









TOTAL E&P PNG LIMITED

PAPUA LNG

Upstream Environmental Impact Statement

Volume 2: Environmental and Social Baseline

Part 10
Physical Oceanography Baseline Report

TOTAL
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BMT WBM

"Where will our knowledge take you?"



Papua LNG Project

Physical Oceanography Baseline Report

August 2017

Prepared for Total Exploration and Production PNG Limited

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Synopsis: **ESBS Technical Report prepared by BMT WBM for Papua LNG Project EIS/ESHIA for the following components: Physical Oceanography**

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3	***Papua LNG ESBS – Physical Oceanography***

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Executive Summary

Background

Total E&P PNG Limited (TEP PNG), a wholly owned subsidiary of TOTAL S.A. (TOTAL), is the largest partner in a joint venture to develop the Elk-Antelope gas field, located in Petroleum Retention License 15 (PRL-15) in Gulf Province, Papua New Guinea. This project, known as the Papua LNG Project, will comprise upstream production, well development and associated infrastructure at the gas field within PRL-15, construction of an upstream central processing facility (CPF) and delivery of gas and condensate via onshore and offshore export pipelines to a liquefied natural gas (LNG) plant site at Caution Bay, Central Province, 20 km northwest of Port Moresby.

This technical report provides the findings of a baseline study in relation to physical oceanography in the study area. This technical report forms part of the Environmental and Social Baseline Study (ESBS) for the Project Environmental Impact Statement/Environmental, Social and Health Impact Assessment (EIS/ESHIA). The study area encompasses three sub-areas, namely (1) Orokolo Bay, including offshore from the adjacent Purari River mouth (Orokolo Bay), (2) the nominal offshore export pipeline corridor through the Gulf of Papua (offshore export pipeline corridor), and (3) relevant parts of Caution Bay (Caution Bay).

The key objectives of the ESBS for physical oceanography are to:

- Identify the national, international and corporate regulatory and policy framework for assessment of impacts associated with physical oceanography, including the technical elements required to conduct an EIS/ESHIA.
- On the basis of review of previous studies, provide a high-level baseline description of physical oceanographic processes within the study area.
- Develop and implement numerical models to simulate the hydrodynamic processes in the study area.

The Project is regulated under the *Environment Act 2000*, the *Oil and Gas Act 1998*, and aspects of the Marine Pollution Acts. This report provides baseline information that adheres to international environmental standards, including the International Finance Corporation (IFC) Performance Standards and TOTAL company environmental performance specifications.

Study Approach

Existing information was reviewed to characterize the physical oceanographic processes in the study area and to identify key information gaps requiring further assessment. Key information sources and gaps identified were as follows:

- Orokolo Bay – No site-specific literature or measured data is available for Orokolo Bay or immediately adjoining areas of the Purari River, other than measured and estimated freshwater flows.
- Offshore export pipeline corridor – Qualitative information is available regarding physical oceanographic processes in this area, mostly derived from the PNG LNG Project EIS. Measured data was available at one location along the pipeline corridor.
- Caution Bay – Measured oceanographic data from the PNG LNG Project EIS are available for this area, together with the published results of previous oceanographic modeling.

Notwithstanding measured data limitations described above, substantial modeled data is available for the study area, developed as part of global/regional numerical models for wave, wind and other metocean conditions. In addition, available datasets outside the study area, developed for the PNG LNG Project EIS, were used in the study. Scientific literature that provides descriptions of whole-of-Gulf processes (e.g. circulation), including the influence of river discharges in the Gulf of Papua, also informed characterization of the physical oceanographic processes in the study area.

In order to supplement gaps, and consistent with good international industry practice, numerical modeling of physical oceanographic processes was undertaken for the study area. This consisted of a numerical modeling system consisting of the following linked models:

- Bathymetric digital elevation model (DEM).
- Three-dimensional (3D) hydrodynamic model.
- 3D advection-dispersion (i.e. water quality) model.
- Wave model.
- Sediment transport model.

Establishment of this modeling system provides a tool for predicting physical oceanographic conditions at specific points within the system boundary. Boundary conditions were determined based on global/regional models with calibration against the available datasets from the PNG LNG Project EIS and further validated by comparison against published descriptions from scientific literature.

Study Findings

Regional Characterization

The Gulf of Papua is subject to two distinctive seasons, experiencing north to northwest monsoon winds from December to March and southeast trade winds from May to October, with April and November acting as changeover periods (Evesson, 1983).

Winds tend to be calmer during the northwest monsoon season. Wind strength gradually increases throughout the year to a peak with the strongest southeast trade winds in July, and then progressively decreases with the return of the northwest monsoon season. The southeast trade winds generate waves with a significant fetch across the Coral Sea, setting up a seasonally averaged significant wave height (average height of the highest one third of the waves) in the Gulf of Papua of 1.5 m (Hemer *et al.* 2004). The significant wave height is larger in deeper water but attenuates as waters become shallower.

Tides are semi-diurnal within the Gulf of Papua and tidal range is highest in the west of the gulf near the mouth of the Fly River at over 5 m (Wolanski *et al.* 1995). Tidal range then attenuates heading eastward, such that maximum tidal range in the vicinity of Orokolo Bay is approximately 3 m. The maximum tidal range at Caution Bay is also approximately 3 m.

The numerical modeling results and literature review reveal that the overall current circulation patterns in the Gulf of Papua are seasonal. During the monsoon period, an anticlockwise circulation on the continental shelf is coupled with a clockwise gyre further offshore (the Hiri current). During the southeast trade winds season, the prevailing winds generate currents towards the northwest in the southern parts of the Gulf of Papua, balanced by a return flow current towards the southeast along the southern coastline of Papua New Guinea.

Large fresh water inflows from the Fly, Bamu, Turama, Kikori and Purari Rivers entering the Gulf of Papua (around 15,000 m^3/s in total) have a significant influence on both hydrodynamics and sediment dynamics in the gulf (Wolanski *et al.* 1995). Available data indicates little seasonal variation in the flow rates of these rivers (Wolanski *et al.* 1984). Wolanski *et al.* (1995) found that the halocline (strong salinity gradient) inhibits tidal mixing in the gulf. Measurements of salinity and temperature profiles undertaken by Robertson *et al*. (1998) indicated that a surface lens of low-salinity water extends across the inner gulf (within 50 km of the coast), with a thickness of up to 40 m. Typical surface salinities were between 25 to 30 parts per thousand (ppt) within 50 km of the Purari River mouth and between 32 to 34 ppt further offshore in the central gulf (for reference, oceanic salinity is 35 ppt).

Orokolo Bay

Two field campaigns were undertaken to collect water depth, temperature and salinity data in the monsoon and southeast trade winds seasons. The measured tidal range was approximately 1 m during the neap tides and approximately 3 m during the spring tides. The data indicate that the water column is significantly stratified within the bay during the southeast trade winds season, with salinity in the top 5 m of the water column between 20 to 23 ppt at all measurement locations. During the northwest monsoon season the observed stratification was more variable, with salinity in the top 5 m of the water column between 2 to 33 ppt across the measurement locations.

The numerical model indicates that current speeds are highest during the southeast trade winds season, and are directed towards the southeast throughout the bay. During the northwest monsoon season the net current direction in offshore parts of the bay (>15 m water depth) is towards the northwest.

The waves during the southeast trade winds season propagate from south to north (with significant wave height up to 1.6 m), while in the northwest monsoon season they are more variable in direction but tend to approach the bay from the south-southwest (with significant wave height less than 1 m).

Offshore Export Pipeline Corridor

The offshore export pipeline corridor traverses the Gulf of Papua upon the continental shelf.

The model results indicate that the maximum tidal range along the corridor is 3 m. Measured current data along the corridor route indicates that net current during the months March to November (southeast trade winds season) is mostly directed towards the southeast, with an average speed of around 0.2 m/s, while the direction during the months December to February (northwest monsoon season) was more variable and often directed towards the west, with an average speed of around 0.1 m/s. The observed current direction towards the southeast during the trade winds season is counterintuitive, since it flows in the opposite direction to the prevailing wind, but can be explained by considering the overall pattern of circulation in the gulf, with water further offshore driven by the wind into the gulf and returning via a coastal current along the southern Papua New Guinea coastline.

The numerical model results indicate that during the southeast trade winds season, the wave direction is predominantly from the south due to the prevailing southeast wind direction and the pattern of wave refraction within the gulf. The significant wave height has an average of around 1.5 m and a maximum of 2 m. During the northwest monsoon season the direction is more variable and the magnitude is much lower, with a maximum significant wave height of around 1 m.

Caution Bay

The bathymetry of Caution Bay is complex and contains numerous coral reef formations, channels and shoals. The main entrance to the bay is to the west, between Redscar Head and Idihi Island. The average water depth within the bay is around 25 m, with numerous irregularly shaped shoals. There are also significant coral reef formations throughout the bay, including offshore coral bommies, barrier reefs and a coral cay. The bay is protected to the south and east by Idihi Island and an outer barrier reef. Beyond the reef to the south, the seafloor depth drops sharply to depths greater than 1,000 m.

Measurements indicate that current speeds within the bay are generally low, being less than 0.5 m/s at Caution Bay East and less than 0.3 m/s at Caution Bay West. The direction tends to vary according to the tide during the northwest monsoon season but has a net northwesterly direction during the southeast trade winds season. The model results indicate that net currents within the bay are very small in magnitude (less than 0.1 m/s).

Within Caution Bay, incident waves from the west (which prevail during the northwest monsoon season) penetrate more effectively than incident waves from the south (which prevail during the southeast trade winds season) due to the fringing reef configuration. Measured data indicates that the significant wave height within Caution Bay is generally below 1 m during the southeast trade winds season and below 1.5 m during the northwest monsoon season.

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1 Introduction

1.1 Project Overview

Joint venture partners, Total E&P PNG Limited (40.13%), ExxonMobil (37.03% – through SPI (208) Limited (35.48%) and SPI Security Holdings Limited (4.55%)), and Oil Search Limited (22.84 % – though Pac LNG Assets Limited (6.75%), Pac LNG International Limited (5.10%), Pac Overseas Limited (5%), Pac LNG Holdings Limited (3.49%) and Pac LNG Investments Limited (2.50%)) are planning the development of the Elk-Antelope gas fields located in Gulf Province, Papua New Guinea. The gas fields are located within Petroleum Retention License 15 (PRL-15). The Project will include infrastructure development inside PRL-15, and the construction of gas and condensate pipelines (export pipeline) to a liquefied natural gas (LNG) plant site at Caution Bay, 20 km northwest of Port Moresby (Figure 1-1).

The Project will comprise upstream production, well development and associated infrastructure at the gas field within PRL-15, construction of an upstream central processing facility (CPF) and delivery of gas and condensate via onshore and offshore export pipelines to a LNG Plant site at Caution Bay, Central Province, 20 km northwest of Port Moresby. The design life for the Project will be 25 years.

The Project area comprises the physical footprint of the various Project components and associated infrastructure as detailed below.

- Production, processing and related facilities (within PRL-15):
  - Wellpads and the associated gathering system (including flowlines and trunkline).
  - Central processing facility (CPF).
  - Logistics base and river offloading facilities, accommodation camps, airstrip, roads and bridges.
  - Quarries, communications infrastructure.
  - Initial section of the onshore export pipeline.
- Onshore pipeline (outside PRL-15):
  - Remainder of the onshore export pipeline to landfall on the Gulf coast including valve stations.
  - Temporary laydown areas and camps.
  - Quarries and communications infrastructure.
- Transport (river) corridors:
  - River transport routes— the Purari, Urika-Ivo and Wame-Varoi rivers.
- Offshore pipeline:
  - Offshore section of the export pipeline to a LNG Plant site at Caution Bay.

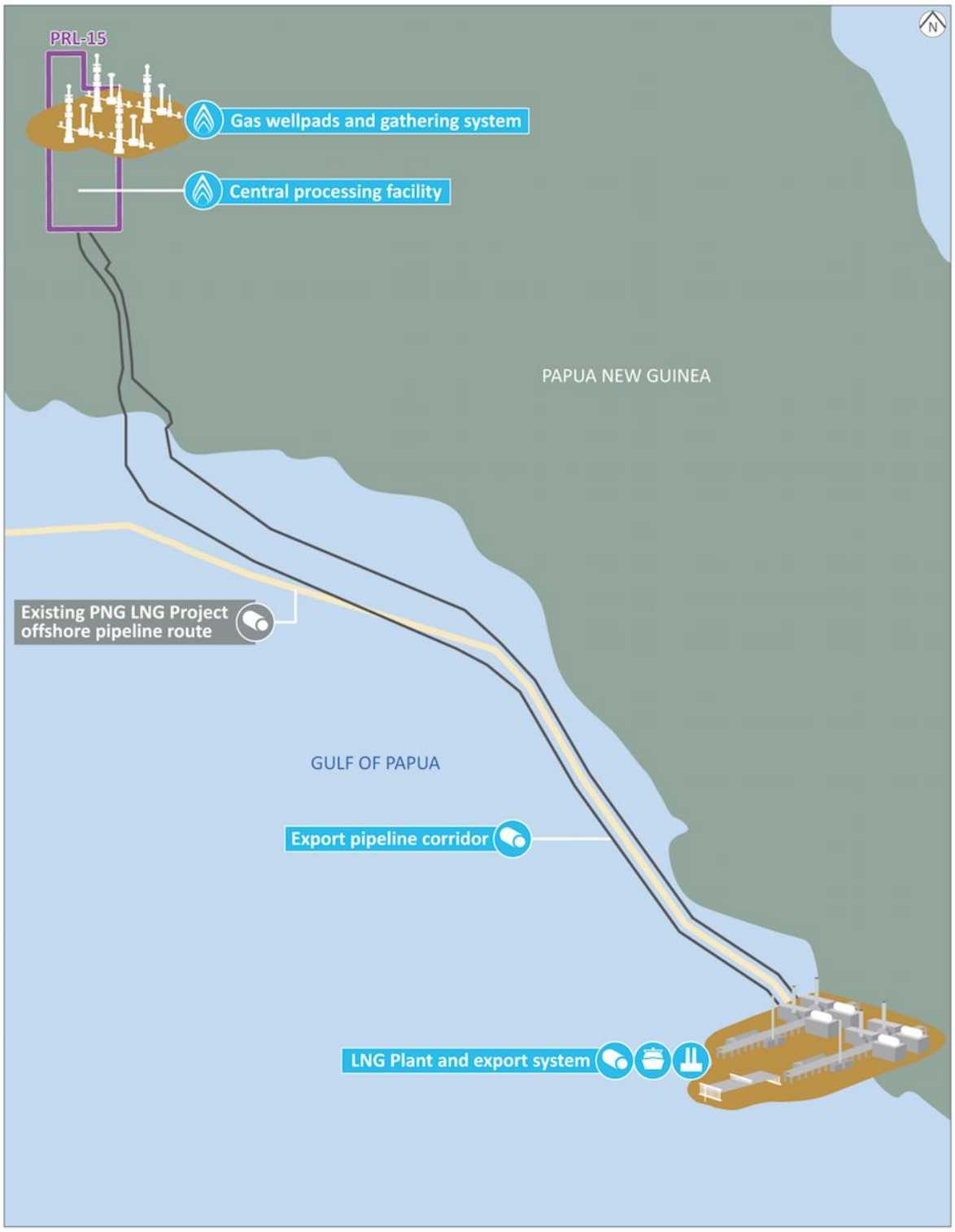


Figure 1-1 Schematic of the Project

1.2 Study and Objectives

This technical report describes the baseline physical oceanography of areas potentially affected by the Project. The report is part of the Physical Oceanography Study for the Environmental Impact Statement, and Environmental, Social and Health Impact Assessment (EIS/ESHIA) for the Project, and is part of the Environmental and Social Baseline Study (ESBS) component of the EIS/ESHIA.

The study objectives of the Physical Oceanography Study are to:

- Characterize and quantify physical oceanographic processes.
- Provide information to design, calibrate and validate hydrodynamic, wave, advection-dispersion and sediment transport numerical model/s for impact assessment.
- Characterize the physical and ocean environment in support of describing marine water, ecology and fisheries baseline conditions, as well as marine ecosystem services.

Within the context of these study objectives, this ESBS technical report achieves the following:

- Identifies the national, international and corporate regulatory and policy framework for assessment of impacts associated with physical oceanography, including the technical elements required to conduct an EIS/ESHIA baseline study.
- Describes numerical models developed and implemented to simulate the hydrodynamic and sediment transport processes in the study area.
- On the basis of a review of previous studies and outputs from the developed models, provide description of existing physical oceanographic processes within the study area. s a

2 Regulatory Framework and Standards

The Project is regulated primarily under the *Environment Act 2000* and the *Oil and Gas Act 1998* together with aspects of the suite of recently introduced Marine Pollution Acts. In addition, TEP PNG will be guided by company environmental performance specifications and international guidelines for the purposes of the EIS/ESHIA. Therefore, there are three sets of performance standards/guidelines applicable to the EIS/ESHIA:

- Papua New Guinea Legislation, including Conservation and Environmental Protection Authority (CEPA) operational procedures and codes of practice under the *Environment Act 2000*.
- International environmental and social guidelines, including the IFC Performance Standards on Environmental and Social Sustainability.
- TOTAL company standards and commitments.

NOTE: There are currently no environmental assessment criteria relevant to characterization of baseline physical oceanography conditions. However, it is noted that physical oceanography underpins water quality and is therefore relevant to assessment criteria for marine water and sediment quality. These criteria are discussed in the Marine Water and Sediment Quality Baseline Report (BMT WBM, 2017b; Part 11 of ESBS Dossier) and will be considered further in later stages of physical oceanography assessments.

2.1 Papua New Guinean Authorities and Legislation

The following Papua New Guinean legislation is considered relevant to the Physical Oceanography Study for the purposes of the Project EIS/ESHIA:

- *Environment Act 2000*, including regulations and operational procedures/information guidelines.
- *Oil and Gas Act 1998.*
- Marine Pollution Acts, including:
  - *Marine Pollution (Preparedness and Response) Act 2013*
  - *Marine Pollution (Sea Dumping) Act 2013* and Marine Pollution (Sea Dumping) Regulation
  - *Marine Pollution: Ships and Installations Act 2013*.

An EIS in Papua New Guinea is required under the *Environment Act 2000* in order to assess and understand the potential environmental impacts of significant activities prior to the issue of an Environment Permit. In particular, an EIS is required for Level 3 Activities identified under the Environment (Prescribed Activities) Regulation 2002. The Project is a Level 3 Activity in accordance with Sub-Category 18 of the Regulation. The *Environment Act 2000* and EIS process is administered by CEPA.

Under the *Oil and Gas Act 1998* the issue of licenses for petroleum projects, including Petroleum Development Licenses (PDLs), Pipeline Licenses (PLs) and Petroleum Processing Facility Licenses (PPFLs) require consideration of environmental aspects and management actions. A PDL can only be issued where the Minister administering the Act is satisfied that the project provides for the

protection of the environment and welfare of people in the project area. In practice, the Minister relies on the EIS developed under the *Environment Act 2000* in making this assessment. The Minister administering the Act is the Minister of the Department of Petroleum and Energy.

The *Marine Pollution (Sea Dumping) Act 2013* requires a Sea Dumping Permit for the purposes of placement of certain waste material within marine waters. This includes dredged material but only where material meets the contaminant guidelines set under the Marine Pollution (Sea Dumping) Regulation 2013. Non-compliant material cannot be placed at sea. An application for a Sea Dumping Permit is considered separately to the application for an Environment Permit, though the assessment of dredged material contamination levels can be undertaken as part of an EIS. This process is administered by the National Maritime Safety Authority (NMSA).

The discharge of pollutants from installations and ships in the marine environment is prohibited under the *Marine Pollution (Ships and Installations) Act 2013* unless approved under an Environment Permit under the *Environment Act 2000*, assessed by CEPA.

In preparing an EIS and applying for an Environment Permit, a proponent is required to follow the process set out in operational procedures and guidelines prepared by CEPA. These include the following:

- Operational Procedure (2013): *Information Requirements for Permit Application & Registration of Intention to Carry Out Preparatory Works*.
- Information Guideline GL-ENV/02/2004: *Guideline for Conduct of Environmental Impact Assessment & Preparation of Environmental Impact Statement*.
- Information Guideline GL-ENV/03/2004: *Guideline for Submission of an Application for an Environment Permit to Discharge Waste.*
- Technical Guideline IB-ENV/04/2004: *Water & Land Discharges*.

In addition to the requirements of these guidelines, the *Marine Pollution (Prevention and Response) Act 2013* requires proponents for new petroleum-related facilities to undertake a marine pollution risk assessment as part of an EIS. This allows for marine pollution risks to be assessed as part of an Environment Permit application. A detailed marine pollution contingency plan must then be developed after the approval of the installation.

2.2 International Standards and Guidelines

TEP PNG has committed to preparing an EIS/ESHIA for the Project consistent with a number of international standards and guidelines. These are:

- Equator Principles and World Bank Safeguards.
- IFC Performance Standards.
- Organization for Economic Cooperation and Development (OECD) Common Approaches.
- International Petroleum Industry Environmental Conservation Association (IPIECA) Guidelines.
- Any international convention ratified by the Government of Papua New Guinea (that has not been given effect under legislation listed above).

2.2.1 Environmental Impact Assessment Requirements

Preparation of an ESHIA for the purposes of environmental due diligence is required under the World Bank Safeguards, Equator Principles and OECD Common Approaches. The IFC Performance Standards provide specific guidance on the ESHIA process.

IFC Performance Standard (PS) 1 establishes the framework for preparing an ESHIA in order to assess and manage the impacts from a particular activity. The remaining Performance Standards (PS2 to PS8) provide more detail on the assessment and management of impacts in particular areas, including pollution/discharges to the environment (PS3) and biodiversity conservation (PS6). The IFC Performance Standards are supplemented by Environmental, Health and Safety (EHS) guidelines which provide examples of good international industry practice (GIIP) for certain activities.

In accordance with the IFC Performance Standards an ESHIA is required to consider the risk of an activity to the environment within the activity's 'area of influence'. This includes consideration of the impacting processes in the relevant industry-specific EHS Guidelines. Waste Management Facilities.

Under PS 3, the ESHIA is required to describe the ambient environment conditions in the area of influence, including the assimilative capacity. This then forms the basis of assessing potential pollution impacts and for the setting of impact criteria. Performance Standard 6 requires the ESHIA to include a distinction between 'modified', 'natural' and 'critical' habitat in order to appropriately quantify and manage impacts to biodiversity and ecosystems services.

The IPIECA has prepared a number of guidelines for the petroleum industry to advise proponents on best practice related to ESHIA processes. These guidelines include a focus on biodiversity and ecosystem services, oil spill preparedness, and water. The key features of the most relevant guidelines include: locating and assessing sensitive areas (including protected areas, sensitive habitats and rare, threatened or endangered species) as part of project planning; assessing baseline ecological conditions to inform the occurrence of and vulnerability to alien invasive species; and assessing the potential impacts of abstraction of and discharge to naturally-occurring water sources, including cumulative impacts and the effects of climate change.

2.3 TOTAL Company Standards and Commitments

TOTAL has developed the following general specifications for the purpose of environmental impact assessment that are relevant to the Project EIS/ESHIA:

- GS EP ENV 120: Environmental impact assessment of E&P activities
- GS EP ENV 111: Environmental Baseline and Monitoring Studies: Onshore Sites
- GS EP ENV 112: Environmental Baseline and Monitoring Studies: Offshore Sites.

GS EP ENV 120 provides details on the process for undertaking an environmental impact assessment and preparing an environmental management plan. The instrument adopts the ISO14001 approach for impact assessment and management. Some relevant specific requirements of the specification include:

- Identification of the physical, biological and socio-economic context of a project, including sensitivities of the environment.

- Assessment of impacts within an ‘area of influence’.
- Use of a modeling study (if relevant) to assess liquid effluent discharges dispersion.

The specifications also identify a methodology for impact assessment and contents of an environmental management plan (including oil spill contingency plan).

GS EP ENV 111 and GS EP ENV 112 specify the type of data to be collected for baseline purposes. These include physicochemical properties of marine sediment and water.

3 Study Area

3.1 Study Area

The Project occurs across the northern and eastern ends of the Gulf of Papua, as shown in Figure 1-1. Various studies are being undertaken across much of this area as part of the EIS/ESHIA. For the purposes of the Physical Oceanography Study, the 'study area' includes only the marine elements of the Project and surrounding area.

Figure 3-1 provides an overview of the study area. This includes the following three subsets:

- Coastal and nearshore environments at Orokolo Bay and offshore the Purari River delta, located at and adjacent to the upstream segment of the export pipeline corridor and offshore potential riverine transport routes along Wame-Varoi, Urika-Ivo and Purari rivers. This area is located in the Gulf Province.
    - Orokolo Bay refers to the bay embayment between the eastern-most mouth of the Purari River delta and the mouth of the Vailala River.
    - Purari River delta represents the area between the Purari and Wame-Varoi river mouths.
- Offshore environments in the Gulf of Papua at and adjacent to the offshore segment of the export pipeline corridor (offshore export pipeline corridor study area). The western segment of the offshore export pipeline corridor is located offshore from the Gulf Province whereas the eastern segment is located offshore from the Central Province.
- Coastal nearshore environments at and adjacent to Caution Bay at the downstream end of the export pipeline corridor (Caution Bay study area). This area is located in the Central Province region.

The study area includes nearshore and offshore waters. For the purposes of this report, 'nearshore' waters are those between mean high water springs and the 15 m depth contour. 'Offshore' waters represent all waters seaward of the 15 m depth contour.



Title:

Physical Oceanography Study Area

Figure: 3-1

Rev: A

BMT WBM endeavours to ensure that the information provided in this map is correct at the time of publication. BMT WBM does not warrant guarantee or make representations regarding the currency and accuracy of information contained in this map.

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Approx. Scale

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3.2 Climate

The following provides an overview of the climatic setting of the study area.

3.2.1 Orokolo Bay and Western Segment of Offshore Export Pipeline Corridor

The two main wind movements in southern Papua New Guinea, which includes the coast of the Gulf Province, are the north to northwest monsoon winds from December to March and southeast trade winds from May to October, with April and November acting as changeover periods. Rainfall at Kerema (to the east of Orokolo Bay) is relatively uniform throughout the year with mean monthly totals ranging from 209 to 437 mm. The wetter months are May to October with mean rainfall totals 299 mm and above. The mean annual rainfall is 3,612 mm, with a mean evaporation rate of 1,420 mm (Evesson, 1983).

The coolest month is August when the mean daily maximum and minimum temperatures are 27ºC and 22ºC respectively. The warmest months are December and January when the mean daily maximum temperature is 31ºC. There is little variation in the mean daily minimum (1ºC) and maximum (3.5ºC) temperatures throughout the year (Evesson, 1983).

Orokolo Bay and the western segment of the offshore export pipeline corridor are north of the main cyclone belt and occurrence of such extremes are rare, with only five named cyclones in 15 years entering the Gulf of Papua, all tracking well south of Orokolo Bay. Cyclones generally occur from February to April (CNS, 2009).

The global the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) model hindcast (Saha *et al.* 2010) was used to generate a long-term wind rose at a particular location on the western segment of the offshore export pipeline corridor (at the location marked ‘North Crossing’ in Figure 6-16) for the southeast trade winds season (Figure 3-2) and the northwest monsoon season (Figure 3-3). Wind roses show the percentage of time that winds blow from particular directions over a specified period. The length of each ’spoke’ around the circle is related to the percentage of the time that the wind blows from that particular direction. Each ‘spoke’ is divided into color-coded bands that show the percentage occurrence of particular wind speed ranges.

The wind during the southeast trade winds season blows from the southeast and south-southeast for over 50% of the time. The modeled average speed is 4.4 m/s. During the northwest monsoon season the winds blows from the north-northwest to north-northeast over 40% of the time, and the wind speeds are generally lower at an average of 3.4 m/s.

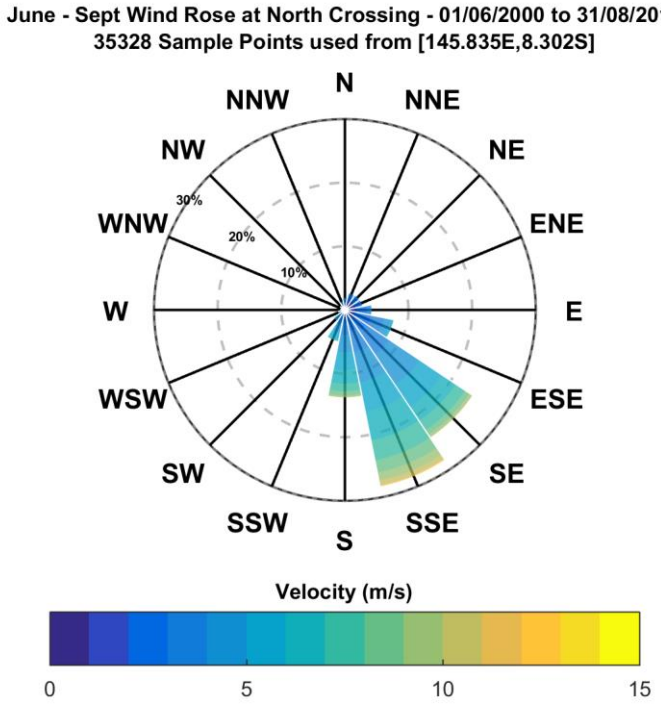


Figure 3-2 Long-term Southeast Trade Winds Season Wind Rose for North Crossing

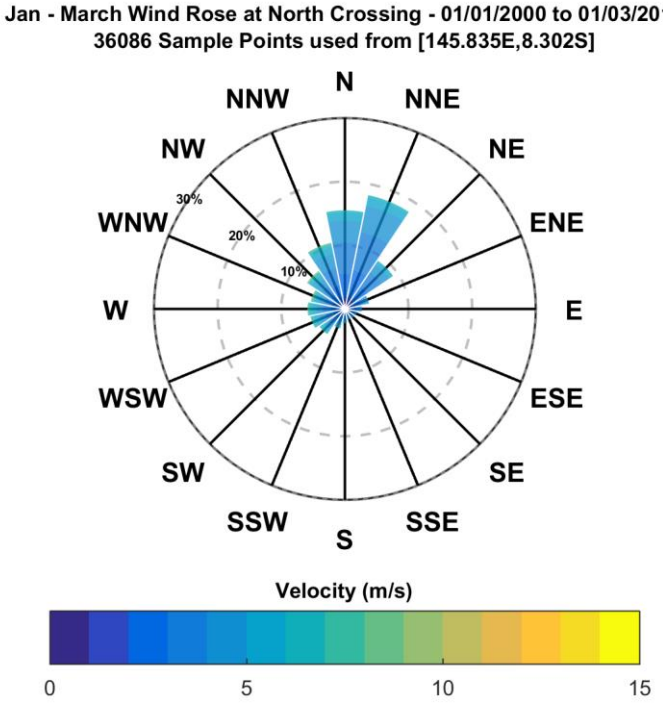


Figure 3-3 Long-term Northwest Monsoon Season Wind Rose for North Crossing

3.2.2 Caution Bay and Eastern Segment of Offshore Export Pipeline Corridor

The climate of the Port Moresby region is seasonal, with dry southeast trade winds season from May to October and a wet northwest monsoon season from December to March (which accounts for approximately 80% of the mean annual rainfall of 1,200 mm). April and November are the transition periods of calmer weather. Monsoon surges with strong northwest winds have been observed in the region (CNS, 2009). These short-lived squalls of about 1 hour's duration with wind speeds of 55 to 65 km/hr (15 to 18 m/s) are known locally as *gubas*.

The coolest months are July and August when the mean daily maximum and minimum temperatures are 28ºC and 23ºC respectively. The warmest months are December and January when the mean daily maximum and minimum temperatures are 32ºC and 24ºC respectively. There is little variation in the mean daily minimum (±1ºC) and maximum (±4ºC) temperatures throughout the year (CNS, 2009).

The main features of the ambient wind conditions in Caution Bay are the:

- Dominance of the southeast trade winds offshore (April to November), similar to Orokolo Bay and the western segment of the offshore export pipeline corridor.
- Existence of katabatic (downslope) winds from high elevation topography to the northeast of the bay.
- Difference in the wind regimes between onshore and offshore sites.

The global NCEP CFSR model hindcast (https://rda.ucar.edu/pub/cfsr.html) was used to generate a long- term wind rose for the offshore Caution Bay area for the southeast trade winds season (Figure 3-4) and the northwest monsoon season (Figure 3-5).

The wind during the southeast trade winds season blows from the southeast and south-southeast for over 55% of the time. The modeled average speed during the season is 4.8 m/s, slightly higher than at the 'North Crossing' location. During the northwest monsoon season the winds blows from the north-northwest to north-northeast over 40% of the time, and the wind speeds are generally lower at an average of 3.4 m/s, the same as that at the 'North Crossing' location.

