



Faculty of Engineering

**Two-dimensional Hydrodynamic Modelling of Tides at Triso Island,
Burung Island and Nearby River Mouths using Delft3D**

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Two-dimensional Hydrodynamic Modelling of Tides at Triso Island, Burung Island and Nearby River Mouths using Delft3D

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DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.



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ABSTRACT

National efforts to reduce energy dependency on fossil fuels have prompted the examination of macrotidal nearshore sites around the Malaysian coastline for potential tidal stream resource development. A number of prospective tidal energy sites in the Sarawak state of Malaysia have been identified, but the local hydrodynamics of these sites are often poorly understood. Tidal energy developers rely on detailed characterization of tidal energy sites prior to turbine installation and field trials. Although first-order appraisals may make macrotidal tidal straits appear attractive for development, detailed, site-specific hydrodynamic and bathymetric models are important for determining site suitability for tidal stream turbine (TST) installation. Therefore, in this research study, a site-specific regional hydrodynamic model was set up for a previously known macrotidal site of Triso Island in Sarawak, to understand the tidal characteristics and to determine the areas of higher tidal stream energy density. Sensitivity analysis has been carried out to get the most suitable values for the model parameters, including time step, Manning's coefficient, Horizontal Eddy Viscosity (HEV), and grid resolution. The suitable values of these parameters were chosen based on criteria of RMSE value of 20 cm for water level. The model has been validated against water level by comparing it with TPXO output data. It was observed that changes on horizontal eddy viscosity and time step do not have any effect on the model performance, while the best value of the Manning's coefficient to compute bottom roughness was observed to be $0.025 \text{ s/m}^{1/3}$. Two sites near Triso Island and Burung Island are identified to be best for tidal energy harnessing among all, the maximum energy density at Triso Island and Burung Island was noted to be 0.4 kW/m^2 and 0.6 kW/m^2 , respectively.

Keywords: Tidal energy, hydrodynamic modelling, Delft3D modelling, Renewable Energy Sarawak

***Pemodelan Hidrodinamik Dua Dimensi Pasang Surut di Pulau Triso, Pulau Burung
dan Mulut Sungai Berdekatan Menggunakan Delft3D***

ABSTRAK

Dalam usaha negara untuk mengurangkan kebergantungan tenaga bahan api fosil telah merintis kajian makrotidal pantai di sekitar pantai Malaysia untuk potensi pembangunan sumber aliran pasang surut. Beberapa tapak tenaga pasang surut berpotensi di negeri Sarawak, Malaysia telah dikenal pasti, namun hidrodinamik tempatan tapak ini belum dikaji. Pemaju tenaga pasang surut bergantung pada pencirian terperinci tapak tenaga pasang surut sebelum pemasangan turbin dan ujian lapangan. Walaupun penilaian peringkat pertama boleh menjadikan selat pasang surut makrotidal agak menarik untuk pembangunan, model hidrodinamik dan batimetri khusus tapak yang khusus adalah penting untuk menentukan kesesuaian tapak untuk pemasangan turbin aliran pasang surut (TPS). Oleh itu, dalam kajian penyelidikan ini, model hidrodinamik khusus tapak disediakan untuk tapak makrotidal pulau Triso di Sarawak yang diketahui sebelum ini, untuk memahami ciri pasang surut serta untuk menentukan kawasan yang mempunyai ketumpatan tenaga aliran pasang surut yang lebih tinggi. Analisis sensitiviti telah dijalankan untuk parameter model untuk mendapatkan nilai optimum model, dan model telah disahkan terhadap paras air dengan membandingkannya dengan data keluaran TPXO. Telah diketahui bahawa perubahan kelikatan pusing mendatar dan langkah masa tidak mempunyai apa-apa kesan ke atas prestasi model, manakala nilai terbaik pekali kendalian untuk mengira kekasaran bawah diperhatikan ialah $0.025 \text{ s/m}^{1/3}$. Dua tapak berhampiran pulau Triso dan pulau Burung dikenal pasti yang terbaik untuk memanfaatkan tenaga pasang surut, ketumpatan tenaga maksimum di pulau Triso dan pulau Burung dicatatkan ialah 0.4 kW/m^2 dan 0.6 kW/m^2 .

Kata kunci: *Tenaga pasang surut, pemodelan hidrodinamik, pemodelan Delft3D, Tenaga Boleh Diperbaharui Sarawak*

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LIST OF ABBREVIATIONS

ADCP	Acoustic Doppler Current Profiler
ADI	Alternating Direction Implicit
AOI	Area of Interest
APD	Average Power Density
AR	Aspect Ratio
CD	Chart Datum
CMEMS	Copernicus Marine Environment Monitoring Service
CRES	Combined Renewable Energy Resources
GEBCO	General Bathymetric Chart of Oceans
HEV	Horizontal Eddy Viscosity
MCE	Multi Criteria Evaluation
OTEC	Ocean Thermal Energy Conversion
OTIS	Oregon State University Tidal Inversion Software
RMSE	Root Mean Square Error
SMD	Sarawak Marine Department
SSI	Site Suitability Index
TEC	Tidal Energy Conversion
TMD	Tide Model Driver
TPXO	Oregon State University TOPEX/Poseidon Global Inverse Solution tidal model
TST	Tidal Stream Turbine
UK	United Kingdom

CHAPTER 1

INTRODUCTION

1.1 Study Background

Coastal areas of the sea are considered as vigorous vicinities as they create a boundary between ocean and land, where intensive exchange processes occur quite frequently. Coastal areas of the sea are also important zones for economic development, by providing an opportunity in terms of fishing, transportation, and energy generation. Observing the hydrodynamics and circulation patterns of the tides at coastal zones need rigorous data collection strategies, that need a lot of time, effort, and significant expenses. However, the numerical models are an attractive option to understand the hydrodynamics and circulation patterns of tides, close to coastal zones. In view of the economic significance of these zones, several numerical models are developed to simulate the sea and land interaction process such as tidal flow, wind current, sediment transport, wave interaction, salinity, temperature distribution, et cetera (etc) (Chen *et al.*, 2013; Guillou *et al.*, 2020; Hagerman *et al.*, 2006). As most of the coastal zones have shallow water, therefore developing a 2-dimensional (2D) model is considered valid to understand the tidal patterns, by averaging the depth of shallow water (Alhunaiti *et al.*, 2021).

The depth-averaged models help understand the local hydrodynamics of macrotidal sites. The understanding of the spatial and temporal changes in the flow field at a tidal site is the initial step to making a macrotidal site an energy generation spot. The initial stage of tidal energy development is the site screening, for which hydrodynamic modelling plays an important role in the inclusion and exclusion of potential areas for tidal energy harnessing within the macrotidal site. After the initial stage, high-resolution hydrodynamic modelling

needs to be done to characterize the site for energy extraction based on energy density, distribution of the mean, and peak tidal current speed, and the water depth. Thanks to the research community around the globe for their interests in tidal energy exploration, as a result of which, several numerical, hydrodynamic models, packages, and open source software have been available (Carballo *et al.*, 2009; Chen *et al.*, 2013; Cossu *et al.*, 2021; Deltares, 2021; Guillou *et al.*, 2020; Hagerman *et al.*, 2006). Utilizing these packages, especially the open-source packages, make it easy for the young scientists, engineers, and industrial community in the tidal energy exploration field to characterize an unexplored tidal energy site and to optimize site selection and turbine form design. One example of such packages is the Delft3D open-source package developed by the Deltares (2021) to solve the shallow water equations and understand coastal hydrodynamics (Deltares, 2021). Delft3D is a hydrodynamic and transport simulation package that can be modelled as 3-dimensional (3D) or 2D, during simulation, the software package computes the non-steady flow resulting from metrological and tidal forces. The Delft3D open source package has a history of successful simulation application of water flow in sea, ocean, coastal, and estuarine sites. Therefore in this study, we utilized the numerical application of Delft3D to simulate the tidal flow at Triso Island, Sarawak Malaysia.

1.2 Problem Statement

Tidal energy development in Malaysia is still in infancy stage. Malaysia's large coastline has potential sites for tidal energy harnessing. However, extensive studies are still required to make them feasible for power generation and to justify these sites for onsite testing of tidal current turbines for power generation. In recent years, some researchers have already taken their part to explore the tidal stream energy generation sites in Malaysia (Goh *et al.*, 2020; Lim & Koh, 2010; Sakmani *et al.*, 2013). The majority of tidal stream

energy sites assessments are focused on the Strait of Malacca. The major tidal energy sites available in the Strait of Malacca have gone through the initial feasibility assessment, and are justified for the onsite testing of tidal current turbines. The assessment was done by developing high-resolution 2D and 3D hydrodynamic models. These hydrodynamic models enable researchers and policymakers to make sure that the estimated tidal energy density was not overestimated. Furthermore, the accuracy of the assessment was justified by assuming the porous plate in the hydrodynamic model to be a tidal current turbine. This way, the effect of installing the turbines at different locations and the optimized sizing and configuration of the turbine array were analyzed. However, these studies are focused on the Strait of Malacca only and not much attention has been given to the other sites in Malaysia. There are several potential locations across the Malaysian coastal zones that can be utilized for tidal stream power generation. These untapped locations include the coastal zone near the Langkawi Island in Malacca strait, Seri Buat Islands on the East coastline of peninsular Malaysia, the West coastal zone of Sarawak State, and a lot of sites in Sabah State (Goh *et al.*, 2020; Lim & Koh, 2010; Sakmani *et al.*, 2013). Another study by Rigit *et al.* (2013) also suggests several locations in Sarawak, see Figure 1.1 (Rigit *et al.*, 2013). The tidal sites suggested by Rigit *et al.* (2013) have higher tidal current speeds when compared to sites in the straits of Malacca (Sakmani *et al.*, 2013). The mapping of the potential sites in Sarawak was done by Rigit *et al.* (2013) based on the statistical analysis of the tidal stream speed data available in Sarawak Tidal Stream Tables (Rigit *et al.*, 2013). A total of 6 sites in Sarawak were analyzed from the Sarawak Tidal Stream Tables, as shown in Figure 1.1. These include Kuala Igan, Bintulu, Off Tanjung Sirik, Off Kuala Paloh, Off Kuala Rajang, and Off Tunjung Po locations.



Figure 1.1: Potential tidal stream energy sites in Sarawak (Rigit *et al.*, 2013)

Among these sites, Kuala Igan has the highest tidal stream speed, as well as meets the depth requirements of 15 m for installing tidal current turbines. Furthermore, on-site measurements were recorded for the location Triso Island, and it was noted that the Triso Island has the highest tidal stream speed of 2.06 m/s, compared to any other site in Sarawak. This site was suggested for further future study, as sufficient data was not available for the resource assessment.

Furthermore, the mapping done by Rigit *et al.* (2013) is based on the statistical analysis only, which is not sufficient to characterize the tidal energy resource site (Rigit *et al.*, 2013). Triso Island in Sarawak was suggested as the most attractive location for tidal stream energy harnessing, but no one has completed the further study so far. The locations were identified based on statistical analysis, but the local hydrodynamics of these locations

are still not understood yet. Moreover, understanding the local hydrodynamics is the initial step in the tidal energy assessment of any site. Therefore, in this study, we set up a regional hydrodynamic model for Triso Island, by utilizing the numerical application of Delft3D. In this way, the hydrodynamical characteristics of tides at Triso Island, Sarawak, can be understood. This further helps to determine the tidal stream power density available at the proposed site and to decide the inclusion and exclusion areas for tidal energy harnessing at the Triso Island site.

1.3 Objectives

This study aims to understand the hydrodynamics of tides at Triso Island, Sarawak, by setting up a regional hydrodynamic model utilizing the numerical application of Delft3D. In particular, the objectives of this study are as follows:

- i. To set up a regional hydrodynamic model for Triso Island, Burung Island, and nearby river mouths using numerical application of Delft3D
- ii. To investigate the sensitivity of the model considering time step, grid resolution, Manning's coefficient, and Horizontal Eddy Viscosity
- iii. To validate the model by comparing it with TPXO output data
- iv. To determine the temporal and spatial characteristics of tides at Triso Island and Burung Island
- v. To evaluate the kinetic energy density available at Triso Island and Burung Island

1.4 Scope

It is expected that the current study will be fundamental for further tidal stream energy development in Sarawak. The current study is a simulation study based on Delft3D software, which focuses on the tidal stream simulation at Triso Island. For this purpose, a regional hydrodynamic model called “Triso-Model” is set up to characterize the proposed site. The bathymetry data in the simulation is collected from Sarawak Nautical Charts and General Bathymetric Chart of Oceans (GEBCO). The data needed for setting up the boundary conditions in simulation is extracted from the TPXO output. The sensitivity analysis is carried out for the Triso-Model based on physical and numerical parameters such as time step, grid resolution, bed roughness coefficient, horizontal eddy viscosity, etc. The scope of the thesis also includes the spatial and temporal analysis of the tides at Triso Island. In this way, the inclusion and exclusion of the area near Triso Island for tidal stream power generation can be decided. Furthermore, the proposed site is characterized based on the spatial distribution of depth-averaged velocity, the temporal variation, the magnitude of the depth-averaged velocity, and the bathymetry. This characterization helps to suggest a suitable location for onsite testing of the tidal current turbine.

1.5 Thesis Structure

There are a total five of chapters in this thesis, the summary of each chapter is discussed below:

Chapter 1: Introduction

This chapter has provided a general introduction to the current study, focusing on the background of hydrodynamic modelling, the fundamental of tidal energy, and the tidal

stream energy potential in Malaysia. Afterward, the problem statement, objectives, and the scope of the current study are also described in this chapter.

Chapter 2: Literature Review

This chapter has discussed the literature review related to the scope of the thesis. The fundamentals of tidal energy and the brief history of tidal energy generation are discussed in detail in this chapter. The chapter also focuses on the tidal energy assessment and the types and scales of tidal energy assessment. Finally, the literature review is presented on the hydrodynamic modelling approach for tidal stream energy assessment.

Chapter 3: Methodology

This chapter provides a detailed description of the methodology adopted to set up the hydrodynamic model for the Triso Island study area. The study on the site is presented to gain the knowledge about the study area. The process flow diagram in this chapter explains each step of data collection, data processing, and setting up the hydrodynamic model. The method of calculating tidal energy density is also explained at the end of this chapter.

Chapter 4: Results and Discussion

In this chapter, the main outcomes of the study are discussed in detail. The results on sensitivity analysis are presented and the model validation is also discussed in this chapter. The focus is given on the spatial and temporal analysis of depth averaged velocity at the study area to identify the best suitable locations for tidal stream energy generation. Finally, the energy density is calculated for the identified locations.

Chapter 5: Conclusion and Recommendation

This chapter provides the highlights of the main outcomes of the current research. Future research study areas are also recommended in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter highlights the importance and historical aspects of tidal energy generation. The history of tidal energy harnessing and various aspects of tidal energy assessment are discussed in detail. The focus has been given to the various hydrodynamic models used in tidal energy assessment and reviewing the related literature in detail. There is a discussion presented on the types of hydrodynamic models and available tools utilized in hydrodynamic modelling.

2.2 Tidal Energy

Tidal energy is form energy, mainly electrical energy, that is harnessed from the tides, by utilizing various methods. The energy converters, or tidal turbines, are installed in the seawater to extract the kinetic energy of moving water during flood and ebb tide. The density of seawater is almost 800 times greater than the air, therefore the potential of tidal current energy is greater when compared to wind energy.

2.2.1 Historical Scenario of Tidal Energy

Tidal energy is not a new technology, people in Europe used to utilize tidal energy by installing tidal mills for grinding the floor. The tidal mills are still available in several areas in Europe that date back to the middle ages, most of the tidal mills are found in England. There are still old tidal mills available from more than 1000 years ago, the eldest known tidal mill is found to be back in 787 (*Tidal Power - History of Tidal Power*, n.d.). In the early stage of tidal energy harnessing, people used to follow the dam-like technique,

where the falling water was utilized to spin the water mill, and then the mechanical power was used to grind the grains. This technique follows the principle of storing the water in ponds during the period of high tide and releasing it during periods of low tides. The releasing tides were utilized for running the tidal water mills, most of these wooden made water mills were used to run the stones for grinding the grains. An example of such a tidal mill is still available in Suffolk England, which is reported to be from 1170, i.e about 1000 years old (*Tidal Power - History of Tidal Power*, n.d.).

The generation of electricity from tidal power started in the 20th century, where the initial tidal power feasibility study was started in the United States and Canada from the year 1924 to 1977. However, during the last decade, several commercial tidal power plants were installed and the onsite testing of tidal current turbines has been carried out in several countries such as France, South Korea, Scotland, Philipines, etc. Back in the year 2010, the world's largest tidal current turbine of 18 m diameter was installed in Scotland (Bowman & Gorlov, 2019). Furthermore, recently in the year 2021, the world's most powerful tidal current turbine was installed in Scotland to generate electricity (*O2 - Orbital Marine*, n.d.). The turbine was installed by Scottish company Orbital Marine Power, having the capacity of 2 MW, 74 m long, and it is called as O2 turbine. According to Orbital Marine Power, the turbine is connected to the local grid via subsea cables and it is expected to generate electricity for fifteen years (*O2 - Orbital Marine*, n.d.).

Furthermore, a lot of tidal current potential has remained untapped and unexplored globally. It is expected that the other countries will start generating electricity from ocean currents in near future. Several countries have already started exploring their tidal current energy generation potential. One example of such studies is research conducted along the

Australian coastline, where the multi-criteria evaluation of tidal energy sites has been completed recently (Marsh *et al.*, 2021).

2.2.2 Fundamentals of Tidal Energy

Tidal energy is harnessed from the movement of tides, the movement is created as a result of the gravitational forces of earth, moon, and sun. The combined effect of the gravitational forces of the sun and moon, and the centrifugal force of the earth's rotation create rise and fall on the ocean surface, this regular rise and fall of the seawater are called a tide (Khojasteh *et al.*, 2022). The effect of these forces creating a water bulge is illustrated in Figure 2.1.

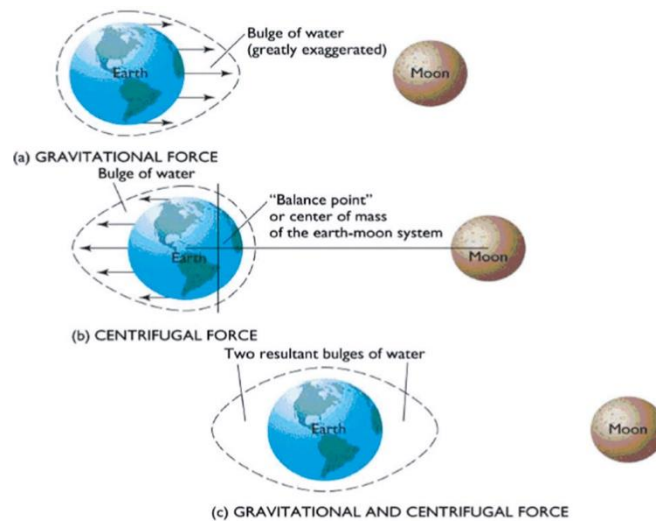


Figure 2.1: Gravitational and centrifugal forces creating a tidal range (Khojasteh *et al.*, 2022)

A tidal cycle can be observed two times every 24 hours, 50 minutes, and 28 seconds (Rourke *et al.*, 2010). The pull of the moon's gravity creates a bulge of water on the surface of the sea/ocean, and the amplitude of this bulge can be observed maximum at the location of the earth nearest to the moon. At the same time, the rotational effect of the

earth-moon creates centrifugal forces, which again create another bulge on the opposite side (i.e the location of the earth farthest from the moon), as explained by Figure 2.1. This water bulge created on the ocean surface is called a tide. Those ocean surfaces that are parallel to the moon will have a high tide at that time, and those that are at an angle of 90° (perpendicular) to the moon will have a low tide. In this way, each of the ocean water experiences two high tides and two low tides when the earth completes a single rotation. Furthermore, because the position of the moon is always changing, the timings of these high and low tides at any particular location of the ocean are also changing every day. The approximate timing of a tide at any particular location will be 50 minutes later every next day (Rourke *et al.*, 2010).

The tides can be classified as the neap tide and spring tide, and the amplitude of the tides depends upon the neap and spring tidal cycle. When the position of the sun and moon are in line with the earth, the magnitude of a tide is the high spring tide. The position of the moon and sun can be either on the same side of the earth or each pulling the water mass from the opposite sides, the resultant tide is a spring tide of the highest range. In contrast to this, when the position of the sun and moon with the earth is at an angle of 90° , the resultant tide is a low neap tide. Each of the tidal cycles creates tidal currents at the coastal zones and estuaries. The tidal current flows in two ways, flowing towards the coastline and coming from the coastline. When the tidal current flows towards the coast, it's called a flood tide, and when the tidal current is coming back to sea, it's called an ebb tide. The magnitude (velocity) of flood tide is always higher than the magnitude of the ebb tide. However, the magnitude of the velocity keeps on changing from maximum to zero, and vice versa. The velocity becomes zero when both the tides are exactly half of the tidal cycle. This time of a flood or ebb tide when the velocity is zero is called as slack period.

