Appendix 5

Description and validation of hydrodynamic and wave models for discharges, spills, geomorphology and dredge spoil disposal ground selection

Ichthys Gas Field Development Project:

Description and validation of hydrodynamic and wave models for discharges, spills, geomorphology and dredge spoil disposal ground selection

Prepared for INPEX, Browse Ltd.

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EXECUTIVE SUMMARY

INPEX proposes to develop gas production facilities at an offshore site within the Browse Basin and to pipe the gas to processing and export facilities that would be developed within Darwin Harbour. Hydrodynamic and wave models were developed to represent ambient current and wave fields affecting both the inshore and offshore development locations. Data produced by the models was required for modelling the fate of various planned or accidental discharges into the marine environment. This report describes the configuration and testing of these models.

The study spans a large area with a wide range of meteorological environments. To optimise the resolution of the models and to represent the important forcing conditions for each environment, the approach taken in this study was to develop different models for each setting. Two hydrodynamic modelling frameworks were applied: BFHYDRO and HYDROMAP, with each model chosen for performance in a given setting. BFHYDRO was applied to modelling within Darwin Harbour because this model supported the use of a boundary conforming grid, to maximise representation of the harbour geometry, and could account for the wetting and drying of the intertidal mudflats, which have a large effect on tidal exchange and current flow inside the harbour arms. HYDROMAP was applied to modelling over both the wider approaches to Darwin Harbour and over the Browse Basin around the offshore production site. This model was more efficient over the large domains required for these applications.

Wave modelling was a necessary input to simulations that tested the stability of dredged sediments placed into alternative offshore spoil grounds. The SWAN wave model was set up over a domain that extended from the Beagle Gulf into Darwin Harbour. The SWAN model was chosen because it accounts for most of the important wave processes in shallow waters, could operate on the same grid used for BFHYDRO modelling over Darwin Harbour and could use the BFHYDRO predictions of current flow to account for modification of the wave field due to the current field. Wave boundary boundary data was sourced from an established global wave model (NWW3) operated by an authoritative source (NOAA).

The performance of the numerical models, as configured for this study, was tested by comparison of model predictions with field observations of tidal elevations, currents and waves. Tests were also conducted on longer term wind records that were available for the study areas to ensure that they were representative.

The BFHYDRO model configuration for Darwin Harbour and Beagle Gulf was successfully validated against current speeds and directions measured at four sites spanning from the harbour entrance to East Arm, with data collected during two periods (February–March 2004 and April–June 2008). Comparisons of measured data showed that tidal currents dominate at each of the sites and that the tidal axis is steered by the local bathymetry. The modelled data faithfully reproduced the distribution of the current data in terms of the current directions and magnitudes. Root mean square errors in current speed, calculated for hourly estimates, were consistently low ($< 0.18 \text{ m s}^{-1}$) for near-surface, mid-depth and near-bottom vertical levels, while the maximum error in current direction at any site was 10°. This outcome indicates that this model was suitable for generating representative current fields over the harbour and approaches.

The two HYDROMAP configurations covering Beagle Gulf (inshore model) and Browse basin (offshore model) were both successfully validated against measurements of tidal elevations and of current speed and direction at sites that were central to the primary areas of interest for each configuration. The inshore model configuration accurately predicted the current speeds and directions at surface, mid-depth and near seabed at a site near the proposed spoil ground. Correlations ranged from 0.73 near the seabed to 0.95 at the surface. The mean error in current speeds was 0.04 m s^{-1} at the surface, increasing to -0.09 m s^{-1} at mid depth and -0.12 m s^{-1} near seabed.

The offshore model was compared to measurements of currents and tidal elevations measured at a fixed depth (~15 m below mean sea level) adjacent to the proposed location of the central processing facility (CPF). The model accurately propagated the timing and magnitude of the tide at the CPF and accurately predicted the magnitude of the currents for the observations period. Discrepancies between the predicted and observed current directions resulted from the increased influence of the wind direction in the predicted current because measures were averaged for the upper 20 m, while observed currents were for a discrete depth level where the wind influence would be lower.

Wave modelling was conducted to account for the effect of wave resuspension in simulations to represent the fate of dredged sediment disposed offshore, to identify the most suitable disposal location. Wave conditions observed at three locations ranging from Beagle Gulf to East Arm indicated that swells are usually generated locally, generally with a low magnitude under non-cyclone conditions. This indicates that wave processes under non-cyclonic conditions would not typically be providing sufficient force for resuspension of sediments from the seabed, compared to tidal currents acting at the seabed. Predictions for the wave fields were consistent with the observations and indicated that swells and waves propagating into the harbour have relatively small magnitude (<0.50 m, with median <0.25 m) and short wave period (<10 s with median <5 s). The SWAN model, using boundary data from the NWW3 global wave model provided suitably representative distributions for the wave magnitudes and bottom orbital velocities compared to the measured data.

1 INTRODUCTION

INPEX Browse, Ltd. (INPEX) proposes to develop the natural gas and associated condensate contained in the Ichthys Field in the Browse Basin at the western edge of the Timor Sea about 200 km off Western Australia's Kimberley coast. The field is about 850 km west south west of Darwin in the Northern Territory.

The two reservoirs which make up the field are estimated to contain 12.8 tcf (trillion cubic feet) of sales gas and 527 MMbbl (million barrels) of condensate. INPEX will process the gas and condensate to produce liquefied natural gas (LNG), liquefied petroleum gas (LPG) and condensate for export to overseas markets.

For the Ichthys Gas Field Development Project (the Project), the company plans to install offshore facilities for the extraction of the natural gas and condensate at the Ichthys Field and a subsea gas pipeline from the field to onshore facilities at Blaydin Point in Darwin Harbour in the Northern Territory. A two train LNG plant, an LPG fractionation plant, a condensate stabilisation plant and a product loading jetty will be constructed at a site zoned for development on Blaydin Point. Around 85% of the condensate will be extracted and exported directly from the offshore facilities while the remaining 15% will be processed at and exported from Blaydin Point.

In May 2008 INPEX referred its proposal to develop the Ichthys Field to the Commonwealth's Department of the Environment, Water, Heritage and the Arts and the Northern Territory's Department of Natural Resources, Environment and the Arts. The Commonwealth and Northern Territory ministers responsible for environmental matters both determined that the Project should be formally assessed at the environmental impact statement (EIS) level to ensure that potential impacts associated with the Project are identified and appropriately addressed.

Assessment will be undertaken in accordance with the *Environment Protection and Biodiversity Conservation Act 1999* (Cwlth) (EPBC Act) and the *Environmental Assessment Act* (NT) (EA Act). It was agreed that INPEX should submit a single EIS document to the two responsible government departments for assessment.

Asia-Pacific ASA (APASA) was commissioned to carry out hydrodynamic modelling associated with INPEX's preparation of the EIS and this technical report was prepared in part fulfilment of that commission.

Obtaining plausible estimates of the environmental impact of operations proposed by INPEX within the Browse Basin and Darwin Harbour, including adjacent waters of Beagle Gulf, requires the development of fit-for-purpose numerical models. Hydrodynamic and wave models provide the forcing specifications for specific modelling studies relating to the impacts of discharges and must produce reliable representation of the local circulation and wave climate.

This report provides descriptions of the hydrodynamic and wave models that were applied to the study, including model set up and the input information that was used, as well as validations of the performance of these models by comparison to field measurements collected by instrumentation placed at several sites within the area of interest. The instrumentation sites span across the geographic extent of the works proposed for the harbour and approaches and measurements cover all seasons experienced in the area, hence provide a representative sample for comparison.

Graphical and statistical comparisons are performed of model input and output parameters with observations of wind, tide, currents and waves collected using instrumentation.

2 DEVELOPMENT OF HYDRODYNAMIC CIRCULATION DATA

Hydrodynamic models were developed and applied in this study to represent the effects of water circulation for various investigations of the fate of products that might be discharged or accidentally spilled into Darwin Harbour and Beagle Gulf. The study area spans two general hydrodynamic regimes with particular demands for the attributes of a hydrodynamic model. Darwin Harbour is a bathymetrically complex, macrotidal, area with extensive areas of intertidal mudflats and mangroves that wet and dry with the tide, resulting in the take-up and release of large volumes of water over a semi-diurnal (twice-daily) cycle and significant changes in the geometry of the system. Modelling of this regime required a model operating at high spatial resolution with representation of the tidal wetting and drying. Beagle Gulf, a more extensive water body than Darwin Harbour, is also predominantly driven by tidal circulation but tidal wetting and drying are not as significant.

Two independent hydrodynamic models were developed for the different model regimes, with the models and case-specific configurations selected to best suit each case.

2.1 General description of the hydrodynamic model applied to Darwin Harbour

BFHYDRO was employed to generate tidal elevations, current velocities and salinity and temperature distributions within Darwin harbour and approaches. BFHYDRO (Boundary-Fitted Hydrodynamic Model) is a three-dimensional, general-curvilinear, hydrodynamic model, which can be applied with both barotropic (tide and wind driven) and baroclinic (density driven) forcing. BFHYDRO is the hydrodynamic model within the WQMAP (Water Quality Mapping Analysis Program) water quality modelling system. This model system has a long history (over 20 years) of development and application world-wide for simulation of hydrodynamic circulation and the fate of various pollutants and the model algorithms have been extensively peer-reviewed and developed over this time (e.g. Huang & Spaulding 1995; Peene, Kim & Swanson 2001; Mathison et al. 1989; Mendelsohn et al. 1999; Ward & Spaulding 2001; Yassuda & Mendelsohn 1997; Yassuda et al. 1999; Zigic 2005; Zigic, King & Lemckert 2005)

BFHYDRO solves the conservation of mass, momentum, salt and temperature on a non-orthogonal, boundary-fitted, curvilinear grid-system (Muin & Spaulding 1997; Sankaranarayanan & Spaulding 2003; Spaulding, Mendelsohn & Swanson 1999). The reader is referred to Muin and Spaulding (1997) for detailed presentation of the governing equations and test cases of the BFHYDRO model.

The boundary-conforming gridding scheme allows the grid boundaries to be closely matched to the geometry of the water body while maximizing spatial resolution in the areas of interest. The boundary-fitted gridding technique proved to be advantageous to this study, due to the geometrically complex nature of the water body. Another important skill of the BFHYDRO model for the study setting, due to the extensive area of intertidal mudflats and wetlands, is the ability to represent tidal wetting and drying by dynamically adjusting the model coastline with the tidal level. The wetting and drying scheme follows the method of Falconer (Falconer & Chen 1991).

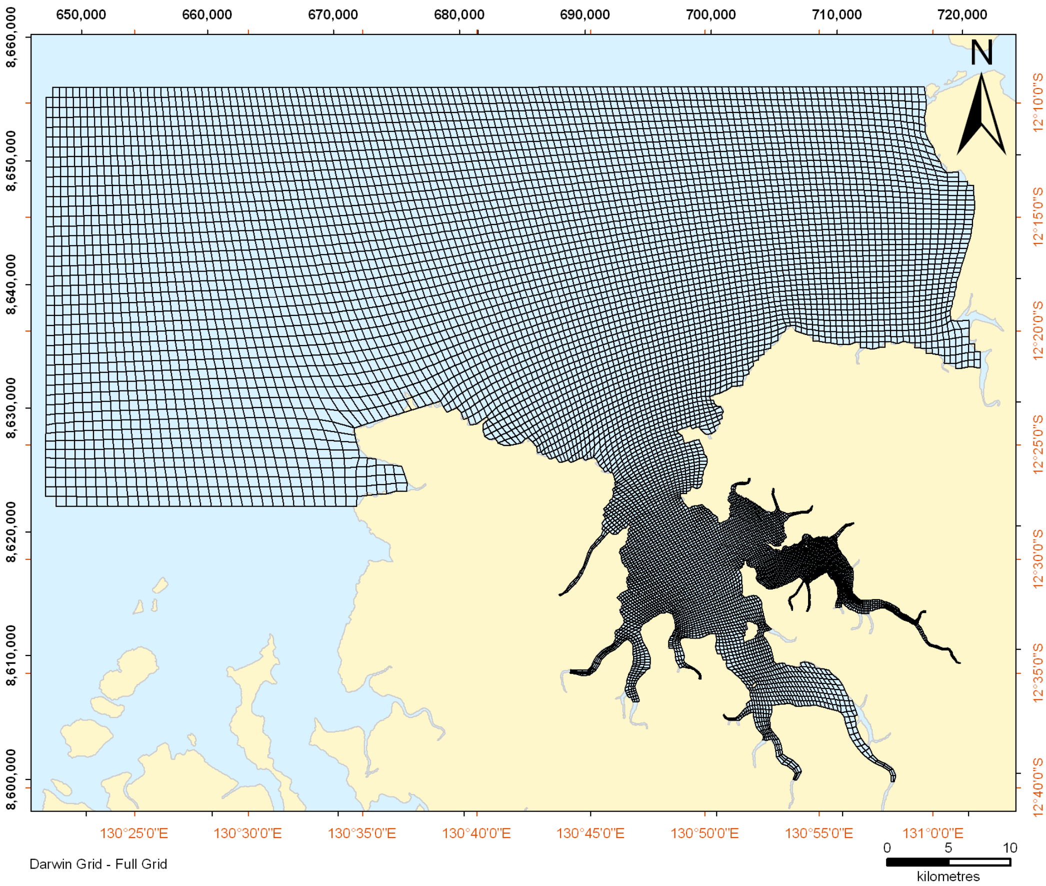
2.2 Configuration of the BFHYDRO model for this study

BFHYDRO simulations were performed in three-dimensional mode over an irregularly-spaced, boundary-conforming, grid that covered Darwin Harbour and an adjacent part of Beagle Gulf (Figure 1). The boundaries of the computational domain were extended well offshore, to encompass the potential migration of discharges of interest to the wider study and to ensure that they were large enough to provide good definition of tidal and wind variations over the approach to Darwin Harbour.

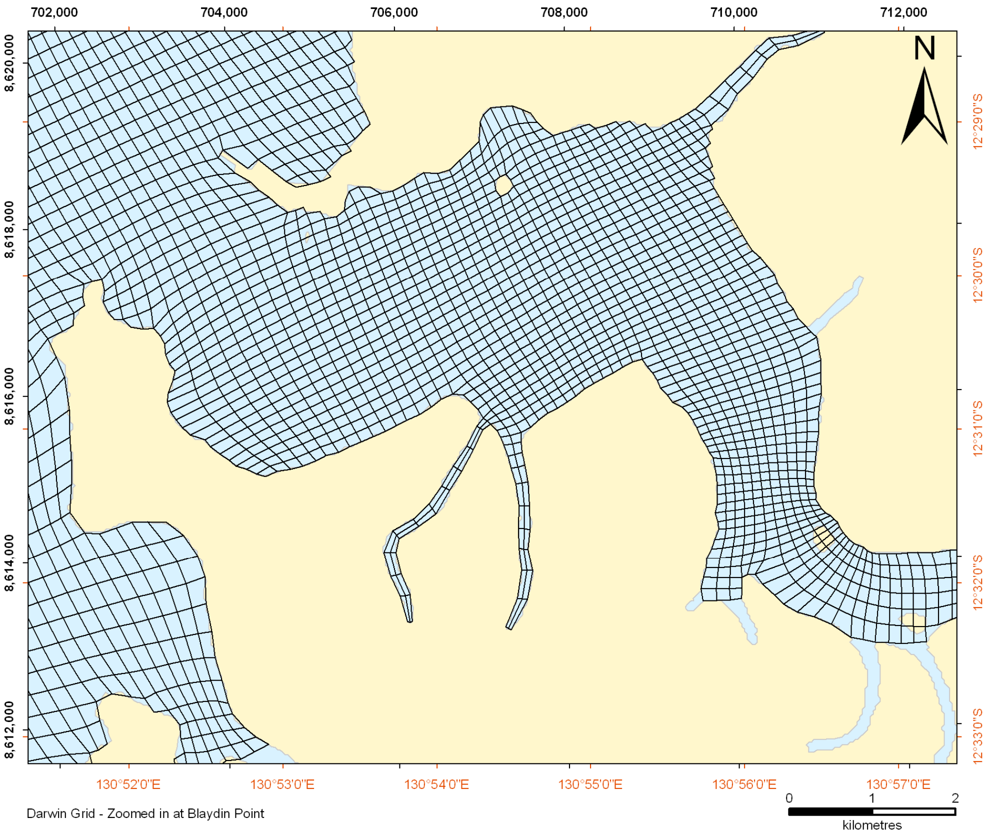
The grid consisted of 11 989 active computational water-cells with 5 depth levels following a sigma-co-ordinate system (where the thickness of the layers varies proportionally with the local depth). The size and shape of cells were varied horizontally over the domain depending on the demands for spatial resolution within the various discharge studies. The finest horizontal grid-resolution (approximately 80 m by 80 m) was defined throughout East Arm and grid cells were gradually enlarged towards the open boundaries of the domain. Resolution at the open boundaries was approximately 700 m by 700 m.

This approach optimised the model resolution over the area of greatest interest and bathymetric complexity while maintaining model efficiency and stability, important to allow sufficiently long simulations to be carried out. Grid cells consisted of quadrilaterals (four-sided shapes) with variable shapes that were conformed as closely as possible to the local coastline. Particular attention was paid to conforming grid boundaries to the coastline of the harbour and structures that could have local impact on circulation. BFHYDRO was configured to operate as a wetting and drying model for this study with the outer extent of the coastline within the harbour defined by the mean high-water spring (MHWS) tidal level. This level accounted for inundation up to 50 m into the lower intertidal fringe of the mangroves.

A complete bathymetric dataset, at consistent scale, was not available for the harbour. In lieu, a composite of different depth data sources were used to describe the bathymetry within the study area. Gridded bathymetric data at 250 m scale were available for Beagle Gulf and Darwin Harbour from Geoscience Australia. These were augmented within the harbour by interpretations of mapped depth contours, at 5 m steps, which were provided by the NT Department of Primary Industry, Fisheries and Mines. All soundings were post-processed to a consistent elevation datum and a spreading routine was applied to fill data gaps. Comparison of the resulting bathymetric shape revealed good agreement with higher resolution maps generated by INPEX, from geophysical surveys, over patches dispersed along a route leading into East Arm. Additional depth measurements were made by APASA over the intertidal and shallow subtidal regions within East Arm, Middle and West Arms (see Appendix*)* and incorporated to correct interpretations over the more significant data gaps.