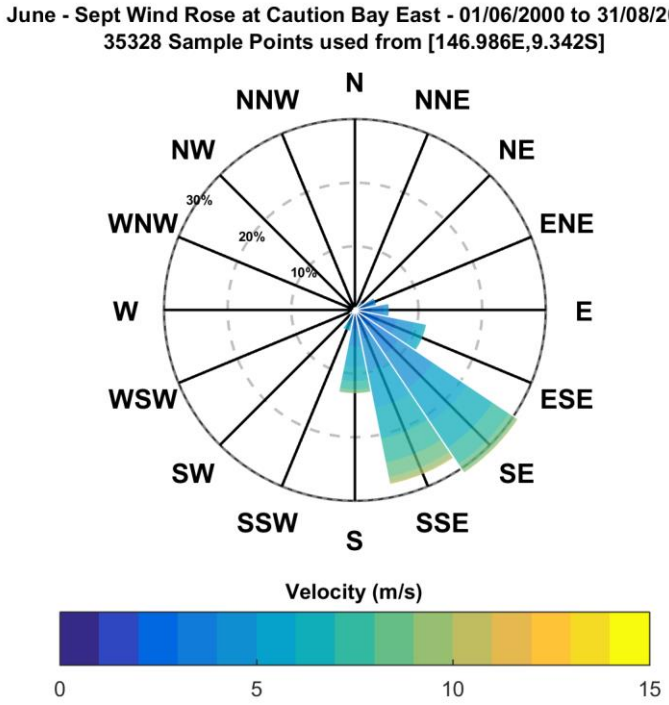


Figure 3-4 Long-term Southeast Trade Winds Season Wind Rose for Caution Bay

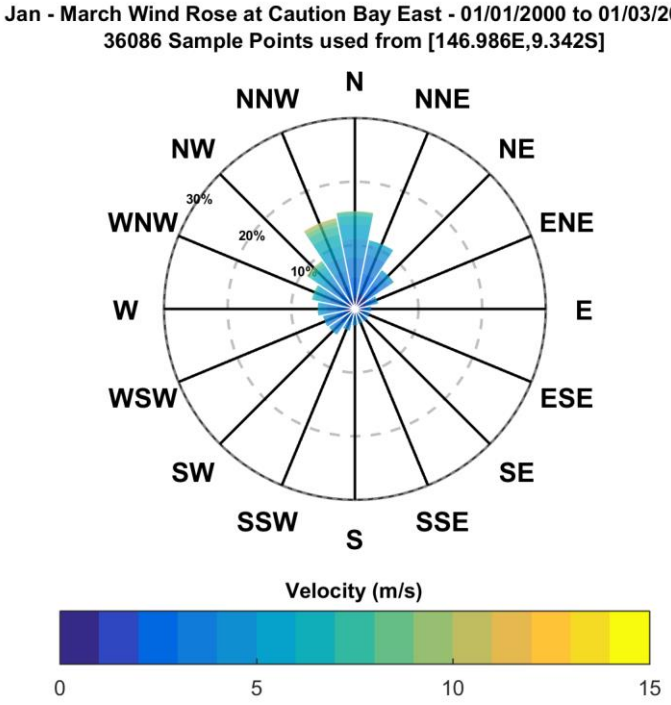


Figure 3-5 Long-term Northwest Monsoon Season Wind Rose for Caution Bay

3.3 Anthropogenic Setting

The following provides an overview of the anthropogenic setting of the study area, including population distribution and marine-based activities. More detailed information is provided in the Upstream Community and Demographics Baseline Report (Finlayson, 2017; Part 14 of ESBS Dossier), Marine Fisheries and Resources Baseline Report (ERIAS Group, 2017a; Part 13 of ESBS Dossier), and Marine and River Traffic and Transport Baseline Report (ERIAS Group, 2017b; Part 22 of ESBS Dossier).

3.3.1 Orokolo Bay and Purari River Delta (Gulf Province)

Population patterns across Orokolo Bay and the Purari River delta are marked by a generally low inland population scattered or concentrated in small villages along riverbanks, and a much denser population in large villages and hamlets across the coastal strip. The principal villages in the Orokolo Bay area are:

- Purari River delta: Akoma, Aivei and Apiope.
- Orokolo Bay: Harevavo and Hororo.

All coastal communities engage in subsistence fishing activities in nearshore and offshore waters, with some limited commercial fishing also occurring. These activities tend to occur out to three nautical miles, beyond which commercial trawling occurs as part of the Gulf of Papua Prawn Fishery (ERIAS Group, 2017a). Fishers typically use small outrigger canoes and y-nets, with canoes primarily used to set gill nets but also to fish in deeper water with hook-and-line. Subsistence and artisanal fishing activities are strongly seasonal, with fishing from outrigger canoes more restricted during the southeast trade winds due to the generation of dangerous sea conditions (ERIAS Group, 2017a).

With the exception of boats from local villages, limited marine traffic occurs in Orokolo Bay and offshore of the Purari River delta as it is outside of existing commercial shipping channels (ERIAS Group, 2017b).

3.3.2 Offshore Export Pipeline Corridor

The offshore export pipeline corridor includes areas within the Gulf of Papua Prawn Fishery, regulated by the National Fisheries Authority (NFA). This fishery occurs at least three nautical miles offshore, in waters up to about 60 m depth and extends from the Purari River delta east as far as the village of Iokea (near the border of Gulf and Central provinces).

An artisanal dive fishery for rock lobsters occurs on the coastal reefs around Yule Island, where lobster annually migrate from the Torres Strait to spawn during November–April.

Various shipping traffic occurs within the Gulf of Papua, including a number of coastal vessels that cross the offshore export pipeline corridor. These include cargo, tanker and passenger vessels, as well as logging ships transiting between ports at Port Moresby, Baimuru, Kumul terminal, Kikori and Daru.

3.3.3 Caution Bay (Central Province)

Along the coastal strip of Caution Bay there are four villages: Lea Lea, Papa, Boera and Porebada. Each of these villages is populated by mixed populations of people from the Koita and Motu people groups. The population density across the area is 10 persons/km^2.

In addition to these villages, the ExxonMobil LNG Plant, part of the PNG LNG project, occupies part of the coastal strip between Papa and Boera. This facility includes an LNG jetty and wharf that extend out into Caution Bay. Brine from a desalination plant is discharged into the bay from a pipeline attached to this jetty, while hydrotest water (produced during construction phase only) was discharged to nearshore waters north of the LNG jetty.

Artisanal fisheries in Caution Bay are considered important for subsistence and income purposes for Lea Lea, Papa, Boera and Porebada. Fishing is primarily undertaken on inshore fringing reefs and shallow shoals, but is also undertaken in mangrove communities and at barrier reefs. Fishing in offshore areas is restricted by sea conditions but is less limited in sheltered inshore areas. Local communities have a high dependence on coastal and marine resources. Subsequent to the development of the LNG plant, a 500 m exclusion zone is maintained around the LNG jetty, restricting fishing activities in this area.

Most boat traffic in Caution Bay is associated with the local villages or with operations of the LNG plant. Commercial shipping traffic, including commercial fishing vessels, generally occurs beyond the outer reef, outside of the bay (ERIAS Group, 2017b).

4 Existing Information

The following section describes the previous studies that are considered relevant to the study area. The actual content of this literature has been integrated, as relevant, into the findings described in Section 6.

4.1 Prior Studies within the Study Area

4.1.1 Environmental Assessment Studies

The following published EIS studies have been conducted in the Gulf of Papua and included data collection and assessments relevant to understanding the physical oceanographic conditions of the study area:

- PNG LNG Project EIS (CNS, 2009), prepared for ExxonMobil.
- Pasca A Development Project EIS (ERIAS Group, 2016), prepared for Twinza Oil Limited.

In addition to these studies, metocean data collection and a wave hindcast study is known to have been conducted at Kerema Bay (to the east of Orokolo Bay). This was undertaken as part of an unpublished draft EIS.

4.1.2 Available Datasets

There are two principal types of dataset available for the study area:

- Measured datasets, i.e. datasets based on actual in-field data, typically collected from instruments deployed for a continuous period of weeks to months.
- Modeled datasets, i.e. datasets derived as outputs of global and/or regional models for particular parameters.

In terms of measured data, the main datasets available are those collected as part of the PNG LNG Project EIS (CNS, 2009) procured by TEP PNG for the purposes of the ESBS Report. The datasets collected provide water level, wave and wind data for a range of locations at Caution Bay, the Omati River, North Crossing and Kumul Terminal – see Table 4-1. These datasets cover various periods between October 2007 and February 2009.

Daniell (2008) has developed a bathymetric grid for the Gulf of Papua, based on multibeam sonar surveys combined with topographic data from NASA's Shuttle Radar Topography Mission (SRTM). This bathymetric grid supplements, and updates in some areas, the existing bathymetric data available from navigational charts (e.g. Australian Hydrographic Charts) held by the Papua New Guinean and/or Australian governments.

Table 4-1 PNG LNG Project EIS Available Datasets

Site	Coordinates	Data Types	Data period
Kumul	144.5667ºE, 8.1333ºS	Water level, wave, wind	Mar 2008 – Apr 2008
North Crossing	145.8349ºE, 8.3023ºS	Water level and velocity	Oct 2007 – Aug 2008
Omati River Mouth	144.179361ºE, 7.82625ºS	Water level	Oct 2008 – Nov 2008

Site	Coordinates	Data Types	Data period
Omati River Landfall	144.137055ºE, 7.607361ºS	Water level	Oct 2008 – Nov 2008
Omati River Mid	144.143055ºE, 7.686361ºS	Water level	Oct 2008 – Nov 2008
Caution Bay East	146.986417ºE, 9.34205ºS	Wave, water level and velocity	Sep 2007 – Feb 2009
Caution Bay West	146.931667ºE, 9.30667ºS	Wave, water level and velocity	Feb 2008 – Jul 2008
Weather Station 1	147.0103ºE, 9.376ºS	Wind	Feb 2008 – Jan 2009
Weather Station 2	147.0103ºE, 9.3769ºS	Wind	Feb 2008 – Jan 2009

Global and/or regional hydrodynamic and wave models that provided modeled datasets for the study area are:

- Oregon State University's global tide model (http://volkov.oce.orst.edu/tides/) – tidal water level boundaries.
- Hybrid Coordinate Ocean Model (HYCOM) (http://hycom.org) – regional current forcing (residual water level, current magnitude and direction) and profiles of temperature and salinity.
- NCEP CSFR model re-analyses (https://rda.ucar.edu/pub/cfsr.html) – wind, air temperature, long and short wave radiation, precipitation and relative humidity.
- WaveWatch III (http://polar.ncep.noaa.gov/waves/ensemble/download.shtml) – waves.

4.2 Studies in Neighboring Regions

There are no relevant environmental impact assessment studies from regions neighboring the study area. However, there is an extensive body of scientific literature that covers much of the Gulf of Papua, as discussed below.

4.2.1 Scientific Literature

A number of scientific publications provide important background information on physical oceanographic and sedimentation processes in the Gulf of Papua.

Slingerland *et al.* (2008) undertook an ocean circulation study which included numerical modeling of tidal currents, wind-driven flows and buoyant river plumes within the Gulf of Papua. They found that tidal flows during spring tides are strong enough to keep sediment up to sand size in motion, allowing wind-driven and baroclinic currents to distribute it from river mouths along and across the shelf. Seaward of the clinoform (sloping depositional surface), the modeling indicated south-westerly directed surface currents and landward directed bottom currents during the northwest monsoon season. During the southeast trade winds season, the modeling indicated north-easterly directed surface currents and landward directed bottom currents.

Wolanski *et al.* (1995) undertook numerical modeling of the Gulf of Papua that indicated significant stratification of the top 20 m of the water column and a counter-clockwise current within the gulf. The freshwater inflows were estimated to be around 15,000 m^3/s with little seasonal variation.

Walsh and Nittrouer (2004) studied the sediment accumulation rates in prograding mangrove banks in the western Gulf of Papua. They found that sediment accumulation in mangrove areas along the coastlines of the gulf is significant, accounting for 2 to 14 percent of the total Gulf of Papua sediment load.

Walsh *et al.* (2004) undertook a study of the mechanics of the prograding clinoform in the Gulf of Papua. They found that muddy terrigenous sediment discharged by the rivers is initially deposited in shallower areas (<15 m depth) but may be remobilized and transported down-slope during periods of large wave-current bed shear stress (more probable during the southeast trade winds season).

Palinkas *et al.* (2006) studied the inner-shelf sedimentation rates in the Gulf of Papua and found that the large volumes of fine sediment discharged to the gulf, together with the relatively low energy receiving environment, leads to significant accumulation of fine sediment. They found that the rates of accumulation at the 20 m depth contour were around 0.6 cm/year in the western part of the gulf, 1.9 to 2.7 cm/year in the central part of the gulf and 0.7 cm/year in the eastern part of the gulf.

Martins and Wolanski (2015) undertook a numerical modeling study of the Fly River flood plume with a focus on the potential for intrusion into the Great North East Channel (southwest of the gulf – see Figure 6-1) and Torres Strait. They found that stratification effects are important and that an anticlockwise coastal current pattern combined with the inclusion of a variable trade wind forcing can lead to brackish plumes extending into the Great North East Channel.

Brunskill *et al*. (1995) studied the characteristics of riverine sediment delivered to the Gulf of Papua and found that these sediments are transported to the north and east and are a large source of terrestrial organic matter found on the seabed in the northern Coral Sea.

4.3 Summary

Based on the studies and datasets cited above, the following information is known to be available for the study area:

- Qualitative assessments of physical oceanographic processes and metocean conditions are provided for most of the study area, especially Caution Bay and the offshore export pipeline corridor. No previous assessments are available focused specifically on Orokolo Bay.
- Measured metocean datasets are available at Caution Bay and other locations in the Gulf of Papua listed in Table 4-1, although the datasets at the various locations do not necessarily overlap in terms of temporal span and/or parameters.
- Modeled metocean data and estimated freshwater flows are available for the entire study area and Gulf of Papua.

Regional/adjoining information is available for Kerema Bay and the Kikori River nearshore areas. This provides some relevant information that can be used to contextualize the study area and/or can be extrapolated to assist with predictions for the study area (particularly Orokolo Bay).

The data limitations compelled the establishment of numerical models in order to produce site-specific modeled datasets for the study area and/or parameters where measured data was not available.

5 Approach and Methods

5.1 General Approach

The assessment of the physical oceanographic environment was based on a combination of both literature and data review and numerical modeling. Literature/data review focused on providing a high-level characterization of the study area, while numerical modeling was utilized to provide more detail information about specific metocean processes relevant to the Project study area.

Complete details of modeling activities are provided within the Marine Waters Modeling Report (Appendix A) but are also summarized below.

5.1.1 Modeling Approach for Physical Oceanography

Modeling for physical oceanography was based on the use of a numerical modeling system, consisting of the following linked models:

- Bathymetric digital elevation model (DEM).
- Three-dimensional (3D) hydrodynamic model.
- 3D advection-dispersion (i.e. water quality) model.
- Wave model.
- Sediment transport model.

Establishment of this modeling system provided a tool for identifying physical oceanographic conditions at specific points within the model domain. The TUFLOW-FV model mesh and domain used for the hydrodynamic and advection-dispersion models is shown in Figure 5-1.

Table 5-1 describes the set-up of the individual models.

Boundary conditions (the data input at the model boundaries) for the modeling system were based on the following (see also Section 4.1.2):

- Salinity, temperature, sea surface anomaly and residual currents from a global ocean circulation model (HYCOM).
- Tides from the Oregon State University's global tide model.
- Atmospheric forcing from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) broadscale meteorological model re-analysis (Saha *et al.* 2010).
- River inflows from the Fly, Bamu, Turama, Kikori and Purari rivers based on available estimates (Wolanski *et al.* 1995).

The modeling system was calibrated where possible using the datasets available from the PNG LNG Project EIS (see Table 4-1). The results of the model calibration are presented in Appendix A. The modeling system was also validated by comparing the model outputs to the available literature describing circulation and sediment transport processes in the Gulf of Papua (refer to Section 6).

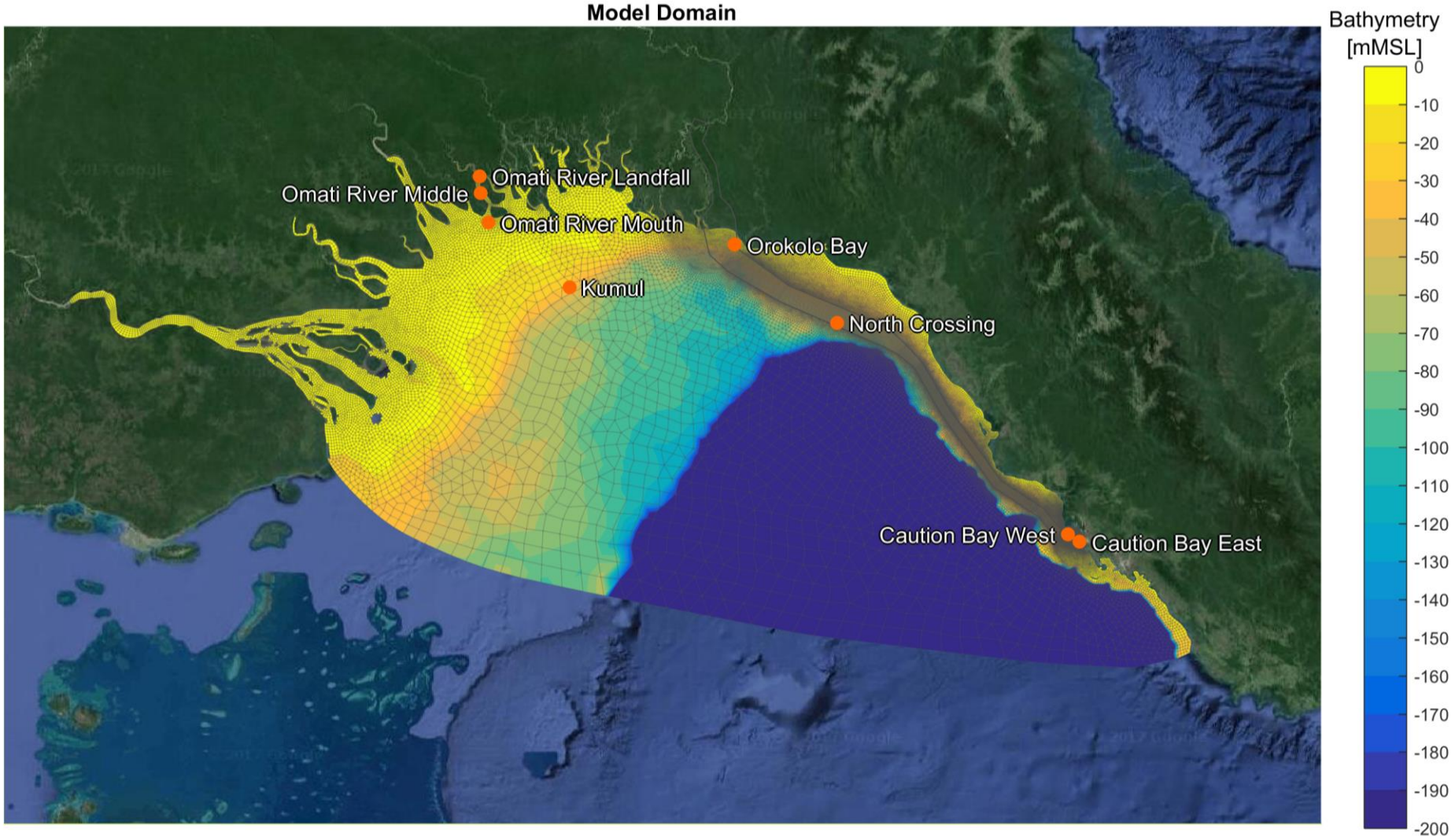


Figure 5-1 TUFLOW-FV Model Mesh Adopted for Numerical Modeling System

Table 5-1 Models within the Physical Oceanography Numerical Modeling System

Model	Setup
Bathymetric DEM	Developed using bathymetric data available from electronic charts and SRTM data
3D hydrodynamic model and 3D advection-dispersion model	Developed using as a flexible mesh model of the entire Gulf of Papua, using TUFLOW-FV software package
Wave model	SWAN wave model (Delft University of Technology, 2006) including a coarse regional-scale grid (~500 m resolution), a nested local-scale grid (~250 m resolution), and two additional nested models (~100 m resolution for Orokolo Bay and Purari River delta and Caution Bay)
Sediment transport model	Based on TUFLOW-FV ST module coupled with 3D hydrodynamic and SWAN wave model outputs.

Simulations run with the modeling system were based on a hindcast simulation for the 2008 calendar year (i.e. the year during which calibration data was available in the Project area – see Table 4-1). This one year period is considered to be suitable for the purposes of characterizing the baseline environment as part of the EIS/ESHIA (but not necessarily for other purposes such as engineering activities).

Comparisons have also been made against the two months of data collected during the June-July 2016 and January 2017 surveys (see below).

5.1.2 Field Data Collection

Due to data paucity at Orokolo Bay, especially in regards to water quality, instrument deployment was undertaken as part of field surveys for the Marine Water and Sediment Quality Baseline Report (BMT WBM, 2017b) and Marine Biodiversity Baseline Report (BMT WBM, 2017c; Part 12 of ESBS Dossier). Turbidity, salinity, temperature and depth data were collected during these surveys, covering two periods:

- One month in June-July 2016.
- One month in January 2017.

5.2 Data Sources

The key data sources used for preparing this report, particularly in the context of modeling, are those described in Section 4.1.2 as well as the turbidity, salinity, temperature and depth data collected from field surveys (Section 5.1.2).

These datasets are in addition to literature discussed in Section 4.2.1 and referenced in Section 10.

5.3 Field Surveys

As discussed in Section 5.1.2, no long-term metocean instrument deployments were undertaken as part of the EIS/ESHIA for the purposes of baseline characterization. Such deployments are anticipated to be undertaken separately to the EIS/ESHIA scope.

5.4 Limitations

The following limitations in the study approach are noted:

- The measured datasets available for calibration of the numerical modeling system do not cover all of the study area. As a result, calibration will not cover all parts of the models, especially at Orokolo Bay. This increases the degree of uncertainty associated with data results at these locations.
- Modeling undertaken for the study area focused only on prevailing conditions and did not consider the influence of long-term cyclical or short-term extreme events (e.g. El Niño/La Niña cycles, tropical cyclones).
- Due to the absence of long-term measured data and comparative modeled data, sediment transport rates provided by the model are indicative only.

These limitations are not anticipated to impact on the ability to characterize the baseline physical oceanography environment suitable for the preparation of an EIS/ESHIA. However, the results of this study are not intended to inform engineering activities.

6 Baseline Characterization

This section provides a description of the existing physical oceanography conditions of the study area. It includes a regional characterization of the area based on a review of literature and summarizes the available data and the numerical modeling results for areas of interest within the study area.

The model results presented in this section are based on a hindcast simulation of the 2008 calendar year (i.e. the year for which calibration data is available). A complete set of the modeling results described in this section is provided in Appendix A.

NOTE: Where modeled results differ from results obtained from in-field measurements, measurements are considered to have a higher level of accuracy and are considered valuable for looking at temporal changes for a particular location. Modeled results are valuable for looking at spatial patterns over a wider area where measurements have not been obtained.

6.1 Regional Characterization

The regional bathymetry is shown in Figure 6-1. The water depth within the Gulf of Papua varies from less than 100 m on the continental shelf to over 2,000 m beyond the shelf edge.

The Gulf of Papua is subject to two distinctive seasons, experiencing north to northwest monsoon winds from December to March and southeast trade winds from May to October, with April and November acting as changeover periods (Evesson, 1983). In the northwest monsoon season, winds tend to be calmer and wind vectors are frequently from the west to northwest (Saint-cast and Condie, 2006). Waves generated by these winds have a small fetch, with late January to February having the most quiescent wave climate. The inter-annual variability of climate and oceanographic conditions in the study area is low.

Wind strength gradually increases throughout the year to a peak with the strongest trade winds in July, and then progressively decreases with the return of the northwest monsoon season. The southeast trade winds generate waves with a significant fetch across the Coral Sea, setting up a seasonally averaged significant wave height (average height of the highest one third of the waves) in the Gulf of Papua of 1.5 m (Hemer *et al.,* 2004). The significant wave height is larger in deeper water but attenuates as waters become shallower.

Tides are semi-diurnal within the Gulf of Papua and tidal range is highest in the west of the gulf near the mouth of the Fly River at over 5 m (Wolanski *et al.* 1995). Tidal range then attenuates heading eastward, such that maximum tidal range in the vicinity of Orokolo Bay is approximately 3 m. The maximum tidal range at Caution Bay is also approximately 3 m.

The Hiri Current forms a clockwise gyre in the Gulf of Papua (Saint-Cast and Condie, 2006), described further in Section 6.3.3. The strength of the Hiri Current is unlikely to be significantly altered by El Niño given a lack of response observed in the Coral Sea Current, which is thought to drive the Hiri Current (Saint-Cast and Condie, 2006). Sediment released from the mouth of the Fly and Purari rivers generally moves in an eastward direction through the northwest monsoon season, and with the onset of strong southeast trade winds, a westward shoreline current develops (Keen *et al*. 2006) pushing sediments westwards back towards the Fly River and into the northern part of Torres Strait.

Fresh water inflows from the large rivers (the Fly, Bamu, Turama, Kikori and Purari) entering the Gulf of Papua have a significant influence on both hydrodynamics and sediment dynamics in the gulf (Wolanski *et al.* 1995). Available data indicates little seasonal variation in the flow rates of these rivers (Wolanski *et al.* 1984). The fresh water plumes in the gulf have a residence time (typical transit time for a plume to reach the boundary of the gulf) of around two months (a distance of ~50 to 100 km; Wolanski *et al.* 1984). Wolanski *et al.* (1995) found that the halocline (strong salinity gradient) inhibits tidal mixing in the gulf. Measurements of salinity and temperature profiles undertaken by Robertson *et al*. (1998) indicated that a surface lens of low-salinity water extends across the inner gulf (within 50 km of the coast), with a thickness of up to 40 m. Typical surface salinities were between 25 to 30 parts per thousand (ppt) within 50 km of the Purari River mouth and between 32 to 34 ppt further offshore in the central gulf (for reference, oceanic salinity is 35 ppt).

Table 6-1 provides estimates of river inflows used in the modeling system developed for this study which were derived from Wolanski *et al.* (1995) and sediment fluxes which were derived from Harris *et al.* (1996).

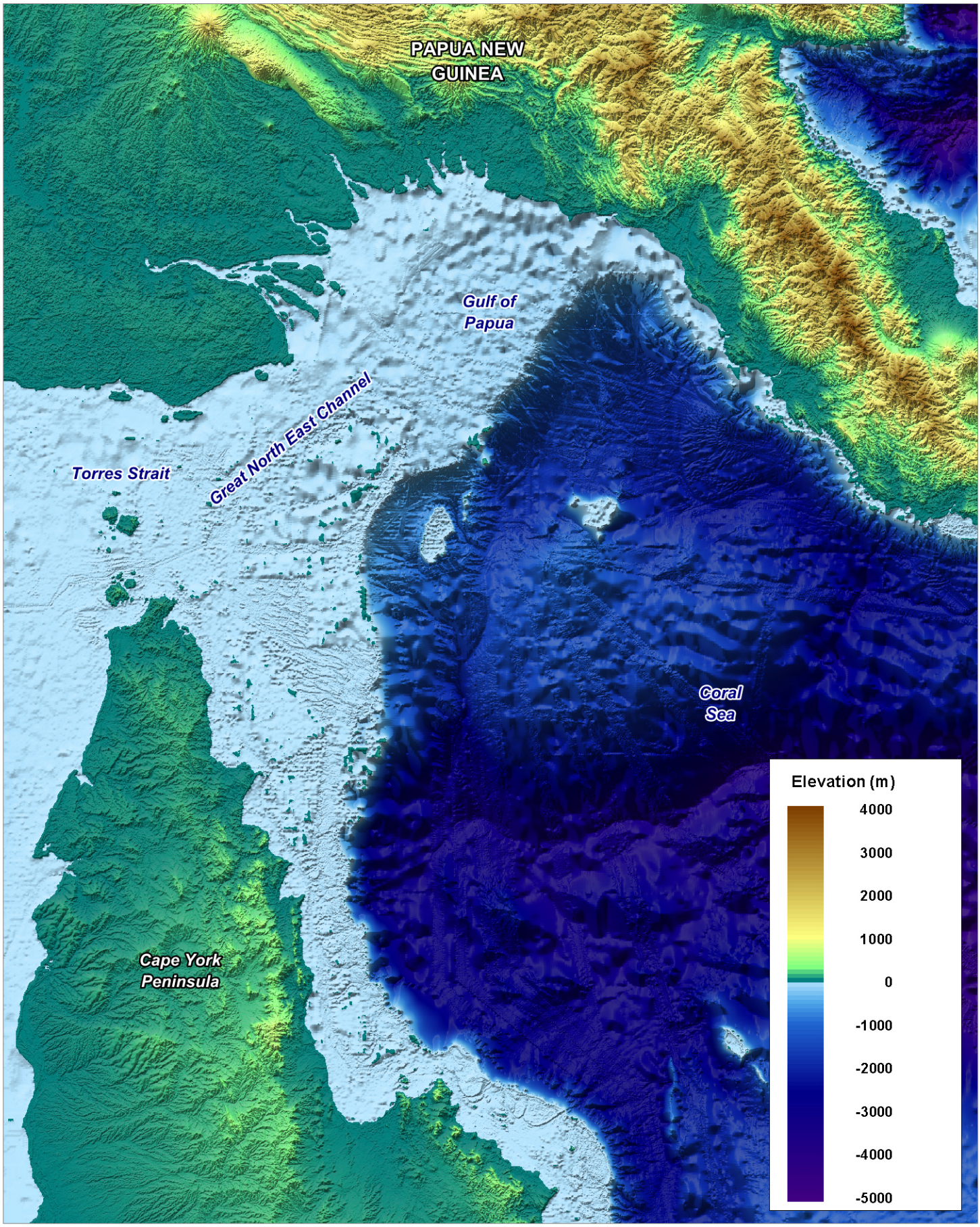
Table 6-1 Modeled Mean Freshwater Flows and Sediment Fluxes from Rivers into the Gulf of Papua

River	Flow (m^3/s)	Sediment flux (kg/s)
Fly	6,000	4,440
Bamu	2,000	1,480
Turama	2,000	1,480
Kikori	2,000	1,480
Purari	3,000	2,220

The sediment dynamics in the Gulf of Papua is driven primarily by waves, with waves and currents mobilizing about 10 times more sediment than currents alone (Saint-cast and Condie, 2006). Therefore, wind and wave-driven sediment resuspension is likely to be highest during the southeast trade winds season.

Caution Bay is subject to the same distinct seasonality as the gulf, with a period dominated by northwest monsoons from December to March, and by southeast trade winds from May to December (GEMS, 2008). As much of the bay is sheltered by a barrier reef (CNS, 2009) the effect of waves is mitigated to some extent, with a mean wave height of 0.42 m (CNS, 2009). A metocean deployment campaign for the PNG LNG Project EIS identified wave height in the area as exceeding 1 m only 10% of the time, with a maximum wave height (H_{max}) of 1.9 m (GEMS, 2008).

Data presented in the Marine Water and Sediment Quality Baseline Report (BMT WBM, 2017b) indicates that measured total suspended solids (TSS) in the water column at Orokolo Bay was generally lower during the northwest monsoon season survey (<10 mg/L) than during the southeast trade winds season survey (<20 mg/L). The measured TSS at Caution Bay was generally lower than at Orokolo Bay, and also lower during the northwest monsoon season survey (<3 mg/L) than during the southeast trade winds season survey (<8 mg/L).



Title:

Regional Bathymetry

Figure: 6-1

Rev: A

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6.2 Orokolo Bay

6.2.1 Bathymetry

The bathymetric chart for Orokolo Bay is shown in Figure 6-2 (depths are provided in meters relative to Lowest Astronomic Tide). The offshore profile is very flat, and the slope is relatively uniform and consistent throughout the bay. The 15 m depth contour (the nominal boundary between onshore and offshore areas) is located approximately 8 km from the shoreline.

It is also notable that none of the shoal features on the Australian Hydrographic Chart shown on Figure 6-2 were verified during field surveys, indicating inaccuracies in this chart for the area of Orokolo Bay. The reef at Site M6 was the only significant feature within the survey area. Reefs and shoals shown on the chart either side of this site, including the two locations west of Auma Point charted as being 3.8 m and 1.3 m depth, were observed to be non-existent during field survey. Waves were breaking on the reef near Site M6 even under calm conditions, with seas less than 0.5 m breaking during the survey.

