Predicting the Surface Currents of Guanabara Bay

Dr Andrew McCowan[1], Elise Lawry[2], Ryan Dermek[3]

[1]Managing Director, Water Technology Pty Ltd, Melbourne, Australia
E-mail: Andrew.McCowan@watertech.com.au

[2]Senior Engineer, Water Technology Pty Ltd, Melbourne, Australia

[3]Engineer, Water Technology Pty Ltd, Brisbane, Australia

The sailing competitions for the 2016 Rio de Janeiro Olympic Games were held in Guanabara Bay to the east of the city, and in the coastal waters outside the entrance to the Bay. This paper provides insight into the challenges involved in providing forecast surface current vectors to assist the Australian Sailing Team in both the Olympic Games and the Paralympic Games.

Guanabara Bay has an area of over 400 km^2 and is connected to the South Atlantic Ocean by a narrow, 1.5km wide, entrance. The entrance is constrained by two major headlands; Punta de Santa Cruz to the east and Punta de Santa Joao to the west, and by a small island, Ilha da Laje, in the western part of the entrance. The entrance channels have depths varying between 10m and more than 50m. Although the ocean tidal range at the mouth of the Bay is only around 1.0m, the narrow entrance results in currents of over 1m/s during spring tides. Significant eddies are shed off the headlands and the island. The timing and strength of these eddies varies from tide to tide, and with any variations in mean sea level due to the impacts of larger scale oceanic circulations at the coast. Additionally, heavy rainfall during the wet season can result in high freshwater catchment runoff across the Bay resulting in surface currents running out across the flood tides at the entrance.

The paper will describe the work done to develop the detailed fully three-dimensional numerical model that was used to provide reliable forecasts of the surface currents during the Games. This work included initial model development and subsequent calibration and refinement using additional data and feedback from the sailing coaches obtained during the regattas leading up to the Games.

1. INTRODUCTION

Water Technology was engaged by Australian Sailing (AS) to establish a hydrodynamic model of Guanabara Bay, Rio de Janeiro, Brazil. This model provided information on current speeds, directions and general hydrodynamic conditions within the Race Areas during the 2016 Brazilian Olympics.

Generation of the model was a staged process, where a preliminary model was established based on available data. This was then refined with additional water level, current speed and bathymetry data recorded with the use of water level loggers, GPS drogues and Acoustic Doppler Current Profiler (ADCP). From this, key model sensitivities were established and incorporated into the model.

This report gives details of the preliminary modelling, and the monitoring and changes made to the modelling to provide calibrated model results at the racing sites to AS.

1.1. Rio de Janeiro

The city of Rio de Janeiro is located on the western side of Guanabara Bay, a large bay with a surface area of over 350km^2. The city of Rio de Janeiro is home to over 6 million people, with more than 11 million living in the catchment of Guanabara Bay.

The race locations are shown in Figure 1-1 below. These have areas that vary in size from 1.5km^2 to over 4.5km^2. Race conditions vary significantly for one race area to another, and also across each individual race area.

