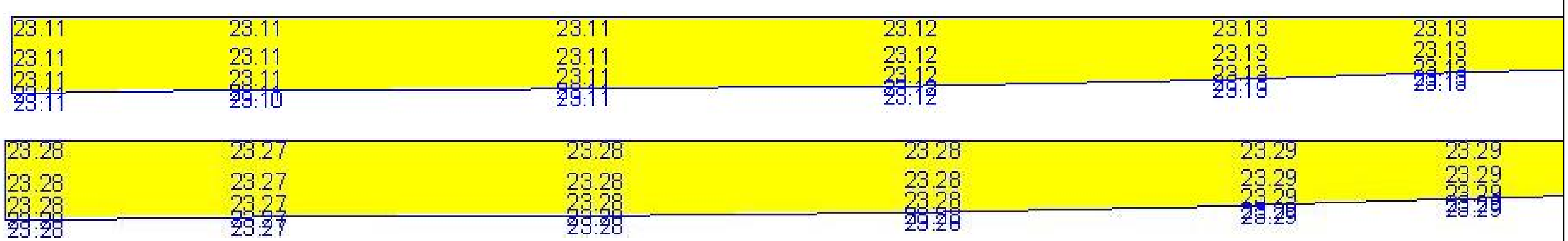
Model – River flow – 20 m^3/s
Simulation time: 24 hours

Figure 3.28

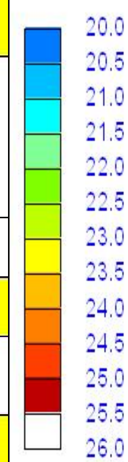
Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Temperature (deg. C)