Whereas the velocity is maximum when the tide is halfway from the slack period (Khojasteh *et al.*, 2022). Both of these characteristics of tides (i.e rise and fall and flood and ebb) are utilized for power generation. For this purpose, vertical axis tidal current turbine is most suitable as it can harness energy in any direction, however, horizontal axis tidal current turbine is more efficient.

2.2.3 Tidal Stream Energy in Malaysia

Considering the alarming issues of climate change and global warming, those countries that are producing fossil fuels, including Malaysia, are searching for renewable and sustainable resources for power generation that also can be utilized in rural electrification. The fact that Malaysia has a very long coastline, surrounded by the south china sea, and peninsular Malaysia is having one of the biggest straits of the world, all of these facts indicate a huge potential for tidal energy (Goh *et al.*, 2020). The government also sets up policies to encourage exploring the ocean resources for renewable energy generation.

There are multiple tidal stream energy sites available in peninsular Malaysia. The majority of these sites are in the strait of Malacca, where the maximum tidal current speed during the peak spring tidal cycle is estimated to be 2.0 m/s to 2.5 m/s (Goh *et al.*, 2020; Lewis *et al.*, 2015). It has been highly appreciated to harness the tidal stream energy in Malaysia, as it helps reduce the carbon footprints, fossil fuel consumption and contributes towards Malaysia's sustainable development. Nevertheless, it also aligns with the United Nation's (UN) sustainable development goals (SDG) (Hannan *et al.*, 2018).

The coastline of Malaysia is mostly dominated with semidiurnal and mixed tides. The upper part of the Straits of Malacca receives the semidiurnal tide while the rest of

peninsular Malaysia has mixed tide with Dominant Semidiurnal, as illustrated in Figure 2.2. However in east Malaysia, the west side of Sarawak receives mixed tides with Dominant Semidiurnal, and the rest of Sarawak side, as well as Sabah receives mixed tides with Dominant Diurnal. It is clear from Figure 2.2 that the type of tide throughout Malaysia is either Semidiurnal tide or mixed tide, however, the Diurnal tide can not be observed at any of the locations. Knowing the type of tide helps to understand the characteristics of the tidal current turbine (TCT), and to understand the required parameters of power generation from the TCT at a particular location.

The tidal energy potential can be calculated by the available energy density, defined by the following Equation 2.1.

$$E = \sum_{t=i}^n \left[\frac{1}{2} \rho V^3 \right]_t \quad \text{Equation 2.1}$$

Where, E stands for available energy density, t is the timesteps starting from i to n , ρ is the density of the seawater, and V is the time series tidal current velocity. During the feasibility analysis of tidal energy source, the hydrodynamic models are developed as 2D, and the tidal current velocity in these hydrodynamic models is depth-averaged.

Tidal stream energy extraction from any site depends upon the characteristics of TCT, therefore the extractable energy from Malaysia will always be lower than the energy density calculated by using Equation 2.1. However, during the resource assessment, the coefficient of TCT is assumed as 1 (Mestres *et al.*, 2019).



Figure 2.2: Types of tides available in Malaysia, adopted from the analytical study done by Lim & Koh (2010)

This way, the energy density for Malaysia based on Equation 2.1 was computed by Lim and Koh (2010) to characterize the macrotidal sites in Malaysia (Lim & Koh, 2010). Tidal stream energy density in Malaysia is shown in Figure 2.3. The Sabah state has a lot of potential sites for tidal energy harnessing, after which the west part of Sarawak. Although it is clear from Figure 2.3 a lot of energy density sites are available in East Malaysia when compared to West Malaysia, still these sites remain untapped.

In particular, the potential tidal energy sites from Figure 2.3 include Kapar, Pontian, Tanjung Karang, Semporna, Kota Belud, Kuching and Sibul. However, an extensive study is required to quantify the extractable energy potential from these sites. Tidal energy extraction also depends upon the advancement and development of tidal current turbines (TCT). The number of tidal stream sites will increase with the advancement and development in tidal stream harnessing technology.

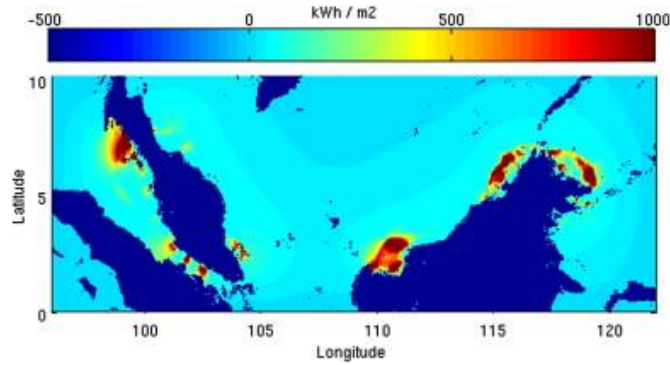


Figure 2.3: Tidal stream energy sources in Malaysia (Lim & Koh, 2010)

The strait of Malacca is considered among the world's largest straits, having a length of 800 km, and the width varies between 50 to 320 km, and with a minimum depth of the channel as 23 m (Sakmani *et al.*, 2013). The strait of Malacca represents the potential tidal energy sites, it is suggested that the major part of West Malaysia can fulfill their energy requirement from this strait's tidal energy potential. The feasibility study completed by Sakmani *et al.* (2013) at Pangkor Island in this strait suggests that the tidal current speed at this Island, flowing from the South China Sea to the Indian Ocean, is between 1 to 2 m/s (Sakmani *et al.*, 2013). The location called Pulau Mentagor in Pangkor Island was suggested to be the suitable site for power generation, after completing the assessment based on factors of tidal current velocity, the water level of tides, seabed roughness, water depth, ADCP measurements, and physical conditions (pH, salinity, temperature, etc) of the seawater (Sakmani *et al.*, 2013).

Another study by Goh *et al.* (2020) justifies the energy generation at the site of Tg Tuan Headland in the Strait of Malacca. From the high-resolution hydrodynamic analysis at this site, it was concluded that a power density of 2.5 kW/m^2 is available at this site. Furthermore, the location was also closed to the nearest power station of Tuanku Jaafar,

which also supports the idea of tidal stream power generation from this site, as the generated power can be linked to the transmission line that connects to the national grid. A number of 233 horizontal axis turbines of 10 m diameter were suggested for installation.

2.3 Tidal Energy Assessment

The assessment of potential macrotidal sites is carried before the development of tidal power plants and testing of the tidal turbine. The decision-makers rely on the knowledge provided to them regarding the energy generation potential and the estimation of the payback period of a particular site so that they can be ease in deciding on tidal form development. There are three main stages of tidal energy assessment after shortlisting the potential sites, evaluating the energy-generating potential, and considering the environmental and physical hindrances. These stages are discussed in the following subsections.

2.3.1 Pre Feasibility Analysis

Prefeasibility analysis is the primary step of the development of tidal energy forms in any country. It can be done through the site survey, collection and analysis of the data, and through the feasibility analysis. The potential macrotidal locations are shortlisted during this stage of tidal energy assessment. Shortlisting of the macrotidal sites can be done from the tidal data collected from the regional offices for local tidal gauge stations installed in any country. Another way of identifying the macrotidal locations is by using the already available global ocean circulation models and databases, such as TPXO, as shown in Figure 2.3 (Lim & Koh, 2010). TPXO is a series of fully-global models of ocean tides, which best-fits, in a least-squares sense, the Laplace Tidal Equations and altimetry data.

An example of this stage of a tidal energy assessment is shown in Figure 2.4, where the macrotidal energy sites in Sarawak were proposed by Rigit *et al.* (2013). This shortlisting of the macrotidal sites was done based on the data of tidal stream velocity, and the data was provided by the Sarawak Marine Department (SMD). Although this stage of assessment is not accurate, it gives a clear picture of the potential locations to be chosen. For example, the locations in Figure 2.4 indicate the higher energy density in Sarawak is experienced along the western side of the Sarawak coastline, which includes the locations between Off Kuala Igan and Off Tanjung Po.

Tidal current energy extraction is specific to the site, therefore it is not evaluated during the pre-feasibility stage (Pacheco & Ferreira, 2016). However, prior to deciding the specific site for energy extraction during this stage, it is crucial to specify the parameters of the tidal energy converter (TEC) to be installed (Pacheco & Ferreira, 2016).

Furthermore, the quantification of the tidal current energy sites can be done during the pre-feasibility stage (Khare *et al.*, 2019). During quantifying process, a site is analyzed for 30 days, for which two or three days of boundary data are set as initial conditions in the computational grid. This tidal analysis can be done by using any tidal analysis software such as T-TIDE, and the remaining days are analyzed by the software based on the initial condition. Apart from this, the history of the high and low tidal current is also analyzed to evaluate the feasibility of energy generation during flood and ebb tide. In this way, the locations are quantified based on the water depth and tidal current velocity during spring tide. The water depth can be set in the range of 25-50 m, while the maximum velocity as 2.5 m/s.

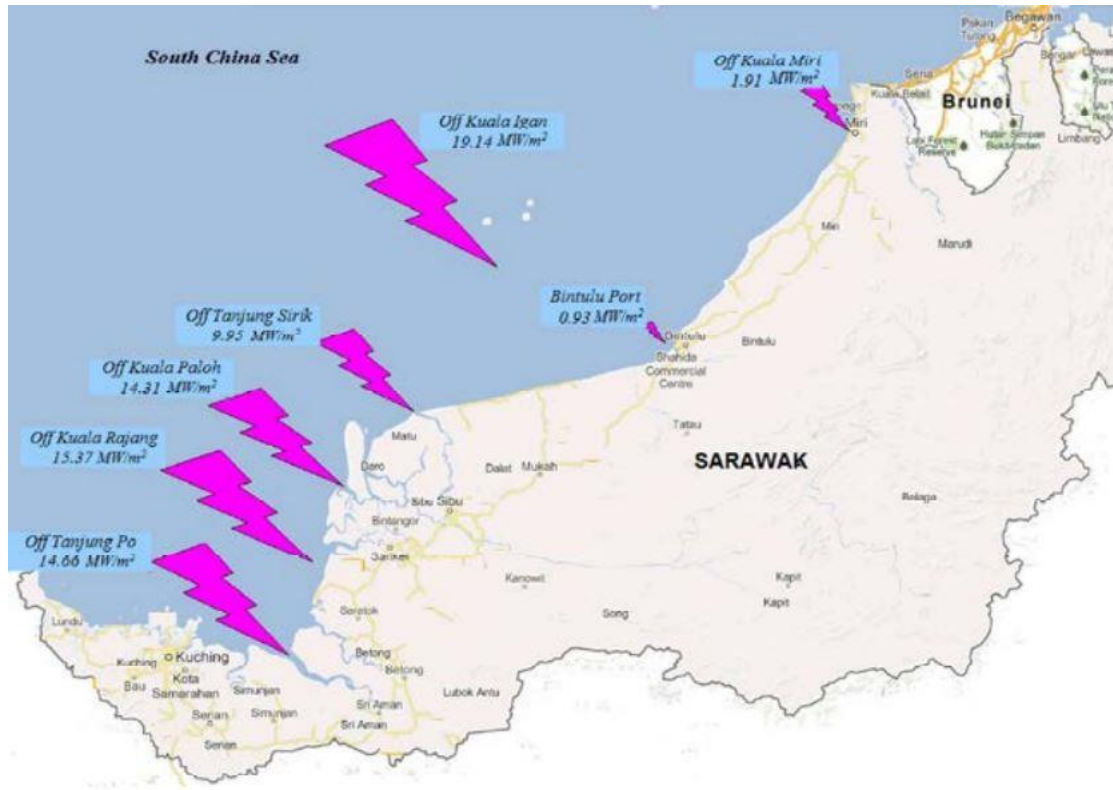


Figure 2.4: Macrotidal location suggested by Rigit *et al.* (2013) along the coastline of Sarawak

2.3.2 Resource Assessment

A detailed resource assessment of the energetic tidal energy site needs to be done in order to evaluate the extractable power from the site. While the detailed resource assessment is started with the understanding of the tidal flow at the site. For this purpose, detailed 2D and 3D hydrodynamic models have been proposed by several researchers to accurately understand the tidal flow and flow behavior when the turbines are installed. Understanding the hydrodynamic characteristics of the energetic tidal sites is crucial before the site can be tested with the onsite trial of the Tidal Stream Turbines (TST). The resource assessment has been already completed in several countries such as the United Kingdom (Neill *et al.*, 2017), France (Guillou *et al.*, 2018), Norway (Carpman & Thomas,

2016), the United States (Cowles *et al.*, 2017), Korea (Hwang & Jo, 2019), Iran (Radfar *et al.*, 2017), Malaysia.

Tidal current energy resource assessment can be of five types described below (O'Rourke *et al.*, 2010):

- i. Theoretical tidal current energy resource assessment, this type of assessment focuses on the evaluation of available tidal energy density. Available tidal current energy density is calculated based on the data about tidal current velocity provided through field surveys, global ocean circulation models and databases, or hydrographic surveys.
- ii. Technical tidal current energy resource assessment, this type of resource assessment considers the hindrances to theoretical assessment, these hindrances include the distance of the grid from the proposed location, velocity profile of tidal current at the site, design of the array of turbines, effect of the wake, the effect of turbulence on the performance of turbines, etc.
- iii. Practical tidal current resource assessment, this type of resource assessment is based on the technical assessment reports, and the further hindrances to the practicality of the tidal current site are included, such as restricted areas, tourist places, military restriction zones, ocean-going vessels route, water depths, frequency of peak velocities, areas of pipelines and networking cables installed beneath the sea, etc.
- iv. Accessible tidal current resource assessment, during this type of resource assessment, the hindrances that are encountered in the practical resource assessment

are evaluated thoroughly. These further hindrances can be due to environmental issues, energy policy of the particular country, ecological policies, etc.

- v. Viable tidal current resource assessment, which focuses to resolve the restrictions that occur during the accessible resource assessment. The main factors considered to resolve include installation costs, energy distribution, energy market, etc.

Tidal current energy resource assessment also considers assessing the potential site for the risks that are associated with the development of tidal current power plant. These risks are associated with the different aspects of tidal current power plants such as technical, industrial services, environmental and social acceptance, and financing matters, as summarized in Figure 2.5. The key components of tidal energy development that need the attention of the research community are to make the tidal energy converting devices reliable, survivable, and stable.

Nevertheless, a detailed understanding of the local tidal hydrodynamics of the tidal energy resource is crucial during the resource assessment. The magnitude of the tidal stream speed and the tidal amplitude depends upon the bathymetry at the site and the physical geography of the resource (Easton *et al.*, 2012). Hence if the hydrodynamic model for the particular energetic tidal source is coarse, a huge uncertainty may occur during the energy generation potential estimation. In this regard, a few studies have investigated the effect of local bathymetry in the strait on the current velocity, by taking the direct onsite measurements (Ramos *et al.*, 2014; Sanchez *et al.*, 2014). Therefore it is crucial to set up or develop the regional hydrodynamic models of the fine grid size so that the regional-scale hydrodynamic data can be obtained (Rourke *et al.*, 2010). The majority of the sites intended for the installation of TST are having a complicated velocity profile and the seabed topology, and a huge variation in the spatial as well as temporal velocity

distribution. The regional conditions are different from the ideal suitable condition for the installation and testing of TST (Evans *et al.*, 2015). The tidal energy developers depend upon the detailed understanding of the local hydrodynamics of the site, before deciding on the sea trial of the TST. Therefore it is important to characterize the tidal flow so that the uneven loading on the swept area of TST due to variable velocity profile can be quantified.



Figure 2.5: Potential risks associated with the development of tidal current energy technologies (Segura *et al.*, 2017)

2.3.3 Multi-Criteria Evaluation

The studies related to Multi-criteria Evaluation (MCE) are mainly focused on assessing and comparing the feasibility and sustainability of the energetic tidal energy sites and tidal current technologies. After completing the MCE, the most feasible tidal energy site is proposed as the tidal energy development site. There can be different factors involved during the MCE stage, many of which are site-specific. During the feasibility analysis of the tidal power development site, the majority of the studies are focused on the

size of the tidal turbine array and the tidal power plant. However, only some of them consider the other factors as well that are equally important during the feasibility analysis. Such other factors can be the distance to a local electrical grid, bathymetry at the site, marine or naval restricted areas, environmental constraints, and other hindrances (Marsh *et al.*, 2021). In this regard, the MCE approach considers all such factors, and an example of the process flow diagram of MCE is shown in Figure 2.6.

The site suitability index (SSI) is computed from the weightage of the importance of each factor. During the MCE methodology, the standard factors are also carefully taken into account to compute the SSI. Furthermore, the MCE is given importance in tidal power development because it serves as a benchmark during the decision-making process, while taking into account all crucial factors (Auguste *et al.*, 2020). The MCE methods are applied in several fields, but, only a few studies can be found for tidal energy site selection.

During the MCE assessment, the importance weightage of every factor is multiplied with the respective factor under consideration, and finally, all of them are summed to get the MCE assessment. Following are the common/key factors considered during MCE (Marsh *et al.*, 2021).

- i. Combined Renewable Energy Resources (CRES), which considers the importance weightage corresponding to the feasibility assessment of individual renewable energy resources. The common renewable energy resources considered during tidal energy MCE are tidal energy, wind energy, and wave energy potential. However, these resources are site-specific, if any site is feasible for other forms of renewable energy, such as Ocean Thermal Energy Conversion (OTEC), such resources may have a considerable weightage of importance in MCE.

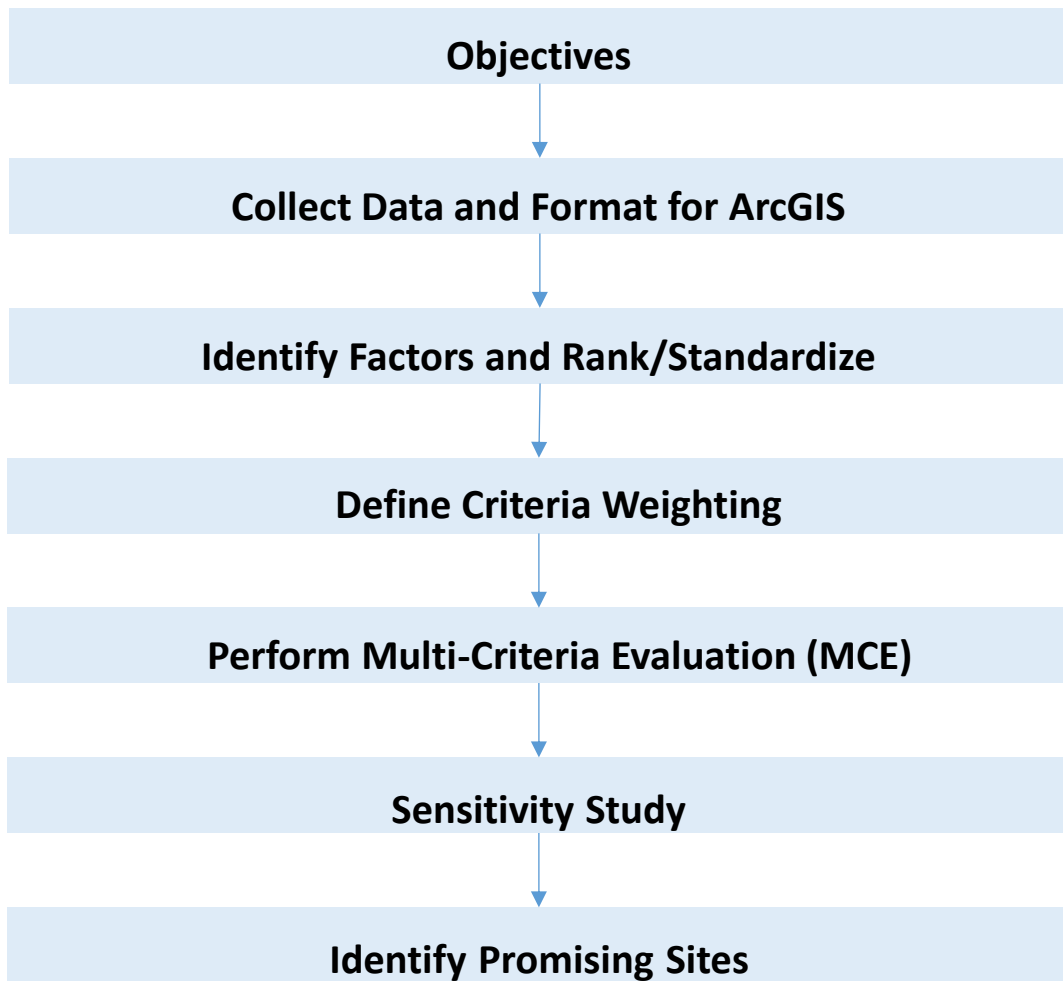


Figure 2.6: Process flow diagram for MCE methodology, adopted from Marsh *et al.* (2021)

- ii. Distance factor (s), during which the weightage of importance is calculated based on the feasibility of connecting to the other infrastructures. The connectivity of CRES sites is calculated based on the distance to the infrastructure and population where the energy demand is high. The common distances under consideration can be the distance to the power station, electrical transmission lines, ports, coastline, and population.