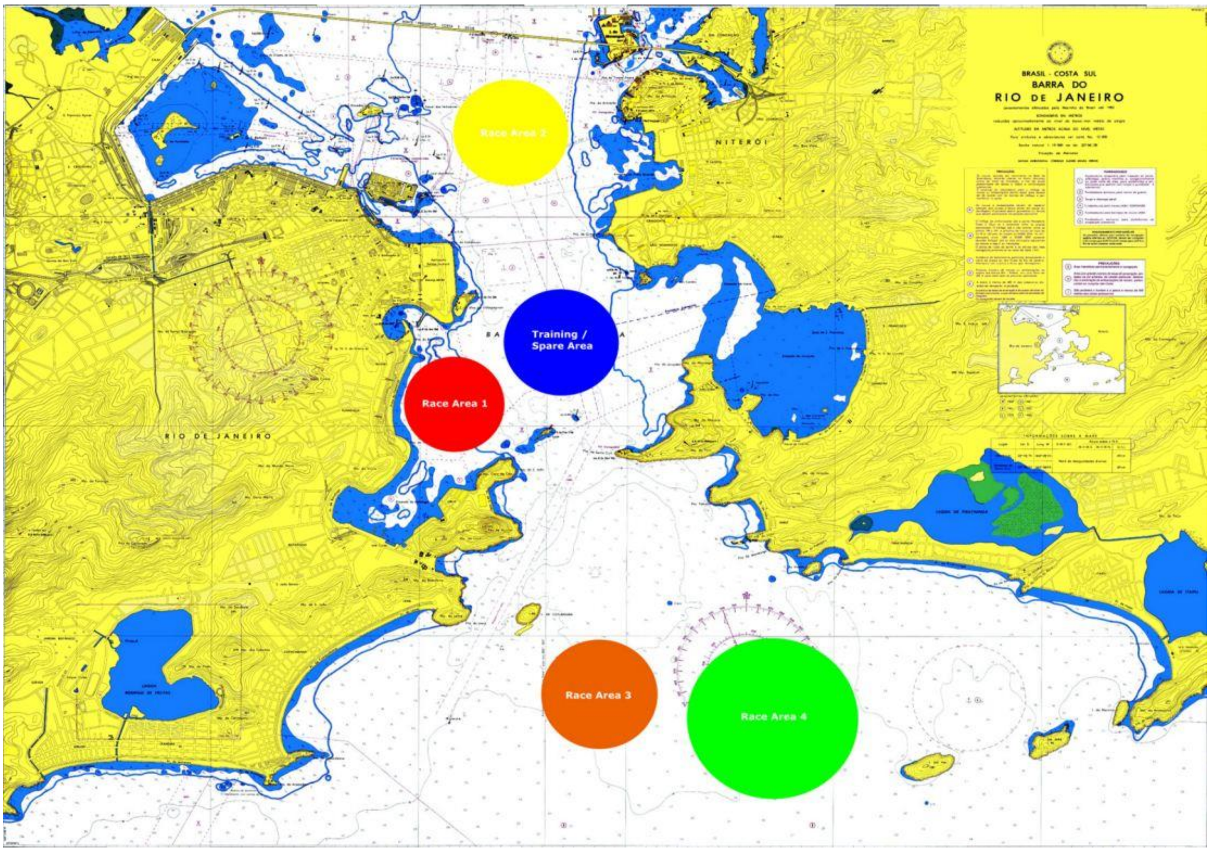

Figure 1-1 Race Locations

1.2. Guanabara Bay

Guanabara Bay (the Bay) has an overall length of around 30 km and a width that varies from around 10 to 15 km (see Figure 2-1). The Bay has a surface area of over 380km^2, a perimeter length of over 130km and a volume at mean sea level of 1.87 x 10^9 m^3 (just under 2 cubic km)(Kjerfve, 1996). It is connected to the sea by a relatively wide deep channel. On average, half of the volume of the Bay is tidally flushed around every 12 days, although at the upper end of the Bay flushing is much slower (Kjerfve, 1996).

The bathymetry of the Bay consists of a large flat, shallow section in the north with a long, wide channel in the south. The channel is typically 1 to 2 km wide and has depths generally in excess 20m, and up to almost 60m at the deepest point.

1.3. Model Development

Model development underwent a number of key stages. Initially, a preliminary model was established based on available data. This was calibrated to predicted tidal conditions in Guanabara Bay. Measured water levels were also collected within Guanabara bay, and model refinements were then aimed at calibration to these measured water levels. However, the nature of competitive sailing required the model to focus on predicting surface currents rather than water levels. Once an appropriate model calibration was achieved on measured water levels, calibration then aimed at reproducing the eddying currents within the race areas. Currents within Guanabara Bay are heavily influenced by factors other than astronomical tides, so the modelling tested a number of sensitivities aiming to reproduce observed currents. A number of GPS drogues, along with Acoustic Doppler Current Profiler (ADCP) measurements were employed to obtain appropriate current velocity and direction within Guanabara Bay for validation of model outputs. Continuous feedback was provided by AS on the model results, allowing for numerous refinements and high accuracy results.

2. PRELIMINARY MODEL SETUP

2.1. Modelling System

The Danish Hydraulic Institute's (DHI) "Mike" Modelling system has been used to establish the preliminary model (the model). Further information regarding DHI models can be found at http://www.dhisoftware.com/Download/MIKEByDHI2012.aspx.

The Mike 21/3 Coupled HD and SW model has been used to simulate the conditions within Guanabara Bay. The modelling details are provided below.

2.2. Model Bathymetry

Initially, bathymetry data was sourced from Jeppsen Marines CMAP database. The CMAP database is a worldwide vector chart database based on official navigation charts. The navigational chart 566: Baia de Guanabara, produced by the United Kingdom Hydrographical Office (using Brazilian Navy data) provides a hard copy of much of the data through the main racing area.

A digital elevation map (DEM) using the CMAP data and is shown below in Figure 2-1. Depths are below Chart Datum (CD) which is approximately the level of Mean Low Water Springs (MLWS).