Section C-C



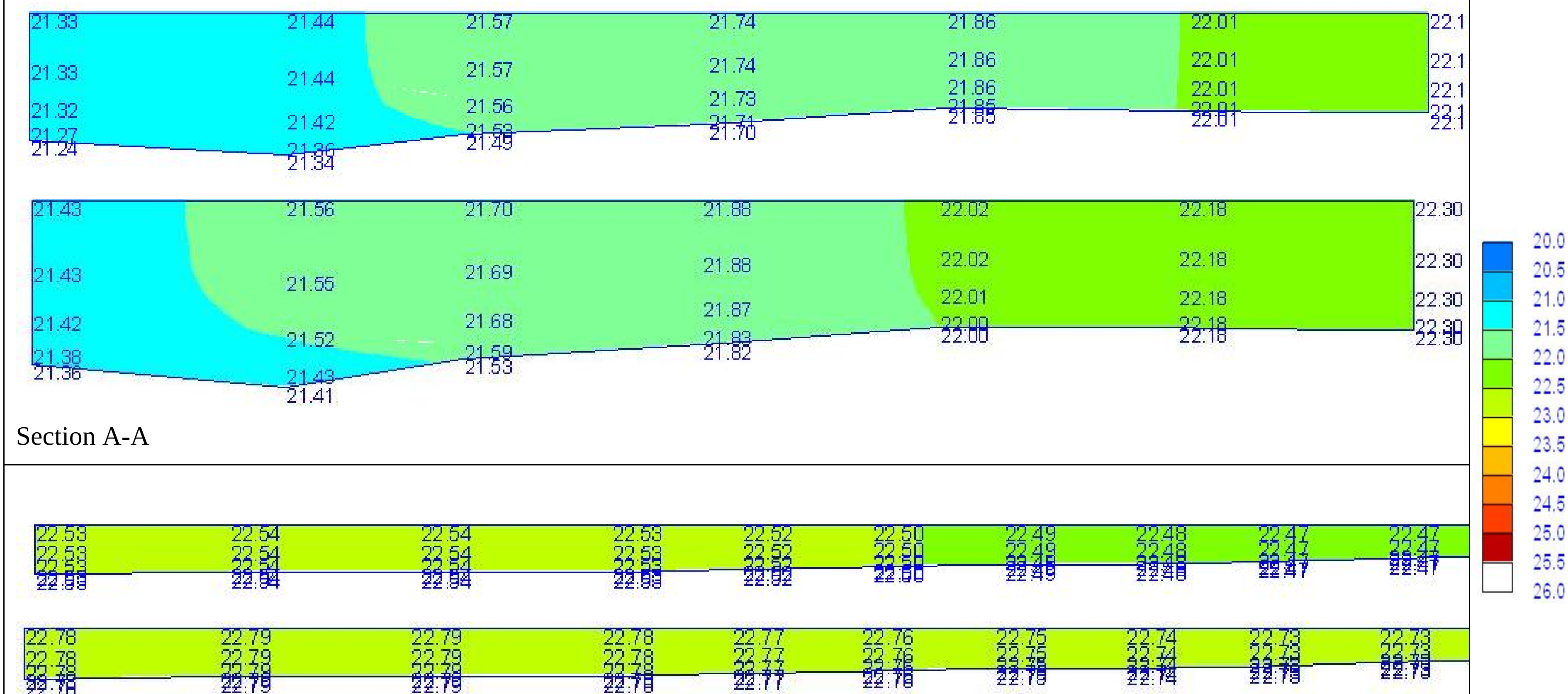
Section D-D



Model – River flow – 20 m^3/s
Simulation time:24 hours

Figure 3.29

Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Temperature (deg. C)



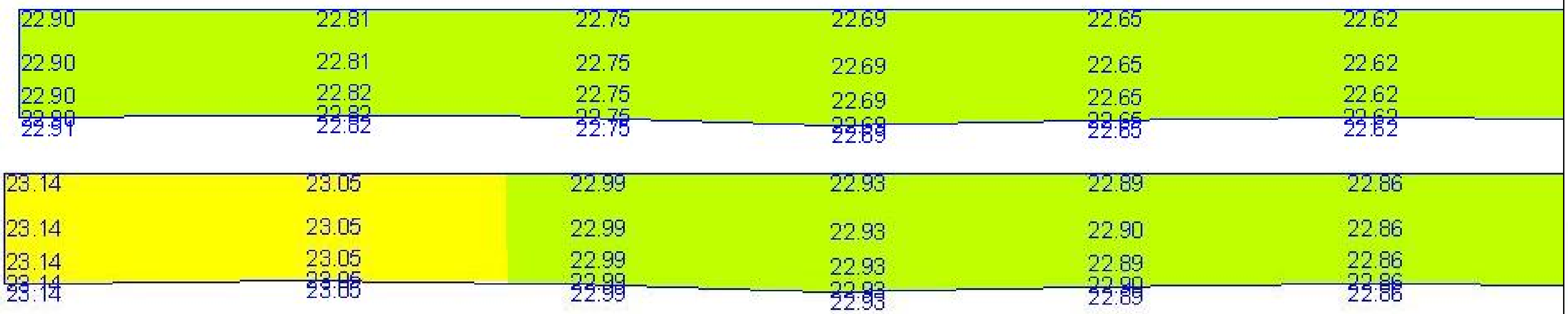
Section A-A

Section B-B

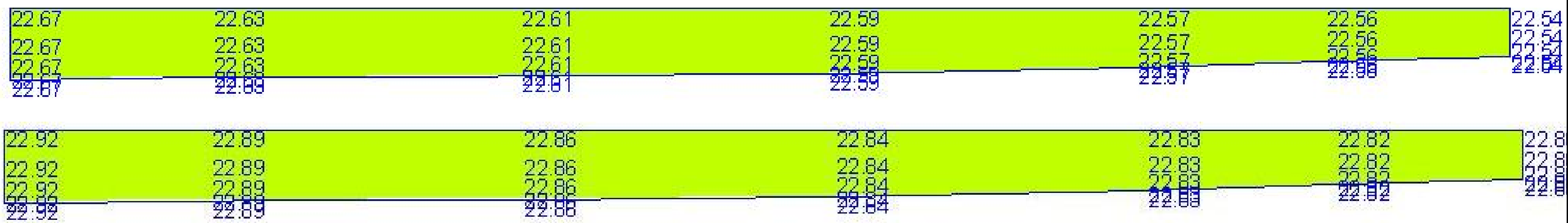
Model – River flow – 20 m^3/s
Simulation time: 48 hours

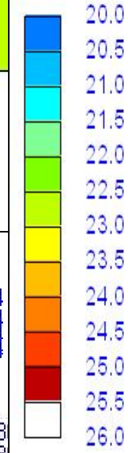
Figure 3.30

Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Temperature (deg. C)