6.2.2 Water Levels, Temperature and Salinity

The maximum tidal range in Orokolo Bay is approximately 3 m, as shown in the measured data presented in the Marine Water and Sediment Quality Baseline Report (BMT WBM, 2017b). Continuous field data was recorded using bottom-mounted instruments during two field campaigns, one during the southeast trade winds season (23/06/2016 to 4/07/2016) and one during the northwest monsoon season (14/01/17 to 25/01/17).

Southeast Trade Winds Season

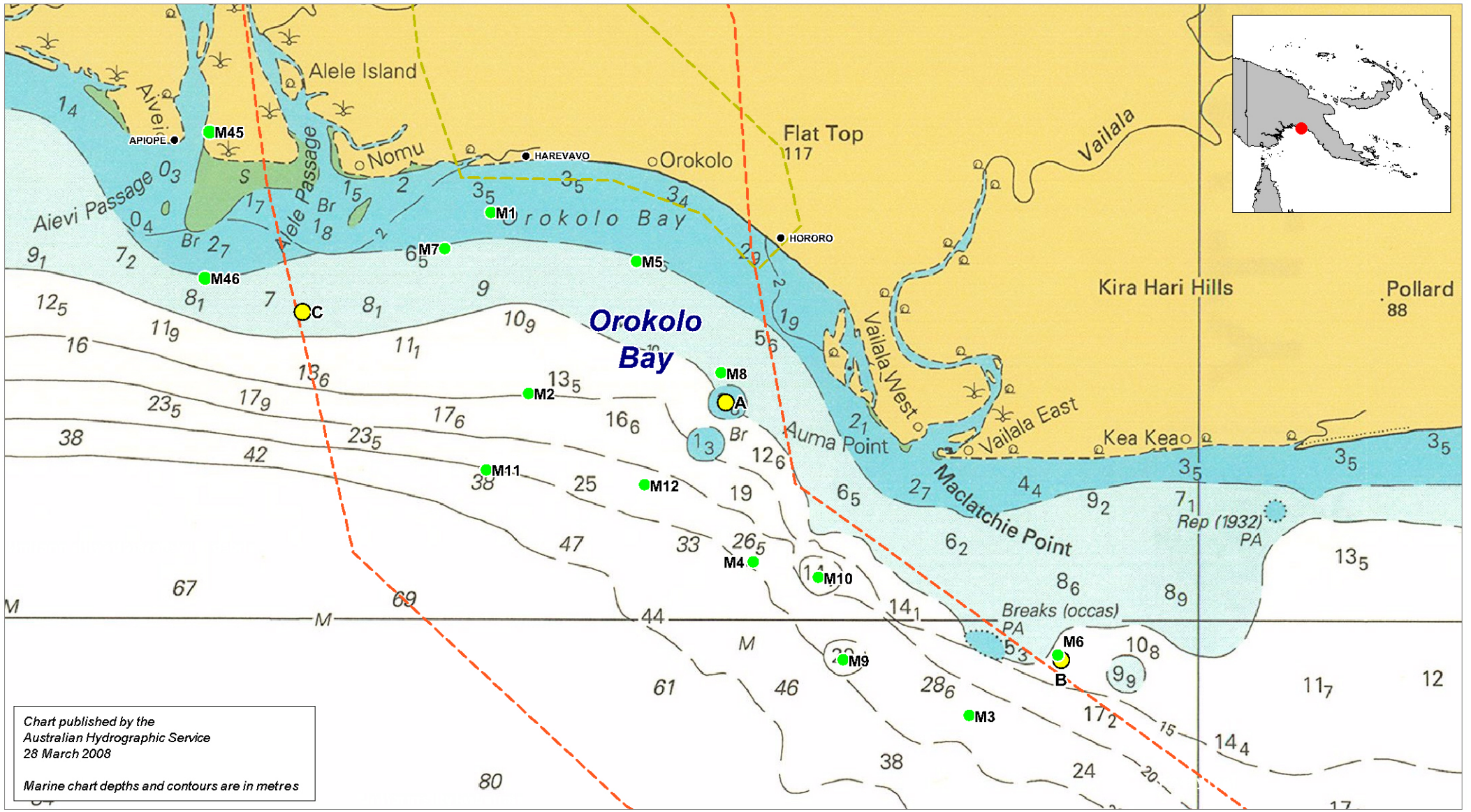
Continuous temperature, salinity and depth data was collected near the sea bed at Site A (mud) and Site B (reef) during the southeast trade winds season survey (locations are shown in Figure 6-2). The instruments were deployed on bottom-mounted frames on the sea floor in the following approximate water depths:

- ~13 m at Site A.
- ~15 m at Site B.

The data presented in the Marine Water and Sediment Quality Baseline Report (BMT WBM, 2017b) indicates that water temperature was maintained around 28 to 29°C, with temperature decreasing slightly at both sites towards the end of the deployment period.

Data from the instrument deployments also indicates that salinity in the lower water layers was variable at both sites, but was maintained within a range of approximately 33 to 36 ppt. The fluctuations in salinity at depth may be the result of occasional mixing of less saline surface waters during varying wind or riverine flow events.

The water depth data indicates that the tidal range during the southeast trade winds season survey was approximately 1 m during the neap tides and approximately 3 m during the spring tides.



LEGEND

- Town/Village
- Sampling sites
- Instrument deployment site
- Pipeline Corridor
- Narrowed Onshore Pipeline Corridor

Title:

Orokolo Bay Bathymetry and Instrument Deployment Sites

Figure: 6-2

Rev: A

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Water quality profiling measurements undertaken at each of the sampling sites shown in Figure 6-2 indicated that the water column was significantly stratified at all measurement sites due to the significant freshwater outflows from the Purari and other rivers. The salinity in the top 5 m of the water column was between 20 and 23 ppt at all sites, increasing to between 30 to 34 ppt in the 5 to 12 m depth range, and 35 ppt at greater depths. The surface water temperature was between 28.8 to 29.8ºC across the measured locations, decreasing to between 28.2 to 28.4ºC at depths greater than 5 m. This data is described in more detail in the Marine Water and Sediment Quality Baseline Report (BMT WBM, 2017b).

Northwest Monsoon Season

Continuous temperature, salinity and depth data was collected near the sea bed at Site B (reef) and Site C (Purari River mouth) during the northwest monsoon season survey (locations are shown in Figure 6-2).

The instruments were deployed on bottom-mounted frames on the sea floor in the following approximate water depths:

- ~10 m at Site C.
- ~18 m at Site B.

The collected data are presented in the Marine Water and Sediment Quality Baseline Report (BMT WBM, 2017b) indicates that water temperature was maintained around 29.0 to 30.0°C at the Purari River mouth (Site C) and around 28.5 to 29.5°C in the deeper waters at Site B.

Salinity was slightly lower at the Purari River mouth (Site C) compared to Site B, and was variable at both sites. A decrease in salinity at Site C coincided with increased freshwater flows in the Purari River as a result of rainfall higher up in the Purari catchment.

Similar to the southeast trade winds season survey, the water depth data indicates that the tidal range during the northwest monsoon season survey was approximately 1 m during the neap tides and approximately 3 m during the spring tides.

Water quality profiling measurements presented in BMT WBM (2017b) showed that the water column was again significantly stratified during this field campaign. The salinity in the top 5 m of the water column was between 24 and 32 ppt at offshore sites and as low as 1.2 ppt at Site M45 near the mouth of the Purari River. Water temperature was more consistent throughout the water column at around 29 to 30°C. The measured profiles are broadly consistent with the profiles measured near the mouth of the Purari River in January 1993 by Robertson *et al.* (1998).

The water level extracted from the numerical model for a two month period in the northwest monsoon season at Site A is provided in Figure 6-3. The maximum tidal range during spring tide periods is 3 m. The neap tidal range is around 1 m.

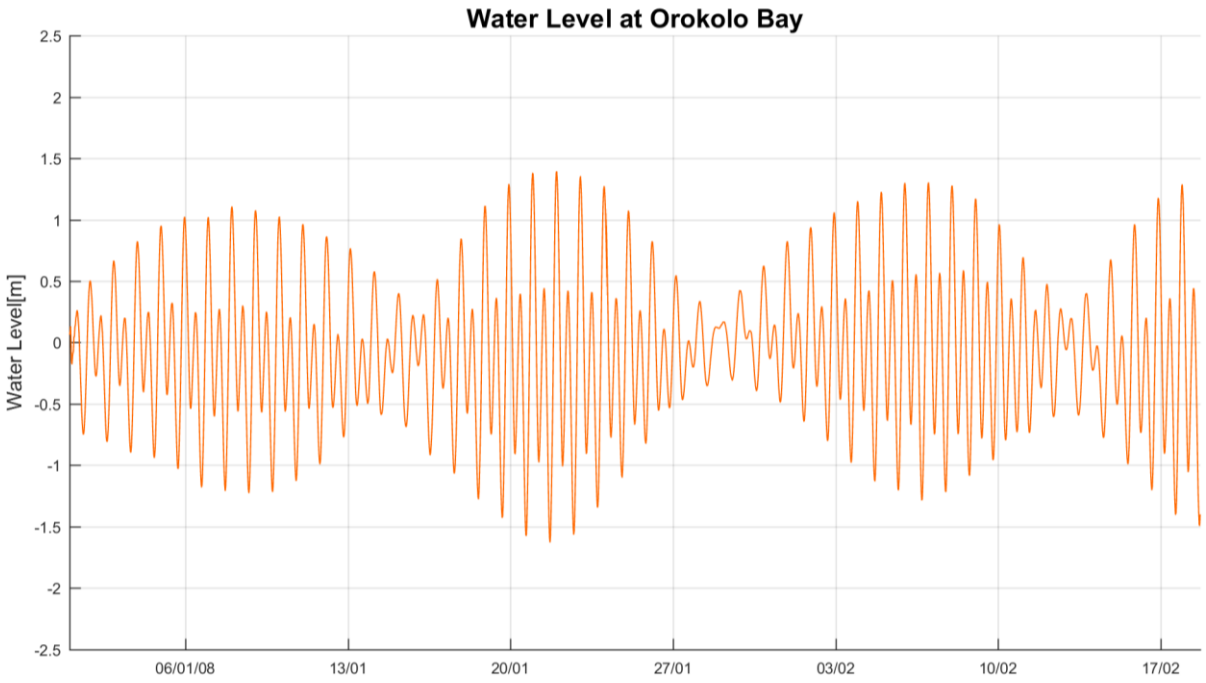


Figure 6-3 Modeled Water Level at Site A in Orokolo Bay

6.2.3 Currents

No current data has been collected in the vicinity of Orokolo Bay. The nearest available recorded current data was collected at the site labelled 'North Crossing' (refer to Figure 6-16 for location).

Time series of current speed and direction were extracted from the TUFLOW FV numerical model at Site A, where the water depth is approximately 13 m (location shown in Figure 6-2). The current speed and direction for the top 3 m of the water column is provided in Figure 6-4 for the southeast trade winds season and in Figure 6-5 for the northwest monsoon season. The current speed and direction for the bottom 3 m of the water column are provided in Figure 6-6 for the southeast trade winds season and in Figure 6-7 for the northwest monsoon season. The surface currents are slightly stronger in the trade winds season than during the monsoon, and are more consistent in direction (most often towards the southeast, but with some tidal variation). The bottom currents are smaller in magnitude than the surface currents and tend to change direction with the tide more regularly than the surface currents (though still most often towards the southeast).

The current rose for the depth-averaged currents at Site A for the southeast trade winds season is shown in Figure 6-8 and for the northwest monsoon season in Figure 6-9.

Typical current speeds are up to 0.4 m/s in both the trade winds season and the northwest monsoon season, typically towards the southeast, although the average speed is higher in the trade winds season. Although the net nearshore currents are directed towards the southeast, the net longshore sediment transport in this area is towards the northwest due to the prevailing wave climate (refer to the following section for description of the wave climate, and to the Seabed and Coastal Geomorphology Baseline Report (BMT WBM, 2017a; Part 9 of ESBS Dossier) for a description of the sediment transport processes).

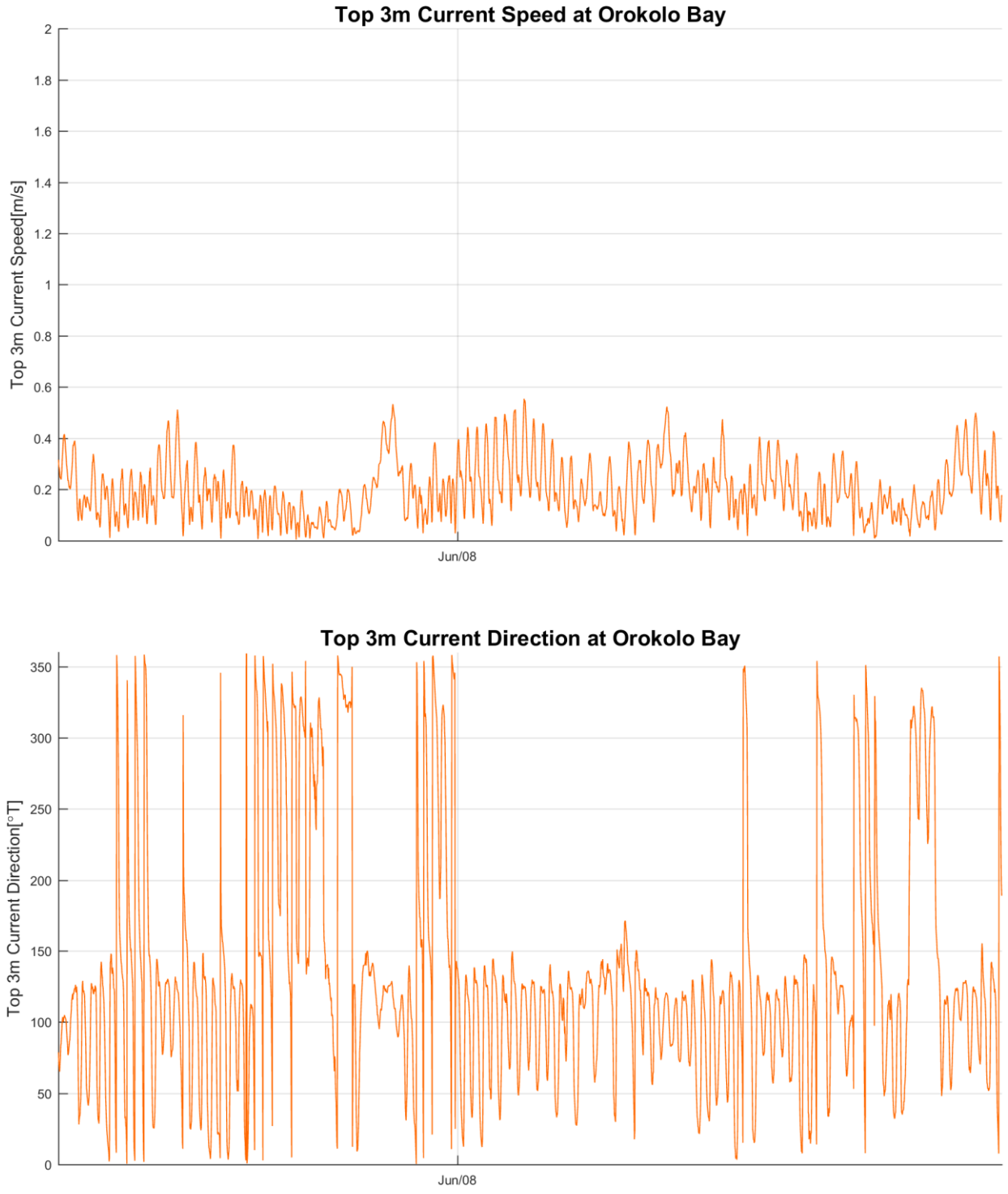


Figure 6-4 Time Series of Current Speed and Direction in the Top 3 m of the Water Column at Site A during the Southeast Trade Winds Season (TUFLOW FV Model)

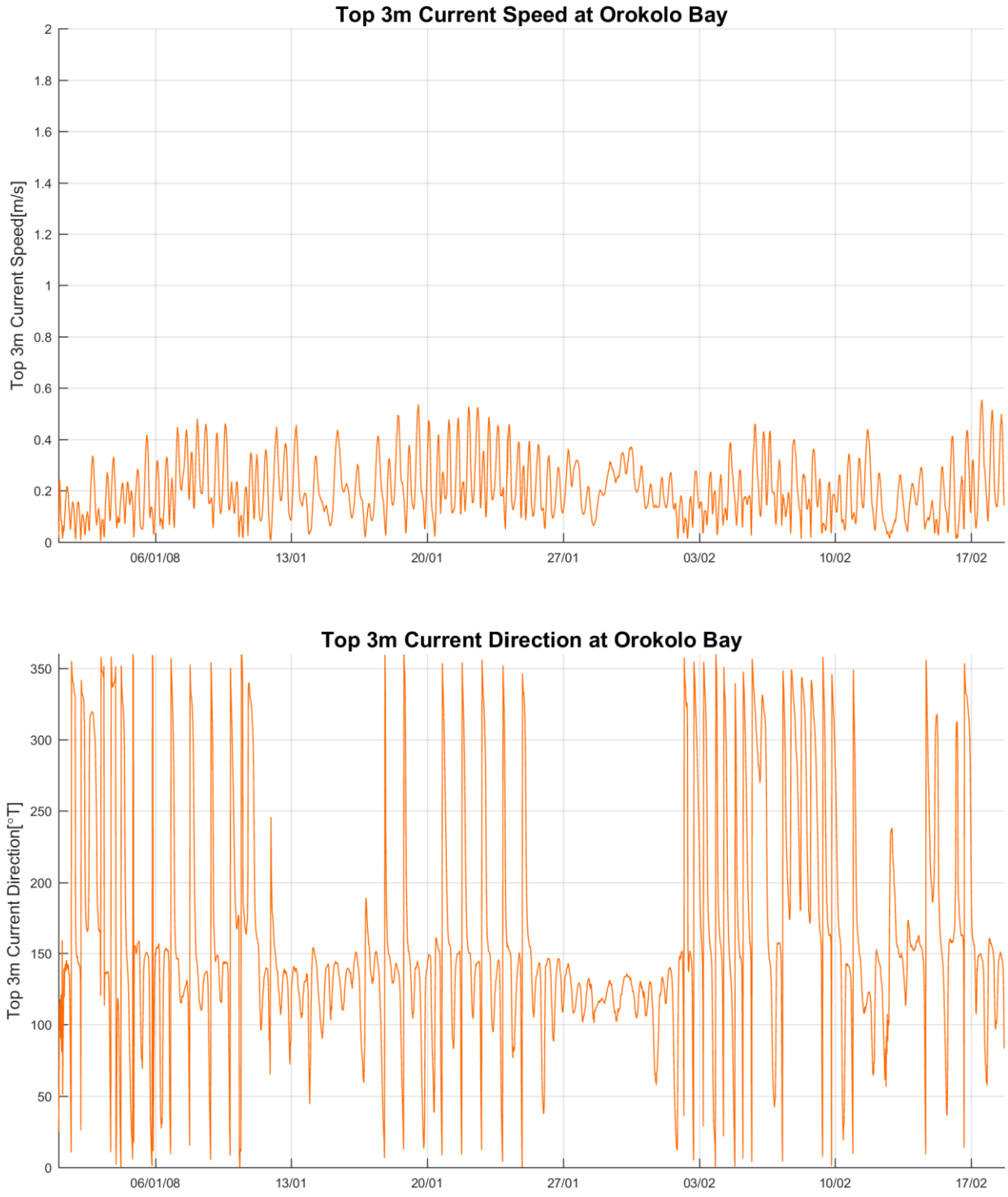


Figure 6-5 Time Series of Current Speed and Direction in the Top 3 m of the Water Column at Site A during the Northwest Monsoon Season (TUFLOW FV Model)

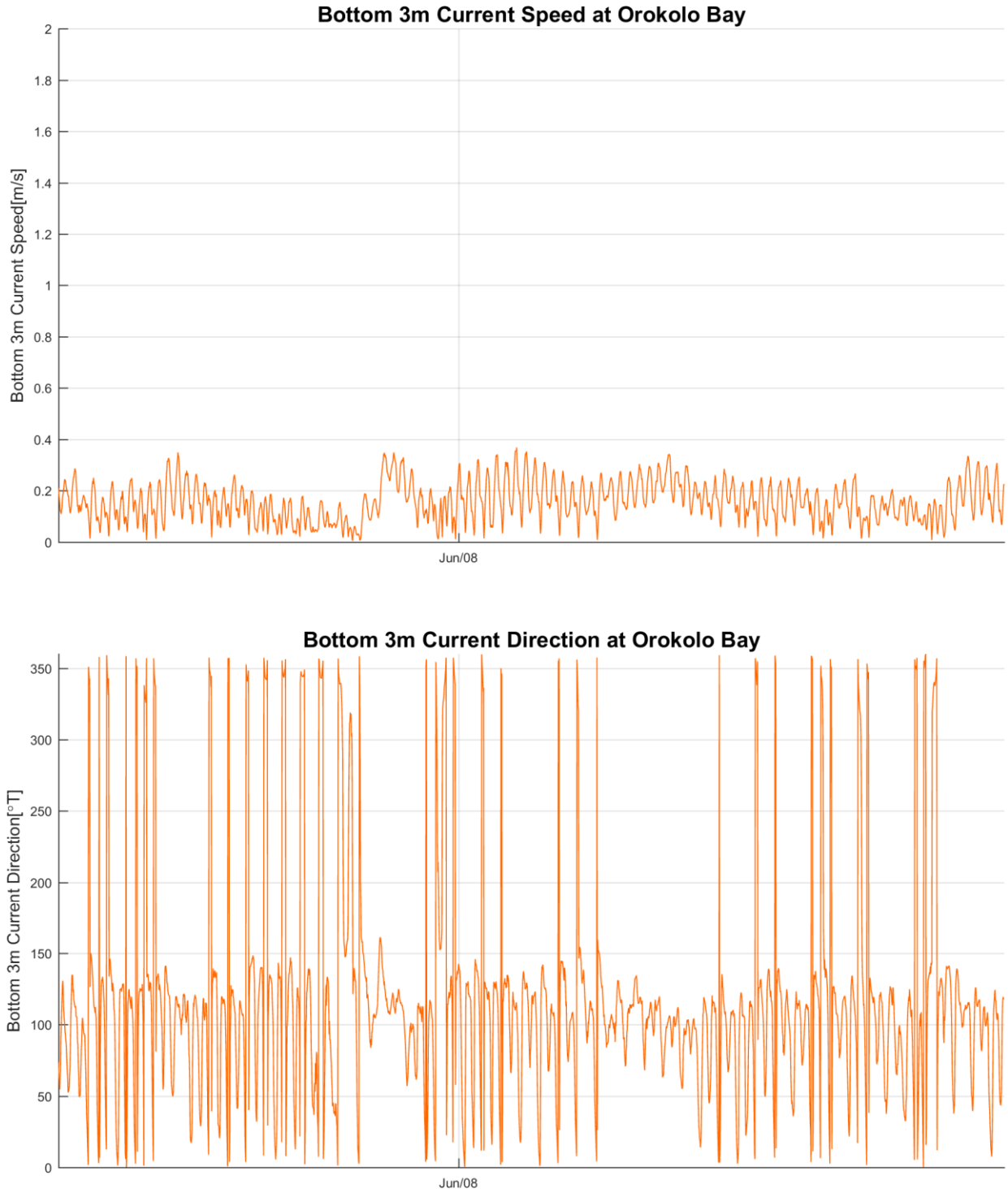


Figure 6-6 Time Series of Current Speed and Direction in the Bottom 3 m of the Water Column at Site A during the Southeast Trade Winds Season (TUFLOW FV Model)

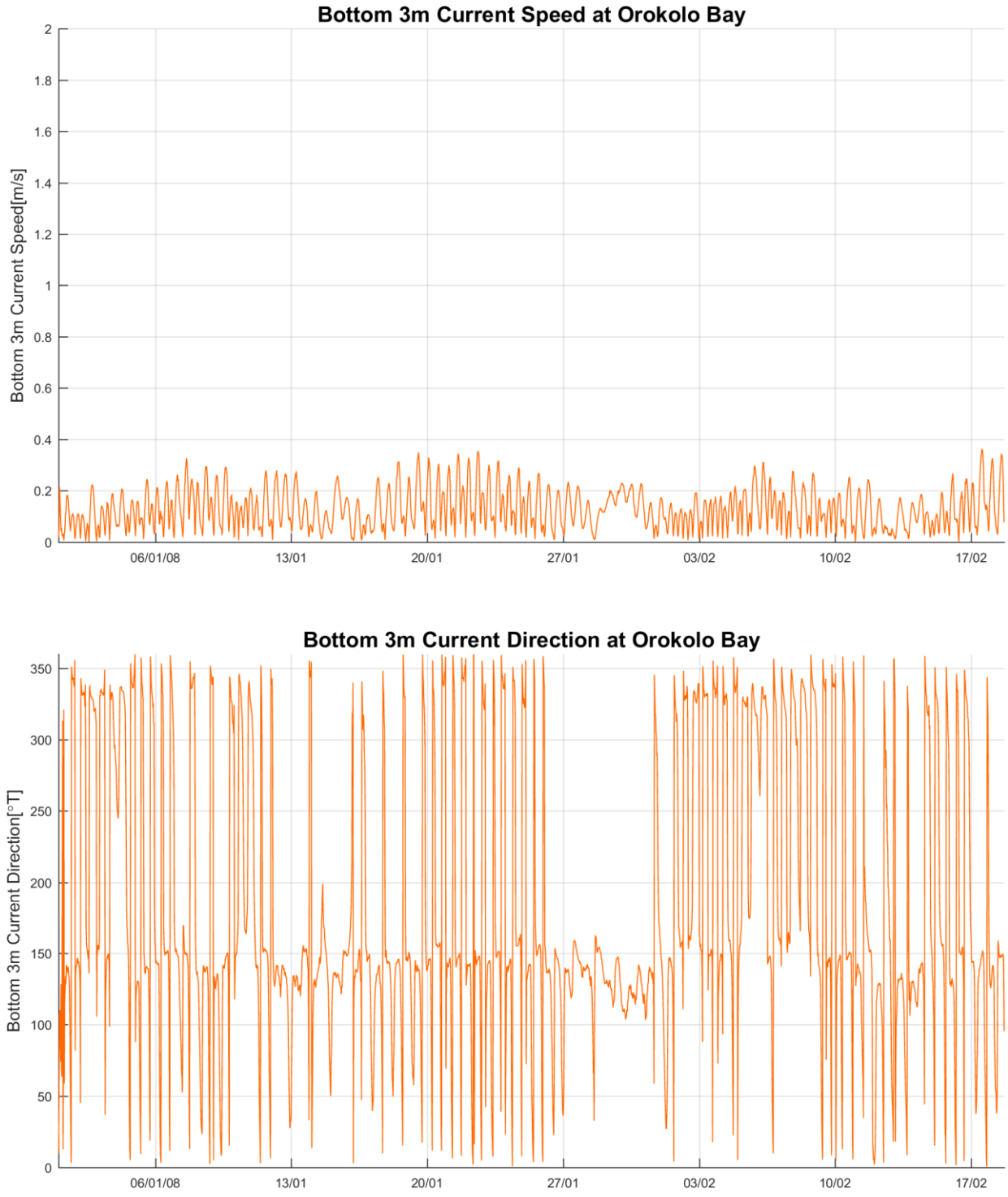


Figure 6-7 Time Series of Current Speed and Direction in the Bottom 3 m of the Water Column at Site A during the Northwest Monsoon Season (TUFLOW FV Model)

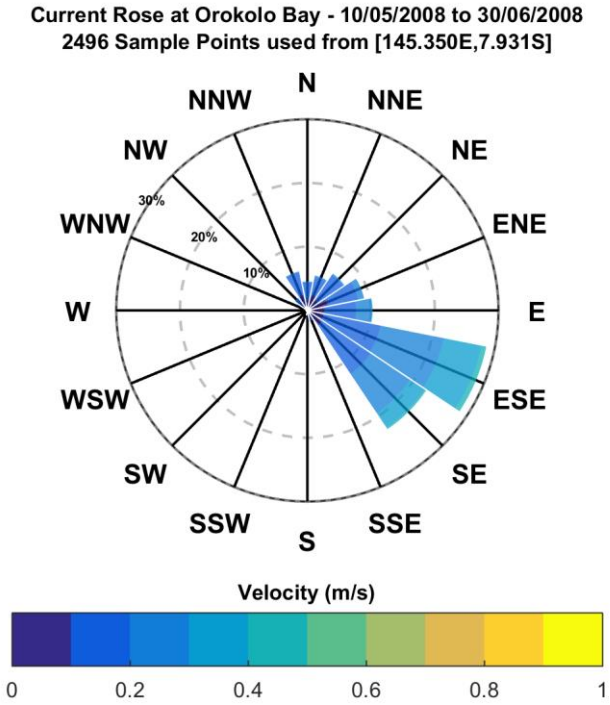


Figure 6-8 Current Rose at Site A during the Southeast Trade Winds Season (TUFLOW FV Model)

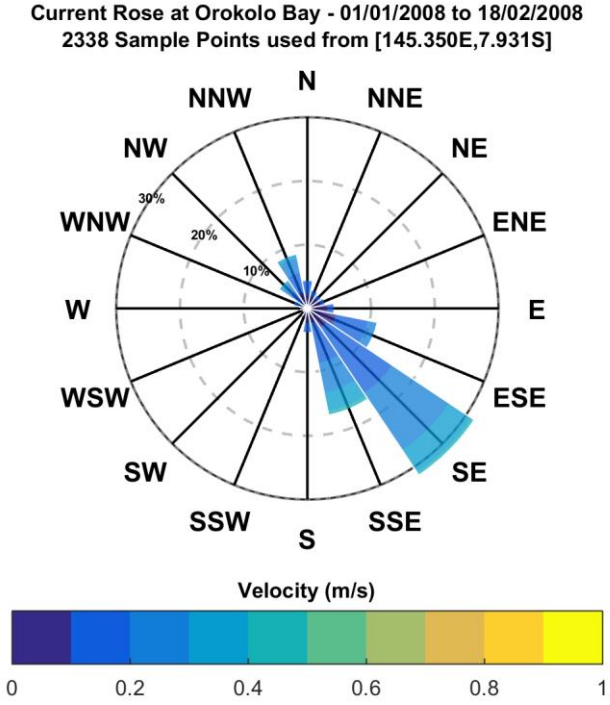


Figure 6-9 Current Rose at Site A during the Northwest Monsoon Season (TUFLOW FV Model)

The net current patterns (top 10 m of the water column) within the bay indicated by the TUFLOW FV model (averaged over two months) is shown in Figure 6-10 for the southeast trade winds season and Figure 6-11 for the northwest monsoon season. The net current velocities during the southeast trade winds season are larger than during the northwest monsoon season, and are directed towards the southeast. This is part of a large-scale clockwise current circulation pattern within the Gulf of Papua (described further in Section 6.3). During the northwest monsoon season the current velocity is generally small (less than 0.2 m/s) and is directed towards the northwest in the offshore part of the bay (>15 m water depth), which is part of an anticlockwise circulation pattern within the Gulf of Papua (described further in Section 6.3). Although the net current magnitude and direction at Site A is similar in both seasons (as shown in Figure 6-8 and Figure 6-9), the current patterns further offshore exhibit much larger seasonal differences.

6.2.4 Waves

Wave roses for Site A (location shown in Figure 6-2) were extracted from the SWAN model (see Appendix A for description) for the southeast trade winds season (Figure 6-12) and the northwest monsoon season (Figure 6-13). The typical significant wave height (H_{sig}) and wave direction in Orokolo Bay during the southeast trade winds season are shown in Figure 6-14, and in Figure 6-15 during the northwest monsoon season. Wave height decreases from offshore to nearshore.

The waves during the southeast trade winds season propagate from south to north (with significant wave height up to 1.6 m), while in the northwest monsoon season they are more variable in direction but tend to approach the bay from the south-southwest (with significant wave height less than 1 m).