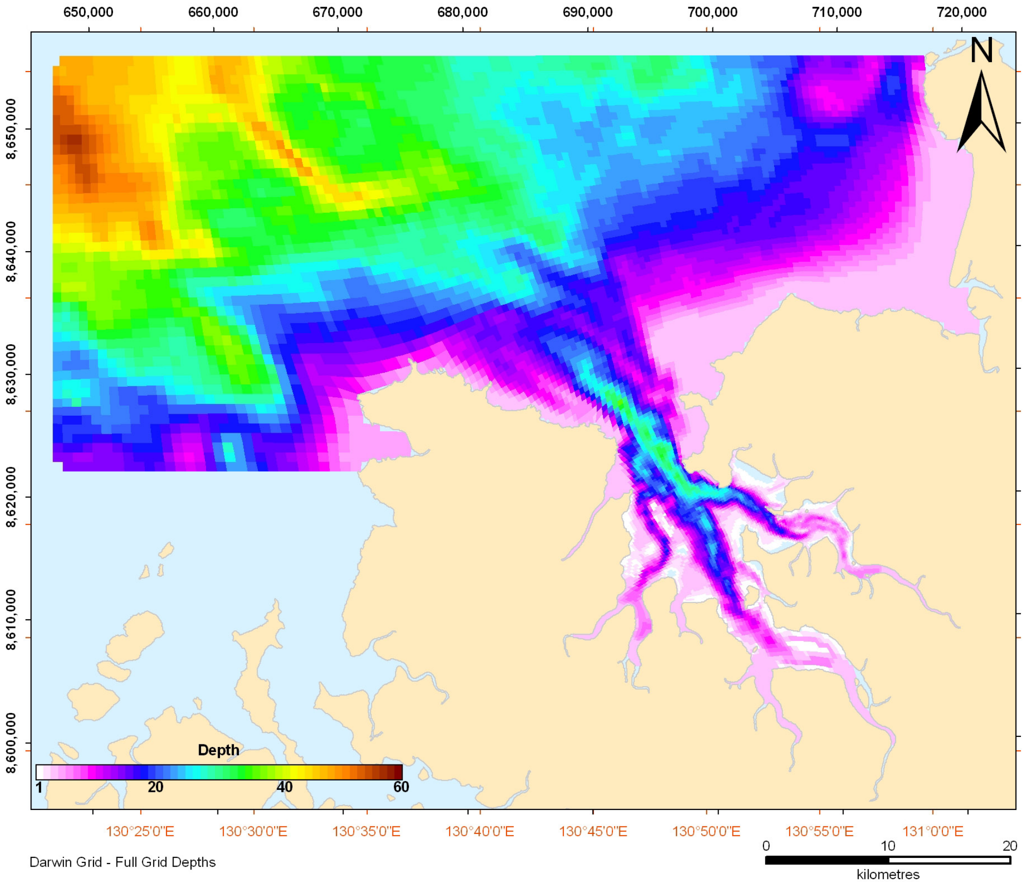


Darwin Grid - Full Grid

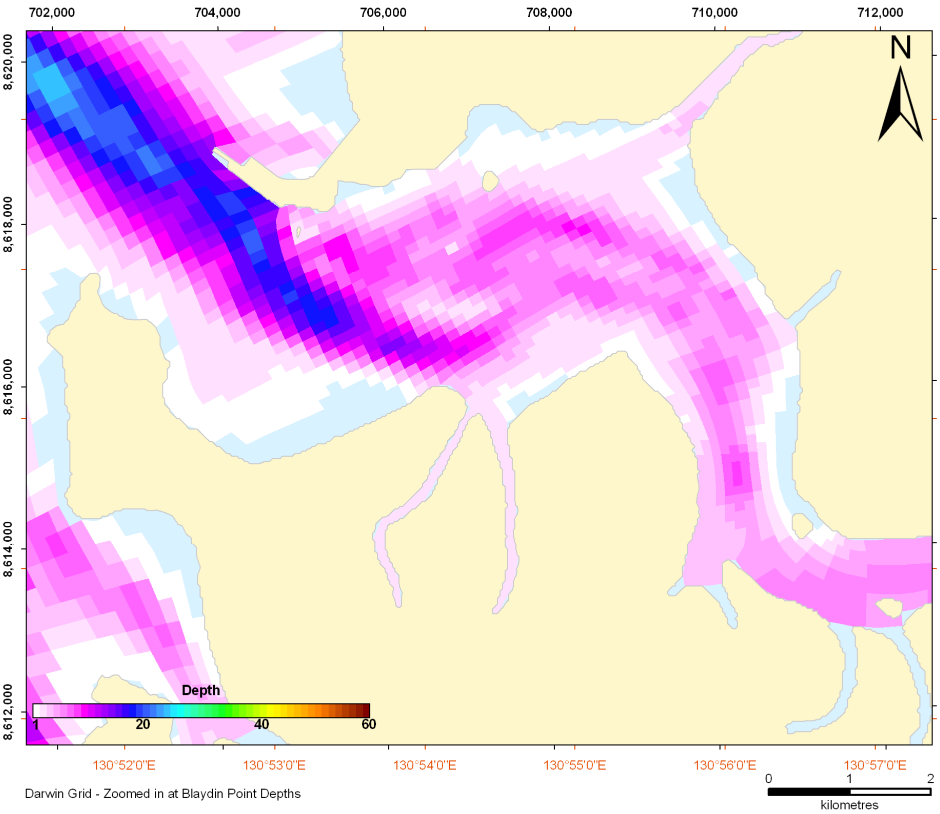


Darwin Grid - Zoomed in at Blaydin Point

Figure 1: Computational domain for the BFHYDRO model of Darwin Harbour and approaches. Top panel shows the entire domain. Lower panel shows a zoom over East Arm



Darwin Grid - Full Grid Depths



Darwin Grid - Zoomed in at Blaydin Point Depths

Figure 2: Details of bathymetry resolved within the BFHYDRO grid: Top panel shows the entire domain. Lower panel shows a zoom over East Arm

Tidal forcing was applied at the outer boundary of the model domain using tidal phase and magnitude data for separate tidal constituents that was spatially interpolated from the Topex/Poseidon v7.2 global tidal database. This is a spatially-gridded set of tidal constituents for the open ocean that is produced and distributed by the United States National Oceanographic and Atmospheric Administration (NOAA). The data have been derived from satellite altimetry data collected since October 1992.

Wind data, which was used to define the influence of wind shear on circulation, were sourced for a 13 year period (1996–2008 inclusive) from the Darwin Airport weather station, which is operated by the Australian Bureau of Meteorology (BoM). The length of this data set supported the representation of interannual variation and the use of the Darwin Airport measurements for model simulations over the harbour was justified by satisfactory comparisons with local wind records collected by APASA at the East Arm Wharf over a 5 month period (April–August 2008; Figure 3). In statistical terms, the correlation coefficient was as high as 85% between the U-components (South-North flow) of wind vectors and as high as 70% between the V-components (West-East flow).

Darwin Harbour is well stratified during the dry-season and seawater salinities extend upstream beyond the area of interest, hence density variations and river flows were not expected to have a significant influence on circulation patterns given the magnitude of the tidal currents. The Harbour does receive river inflow from the surrounding catchment during the wet season (December-March). However, due to the magnitude of the tidal currents, the water column typically remains stratified with only relatively small changes in salinity extending as far upstream as the back of East Arm, except during occasional and short-lived rainfall events (Duggins 2006, NRETA 2007), indicating that it would be appropriate to assume a density stable water column where density variations did not significantly influence the flow field in comparison to tidal effects. This assumption was supported by two lines of evidence.

Firstly, the model was applied to predict current speeds at 3 locations within East Arm (Figure 4). Freshwater inflow was specified at the upstream extent of the model domain at the confluence with the Elizabeth River using time-varying flow data provided by NRETA (gauging station G8150018). The simulation indicated that inflow of the measured magnitudes would have an influence on current speed predictions at the upstream extent of the model domain but this influence would be lost by midway along East Arm, beyond the main area of interest to the study (Figure 5).

Secondly, predictions of current speed and direction made by the model, using only wind and tide forcing and neglecting density effects or river inflow, were found to be comparable to current measurements, made by acoustic Doppler current profilers (ADCPs), during both wet and dry seasons. Validation of the model configuration is described in further detail below (Section 2.3.2).

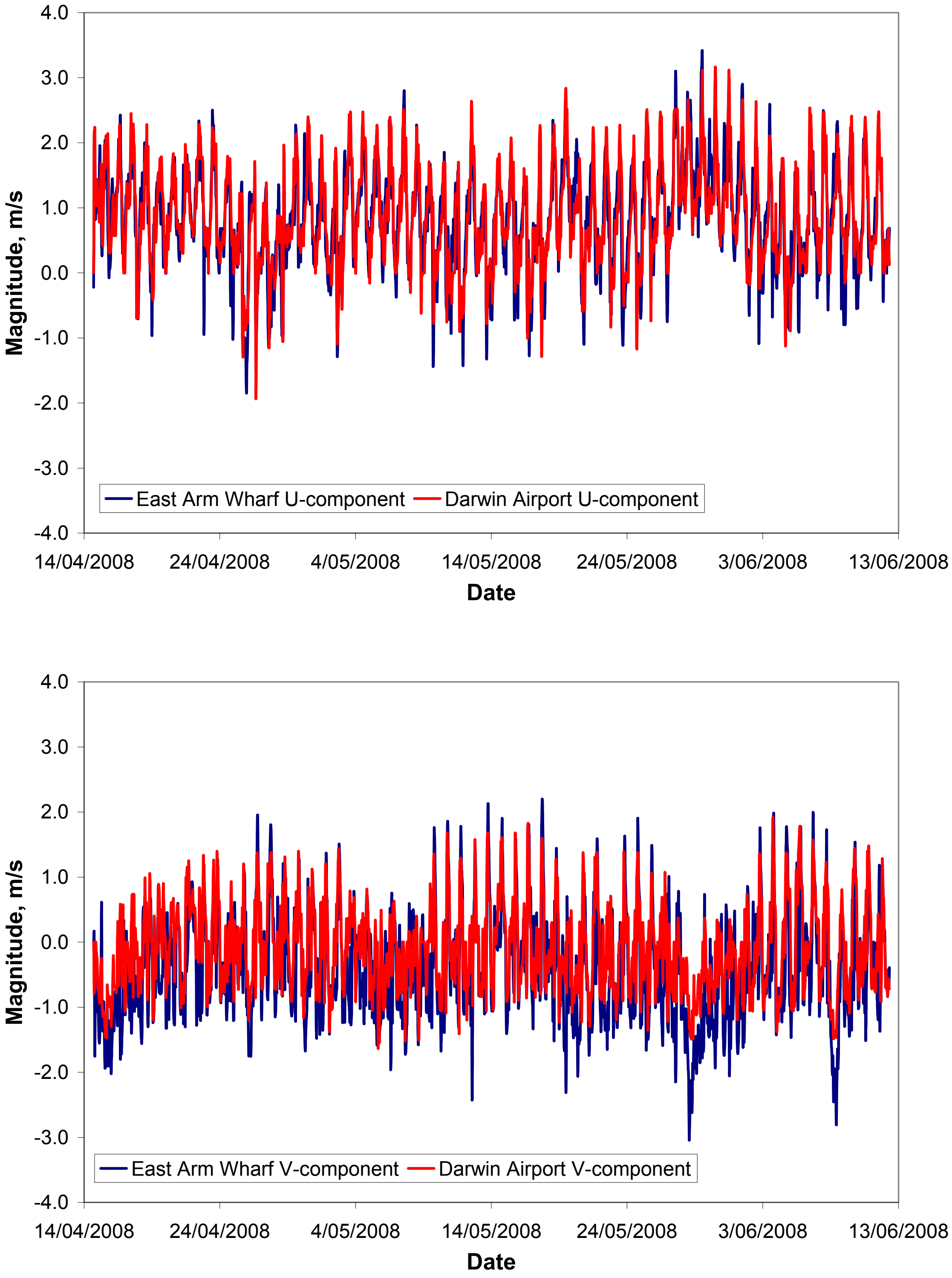


Figure 3: Inter-comparisons of East Arm Wharf and Darwin Airport winds: U-component in top panel and V-component in bottom panel

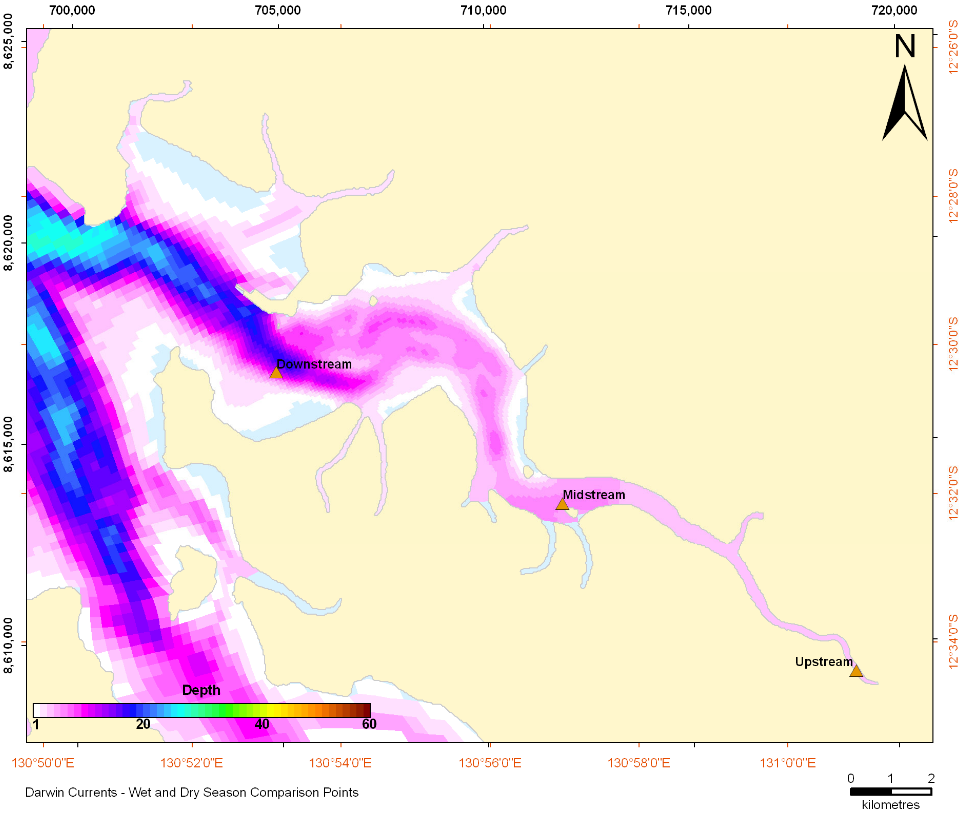
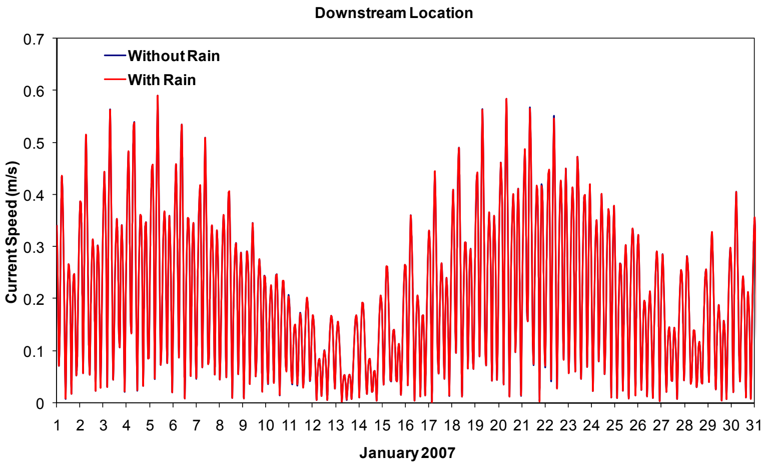
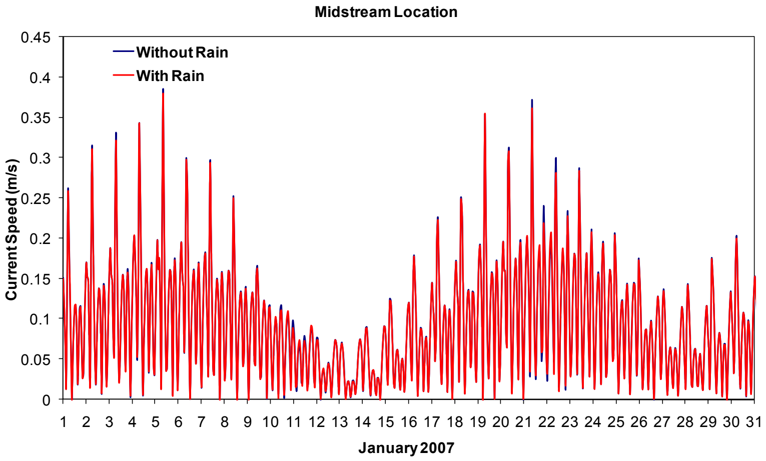


Figure 4: Location of comparison points for tests of river inflow effects





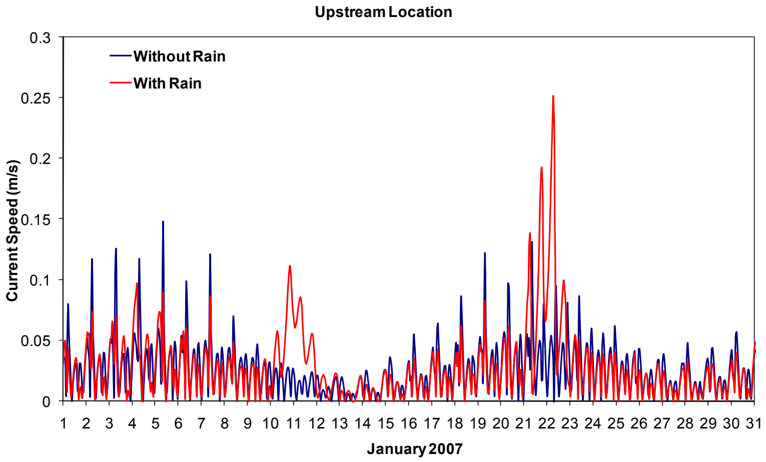


Figure 5: Comparison of predicted current speeds at three locations along East Arm and Elizabeth River with and without the representation of rain-induced river inflow. Inflow data were time-varying, derived from river gauge data for the Elizabeth River Gauging station over January 2007 (NRETA, undated)

2.3 Validation of the BFHYDRO model output

2.3.1 Tide comparisons

Tidal predictions from the BFHYDRO model were validated against measurements collected at four pressure gauging sites within East Arm (Figure 6; for specific locations see Table A3 in Appendix). The tide gauges were deployed by APASA for the period 14 May–11 June 2008, capturing a spring–neap–spring tide period.

The comparisons demonstrated that BFHYDRO was faithfully predicting the magnitude and timing of tidal variations over individual tidal fluctuations as well as both the spring and neap phases (Figure 7, Figure 8). This indicates that the model is accurately propagating the net tide into East Arm using the Topex/Poseidon data provided at the open boundaries of the domain.