- iii. Other restrictions, considers any conflicts with the other users that are within the navigation routes to CRES. There can be other restrictions to the CRES locations such as the bathymetry and environmental concerns. The common restrictions are faced due to pre-existing infrastructure such as sub-sea pipelines.

It is worth mentioning that the key to an effective MCE is the identification of the site's relevant factors. One way of identifying the relevant factors is through meetings and workshops with the government bodies and stakeholders (Marsh *et al.*, 2021).

2.4 Hydrodynamic Modelling

Hydrodynamic modelling plays an important role in modelling the turbines for tidal stream energy harnessing before the real turbine can be installed at the site. It is also helpful to identify the areas of strong tidal currents within the energetic tidal energy site. The hydrodynamic modelling for tidal energy assessment can be done at several scales, these scales are described below:

- i. Blade Scale, in which the computational fluid dynamics (CFD) analysis is carried out on the blade of a tidal current turbine to get an optimized hydrodynamic shape. The main focus of the study at this scale is to evaluate the lift and drag properties of the turbine blade (Li *et al.*, 2016). More detail on the blade design of the tidal current turbine can be found in Li *et al.* (2016).
- ii. Turbine Scale, which focuses on the hydrodynamic behavior of an isolated tidal current turbine under variable flow conditions. It tends to get a hydrodynamically optimized configuration of the isolated tidal current turbine. This type of hydrodynamic study also investigates the flow augmentation techniques for getting an optimized turbine configuration (Cresswell *et al.*, 2015). The other aspects of the

turbine scale study can be related to the wake characteristics, rotor size and configuration, thrust load on the turbine, etc.

- iii. Array Scale, which mainly focuses on the resulting hydrodynamic effects of turbine interaction. The number of turbines is not fixed, as long as the focus is on the interaction between the turbines, the hydrodynamic scale will be called as array scale. An example of hydrodynamic modelling of a turbine array is shown in Figure 2.7, which evaluates the resultant tidal stream speed due to the presence of a different number of turbines (Orhan & Mayerle, 2020).

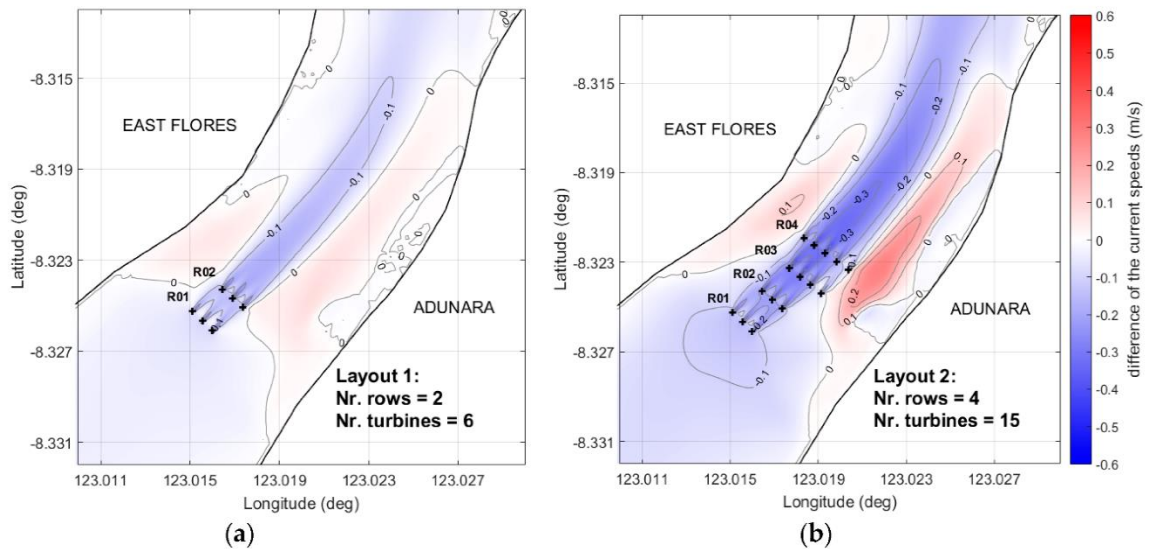


Figure 2.7: Array Scale hydrodynamic modelling for (a) 6 number of turbines (b) 15 number of turbines (Orhan & Mayerle, 2020)

- iv. Site Scale, which mainly focuses on the understanding of hydrodynamic characteristics of a particular site. The researchers intend to evaluate the flow, spatial and temporal tidal variation, and realistically readiness of the site for tidal power harnessing. The scope of this scale of hydrodynamic modelling also involves the modelling of the tidal flow and turbine interaction (Adcock *et al.*, 2015). An example of the site scale hydrodynamic modelling is shown in Figure 2.8, for the

case study of an energetic tidal strait Ramsey Sound in the United Kingdom (UK). That focuses to investigate the hindrances on extracting the tidal energy at the site. The flood and ebb-tidal stream velocities were evaluated to investigate the effect of seabed topology and the coastal boundary on flow speed (Evans *et al.*, 2015). It was concluded that the major physical bodies such as submerged huge rocks and the roughness of the coastal boundary are the major constraints for extracting the tidal power. The depth-wise flow was also evaluated considering the swept area of turbine.

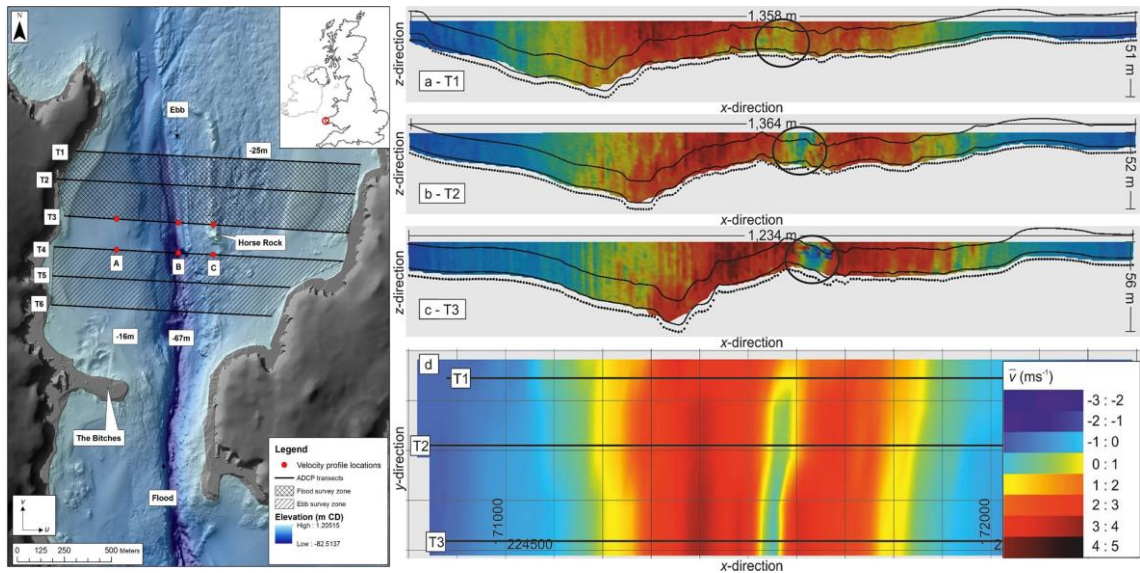


Figure 2.8: Hydrodynamic modelling of the site Ramsey Sound, a strait in the UK. The flow variation with depth is shown by a-T1, b-T2, and c-T3 for the crosssections T1, T2, and T3 in the map. The spatial variation of the flow for the farm T1-T3 in the map is shown by d, (Evans *et al.*, 2015)

- v. Regional Scale, which mainly covers a coastal region to study the magnitude and direction of the tidal currents how they are affected due to the geography, coastal geometry, and seabed frictional interaction. Furthermore, the scope of this scale of hydrodynamic modelling also includes studying the changes in tidal streamflow due to tidal farms, by assuming the array of the TCTs (Adcock *et al.*, 2015). The

purpose of regional-scale modelling remains to quantitate the likely impact on the natural environment due to the installation of tidal farms, and also to assess the resource potential for power generation. Regional-scale hydrodynamic modelling has three key aspects to be assessed. The first of that include deciding the best suitable hydrodynamic modelling tool and selection of 2D and 3D approach for that. The second aspect includes deciding on how to model the extraction of tidal energy, which usually follows the momentum sink approach (Auguste *et al.*, 2020). The third aspect is to finalize the extent of the hydrodynamic model.

2.5 Chapter Summary

This chapter has summarized the fundamentals of tidal stream energy generation and its historical scenario. The main focus of this chapter was to review the prospect of tidal stream energy in Malaysia. From the literature review, it was found that there is still a gap on tidal energy research in East Malaysia, especially Sarawak State. The findings from the literature review also conclude that the area near Triso Island can be studied further for tidal stream energy generation. Furthermore, the chapter also includes the focus on scales of tidal energy assessment and hydrodynamic modelling approaches used in tidal energy assessment. It was found that 2D hydrodynamic modelling approach is suitable to be used during pre-feasibility stage of tidal energy assessment. It can be concluded that the tidal energy study on Triso Island is classified in the pre-feasibility stage of tidal energy assessment, in which the local tidal hydrodynamics needs to be understood. Therefore in methodology chapter, 2D hydrodynamic model is constructed for the area in the vicinity of Triso Island. Lastly, it was also found during the literature review that the hydrodynamic modelling for tidal stream energy assessment is done using the Delft3D software.

Therefore, the Delft3D software is used in the methodology chapter for setting up the regional hydrodynamic model.

CHAPTER 3

METHODOLOGY

3.1 Overview

Tidal energy assessment deeply relies on the characterization of tides, and the understanding of the tidal hydrodynamics at the site. The scope of this thesis is related to tidal energy exploration in the Sarawak state of Malaysia, for which a hydrodynamic model has been constructed for Triso Island, which is known a macrotidal site in Sarawak. This chapter highlights the steps taken in setting up the hydrodynamic model, understanding the numerical aspects, and the physical and numerical parameters used in construction of the model.

3.2 Site Study

Connected to the South China sea, Triso Island is geographically located at latitude $1^{\circ} 31' 1'' 118 \text{ N}$ (1.517 degrees), and Longitude $110^{\circ} 58' 58'' \text{ E}$ (110.983 degrees). The Island is located at an elevation of 1 m above the mean sea level, at the river mouth of Batang Lupar in Sarawak. It is a place where ocean and fluvial waters mix. The river mouth of Batang Lupar represents a Strait, having Triso Island at its center, as shown in Figure 3.1. The strait starts diverging its width just before the Island, which starts from 3.5 km just before the Triso Island location, to a maximum width of 9.7 km. According to the information provided in Sarawak nautical chart SAR122, the water depth around the Triso Island typically ranges from 5 m to 12.1 m below the Chart Datum (CD). The coastline converges roughly to this Island, and this geometry of the coastline can result in accelerating the tidal stream flow towards this site. Apart from tidal energy generating site, the Island is planned to be a recreational activities destination for tourists.

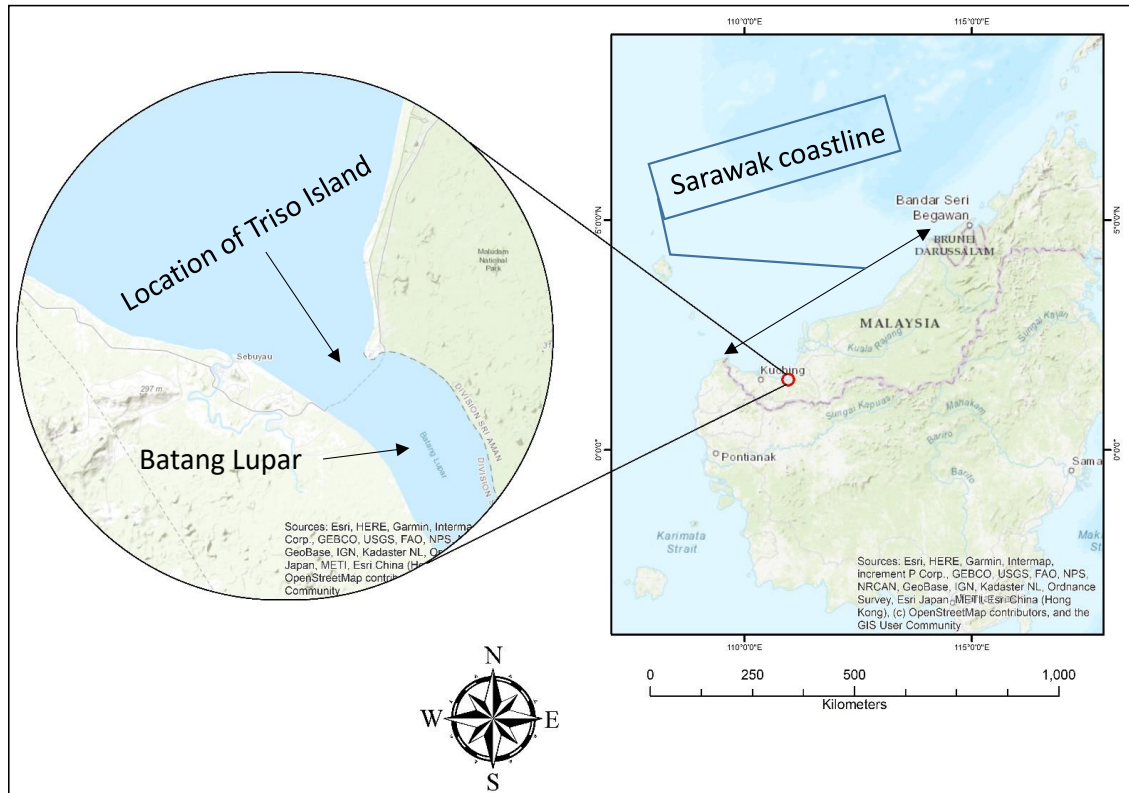


Figure 3.1: The location of Triso Island at the river mouth of Batang Lupar

The government is planning to construct a 5.1 km long bridge that will connect Triso Maludam-Pusa in Betong to Sebuyau in Samaraham, by the year 2025 (Bong & Bishop, 2021). This long bridge will facilitate the people to travel easily to both sides of the river, as well as providing a spot for tourists. Therefore, tidal energy generation at this site can be a green source option to provide sufficient electric power for the road light on this bridge and the nearby places/villages.

3.3 Hydrodynamic Model Description

The numerical application of Delft3D FLOW was used to set up the hydrodynamic model for Triso Island, to understand the tidal hydrodynamics. Delft3D is a package of finite difference code to solve the Navier-Stokes equations, considering the Boussinesq and shallow water assumptions (Lesser *et al.*, 2004). The Graphical User Interface (GUI)

of the Delft3D software is shown in Figure 3.2. The software Delft3D flow has been prepared by Delft Hydraulics, which is now an open-source software package freely available to all academic users (Deltares, 2021).

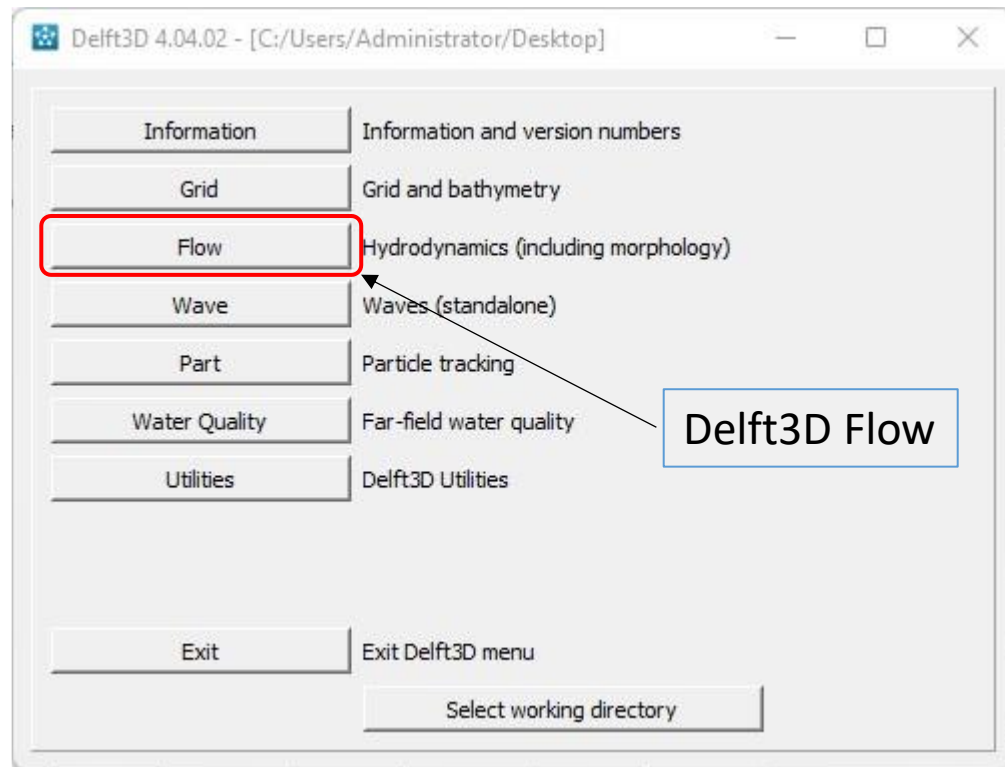


Figure 3.2: The Graphical User Interface (GUI) of the Delft3D software showing Delft3D FLOW module

The two important assumptions in Delft3d FLOW are that the grid is well structured and orthogonal. The specifications of variables in grid cells follow the Arakawa C-grid pattern (Martin-Short *et al.*, 2015). This pattern of arrangement for the variables of shallow water equations is illustrated in Figure 3.3. The velocity components are defined perpendicularly to each of the grid cell faces, while the pressure points or the water level points are specified at the center of the grid cell. The depth points are specified at the corners or node points within the Arakawa C-grid arrangement (Ramos & Iglesias, 2013).

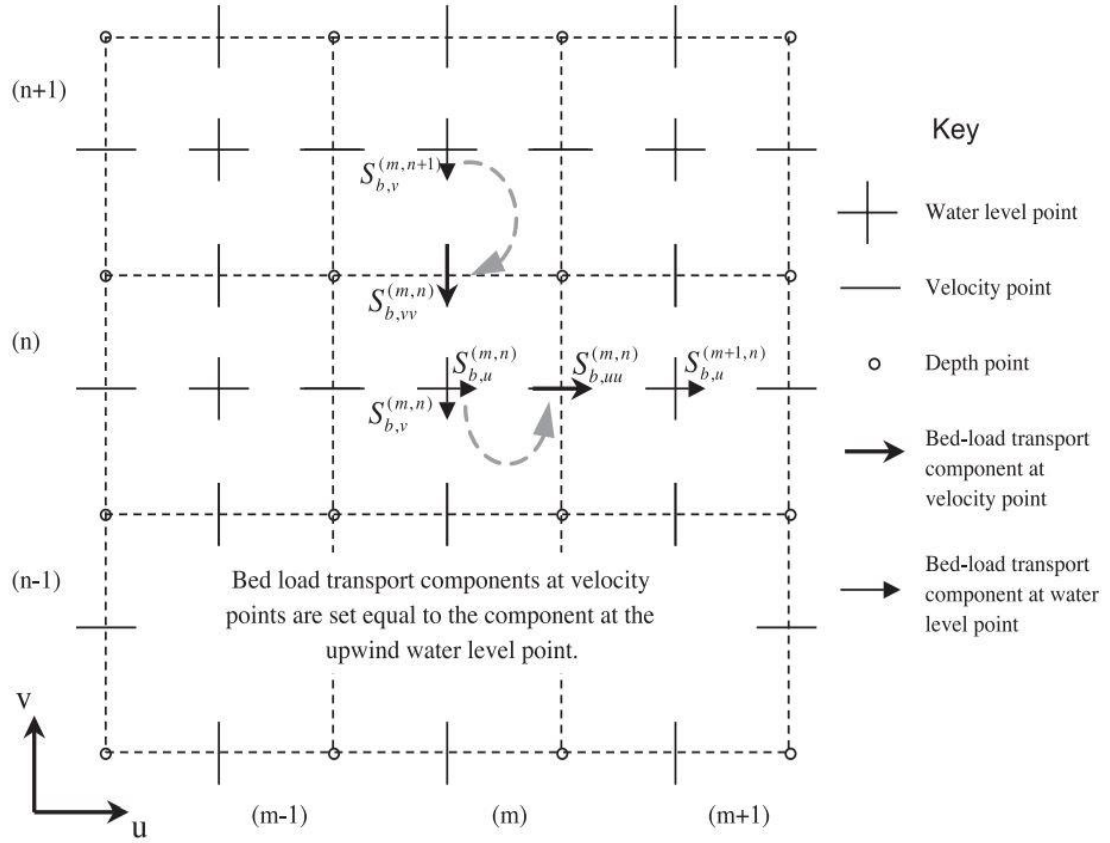


Figure 3.3: The Arakawa C-grid arrangement method of the variable, adopted by Delft3D FLOW to solve shallow water equations (Lesser *et al.*, 2004)

For the case study of Triso Island, where the flow usually has negligible vertical gradients, the depth-averaged numerical simulation model Delft3D FLOW stands as a sound application for the tidal hydrodynamic simulation. The software solves the shallow water equations, which were obtained by reducing the vertical momentum equation to hydrostatic pressure. The mass and momentum equations solved by Delft3D FLOW in the current model are given by the following Equation 3.1 and Equation 3.2, whereas the transport equation is given in Equation 3.3. The solution of problems associated with the salinity and temperature is computed by Equation 3.3. Another assumption in solving these equations by the Delft3D FLOW module is that the fluid is incompressible (Chatzirodou *et al.*, 2017).

$$\frac{\partial \zeta}{\partial t} + \frac{\partial [(d+\zeta)U]}{\partial x} + \frac{\partial [(d+\zeta)V]}{\partial y} = Q \quad \text{Equation 3.1}$$

$$\begin{aligned} \frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} - f \cdot V &= -g \frac{\partial \zeta}{\partial x} - \frac{g}{\rho_o} \int_{-d}^{\zeta} \frac{\partial \rho'}{\partial x} dz + \frac{\tau_{sx} - \tau_{bx}}{\rho_o \cdot (d+\zeta)} + v_h \nabla^2 U, \\ \frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} - f \cdot U &= -g \frac{\partial \zeta}{\partial y} - \frac{g}{\rho_o} \int_{-d}^{\zeta} \frac{\partial \rho'}{\partial y} dz + \frac{\tau_{sy} - \tau_{by}}{\rho_o \cdot (d+\zeta)} + v_h \nabla^2 V \end{aligned} \quad \text{Equation 3.2}$$

$$\frac{\partial (\zeta+d)c}{\partial t} + \frac{\partial [(d+\zeta)Uc]}{\partial x} + \frac{\partial [(d+\zeta)Vc]}{\partial y} = D_h \nabla^2 c - \lambda_d (d + \zeta)c + R \quad \text{Equation 3.3}$$

Where, ζ denoted water level, and “ d ” denoted reference plane related water depth. The eastward and northward components of vertically averaged velocities are represented by “ U ” and “ V ”, respectively. “ Q ” stands for mass source intensity per unit area, “ f ” for Coriolis parameter, and “ v_h ” horizontal eddy viscosity. “ ρ_o ” represents reference density and “ ρ' ” represents anomaly density. The wind stress components on the sea surface are represented by “ τ_{sx} ” and “ τ_{sy} ”, and the bottom shear stress components are represented by “ τ_{bx} ” and “ τ_{by} ”. The other symbols in transport Equation 3.3 are c : temperature or salinity, λ_d : first-order decay process, D_h : horizontal eddy diffusivity, and R : per unit area source term. Furthermore, the numerical stability of the simulation depends upon the computation time step adopted in the simulation.