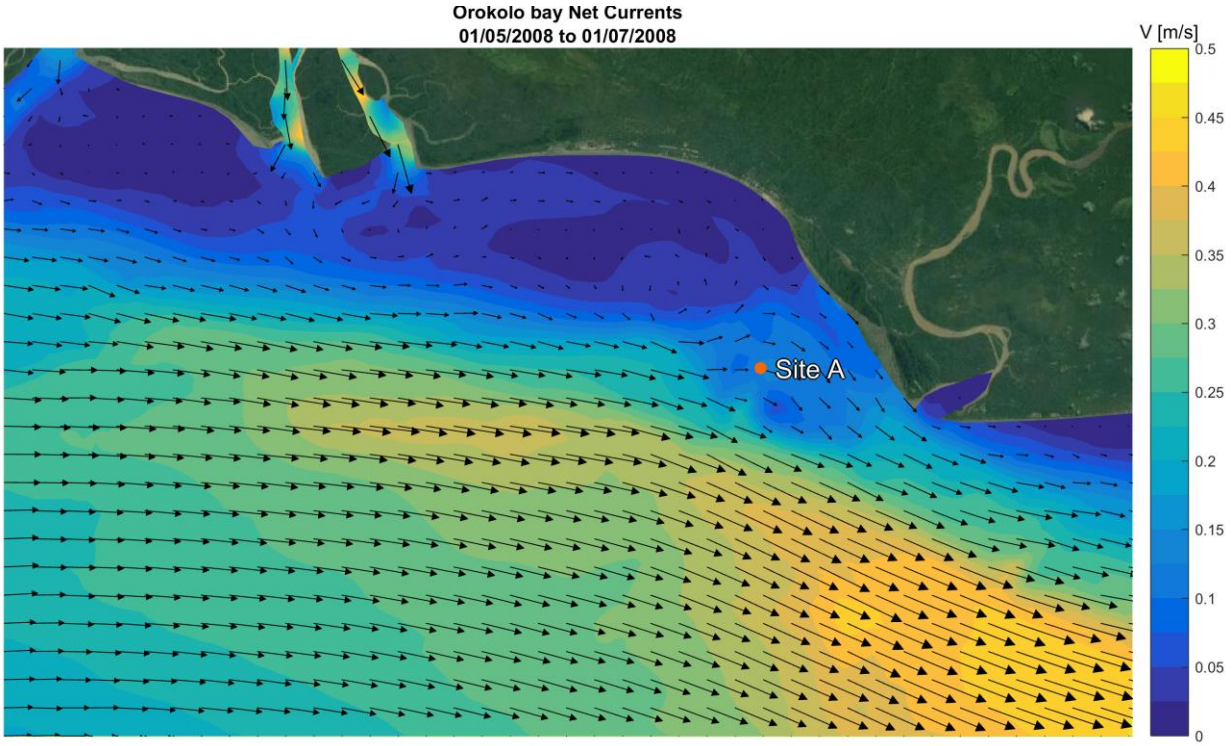


Figure 6-10 Modeled Net Current Pattern (Top 10 m of the Water Column) within Orokolo Bay in the Southeast Trade Winds Season

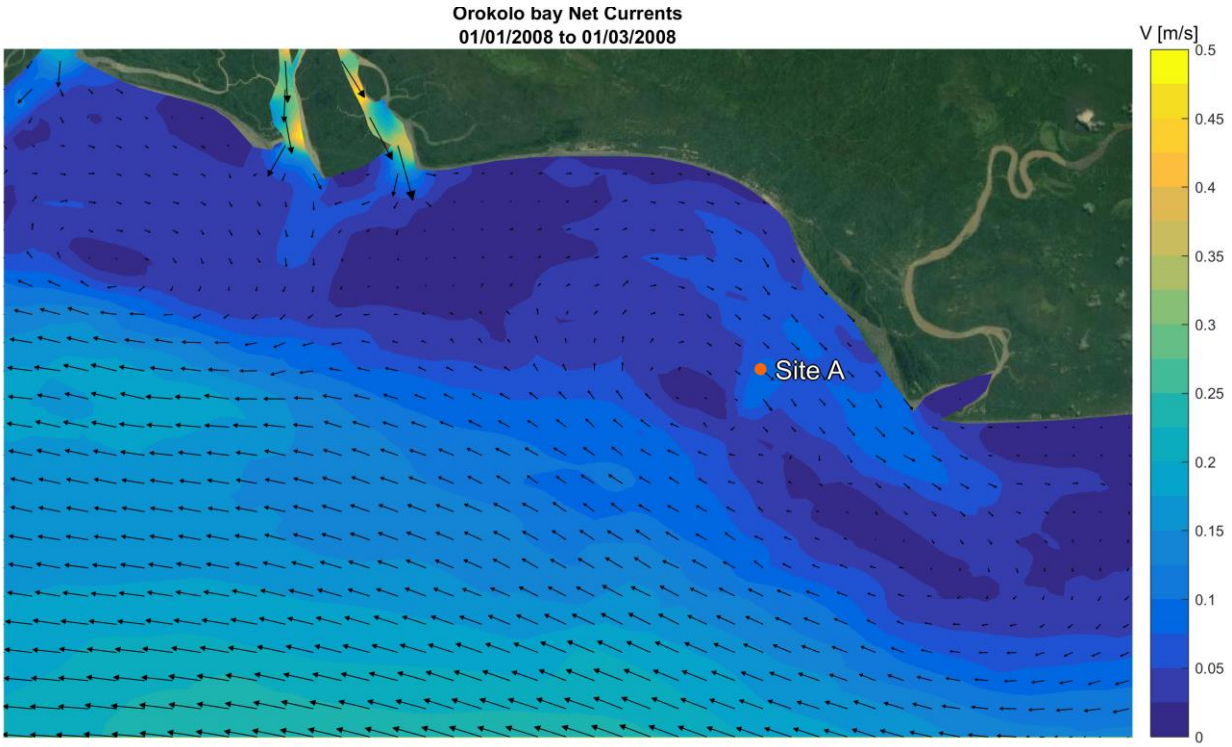


Figure 6-11 Modeled Net Current Pattern (Top 10 m of the Water Column) within Orokolo Bay in the Northwest Monsoon Season

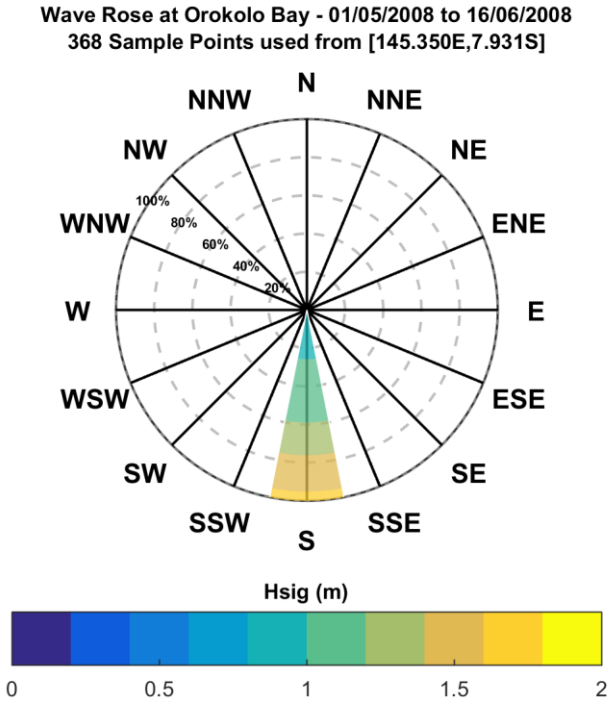


Figure 6-12 Wave Rose at Site A in Orokolo Bay during the Southeast Trade Winds Season (modeled data)

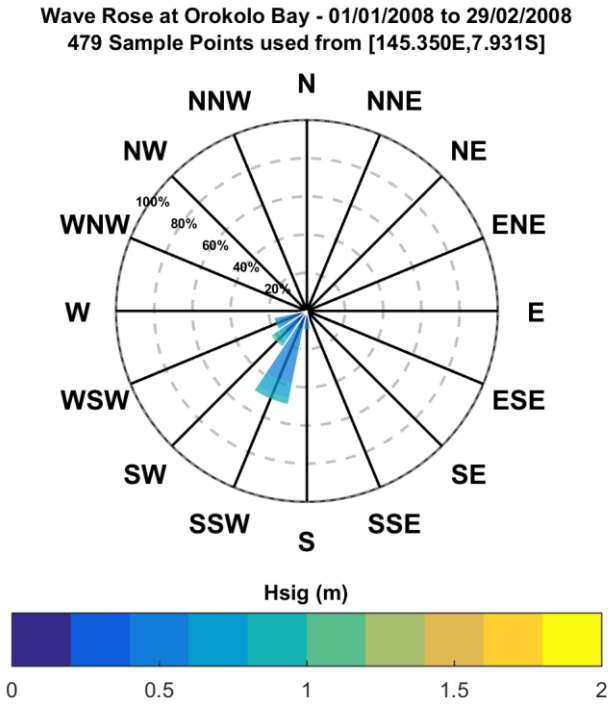


Figure 6-13 Wave Rose at Site A in Orokolo Bay during the Northwest Monsoon Season (modeled data)

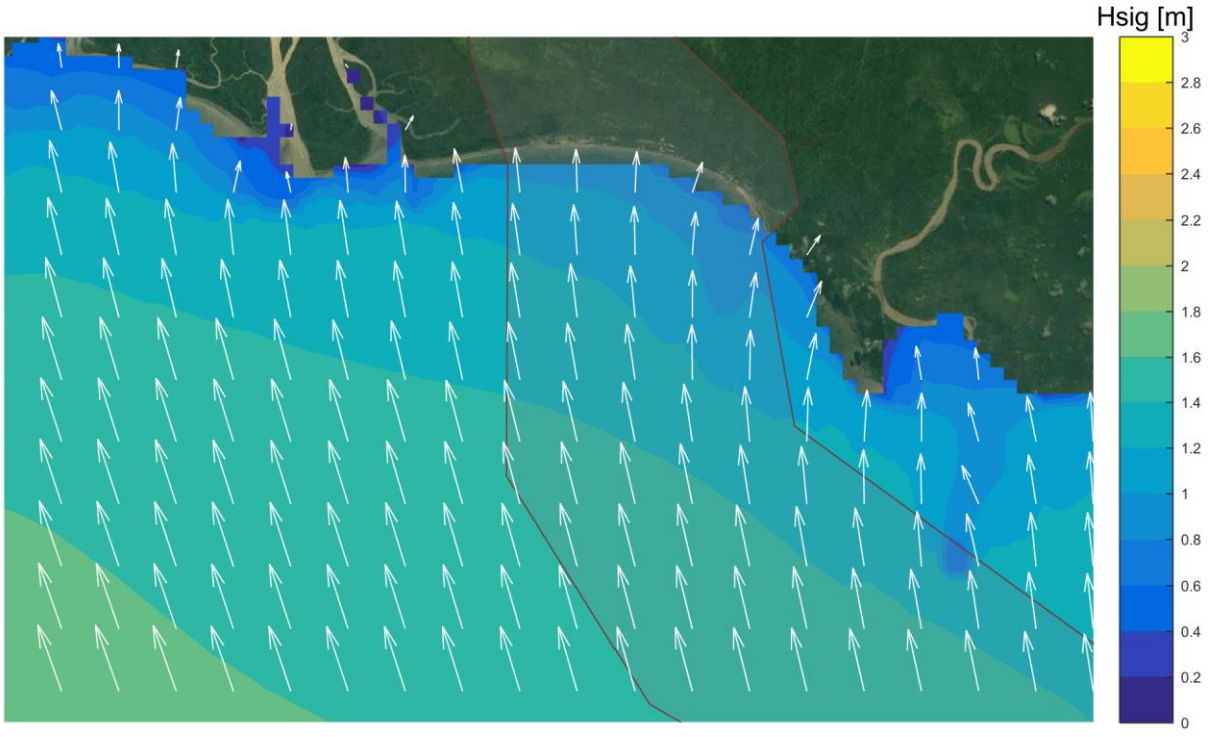


Figure 6-14 Typical Wave Pattern in Orokolo Bay During the Southeast Trade Winds Season (SWAN Model)

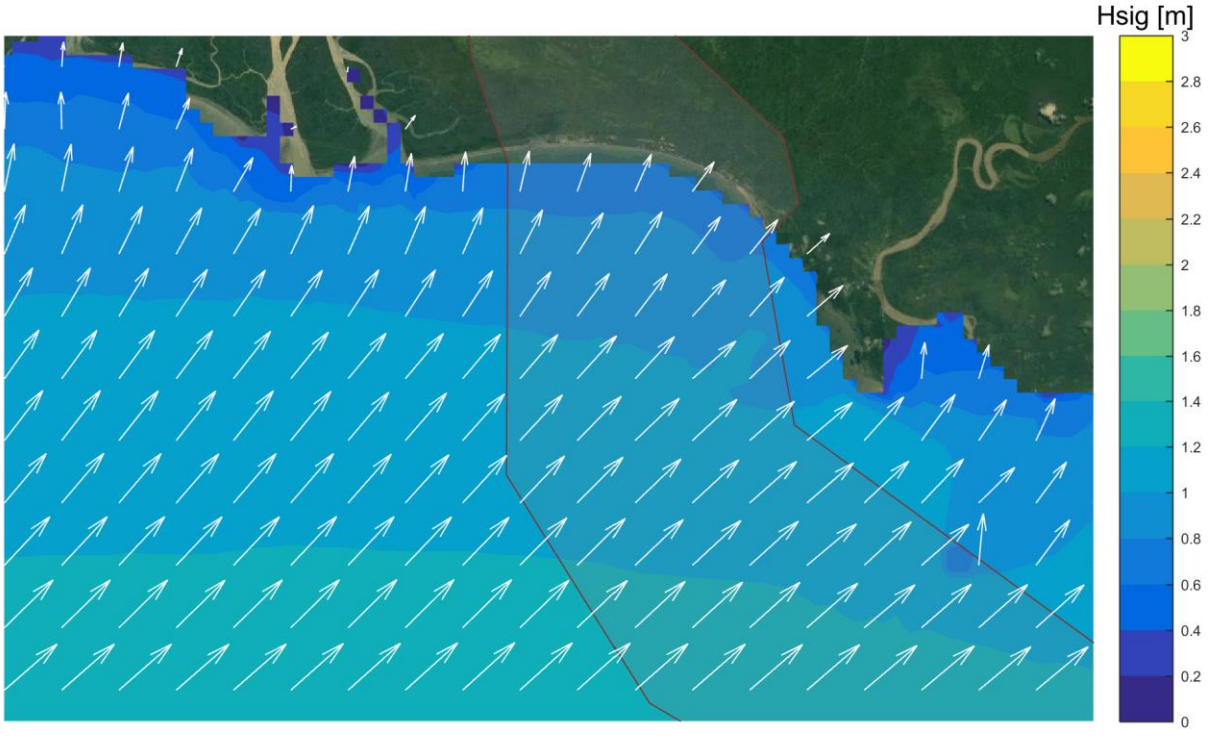


Figure 6-15 Typical Wave Pattern in Orokolo Bay During the Northwest Monsoon Season (SWAN Model)

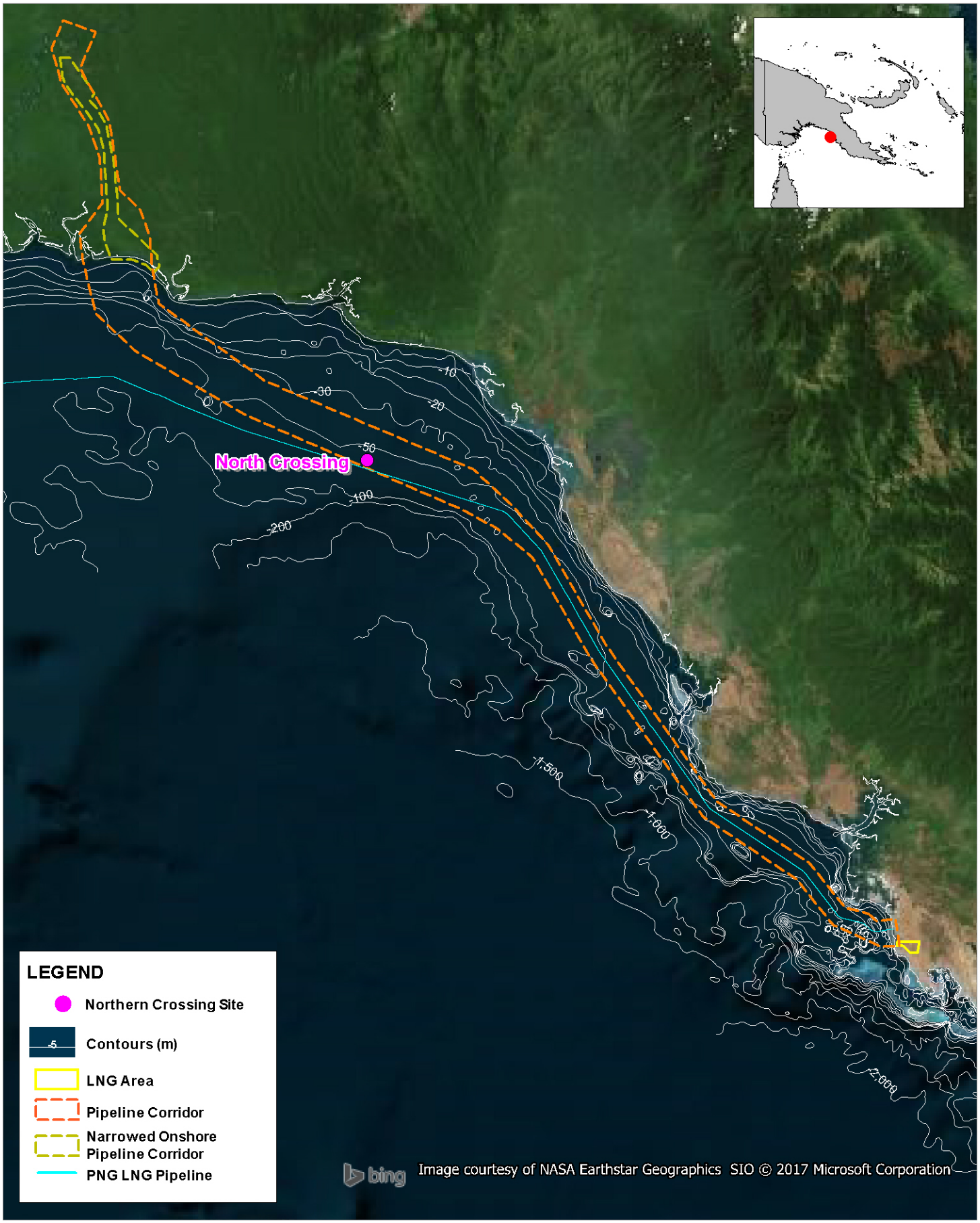
6.3 Offshore Export Pipeline Corridor

6.3.1 Bathymetry

The offshore export pipeline corridor traverses the Gulf of Papua continental shelf edge (see Figure 6-1 for regional bathymetry). The bathymetry along the pipeline corridor is shown in Figure 6-16. This figure includes the location where the offshore export pipeline corridor meets the PNG LNG Project pipeline route (North Crossing). Metocean data was collected at this location as part of the PNG LNG Project (refer Table 4-1).

In the deepest part of the corridor (up to 90 m), the seafloor sediment composition varies from soft clays to well-layered interbedded sand, silt and clay layers, as described by Coffey Natural Systems (2008) and observed during the 2016 and 2017 field surveys.

As the pipeline corridor rises again (depths of 35 to 60 m) up to the edge of Caution Bay the substrate changes to a slightly silty clay (CNS, 2008). This area also includes some rocky outcrops.



Title:

Bathymetry Along Offshore Pipeline Route

Figure: 6-16

Rev: A

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6.3.2 Water Levels

The maximum tidal range is approximately 3 m along the length of the offshore export pipeline corridor based on the TUFLOW FV model output. Measurements of water levels at the North Crossing site (refer to Figure 6-16) were collected as part of the PNG LNG Project EIS (CNS, 2009) and are shown in Figure 6-17. The maximum tide range during the measurement period was approximately 2.9 m, slightly less than the long-term maximum of 3 m indicated by the model.

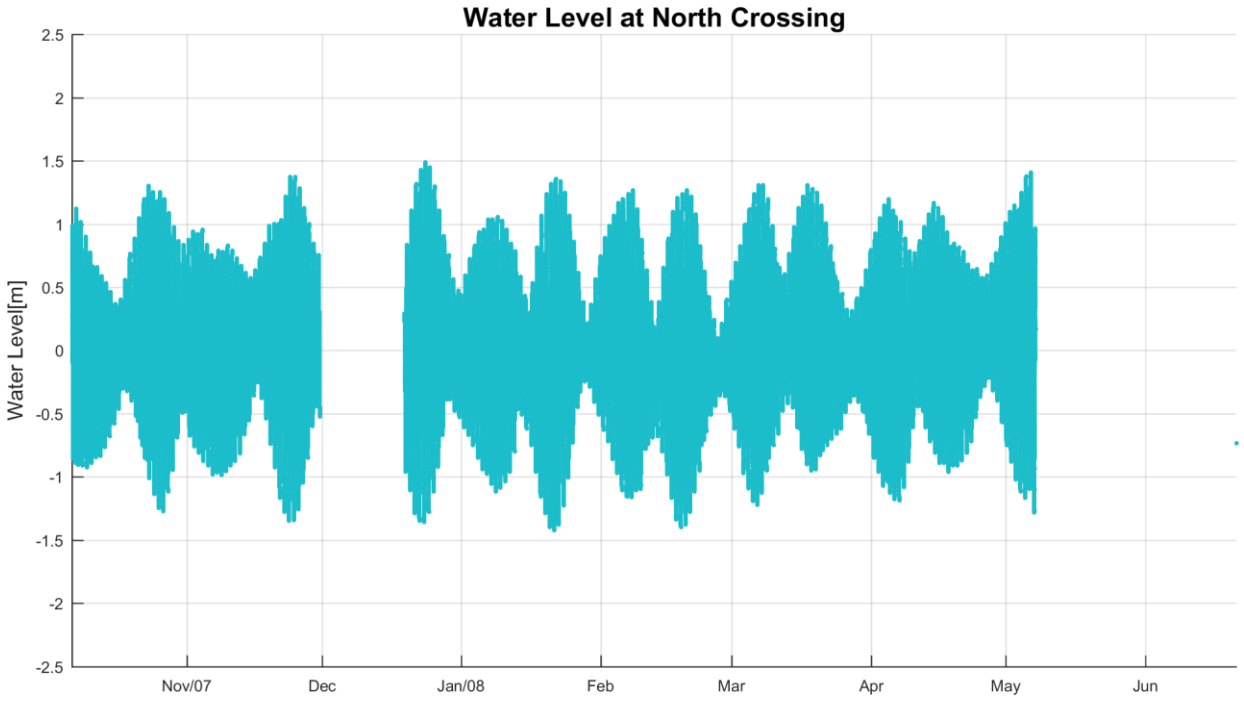


Figure 6-17 Recorded Water Level Time Series at North Crossing (ADCP Measurement)

6.3.3 Currents

Current magnitude and direction was recorded at the North Crossing site (refer to Figure 6-16) as part of the PNG LNG Project EIS (CNS, 2009) and are shown in Figure 6-18. The measured depth-averaged current speed had an overall maximum of around 0.6 m/s and a regular tidal variation of around 0.2 m/s. The net current during the months March to November was usually directed towards the southeast, with an average speed of around 0.2 m/s, while the direction during the months December to February was more variable and often directed towards the west, with an average speed of around 0.1 m/s. Current roses based on the recorded data at the North Crossing site are provided for the southeast trade winds season in Figure 6-19 and for the northwest monsoon season in Figure 6-20. The observed current direction towards the southeast during the trade winds season is counterintuitive, since it flows in the opposite direction to the prevailing wind, but can be explained by considering the overall pattern of circulation in the gulf where the water further offshore is driven by the wind into the gulf and returns via a coastal current along the southern Papua New Guinea coastline.

The net current patterns indicated by the TUFLOW FV numerical model (top 10 m of the water column, averaged over two months) are presented in Figure 6-21 for the southeast trade winds season and Figure 6-22 for the northwest monsoon season. The modeled current patterns are consistent with the measured currents at North Crossing. The model results indicate that the currents along the offshore export pipeline corridor during the southeast trade season are generally directed towards the southeast, while the currents during the northwest monsoon season are smaller in magnitude and are directed towards the northwest along the northern part of the pipeline corridor and to the southeast along the southern part of the pipeline corridor. The model results indicate that the Hiri current clockwise gyre operates further offshore in the northwest monsoon season (off the continental shelf) in concert with a separate anti-clockwise gyre within the gulf (which is also referred to by Wolanski *et al.* 1995). In the southeast trade winds season, the model indicates that the prevailing winds from the southeast set up a larger clockwise gyre that encompasses the entire gulf.

The current patterns indicated by the numerical model are consistent with the results of previous studies, including Slingerland *et al.* (2008).

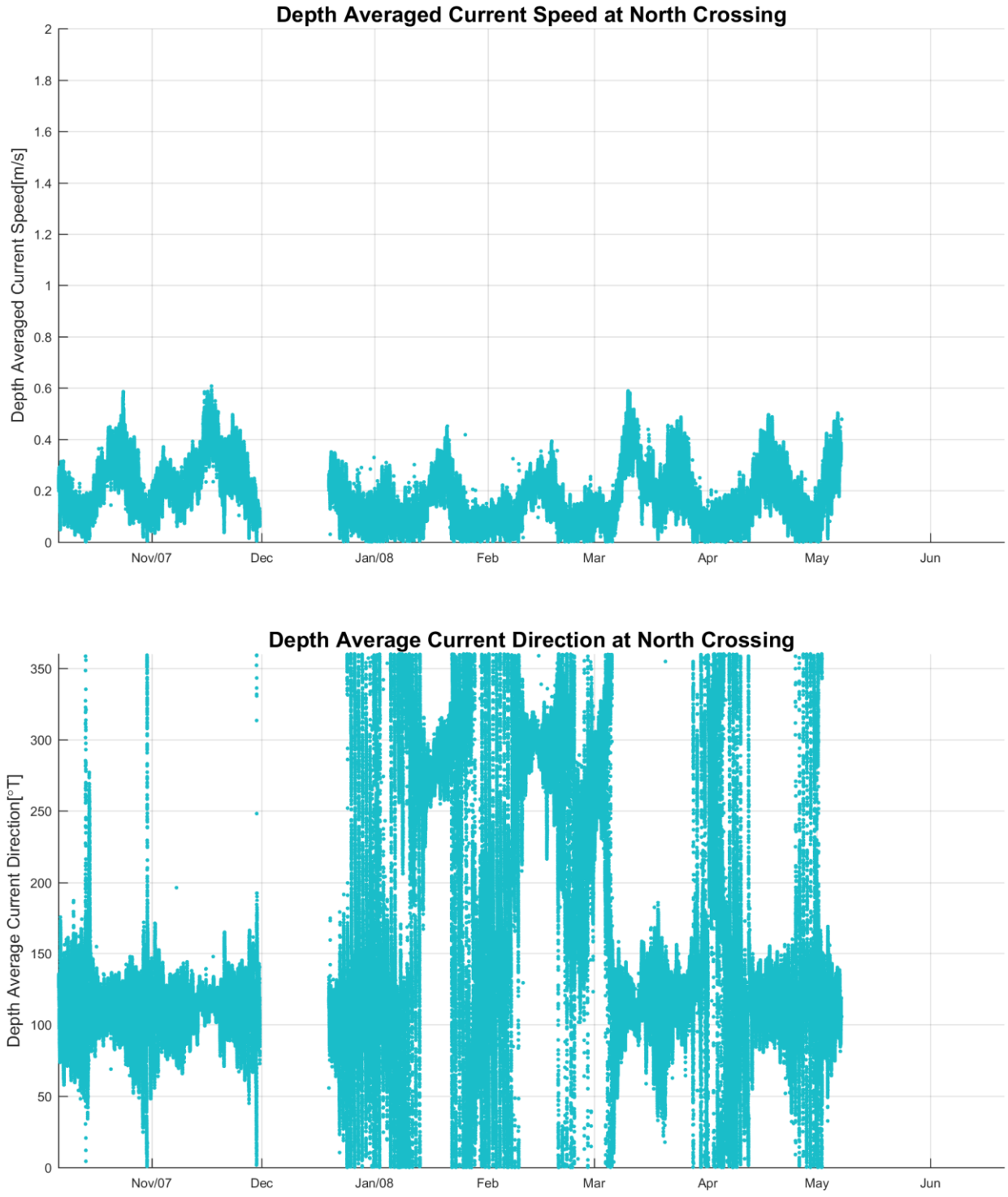


Figure 6-18 Current Speed (Top) and Direction (Bottom) at North Crossing (ADCP Measurement)

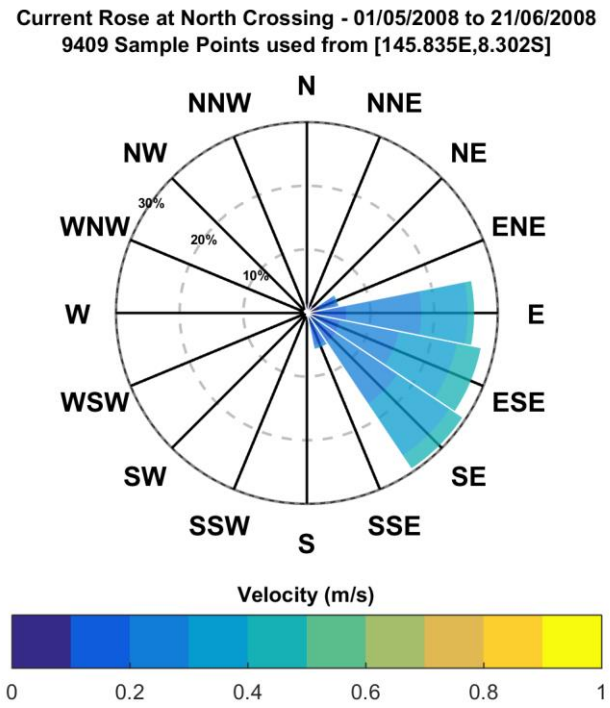


Figure 6-19 Current Rose at North Crossing during the Southeast Trade Winds Season (ADCP Measurement)

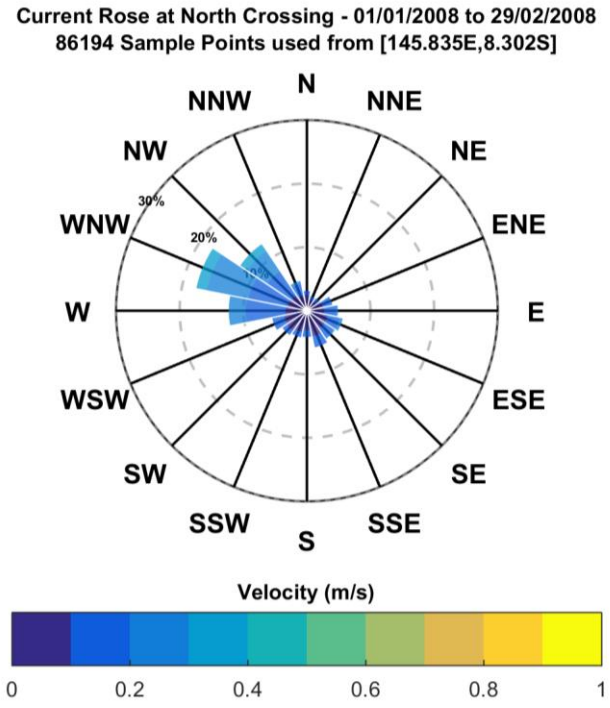


Figure 6-20 Current Rose at North Crossing during the Northwest Monsoon Season (ADCP Measurement)

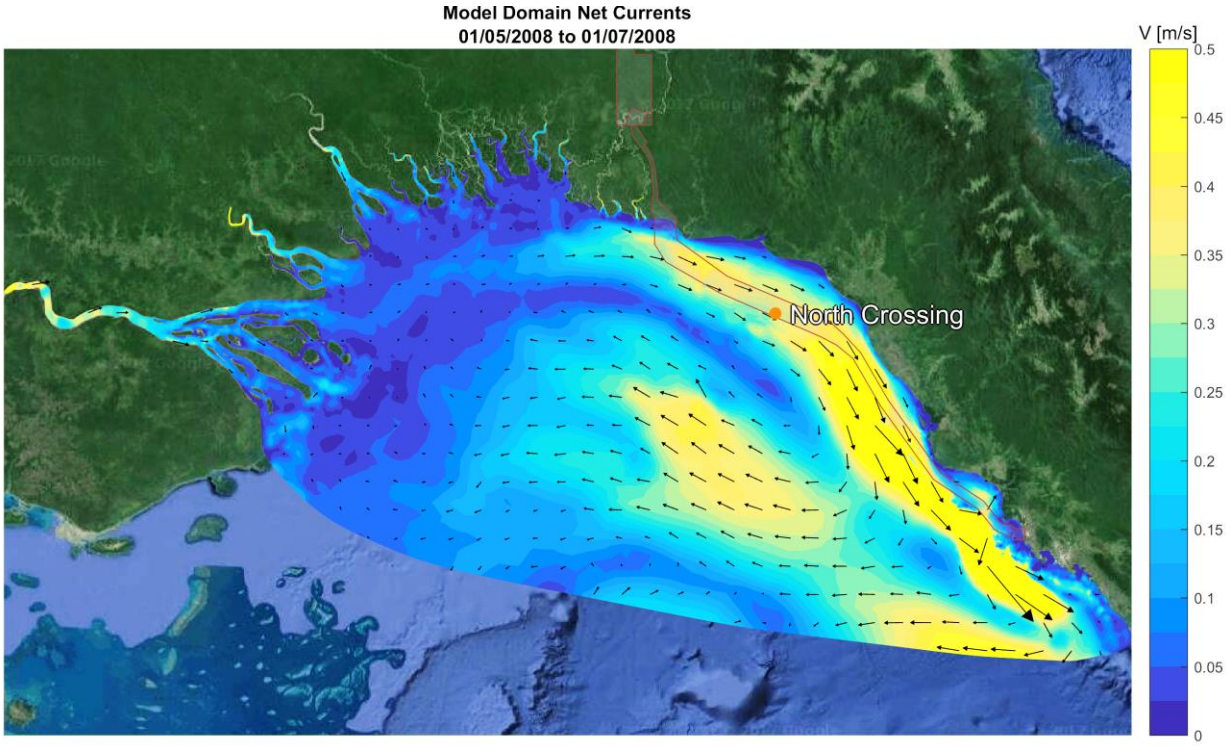


Figure 6-21 Net Current Pattern in the Gulf of Papua During the Southeast Trade Winds Season (Top 10 m of the Water Column) (TUFLOW FV Model)

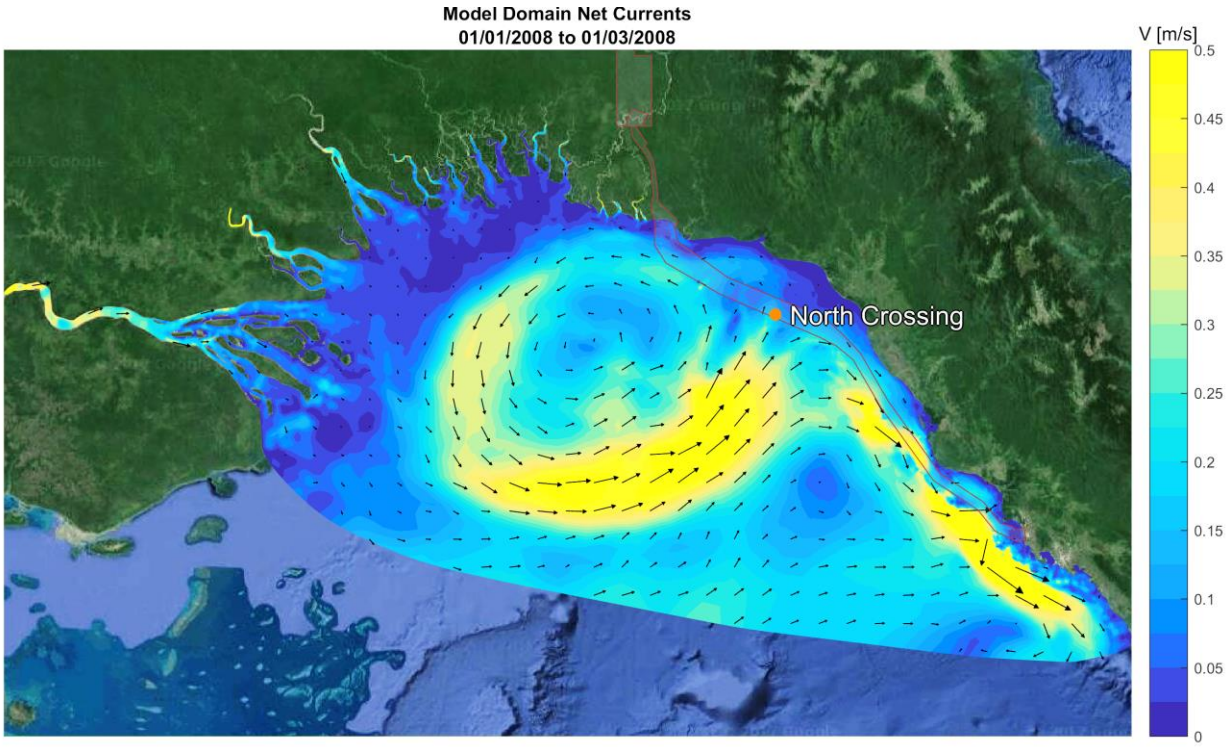


Figure 6-22 Net Current Pattern in the Gulf of Papua During the Northwest Monsoon Season (Top 10 m of the Water Column) (TUFLOW FV Model)

6.3.4 Waves

Wave roses for the North Crossing site (location shown in Figure 6-16) were extracted from the SWAN wave model (see Appendix A for description) for the southeast trade winds season (Figure 6-24) and the northwest monsoon season (Figure 6-25). During the southeast trade winds season, the wave direction is predominantly from the south at North Crossing due to the prevailing southeast wind direction and the pattern of wave refraction within the gulf. The significant wave height (H_{sig}) has an average of around 1.5 m and a maximum of 2 m. During the northwest monsoon season the direction is more variable and the magnitude is much lower, with a maximum significant wave height of around 1 m.