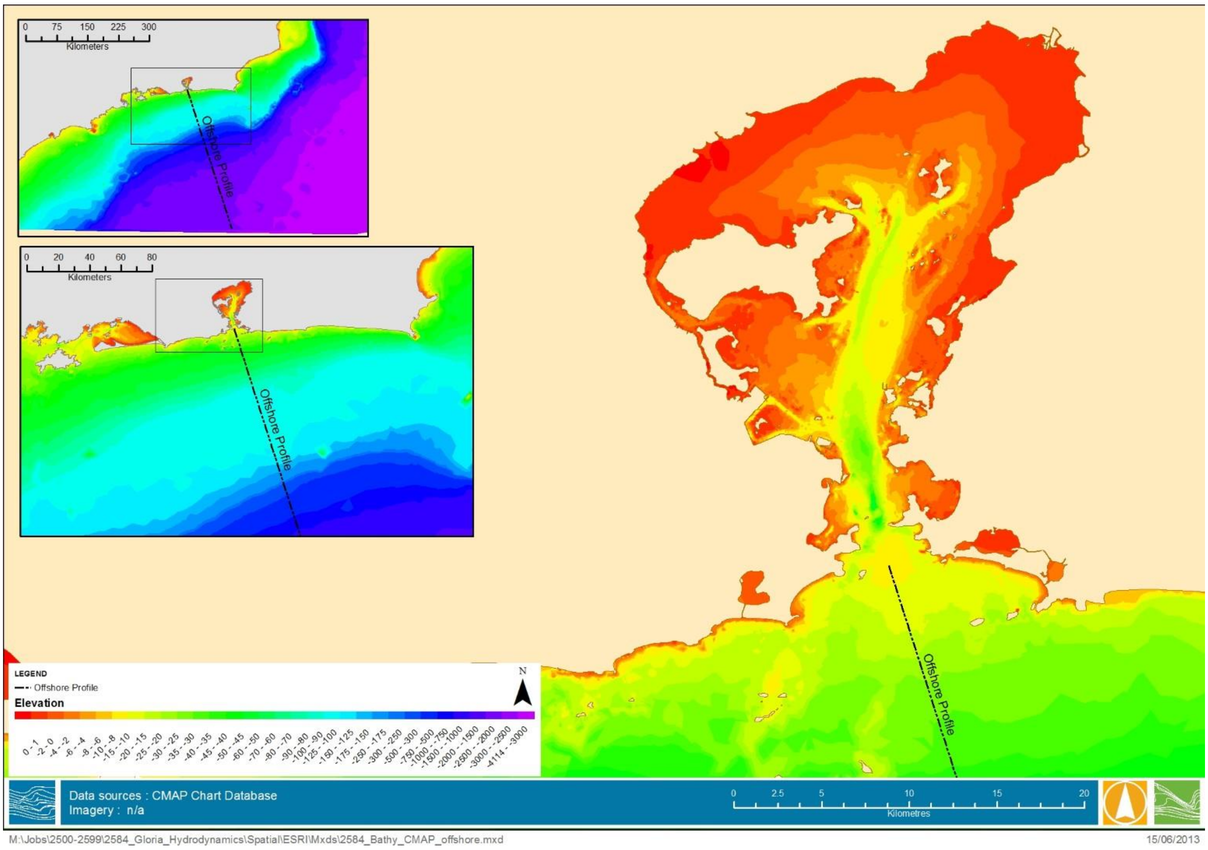

Figure 2-1 CMAP Bathymetry – Offshore (CMAP Database)

From this bathymetry, a flexible mesh grid was interpolated for use in the model. The model bathymetry is shown in Figure 2-2. The mesh resolution varies across the bathymetry to allow for optimisation of run time. Within Race Area 1 where current movement is more dynamic, the mesh resolution is in the order of 100m. In the offshore area near the boundary the mesh resolution is in the order of 2km.

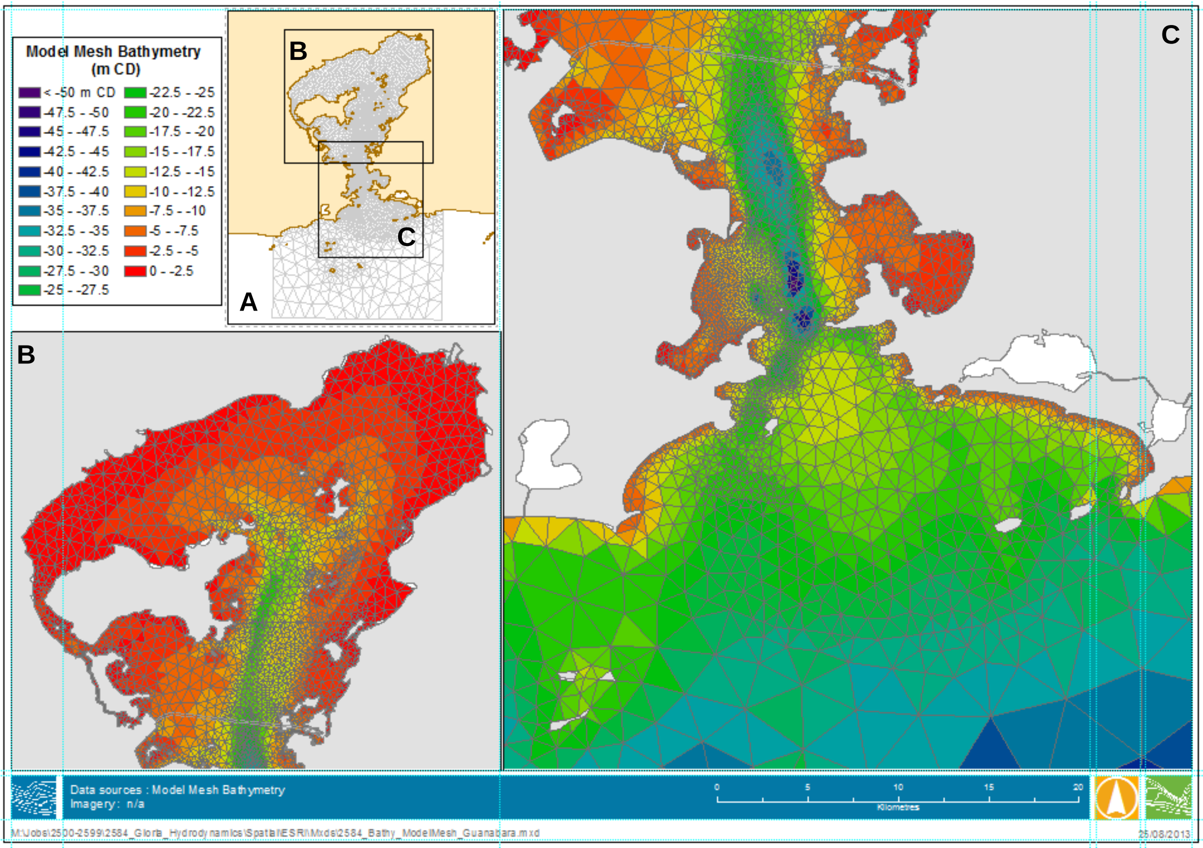

Figure 2-2 Model Bathymetry, mesh extent (A), northern Bay (B), Bay entrance and Race Areas (C)

Whilst the chart database proved suitable for preliminary model setup, a number of refinements were necessary to the based on updated data collected by AS to obtain a suitable mdoel validation. This is further discussed in Section 3.1.

2.3. Astronomic Tides

Tidal constituents were provided in Kjerfve (1996) for a number of stations across Guanabara Bay as shown in Figure 2-3. Tidal constituents derived from the Oregon State University Tidal Inversion Software (OTIS) were also extracted at points in the offshore zone, also shown in Figure 2-3.

Tides within Guanabara Bay and along the south-east coast of Brazil are semi-diurnal with an increasing semi-diurnal inequity to the west. The mean high water spring tidal range from the ocean across the Bay is shown in Figure 2-3 and illustrates the change in tidal range through the entrance of the Bay. Tidal plane information at a number of locations shown in Figure 2-3 is described in Table 2-1 below. The reduction in spring and neap tidal range from the northern section of the Bay (T14) to the offshore zone is in the order of 0.27m and 0.05m respectively. The larger ranges within the northern section of the Bay indicate there is some resonance of the tide within the Bay.