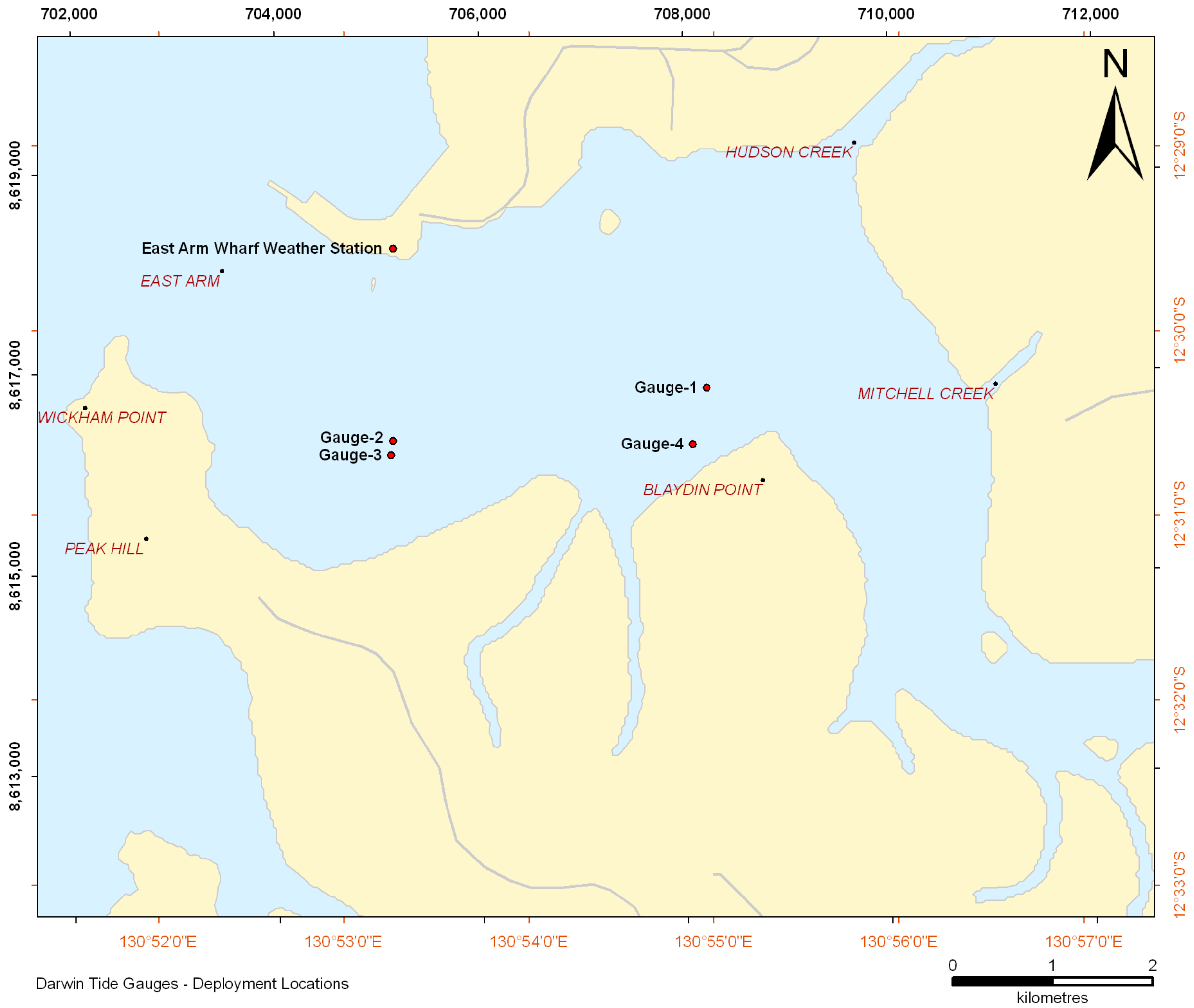
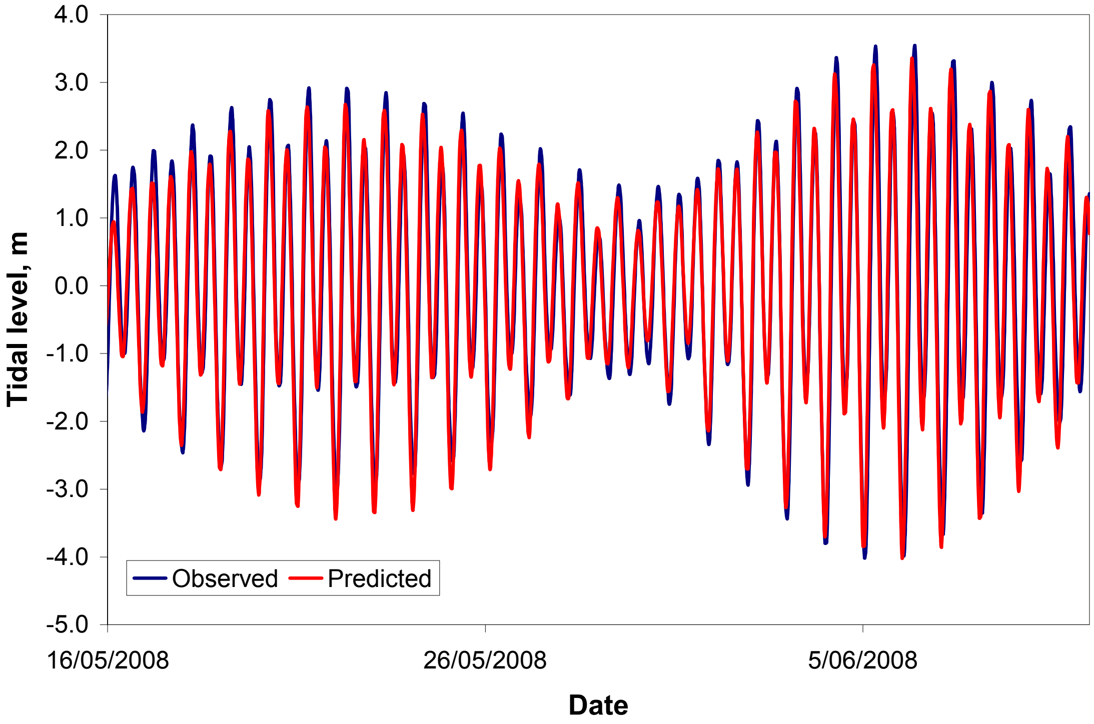


Figure 6: Location of pressure gauging stations within East Arm



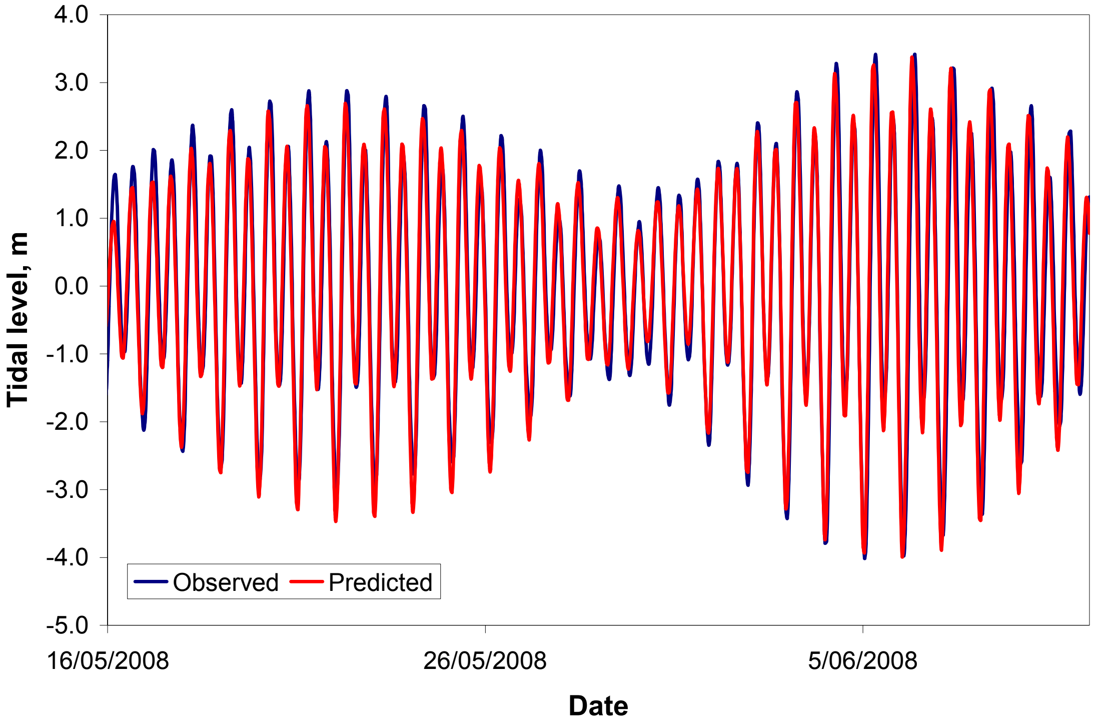
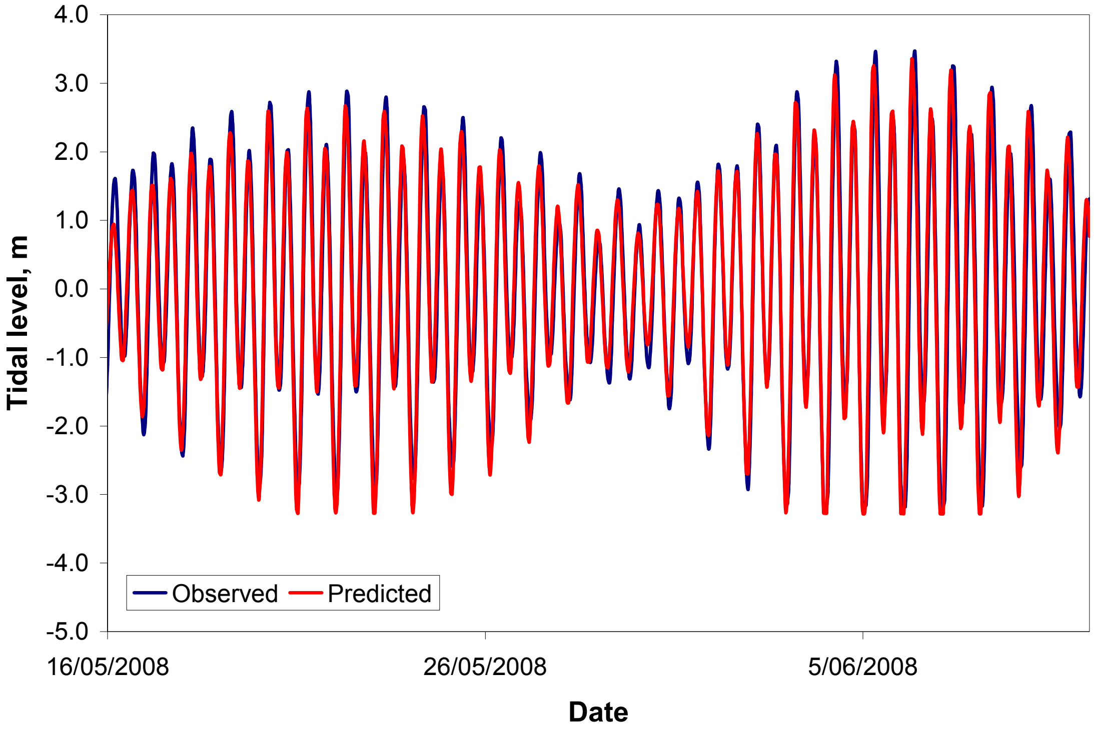


Figure 7: Inter-comparisons of measured and predicted tidal elevations: Results are shown for Gauge 1 (top panel) and Gauge 2 (bottom panel)



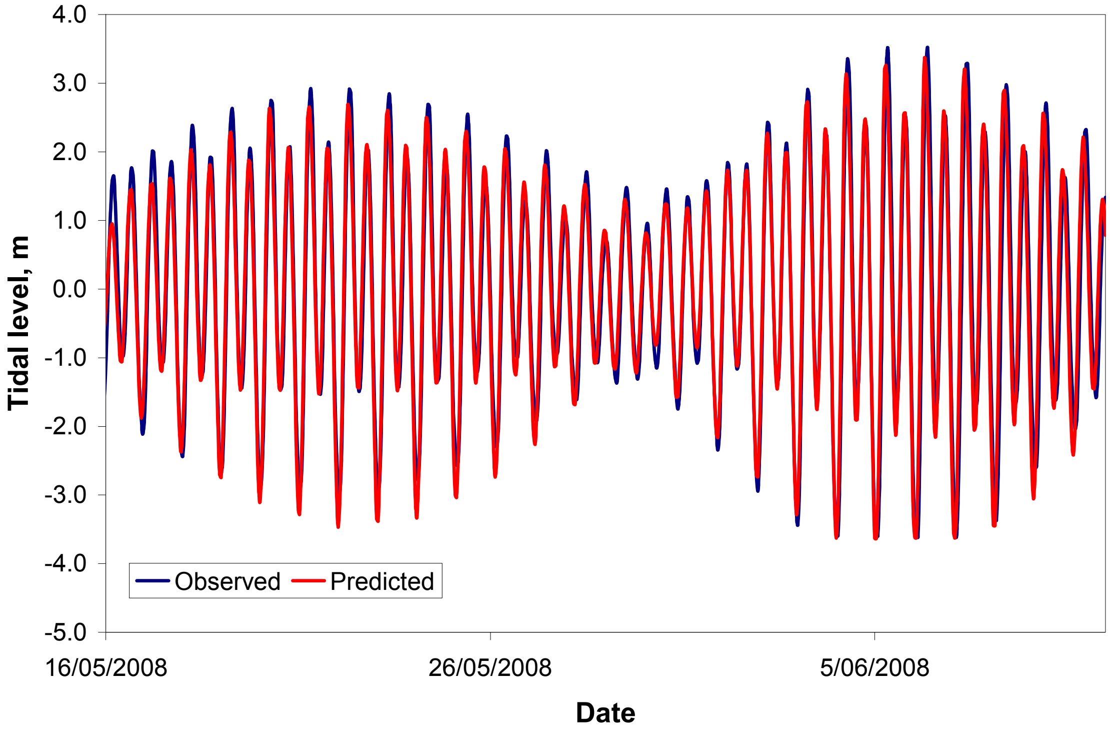


Figure 8: Inter-comparisons of measured and predicted tidal elevations: Results are shown for Gauge 3 (top panel) and Gauge 4 (bottom panel)

2.3.2 Current validation

Validation of BFHYDRO predictions for current speeds and directions was performed by comparing model predictions to measurements from ADCPs deployed in Darwin Harbour and Beagle Gulf. All ADCPs were bottom mounted and measured the currents at vertical steps through the water column. Data suitable for comparison to model predictions were available for 4 deployments. Data from 3 deployments (Monitor 1, Monitor 2 and Sentinel 1) were measured by APASA. Data from the 4th deployment (denoted as Wickham Pt) was measured by NRETA in February–March 2004. NRETA also provided ADCP measurements for several other sites for the years 2002 and 2004 but the data sets could not be used for comparison because the depth of the deployment and sea level records could not be supplied.

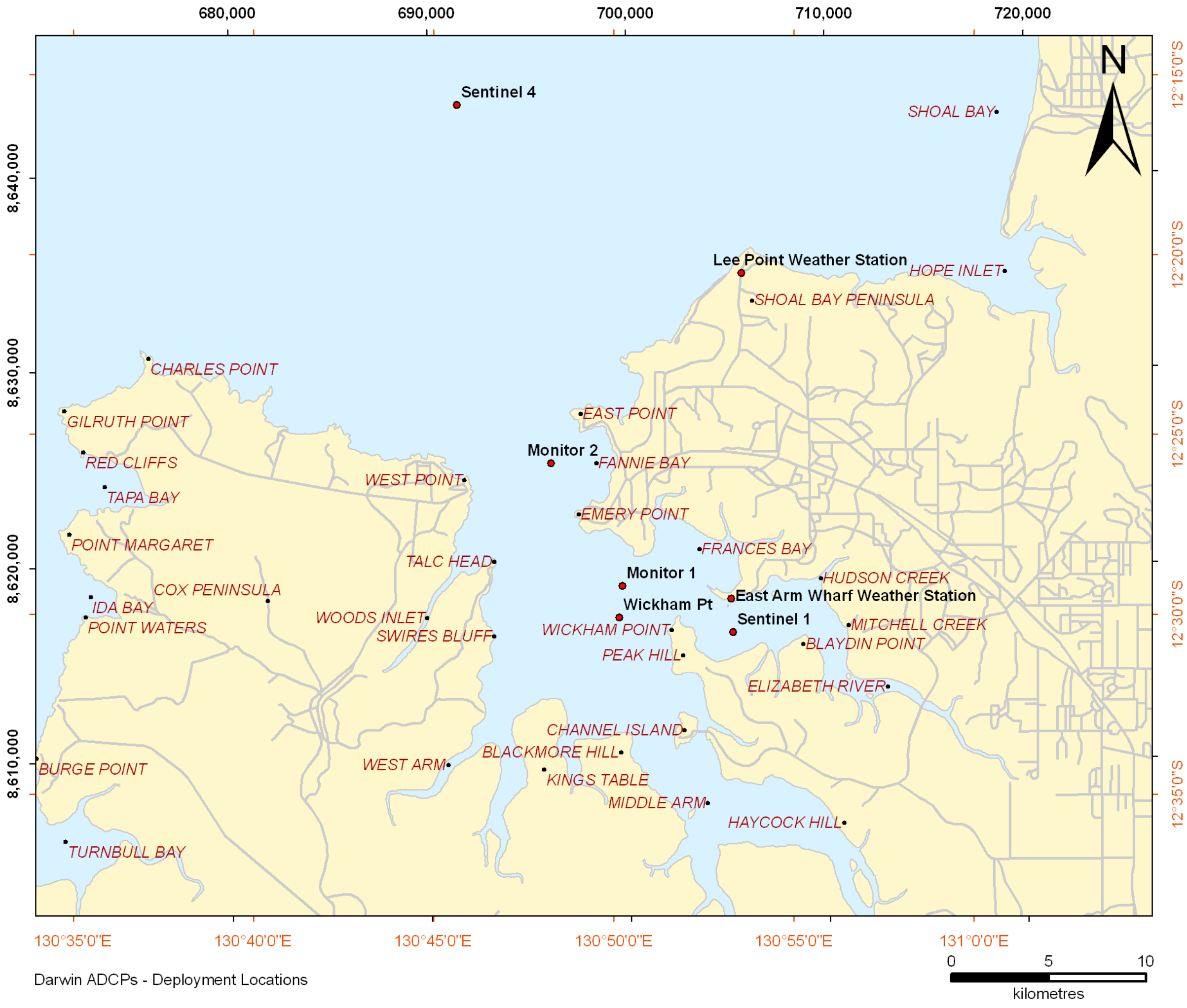


Figure 9: Locations of current and wind measurements used to validate current predictions

The hydrodynamic model predictions for current speed and direction were to be used to represent the patterns and variations in the prevailing currents in Darwin Harbour and adjacent Beagle Gulf. Hence it was most important for the model data to reproduce a representative distribution of the current speeds and directions. This was confirmed by comparing scatter plots of the observed and simulated currents, using model output for the closest model cell and depth corresponding to the instrumentation. Statistical analyses were also applied to quantify the scale of errors.

