RACIC 9 (1) (2024)

JURNAL RAB CONTRUCTION RESEARCH

http://jurnal.univrab.ac.id/index.php/racic

NUMERICAL MODELING OF COASTAL TIDES AND CURRENT PATTERN AT NORTHERN PEAT COAST OF BENGKALIS ISLAND

Daly Riandi[1*], Sigit Sutikno[2], Muhamad Yusa[3]
[1*,2,3]Magister Teknik Sipil, Fakultas Teknik, Universitas Riau
Alamat E-mail: daly.riandi@student.unri.ac.id

Info Artikel

Sejarah Artikel:

Diterima: Nov 2023
Disetujui: April 2024
Dipublikasikan: Juni 2024

Keywords:

Current Pattern, Tidal, Bengkalis, Numerical Modelling

Abstrak

Provinsi Riau mengalami kehilangan garis pantai setiap tahunnya akibat erosi. Pesisir utara Pulau Bengkalis tidak lepas dari bencana perubahan garis pantai tersebut, dimana sebagian besar permukaan tanahnya tersusun dari tanah gambut. Selain akibat keruntuhan tanah, erosi disebabkan oleh kondisi perairan disepanjang pantai. Untuk dapat melakukan penanggulangan bencana yang baik, pemodelan hidrodinamika pantai yang akurat tentu menjadi penting dilakukan. Beberapa komponen penting hidrodinamik yaitu karakteristik pasang surut dan pola arus. Komponen penting ini diidentifikasi menggunakan model numerik. Kalibrasi parameter Manning digunakan untuk meningkatkan akurasi model. Karakteristik pasang surut diperoleh yaitu campuran condong harian ganda. Sedangkan pola arus pasang diketahui dari arah pergerakannya. Pada kondisi pasang, air bergerak menuju arah selatan dan barat daya dengan kecepatan rata-rata 0,210 m/dtk dan saat surut menuju arah timur laut dengan kecepatan rata-rata -0,232 m/dtk.

Kata Kunci: Pola Arus, Pasang Surut, Bengkalis, Model Numerik.

Abstract

Riau Province experiences a loss of coastline every year due to erosion. The northern coast of Bengkalis Island is prone to coastal setback. Apart from land collapse, erosion is also caused by the flow of water along the coast. To be able to carry out good disaster management, accurate coastal hydrodynamic modelling is important. Some important components of hydrodynamics are tidal characteristics and current patterns. These important components are identified using numerical models. Manning parameter calibration is used to improve the model's accuracy. The tidal characteristic obtained was mixed, predominantly semidiurnal. Meanwhile, the pattern of tidal currents is known from the direction of movement. At spring tide, water moves towards the south and southwest with an average speed of 0.210 m/s and at neap tide, it moves towards the northeast with an average speed of -0.232 m/s.

✉ Alamat korespondensi:
E-mail: daly.riandi@student.unri.ac.id
ISSN 2527-7073

INTRODUCTION

As one regency of Riau Province, Bengkalis Regency has a separate island from Sumatera, which comprises Rupat Island and Bengkalis Island. Bengkalis Island itself has a total area of 905,445 km2 [1]. This island is where government and many other soial and economic activities mostly take place. As a vital place, this island is prone to natural disasters both on land and in the coastal area. In recent years, coastal problems have become more concerning, especially in coastal areas where erosion has occurred in the majority of Bengkalis Island [2].

More than 160 ha of peatland on the coastal coast of Riau Province is lost every year due to erosion [3]. Erosion has continuously occurred on the northern coast of Bengkalis Island, which is close to the Malaca Strait. This tidal zone is formed by peat material, a soil with a high organic content made of organic elements, and partially degraded vegetation [4], as the mainland is also mainly composed of the same material.

In the area where mangroves did not exist, the erosion rate was high [3]. Moreover, shorelines dynamically change over time, and in extreme conditions, up to 30 m/year coastal setbacks take place [5]. As the erosion progresses, a peat landslide brought on by the erosion creates the peat cliff that took place in the northern coast area [5]. Therefore, it is crucial to correctly estimate the hydrodynamic behavior, particularly on the coast that is directly impacted by the erosion. Regarding risk management, it is also essential to comprehend and accurately model coastal hydrodynamics.

To accurately mimic reality and offer data that would be quite difficult to acquire through surveys or future estimates, numerical models have proven to be one of the greatest methods available [6]. One of many numerical models that are widely used in hydrodynamic cases is Delft3D ([7], [8], [9], [10]). Erosion rate is morphodynamic response due to hydrodynamic proses on coastal. Although this process was part of sediment transport, the movement of the sediment material is led by tides and currents movement. Identifying the pattern of tides and currents would help one understand how coastal hydrodynamics behave in a specific coastal area ([7], [8], [9], [10], [11]).