3.4 Model Setup

The hydrodynamic model for Triso Island is set up by utilizing the numerical application of Delft3D. The process involved in data collection, data processing, model set up, analysis, and validation is illustrated in Figure 3.4. The data required to set up the model include land boundary for the study area, bathymetry data, and boundary condition data. The land boundary for the study area was obtained from the shapefile of Malaysia, which was then converted to land boundary data by the Delft3D QUICKPLOT module. There were two sources of bathymetry data for the study area, the General Bathymetric

Chart of the Oceans (GEBCO) database, and Sarawak nautical charts. The boundary conditions were set as time series and astronomical water levels, for which the data was extracted from the TPXO global tidal model. TPXO is a series of fully-global models of ocean tides, which best-fits, in a least-squares sense, the Laplace Tidal Equations and altimetry data.

Once the data is available and all of the required files are ready to set up the Delft3D model for Triso Island, the initial step of setting up the model was started with the Delft3D RFGRID module. In this module, the rectilinear grid was set up for the study of Triso Island, which was well structured and orthogonalized. After setting up the grid of desired resolution, the bathymetry data were interpolated to the grid by using the Delft3D QUICKIN module, by following the triangular interpolation and internal diffusion processes. At this stage, all of the files were ready to set up the flow simulation problem for the tides in the Delft3D FLOW module.

These files include the computational grid, grid enclosure, and depth files. In setting up the simulation problem, the time step, simulation computation period, numerical parameters such as Manning's Coefficient, horizontal eddy viscosity (HEV), boundary conditions, and open boundaries, and the observation points were specified in the Delft3D FLOW module. The output from this module was a .mdf file, which was ready to start the simulation. After the simulation was finished, the results were analyzed in the Delft3D QUICKPLOT module.

The time-series water level results were compared with the TPXO output, for the same location as the observation point in the model. The comparison with TPXO output was done by computing the Root Mean Square Error (RMSE) and Pearson's Correlation Coefficient (γ).

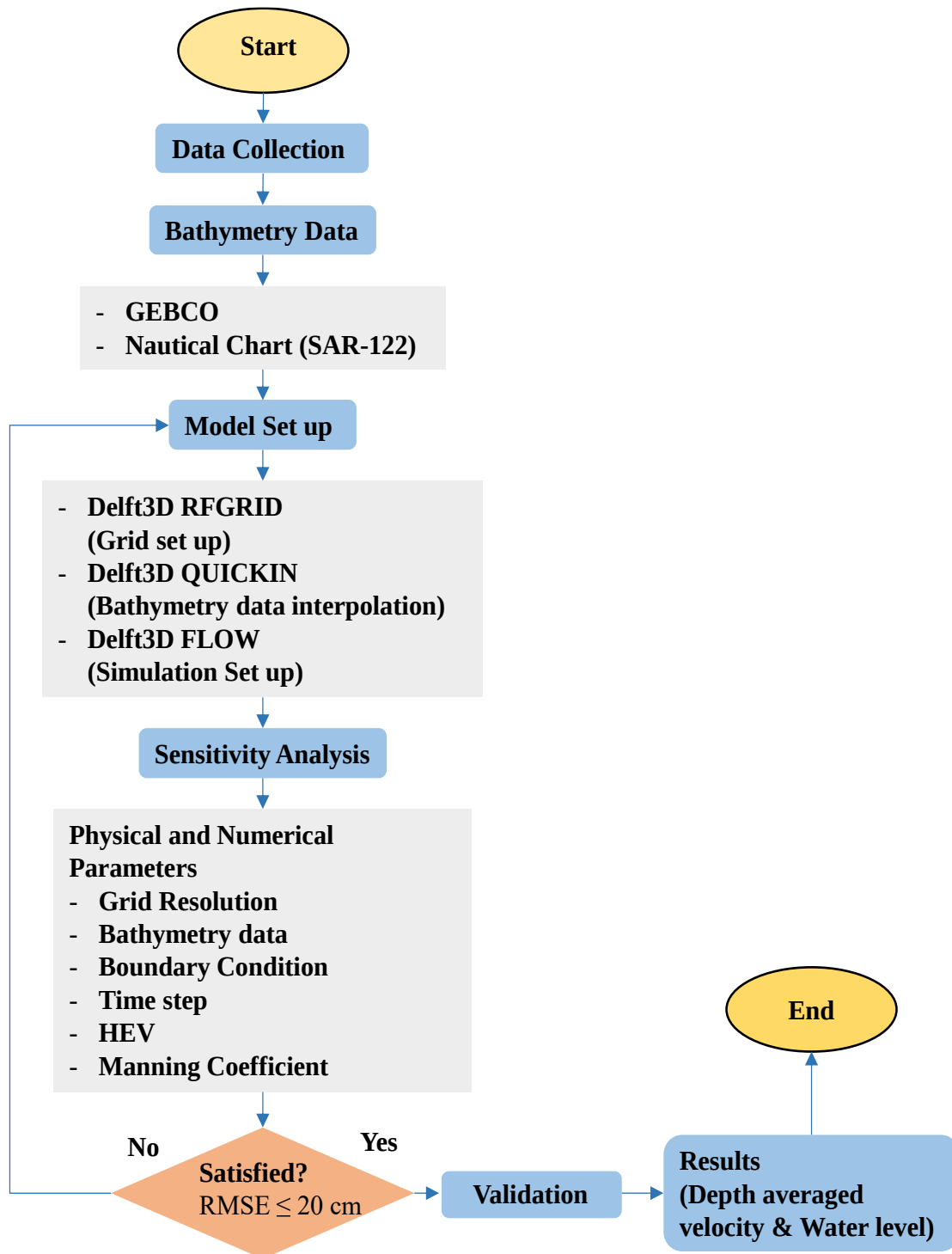


Figure 3.4: Process flow diagram

The sensitivity of the model was tested for all of the numerical and physical parameters, for which the simulation was repeated for each parameter and then compared

with TPXO output until satisfactory results have been achieved. The RMSE of 20 cm was set as a benchmark to indicate the satisfaction of the results.

3.5 Computational Grid

The computational grid used in Delft3D hydrodynamic modelling is Arakawa C-grid. The structural rectilinear grid was constructed for the area of interest (AOI) to set up the hydrodynamic model for Triso Island. The grid settings adopted to construct the computational grid is shown in Figure 3.5. The area covering the computational grid was wide enough and the open boundaries were placed sufficiently far from the Triso Island (AOI). In this way, any instability in the simulation at the open boundary will not affect the simulation results at AOI. The distance of the North open boundary from the Triso Island was up to 85 km, while the diagonal distance from the Triso Island to the North-West corner of the grid was about 100 km. The grid structure is shown in Figure 3.6 and the properties of the grid are listed in Table 3.1.

The main criteria while constructing the grid in the Delft3D RFGRID module are that the grid needs to be smooth, orthogonal, and fit closely to the land boundary. The quality of the construction is evaluated based on three criteria of orthogonality, smoothness, and aspect ratio. The orthogonality shows that the grid lines are intersecting perpendicularly. In the Delft3D RFGRID module, the orthogonality is measured by the cosine value at the center of each grid cell. It is recommended that at the inner grid cells, the orthogonality needs to be less than 0.04. While for the area out of interest within the domain, the values in the range of 0.05 to 0.10 can be accepted.

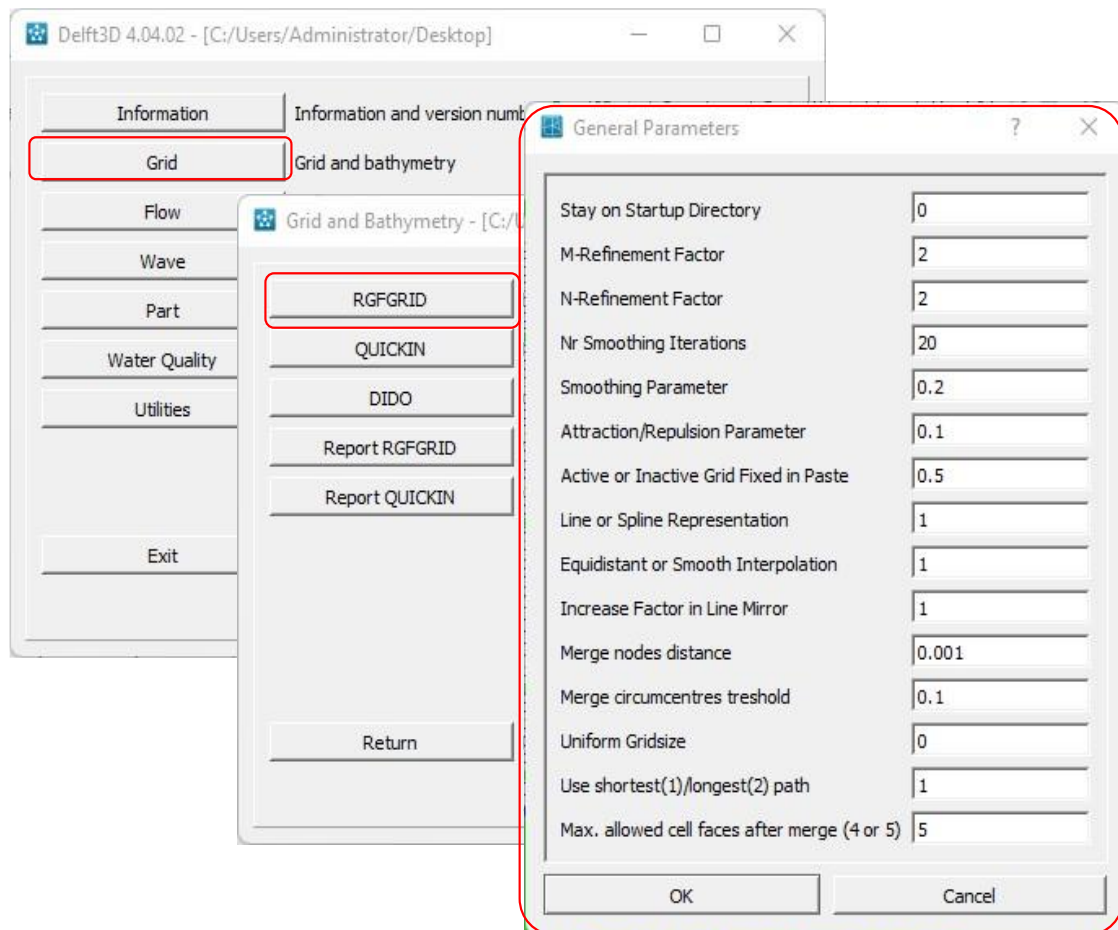


Figure 3.5: The grid settings adopted to refine and derefine the Computational Grid

The orthogonal values that are too small, may lead to encounter errors in the direction pressure gradient in FLOW while performing the simulation. The orthogonality value for the grid cells within the AOI in Figure 3.6 was in the range of 0.006 to 0.013, while only a few of the grid cells close to the land boundary had an orthogonality value up to 0.203. Nevertheless, this high orthogonality of the grid cells at the land boundary can be tolerated, as the purpose was to fit the land boundary and these grid cells were also not the focus of the study. The overall orthogonality of the grid was sufficient to maintain the quality of the grid.

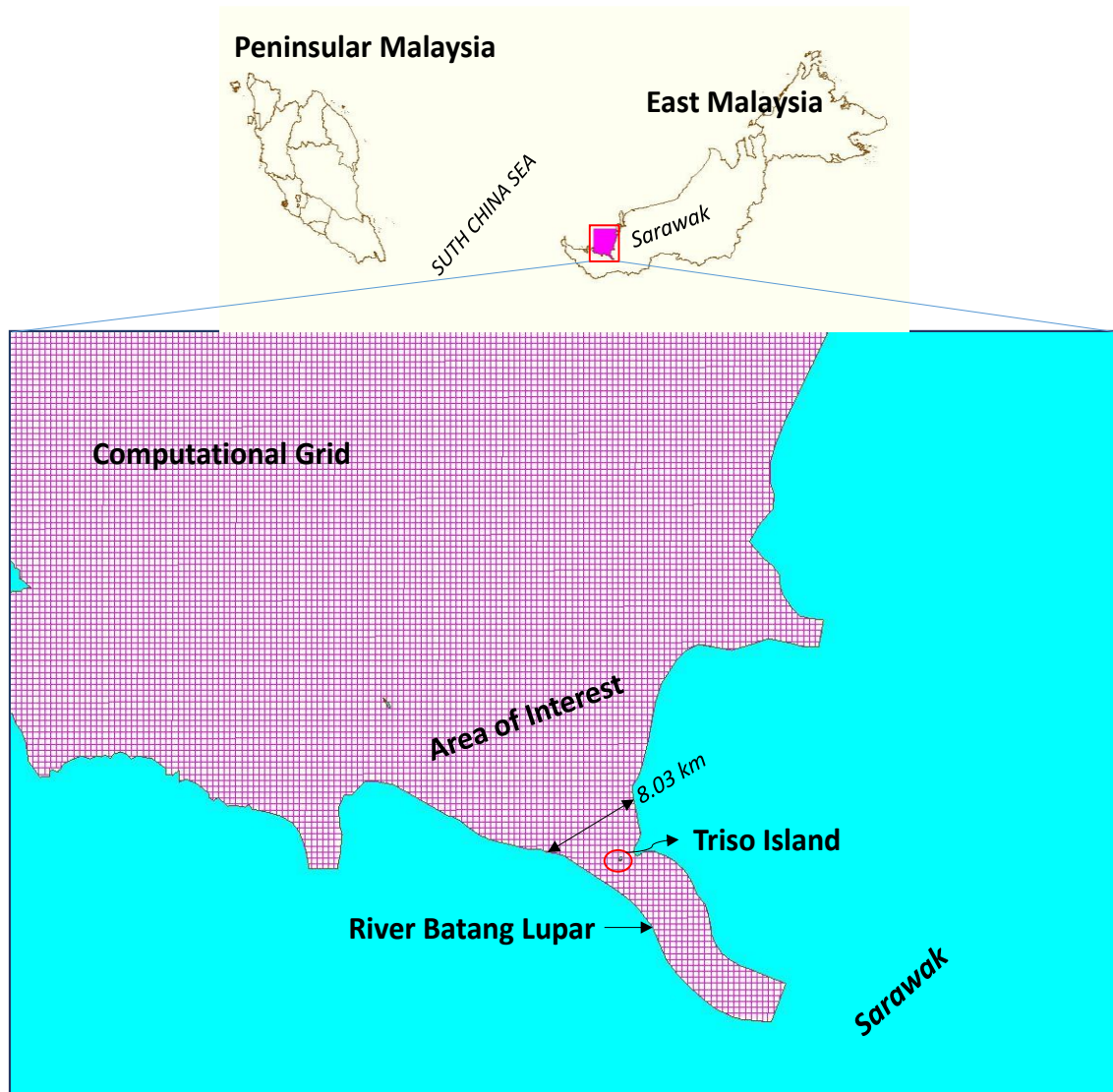


Figure 3.6: Computational Grid setup for the study area

The quality of the grid also depends upon the smooth change of grid spacing in the domain. In the Delft3D RFGRID module, it is computed from the ratio of neighbouring cell dimension in the computational grid domain. The value of smoothness should be not more than 1.1 for the area under focus. Furthermore, the aspect ratio (AR) is computed from the ratio of cell dimension in the M and N direction. The value of the AR in the range of 0.5 to 2 is considered suitable to maintain the quality of the computational grid. In the current grid, the AR value was maintained in the range of 1.00 to 1.006, for the grid cells in the AIO, as shown in Figure 3.6.

Table 3.1: Properties of the grid set up in the current model

No.	Parameter	Minimum Value	Maximum Value
i.	Resolution	215 m ²	604 m ²
ii.	Orthogonality	0.006	0.203
iii.	Aspect ratio	1.006	6.96
iv.	M Smoothness	1.11	5.48
v.	N Smoothness	1.10	5.62
vi.	No. of grid cells in M-direction		174
vii.	No. of grid cells in N-direction		198
viii.	Grid elements		23187

3.6 Bathymetry

There were two sources of bathymetry data available to be used in setting up the model. The one of which was to download the bathymetry data from the GEBCO database (*GEBCO - The General Bathymetric Chart of the Oceans*, n.d.), and the second source was to get the Sarawak Nautical charts from the Sarawak Marine Department (SMD) in Kuching city. The data acquired from both sources were not in the form or ready to be used in the Delft3D QUICKIN module, therefore some processing was done to convert it into the format that can be imported into the module.

The bathymetry data for the Triso Island model area was acquired from both sources, and both the sources were utilized as independent and combined in the sensitivity analysis stage, as illustrated in Figure 3.7. The data available from the GEBCO database was extracted from the latest available dataset, called the GEBCO_2021 Grid. This is a global terrain model for both oceans as well as land, that provides the data about elevation (in meters). The elevation data is available at the interval of a 15 arc-second grid.

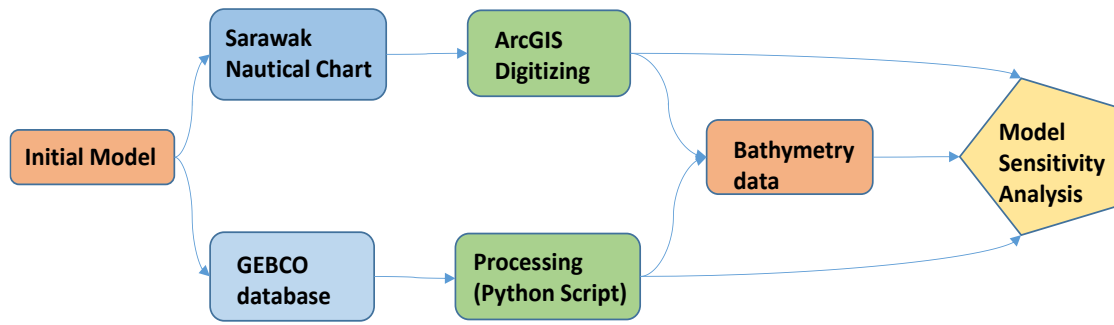


Figure 3.7: Process flow diagram of bathymetry data acquisition

The data was directly downloaded from the database, and it was converted to the Delft3D QUICKIN format by a python script. Another source of bathymetry data is the Sarawak nautical Charts, in particular, two charts were collected from SMD in Kuching city, namely SAR122 and SAR13. Both the charts were sufficient to provide the bathymetry data for the study area. However, the nautical charts obtained from the SMD were in printed paper format. Therefore processing needs to be done to obtain the information from these charts, and then convert it into the file format that can be acceptable in the Delft3D QUICKIN module. For this purpose, the nautical charts were scanned and imported into ArcMap to digitize them.