Section C-C



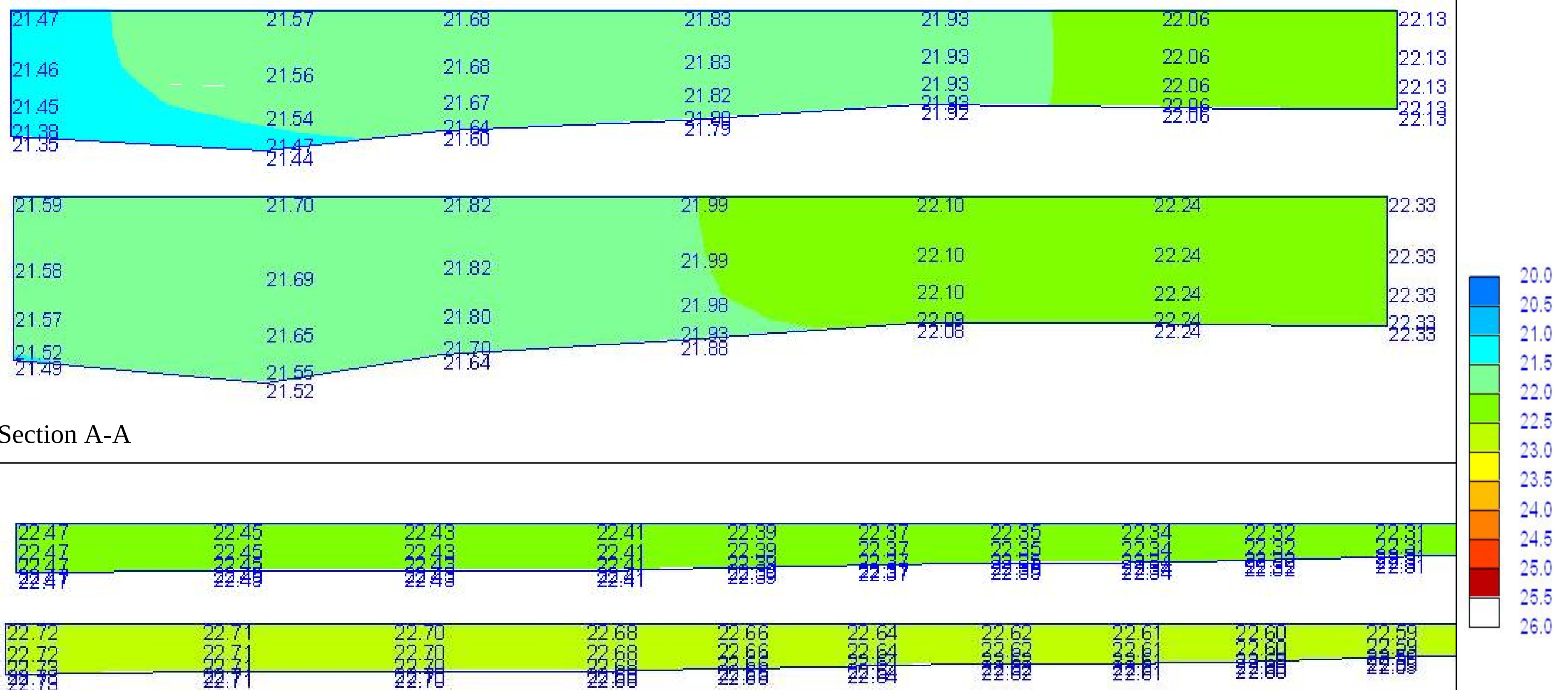


Section D-D

Model – River flow – 20 m^3/s
Simulation time 48hours

Figure 3.31

Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Temperature (deg. C)