LITERATURE REVIEW

Coastal Hydrodynamic

The coast is a region of land that is adjacent to the ocean and is yet subject to marine impacts like tides, sea breezes, and seepage of seawater. The shore is a location near the water's edge that is impacted by both high tides and low tides. The coastline is the line separating land from the ocean, and because it is subject to tides and coastal erosion, its position is not fixed.

The study of hydrodynamics is impacted by tides, currents, and waves. Coriolis, friction, and gravitational forces each have an influence on marine hydrodynamics [7]. In hydrodynamics, gravitational force predominates. The term "tide" refers to the vertical rise and fall of the water's surface, while "tidal current" (or "tidal stream" in some places) refers to the accompanying horizontal flow. The primary solar tide has a duration of 12 hours, but the primary lunar tide has a period of 12,42 hours. M2 and S2 are the names of these tidal constituents (or tidal components). The ratio can be utilized to determine the relative relevance of diurnal and semidiurnal harmonics. This ratio or F (Formzahl number), where:

$$F \frac{K_1 + O_1}{M_2 + S_2} \tag{1}$$

According to harmonic analysis, the variation in water level is the result of the addition of a constant mean level, contributions from particular harmonics, and a "residual" (Reeve, et al., 2018):

$$\eta = Z_0 + \sum_{i=1}^{n} a_i \cos(\Omega_i t - \phi_i) + R(t) \tag{2}$$

Where:

η	=	water level (m)
Z_0	=	mean water level above (or below) local datum (m)
Ω_i	=	frequency of i^{th} harmonic component (1/h)
a_i	=	amplitude of the i^{th} harmonic component (m)
ϕ_i	=	phase of i^{th} harmonic component (degrees)
n	=	number of harmonics used to generate the tide
t	=	time (h)
$R(t)$	=	residual water level variation

The tide movement into and out of a bay is referred to as the flood current and ebb current, respectively. This reversing tidal current is a one-dimensional scalar quantity, similarly to the tide. The current fluctuates between its maximum positive value, known as maximum flood, and its maximum negative value, known as maximum ebb, within a single tidal cycle. It then returns to maximum flood through slack water.

Numerical Modelling of Delft3D

One of the numerical models used for coastal dynamics is Delft3D. Delft3D is software for multidimensional (2D or 3D) hydrodynamic simulation or modeling thatfunctions for calculating coastal areas, rivers, and estuaries. This program can simulate current waves, sediment transport, water quality, and ecological analysis in coastal areas. Delft3D has a main module, namely the FLOW module, which functions to calculate hydrodynamic conditions. In calculating hydrodynamic conditions, Delft3D-FLOW uses the solution of the Navier-Stokes equations using Boussineq assumptions [8]. The equations are written in spherical co-ordinates on the globe or orthogonal curvilinear coordinates. In Delft3D-FLOW models, a curvilinear grid is considered as a simplified version of a rectangular grid (Cartesian frame of reference).

METHODOLOGY

Study Area

The study area of this research is on the Northern Coast of Bengkalis Island, Bengkalis Regency, Riau Province, Indonesia. The map location of the study area is described in the figure below.

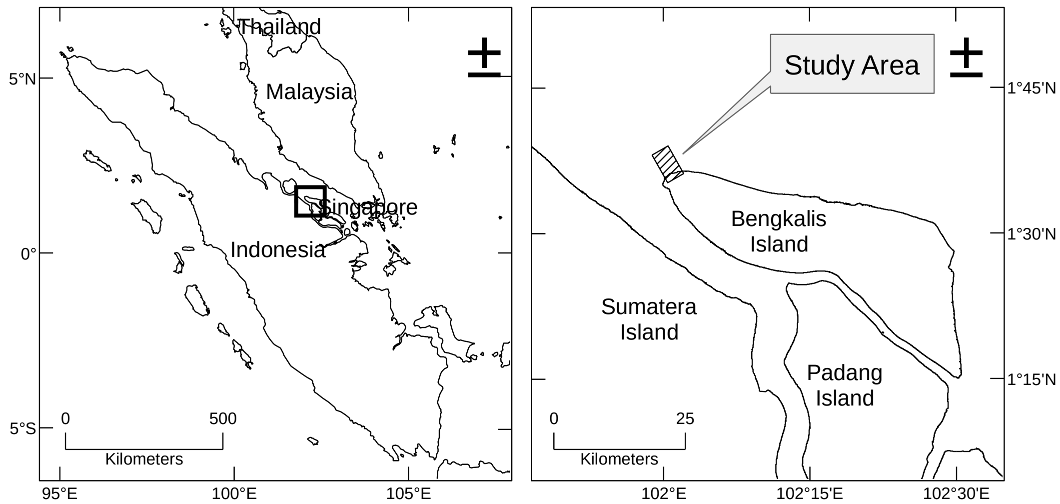


Figure 1. Study Area

In administration, this study area covered two villages, Simpang Ayam and Prapat Tunggal [9]. For this research, the domain area is a rectangular with dimensions of 6 km x 3,5 km. The decision for those dimensions is to cover a wide area along the shoreline and the coastal area. Moreover, water level and velocity observation data must be located on the domain boundary. The details of the domain area are described in the figure below.