There is a large annual tidal constituent, Sa, within the tidal signal. The large Sa value is a response to the annual water level variation due to the large change in seasonal water temperatures, the freshwater runoff cycle (more inflows during warmer weather), and systematically varying wind and pressure.

As a result, the seasonal mean sea level fluctuates by approximately 0.06m near the ocean entrance and by 0.22m at inner margin of Bay (T11), the high water occurring Dec-Jan. During an average year, the mean sea level may be as much as 0.06m higher within the inner reaches of the Bay compared to the entrance, principally due to fresh water discharge at the north-eastern end of the Bay.

The model was initially calibrated to astronomic tides, as discussed in Section 2.10.

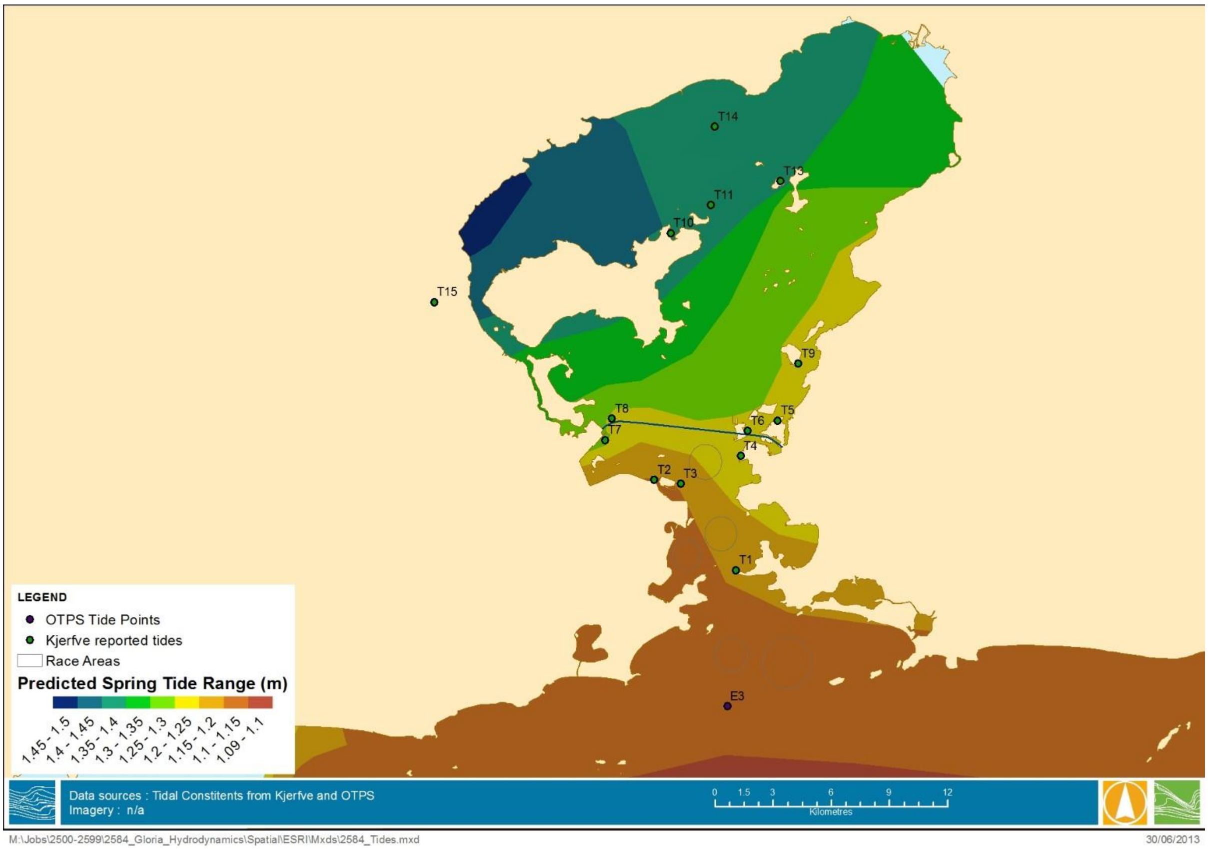

Figure 2-3 Tidal Stations and Approximate Spring Tidal Range

Table 2-1 Tidal Plane Levels

						Tidal Range (m)	
Location	**HAT**	**MHWS**	**MHWN**	**MLWN**	**MLWS**	**Spring**	**Neap**
Fortaleza Santa Cruz (T01)	0.64	0.54	0.13	-0.06	-0.63	1.17	0.19
Ilha Fiscal (T03)	0.64	0.54	0.13	-0.07	-0.61	1.16	0.20
Batalha (T14)	0.88	0.71	0.06	-0.13	-0.64	1.35	0.19
Point 43.15W, 23S	0.58	0.50	0.09	-0.06	-0.61	1.10	0.15
Point 43.15W, 23.15S	0.57	0.49	0.09	-0.05	-0.60	1.08	0.14

2.4. Currents

Some current speeds have been measured, including over a 15 day period in October-November 1992 (Kjerfve, 1996) and Prooceano using drifting buoys on a roughly monthly basis from mid-2010 to early-2013 across the Bay. Measured current speeds are predominantly below 0.5m/s at the surface, and up to 2.0m/s on occasion, with some outlying values above this. These current speeds were not incorporated into the preliminary modelling, as surface currents were a key focus of data collection and model verification, and are further discussed in Section 3 and Section 4.2.

2.5. Winds

Wind data are measured at a number of stations around Guanabara Bay. Winds are predominantly recorded by IMNET, the Brazilian Meteorological Department. The steep topographical variation around the Bay means that a spatially varying wind speed and direction was required. For the race forecast, weather forecasting provider UBIMET provided a daily prediction of wind forecasts in grid format. These spatially varying winds were incorporated into the model inputs, however surface currents in the model were not found to be highly sensitive to wind.