The typical wave patterns (significant wave height and direction) along the offshore export pipeline corridor during the southeast trade winds season are shown in Figure 6-23. The prevailing southeast winds generate waves travelling from the southeast to the northwest, refracting as they propagate into shallower water.

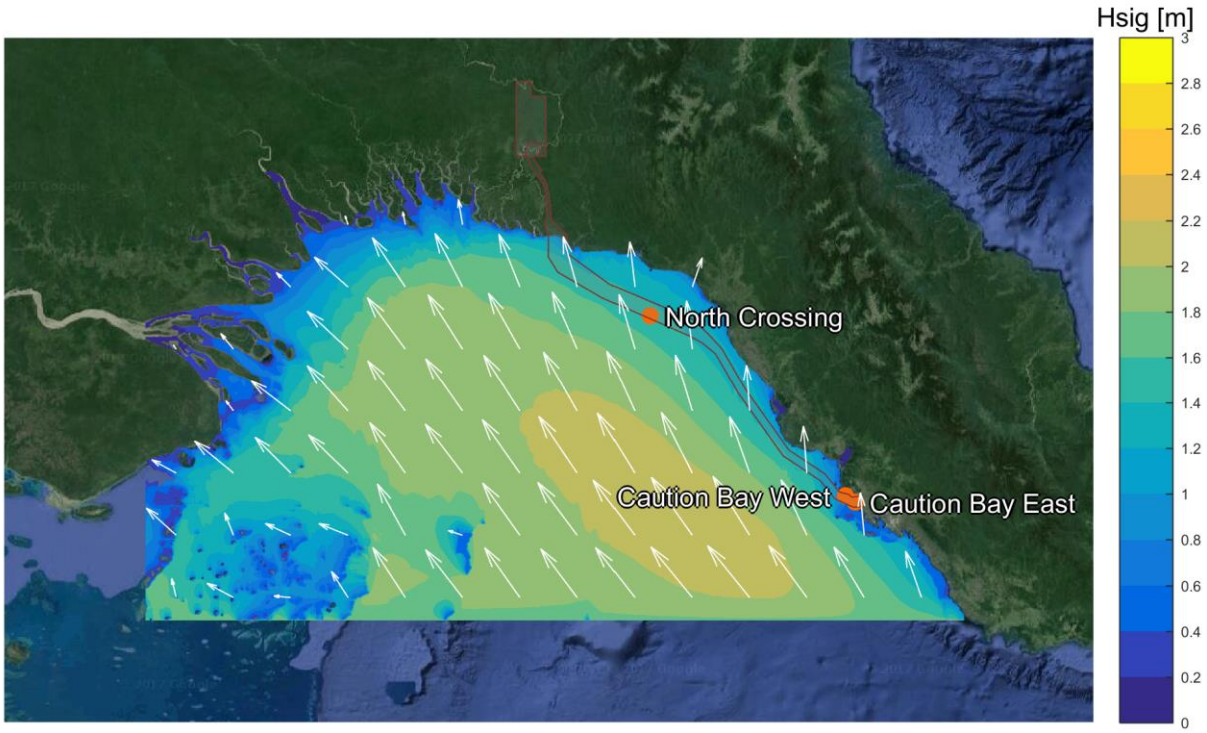


Figure 6-23 Typical Wave Pattern Along the Offshore Export Pipeline Corridor During the Southeast Trade Winds Seasons (SWAN Model)

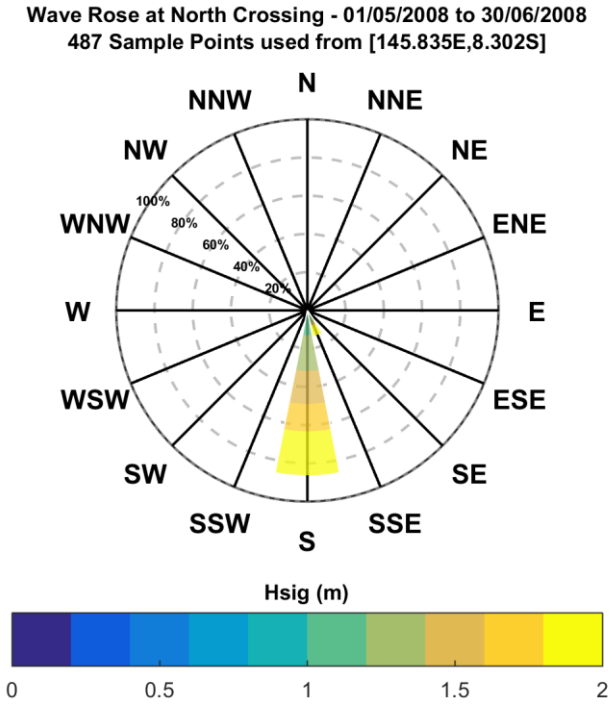


Figure 6-24 Wave Rose at North Crossing during the Southeast Trade Winds Season (modeled data)

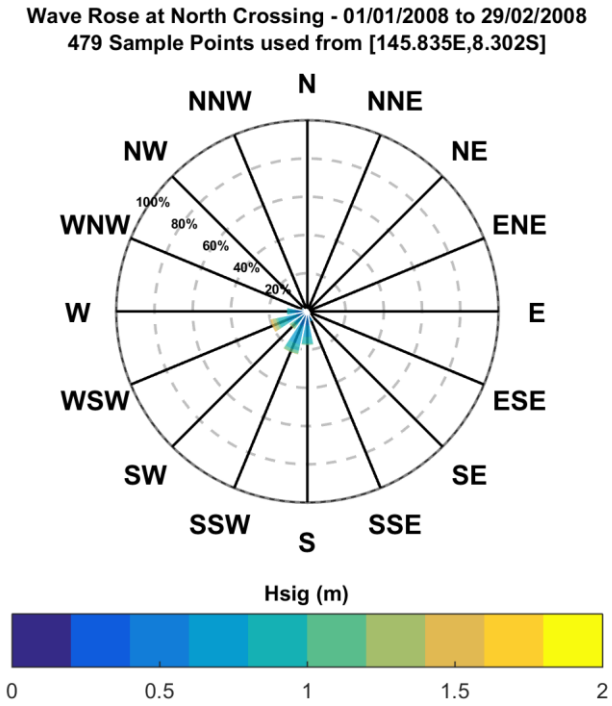
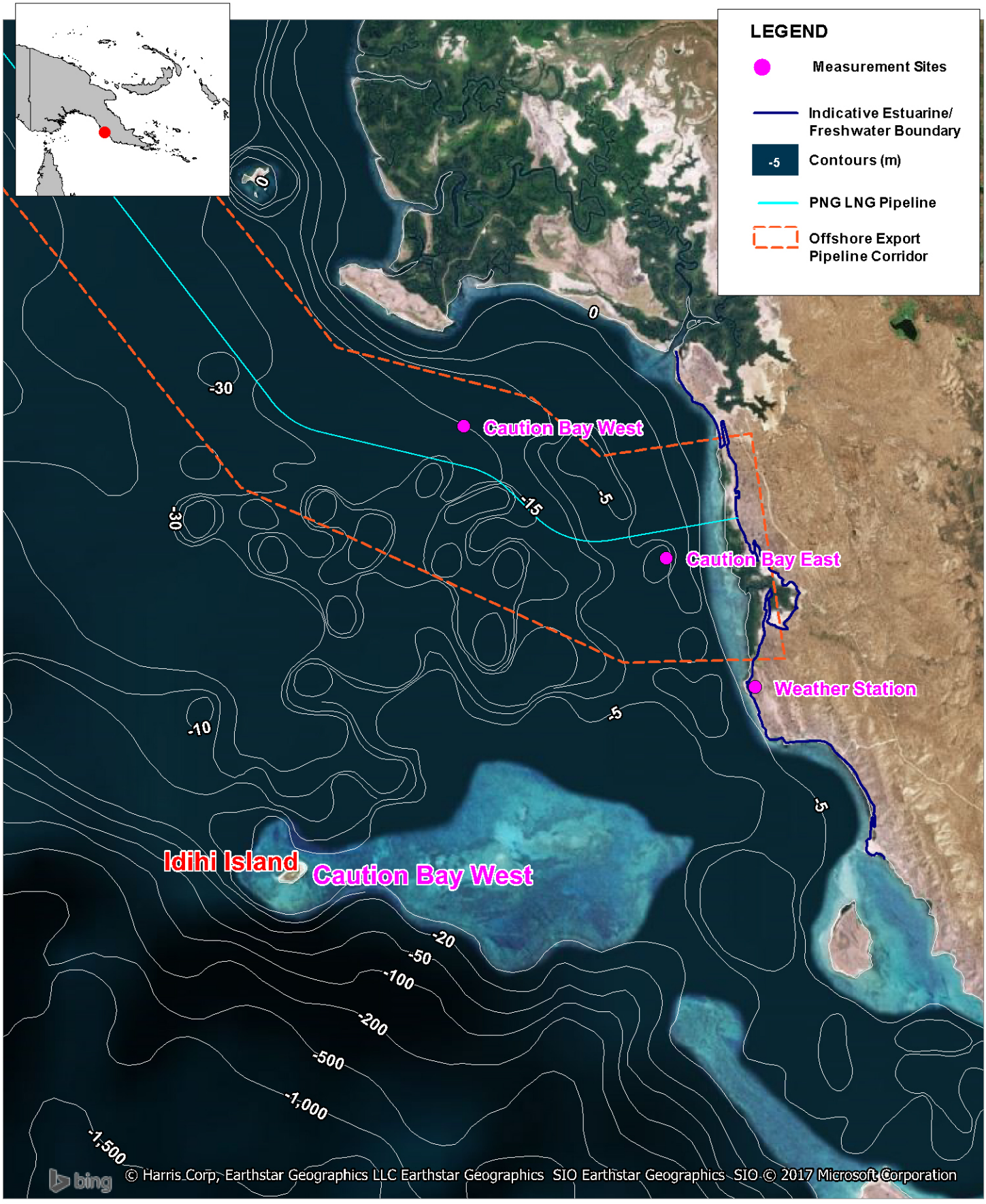


Figure 6-25 Wave Rose at North Crossing during the Northwest Monsoon Season (modeled data)

6.4 Caution Bay

6.4.1 Bathymetry

The bathymetry of Caution Bay is complex and contains numerous coral reef formations, channels and shoals (Figure 6-26). The main entrance to the bay is to the west, between Redscar Head and Idihi Island. The average water depth within the bay is around 25 m, with numerous irregularly shaped shoals. There are also significant coral reef formations throughout the bay, including offshore coral bommies, barrier reefs and a coral cay. The bay is protected to the south and east by Idihi Island and an outer barrier reef. Beyond the reef to the south, the seafloor depth drops sharply to depths greater than 1,000 m (see Figure 6-26).



Title:

Bathymetry at Caution Bay

Figure: 6-26

Rev: A

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6.4.2 Water Levels

The tides in Caution Bay are semi-diurnal, with two high and low tides per day. Water levels were recorded at two sites by a bottom-mounted Acoustic Doppler Current Profiler (ADCP) (Caution Bay East and Caution Bay West, shown in Figure 6-26) as part of the PNG LNG EIS project. The water level recordings for extended periods in 2008–2009 are shown in Figure 6-27. The spring-neap variation in tidal range is clearly visible, with the maximum recorded tidal range approximately 3 m.

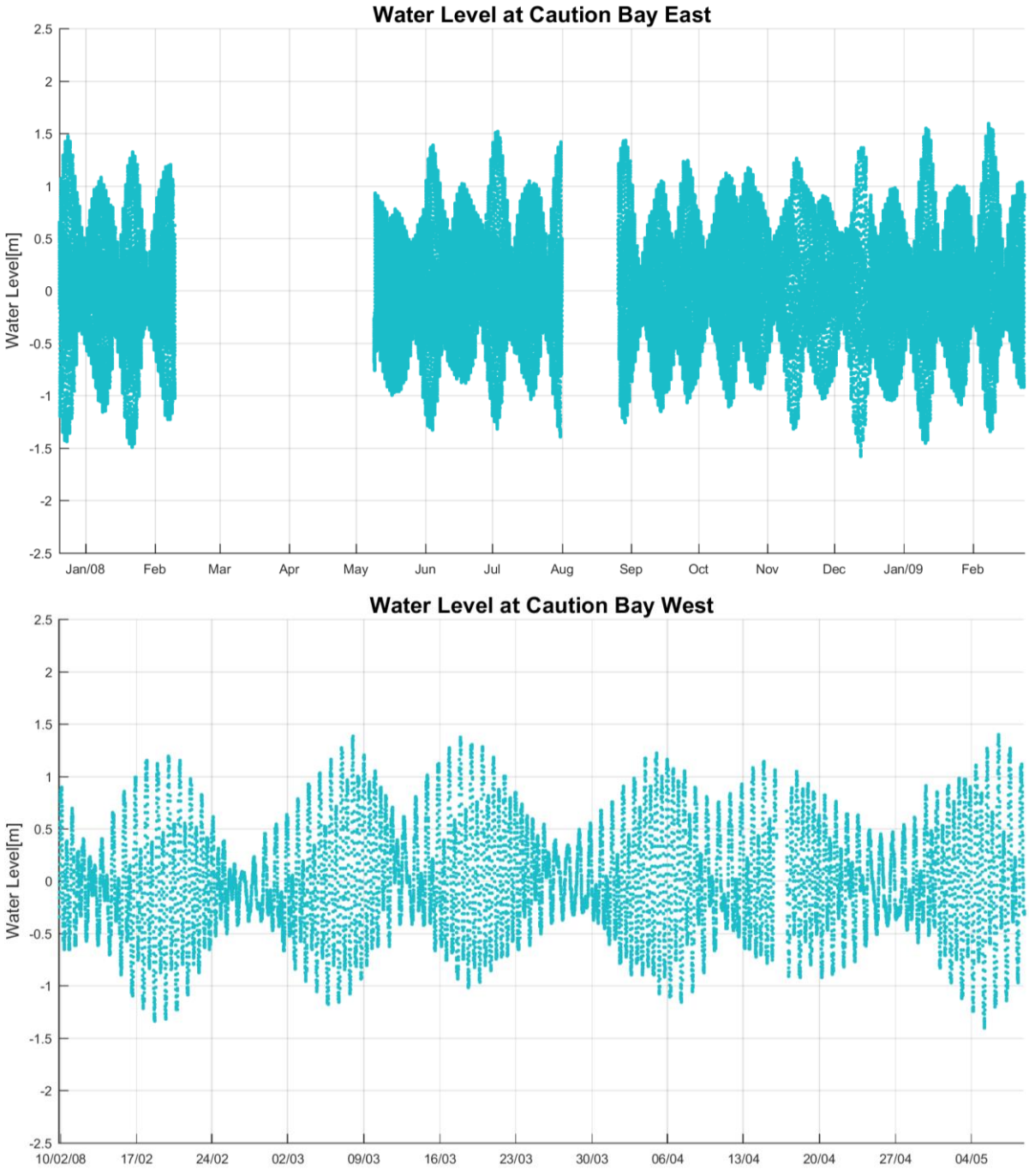


Figure 6-27 Water Level Recordings at Caution Bay East (Top) and Caution Bay West (Bottom) (ADCP Measurement)

6.4.3 Currents

Current speed and direction were recorded by a bottom-mounted ADCP at two sites (Caution Bay East and Caution Bay West, shown in Figure 6-26) as part of the PNG LNG EIS project. The recordings for extended periods in 2007–2009 are shown in Figure 6-28 for Caution Bay East and Figure 6-29 for Caution Bay West.

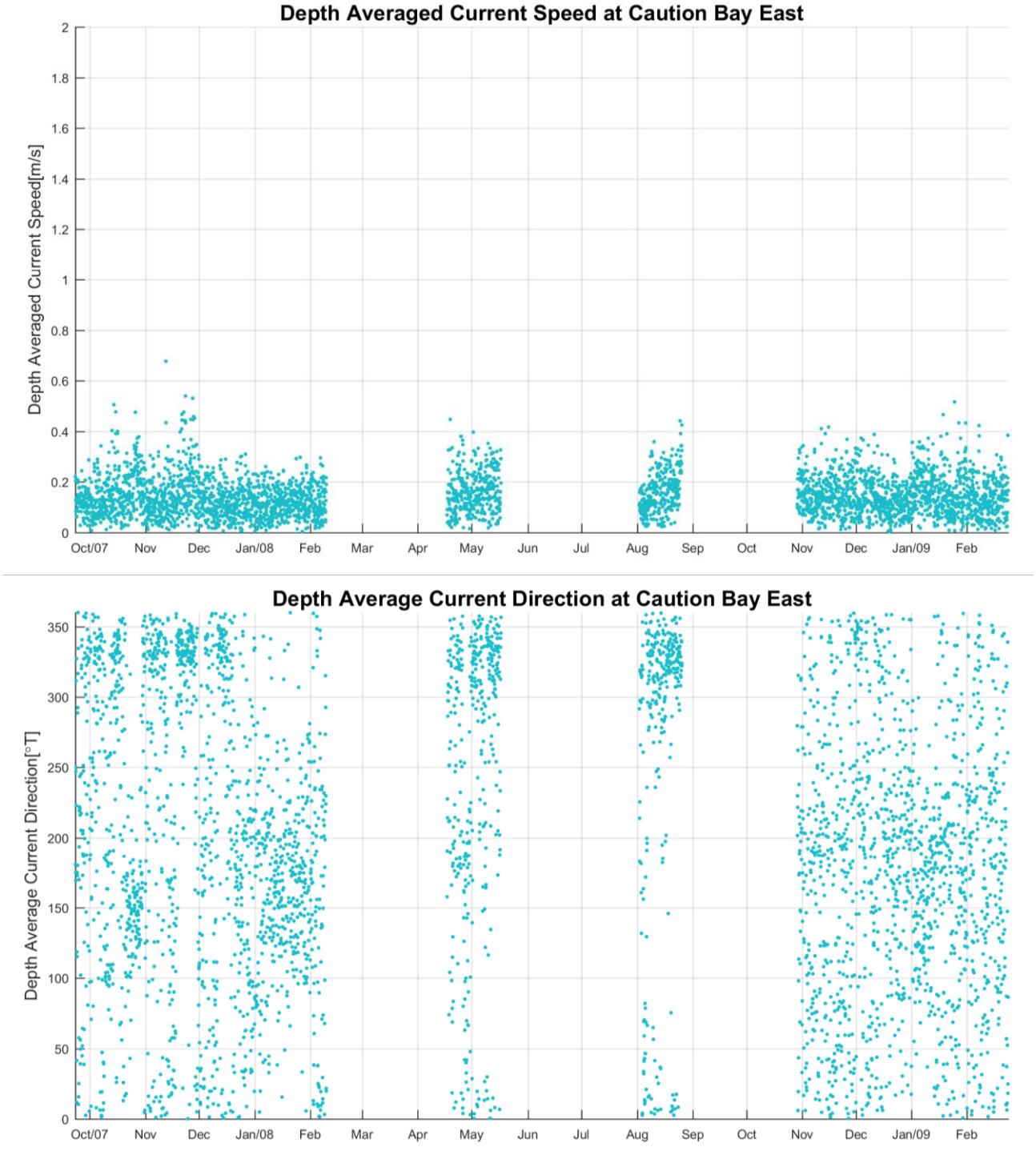


Figure 6-28 Current Speed (Top) and Direction (Bottom) at Caution Bay East (ADCP Measurement)

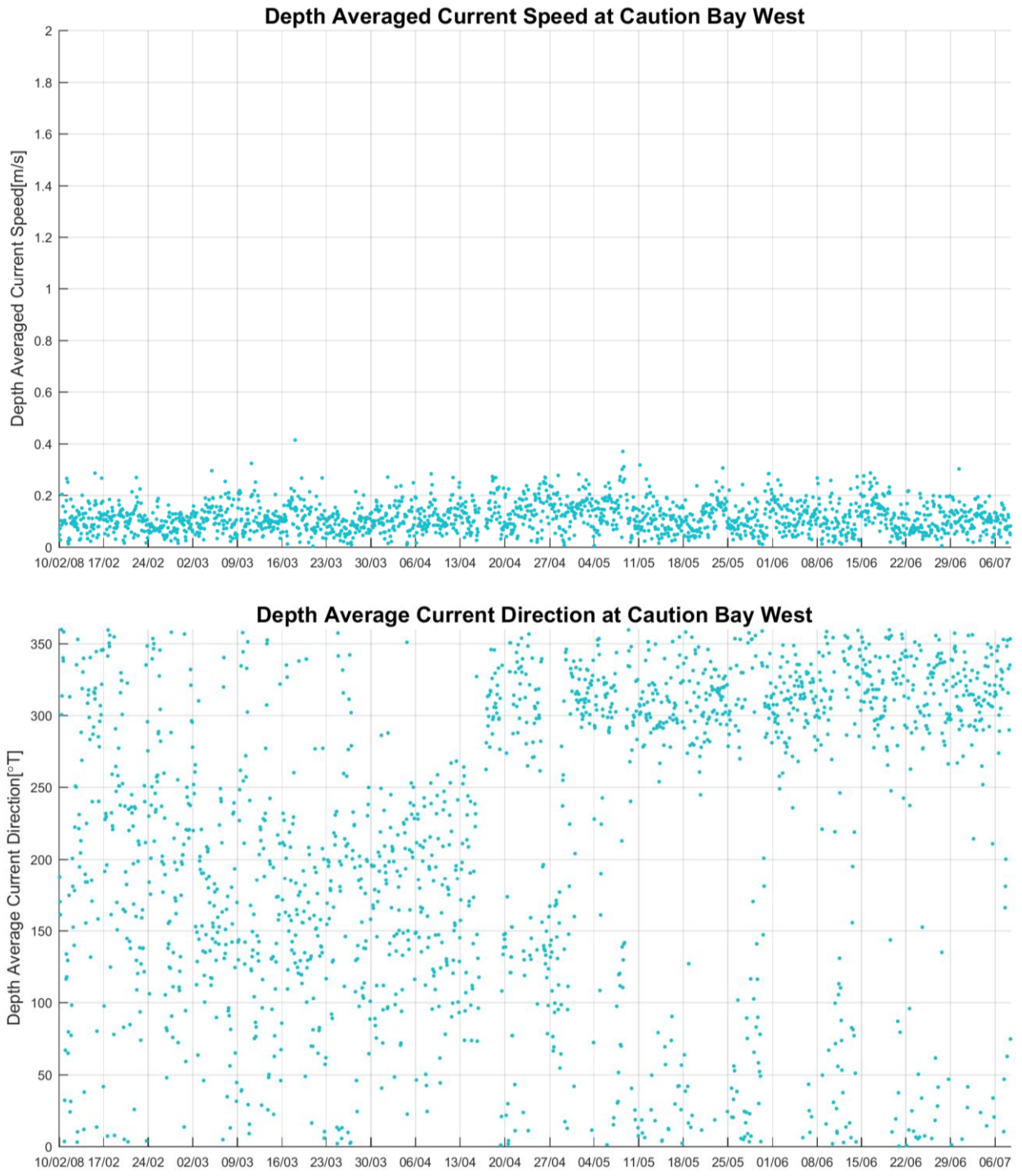


Figure 6-29 Current Speed (Top) and Direction (Bottom) at Caution Bay West (ADCP Measurement)

The current measurements indicate that current speeds within the bay are generally low, being less than 0.5 m/s at Caution Bay East and less than 0.3 m/s at Caution Bay West. The direction tends to vary according to the tide during the northwest monsoon season but has a net north-westerly direction during the southeast trade winds season (May to September). This is likely a local current within the bay generated by the prevailing south-easterly winds, unlike the measured currents at North Crossing which are part of a much larger scale circulation pattern. Current roses at each of the two locations are provided for the southeast trade winds season in Figure 6-30 and Figure 6-31, and for the northwest monsoon season in Figure 6-32 and Figure 6-33.

The net current patterns (top 10 m of the water column, averaged over two months) indicated by the TUFLOW FV numerical model are presented in Figure 6-34 for the southeast trade winds season and Figure 6-35 for the northwest monsoon season. The model indicates very small net currents within Caution Bay (less than 0.1 m/s). The numerical model does not replicate the observed net currents towards the northwest during the southeast trade winds season at the two measurement locations, possibly due to inaccuracies in the modeled wind input data. Due to the low magnitude of the modeled and measured currents, this difference is not considered to be a significant issue.