In the initial step, the charts were georeferenced to accurately match the coordinates. Then the point shapefile was created for each of the data points on the nautical charts. The point shapefiles were assigned the respective depth value as available on the nautical charts. In this way, the paper-printed nautical charts were digitized and the extracted data was converted in the three-column matrix, to import into the Delft3D QUICKIN module for interpolation. The combined bathymetry from both sources is shown in Figure 3.8, which represents the computational domain.

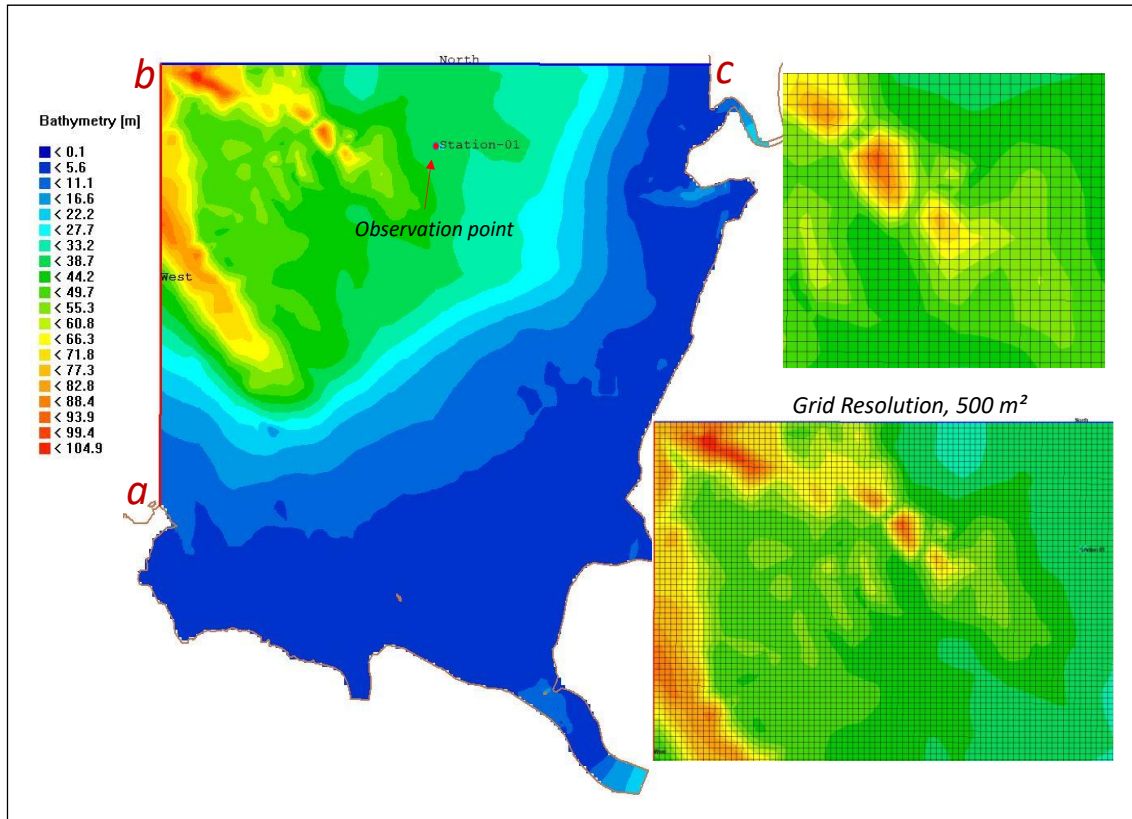


Figure 3.8: Bathymetry in the computational domain

It can be noted that the deepwater area is available at the North-West side of the domain (i.e near point b in Figure 3.8), the seawater at this area is up to 100 m deep. However, the seawater depth at the AOI ranges between 10 to 20 m. There is also a shallow water area available ahead of the AOI.

3.7 Boundary Conditions

The boundary conditions are important in any of the hydrodynamic modelling. It is important to consider that the boundaries specified in a hydrodynamic model affect the simulation result. There are three main boundary types that are initiated in Delft3D FLOW hydrodynamic modelling for tidal energy assessment, including time-series water level, time-series tidal current, and astronomical tidal constitutes (Ramos *et al.*, 2019). Introducing the boundary data at open boundaries to initiate the simulation in Delft3D

hydrodynamic modelling is case-sensitive (Edwards *et al.*, 2011). The sensitivity of the model in this study is tested for all of these three boundary types as illustrated in. The other type of boundary conditions introduced as time-series, astronomic, or harmonic available in the Delft3D FLOW module include water level, current, discharge, Neumann, and Riemann.

The data for boundary conditions can be extracted from the global model, on-field survey, acoustic doppler current profiler (ADCP), or from the marine department of the respective country. These are different types of tidal data which include data about tidal current speed and water level. These data are used as inputs to set the boundary conditions in the simulation. The result may vary depending upon the source from which data is collected. Therefore, the regional model must be calibrated and undergo the sensitivity test to determine the suitable location and type of boundary in a regional hydrodynamic model. The boundary condition data is defined at the open boundaries of the model to initiate the simulation. The current model has two open boundaries that are connected to the South China Sea, as indicated in Figure 3.8. One of these open boundaries is named West and the other as North. Both the open boundaries are sufficiently far from the AOI so that the instabilities at the open boundary can not affect the results at AOI.

The tidal forcing at the open boundaries is selected as elevation and the initial condition is selected as null free surface elevation. The large-scale ocean circulation effect is included by the time series boundary conditions at the open boundaries, i.e western and northern boundary in Figure 3.8. The hourly time series data for water level boundary conditions are generated by OSUTOPEX/POSEIDON Crossover database (TPXO 9.2) by the Tide Model Driver (TMD) Matlab version, which is the database for the properties of global tides (Padman & Erofeeva, 2005). The database is established by the Oregon State University Tidal Inversion Software Package (OTIS), in which Laplace Tidal equations

are applied to the Ocean data acquired from the satellites, namely TOPEX/Poseidon and Jason (Egbert & Erofeeva, 2002).

The boundary condition data is interpolated at the begin point and endpoints of each open boundary, and then the data is linearly interpolated between both the points. The boundary condition data interpolated at the open boundaries are presented in Figure 3.9, in which the water level is extracted considering the major tidal constituents of semidiurnal tides (i.e M2, S2, K2, N2) and diurnal tides (i.e K1, O1, P1, Q).

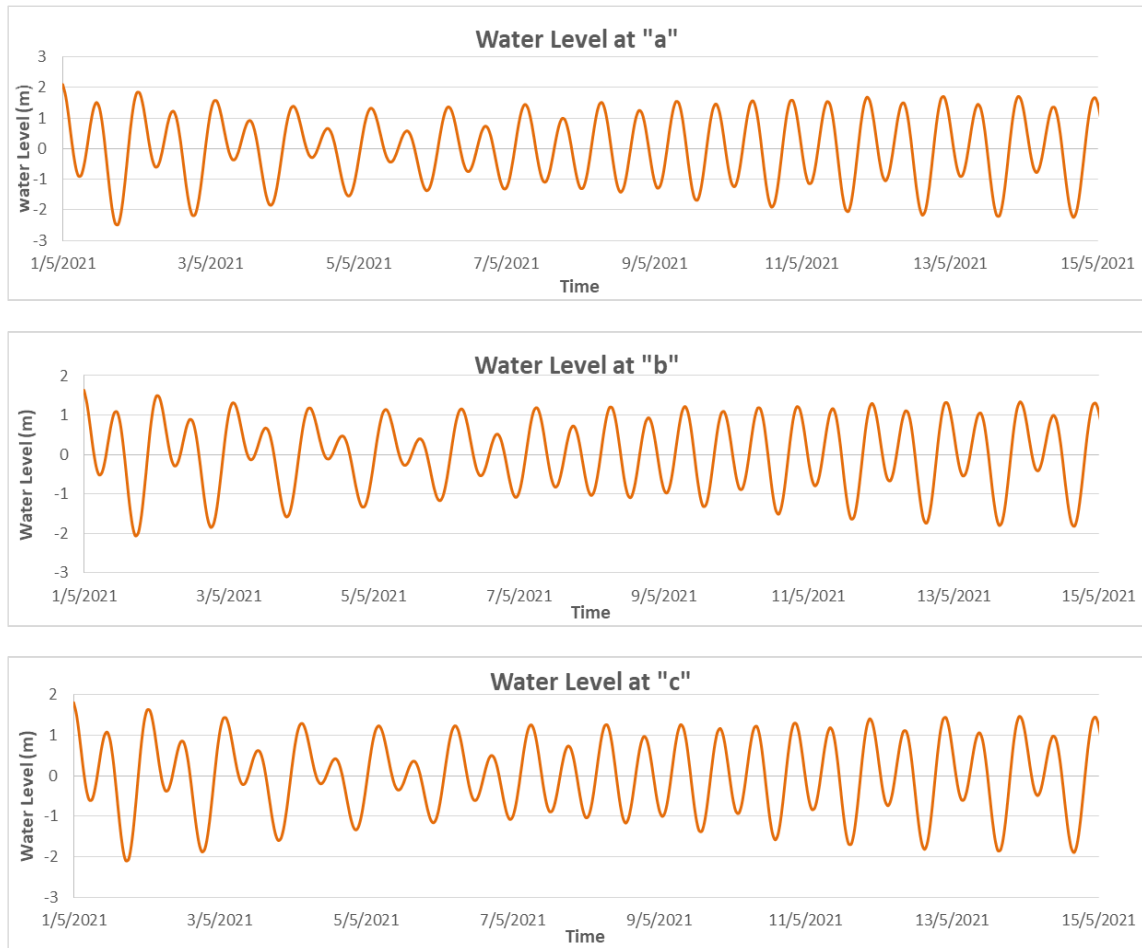


Figure 3.9: Hourly time-series water level data interpolated as boundary conditions at open boundaries

3.8 Time Step

The solver for the shallow water equation has to be made suitable for time-dependent problems and need to be computationally efficient. There are some limitations set for the numerical parameters. One of such limitations is set for the time step integration in shallow water equations. The current solution method follows the Alternating Direction Implicit (ADI) method, and the mode of the solution following the ADI method is barotropic (Deltares, 2021). Therefore, in Delft3D, the accuracy for this model is ensured by the Courant Friedrichs Lewy (CFL) criteria, for which the limit is set as $4\sqrt{2}$, and this is defined by the following Equation 3.4 (Courant *et al.*, 1928).

$$C_{r-tide} = 2\Delta t \sqrt{gh} \sqrt{\left(\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2}\right)} < 4\sqrt{2} \quad \text{Equation 3.4}$$

Where, the Δx and Δy show the smallest distances of grid cells (i.e grid resolution), g stands for the gravitational acceleration, h shows the depth at respective grid cell, and Δt is the time step adopted to integrate into shallow water equations. Furthermore, the limitations set in the Delft3D solver code to ensure accuracy and stability also depend upon the application scale, i.e length scale, velocity scale, inclusion or exclusion of density coupling, etc (Deltares, 2021).

3.9 Tidal Energy Density

The TSTs follow the same mechanism for energy extraction as wind turbines harness the kinetic energy of wind for power generation. The majority of TSTs are lift-based because their power generation efficiency is comparatively higher. While considering the minimum tidal current velocity and the shallow water areas, the drag-driven TSTs are more suitable. Although the TSTs operate at lower rpm when compared with the wind turbine, still the higher density of seawater enables them to generate same

power. The TSTs can operate up to 11 rpm under extreme conditions, at the same time the wind turbines can operate between 30 to 60 rpm (*How Does a Wind Turbine Work?*, 2019). Furthermore, the operational hazards of TST due to the over-speed rotation under extreme are also minimum. However, the higher seawater density increases the effect on the durability of the turbine (Roberts *et al.*, 2016).

The maximum theoretical power that a TST can potentially generate depends upon the kinetic energy of the seawater available to the turbine rotor (i.e swept area), it can be computed from the momentum theory defined by the following Equation 3.5.

$$P(x, y) = \frac{1}{2} \rho(x, y) \cdot A \cdot V(x, y)^3 \quad \text{Equation 3.5}$$

Where, P shows the power generated by the turbine from an undisturbed upstream tidal velocity at a given position (x, y) , ρ is the seawater density at the same position (x, y) , in this study, the density is assumed to be 1025 kg/m^3 , A is the swept area of the turbine, and V is the magnitude of tidal current velocity at the turbine position (x, y) . The tidal current velocity obtained from the Delft3D is depth-averaged velocity results.

Furthermore, Equation 3.5 defines the generic theoretical power that a turbine can generate, whereas the actual theatrical power generated by the turbine depends upon the turbine parameters and its capability to generate power efficiently.

Using Equation 3.5 for estimating the energy density will overestimate the results. Therefore the Average Power Density (APD) is utilized to compute the energy density available at the particular site during the tidal energy assessment (Mestres *et al.*, 2019). The APD can be defined as the available kinetic energy for generating tidal power from a 1 m^2 area and averaged for the representative time period. The representative time period

during tidal energy assessment can be considered as the time period of the full tidal cycle. The APD can be computed by using the following Equation 3.6.

$$APD(x, y) = \frac{1}{2} \frac{1}{N} \sum_{i=1}^N \rho(x, y) \cdot A \cdot V_i(x, y)^3 \quad \text{Equation 3.6}$$

Where, the term $V_i (i = 1, 2, 3, \dots, N)$ shows the tidal current velocity at time intervals of $t_i (i = 1, 2, 3, \dots, N)$, and N shows the number of data values (i.e hourly data) during the tidal cycle. During the current study, the $V_i (i = 1, 2, 3, \dots, N)$ are taken as the discrete-time series values of depth-averaged velocity obtained from the Delft3D simulation results.

Moreover, the losses occurring during the energy generation and energy transmission processes also need to be considered. In this way, the power generation computation based on Equation 3.5 and Equation 3.6 will be always lower than the power generated by an actual operational turbine. In configuring this additional loss, another term as Power Coefficient (C_p) can be added in Equation 3.6. The value of C_p depends upon the performance of the individual turbine that is considered for installation. It helps in the estimation of effective power generated by the tidal turbines, defined by following Equation 3.7.

$$APD(x, y) = \frac{1}{2} \frac{1}{N} \sum_{i=1}^N \rho(x, y) \cdot A \cdot V_i(x, y)^3 \quad \text{Equation 3.7}$$

Where C_p configures the loss of energy from the theoretical available power density. Each turbine has an individual for generating the power, as configured by its efficiency. The C_p of the turbine also ranges individually, while considering the individual turbine for tidal energy assessment studies the C_p value ranges between 0.3 to 0.5 (Mestres *et al.*, 2019). As the scope of this study covers the available tidal energy density, therefore for this purpose, the value of C_p is selected as 1. A similar value is also selected by other

researchers when computing the energy density (Carballo *et al.*, 2009; Mestres *et al.*, 2019).

The loss of energy from the maximum available theoretical power depends upon several factors that reduce the efficiency of the tidal current turbine. Nevertheless, the energy generated by the tidal current turbine is directly proportional to the cube of tidal current velocity at the turbine swept area. There is a velocity limit for power generation for the tidal turbines, as the turbines are designed at certain cutin and cutoff speeds. Therefore the turbine will not generate power if the velocity is too low or too strong.

There is also a theoretical limit to the maximum energy generation capability of the TSTs. According to Betz Limit, the maximum efficiency of an actuator disc can be 59.3%, while the efficiency increases by increasing the number of discs. For the double actuator discs, as in the case of cross-flow tidal stream turbine, the corresponding limit is 64.0%, whereas the general limit for the multiple discs is 66.6% (Newman, 1983, 1986; Roberts *et al.*, 2016).

3.10 Chapter Summary

This chapter focuses on the methodology adopted in setting up the Delft3D hydrodynamic model for Triso Island. In the initial part of this chapter, the location and geographical characteristics of the site are studied. Afterward, the steps taken in setting up the model are described and illustrated by the process flow diagram. The key steps in setting up the model are discussed in detail such as the data required to set up the model, processing of the data, and setting up the boundary conditions. The method to ensure the satisfactory performance of the hydrodynamic model follows the sensitivity analysis of the numerical and physical parameters described in this chapter. The chapter ends by describing the method for computing the tidal power density.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Overview

The site-specific regional Delft3D hydrodynamic model was set up for the Triso Island, to characterize the site for tidal power generation. This chapter presents the results of the hydrodynamic model and discusses the main outcome. The results of the sensitivity analysis for the numerical and physical parameters are discussed. The stability of the model is ensured by validating it with TPXO output results, as discussed in the validation section of this chapter. And finally, the simulation results are presented based on depth-averaged velocity and the available kinetic energy flux.

4.2 Model Sensitivity Analysis

To check the stability of the regional model set up for Triso Island, the sensitivity analysis was carried out for its physical and numerical parameters. During the sensitivity test, the parameters considered to optimize the stability model include the type of bathymetry data, grid resolution of the domain, time step, value of Manning's coefficient, and the effect of horizontal eddy viscosity (HEV). The sensitivity analysis was carried out based on the comparison between the simulation results and TPXO output data. The agreement between both the results was ensured by calculating the Root Mean Square Error (RMSE) and Pearson's Correlation Coefficient (γ), based on Equation 4.1 and Equation 4.2, as adopted by Orhan and Mayerle (2020).

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (X_{obs,i} - X_{model,i})^2}{n}} \quad \text{Equation 4.1}$$

$$\gamma = \frac{\sum_{i=1}^n (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^n (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^n (P_i - \bar{P})^2}} \quad \text{Equation 4.2}$$

4.2.1 Comparison of Bathymetry data from GEBCO and SMD

The bathymetry data were interpolated in the computation grid by following the triangular interpolation method and internal diffusion in Delft3D RFGRID. There were two sources for getting the bathymetry data, one from the GEBCO database and the other from nautical charts provided by Sarawak Marine Department namely SAR 13 and SAR122. The nautical charts provided by SMD were in the printed paper format, therefore processing was done in ArcGIS to digitize the maps. The data from the GEBCO database was directly extracted from the database and converted to depth format by a python script. The model was run by interpolating the bathymetry data from both of these sources as individual and as combined. The effect of bathymetry was then analyzed by comparing the water level results of simulation and TPXO database to evaluate the effect of bathymetry data type. The simulation result were exported using Delft3D QUICKPLOT module, as illustrated in Figure 4.1. The comparison is shown in Figure 4.2.

It can be clearly seen from the comparison of hourly time series results that the type of bathymetry data does not have much effect on the model performance. The RMSE value was the same as 0.15 m when the bathymetry was used as combined and from the Sarawak charts as alone. Whereas the RMSE was 0.12 m when the bathymetry was selected from the GEBCO database. However, the γ value during all of the three scenarios was 0.99. Although during all of the three scenarios, the model performance was within acceptable limits, the bathymetry data was selected from the Sarawak Nautical charts (i.e SAR13 and SAR122).

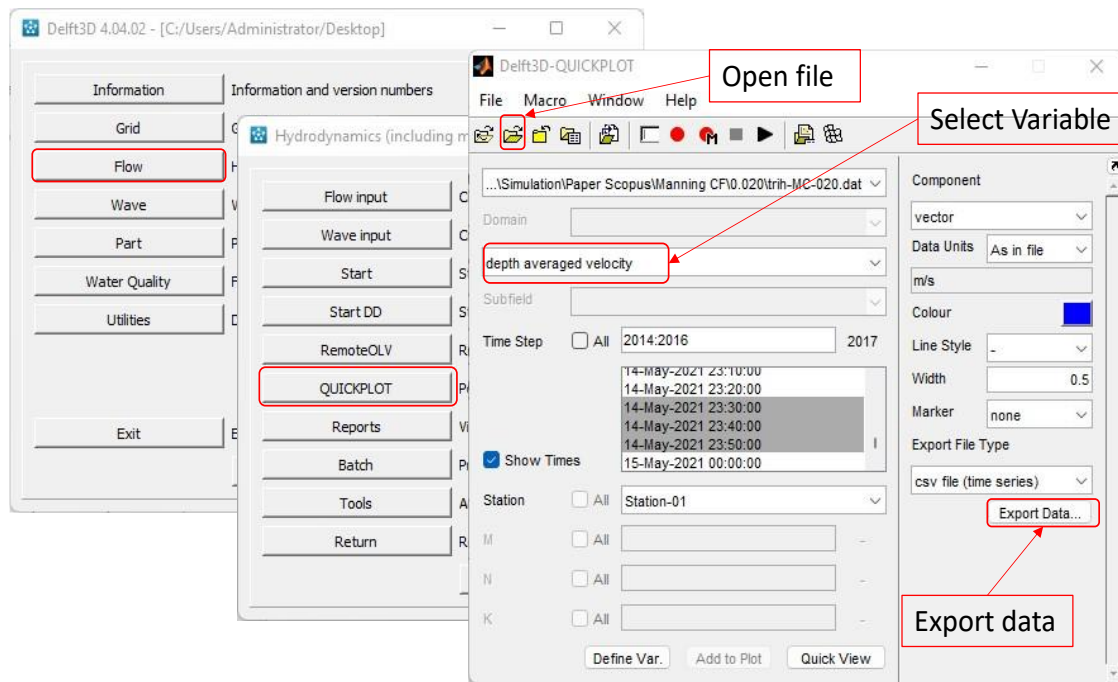


Figure 4.1: The GUI of Delft3D QUICKPLOT explaining the process of extracting the temporal results

This is because the bathymetry in the nautical charts is more site-specific and data presented in these charts are also from the survey conducted by SMD Kuching. The comparison of spatial changes in depth averaged velocity for both the bathymetry data types is shown in Figure 4.3, for the same time. It can be clearly seen that the result of depth averaged velocity is smoother when the bathymetry data is included from SAR maps. In the bathymetry data exported from the GEBCO database, some points within the domain appear as land, and this also affects the simulation results. The wake is created due to these data points and the simulation result is not smooth. Therefore, bathymetry data from the Sarawak nautical charts SAR13 and SAR122 was selected in the model.