2.6. Waves

Wave data is available from two offshore buoys to the northeast and southwest of Guanabara Bay, and indicates offshore waves range generally from 0.5 – 4.0m. Offshore wave data was not included in the model, as surface currents in the race areas were not found to be sensitive to offshore waves. Local wind-waves are included in the model, however are also considered a minor influence on surface currents in the key race areas.

2.7. Residual Water Levels

Measured water levels have been obtained from the gauge at Ilha Fiscal for the period 1963 through 2012 from the University of Hawaii (UH). The UH receives this data from the Brazilian Navy Centre of Hydrography (DHN).

Figure 2-4 shows the measured water level (black) and the astronomical predicted water level (blue) at Ilha Fiscal is shown for the month of August 2012. The influence of winds, waves and other atmospheric conditions can be seen in residual water level, illustrated as an instantaneous (from hourly recordings) and 24 hour average shown in red and green respectively. These meteorological and oceanographic influences can add over 0.5m to the water level over a 24 hour average, significantly changing the tidally driven currents within the Bay.

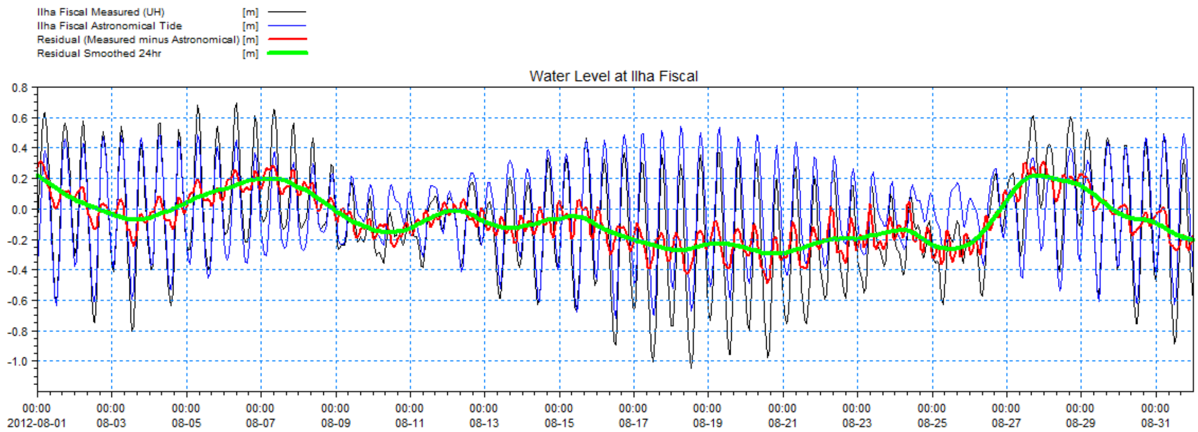

Figure 2-4 Measured Water Level, Ilha Fiscal (UH)

Residual water levels have a significant influence on the water levels within Guanabara Bay. Model testing suggested the surface currents within the model were also highly sensitive to the residual water level, and were therefore incorporated into the model. Residual water level was incorporated into the modelling via the global Hybrid Coordinate Ocean Model (HYCOM) sea level surface anomaly outputs. HYCOM is a global ocean circulation model, which incorporates satellite readings to inform sea level fluctuations, and is capable of providing a five day forecast and hindcast. The forecasting capabilities of the model were critical, as model results needed to be prepared prior to Olympic competition. Comparison of measured mean sea levels and that provided by HYCOM was undertaken, and whilst HYCOM was found to generally underestimate the residual water levels as shown in Figure 2-5, it improved forecast model results.