Comparison of scatter plots for predicted and observed current speeds and directions (Figure 10, Figure 13) demonstrated that the model was providing good simulation of the current speeds and directions of flow at each of the sites ranging from Beagle Gulf into East Arm. The observed current data were tightly distributed along a main axis at all sites, demonstrating the strong influence of tidal flow on circulation.

The measured data shows that the tidal axis is steered by the local bathymetry. At the Monitor 2 site, located near the entrance to the harbour, tidal currents flow along the axis of the main entrance channel, which is orientated north-north-west to south-south-east (Figure 10). Measurements at the closely located Monitor 1 and Wickham Pt sites, which are positioned across the entrance to East Arm, show the splitting of the tidal flow between East and Middle Arms. The tidal axis at Monitor 1 shifts to flow west-north-west to east-south-east (Figure 11) while the axis at Wickham Pt, where the flow is steered along the channel into Middle Arm, the prevailing tidal currents have a north-west – south-east orientation (Figure 12). At Sentinel 1 the major tidal axis is oriented along the channel into East Arm, running west-north-west to east-south-east (Figure 13). The model accurately predicted the tidal axis and the magnitude of currents at all sites for each of the depth levels indicating that the model was representing the magnitude and variations in currents throughout the areas of interest at a suitable resolution for the discharge investigations.

Statistical comparisons of the measured and observed current speeds and directions, at hourly time steps, also supported the validation of the model. The root mean square error in current speed was consistently low at all sites and depths, remaining within the limits 0.09–0.18 m s^{-1} (Table 1). The maximum deviations in predicted current directions were <10°.

Minor discrepancies between the observed and modelled speeds and directions are likely to be due to a combination of the accuracy and spatial resolution of the bathymetric grid and discrepancies between the time-step of the observed and modelled data (10 minute versus 1 hour, respectively). Due to the strong bathymetric steering of tidal currents, discrepancies in the necessarily smoothed representation of bathymetry used in the model would introduce errors in the current direction. Similarly, the longer time step of the model can miss-represent temporal changes in current speed and direction, particularly at the turning of the tide where changes are rapid (<1 hour). These are typical model limitations and the data comparisons indicate that their magnitudes would not introduce any serious errors into the environmental modelling.

Measurement at Wickham Pt was conducted during the wet season (February-March), while measurements at Monitor 1 and 2 were over the transition between the wet and dry season (April-May). The good fit of the data using forcing by wind and tide only indicated that it was reasonable to negate density and river inflow effects.

Table 1: Estimates of the root mean square errors in current speed (m s^{-1}) between currents predicted by the BFHYDRO model and observed using ADCP instruments

Location	Latitude South	Longitude East	Surface layer	Middle layer	Bottom layer
Monitor 2	12°25′48.8″	130°48′20.7″	0.18	0.18	0.18
Monitor 1	12°30′29.5″	130°53′19.2″	0.15	0.14	0.14
Wickham Pt	12°30′04.7″	130°50′09.2″	0.15	0.14	0.15
Sentinel 1	12°29′11.9″	130°50′14.6″	0.14	0.12	0.12

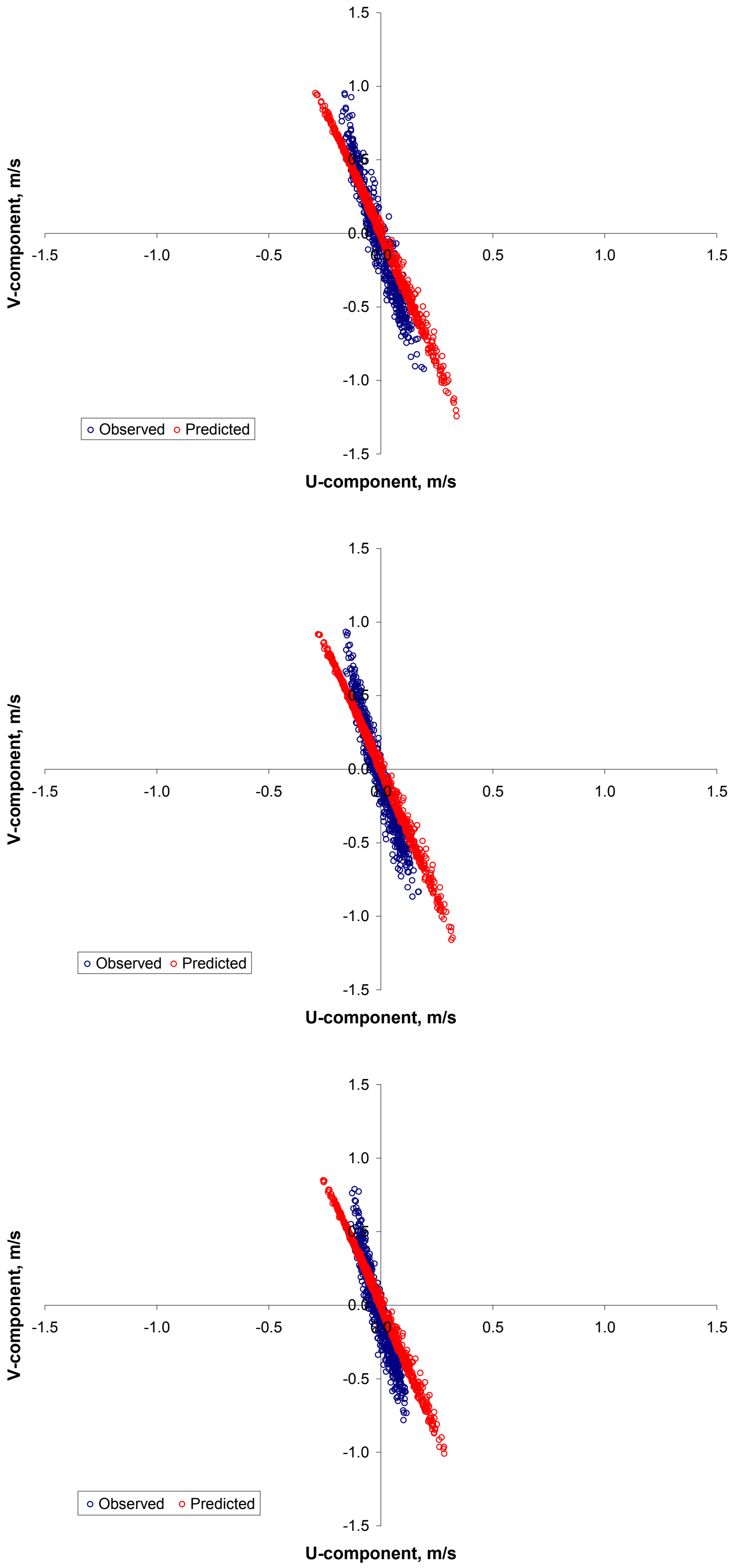


Figure 10: Comparison of currents observed at Monitor 2 site and simulated by BFHYDRO three-dimensional surface layer (top panel), mid-layer (middle panel) and bottom layer (bottom panel)

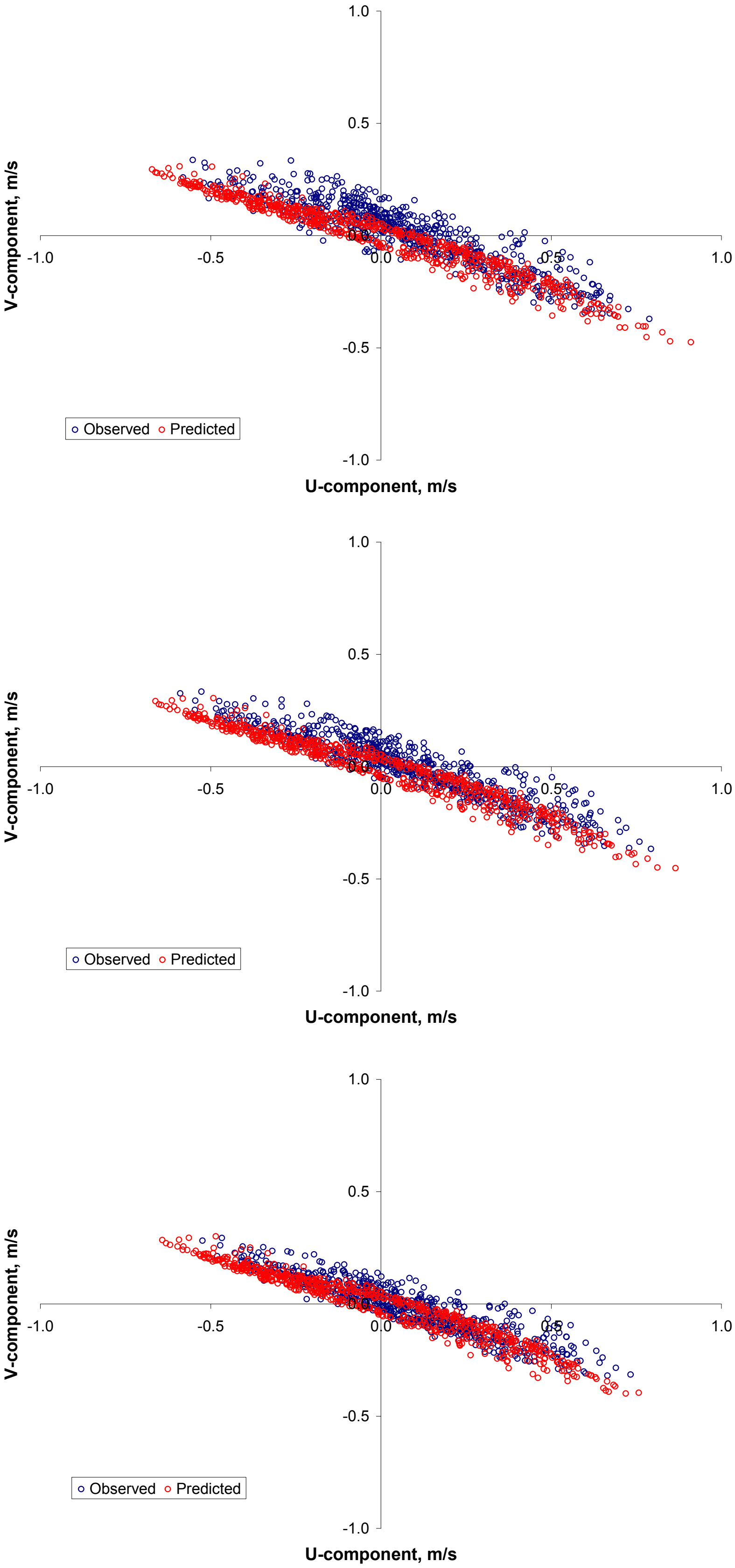


Figure 11: Comparison of currents observed at Monitor 1 site and simulated by BFHYDRO three-dimensional surface layer (top panel), mid-layer (middle panel) and bottom layer (bottom panel)

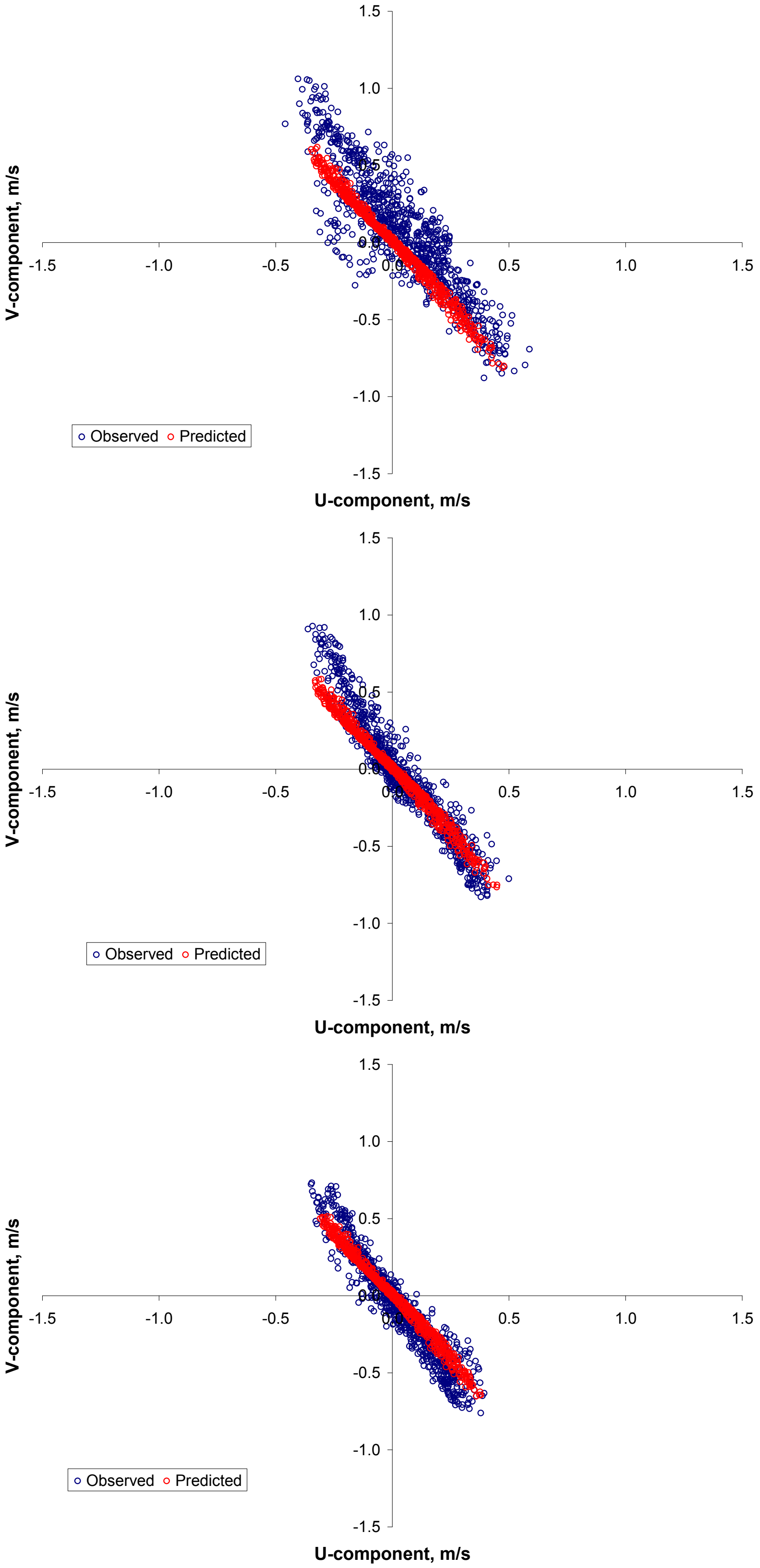


Figure 12: Comparison of currents observed at Wickham Pt site and simulated by BFHYDRO three-dimensional surface layer (top panel), mid-layer (middle panel) and bottom layer (bottom panel)

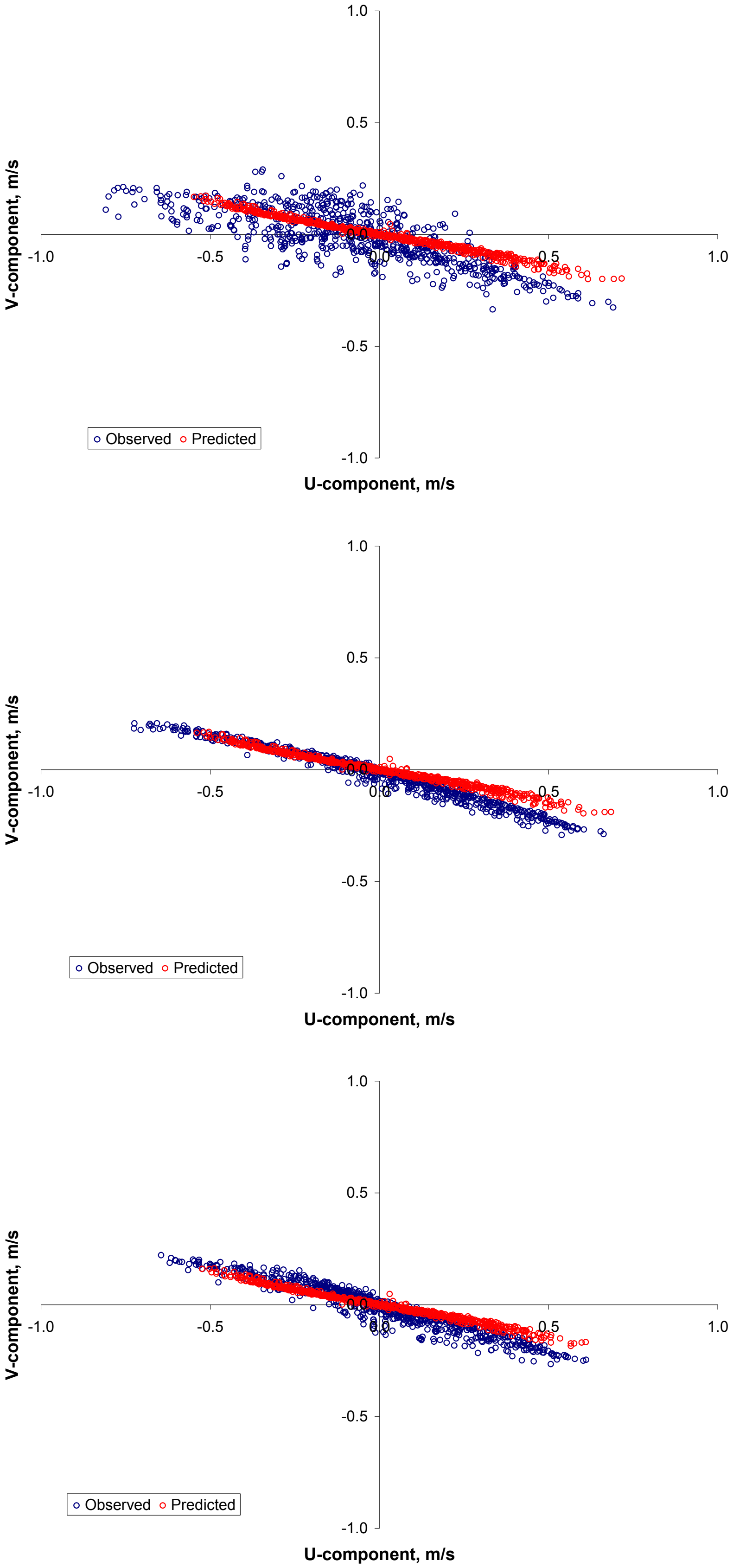


Figure 13: Comparison of currents observed at Sentinel 1 site and simulated by BFHYDRO three-dimensional surface layer (top panel), mid-layer (middle panel) and bottom layer (bottom panel)

2.4 General description of the hydrodynamic model applied offshore from Darwin Harbour

The HYDROMAP hydrodynamic model was applied to represent current circulation over the wider region beyond Darwin Harbour, for applications where the discharge location and potential migrations were outside of the Darwin Harbour model.