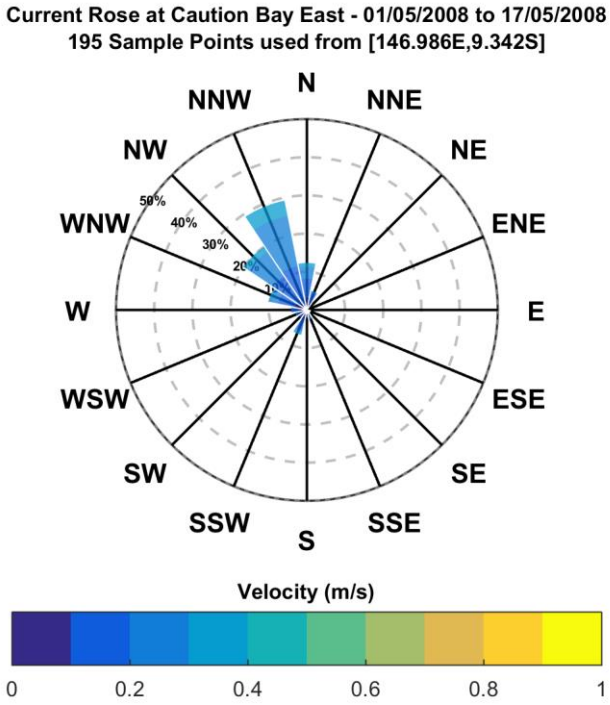


Figure 6-30 Current Rose at Caution Bay East during the Southeast Trade Winds Season (ADCP Measurement)

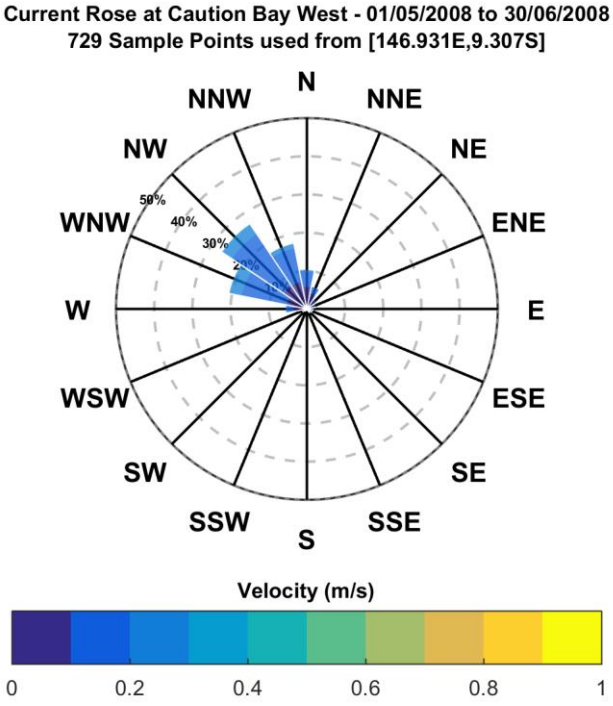


Figure 6-31 Current Rose at Caution Bay West during the Southeast Trade Winds Season (ADCP Measurement)

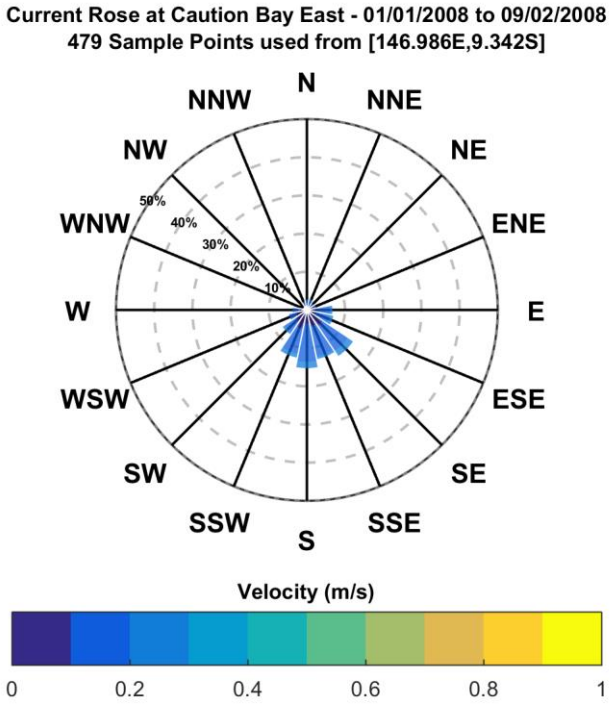


Figure 6-32 Current Rose at Caution Bay East during the Northwest Monsoon Season (ADCP Measurement)

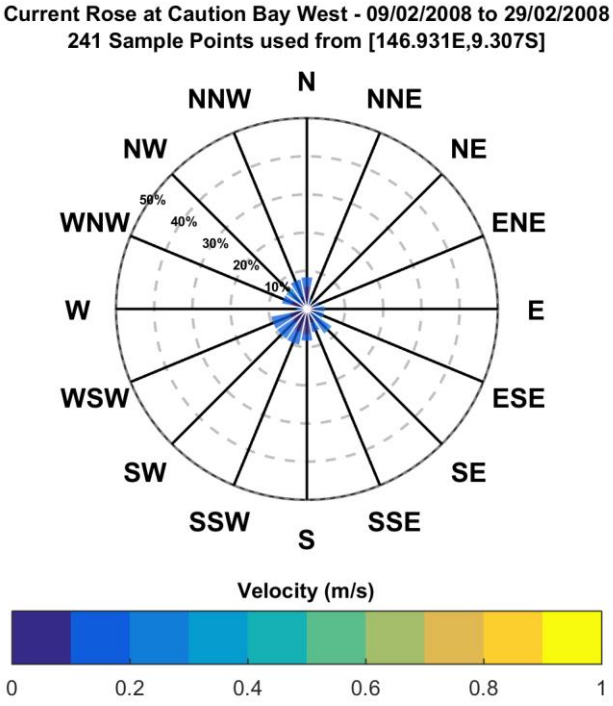


Figure 6-33 Current Rose at Caution Bay West during the Northwest Monsoon Season (ADCP Measurement)

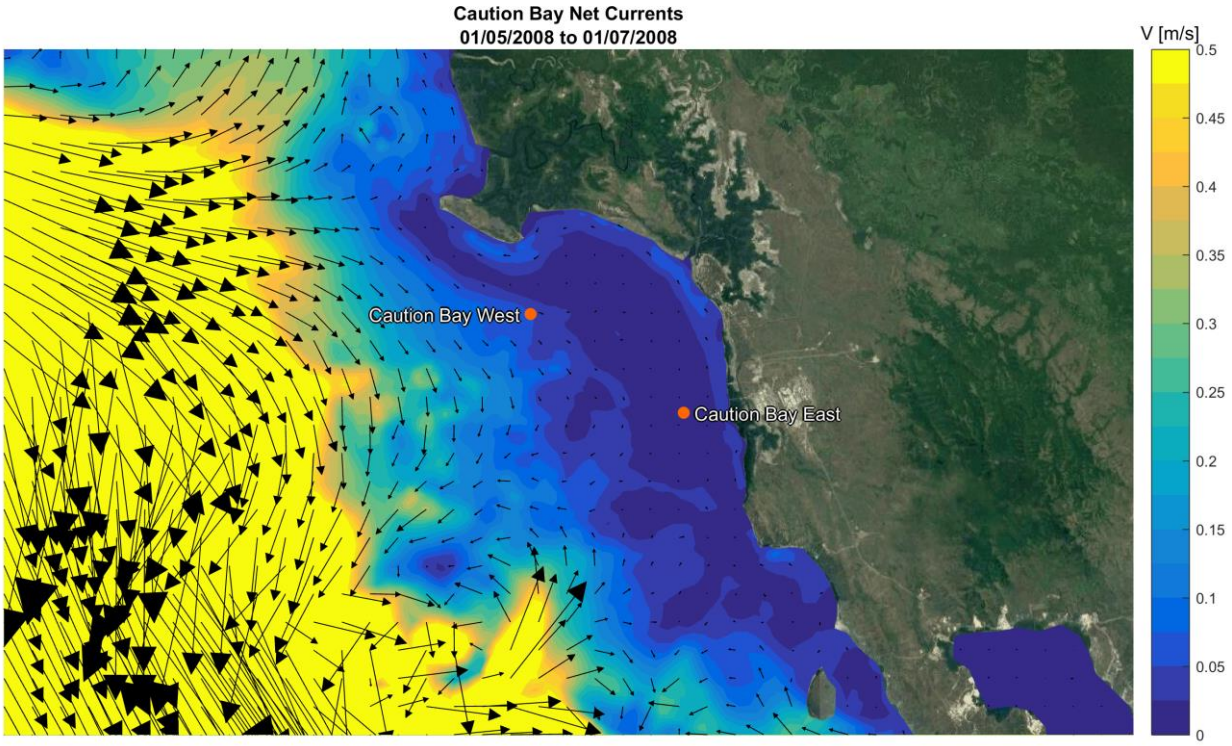


Figure 6-34 Net Current Pattern in Caution Bay During the Southeast Trade Winds Season (Top 10 m of the Water Column) (TUFLOW FV Model)

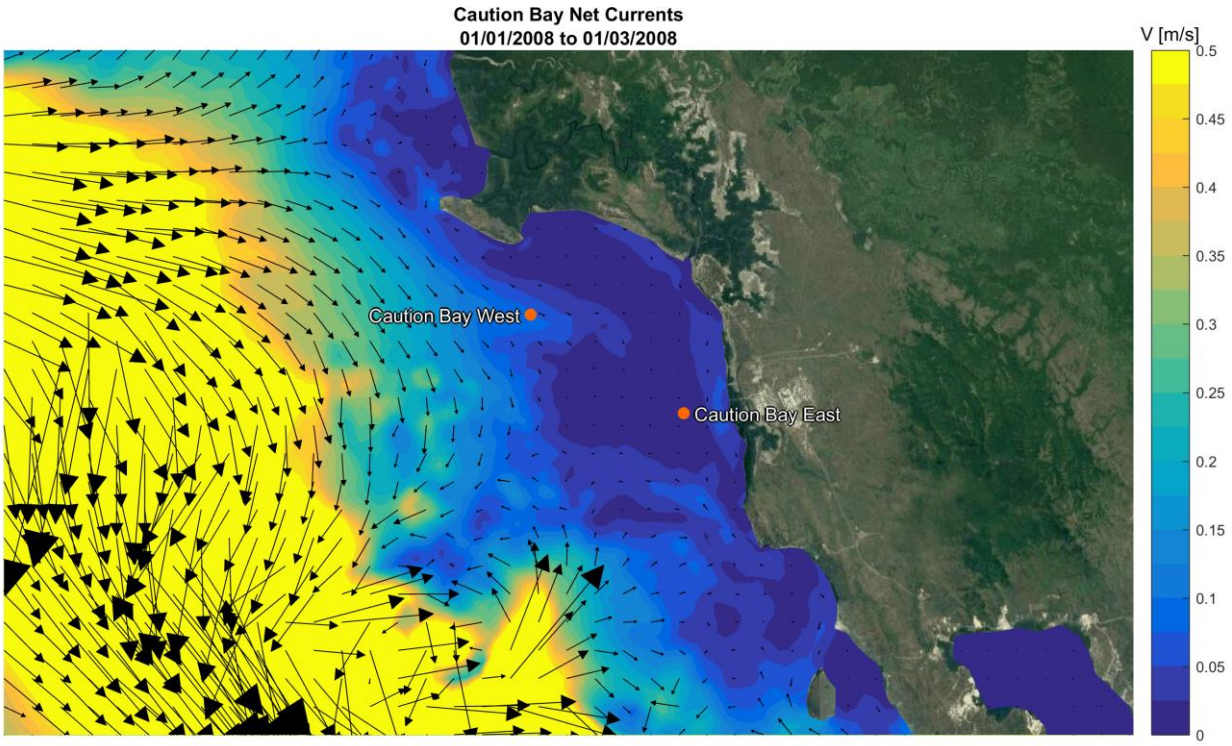


Figure 6-35 Net Current Pattern in Caution Bay During the Northwest Monsoon Season (Top 10 m of the Water Column) (TUFLOW FV Model)

6.4.4 Waves

Wave height and direction were recorded by a bottom-mounted ADCP at two sites (Caution Bay East and Caution Bay West, shown in Figure 6-26) as part of the PNG LNG EIS project. The recordings for extended periods in 2007–2009 are shown in Figure 6-36 for Caution Bay East and Figure 6-37 for Caution Bay West. The data indicates that the significant wave height at Caution Bay East is generally below 1 m during the southeast trade winds season and up to 1.5 m during the northwest monsoon season. The wave direction at Caution Bay East is predominantly from the west. The significant wave height at the Caution Bay West location is a similar magnitude to the Caution Bay East location but the direction is more commonly from the southwest. The higher wave heights recorded during the northwest monsoon season are likely due to a higher incidence of waves from the less protected westerly direction (shoals and a coral cay protects the bay from waves approaching from the south). Wave roses for the two instrument locations (based on the measured data) for the southeast trade winds season are provided in Figure 6-38 and Figure 6-39 and for the northwest monsoon season in Figure 6-40 and Figure 6-41.

The typical wave patterns (significant wave height and direction) within Caution Bay during a south-easterly trade winds season condition are shown in Figure 6-42, and during a northwest monsoon season condition in Figure 6-43. It is apparent that wave propagation into the bay can be much more significant during the northwest monsoon season under westerly/northerly wind conditions.

Extreme wave conditions are generated by tropical cyclones, but the probability of a tropical cyclone tracking so far north is extremely low. The PNG LNG Project EIS noted that a search of the tropical cyclone database back to the 1950s did not reveal any incidence of tropical cyclone genesis in the northern part of the Gulf of Papua (CNS, 2009). The most relevant recent cyclonic event which influenced Caution Bay was Cyclone Guba in 2007, which generated a significant wave height of only 1 m at the Caution Bay jetty site, with peak currents of 0.2 m/s.

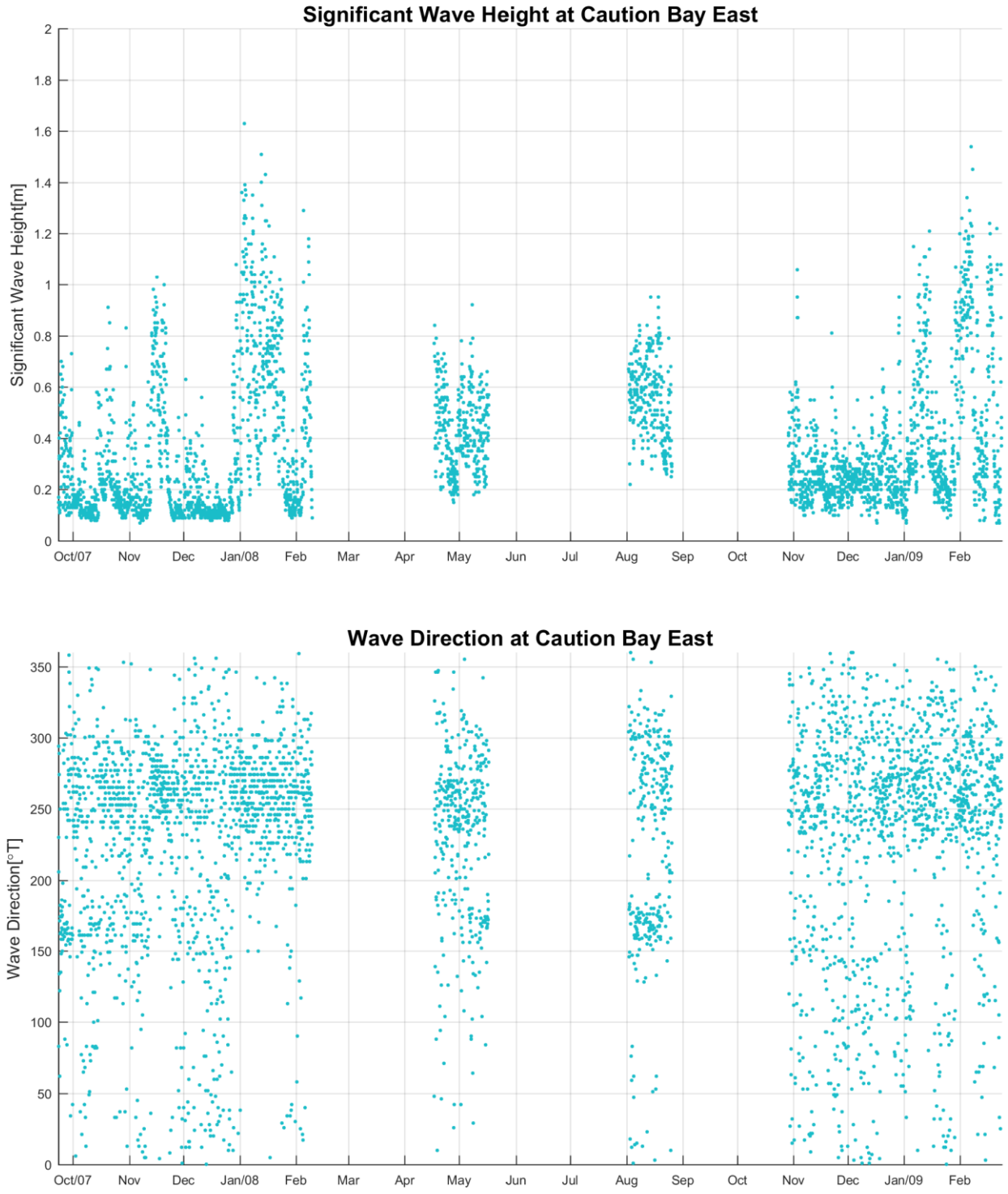


Figure 6-36 Significant Wave Height (Top) and Peak Wave Direction (Bottom) at Caution Bay East (ADCP Measurement)

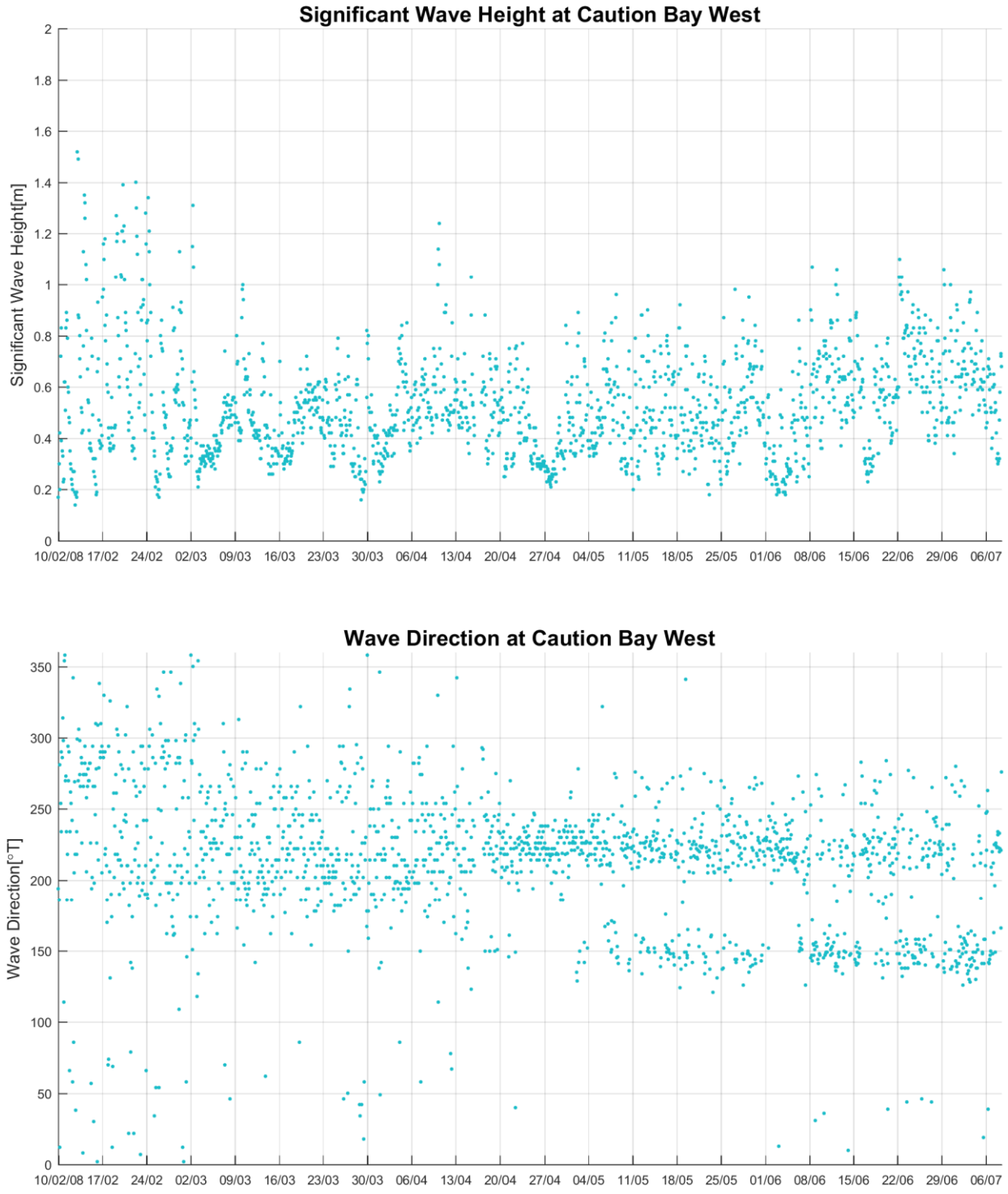


Figure 6-37 Significant Wave Height (Top) and Peak Wave Direction (Bottom) at Caution Bay West (ADCP Measurement)

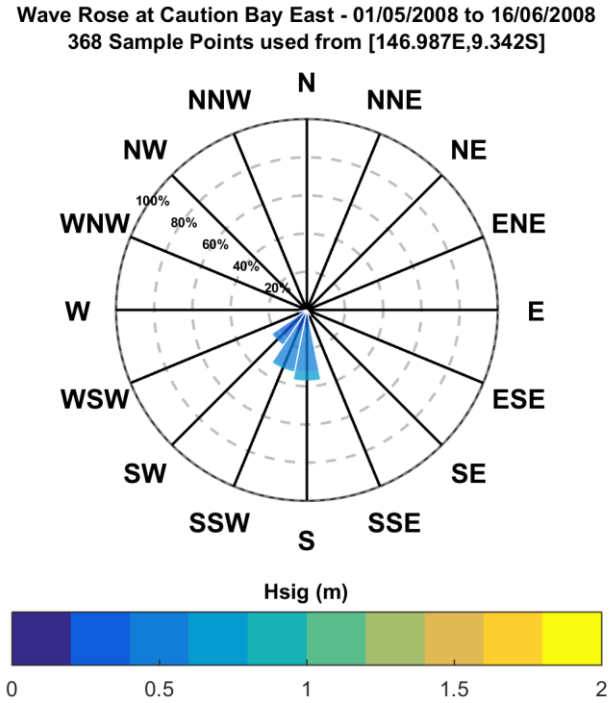


Figure 6-38 Wave Rose at Caution Bay East during the Southeast Trade Winds Season (ADCP Measurement)

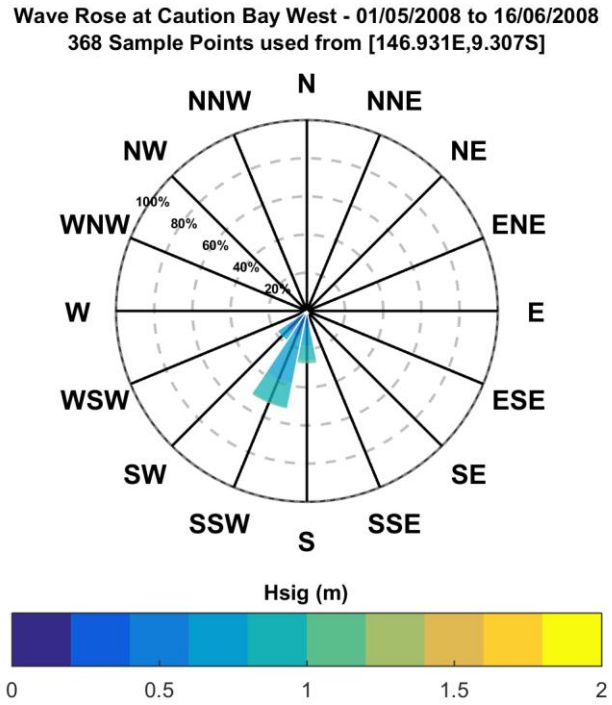


Figure 6-39 Wave Rose at Caution Bay West during the Southeast Trade Winds Season (ADCP Measurement)

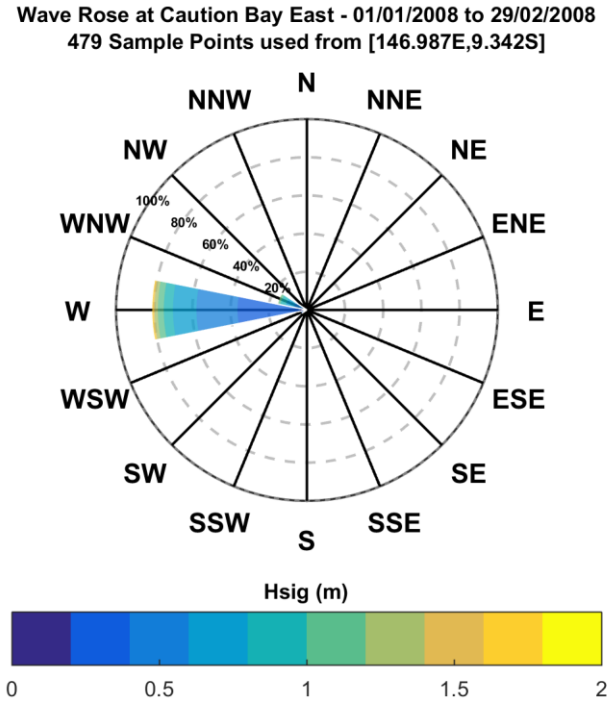


Figure 6-40 Wave Rose at Caution Bay East during the Northwest Monsoon Season (ADCP Measurement)

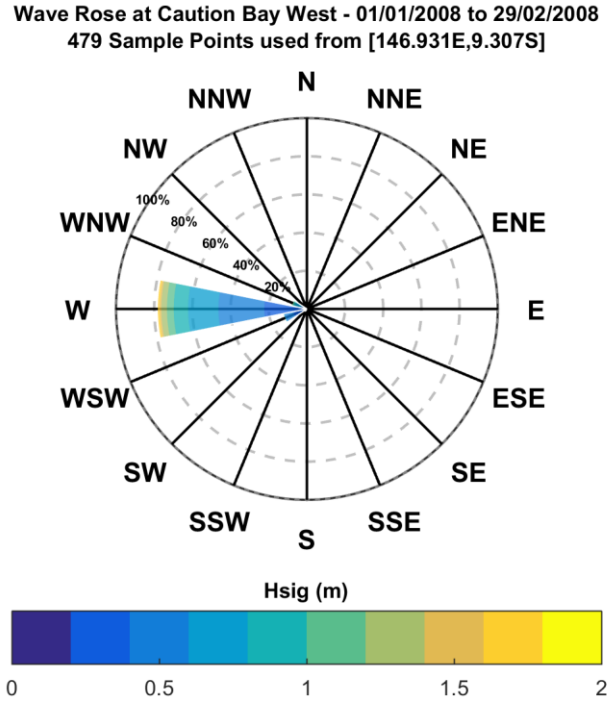


Figure 6-41 Wave Rose at Caution Bay West during the Northwest Monsoon Season (ADCP Measurement)

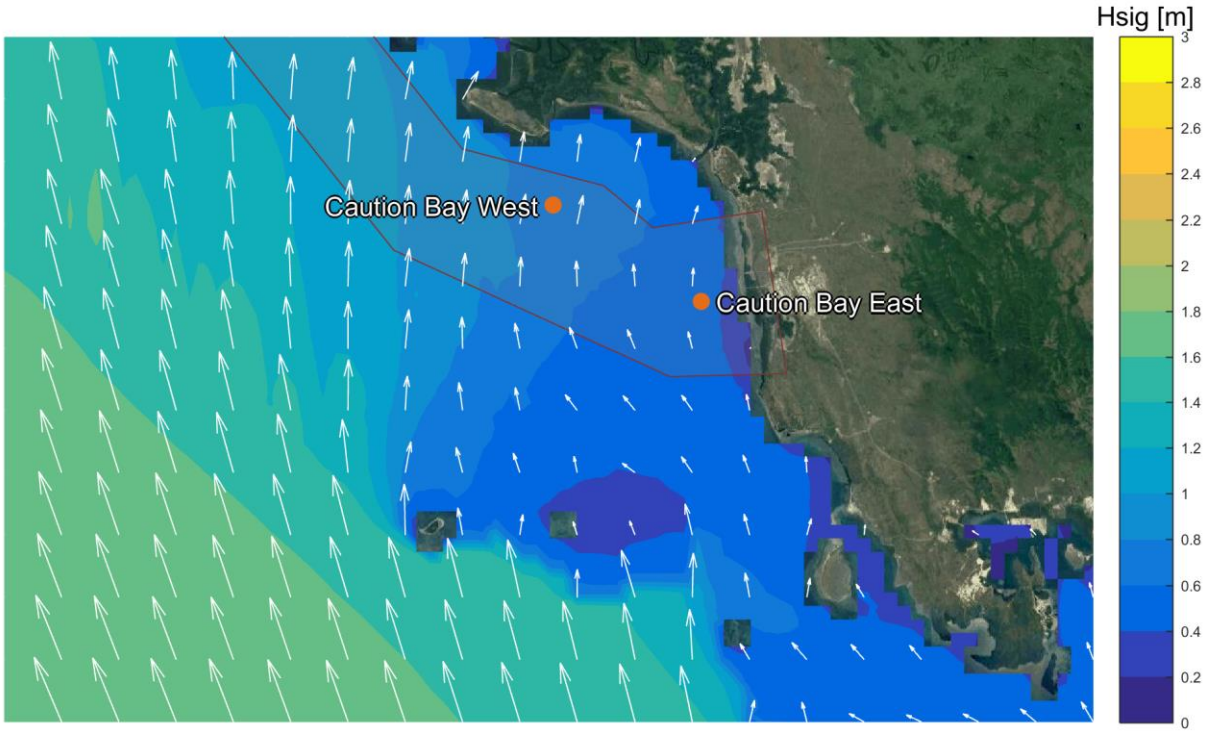


Figure 6-42 Wave Pattern within Caution Bay During Typical Southeast Trade Winds Season Conditions (SWAN Model)

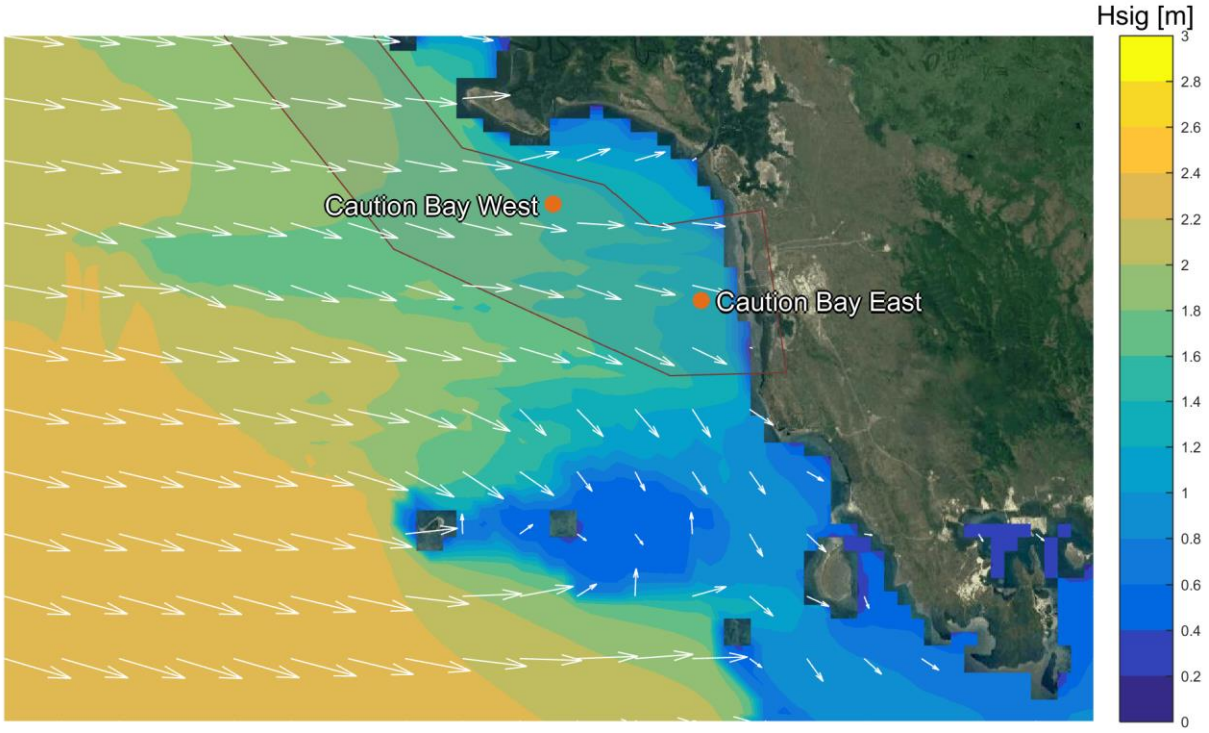


Figure 6-43 Wave Pattern within Caution Bay During Typical Northwest Monsoon Season Conditions (SWAN Model)

6.5 Summary

6.5.1 Regional Characterization

The Gulf of Papua is subject to two distinctive seasons, experiencing north to northwest monsoon winds from December to March and southeast trade winds from May to October, with April and November acting as changeover periods (Evesson, 1983).

Winds tend to be calmer during the northwest monsoon season. Wind strength gradually increases throughout the year to a peak with the strongest southeast trade winds in July, and then progressively decreases with the return of the northwest monsoon season. The southeast trade winds generate waves with a significant fetch across the Coral Sea, setting up a seasonally averaged significant wave height in the Gulf of Papua of 1.5 m (Hemer *et al.* 2004). The significant wave height is larger in deeper water but attenuates as waters become shallower.

Tides are semi-diurnal within the Gulf of Papua and tidal range is highest in the west of the gulf near the mouth of the Fly River at over 5 m (Wolanski *et al.* 1995). Tidal range then attenuates heading eastward, such that maximum tidal range in the vicinity of Orokolo Bay is approximately 3 m. The maximum tidal range at Caution Bay is also approximately 3 m.

The numerical modeling results and literature review reveal that the overall current circulation patterns in the Gulf of Papua are seasonal. During the monsoon period, an anticlockwise circulation on the continental shelf is coupled with a clockwise gyre further offshore (the Hiri current). During the southeast trade winds season, the prevailing winds generate currents towards the northwest in the southern parts of the Gulf of Papua, balanced by a return flow current towards the southeast along the southern coastline of Papua New Guinea.

Large fresh water inflows from the Fly, Bamu, Turama, Kikori and Purari rivers entering the Gulf of Papua (around 15,000 m^3/s in total) have a significant influence on both hydrodynamics and sediment dynamics in the gulf (Wolanski *et al.* 1995). Available data indicates little seasonal variation in the flow rates of these rivers (Wolanski *et al.* 1984). Wolanski *et al.* (1995) found that the halocline (strong salinity gradient) inhibits tidal mixing of surface and bottom water in the gulf. Measurements of salinity and temperature profiles undertaken by Robertson *et al*. (1998) indicated that a surface lens of low-salinity water extends across the inner gulf (within 50 km of the coast), with a thickness of up to 40 m. Typical surface salinities are between 25 to 30 ppt within 50 km of the Purari River mouth and between 32 to 34 ppt further offshore in the central gulf (for reference, oceanic salinity is 35 ppt).

6.5.2 Orokolo Bay

Two field campaigns were undertaken to collect water depth, temperature and salinity data in the monsoon and southeast trade winds seasons. The measured tidal range was approximately 1 m during neap tides and approximately 3 m during spring tides. The data indicate that the water column is significantly stratified within the bay during the southeast trade winds season, with salinity in the top 5 m of the water column between 20 to 23 ppt at all measurement locations. During the northwest monsoon season the observed stratification was more variable, with salinity in the top 5 m of the water column between 2 to 33 ppt across the measurement locations.

The numerical model indicates that current speeds are highest during the southeast trade winds season, and are directed towards the southeast throughout the bay. During the northwest monsoon season the net current direction in offshore parts of the bay (>15 m water depth) is towards the northwest.

The waves during the southeast trade winds season propagate from south to north (with significant wave height up to 1.6 m), while in the northwest monsoon season they are more variable in direction but tend to approach the bay from the south-southwest (with significant wave height less than 1 m).