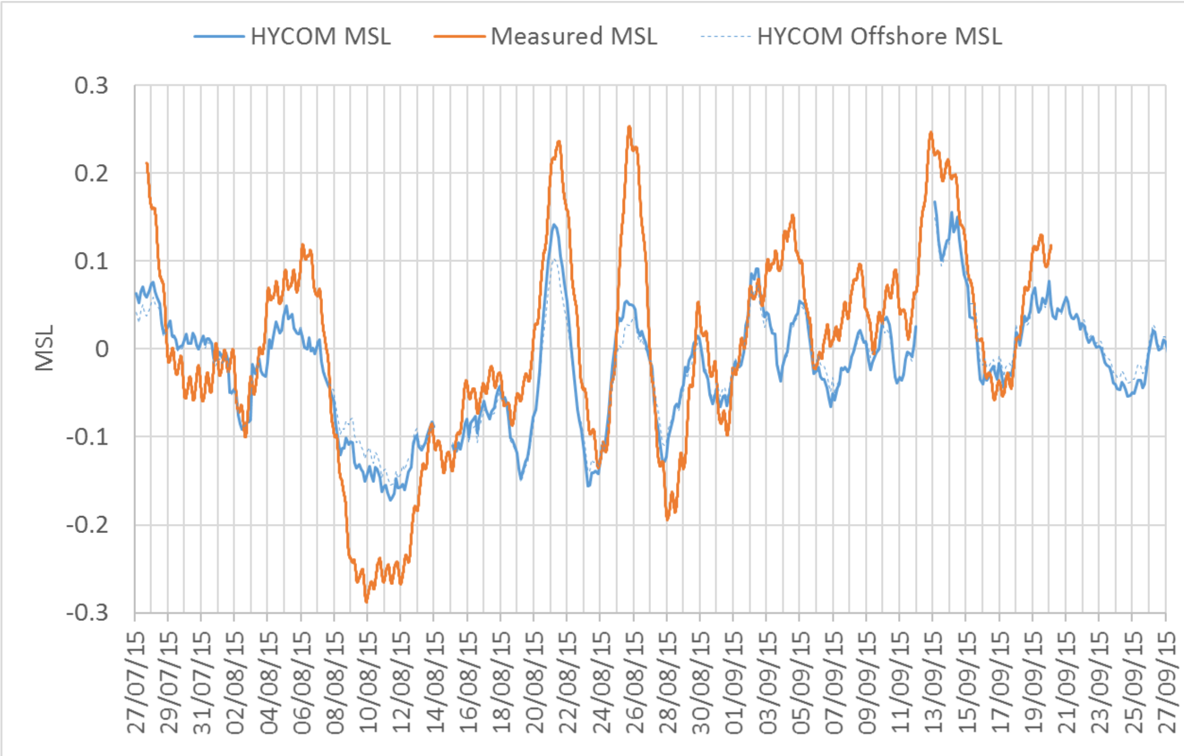

Figure 2-5 Comparison of Global HYCOM model with Measured Mean Sea Level (MSL)

2.8. Freshwater Inflows

Guanabara Bay drains an area of over 4,080km^2 through a number of rivers, the majority of which discharge into the northern section of the Bay. Kjerfve (1996) reports the total mean annual freshwater discharge into the Bay is in the order of 100m^3/s. Six rivers are responsible for 85% of this discharge, however, the typically the volume of freshwater inflow causes only a minor impact on hydrodynamics within the Bay due to the large tidal prism and volume of the Bay. During a training event in December 2016, over the wet season there was a number of significant rainfall event and therefore high freshwater inflow into Guanabara Bay. This influx of freshwater caused a less saline Guanabara bay to behave differently in terms of eddy generation and had a significant influence on model calibration. The model was therefore setup to enable freshwater inflows into the bay at a number of key river discharge points, in the case of a large rainfall event during the Olympic Games. However, the Olympics were held over the typically driest month in Brazil (August), and no significant inflows were recorded during the games, so the freshwater influence was not required.

2.9. Salinity and Temperature

Salinity, density and temperature profiles have been measured across the Bay as part of the Prooceano project. The change in both salinity and temperature suggests that the warmest water temperatures at the surface recorded in January, along with a large change in salinity with depth. During the January recordings, there is a large saline wedge across the Bay, potentially the result of higher flows occurring during the wet summer.

The measurements taken during May 2012 just prior to the dry winter season show a uniform temperature-depth profile across the Bay and less salinity variation in the lower section of the Bay.

Within the race areas salinity and temperature are more uniform, particularly during the dry winter months, with the August recording showing little variation in salinity with depth until in the very upper portion of the Bay. Typical salinity and surface temperature values were incorporated into the model, and apart from an extreme freshwater inflow as previously discussed in Section 2.8, the model was not found to be sensitive to these values.

2.10. Model Calibration to Predicted Tide

The tidal model was initially calibrated to astronomical tidal water levels and current speeds and directions throughout the Bay. These were developed from constituents provided in Kjerfve, 1996. The water level constituents reported by Kjerfve were derived from measurements taken by a number of organisations, from as early as 1906-07 through to 1984-86. The reported current constituents were derived from a 2-week period of measurement undertaken during Oct/Nov 1992.

The modelled water levels show a good level of correlation to the predicted water levels at a number of tidal stations through the Bay, as shown in Figure 2-4. Differences in water levels at T01, at the entrance to the Bay, are less than 0.02m, whilst at the northern end of the Bay at T13 the difference is up to 0.15m. However, constituents in the northern end of the Bay are derived from measurements taken early last century. Since then it is understood that the north end of the Bay has undergone considerable siltation and the difference in modelled and predicted tidal results are not considered significant.