HYDROMAP is an ocean and coastal circulation model that simulates the flow of ocean currents within a model region due to forcing by astronomical tides, wind stress and bottom friction and can assimilate current vectors from other sources (e.g. large-scale drift currents). The model has been designed for efficient relocation to any region on the globe. A local grid is generated to fit the geometry of the area of interest. Local specifications are used for the bathymetry, tidal forcing, wind field, seabed drag and other forcing.

HYDROMAP follows the finite-difference solutions for regular grids (Davies 1977a & b; Owen 1980) further developed to employ a space-staggered gridding strategy to support two-way nesting over sub-areas (Gordon 1982; Isaji & Spaulding 1984; Isaji et al. 2001). The grid may contain multiple areas of sub-gridding and each sub-grid may have up to six levels of spatial resolution in the horizontal plane. Each level of sub-gridding results in the subdivision of cells into four equal sized cells. Thus, each level of gridding results in halving of the horizontal scale and six levels of sub-gridding can result in a 64 times reduction in grid cell size (and therefore increase in spatial resolution) within the one domain. Calculations for the continuity of mass and momentum are calculated across all levels of sub-gridding on the same time step. The model therefore generates a continuous current field spanning all levels of resolution. A practical advantage of this scheme is that the spatial resolution of circulation patterns can be optimized for areas of high interest or hydrodynamic complexity, such as channels and passages between islands, while the current field can also span a larger domain. These characteristics make the model particularly well suited to simulating pollutant transport in complex coastal areas. Proofs of the general accuracy of the scheme and freedom from numerical artefacts are provided in Isaji et al. (2001).

HYDROMAP has been widely applied to studies of hydrodynamic circulation and the fate of spills and discharges on the Northwest Shelf and over the Timor Sea for several years. Satisfactory validations of the model algorithms have been demonstrated in multiple comparisons against current measurements and drogue tracks at many sites. The model is the hydrodynamic engine used by the Australian National Oil-spill Response System (AMSA) and the Western Australian marine search and rescue system (WA Police).

HYDROMAP is a barotropic forcing model, which means that it uses variations in sea level due to astronomical tides and ocean set-up together with wind shear and seabed drag effects to calculate circulation over a model domain. The model may be used to calculate depth-averaged or depth-varying circulation.

Forcing due to astronomical tidal variations is specified from tidal constituent values that define the wavelength and amplitude of individual tidal constituents. Unique values for tidal constituents may be entered to each boundary cell within the model domain, providing for high spatial variability in tidal forcing. The model is configured to interpolate tidal constituent values from previous simulations over a wider domain or directly from established databases of gridded tidal data (e.g. Topex/Poseidon undated; Schwiderski 1980).

2.4.1 HYDROMAP model setup for this study

HYDROMAP was set up over two domains, one focusing on the waters immediately offshore from Darwin Harbour (Inshore model), the other focussing over waters surrounding the proposed location of the offshore production facilities in the Browse Basin (Offshore model).

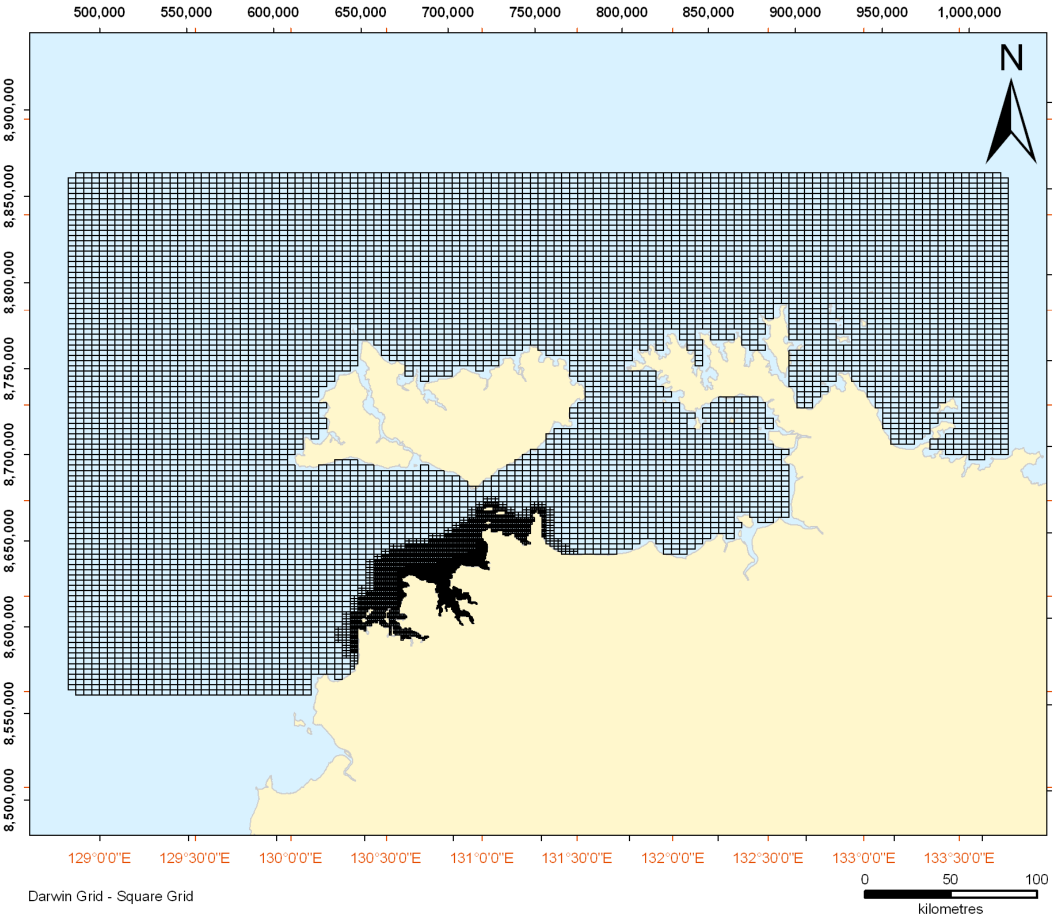
Inshore model

The domain for the inshore model covered the main channels of Darwin Harbour and extended over a large seaward area (total domain size: 540 km by 305 km), encompassing Bathurst and Melville Islands as well as Beagle and Van Diemen Gulfs to ensure that there was good exposure to tidal variation resolved from satellite-derived tidal data for the Timor Sea and that the resulting current fields would cover the potential migration distance of discharges under study (Figure 14). Cell sizes were varied in a space-staggered fashion from 4000 m by 3000 m, at the outer boundaries, down to 275 m by 190 m inside Darwin Harbour. The sources of the bathymetric data for the HYDROMAP model domain were the same as for the model domain used in the BFHYDRO set up (Section 2.2). Similarly, tidal input at the outer boundary of the model domain was specified by spatially-interpolating the phase and magnitude of tidal constituent data from the Topex/Poseidon v7.0 global tidal database as per the BFHYDRO application.

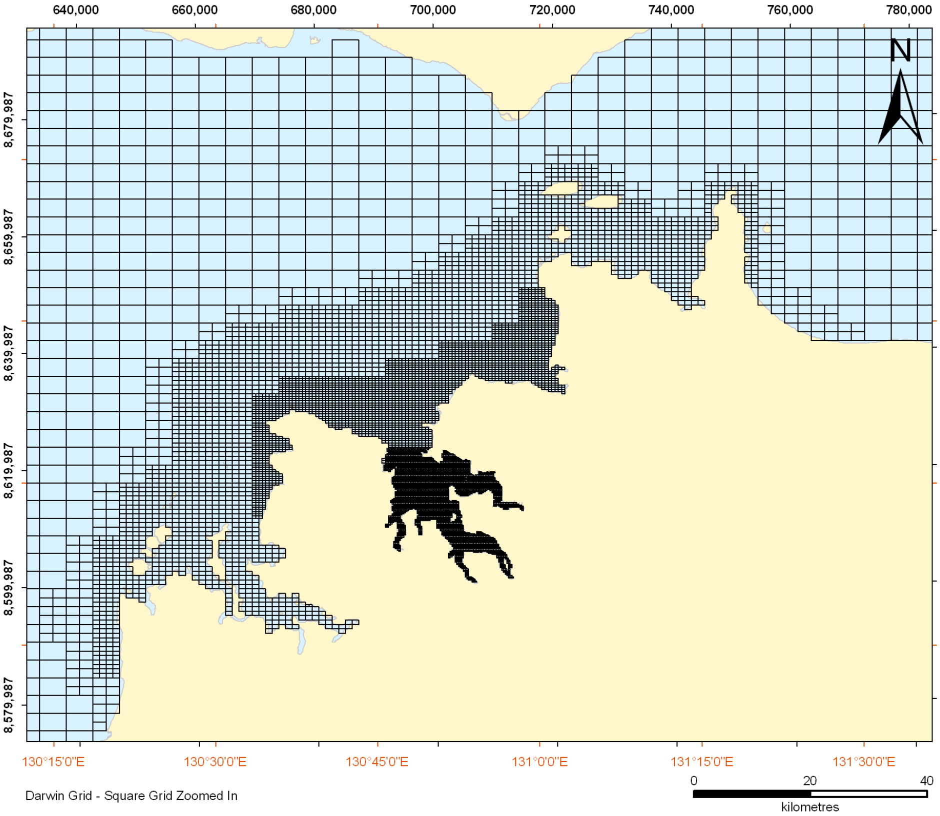
Offshore model

To correctly propagate tidal and wind forcing over the outer shelf waters around the CPF location, HYDROMAP was set up over a space-staggered grid covering 720 km by 655 km (Figure 16). The grid was optimised for the large domain, and with the lower spatial variation in currents that occur in deeper water, spatial resolution was relaxed. Spatial variation at the outer boundaries was set at 5000 m. Three levels of spatial subgridding were applied to increase the resolution up to 1200 m around islands and into the nearshore waters off the Australian coast. The bathymetric grid was developed from the 250 m-scale bathymetric data set developed by Geoscience Australia and tidal forcing was specified by interpolation of the Topex Poseidon gridded tidal database (NOAA).

An analysis of wind measurements available for the outer shelf in the area of the CPF showed that there are two prominent wind seasons. From October till February, winds prevail from the west. There is then a rapid shift to easterly winds, which prevail from May to July. Two transition periods occur between these longer periods, usually March–April and August-September, when there is no clear prevailing wind direction. Modelled wind data were available for multiple years for the outer shelf from the NCEP/NCAR atmospheric reanalysis project, developed by the NOAA Earth System Research Laboratory. The database is generated from atmospheric modelling system that assimilates and hindcasts from weather observations (Kalnay et al. 1996). The NCEP/NCAR wind data provided an uninterrupted data set spanning multiple years (1999-2006), with representation of spatial variation over the shelf. The data closely reproduced the seasonal distributions represented by measured data from the Australian Bureau of Meteorology stations at Browse and Troughton Islands.

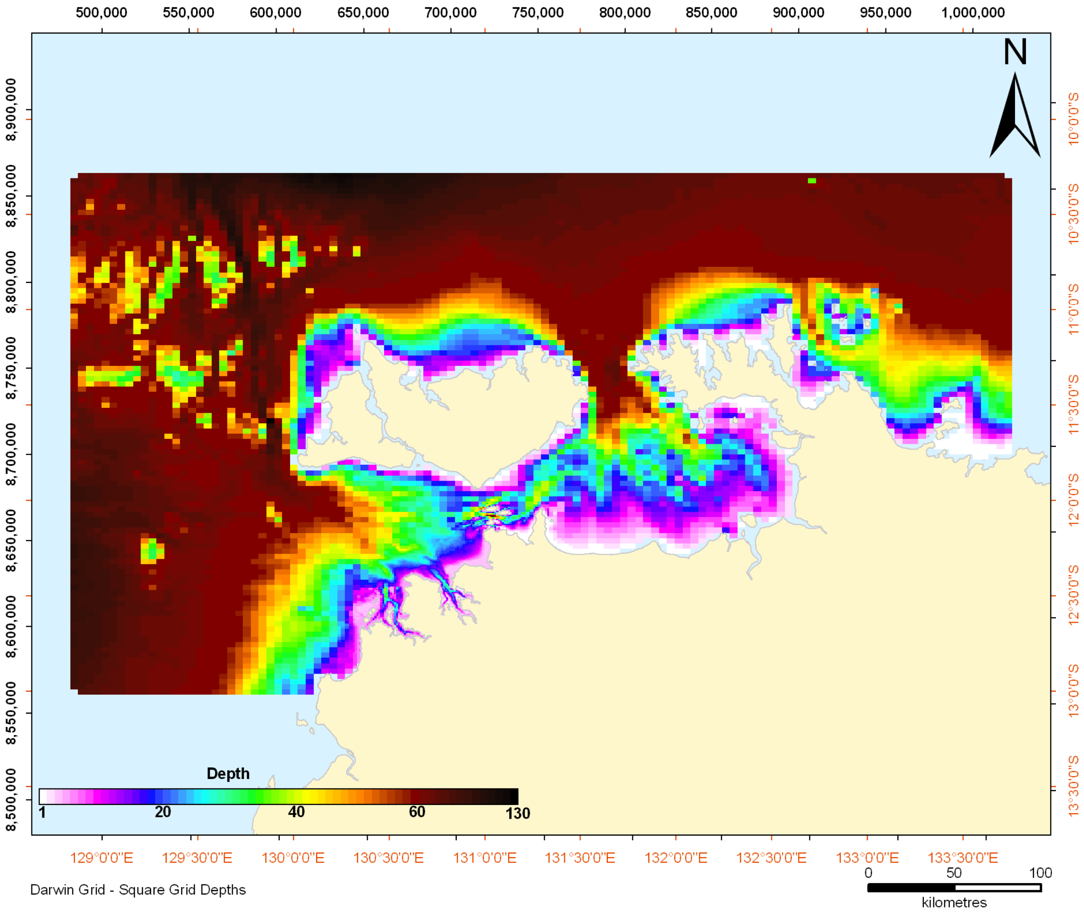


Darwin Grid - Square Grid

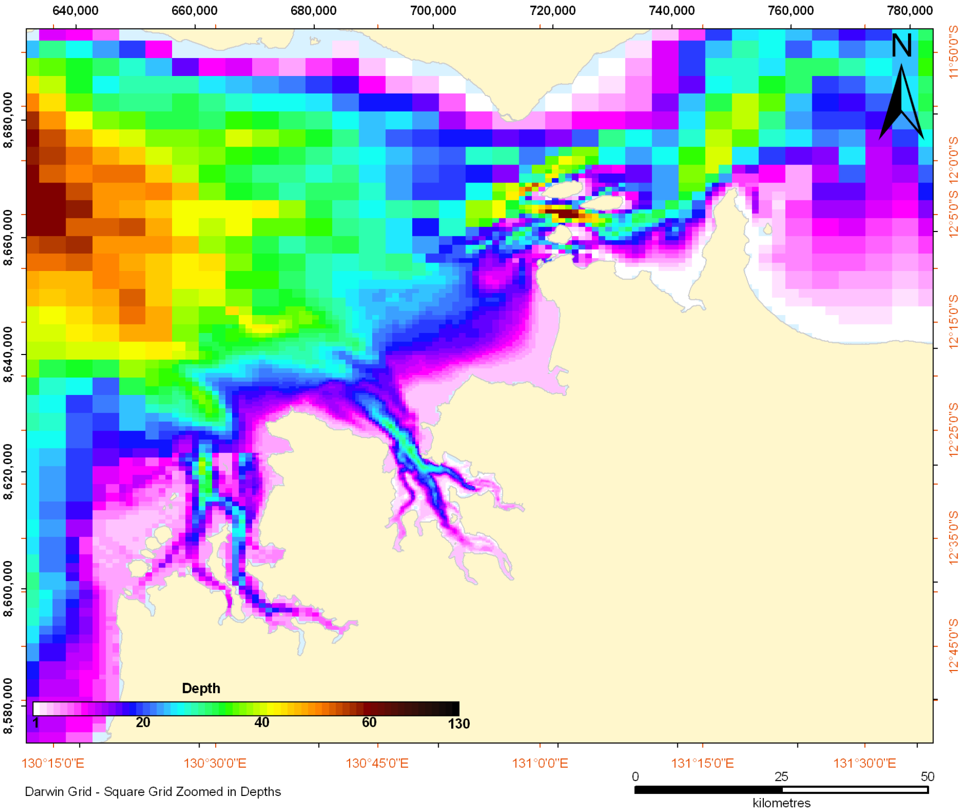


Darwin Grid - Square Grid Zoomed In

Figure 14: Computational grid developed for the HYDROMAP Inshore model. The lower panel shows a zoomed view with details of the space-staggered grid



Darwin Grid - Square Grid Depths



Darwin Grid - Square Grid Zoomed in Depths

Figure 15: Bathymetric grid defined for the HYDROMAP Inshore model

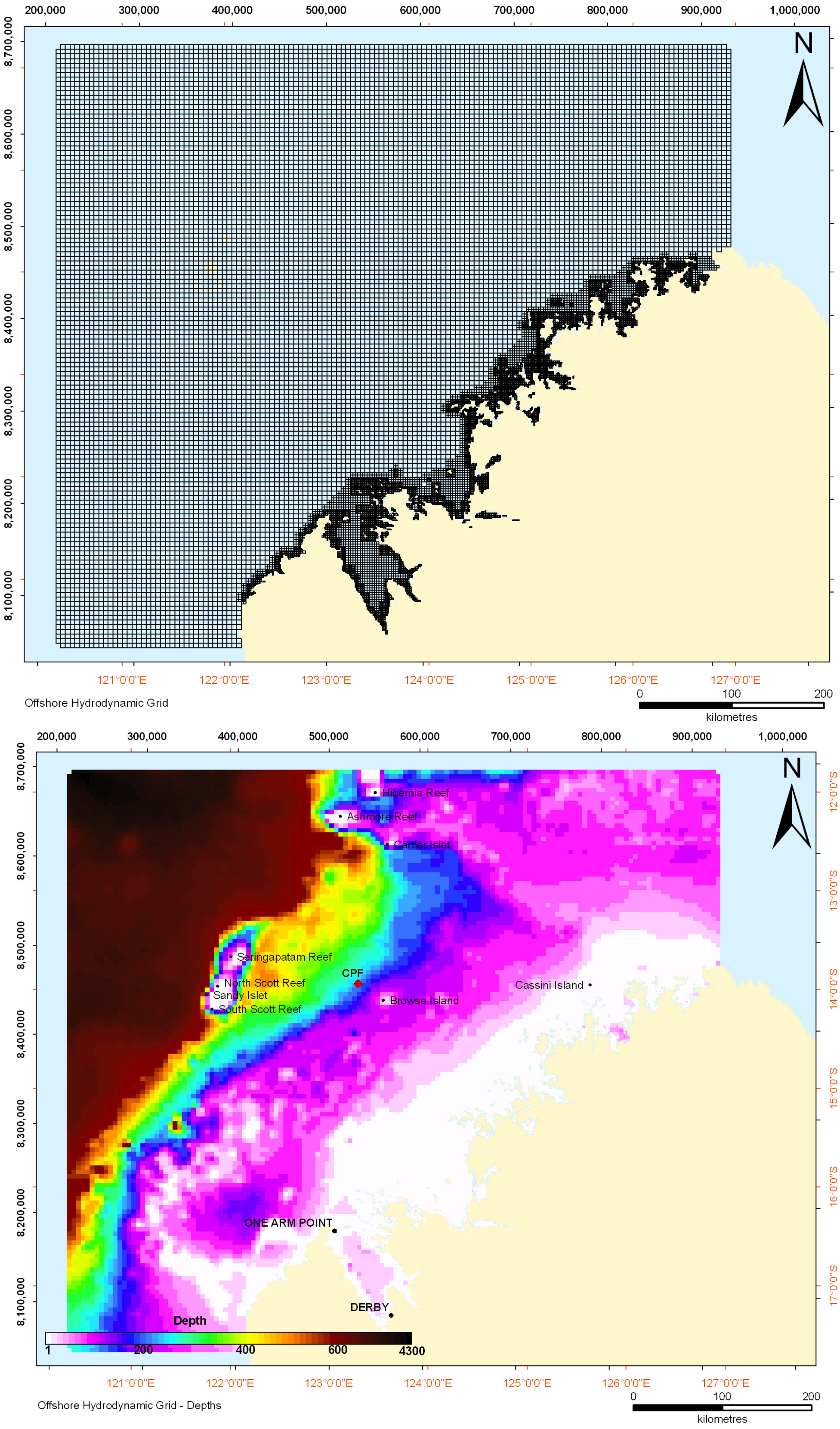


Figure 16: Computational grid (top) and bathymetry (bottom) developed for the HYDROMAP Offshore model

2.4.2 Validation of the HYDROMAP configurations

Inshore model

Validation of the HYDROMAP configuration for the inshore model was performed by comparing model predictions to measurements from an ADCP deployed at a location near the proposed spoil ground (Sentinel 4; Figure 9). Measurements spanned the period 8 October–5 November 2008. The ADCP was bottom mounted and measured the currents at discrete levels throughout the water column.