6.5.3 Offshore Export Pipeline Corridor

The offshore export pipeline corridor traverses the Gulf of Papua continental shelf edge (see Figure 6-1 for regional bathymetry and Figure 6-16 for detailed bathymetry along the corridor).

The model results indicate that the maximum tidal range along the corridor is 3 m. Measured current data at the North Crossing location along the offshore export pipeline corridor indicates that the net current during the months March to November (southeast trade winds season) is mostly directed towards the southeast, with an average speed of around 0.2 m/s. The current direction during the months December to February (northwest monsoon season) is more variable and often directed towards the west, with an average speed of around 0.1 m/s. The observed current direction towards the southeast during the trade winds season is counterintuitive, since it flows in the opposite direction to the prevailing wind. This can be explained by considering the overall pattern of circulation in the gulf, with water further offshore driven by the wind into the gulf and returning via a coastal current along the southern Papua New Guinea coastline.

The numerical model results indicate that, during the southeast trade winds season, the wave direction is predominantly from the south at the ‘North Crossing’ site due to the prevailing southeast wind direction and the pattern of wave refraction within the gulf. The significant wave height has an average of around 1.5 m and a maximum of 2 m. During the northwest monsoon season the direction is more variable and the magnitude is much lower, with a maximum significant wave height of around 1 m.

6.5.4 Caution Bay

The bathymetry of Caution Bay is complex and contains numerous coral reef formations, channels and shoals (Figure 6-26). The main entrance to the bay is to the west, between Redscar Head and Idihi Island. The average water depth within the bay is around 25 m, with numerous irregularly shaped shoals. There are also significant coral reef formations throughout the bay, including offshore coral bommies, barrier reefs and a coral cay. The bay is protected to the south and east by Idihi Island and an outer barrier reef. Beyond the reef to the south, the seafloor depth drops sharply to depths greater than 1,000 m (see Figure 6-26).

Measurements indicate that current speeds within the bay are generally low, being less than 0.5 m/s at Caution Bay East and less than 0.3 m/s at Caution Bay West. The direction tends to vary according to the tide during the northwest monsoon season but has a net north-westerly direction during the southeast trade winds season (May to September). The model results indicate that net currents within the bay are very small in magnitude (less than 0.1 m/s).

Within Caution Bay, incident waves from the west (which prevail during the northwest monsoon season) penetrate more effectively than incident waves from the south (which prevail during the southeast trade winds season) due to the fringing reef configuration. Measured data indicates that the significant wave height within Caution Bay is generally below 1 m during the southeast trade winds season and below 1.5 m during the northwest monsoon season.

6.5.5 Summary Table

A summary of the meteorological and oceanographic conditions in each part of the study area is provided in Table 6-2.

Table 6-2 Meteorological and oceanographic conditions

Location/ Region	Season	Parameter	Measured/ Modeled	Direction	Speed (m/s)	Height (m)
Orokolo Bay	Trade Winds (May - Oct)	Wind	Modeled	From S/SE	4.4	-
Orokolo Bay	Monsoon (Dec - Mar)	Wind	Modeled	From N/NW	3.4	-
Caution Bay	Trade Winds (May - Oct)	Wind	Modeled	From SE/SSE	4.8	-
Caution Bay	Monsoon (Dec - Mar)	Wind	Modeled	From NNW/NNE	3.4	-
Orokolo Bay	Trade Winds (May - Oct)	Current	Modeled	To SE	up to 0.4	-
Orokolo Bay	Monsoon (Dec - Mar)	Current	Modeled	To SE	up to 0.4	-
Offshore Export Pipeline Corridor	Trade Winds (May - Oct)	Current	Measured	To SE/E	average 0.2	-
Offshore Export Pipeline Corridor	Monsoon (Dec - Mar)	Current	Measured	To WNW	average 0.1	-
Caution Bay	Trade Winds (May - Oct)	Current	Measured	To NW/NNW	up to 0.5	-
Caution Bay	Monsoon (Dec - Mar)	Current	Measured	Variable	up to 0.5	-
Orokolo Bay	Trade Winds (May - Oct)	Wave	Modeled	From S	-	up to 1.6
Orokolo Bay	Monsoon (Dec - Mar)	Wave	Modeled	From S/SW	-	up to 1
Offshore Export Pipeline Corridor	Trade Winds (May - Oct)	Wave	Modeled	From S	-	up to 2
Offshore Export Pipeline Corridor	Monsoon (Dec - Mar)	Wave	Modeled	Variable	-	up to 1
Caution Bay	Trade Winds (May - Oct)	Wave	Measured	From SSW/W	-	up to 1
Caution Bay	Monsoon (Dec - Mar)	Wave	Measured	From SSW/W	-	up to 1.5

7 Conclusions

The EIS/ESHIA for the Papua LNG Project requires consideration of the relevant baseline conditions for physical oceanography. While some previous studies have been conducted in the Gulf of Papua, further studies have been required in order to provide an appropriate baseline characterization. This has been the case in particular for Orokolo Bay.

Physical oceanography modeling was conducted using existing data for the Project area, supplemented with additional data from short-term instrument deployments. This modeling is considered suitable for the purposes of characterizing the baseline environment for the EIS/ESHIA.

The physical oceanographic processes within the study area have been characterized by reviewing available literature and datasets, and undertaking numerical modeling of water levels, currents and waves to fill in gaps in the available information. The modeling system was calibrated and validated using available measured data and literature sources (refer to Appendix A for details) and is considered to be sufficiently accurate for the purposes of the study.

The key findings of the baseline characterization are as follows:

- The tides throughout the study area are semi-diurnal, with a tidal range of around 3 m.
- The hydrodynamics of the Gulf of Papua are influenced by the large volumes of fresh water delivered by the river systems feeding the gulf. The water column is often stratified even at significant distance from the coast, which inhibits tidal mixing.
- Current velocities along the offshore export pipeline corridor are generally small and the current direction is predominantly towards the southeast, particularly during the southeast trade winds season. The modeling results indicate that during the monsoon period there is an anticlockwise circulation on the continental shelf during the monsoon period coupled with a clockwise gyre further offshore. During the southeast trade winds season, the prevailing winds generate currents towards the northwest in the southern parts of the Gulf of Papua, balanced by a return flow current towards the southeast along the southern coastline of Papua New Guinea, forming a larger-scale clockwise gyre.
- Wind and wave patterns are highly seasonal, with south-easterly wind and waves during the months May to October (the southeast trade winds season) and more variable wind and waves generally from the north during the months December to March (the northwest monsoon season).

8 Study Team

The study team responsible for the preparation of the Physical Oceanography Baseline Report are listed in Table 8-1 below.

Table 8-1 Physical Oceanography Study Team

Personnel	Role	Qualifications
Dr Ian Teakle	Technical Lead for Physical Oceanography Modeling Peer Review	Bachelor of Civil Engineering Doctor of Philosophy
Dr Paul Guard	Physical Oceanography Modeling	Bachelor of Civil Engineering Doctor of Philosophy
Steven Ettema	Physical Oceanography Modeling	Bachelor of Civil Engineering
Toby Devlin	Physical Oceanography Modeling	Bachelor of Civil Engineering
Jeremy Visser	Study Coordinator	Bachelor of Laws Bachelor of Environmental Management
Lyn Leger	Study Manager	Bachelor of Laws Bachelor of Science (Honors) Master of Laws

9 Glossary and Abbreviations

ADCP	Acoustic Doppler Current Profiler
Caution Bay	Subset of the study area, including all the waters of Caution Bay, as far seaward as the line between Redscar Head and Idihi Island
CEPA	Conservation and Environment Protection Authority of Papua New Guinea
CFSR	Climate Forecast System Reanalysis
Clinoform	Sloping depositional surface of a major morphological feature
CNS	Coffey Natural Systems
Coastal	The land and sea areas bordering the shoreline
CPF	Central Processing Facility
DEM	Digital elevation model
EHS Guideline	Environment, Health and Safety Guidelines, developed by the IFC as representation of good international industry practice
EIS	Environmental Impact Statement
Elk/Antelope Gasfield Project	Gas extraction, transport and processing project proposed by InterOil. Involves operation of Elk-Antelope gas fields in Gulf Province and transport to a LNG Plant on Purari River, Gulf Province.
ESBS	Environmental and Social Baseline Study
ESHIA	Environment, Social and Health Impact Assessment
GIIP	Good International Industry Practice
GL-ENV/02/2004	*Guideline for Conduct of Environmental Impact Assessment & Preparation of Environmental Impact Statement*, prepared by (former) Department of Environment and Conservation (2004)
GS EP ENV 120	*Environmental impact assessment of E&P activities*, General Specification prepared by TOTAL (2007)
GS EP ENV 111	*Environmental Baseline and Monitoring Studies: Onshore Sites*, General Specification prepared by TOTAL (2012)
GS EP ENV 112	*Environmental Baseline and Monitoring Studies: Offshore and Nearshore Sites*, General Specification prepared by TOTAL (2012)
HYCOM	Hybrid Coordinate Ocean Model
IFC	International Finance Corporation
IPIECA	International Petroleum Industry Environmental Conservation Association
Katabatic winds	Technical name for a drainage wind, a wind that carries high density air from a higher elevation down a slope under the force of gravity
LNG	Liquid natural gas
NASA	National Aeronautics and Space Administration
NCEP	National Center for Environmental Prediction
Nearshore	The zone extending from the shoreline to the 15 meter depth contour
NMSA	National Maritime Safety Authority
OECD	Organization for Economic Cooperation and Development
Offshore	The zone where the water depth is greater than 15 meters

Offshore export pipeline corridor	Subset of the study area based on the offshore export pipeline corridor defined for the Project
Papua LNG	Gas extraction, transport and processing project proposed by TEP PNG. Involves operation of Elk-Antelope gas fields in Gulf Province, and onshore and subsea pipeline via Orokolo Bay to LNG Plant at Caution Bay, Central Province
PDL	Petroleum Development License
PL	Pipeline License
PNG LNG	Gas extraction, transport and processing project operated by ExxonMobil. Involves operation of gas fields in Hela and Western Provinces, and onshore and subsea pipeline to LNG Plant at Caution Bay, Central Province
PPFL	Petroleum Processing Facility License
ppt	Parts per thousand
Project	The Papua LNG Project
PS	IFC Performance Standard
Orokolo Bay	Subset of the study area, including the waters immediately adjacent to the Purari River mouth through Orokolo Bay to the Vailala River mouth, as far seaward as the 30 m depth contour
Significant Wave Height	The mean wave height (trough to crest) of the highest third of the waves (H_{sig})
SRTM	Shuttle Radar Topography Mission
Study Area	The area which is the focus of this ESBS report, consisting of the following three subsets: (i) Orokolo Bay (ii) Offshore export pipeline corridor (iii) Caution Bay
SWAN	Wave model, developed by Delft University of Technology
TEP PNG	Total E&P Papua New Guinea
TSS	Total suspended solids

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Appendix A – Marine Waters Modeling Report

Document Control Sheet

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Synopsis: **This report provides information on the configuration and calibration of the hydrodynamic and wave models developed for the Papua LNG Project EIS**

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1 Introduction

As part of the environmental impact assessment for the Papua LNG Project, numerical models were developed to enhance the description of the existing environment and physical oceanographic processes and to allow assessment of the significance of potential environmental impacts of the project. These potential impacts include changes to hydrodynamics, wave climate, shoreline sediment transport rates, siltation, and suspended sediment concentrations. In order to undertake these impact assessments, the numerical models must be able to accurately represent the key physical processes of the existing environment.

The objective of this report is to describe the numerical models that were developed to understand physical oceanographic processes and demonstrate that they have been calibrated and validated using appropriate data sets. The hydrodynamic and wave processes within the Gulf of Papua are modeled using a numerical TUFLOW FV model. Wave processes are modeled using a 3rd generation SWAN spectral wave model (Delft University of Technology, 2006). Field campaigns were undertaken to collect new oceanographic data to supplement data sets from previous studies in the area. Measured data included wave parameters, turbidity, salinity, temperature, water level and water velocity at a number of locations within the study area.

2 Model Setup and Calibration

2.1 Hydrodynamic Model Description

2.1.1 Numerical Modeling Software

The hydrodynamic modeling component of these assessments was undertaken using TUFLOW FV software, which is developed and distributed by BMT WBM (https://tuflow.com/). TUFLOW FV is a numerical hydrodynamic model for the three-dimensional (3D) Non-Linear Shallow Water Equations (NLSWE). The model is suitable for solving a wide range of hydrodynamic systems ranging in scale from open channels and floodplains, through estuaries to coasts and oceans.

The Finite-Volume (FV) numerical scheme employed by TUFLOW FV is capable of solving the NLSWE on both structured rectilinear grids and unstructured meshes comprised of triangular and quadrilateral elements. The flexible mesh allows for seamless boundary fitting along complex coastlines or open channels as well as accurately and efficiently representing complex bathymetries with a minimum number of computational elements. The flexible mesh capability is particularly efficient at resolving a range of scales in a single model without requiring multiple domain nesting. Further details regarding the numerical scheme employed by TUFLOW FV are provided in the TUFLOW FV Science Manual (BMT WBM, 2013).

The TUFLOW FV model was configured as a 3D model with baroclinic coupling from both salinity and temperature variations. Atmospheric heat fluxes and water column heat dynamics were simulated internally within TUFLOW FV. The inclusion of baroclinic pressure gradient terms in the solution scheme allows for the development of a stratified water column. This is necessary to accurately model the currents within the Gulf of Papua due to the large inflows of fresh water from rivers.

A hybrid z-coordinate vertical grid configuration with 3 surface ‘sigma’ layers was adopted for the hydrodynamic model. The vertical mesh had 25 layers representing the water column with high resolution towards the surface (2 meters) and gradually decreasing resolution down to 2000 meters depth.

The General Ocean Turbulence Model (http://www.gotm.net/) was linked with TUFLOW FV to control vertical mixing of both momentum and sediment, employing a 2-equation k-omega turbulence scheme. A Smagorinsky model was used for the estimation of the horizontal eddy viscosity and diffusivity coefficients.

2.1.2 Model Domain and Mesh

A TUFLOW FV flexible mesh was developed for the southern coastline of Papua New Guinea with extents ranging from the mouth of the Fly River through to Gabagaba. This covers an area of more than 70,000 km^2. Cells ranging from 10 km wide offshore down to 100 meters within the areas of interest around Caution Bay and along the offshore export pipeline corridor were used to build an effective and efficient model mesh for the TUFLOW FV model. The TUFLOW FV model mesh is presented in Figure 2-1.

2.1.3 Bathymetric Data

Bathymetric data for the Gulf of Papua was developed from a series of charts and digital elevation models (DEMs). The DEM was created by layering the raw datasets over each other and applying preference to the higher resolution datasets. This methodology ensured that the most accurate bathymetric information is used. The data sources are listed in Table 2-1 and the adopted model bathymetry is illustrated in Figure 2-1.

Table 2-1 Bathymetric Data Sources

Data Type	Description	Application
Australian Electronic Navigation Charts (AUSENC)	• Chart made primarily for navigational purposes • All values are in reference to lowest astronomical tide (LAT) • Scattered data with higher resolution around shoreline	1st preference
NASA's Shuttle Radar Topography Mission (SRTM)	• Resolution of ~900 m in across entire domain	2nd preference

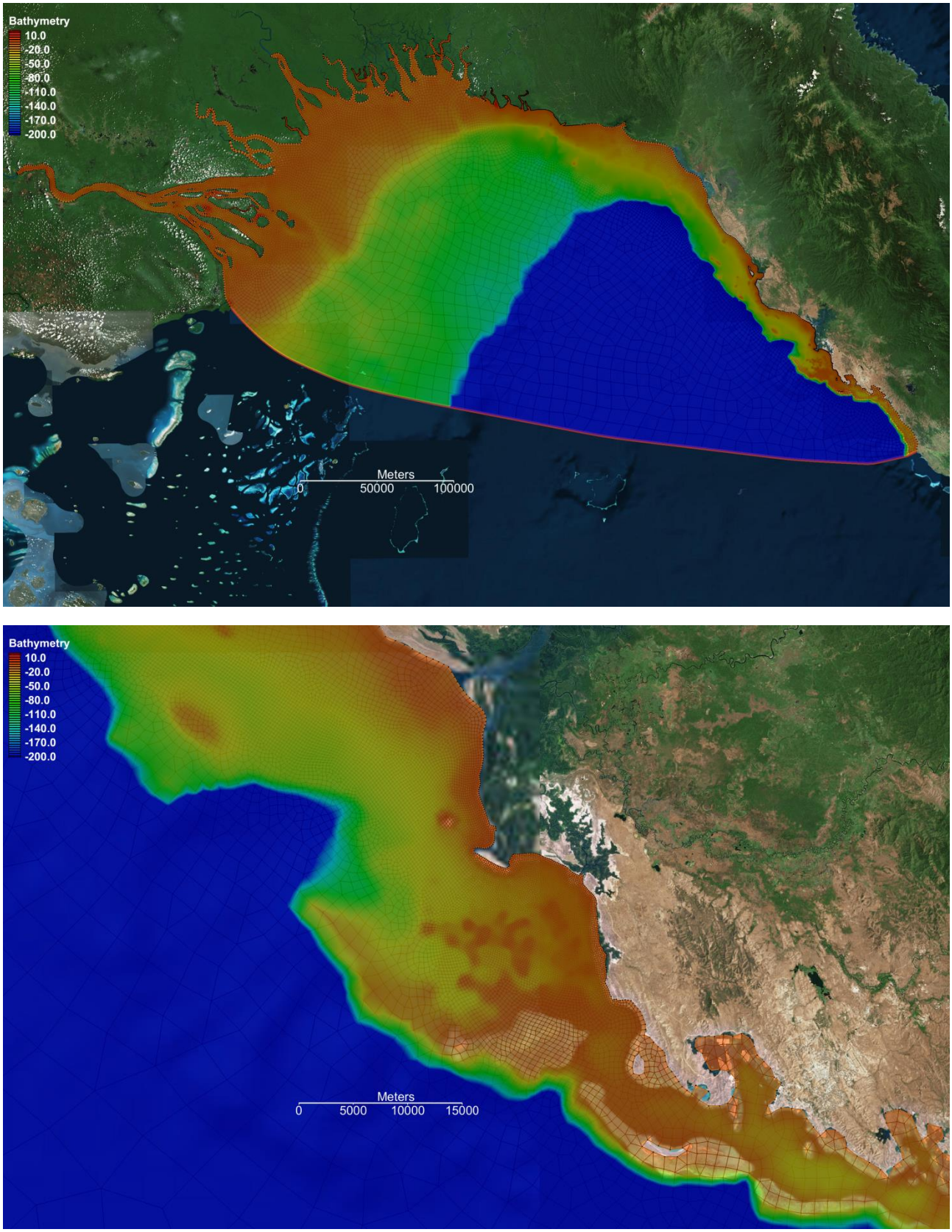


Figure 2-1 TUFLOW FV Model Mesh

2.2 Wave Model Description

A wave model was developed in order to simulate the wave-related stresses (particularly bed shear stresses) that have an influence on hydrodynamics, sediment re-suspension and sediment transport. The SWAN (Delft University of Technology, 2006) numerical model was used for this purpose. SWAN is a third-generation spectral wave model, which is capable of simulating the generation of waves by wind, dissipation by whitecapping depth-induced wave breaking, bottom friction and wave-wave interactions in both deep and shallow water. SWAN simulates wave/swell propagation in two-dimensions, including shoaling and refraction due to spatial variations in bathymetry and currents. The SWAN wave model included a coarse regional-scale grid (~500 m resolution) and a nested local-scale grid (~250 m resolution). Two additional nested SWAN models (~100 m resolution) were also created for both Orokolo Bay and Caution Bay. The domains of the four SWAN grids are shown in Figure 2-2.

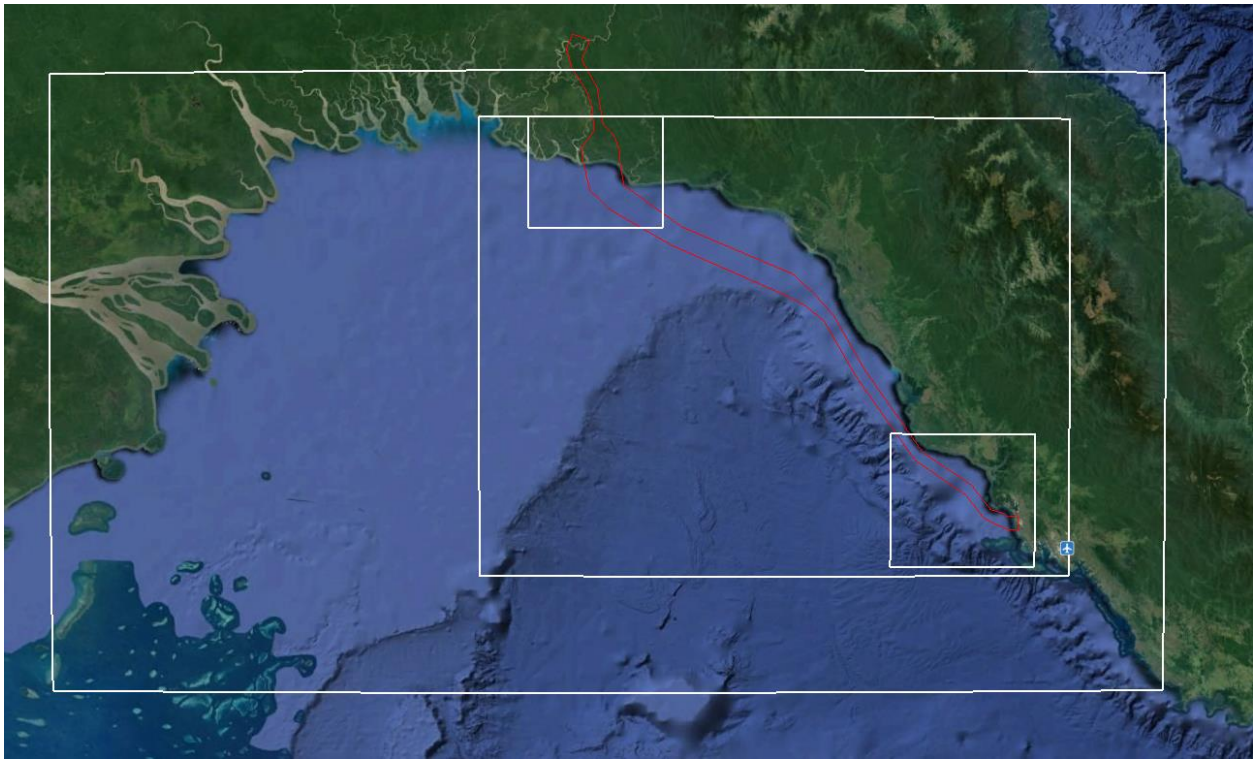


Figure 2-2 SWAN Wave Model Grids (White Rectangles)

2.3 Model Boundary Conditions

2.3.1 Oceanic Currents

Regional current forcing (residual water level, current magnitude and direction), and profiles of temperature and salinity were also applied on the open model boundaries of the model. These were derived from the ocean general circulation model, HYCOM (http://hycom.org/) and varied both in space (longitude, latitude and elevation) and time. The HYCOM model has a spatial resolution of approximately 8 kilometers and a temporal resolution of 24 hours.

2.3.2 Tide

Tidal boundary conditions for the model were sourced from the Oregon State University's global tide model (http://volkov.oce.orst.edu/tides/).

2.3.3 Wind

Wind velocity boundary conditions for the calibration period were obtained from global NCEP CFSR model reanalyzes (Saha *et al.* 2010). The CFSR model has a spatial resolution of 0.2 degrees in the study area which is high enough to minimize errors arising from interpolation in the vicinity of the shoreline. The temporal resolution of the CFSR outputs is one hour. This wind field was applied to both the hydrodynamic and wave models.

2.3.4 Atmospheric Forcing

Boundary condition data including air temperature, long and short wave radiation, precipitation and relative humidity were also obtained from global NCEP CFSR model reanalyzes (Saha *et al.* 2010). These model outputs had the same spatial and temporal resolution as the wind outputs and were applied to the hydrodynamic model only.

2.3.5 Fresh Water Inflows

Fresh water inflows from the rivers entering the Gulf of Papua are a significant driver of both hydrodynamics and sediment dynamics in the gulf. Available data indicates little seasonal variation in the flow rates (Wolanski *et al.* 1984). The fresh water plumes in the gulf have a residence time of around two months (Wolanski *et al.* 1984). Table 2-2 provides estimates of river inflows used in the modeling system which were derived from Wolanski *et al.* (1993) and sediment fluxes which were derived from Harris *et al.* (1996).

Table 2-2 Modeled Fresh Water Flows from Rivers into the Gulf of Papua

River	Flow (m^3/s)	Sediment flux (kg/s)
Fly	6,000	4,440
Bamu	2,000	1,480
Turama	2,000	1,480
Kikori	2,000	1,480
Purari	3,000	2,220

2.4 Model Calibration and Validation

2.4.1 Available Data

A review of available hydrodynamic and wave data was undertaken.

Acoustic Doppler Current Profiler (ADCP) data was sourced from the Marine Geoscience Data System (http://www.marine-geo.org/tools/search/entry.php?id=VANC30MV) for two locations in the Gulf of Papua from a field campaign carried out in April-May 2004. The data is summarized in Table 2-3. This data was used for preliminary calibration of the hydrodynamic model.

Table 2-3 Available Data from Marine Geoscience Data System

Site	Coordinates	Data Types	Data period
Site 01	144.2952°E, 8.3365°S	Velocity	Apr 2004– May 2004
Site 02	144.2585°E, 8.3005°S	Velocity	Apr 2004– May 2004

The datasets collected as part of the PNG LNG Project Environmental Impact Statement (EIS) (CNS, 2009) were used for more detailed calibration of the model within the Project area. The datasets collected provide water level, wave and wind data for a range of locations at Caution Bay, the Omati River and Kumul Terminal – see Table 2-4. These datasets cover various periods between October 2007 and February 2009.

Table 2-4 Available Data from the PNG LNG Project EIS

Site	Coordinates	Data Types	Data period
Kumul	144.5667°E, 8.1333°S	Water level, wave, wind	Mar 2008– Apr 2008
North Crossing	145.8349°E, 8.3023°S	Water level and velocity	Oct 2007 – Aug 2008
Omati River Mouth	144.179361°E, 7.82625°S	Water level	Oct 2008 – Nov 2008
Omati River Landfall	144.137055°E, 7.607361°S	Water level	Oct 2008 – Nov 2008
Omati River Mid	144.143055°E, 7.686361°S	Water level	Oct 2008 – Nov 2008
Caution Bay East	146.986417°E, 9.34205°S	Wave, water level and velocity	Sep 2007 – Feb 2009
Caution Bay West	146.931667°E, 9.30667°S	Wave, water level and velocity	Feb 2008 – Jul 2008
Weather Station 1	147.0103°E, 9.376°S	Wind	Feb 2008 – Jan 2009
Weather Station 2	147.0103°E, 9.3769°S	Wind	Feb 2008 – Jan 2009

2.4.2 Hydrodynamic Model Calibration

Preliminary calibration of water levels and velocities was undertaken using the data sources listed in Table 2-3. The comparison between measured and modeled water levels at the two measurement locations is shown in Figure 2-3. The model replicated the tidal phasing well and also reproduced the spring-neap variation in tidal amplitude, but did underestimate the tidal range somewhat. Figure 2-4 and Figure 2-5 show the measured and modeled depth-averaged tidal velocities. The model accurately represented the velocity direction and neap tidal amplitudes but underestimated the magnitude of the spring tidal currents. The likely source of error in these comparisons is the boundary forcing data (modeled water levels and currents) as well as the relatively coarse bathymetric data available in the Gulf of Papua.

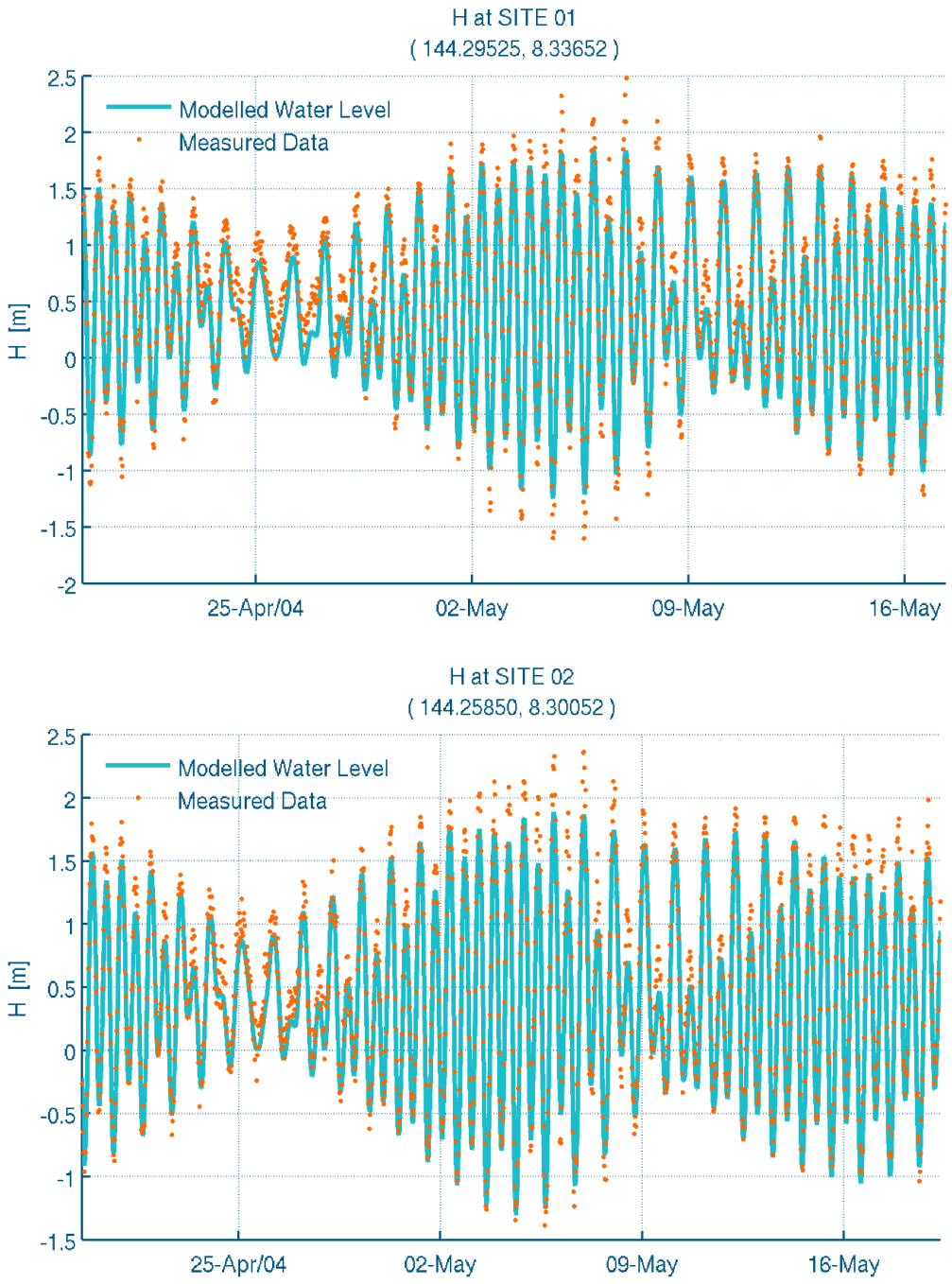


Figure 2-3 Measured and Modeled Water Levels at Sites 1 and 2 in the Gulf of Papua (Refer to Table 2-3 for Locations)