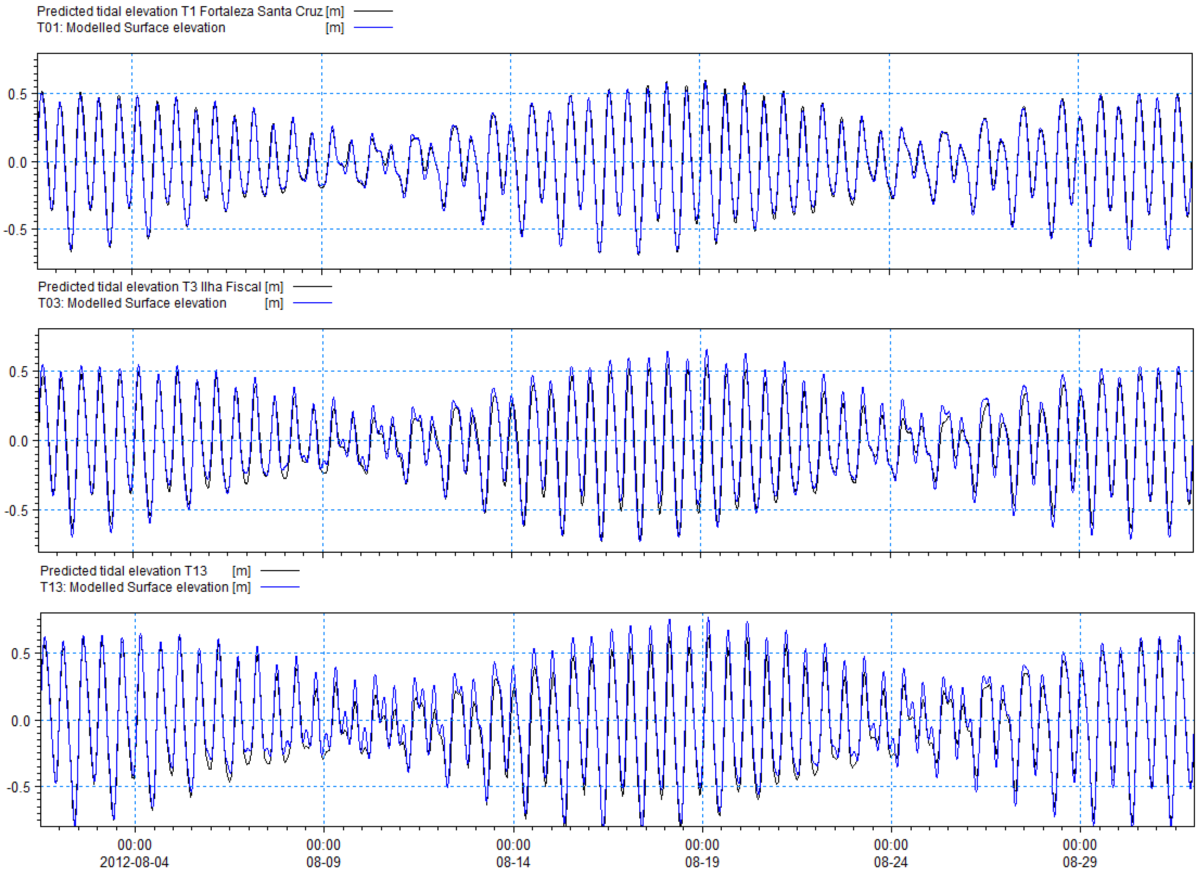

Figure 2-6 Modelled versus predicted water levels at T01 (top), T03 (middle) and T13 (bottom)

3. DATA COLLECTION

Data collection was a key part of the project, with AS at the Guanabara Bay site a number of times for a number of years leading to the Olympics, a range of data was collected to aid in the model calibration.

3.1. Bathymetry Data

Bathymetric data was able to be collected at a number of key locations over the course of the project. Bathymetric updates were incorporated into the model mesh, new model results supplied to AS and compared to near real-time calibration data from water loggers, GPS drogues and ADCP profiles. Each time a bathymetric update was incorporated into the model, a mesh update occurred, eventuating in 18 different mesh updates. These bathymetric updates often provided marginal improvements in surface current outputs, with the changes primarily due to the changes in volumes that occur when the bathymetry is updated.

3.2. Water Level Data

Water level data was consistently monitored via placement of water level logger in Marina De Gloria on the western side of Guanabara Bay. Placement of loggers in other locations proved difficult due to the naval presence adjacent to the race area. Water level data measurements were critical to allow calibration of the significant residual water level encountered in Guanabara Bay. The measurements allowed for testing of the accuracy of modelled water levels when including HYCOM sea level surface information into the model.

3.3. Acoustic Doppler Current Profiler (ADCP)

ADCP profiles were taken at many sites throughout the bay, typically towed behind a slow-moving boat. ADCP readings provided velocity readings from the top of the water level to the seabed, along the continuous sampled profile line. Calibration was aimed at the surface layer of the profile reading, which was compared to the top vertical layer in the hydrodynamic model, as this is the critical layer for interaction with the sailing vessels. The profiles were used to inform whether any areas of the model required refinements, typically in the form of updated bathymetry or more precise incorporation of the critical model effects previously discussed.

3.4. GPS Drogues

GPS drogues were also released on a number of locations, and proved to be very successful in capturing typical currents and eddy information. The drogues were released at pre-determined locations of interest at appropriate times, and tracked via GPS until they had reached an end location. This location was heavily dependent on the current conditions at the time, and was able to give insight on model refinements that needed to occur.

3.5. Anecdotal Evidence

Another key source of information was anecdotal evidence provided by AS. They were sailing every day for weeks at a time, so could provide direct evidence on current patterns and eddy generation. These inputs were utilised for model validation.

4. MODEL VALIDATION AND OUTPUTS

4.1. Water Level Calibration

Whilst the model was initially calibrated to predicted tidal water levels, the residual water levels in Guanabara Bay are significant and required further calibration. HYCOM residual water levels were included in the modelling, and was able to improve the calibration to measured water levels as shown in Figure 4-1.

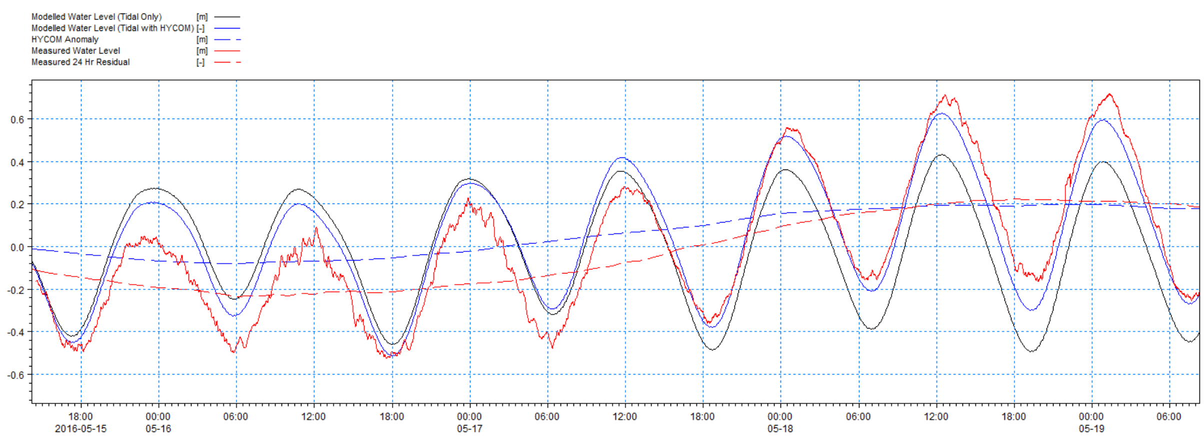

Figure 4-1 Example of modelled verse measured water levels leading up to the Olympic games

4.2. Current Speed and Direction Calibration

Current speed and direction was primarily validated through the use of ADCP profiles, GPS drogues and anecdotal evidence. Final outputs were reported during the Olympics to provide an accurate representation of the current conditions experienced during the events.