Measurements showed that currents at this site flowed over a tidal axis that was orientated approximately east-west at speeds up to 1 m s^{-1}. The spread of measurements around the east-west axis was wider at this offshore site indicating that the current direction swings with the tidal state. Variations are also marginally larger at the surface, indicating increased influence of wind forcing on the resulting currents. The modelled data closely complied with the distribution of the observed data in terms of the tidal axis, range of magnitudes and the variations with depth.

Comparison of modelled and measured data, at an hourly time step, indicated high correlation coefficients between the simulated and observed current components. Correlations ranged from 0.73 to 0.95 depending on the axis and depth level, and were highest for the mid to deep layers (Table 2). The root mean square error in the magnitudes of the simulated current speeds was within the limits 0.16–0.25 m s^{-1}, smallest in the near-bottom water layer and largest in the near-surface layer. The mean error in the current speeds was estimated at 0.04 m s^{-1} at the surface, increasing to -0.09 m s^{-1} at mid depth and -0.12 m s^{-1} near seabed (Table 2). The small negative errors in the mid to bottom layer indicates that current speeds were marginally underestimated at lower depths. The absolute mean error in the values of the simulated current directions were 3° at the seabed rising to 11° at the surface. Collectively, the comparisons indicated that the inshore HYDROMAP model produced predictions for the current speed and direction that were suitable for representing three-dimensional currents over the approach to Darwin Harbour, including the proposed spoil ground.

Table 2. HYDROMAP validation statistics

	Surface layer	Middle layer	Bottom layer
U correlation coefficient	0.73	0.84	0.95
V correlation coefficient	0.75	0.92	0.80
Speed RMSE (m s^{-1})	0.25	0.18	0.16
Speed ME (m s^{-1})	0.04	-0.09	-0.12
Direction ME (°)	-11	-4	-3

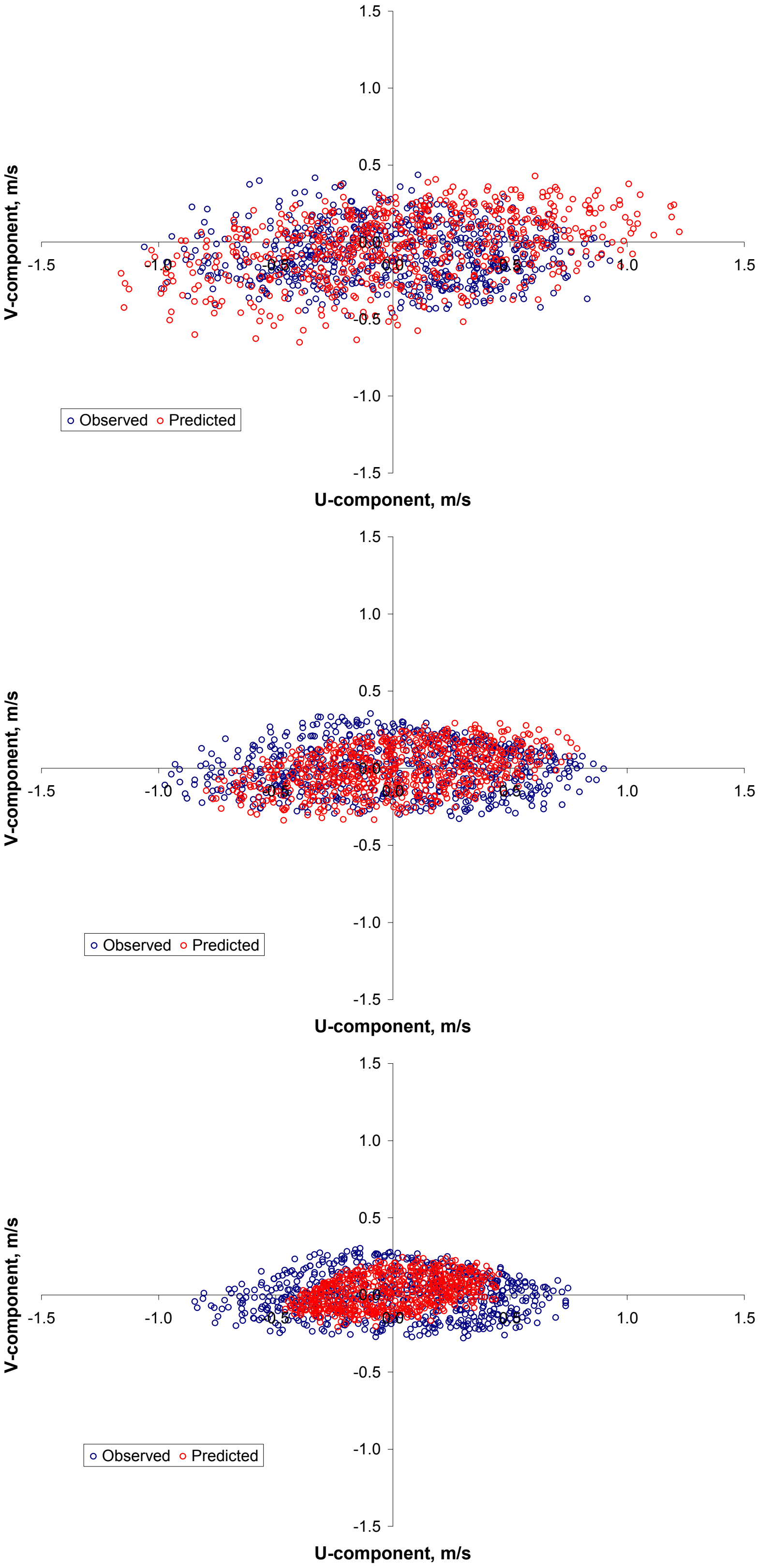


Figure 17: Comparison of currents observed at Sentinel 4 site and simulated by HYDROMAP (Inshore model) in surface layer (top panel), mid-layer (middle panel) and bottom layer (bottom panel)

Offshore model

The accuracy of the offshore model was validated against tidal elevation and current records available from a current meter deployed by MetOcean Engineers at the Titanichthys site over two periods (16-30 September 2004 and 16-31 January 2005; Figure 18). Current measurements were at approximately 15 m below mean sea level.

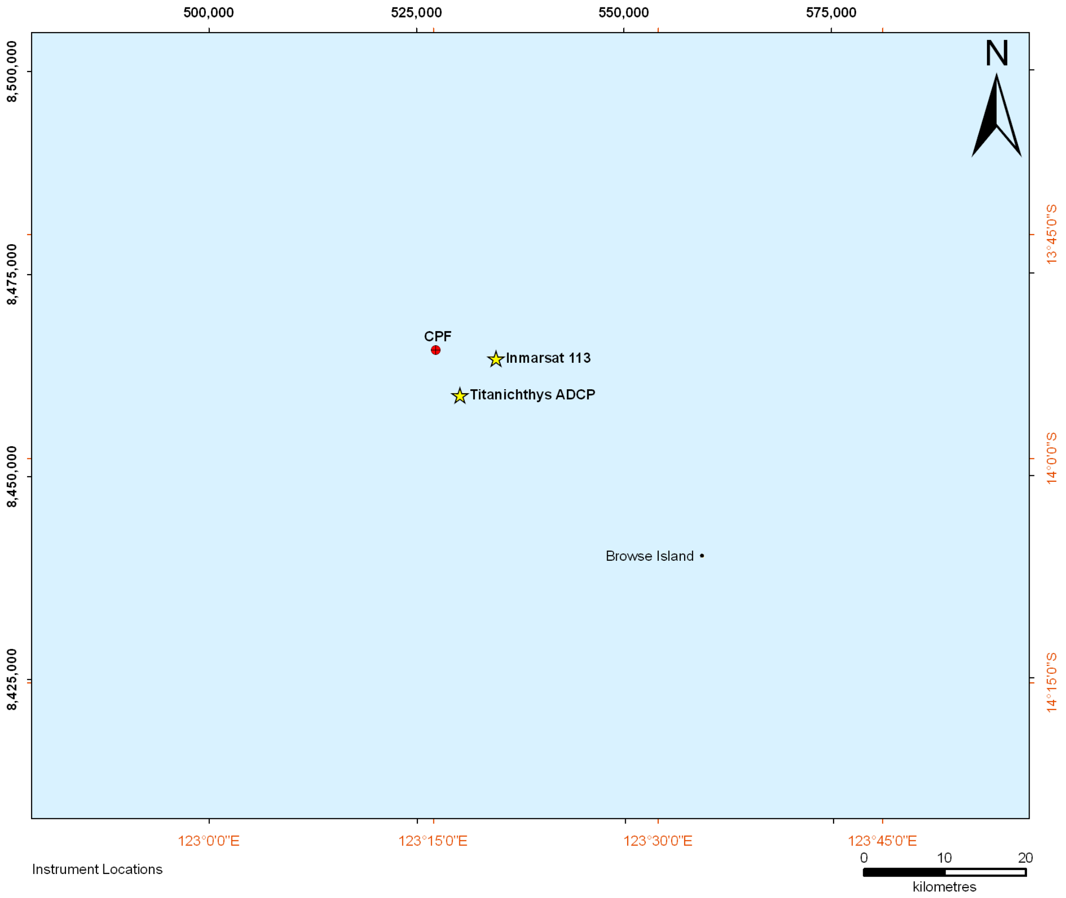
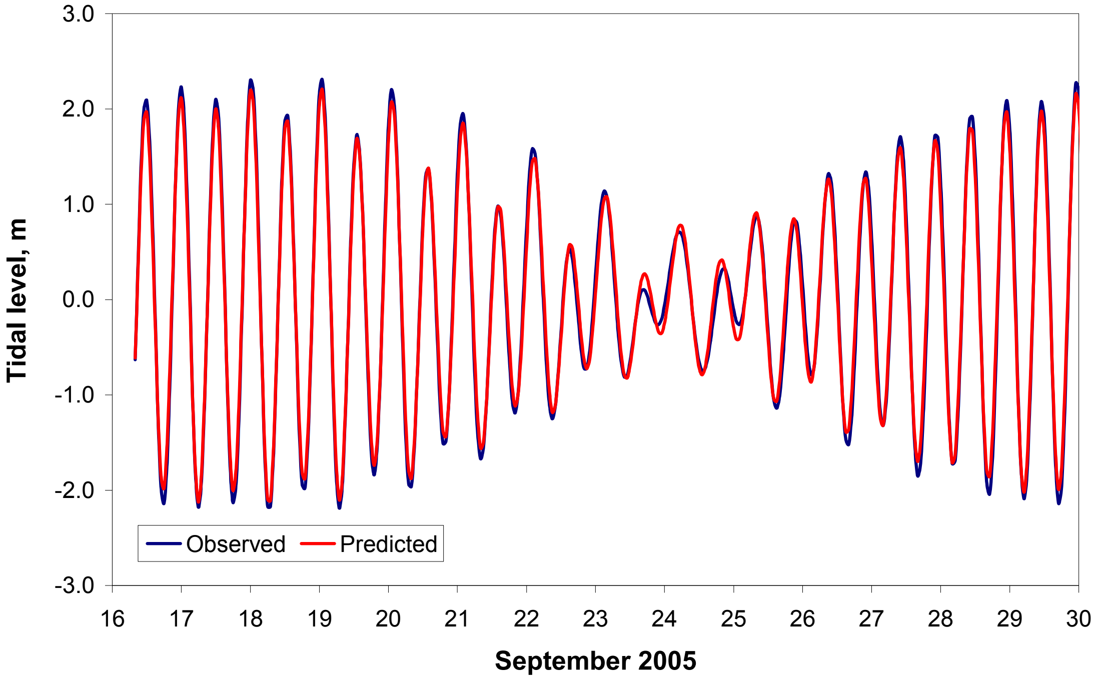


Figure 18: Locations of current measurement (Titanichthys ADCP) and wind measurement (Inmarsat 113) in proximity to the proposed CPF location

Time series plots of the predicted and measured tidal variations over both measurement periods (Figure 19) demonstrated that the HYDROMAP model was closely predicting the timing and magnitude of the tides. HYDROMAP accurately estimated the magnitude of current speeds (range 0-0.5 m s^{-1}) but tended to show increase influence of the wind at the depth of the current measurements (~15 m below surface), due to the thickness of the model output layers (~20 m) in the depth of water over the site.



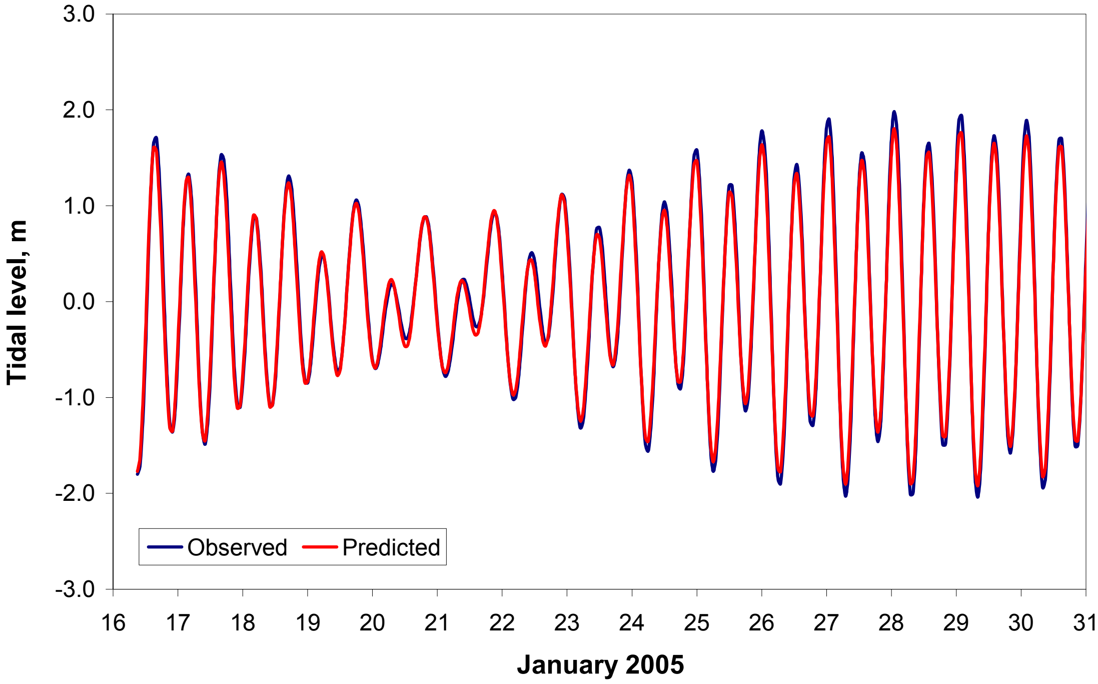
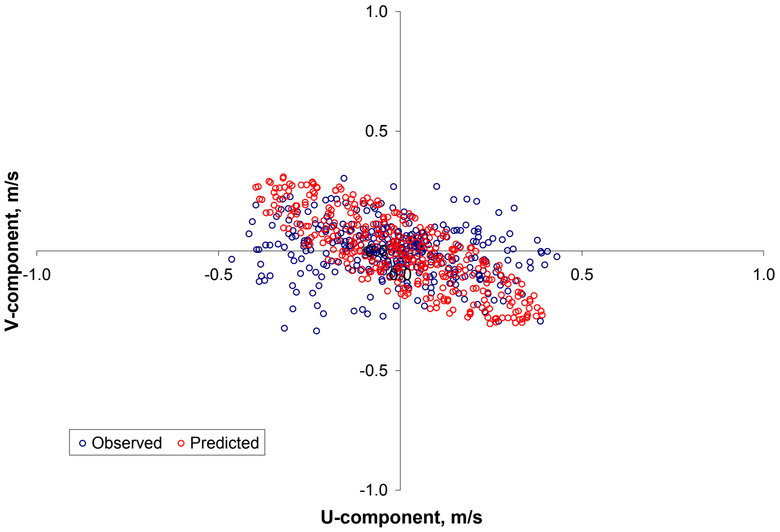


Figure 19: Tidal elevations predicted by HYDROMAP (Offshore model) and observed by gauging at the Titanichthys site. Upper panel covers the period 16-30 September 2004. Lower panel covers the period 16-31 January 2005



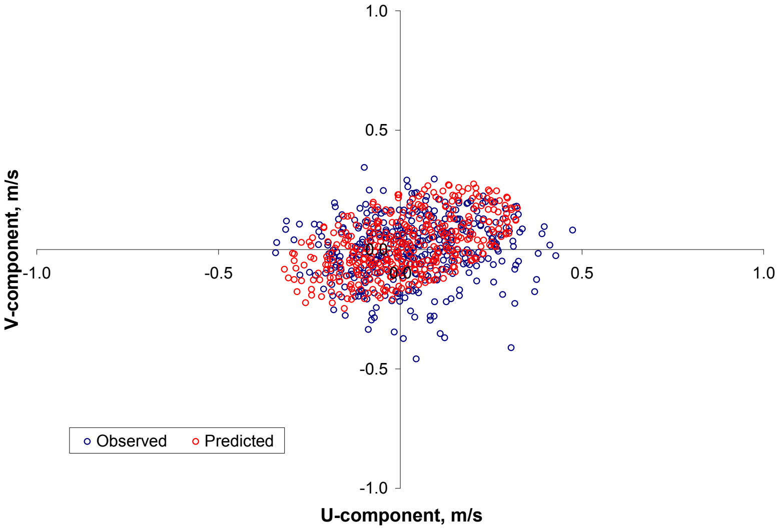


Figure 20: Comparison of current speeds and directions predicted by HYDROMAP (Offshore model) and observed by gauging at the Titanichthys site. Upper panel covers the period 16-30 September 2004. Lower panel covers the period 16-31 January 2005

3 DEVELOPMENT OF WAVE DATA

3.1 General description of the wave model applied to Darwin Harbour and approaches

Waves can play an important role in sediment transport processes within shallow water. The Simulating Waves Nearshore (SWAN), phase-averaging, wind-wave model was used to account for wave influences on sediment disposal operations offshore from Darwin Harbour. SWAN was initially developed by Delft Hydraulics with support from the Office of Naval Research (USA) and Rijkswaterstaat (the Ministry of Transport, Public Works and Water Management, the Netherlands). The model has since been implemented and extended through research and applied studies around the world, including Australia (e.g. Holthuijsen et al. 1997; Ris 1997; Makarynskyy et al. 2001).