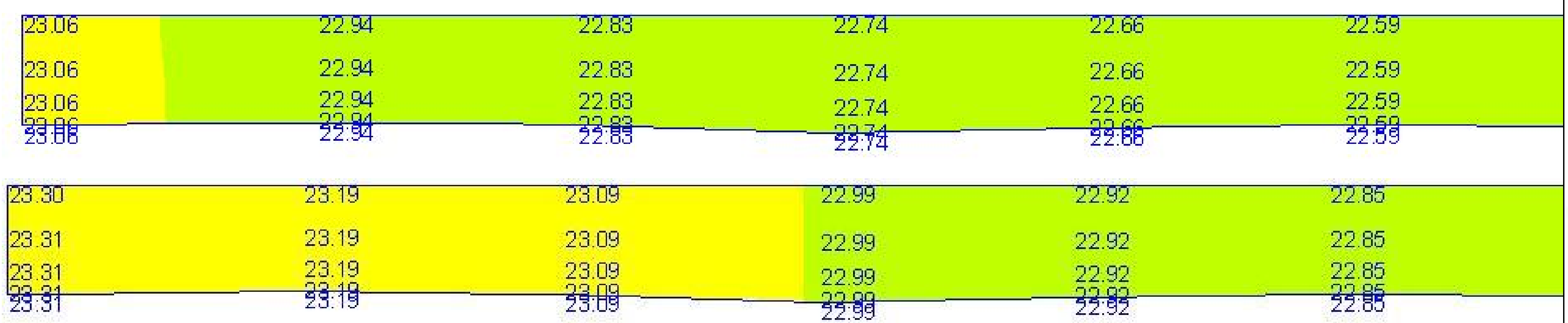
Section A-A

Section B-B

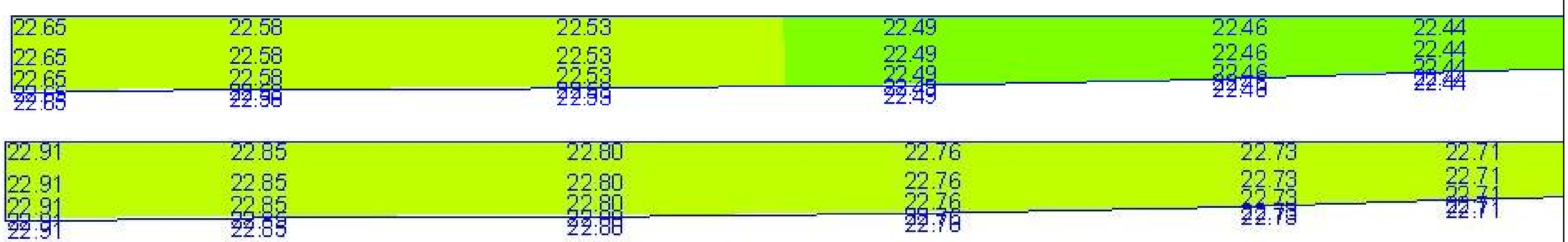
Model – River flow – 20 m^3/s
Simulation time: 72 hours

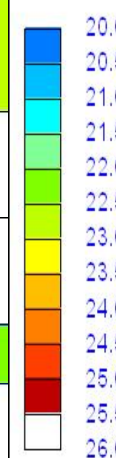
Figure 3.32

Falmouth Cruise Ship Facility
RMA-10 3D Hydrodynamic Model Results – Temperature (deg. C)



Section C-C





Section D-D

Model – River flow – 20 m^3/s
Simulation time 72 hours

Figure 3.33

4 CONCLUSIONS

A 3-D finite element model of the Falmouth area, including the mouth of the Martha Brae River was established. Driving forces included in the model were river flow and an oscillating tidal open sea boundary.

Simulations were run using a river flow rate of 20 m^3/s, which represents an increase above the mean daily flow, but is significantly less than the annual maximum event.

Simulations were run for a period of 72 hours in order to allow for the flushing effects of the tide to be observed.

The calibrations were based on observed stratification within the estuary, following moderate runoff events.

As the primary purpose was to examine the nature of the anticipated impacts of the dredging and land reclamation, detailed comparisons between the model results using the existing and proposed shoreline and seabed configurations were made.

Comparisons of the model results showed minor changes to the current patterns within the estuary. These changes are typical of those that occur when dredging or small land reclamation is undertaken. Changes are noticeable where depths have been altered, however, further away from the points where dredging or land reclamation has been done, the changes to the current patterns become negligible.

Changes to the surface salinity were predicted to occur. The 3D model predicts that the surface salinity within the estuary is reduced less for the proposed configuration than the existing case. The model predicts that the dredging and land reclamation will increase surface salinity.

Cross-sections through the model were plotted in order to assess changes to the vertical stratification. The changes that were predicted by the model resulted in the fresh water flowing from the Martha Brae River having a smaller influence on the salinity within the estuary. In all cases, the model appears to predict that additional saline water will enter the estuary and reduce the impact of the Martha Brae River, which tends to temporarily decrease the salinity.

Changes to the temperature stratification were predicted to be quite small.

Based on the results of the 3D hydrodynamic model, which predict a smaller fresh water plume from the Martha Brae River following the dredging AND the behaviour of the dinoflagellates, which were observed to descend into the saline waters following a flood event, the long-term impact of the land reclamation and dredging does not appear to be detrimental to the dinoflagellates. Therefore further investigations and measurements do not appear to be warranted.

It must be noted that impacts DURING the dredging and land reclamation have not been predicted by this 3D model and measures to mitigate against those potential impacts must be implemented.