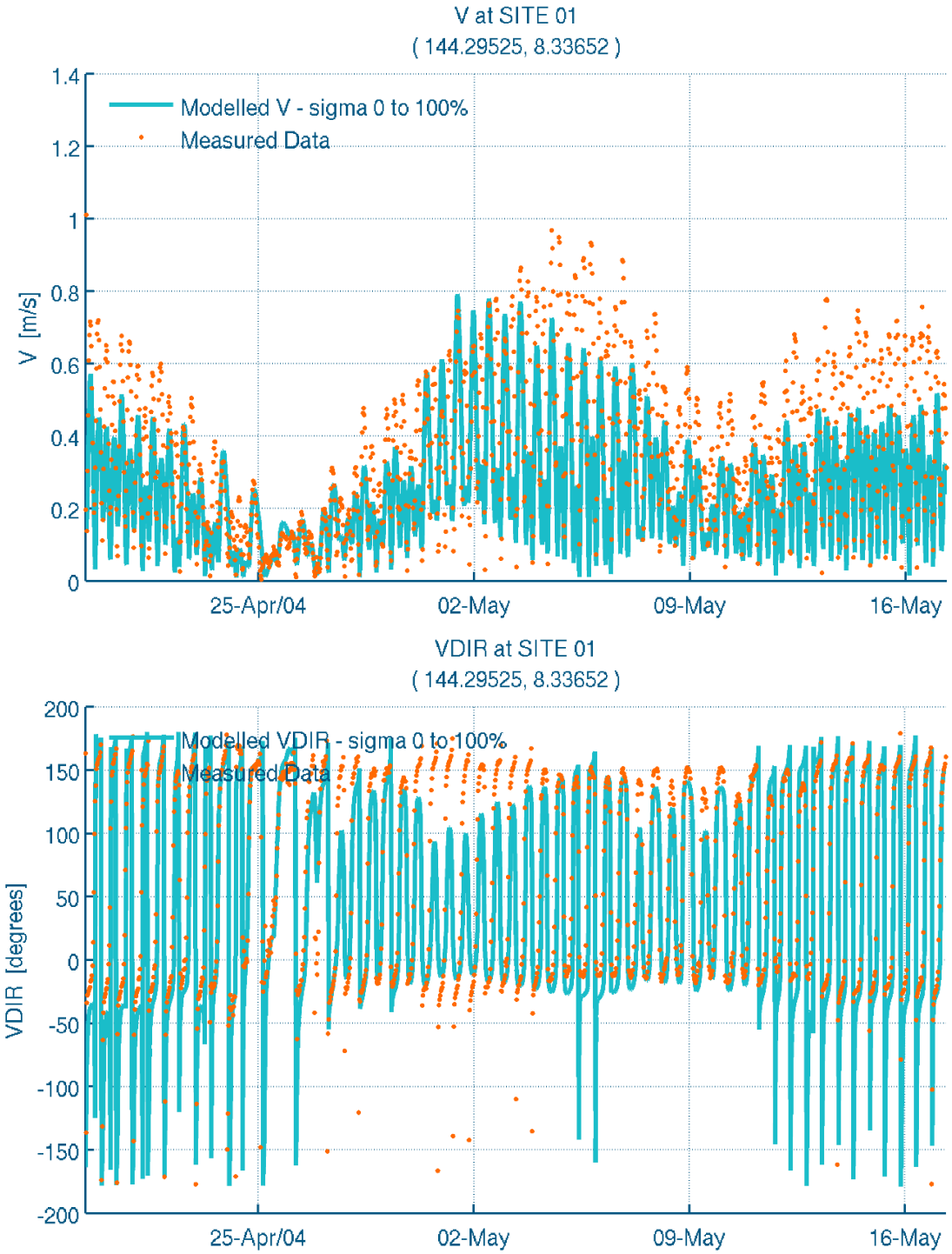


Figure 2-4 Measured and Modeled Water Velocity at Site 1 in the Gulf of Papua (Refer to Table 2-3 for Locations)

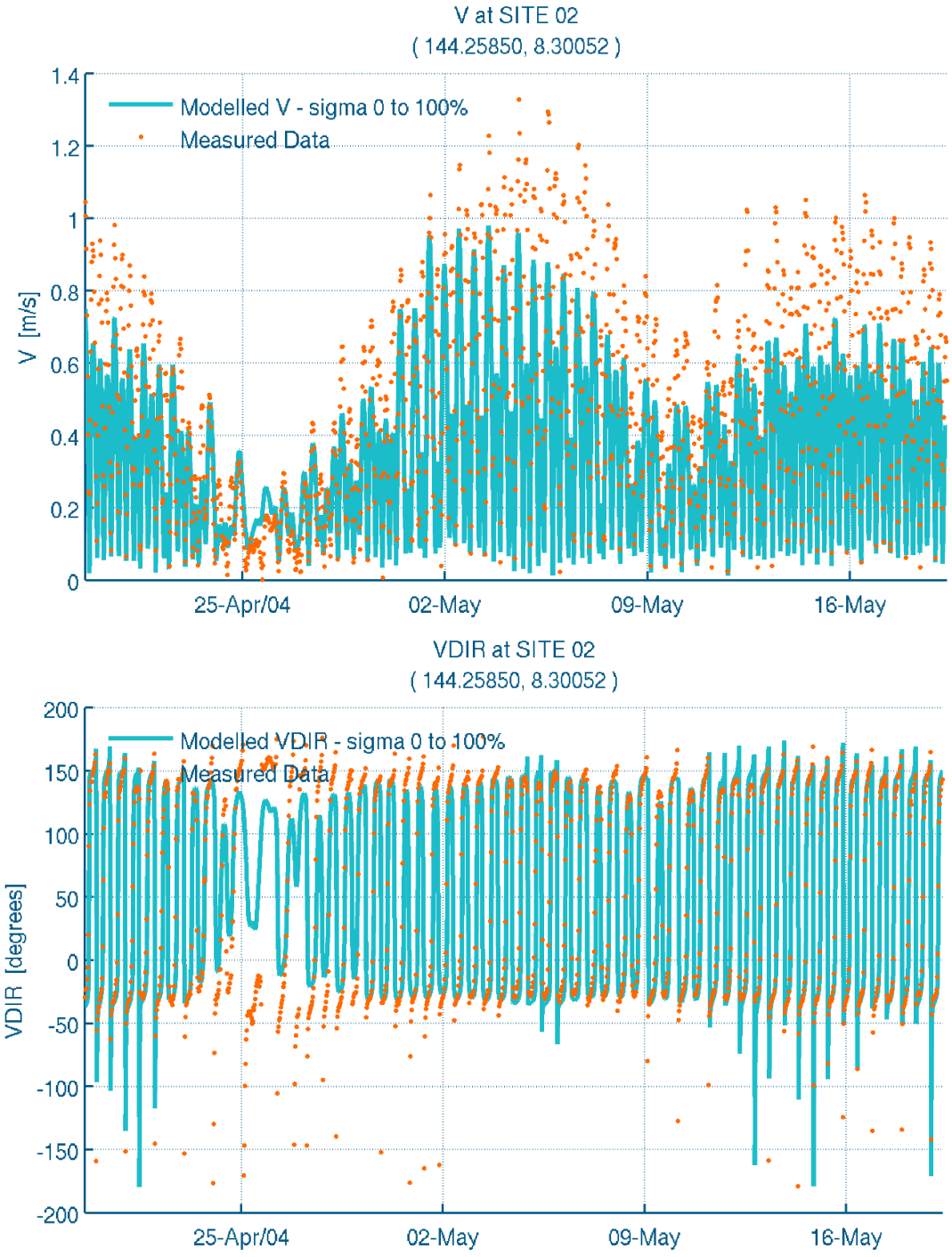


Figure 2-5 Measured and Modeled Water Velocity at Site 2 in the Gulf of Papua (Refer to Table 2-3 for Locations)

Water level data from the Caution Bay sites in the PNG LNG Project EIS (refer to Table 2-4) is shown together with the model output in Figure 2-6. The model accurately reproduced both the phase and amplitude of the measured water levels.

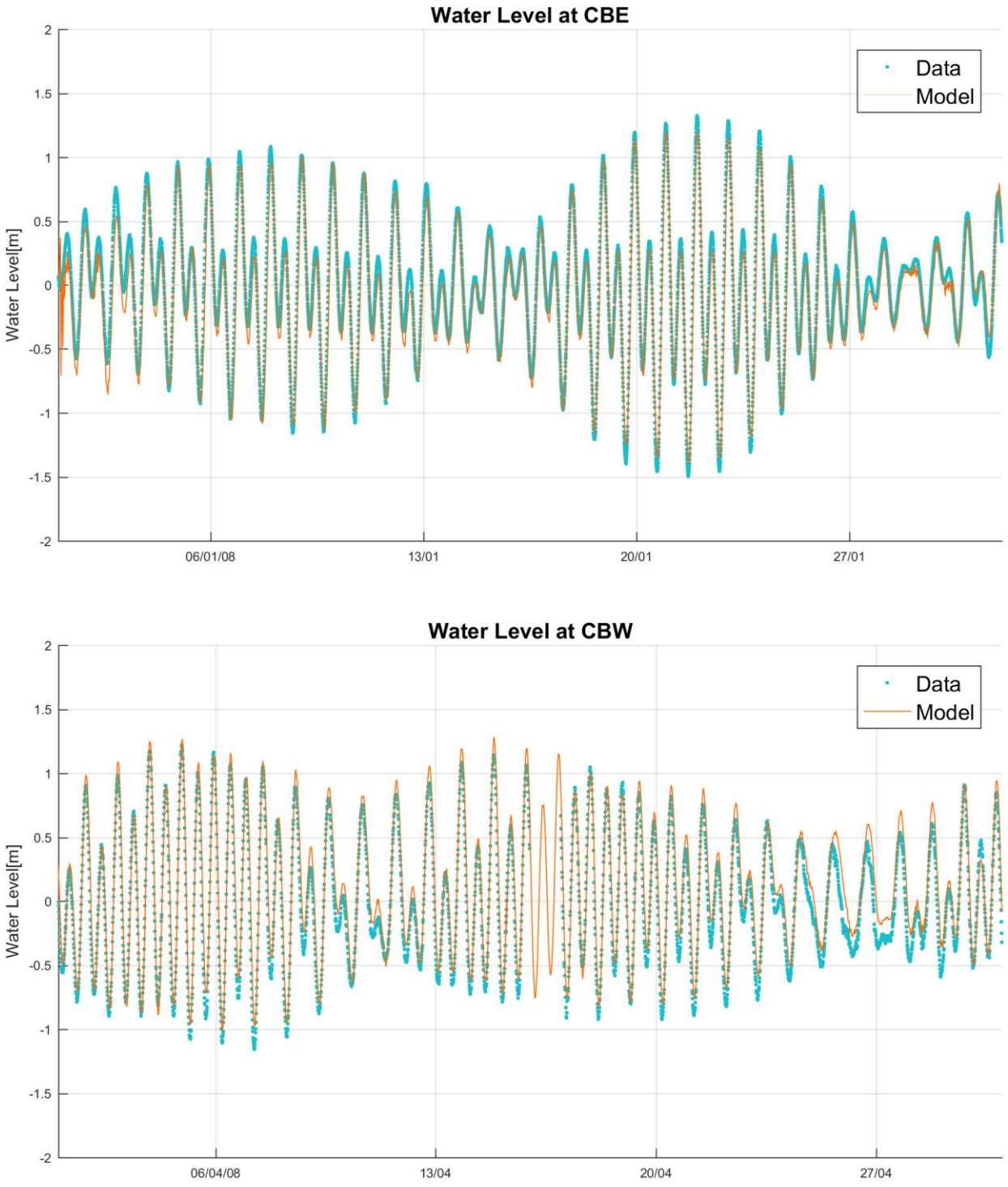


Figure 2-6 Measured and Modeled Water Level at Caution Bay East (CBE, Top) and Caution Bay West (CBW, Bottom) (Refer to Table 2-4 for Locations)

Water level data from the Kumul and North Crossing sites in the PNG LNG Project EIS (refer to Table 2-4) is shown together with the model output in Figure 2-7. The model accurately reproduced both the phase and amplitude of the measured water levels, although the tidal range is slightly underestimated by the model at times.

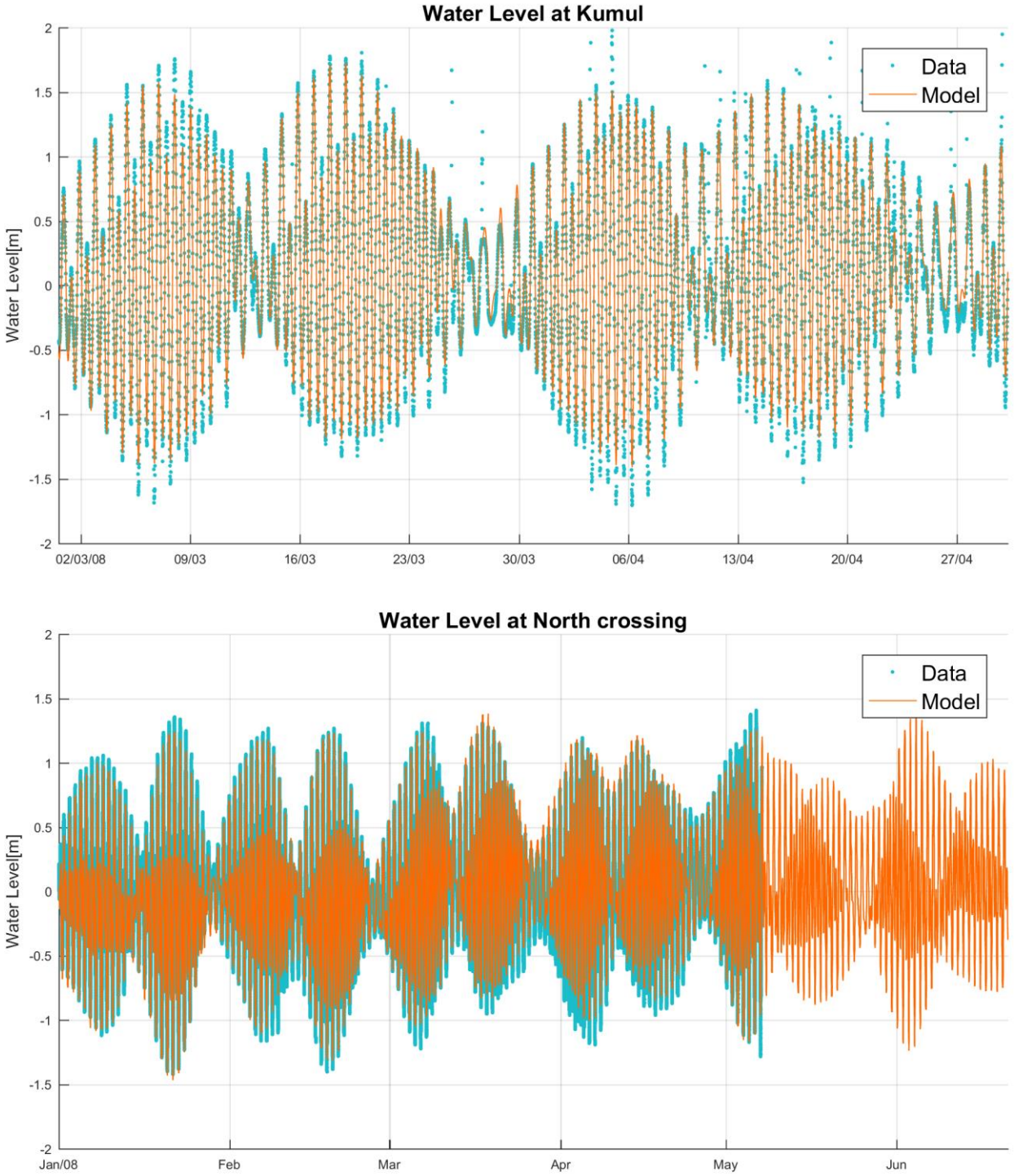


Figure 2-7 Measured and Modeled Water Level at Kumul (Top) and North Crossing (Bottom) (Refer to Table 2-4 for Locations)

Current velocity data from the North Crossing site in the PNG LNG Project EIS (refer to Table 2-4) is shown together with the model output in Figure 2-8. The model accurately reproduced both the direction and magnitude of the measured depth-averaged currents.

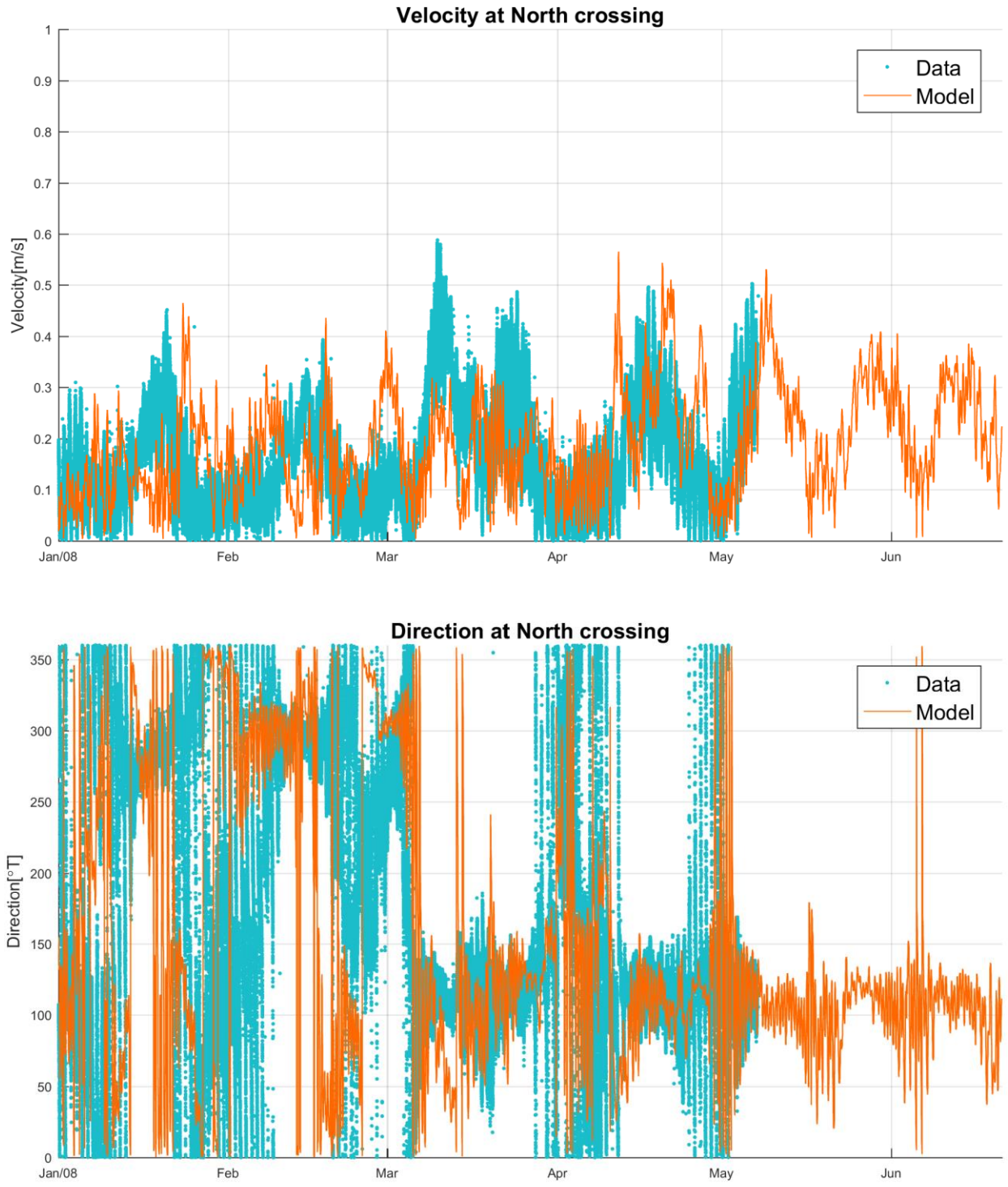


Figure 2-8 Measured and Modeled Current Velocity at North Crossing (Refer to Table 2-4 for Locations)

Current velocity data from the Caution Bay East site in the PNG LNG Project EIS (refer to Table 2-4) is shown together with the model output in Figure 2-9. The model reproduced both the direction and magnitude of the measured depth-averaged currents with reasonable accuracy.

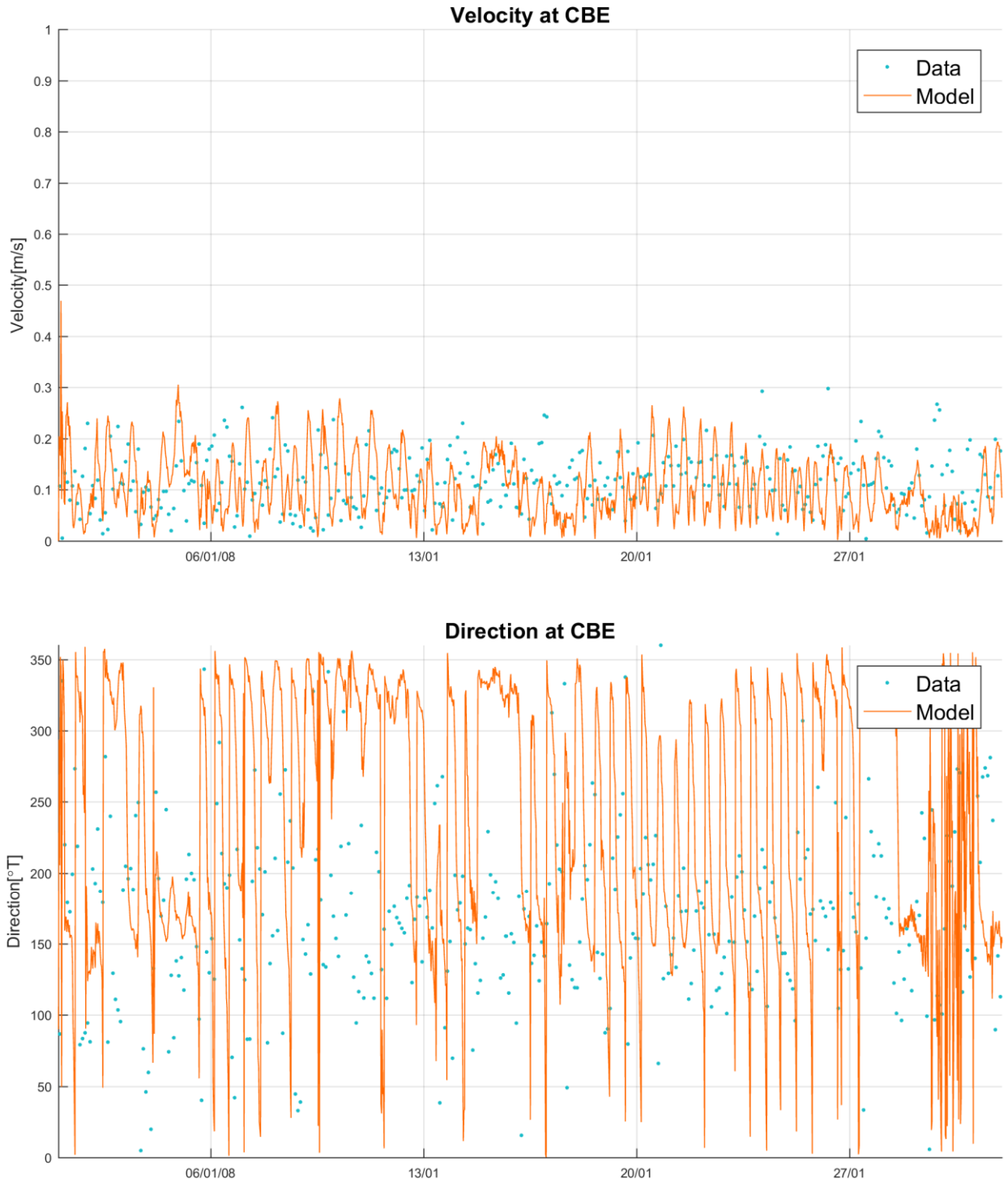


Figure 2-9 Measured and Modeled Current Velocity at Caution Bay East (Refer to Table 2-4 for Locations)

Current velocity data from the Caution Bay West site in the PNG LNG Project EIS (refer to Table 2-4) is shown together with the model output in Figure 2-10. The model reproduced the magnitude of the measured depth-averaged currents with reasonable accuracy. The current direction was not always accurately represented by the model, possibly due to inaccuracies in the applied wind forcing data, but due to the low magnitude of the measured currents this inaccuracy is not considered significant.

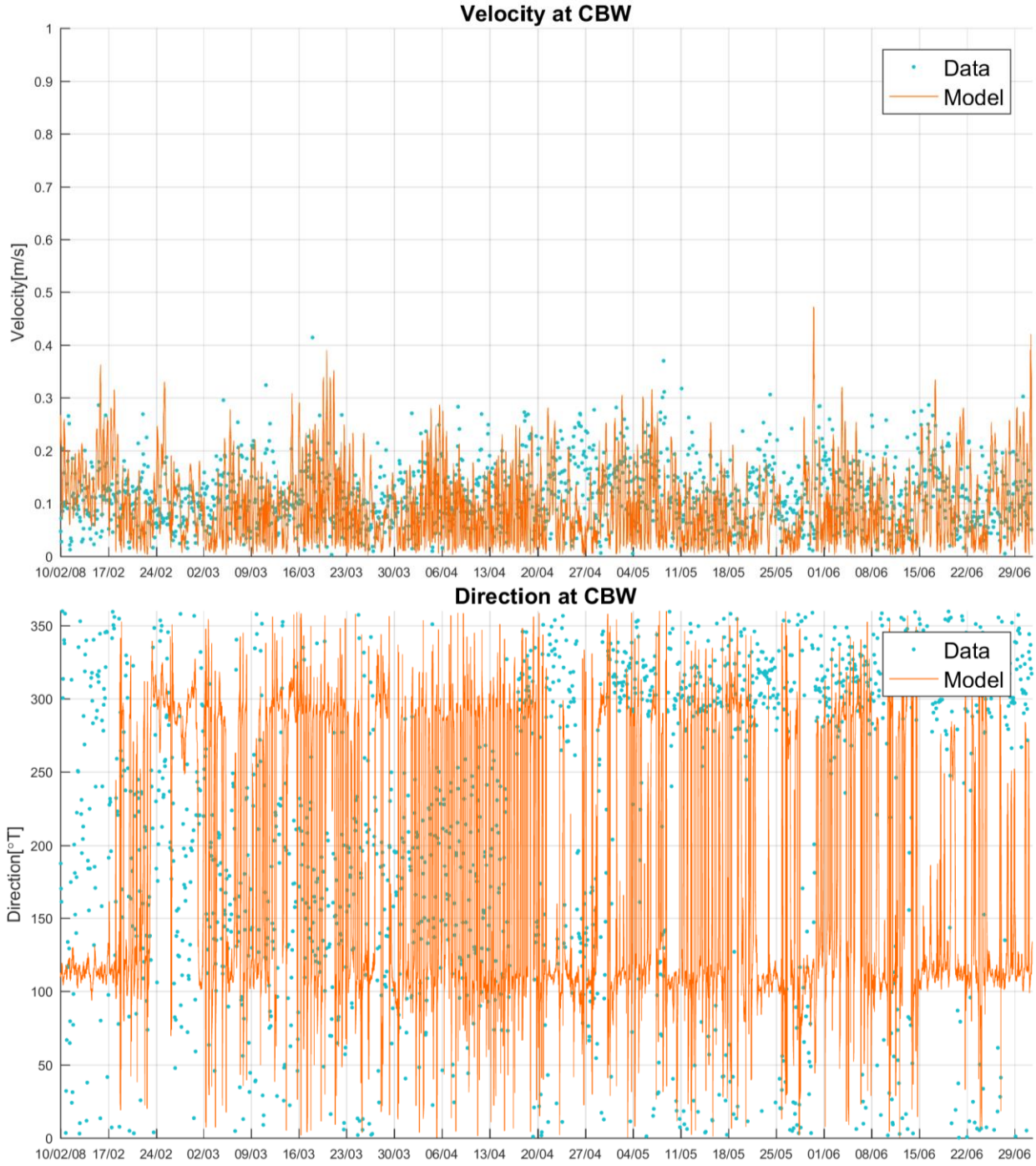


Figure 2-10 Measured and Modeled Current Velocity at Caution Bay West (Refer to Table 2-4 for Locations)

2.4.3 Wave Model Calibration

The measured and modeled significant wave height at Caution Bay East and Caution Bay West are shown in Figure 2-11. The model accurately reproduced the wave heights at Caution Bay East but tended to underestimate the wave height variation at Caution Bay West.



Figure 2-11 Measured and Modeled Significant Wave Height at Caution Bay Sites

The measured and modeled peak energy wave direction at Caution Bay East and Caution Bay West are shown in Figure 2-12. The modeled direction tended to be more northerly than the measured data at both locations for the calibration period.



Figure 2-12 Measured and Modeled Peak Energy Wave Direction at Caution Bay Sites

The measured and modeled peak energy period at Caution Bay East and Caution Bay West are shown in Figure 2-13. The model reproduced the peak period accurately during the first part of the calibration period at Caution Bay East, but tended to overestimate the peak period at Caution Bay West.

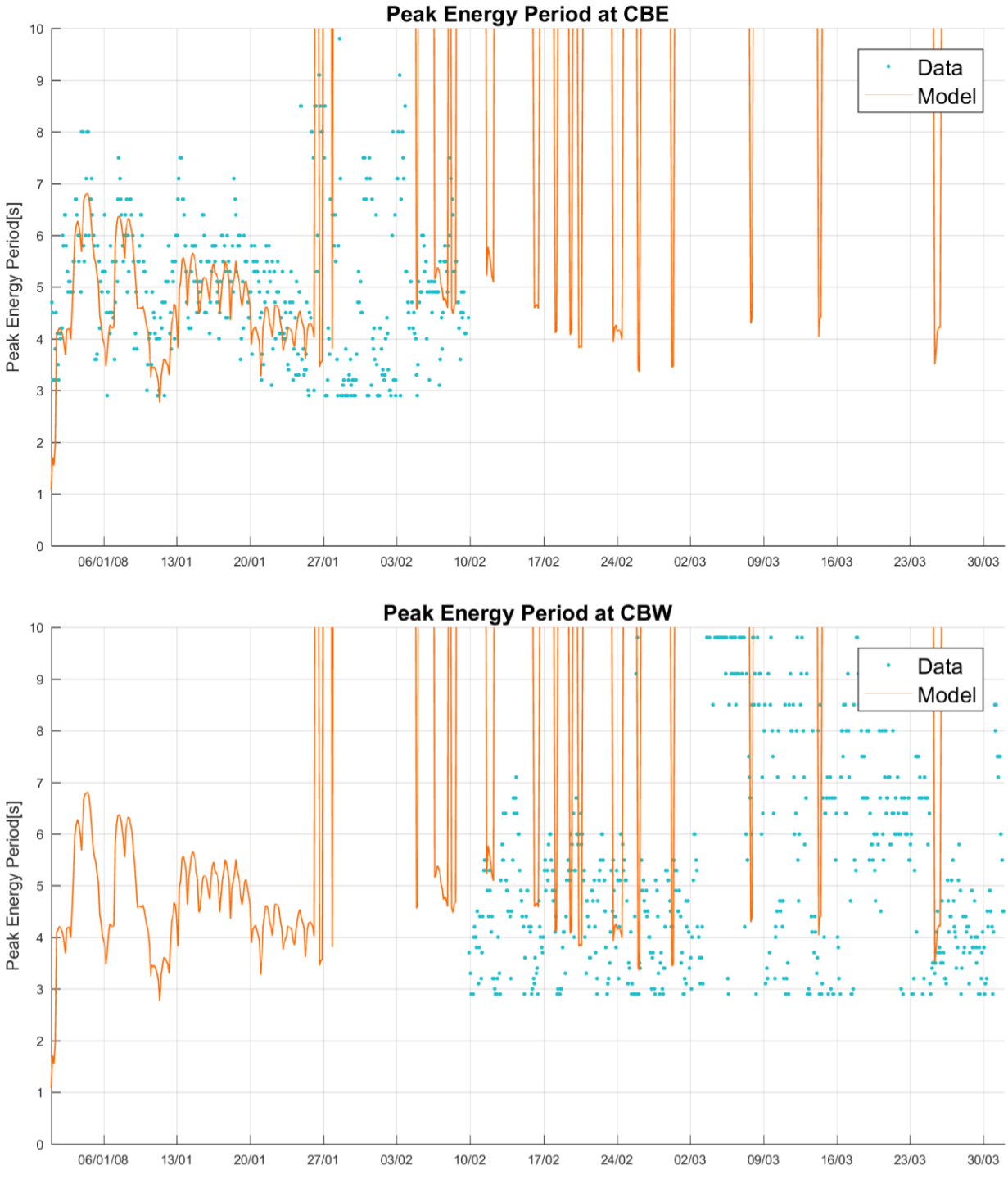


Figure 2-13 Measure and Modeled Peak Energy Period at Caution Bay Sites

3 Conclusion

This report describes the numerical models that were developed to understand physical oceanographic processes as part of the environmental impact assessment for the Papua LNG Project. The hydrodynamic and wave processes within the Gulf of Papua are modeled using a numerical TUFLOW FV model. Wave processes are modeled using a 3rd generation SWAN spectral wave model (Delft University of Technology, 2006). Field campaigns were undertaken to collect new oceanographic data to supplement data sets from previous studies in the area. Measured data included wave parameters, turbidity, salinity, temperature, water level and water velocity at a number of locations within the study area.

The collated data was used to calibrate and validate the numerical models and the comparisons presented in this report illustrate that the numerical models are sufficiently accurate to characterize the important physical oceanographic processes within the study area. Some minor inaccuracies in the modeled current direction were noted at the Caution Bay West location, but this is not considered a significant issue due to the low magnitude of the recorded currents at that site. The numerical models developed for the project are suitable for the purpose of describing existing conditions and predicting impacts as part of an environmental impact assessment.

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