SWAN is a third-generation numerical wave model that accounts for effects of wave generation by wind and dissipation by white-capping, depth-induced wave breaking, bottom friction, and redistribution of wave energy by non-linear wave to wave interactions. SWAN accounts for most of the wave-propagation processes over shallow water, including: propagation through geographic space, refraction, diffraction, reflection from obstacles, shoaling due to bottom and current variations, blocking and reflections by opposing currents and transmission through or blockage by sub-grid obstacles. Input data that is required for modelling over coastal areas include wave spectra data for the open boundary, which is important to represent the input of swells that are not generated locally. Local wave generation and modification uses specification of the bathymetry, surface wind, currents and sea level variations. The effects of changing water levels and currents are important input variables for a wave model. Water levels affect both wave breaking and wave refraction due to alteration of water depth. Currents mainly affect the wave refraction but also contribute to wave setup.

3.2 Wave model setup for Darwin Harbour and approaches

The SWAN model was set up to operate on the same boundary conforming grid that was used for current predictions using the BFHYDRO model (Section 2.2). The benefit of this approach was that the wave model could use elevation and current data predictions from BFHYDRO as direct input, on a cell by cell basis, while accounting for dynamic wetting and drying of the intertidal zones. In addition, the wave output data was produced on a consistent spatial grid as the current data, which was optimal for the proposed application of this data to sediment disposal studies.

The SWAN model uses estimates for the significant wave height and period of waves arriving at the boundary of the model to represent the propagation of swell waves from offshore waters. Thus, to hindcast the wave regime over a given period it is important to have suitable estimates of the swell climate outside of the model domain. From a review of available wave data for the study area, the source that offered the best definition of temporal and spatial variability of wave conditions over the wider study area were operational wind and wave hind-casts produced by the US National Oceanic and Atmospheric Administration (NOAA) at the National Centre for Environmental Prediction (NCEP; e.g. Kalnay et al. 1996).

NCEP produces operational forecasts for wind and wave conditions from global-scale models, including the Global Forecast System (GFS), which produces wind hind-casts based on the Global Data Assimilation System (GDAS) (e.g. Caplan et al. 1997; Kanamitsu et al. 1991) and the wave model WAVEWATCH III (WWIII) (Tolman 2002a). Operational ocean-wave hind-casts and predictions that are performed with WWIII predictions using GFS wind input are termed NWW3 (as an acronym for NOAA WAVEWATCH III). These hind-casts have previously been validated against ocean buoy wind/wave records in many experiments (e.g. Tolman 2002b). Outputs of NWW3 (the significant wave height, H_s; the mean wave period, T_p; and the direction of the peak period, D_p) were extracted from the computational point closest to the area of interest (12°S, 130°E) and used as wave boundary data.

3.3 Validation of the SWAN model

Investigation of the observed wave data for the three ADCP deployments, ranging from Beagle Gulf to East Arm, indicated that swells, with a peak period of 9 s, were being generated locally within Darwin Harbour and Beagle Gulf at the time of these deployments, rather than projecting in from deeper offshore waters.

The global scale NWW3 has coarse spatial resolution of 1.25° by 1.25° and the boundary data was found to be limited because it did not represent this locally generated swell. However, the magnitudes of these locally generated swells were observed to be very small (< 30 cm), indicating that wave processes under non-cyclonic conditions would not typically be providing sufficient forcing for sediment resuspension.

Figure 21, Figure 23 and Figure 25 show that the model was responsive to the forcing conditions provided by the NWW3 model and was calculating the propagation of waves across the domain at a suitable scale. Bottom orbital velocities computed from both the measurements and the model results were generally very small with magnitudes below 0.06 m/s (Figure 22, Figure 24, Figure 26). Such bottom orbital velocities are one order of magnitude smaller than the tidal current velocities observed in the area, indicating a small effect on bed shear stress.

To confirm this, Figure 27 to Figure 29 show time series of current speeds and significant wave heights measured at inner harbour (Sentinel 1 and Monitor 1) and outer harbour (Sentinel 4) deployment sites as well as bed shear stress computed on the basis of the ADCP measurements. Currents at all these sites were strong (up to 1 m s^{-1}) and of a similar order of magnitude. At the same time, significant wave heights were small - from about 0.20 m at the inner harbour Monitor 1 site up to 0.40 m at the outer harbour Sentinel 4 site. Bed shear stress (calculated using the Sentinel 1, Monitor 1 and Sentinel 4 current and wave measurements) was clearly dominated by the tidal current with very minor input from wind waves. The calculated bed shear stress values (below 4 Pa in the harbour and up to 5 Pa out of it) imply that, at these sites, the tidal currents can resuspend particles coarser than coarse sand. On the other hand, an analysis of the wave parameter magnitudes supported the conclusion that wave processes would not typically provide efficient forcing for resuspension of finer particles under non-cyclonic conditions, and thus would play a minor role in sediment transport in Darwin Harbour and in Beagle Gulf.

Analysis of the NWW3 data showed that swell period waves were represented at low frequency during and outside of the periods of the ADCP measurements and these were represented in the SWAN model output. Hence, the SWAN data was considered suitable for representing short-duration wave effects of sufficient magnitude to affect resuspension in the sediment fate modelling.

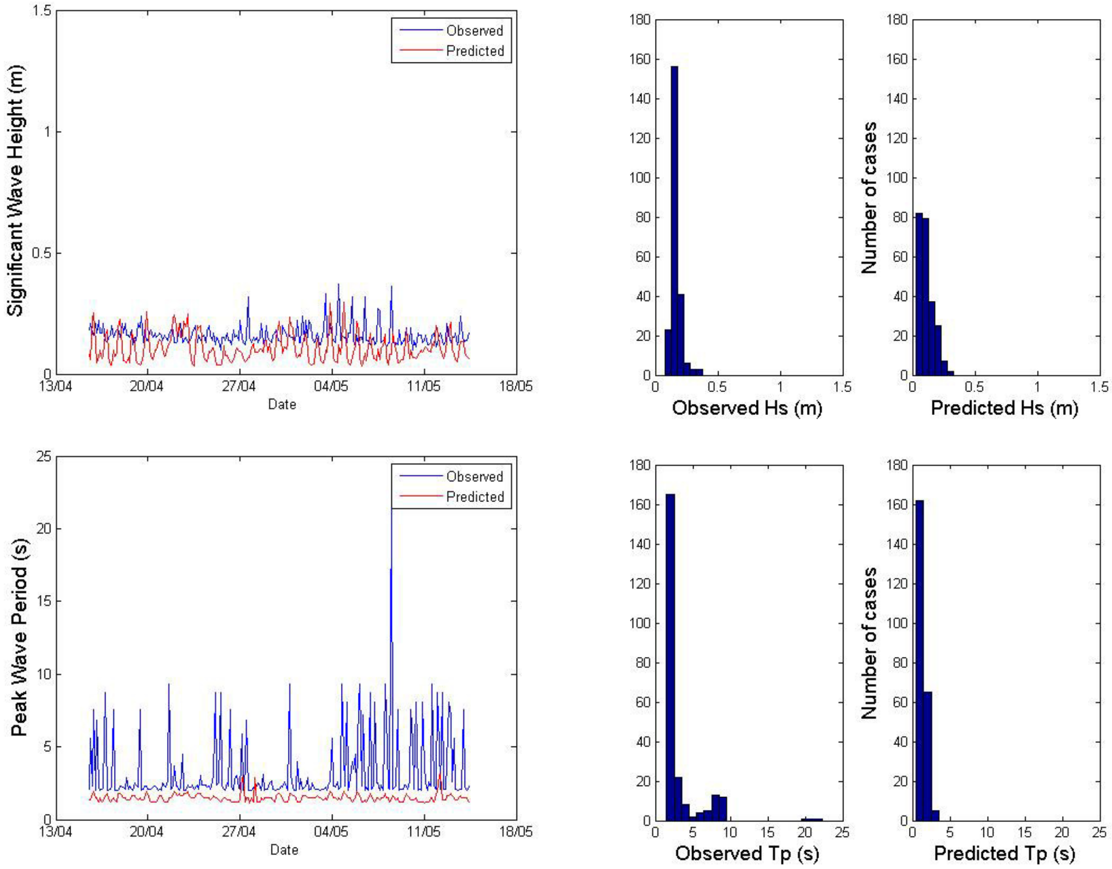


Figure 21: Inter-comparisons of observed and predicted significant wave heights and peak wave periods at the Sentinel 1 location

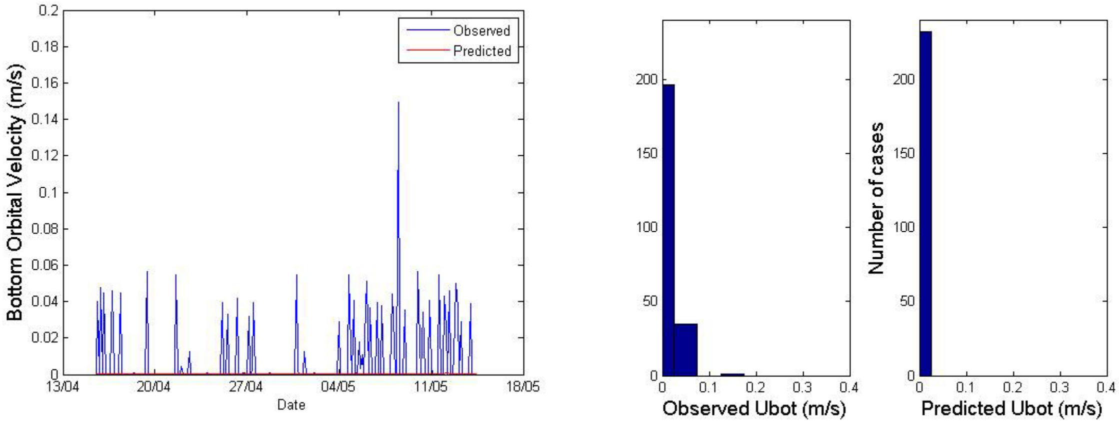


Figure 22: Inter-comparisons of bottom orbital velocities computed from observations and predictions at the Sentinel 1 location

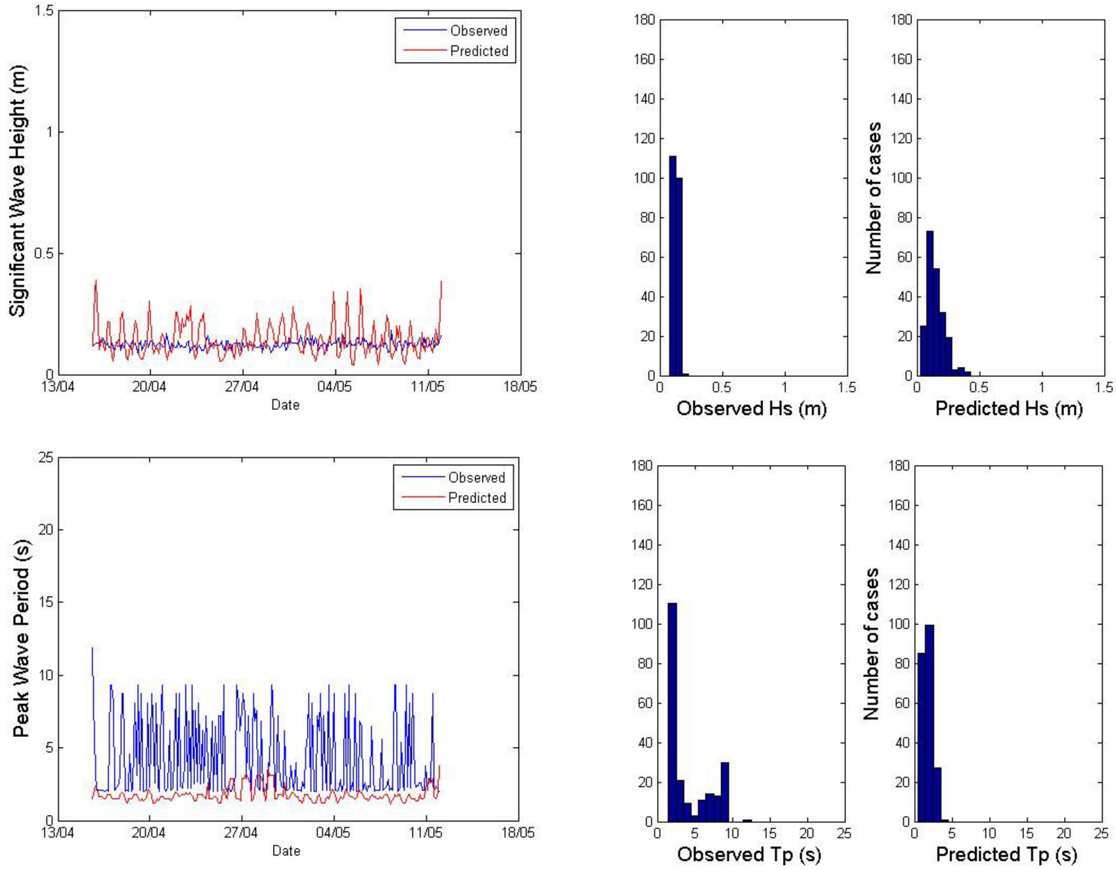


Figure 23: Inter-comparisons of observed and predicted significant wave heights and peak wave periods at the Monitor 1 location

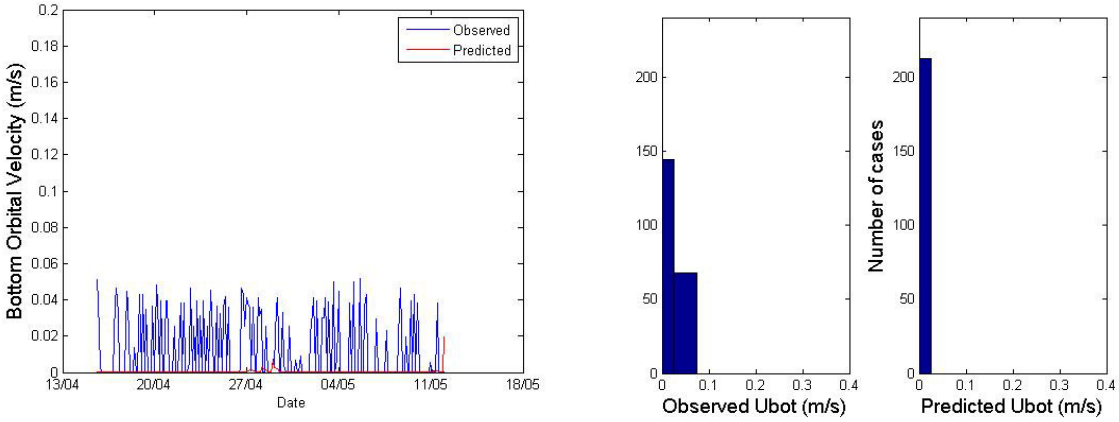


Figure 24: Inter-comparisons of bottom orbital velocities computed from observations and predictions at the Monitor 1 location

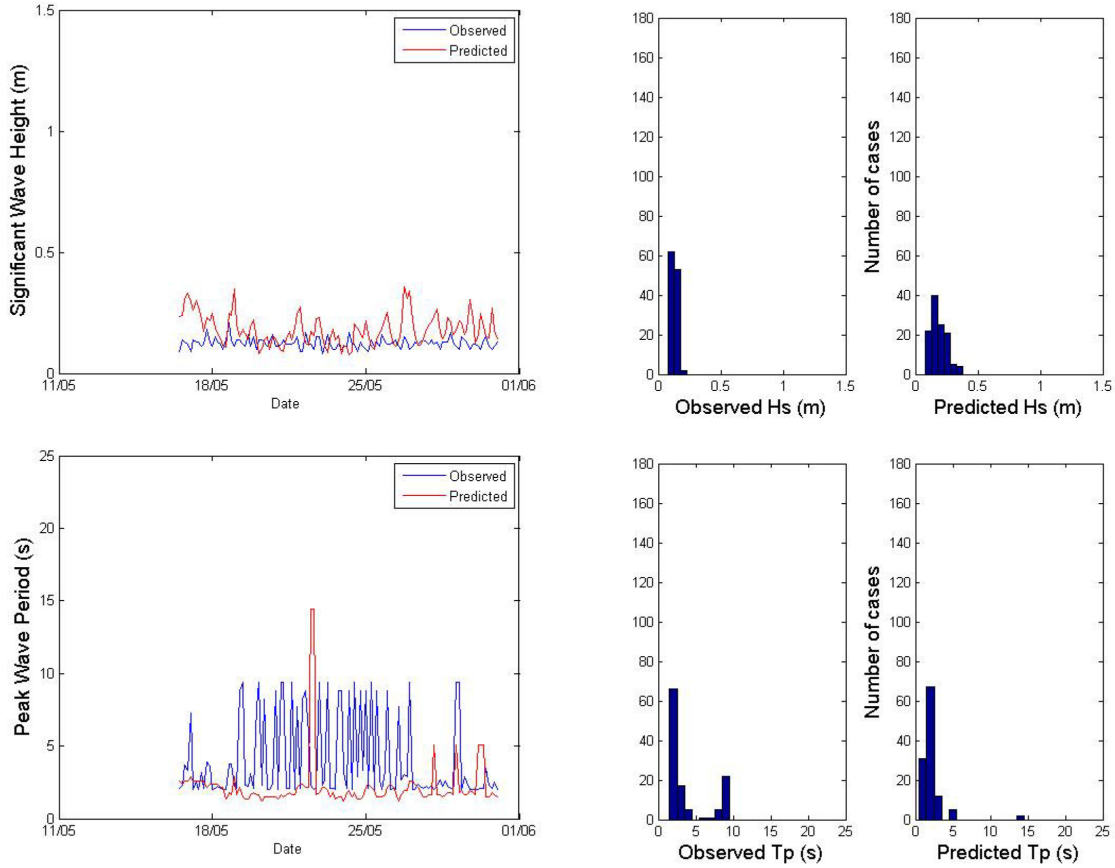


Figure 25: Inter-comparisons of observed and predicted significant wave heights and peak wave periods at the Monitor 2 location