4.2.2 Effect of Grid Resolution

The Delft3D has a separate module called RFGRID to set up the grid and the computation domain. The grid set up in this module is rectilinear and well structured.

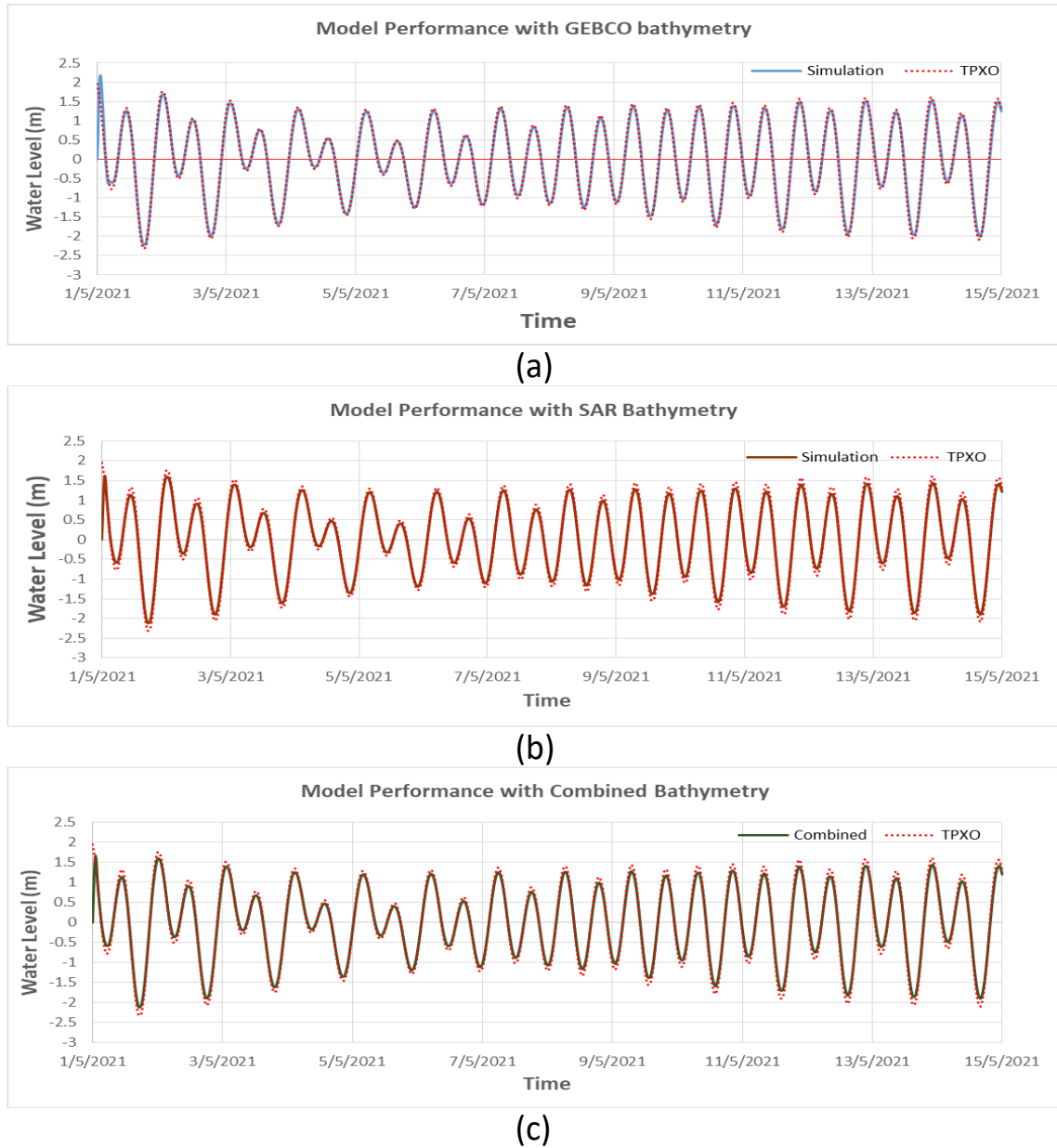


Figure 4.2: Effect of Bathymetry data type on the performance of the model (a) GEBCO bathymetry data, (b) SAR Maps bathymetry data, and (c) Combined data

Therefore extra care was put while constructing the grid to maximize the orthogonality. However, the sensitivity of the model was analyzed for the grid resolution. The effect of grid resolution was checked for the resolution of 1000 m^2 , 500 m^2 , and 250 m^2 . The splines, grid, and settings adopted in grid refinement are shown in Figure 4.4.

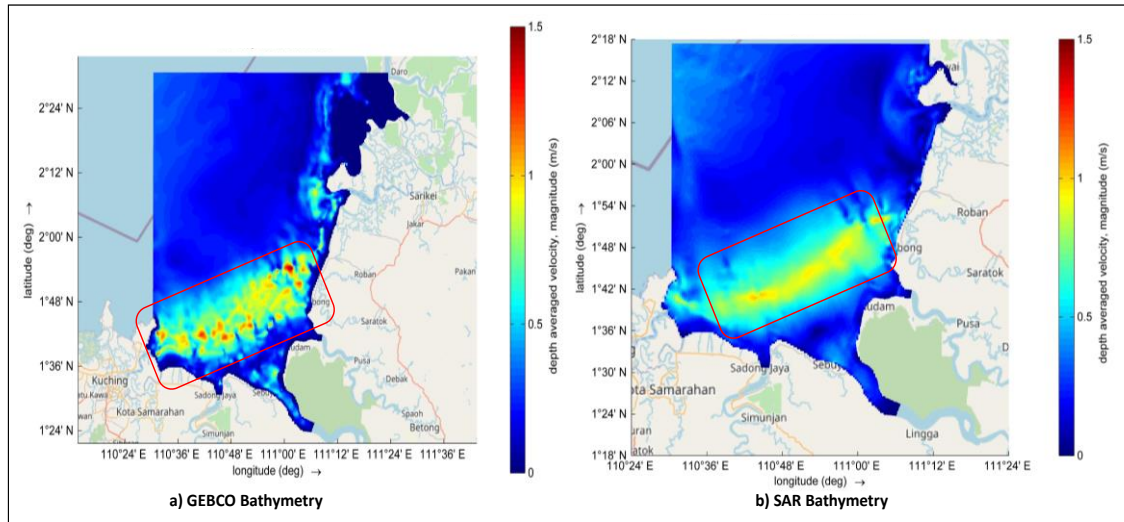


Figure 4.3: Simulation result of depth averaged velocity (m/s) for the bathymetry data type of (a) GEBCO and (b) SAR maps

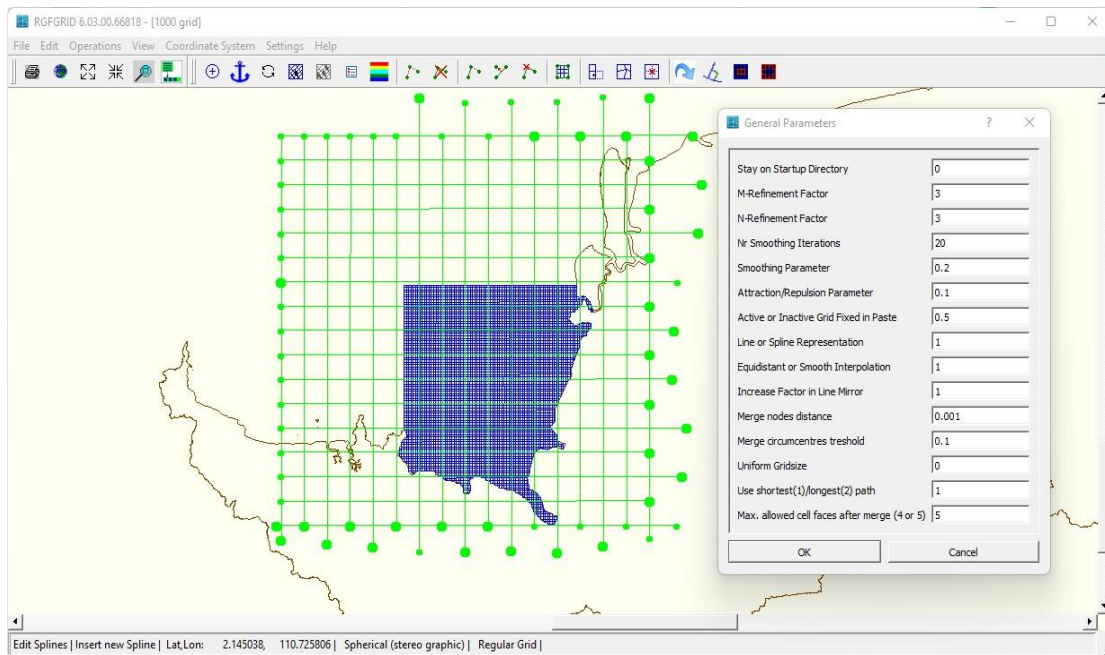


Figure 4.4: The splines used for grid construction and the setting adopted in grid reinement

During each of the grid resolutions, the orthogonality, aspect ratio, and smoothness were well maintained, as mentioned in Table 3.1. The initial test was carried out for the grid resolution of 500 m², and then the grid was refined and derefined by the factor of 2 in

the RFGRID module. The grid resolution of 500 m² was decided by following the grid construction approach of Goh *et al.* (2020).

The simulation result and comparison with the TPXO result at variable grid resolution for all three scenarios are presented in Figure 4.5. The model did not show much difference for the grid resolution of 500 m² and 1000 m², under both the scenarios, the model had also a good accuracy with an RMSE value of 0.15 m and γ value of 0.99. However for the senario of 250 m², the RMSE value was a bit higher than the acceptable value, which was 0.22 m and the γ value was 0.97.

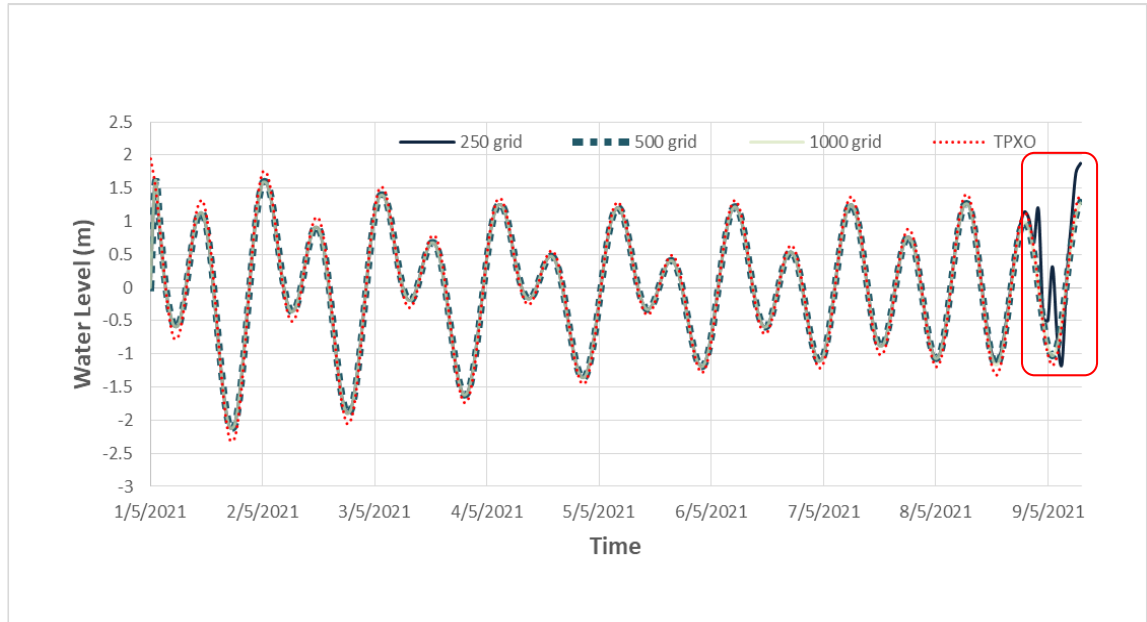


Figure 4.5: Model performance at a variable grid resolution of 250 m², 500 m², and 1000 m²

The temporal performance of the model is not stable for the grid resolution of 250 m², as shown in Figure 4.5. The courant number for the 250 m² scenario was also above the threshold limit of $4\sqrt{2}$, as defined in Equation 3.4. Whereas, although the performance of the model for grid resolution of 1000 m² was within the acceptable limits, the grid cell

size was too coarse in this scenario. Therefore the grid resolution for the computational domain was maintained at 500 m², this is shown in Figure 3.6 as well as in Figure 3.8.

4.2.3 Time Step

During the sensitivity analysis, the effect of time step was also evaluated for three scenarios of setting time step 0.25 minutes (15 sec), 0.5 minutes (30 sec), and 1 minute (60 sec). The time-series analysis of the obtained results did not show much difference due to the change of time step. The model showed the same performance under all three time steps, having the same value of RMSE as 0.15 m, and the value of γ as 0.99. Therefore the default time step of 1 minute was selected during simulation.

4.2.4 Effect of Manning Coefficient

In the Delft3D model setup for the Triso Island, the bottom roughness was computed by selecting the Manning's coefficient. The Manning's coefficient selected in the computation domain characterizes the magnitude of shear stress, exerted by the terrain or vegetation. It is defined by the following Equation 4.3 (Deltares, 2021).

$$n = \frac{H^{1/6}}{c} \quad \text{Equation 4.3}$$

Where, n stands for manning coefficient ($m^{-1/3} \cdot s$), the value of n depends upon the water depth H . A typical Manning's coefficient value is utilized as 0.02 ($m^{-1/3} \cdot s$), whereas this model was tested for the Manning's coefficient between 0.020 to 0.028 ($m^{-1/3} \cdot s$). The temporal analysis is shown in Figure 4.6 and the performance of the model is presented in Table 4.1.

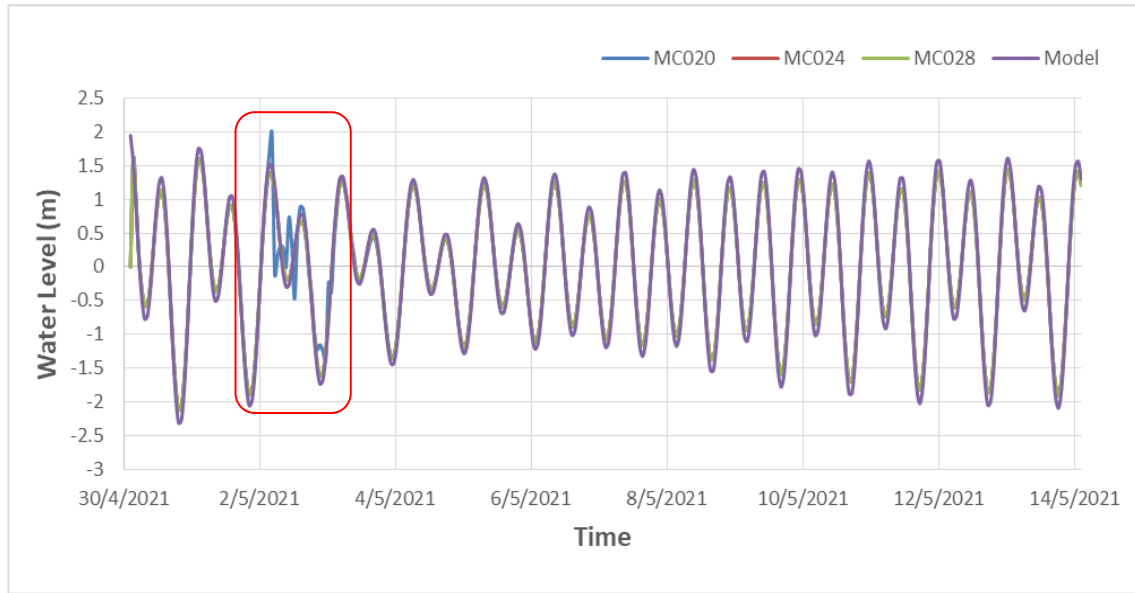


Figure 4.6: Model performance at a variable manning coefficient of 0.020, 0.024, and 0.028 ($m^{-1/3} \cdot s$)

Table 4.1: Performance of the model based on variable manning coefficient

No.	Manning Coefficient	RMSE	γ Value
i.	0.020	0.195	0.98
ii.	0.024	0.15	0.99
iii.	0.028	0.151	0.99

Some instability in the simulation results were observed in the starting of simulation for the Manning's coefficient of 0.020 ($m^{-1/3} \cdot s$), as shown in Figure 4.6, having the RMSE value of 0.195 m and γ value of 0.98. While the simulation has a good agreement with TPXO output data at the Manning's coefficient of 0.024 ($m^{-1/3} \cdot s$) with RMSE error of 0.15 m and the γ value of 0.99. However, the results were slightly underperformance at a Manning's coefficient of 0.028 ($m^{-1/3} \cdot s$), having RMSE error 0.151 m of and the gamma value of 0.99. Therefore, it was decided to choose the Manning's coefficient of 0.025 ($m^{-1/3} \cdot s$) for the Triso Island hydrodynamic model. The

Manning's coefficient of $0.025 (m^{-1/3} \cdot s)$ have been used by other researchers, and since it was very much closed to $0.024 (m^{-1/3} \cdot s)$, therefore it was chosen in this study (Goh *et al.*, 2020). Furthermore, the upper limit for the Manning's coefficient in the Delft3D FLOW module is $0.04 (m^{-1/3} \cdot s)$ while the lower limit is $0.00 (m^{-1/3} \cdot s)$.

4.2.5 Horizontal Eddy Viscosity

The effect of the horizontal eddy viscosity (HEV) coefficient can be vital in ocean circulation models, as the horizontal scale of the basin is different from the molecular diffusivity. The value of the HEV coefficient is huge when compared with the value of molecular viscosity (Maulik & San, 2016). Therefore to assess its effect on the current model, the sensitivity analysis test was carried out with variable HEV coefficients, as shown in Table 4.2. The results showed that the performance of the model was not much influenced by the variable values of HEV coefficients. Compared to other variables considered in sensitivity analysis, the performance was constant under all variable HEV coefficient values.

Table 4.2: The result of sensitivity analysis test of HEV coefficient

No.	HEV (m^2/s)	RMSE	γ Value
i.	$1 m^2/s$	0.151	0.993
ii.	$5 m^2/s$	0.15	0.993
iii.	$10 m^2/s$	0.153	0.992
iv.	$20 m^2/s$	0.15	0.993
v.	$60 m^2/s$	0.151	0.993

The effect of the HEV coefficient during the sensitivity analysis stage was checked for the values of $1 m^2/s$ to $60 m^2/s$, as shown in Table 4.2. The agreement between the water level from the simulation results and the TPXO output data was constant, with

having the RMSE error of 0.15 m and the γ value of 0.99. Therefore the default value of 5 m^2/s for HEV was selected in the Delft3D hydrodynamic model for Triso Island.

4.2.6 Discussion

The sensitivity analysis tests were carried out for the numerical and physical parameters, to set up a flawless modal for Triso Island and Burung Island. The parameters considered during the sensitivity analysis include the type of bathymetry data, grid resolution, time step, Manning's coefficient, and the horizontal eddy viscosity. Before starting the simulation for each of these parameters, the observation point was set in the middle of the domain to record the time series simulation results, as shown in Figure 3.8. The hourly time series data for water level was extracted from the TPXO output for the same location of the observation point, and the water level from the simulation results and the TPXO output was compared to evaluate the effectiveness of the model for each of the parameters. The performance was evaluated from the agreement between both the time series results by calculating the RMSE error and the Pearson's Correlation Coefficient (γ), as defined in Equation 4.1 and Equation 4.2 respectively. The performance for all of the parameters is shown in Table 4.3.

During the sensitivity analysis, it was observed that some of the parameters, such as time step and HEV, did not have any effect on the model. Therefore, for these parameters default value was selected during simulation. The final optimum values based on sensitivity analysis for all of the numerical and physical parameters used in setting up the model for Triso Island are shown in Table 4.4. After finalizing the optimum values of the parameters, the hydrodynamic model for Triso Island is set up in the Delft3D FLOW module. The computational time step was selected as 1 minute (60 sec) and the forcing type was chosen as tidal forces.