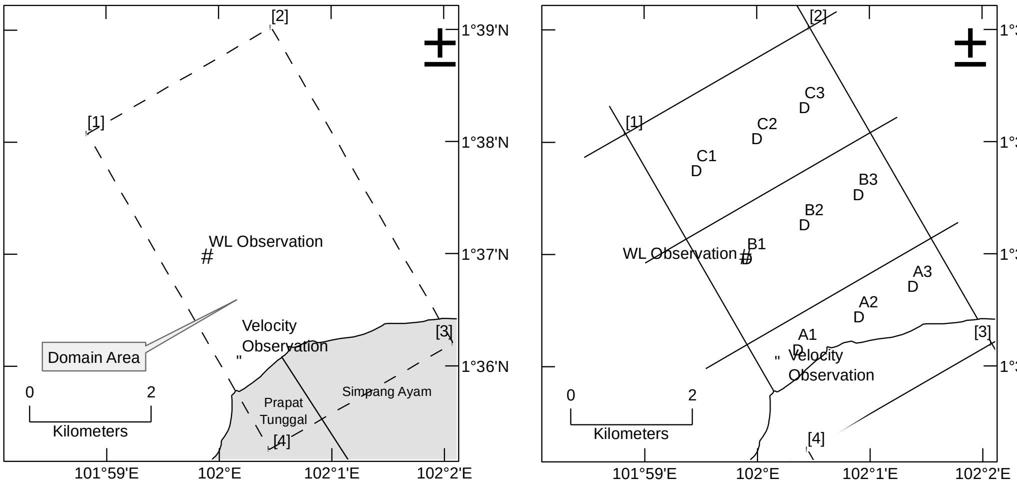


Figure 2. Domain Area and Monitoring Location

There are 10 monitoring locations that consist of 2 observation points and other the points are spread in domain area that is shown the figure above.

The Type and Source of Data

The main data for this research is comprised of bathymetry, shoreline, weather, and water level and velocity observations. Bathymetry data is retrieved from BIG which is called BATNAS (Batimetri Nasional). BATNAS data covered all Indonesian regions from 90°E to 150°E and 20°S to 20°N. This bathymetry data has advantages in coastal areas and shallow waters using surveys from the Center for Marine and Coastal Environment (Pusat Kelautan dan Lingkungan Pantai, PKLP), BIG [10].

Data Preparation and Processing

Firstly, the bathymetry data needs to be extracted from the area of interest or domain area. Land boundary which is represented as shoreline data, are digitized from imagery, as mentioned above. The atmospheric data to be used is ERA5 hourly data and was obtained from Copernicus Climate Data Sore. This data consists of Surface pressure in Pa and 10m u,v-component of wind in m/s.

The grid will be setup in three different zones, the first part is A, representing the coastal zone with 50x50m grid, and the rest of the zone, B and C representing the offshore with 100x50m and 200x50m grid. Astronomical constituents from water level data need to be analyzed using harmonic analysis. The amplitude and phase will be used as forcing boundary. The result from the simulation will then be evaluated, especially model performance, which can be quantified using mean absolute percentage error (MAPE), root mean square error (RMSE), and the Pearson correlation (r) coefficient.

RESULT AND DISCUSSION

Tidal Analysis

Raw data from the observed water level was analyzed to obtain astronomical constituents. These parameters comprise the tidal amplitude and phase. The results of the performance of analysis are shown in the figure below.

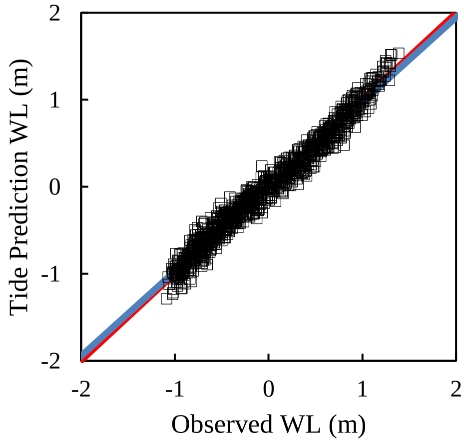


Figure 3. Linear Regression of Observed and Tide Prediction

The figure above shows that the tide prediction has a good result, with RMSE = 10,321cm and R^2 = 0,9728. In this case, the astronomical constituents can be accepted for further analysis. Provided by the astronomical constituents, in which the amplitude values, the Formzahl number (F) can now be calculated as follows:

$$F\frac{K_1 + O_1}{M_2 + S_2} = \frac{14{,}015 + 23{,}543}{67{,}348 + 32{,}363} = 0{,}377$$

Based on the F values, the type of tide of the study area is mixed, predominantly semidiurnal, in which there are two daily high and low waters.