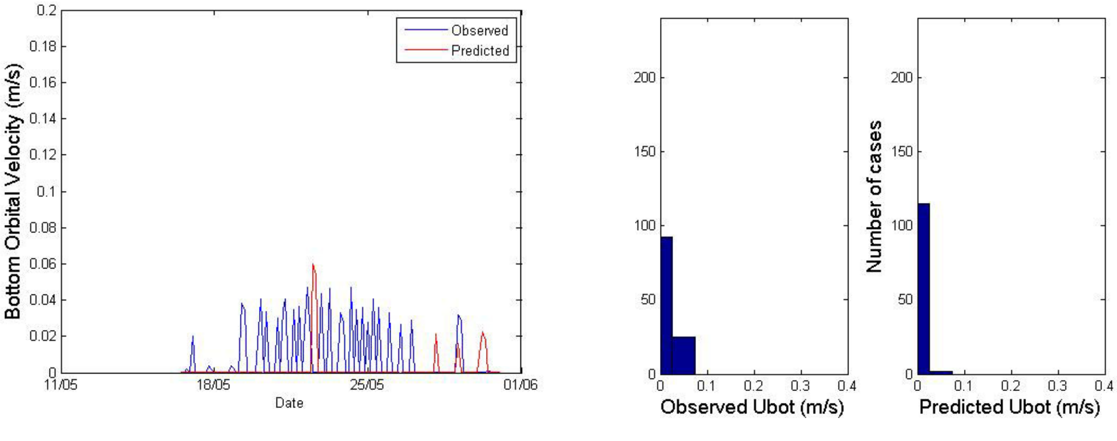


Figure 26: Inter-comparisons of bottom orbital velocities computed from observations and predictions at the Monitor 2 location

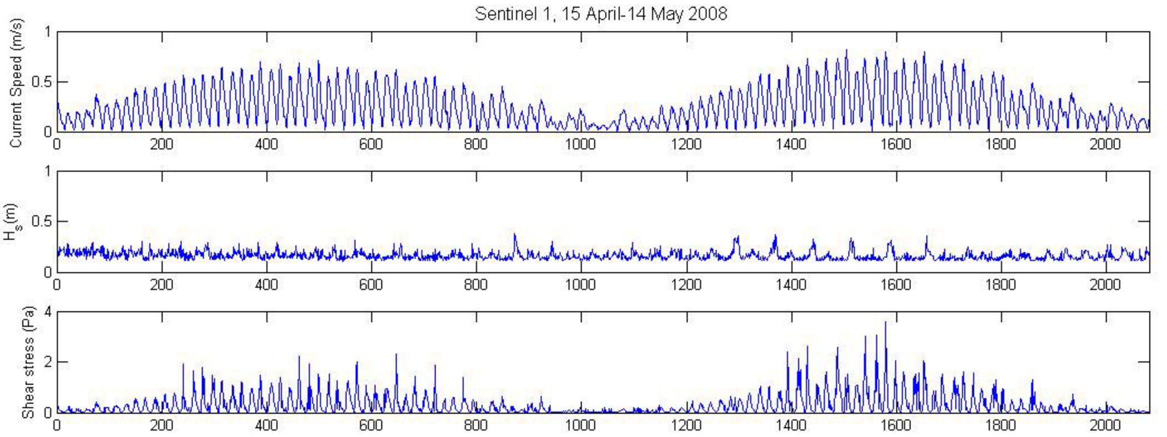


Figure 27: Current speeds, significant wave heights and calculated bed shear stress measured by Sentinel 1

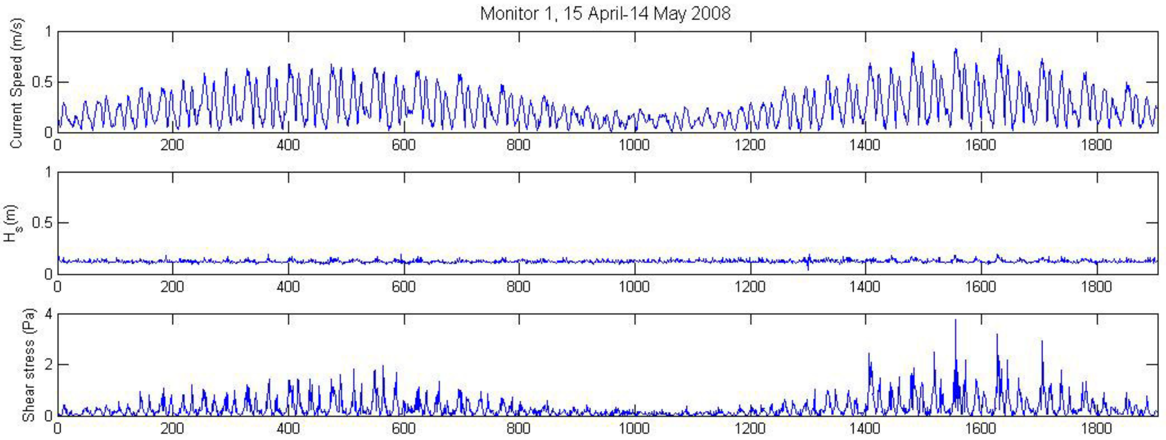


Figure 28: Current speeds, significant wave heights and calculated bed shear stress measured by Monitor 1

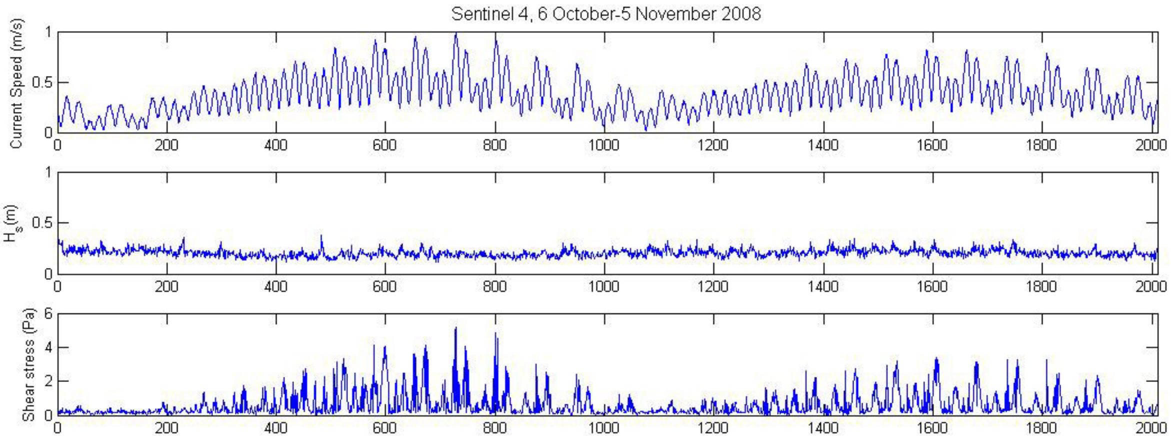


Figure 29: Current speeds, significant wave heights and calculated bed shear stress measured by Sentinel 4

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Appendix

APASA Project J0036

INPEX Browse, Ltd.

Ichthys Gas Field Development Project

Field data collection campaign

April–August 2008

October-November 2008

APASA have carried out field measurement to support environmental assessments and engineering studies associated with the proposed Ichthys Project. The following is a summary of the instrumentation that was used along with the locations and durations of measurements. The positional datum for all deployments is WGS84.

Atmospheric measurements

A weather station **WeatherMaster 1600** was deployed at two different sites (Figure A1). Durations and locations of the deployments are itemised in Table A1.

The first deployment was at East Arm Wharf, courtesy of the East Arm Wharf Harbourmaster. The aim of these observations was to provide local winds for the environmental modelling of inner Harbour and East Arm.

The second deployment was at Lee Point Village Resort, courtesy of the Resort owner and management. The deployment at this location provided wind records for Spoil Ground Site 9.

The station registered the following meteorologic parameters:

- wind speed
- wind direction
- maximum peak wind gust
- air temperature
- air humidity.

Table A1.

Dates	Site	Latitude South	Longitude East	Height above ground, m
2008-04-14–2008-08-14	East Arm Wharf	12°29′33.0″	130°53′09.9″	~8.0
2008-10-07–2008-11-05	Lee Point Resort	12°20′29.8″	130°53′32.6″	~8.0

Measurements of currents and sea level variations

Acoustic Doppler current profilers (ADCPs) were deployed on the seabed in frames, with the instruments facing upwards toward the surface. Deployment details are summarised in Table A2 and Figure A1.

The ADCPs registered the following oceanographic parameters:

- water currents at levels through the water column
- sea level variations

- wind-wave parameters
- in-situ water temperature.

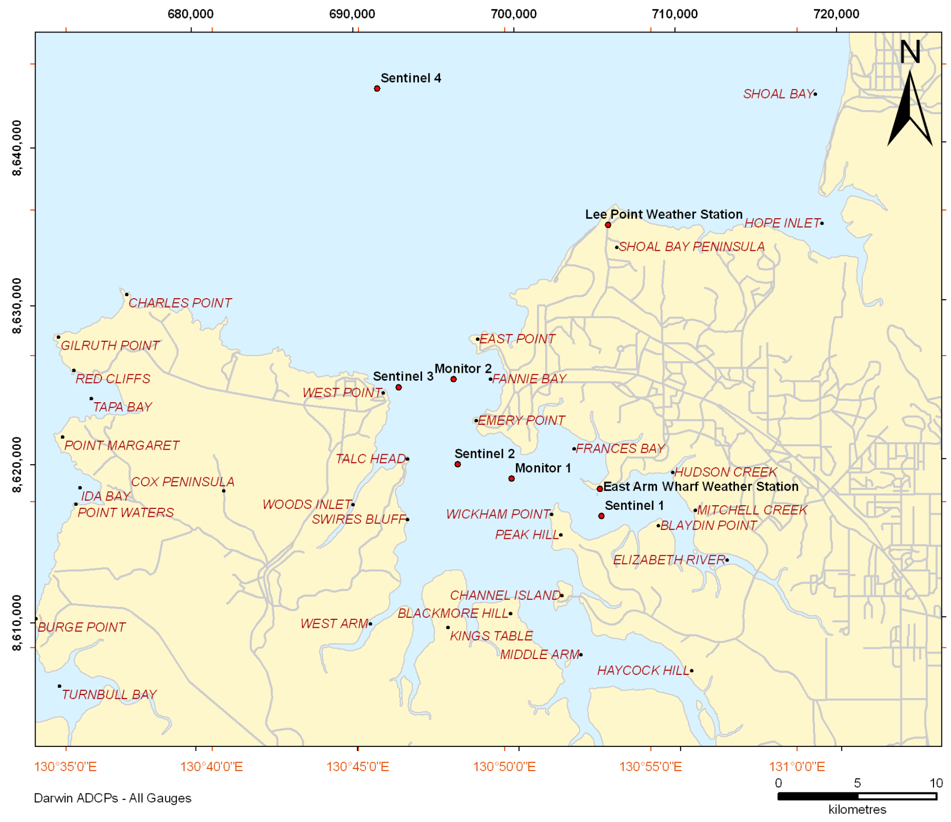

Figure A1. Location of weather station and ADCP measurements

Table A2. ADCP deployment information

Dates	ADCP	Latitude South	Longitude East	Depth (at the time of deployment), m
2008-04-15–2008-05-15	Monitor 1	12°29′11.9″	130°50′14.6″	12.4
2008-04-15–2008-05-15	Sentinel 1	12°30′29.5″	130°53′19.2″	13.2
2008-05-16–2008-06-11	Monitor 2	12°25′48.8″	130°48′20.7″	16.4
2008-06-11–2008-07-15	Sentinel 2	12°28′43.0″	130°48′24.3″	10.5
2008-07-15–2008-08-13	Sentinel 3	12°26′04.3″	130°46′22.9″	11.0
2008-10-08–2008-11-05	Sentinel 4	12°15′50.2″	130°45′39.1″	18.4

Tidal elevations over intertidal mudflats

Four **pressure sensors** were deployed over the intertidal mudflats within East Arm (Table A3; Figure A2). The pressure gauges were fixed to posts and registered water pressure over the period 14 May–11 June 2008.

Table A3: Pressure gauge deployment information

Gauge N	Latitude South	Longitude East	Depth m
1	12°30′18.2″	130°54′58.1″	5.0
2	12°30′35.4″	130°53′16.2″	4.2
3	12°30′39.2″	130°53′15.6″	2.1
4	12°30′31.1″	130°54′57.4″	2.4

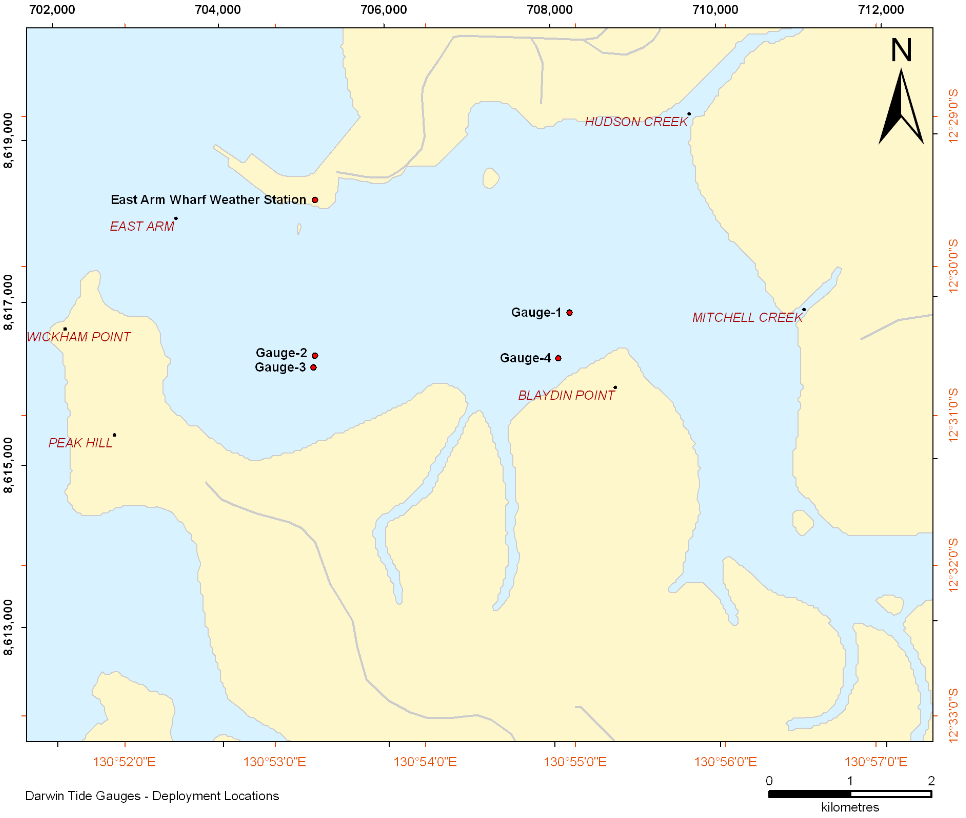

Figure A2: Location of pressure gauging sites

Bathymetry

A **GPS echo sounder** was used to survey bathymetry in previously un-surveyed parts of Darwin Harbour (Figure A3) during two field campaigns: 13 May–17 May 2008 and 10 June–13 June 2008. The survey data were post-processed to adjust for tidal variations.

Background suspended sediment concentrations

Estimates of suspended sediment concentrations were derived from the records of the ADCP instruments using the Sediview program, which uses the acoustic backscatter intensity to derive volume estimates for suspended particles. Volume estimates were converted to mass estimates using the density estimates derived from physical sampling.

Replicate water samples were collected at the ADCP locations over time for the first 100 minutes of deployment to provide calibration data. Samples were collected using 2 litre Niskin bottles. Total suspended solid estimates were made by NT Environmental Laboratories.

A **laser in situ scatterometer and transmissometer** (LISST) instrument was also deployed to profile concentrations of suspended sediments, by particle size, along a transect leading from East Arm to the outside of Darwin Harbour (Figure A3) over the period 13-17 May 2008.

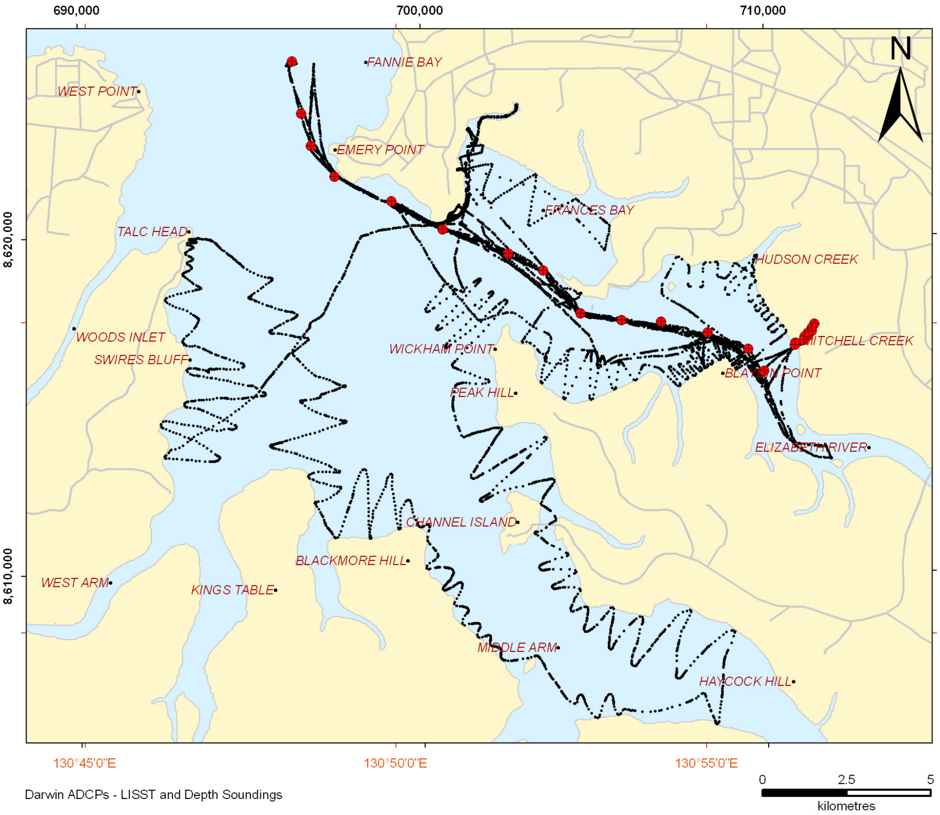

Figure A3. Location of the LISST transects within Darwin Harbour as well as bathymetric survey tracks