Table 4.3: Statistical analysis (RMSE and γ) of sensitivity of the hydrodynamic model set up for Triso Island

No.	Parameter	Independent Variable Value	Performance	
			RMSE	γ Value
i.	Bathymetry	GEBCO	0.128	0.99241
		SAR Maps	0.15	0.993109
		Combined	0.15	0.993164
ii.	Grid Resolution	1000 m^2	0.15	0.993121
		500 m^2	0.15	0.993109
		250 m^2	0.226	0.971383
iii.	Time Step	15 sec	0.152	0.99302
		30 sec	0.151	0.99291
		60 sec	0.15	0.993104
iv.	Manning Coefficient (n)	0.020 $s/m^{1/3}$	0.195	0.984491
		0.024 $s/m^{1/3}$	0.15	0.993099
		0.028 $s/m^{1/3}$	0.151	0.993116
v.	Horizontal Eddy Viscosity (HEV)	1 m^2/s	0.151	0.993159
		5 m^2/s	0.15	0.993104
		10 m^2/s	0.153	0.9928
		20 m^2/s	0.15	0.993106
		60 m^2/s	0.151	0.993102

Table 4.4: The optimum values of independent variables adopted to set up the Delft3D hydrodynamic model for Triso Island

No.	Parameter	Value	Unit
i.	Bathymetry Type	SAR Maps	---
ii.	Grid Resolution	500	m^2
iii.	Time Step	60	sec
iv.	Manning Coefficient (n)	0.025	$s/m^{1/3}$
v.	Horizontal Eddy Viscosity (HEV)	5	m^2/s

There were two open boundaries selected to start the simulation, as shown in Figure 3.8. The boundaries conditions at both the open boundaries were set as time series water levels. The hourly time series data for boundaries conditions was extracted from the TPXO output. Then the simulation was started as null free water level. The simulation for Triso Island was run for 15 days, from 1st May 2021 to 15th May 2021. This time was sufficient to get the data for one complete spring and neap tidal cycle. Furthermore, several observation points were also selected inside the domain to record the time series data, and then the temporal analysis on time series data was carried out in Microsoft Excel and Matlab. The QUICKPLOT module of the Delft3D was utilized for the spatial analysis.

4.3 Validation

The boundary conditions data to run the simulation was generated from the TPXO 9.1. Therefore, for the validation of the model, the same data source is utilized to compare the time series water level data of TPXO output and simulation results. In this way, the model is validated against the water level. The validation results are shown by the comparison of simulation and database results, presented in Figure 4.7, and the accuracy of the model is reflected by the statistical analysis presented in Table 4.5.

The general criteria for water level and the tidal current speed are 20 cm and 20cm/s, which is considered good and adopted by several researchers (Mestres *et al.*, 2019; Orhan & Mayerle, 2017, 2020). The current model is validated against the water level, following Orhan & Mayerle (2020) in which the authors validated the Delft3D hydrodynamic model for the Strait of Larantuka, Indonesia, against the water level only.

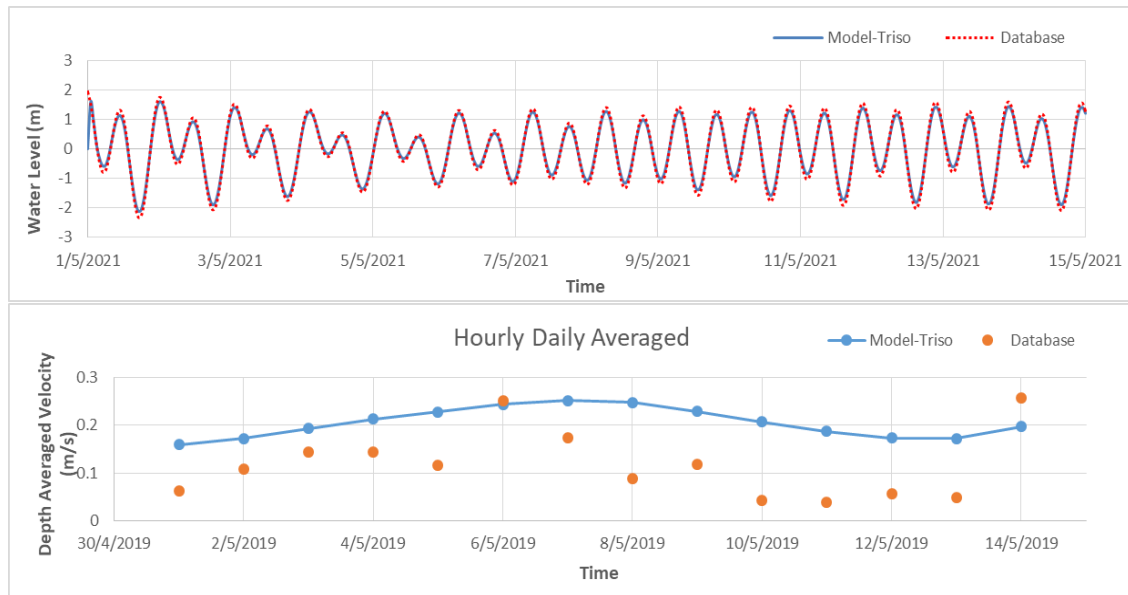


Figure 4.7: Comparison of simulation results with the data extracted from the database for (a) water level (m) and (b) depth averaged velocity (m/s)

Table 4.5: The performance of Model-Triso when water level and depth averaged velocity is compared with the database

No.	Quantity	Performance	
		RMSE	γ
i.	Water Level (m)	0.151	0.99
ii.	Depth Averaged Velocity (m/s)	0.107	0.47

Furthermore, validation is performed by comparing the simulation results with the database results, as due to the lack of any tidal station, the onsite measurements for the study area (and near the study area) were not available at Sarawak Marine Department, Kuching.

The hourly time series data for water level from the simulation are compared with the hourly time series water level data from the TPXO 9.0, and a good agreement between both the results was observed having the RMSE error of 15.1 cm and the γ value of 0.99, as shown in Table 4.5. This proves that the simulation has a strong positive linear

relationship with the TPXO output data, as shown in Figure 4.7 (a), and hence the model can be considered as validated.

As mentioned above, due to the lack of a tidal station near the study area, the data for depth averaged velocity was also not available. The results of depth averaged velocity from the simulation are compared with the surface current data extracted from the Copernicus Marine Environment Monitoring Service (CMEMS) database (*Homepage | Copernicus*, n.d.). The CMEMS is the reanalysis product of the global ocean eddy-resolving model, covering the global ocean with a horizontal resolution of $1/12^\circ$. The data about the surface currents corresponding to the location of Station-01 is extracted from 1st May to 15th May 2021, which was available as a daily average, (i.e one data unit for a day instead of being hourly time series). The γ values of depth averaged velocity and water level are 0.47 and 0.99, respectively, and the RMSE for depth averaged velocity and the water level is 10 cm/s and 15 cm, respectively. Although Pearson's coefficient for depth averaged velocity is lower, the RMSE value of 10 cm/s shows a minimum error, which is also much lower than the validation criteria discussed above. The main reason for the γ value is because the tidal current velocity from the simulation results is depth averaged, whereas the tidal current velocity from the database is surface currents. Furthermore, the surface current data at the database is available as a daily average, whereas the simulation results were the hourly time series, which was then daily averaged before comparison. This further creates an error from being perfectly linear. Furthermore, the driving force in the hydrodynamic model at the open boundaries was the time series water level.

Therefore the γ value for water level is much higher (perfectly linear) than the depth averaged velocity. Nevertheless, the validation criteria for tidal current speed discussed above is 20 cm/s, and the depth averaged velocity had the RMSE error of 10 cm/s (even lower than the water level), and none of the data points had a difference greater

than the 20 cm/s during the comparison analysis. Therefore, considering the strong linear relationship of water level and the lower RMSE error of depth averaged velocity, the current model can be considered as good for the study.

4.4 Water Level

The Delft3D hydrodynamic model was set up for the Triso Island and the simulation was run for 15 days, from 1st May 2021 to 15th May 2021. The spatial and temporal analysis has been carried out on the water level of simulation results. The spatial analysis for the water level indicated that the tide starts from the open boundaries and begins forwarding towards the shoreline. At the start of reaching the shoreline, the magnitude of water level is higher at three locations, namely a) Sungai Sabang, b) Batang Sadong, and c) Batang Saribas, as shown in Figure 4.8. After about 2 hours, the magnitude of water level is higher at Triso Island, and this is the location where the flood tide ends. In this way, a total of four hotspot locations are identified where the magnitude of the water level is higher, namely a) Sungai Sabang, b) Batang Sadong, c) Batang Saribas, and d) Batang Lupar, as shown in Figure 4.8. The temporal analysis is carried out for all of these four locations for further understanding the time variance. The comparison of water levels for all these four locations during neap and the spring tide is presented in Figure 4.9.

The water level during peak neap flood tide reaches up to 1.5 m for three locations, of a) Sungai Sabang, b) Batang Sadong, and c) Batang Saribas. While the water level during the peak neap ebb tide for these locations is about 0.51 m. The lowest water level among the four locations was observed for Batang Sadong, with a magnitude of -0.5 m. The location of Batang Sadong has the highest water level difference of about 3 m, it can be considered for tidal range energy generation.

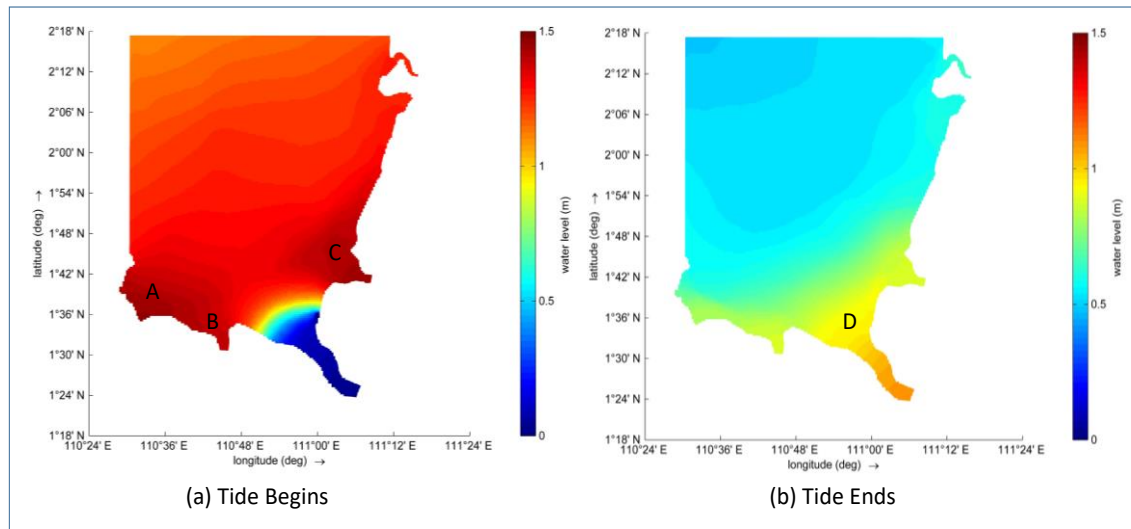


Figure 4.8: Spatial distribution at the beginning and end of a tidal cycle, indicating the hotspots A) Sungai Sabang, B) Batang Sadong, C) Batang Saribas, and D) Batang Lupar (Triso Island)

However, further study will be required on constructing the barrage and the resulting environmental effects if the location is considered for tidal range power generation. Furthermore, it can also be noted that the difference between peak flood and peak ebb tide during neap tidal hours was about 1 m, for three locations. While the same difference during spring tidal hours was minimum, about 0.25 m. Furthermore, the water level at Triso Island was 1 m during the peak flood and ebb tide during spring tidal hours, creating a constant water level difference of 1 m between the high tide and low tide. Whereas, the peak flood and ebb tide during the neap tidal hours were 1 m and 0.5 m, respectively.

The lowest tide was observed as 0 m during both the neap and the spring tides. Furthermore, the comparison between a complete spring and neap tide is shown in Figure 4.10, which clearly indicates that the nature of tide available at the study area is mixed semidiurnal. The amplitude of both the tides is relatively small, mainly because of the proximity of the amphidromic system.

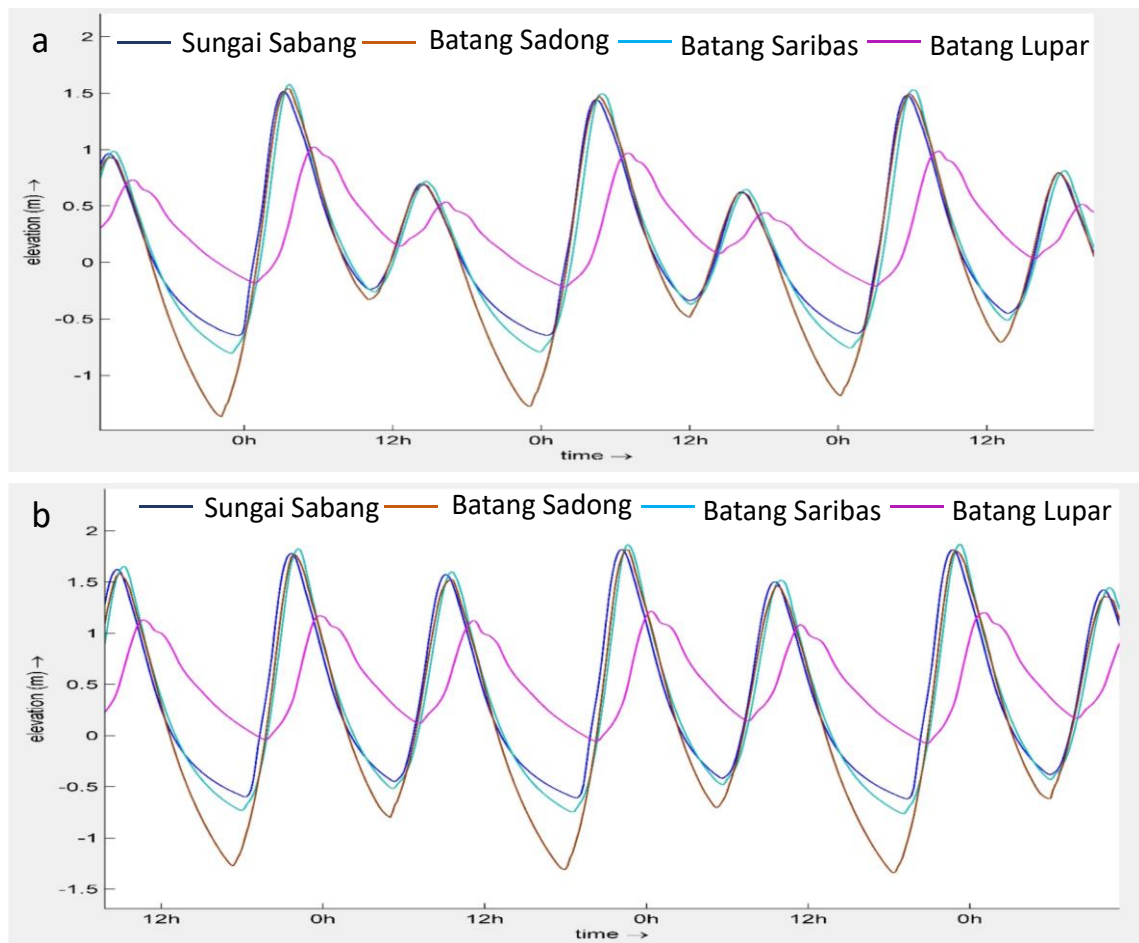


Figure 4.9: The comparison of locations during (a) Neap tide and (b) Spring tide

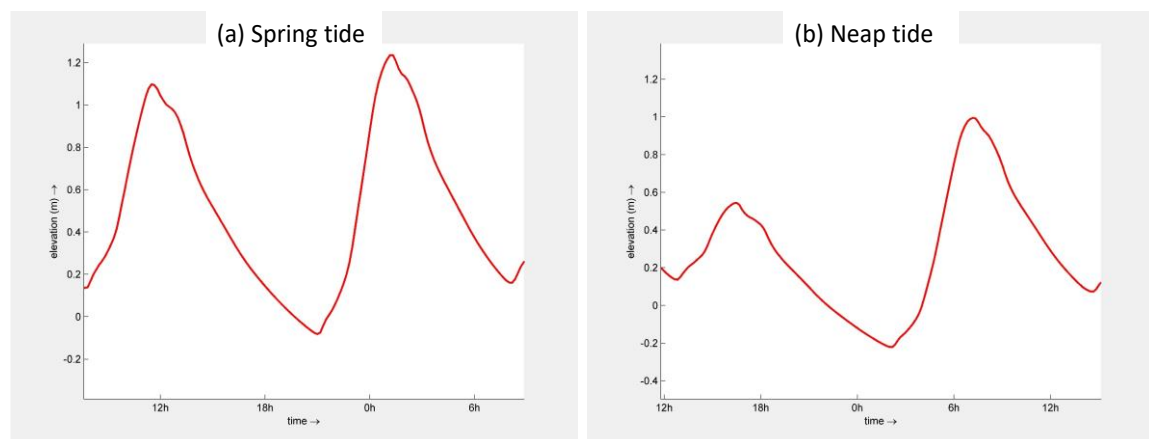


Figure 4.10: The comparison of a complete tidal cycle during (a) Spring tide and (b) Neap tide

The analytical assessment by Lim and Koh (2010) on the tidal currents in Malaysia also confirms that the nature of tide in this region of Sarawak is mixed semidiurnal (Lim & Koh, 2010).

4.5 Depth Averaged Velocity

The hydrodynamic model for the Triso Island is set up as 2D, utilizing the numerical application of Delft3D. The results of tidal current speed from the simulation are available as depth averaged velocity. From the literature, it was highlighted that the area near Triso Island, at Batang Lupar, has the highest potential for tidal current energy generation (Rigit *et al.*, 2013). Therefore in this model study, the same area is considered to be given the main focus for understanding the temporal and spatial distribution of depth averaged velocity.

4.5.1 Spatial Analysis of Depth Averaged Velocity

The simulation was run to cover the one complete spring and the neap tidal cycle, for 15 days, starting from 1st May 2021 to 15th May 2021. The spatial analysis for depth averaged velocity helped to understand the suitable areas where the tidal current velocity can be observed as higher. The spatial distribution of depth averaged velocity result from the simulation is presented in Figure 4.11. It shows the depth averaged velocity result during the mid of flood tide during both spring tidal hours and the neap tidal hours. It is clear that the magnitude of velocity is higher during the spring tides, and the spring tide also helped to identify the areas with higher tidal velocity.

From the spatial distribution during spring tide, the four locations are identified as a hotspot to receive the maximum tidal current velocity. The four locations are marked as A, B, C, and D in Figure 4.11, namely a) Triso Island, b) Assar Senari, c) Burung Island, and d) Belawai.

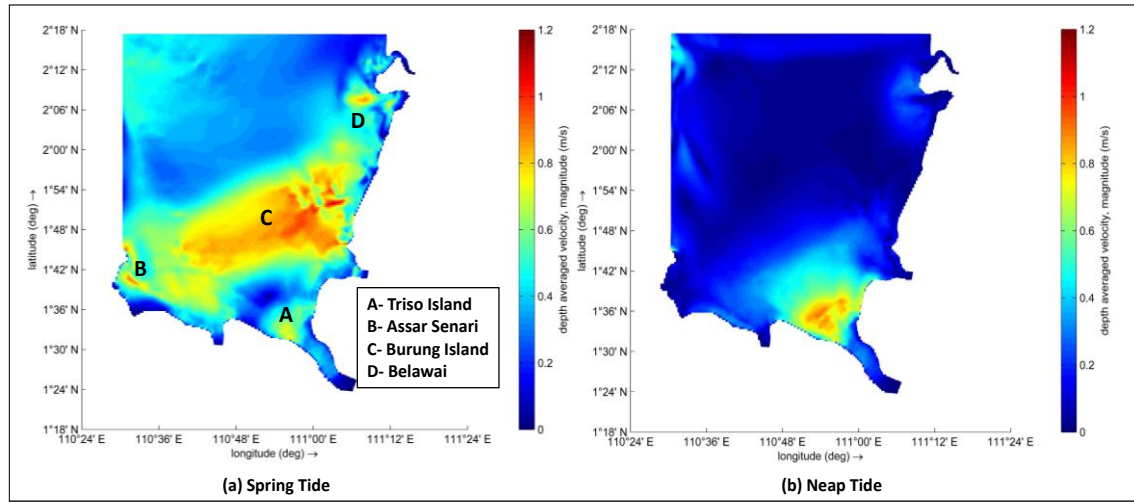


Figure 4.11: The spatial distribution of depth averaged velocity during the mid flood tide during (a) spring tide and (b) neap tide

These names are the nearest famous locations for these identified hotspots, however, the actual higher tidal current velocity site is near to these sites, not exactly these locations. The first location is ahead of Triso Island, the second location is in the sea while the Assar Senari port is inland in the Sarawak River. Similarly, the third location is far from the shoreline, which is ahead of Burung Island, and the fourth location is near the Belawai beach in Sarawak. The magnitude of tidal current velocity ranges between 1 m/s to 1.5 m/s, as indicated from spatial distribution.