4.3. Model Output for use by Australian Sailing Team

Delivery of model outputs was a critical part of the project as they needed to be easily read by sailors and coaches. Whilst grib files were provided to AS of the raw data for use in their instrumentation, output animations were also provided at 10 minute intervals with a spatial map of current speeds and directions, overlaid with graphs of water levels and current speed at key locations, as shown in Figure 4-2. These were supplied as images so the team could select a specific time they were interested in, and as animations so the animation could be watched for the race times.

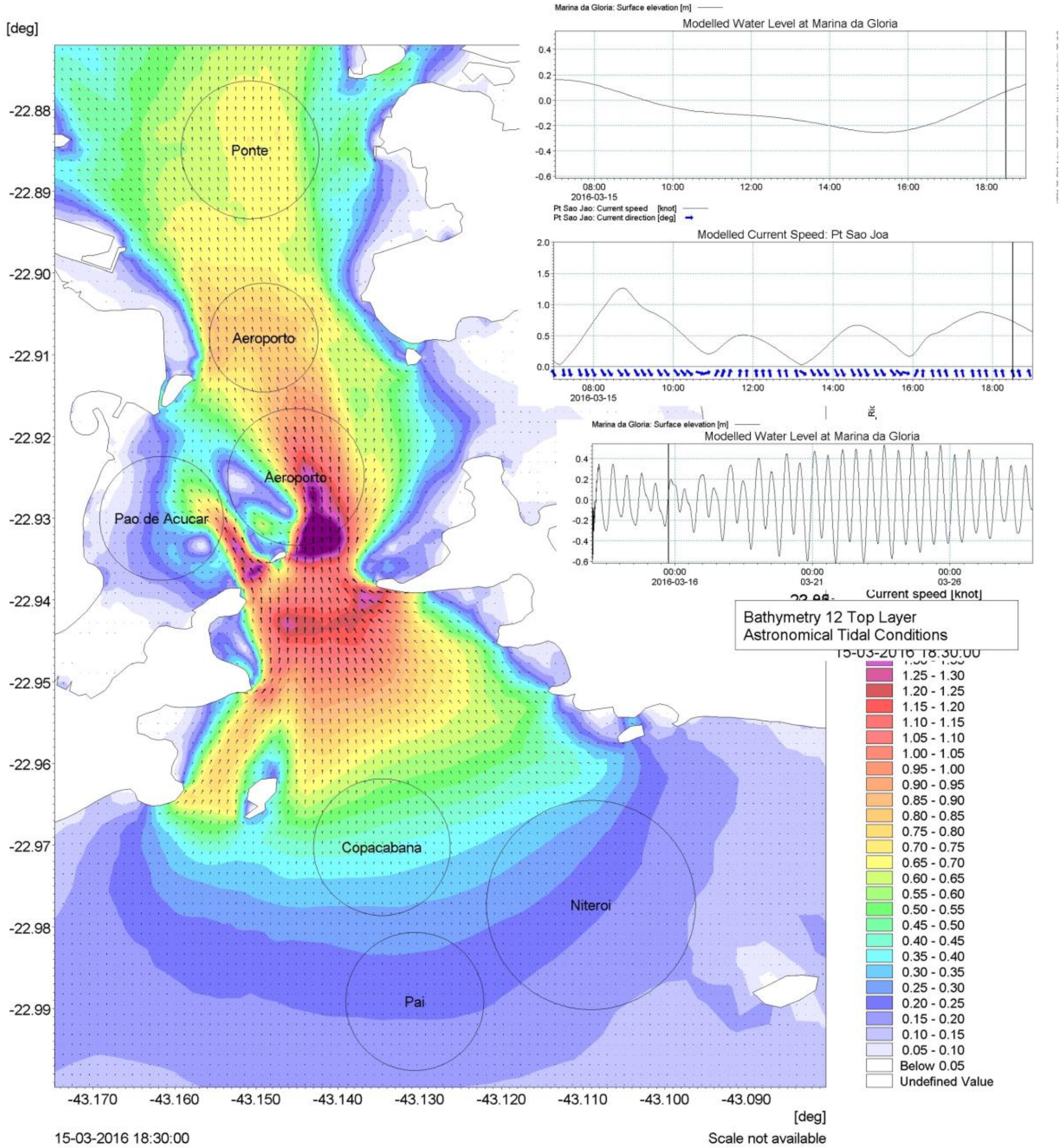

Figure 4-2 Example model output provided to AS

5. CONCLUSION

The Olympic sailing events in Guanabara Bay provided a difficult location for sailors to optimise race currents, as tidal currents through the bay form a complex pattern of eddys through the race areas. Hydrodynamic modelling was able to inform AS about the expected current conditions that would be experienced during the races.

The surface currents in Guanabara Bay proved to be highly sensitive to astronomical tidal conditions and weather induced residual water levels. Model calibration to predicted astronomical conditions was able to be achieved, however calibration of residual levels proved more difficult, and is hampered by a short forecast time. This forecast time was limited by the accuracy and forecast length of the global current model, HYCOM.

ADCP and GPS drogues were able to provide detailed current speed and direction information, allowing model calibration to be refined. Anecdotal evidence from sailors also proved important in ensuring accurate model outputs.

6. ACKNOWLEDGMENTS

This work was conducted as a collaboration between AS and Water Technology for the 2016 Rio De Janeiro Olympic Games. Numerous members of the AS team, especially Andrew Lechte, Peter Logan, Peter Conde, Bruce Buckley, Damian Carter, Emmett Lazich and Michael Blackburn were instrumental in providing feedback on model calibration and collection of logger data. Apart from the authors of this paper, several engineers and scientists at Water Technology also provided input to this project.

7. REFERENCES

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