It is clear from the spatial analysis that location C, which is near Burung Island, has a huge area that covers the tidal current speed in the range of 1 m/s to 1.5 m/s. Whereas, locations B and C have the minimum area. However, during the neap tidal hours when the magnitude of the tide is low, all of these locations do not receive sufficient tidal current speed except location A, which is near Triso Island. The channel width across the Triso Island at location A is around 28 km, measured from Google maps. This is also sufficient for the installation of an array of turbines for power generation. Although location C seems to cover a large area as shown in Figure 4.11, the distance factor (i.e 30

km) from the nearby population of Sebuyau town may not make it attractive for power generation. Whereas, location A is attached to the shoreline near the Sebuyau town.

Furthermore, there is no population near location D and location B is the route of ocean-going vessels to Assar Senari port and the Kuching city. The installation of turbines at location B will disturb the ships going to the city. Therefore, locations B and D are ignored to consider for tidal current energy generation in this study. Furthermore, the water depth at all of these four locations is compared in Figure 4.12. From the temporal analysis on water depth, location B- Assar Seanri can not be considered as a suitable site due to low water depth.

The maximum depth among these four locations is for Triso Island, where the depth ranges up to 13 m. This depth of 13 m is only sufficient for small tidal current turbines, however, the minimum requirement for large turbines is 20 m. Furthermore, location C and D has almost the same water depth that ranges between 7 m to 8 m. Considering the large area for depth-averaged velocity at location C- Burung Island, it can be considered as a suitable site for power generation if the small scale turbines are installed. Therefore, it can be concluded from the spatial study on depth averaged velocity that the two locations including Triso Island and Burung Island are suitable to consider for tidal current energy generation.

4.5.2 Temporal Analysis of Depth Averaged Velocity

The temporal analysis was carried out on the simulation results of depth averaged velocity for the four locations identified in Figure 4.11. The hourly time series data for one complete spring and neap tidal cycle for all of these locations are compared in Figure 4.13. It is clear that the magnitude of location A- Triso Island is higher than the other locations during both the tides.

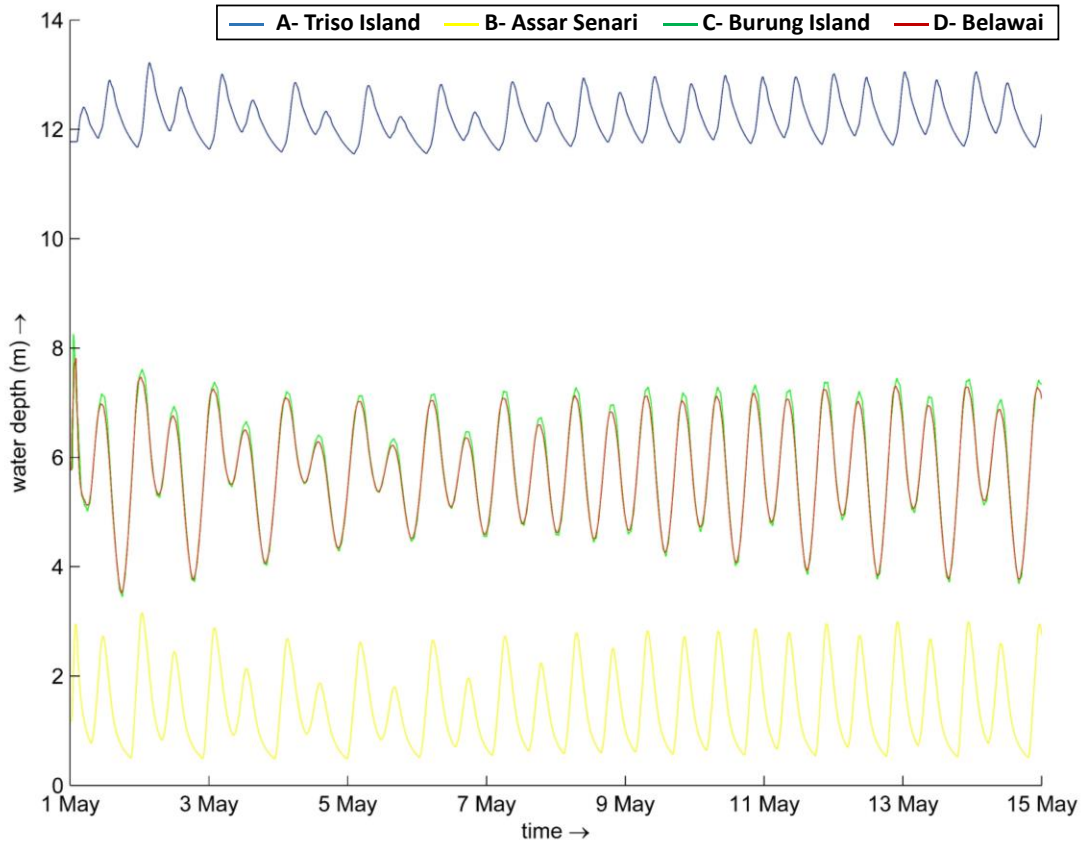


Figure 4.12: The comparison of water depth at identified locations from the spatial analysis at a) Triso Island, b) Assar Senari, c) Burung Island, and d) Belawai

The second best magnitude is for location C- Burung Island, which is 0.8 m/s during peak spring tide. However, for both the locations, the depth averaged velocity was noted to be above 1 m/s during the spatial analysis. However, the location B- Assar Senari has a depth of 3 m and the magnitude of depth averaged velocity during peak spring tide is 0.75 m/s. Therefore this site can not be considered for tidal current energy generation. Whereas location D- Belawai has a water depth of 7.5 m and the depth-averaged velocity during peak spring tide is 0.6 m/s.

The area covering the maximum depth average velocity is also minimum, and there is no population nearby this location. Due to these reasons, location D- Belawai can also be ignored for consideration. However, the attractive locations under consideration are the

areas under the vicinity of A- Triso Island and C- Burung Island. The depth-averaged velocity for both locations is predicted in Figure 4.14.

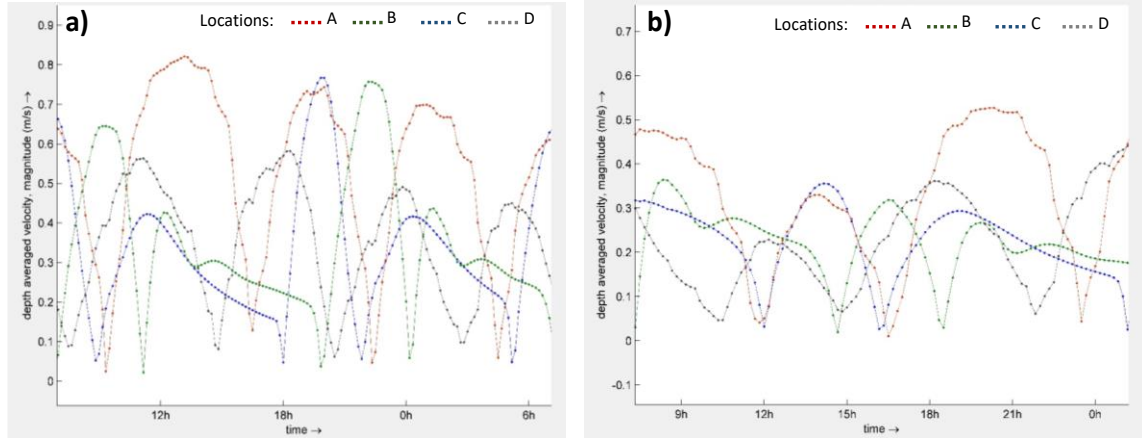


Figure 4.13: The comparison of depth averaged velocity during a) spring tidal cycle and b) neap tidal cycle

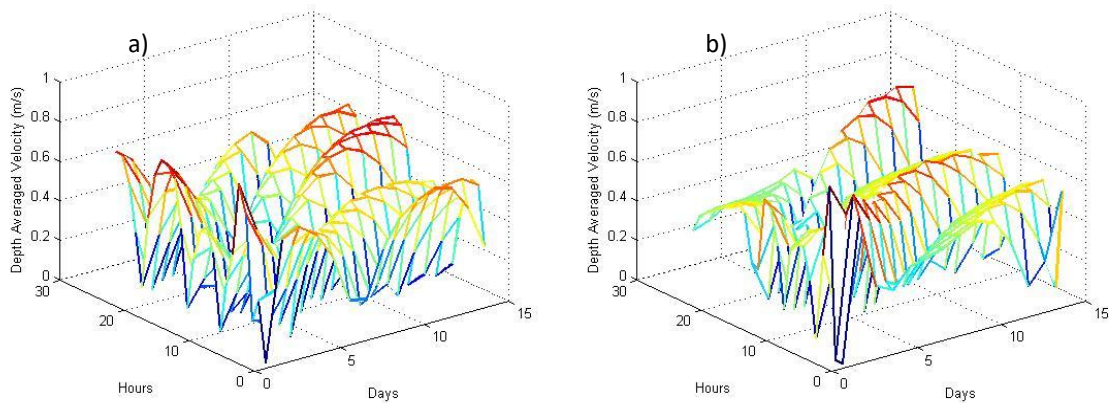


Figure 4.14: Predicted depth averaged velocity results at a) Triso Island and b) Burung Island

4.6 Tidal Energy Density

The tidal energy density or the kinetic energy flux is computed based on Equation 3.7. The time series simulation result of depth average velocity is used to determine the available kinetic energy flux, during low and high tides (i.e. spring and neap tides), as

shown in Figure 4.15. The tidal energy density in this figure is the maximum theoretical kinetic energy flux. The kinetic power shown in Figure 4.15 represents the power available in the fluid in a cylinder whose diameter is the same as the rotor of a TST.

The tidal energy density reflects the estimation of sites that are attracted for turbine installation, these sites include A- Triso Island and C- Burung Island. The tidal energy flux is maximum at location C- Burung Island during spring tide, while it is maximum at location A- Tris Island during neap tide. The maximum tidal current power flux at Triso Island is 0.4 kW/m^2 . While the maximum tidal current power flux at the Burung Island site is up to 0.6 kW/m^2 .

Furthermore, the extractable tidal power depends upon the local sea environmental condition, characteristics of the turbine, and the efficiency of generated and transmitted power. The tidal current turbines depend upon the velocity profile at the location where they are installed. There is also a minimum requirement of tidal stream velocity (cut-in speed) for the turbine to operate. The cut-in speed is an important parameter to be considered while estimating the extractable tidal power. While doing the tidal energy assessment, the cut-in speed is considered between 0.5 m/s to 1 m/s , which further depends upon the design of the actual turbine (Orhan & Mayerle, 2017). The area near the Triso Island and Burung Island are suggested for further study on developing the 3D hydrodynamic model, and tidal current turbine testing and installation.

The selection of these sites is suggested based on the criteria of the minimum tidal current velocity of 0.5 m/s , the sea area for turbine installation greater than 5 m^2 , the minimum water depth of 7.5 m , and no hindrance of ocean-going vessels (Wang *et al.*, 2020; Wang & Yang, 2020).

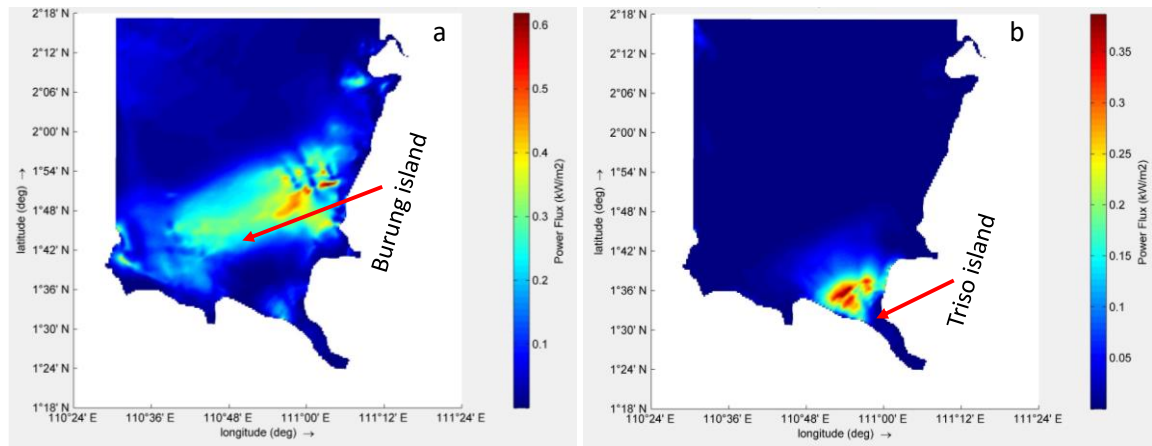


Figure 4.15: Tidal energy density in the computational domain during a) spring tide and b) neap tide, the location of Burung Island and Triso Island

4.7 Chapter Summary

This chapter discusses the results of the hydrodynamic model set up for Triso Island, utilizing the numerical application of Delft3D. In the initial stage, the sensitivity analysis was carried out on the numerical and physical parameters to get the optimum values. During the sensitivity analysis, it was noted that the HEV and time step do not have any effect on the model performance, so the default value was set for both parameters. The spatial and temporal analysis was carried out for the water level and depth-averaged velocity to characterize the suitable site in the model domain. Two locations are identified as the best suitable locations to consider for tidal current energy generation, which were in the vicinity of Triso Island and Burung Island.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The hydrodynamic model has been set up for the Triso Island, in the Sarawak state of Malaysia, to understand the hydrodynamics of tides for tidal current energy generation. The model has been calibrated and validated against TPXO output data to get the best temporal and spatial results. The hourly time series comparison of water level from the model result has been compared with the hourly time series result of TPXO 9.0 output. A good agreement was observed between both the results, showing a positive linear relationship to authenticate the model. Furthermore, the sensitivity analysis was also carried out for the numerical and physical parameters, to check their effect on the model performance. All the objectives described in Chapter1 have been achieved and are concluded below:

The site specific hydrodynamic model has been constructed for the Triso Island, Burung Island, and nearby river mouths using Delft3D software.

The model sensitivity was investigated considering the physical and numerical parameters. It was concluded that the horizontal eddy viscosity and the time step have no effect on the performance of the model, while the model was greatly affected by the grid resolution and Manning's coefficient. The best value of the Manning's coefficient to compute the bottom roughness has been investigated to be $0.025 \text{ s/m}^{1/3}$.

The model has been validated by comparing the simulation results with TPXO output data. The comparison results were within the acceptable limit of RMSE value of 20

cm for water level. Therefore the model has been considered as valid for tidal simulation at Triso Island and Burung Island.

The spatial and temporal characteristics of tides at Triso Island, Burung Island, and nearby river mouths have been investigated. It was concluded that the nature tide at the Triso Island and nearby location in the coastline of Sarawak is mixed semidiurnal. The highest water level is observed to be 1.5 m, at the locations of Sungai Sabang, Batang Sadong, and Batang Saribas. The water depth at Triso Island is observed to be 13 m, and at Burung Island it is 7.5 m. The maximum depth averaged velocity available at Triso Island and Burung Island is observed to be 1 m/s.

Analysis on available kinetic energy density has been carried out. It was concluded that the suitable location for tidal range energy generation is Batang Sadong, having the highest tidal range value among other locations of 3 m. Two locations are shortlisted as the most suitable for tidal current energy generation, which includes the area near Triso Island and Burung Island. The tidal energy density is maximum at Burung Island with the value of 0.6 kW/m^2 , while the tidal density at Triso Island is 0.4 kW/m^2 during peak spring tide.

5.2 Recommendations

The recommendations for future research on tidal current energy development at Triso Island, Sarawak, and hydrodynamic modelling are given below:

- a) The current hydrodynamic model set up for Triso Island is 2D, the detailed understanding of tidal characteristics at this site can be accomplished by developing 3D models.
- b) The hydrodynamic model can be improved by including the effect of wind stress, temperature, and salinity, on tidal currents.

- c) Sarawak is a tropical region, where sometimes the rain causes a flood. The tidal energy assessment can be completed considering the effect of extreme water flow (i.e flooding).
- d) A tidal current energy assessment can be improved by considering the effect of tidal current turbines in the model. The porous plate can be added in the model domain to reflect the characteristics of a tidal current turbine.
- e) It is suggested to collect the onsite data tidal stream speed, in this way the model validation and tidal energy assessment can be improved.

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APPENDICES

Appendix 1: Journal Publication

1. **Title:** Tidal Energy Assessment with Hydrodynamic Modelling

Authors: **Imran Ali**, Andrew Ragai Henry Rigit, Omar bin Yaakob, Jakhrani, Jane Labadin, Altaf Hussain Rajpar

Journal Title: Indonesian Journal of Electrical Engineering and Computer Science (Scopus Indexed)

Year: 2022

Status: Editing Stage of Publication

Appendix 2: Conference Publication

1. **Title:** Hydrodynamic Modelling Boundary Conditions for Tidal Stream Energy Assessment at Triso Island, Malaysia.

Authors: **Imran Ali**, Andrew Ragai Henry Rigit, Yanuar Z. Arief, Altaf Hussain Rajpar, Abdul Qayoom Jakhrani

Conference Title: The 14th International UNIMAS Engineering Conference 2022 (EnCon2022)

Date of presentation: 24th February 2022

Appendix 3: Supplementary Data

```
# -*- coding: utf-8 -*-
'''
Created on Mon March 16 12:57:45 2020

Script
'''
import numpy as np
from netCDF4 import Dataset
import csv

#write name of input and output file
ncfile = 'Test2.nc'
ascii3d = 'Test2.xyz'

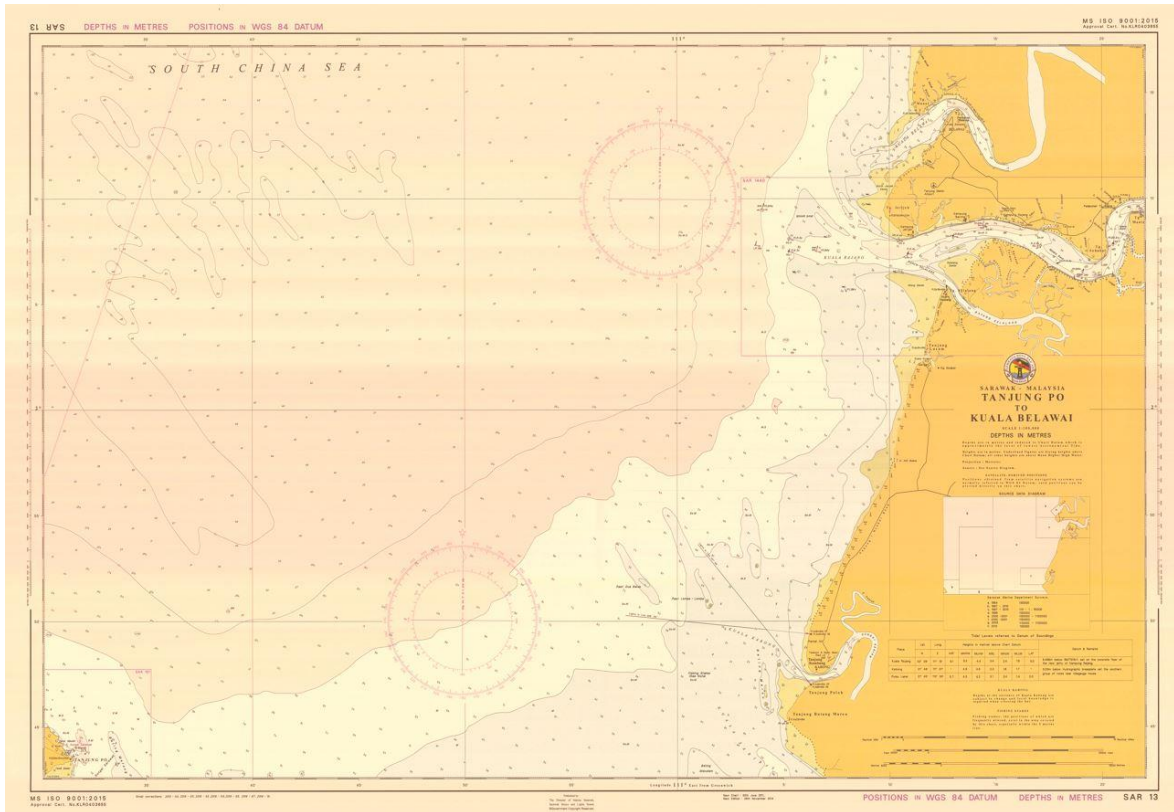
#open file nc
dset = Dataset(ncfile, 'r')

#adjust name of variable data like lat, lon and depth
lat = dset.variables['lat'][:]
lon = dset.variables['lon'][:]
depth = dset.variables['elevation'][:]

with open(ascii3d, 'w') as tulis_file:
    datawriter = csv.writer(tulis_file, delimiter=',')
    for i in xrange(len(lon)):
        print 'progress', i
        for j in xrange(len(lat)):
            datawriter.writerow ([lon[i], lat[j], depth[j,i]])
print '!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
print '! PROCESSING BATHYMETRIC DATA SUCCESSFUL !'
print '!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
```

Python Script for GEBCO Data Conversion

Sarawak Nautical Chart (SAR122)



Sarak Nautical Chart (SAR13)