Water Level Calibration

The calibration parameter for the water level is roughness, which is represented by Manning’s values. After the water level calibration is satisfied, the velocity calibration will use Manning’s values for velocity modeling. The reflection parameter alpha is then used for the velocity calibration. In short, relationships between calibration parameters will be measured with RMSE and R^2. The MAPE value is then calculated with the optimized parameters. The result of the water level calibration parameters is shown in the figure below.

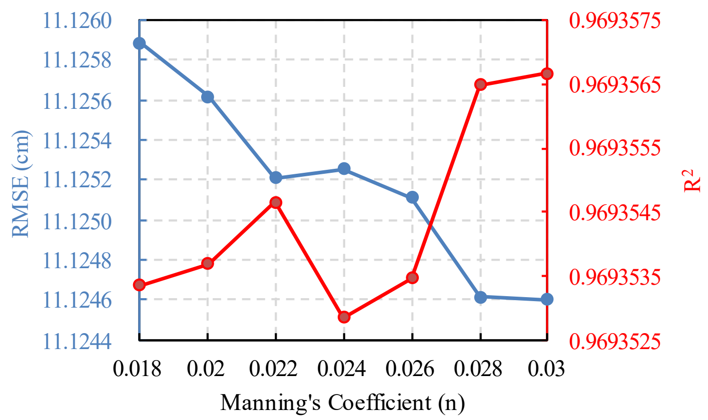


Figure 4. Manning’s Calibration in Water Level Simulation

The variation of Manning’s values is from 0,018, to 0,03. As shown in the figure above, Manning’s value of 0,03 result in the best performance of RMSE and R^2, with each value being 11,1246cm and 0,969357. Also, the MAPE result is 1,24%.

Water Level

Water level is described as two conditions, Spring tide and Neap tide. Each condition will have highest and lowest water level. To describe the water level situation, a 2D area map is produced for each tide and water level. Those maps are shown in the figure below. As the figure shows, the most distinct area where significant water level differences can be seen is in the south-east and south-west areas of the coast.

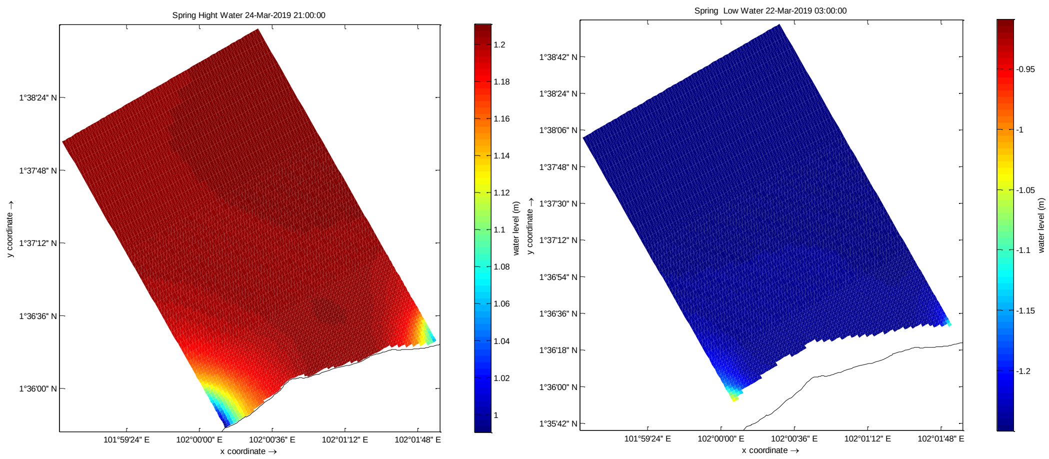


Figure 5. Spring Highest and Lowest Water Level

The water level difference in spring conditions at the lowest level is 8mm apart, while at the highest level it is 27mm apart. Meanwhile, for the neap conditions at the lowest level, the water level difference is 0,4mm and for the highest level, it is 1,5mm. In the neap tide conditions, water level differences are not much different, while in the spring tide, a distinct difference takes place at the highest level. A time series of the water level from the simulation can be seen in the figure below.

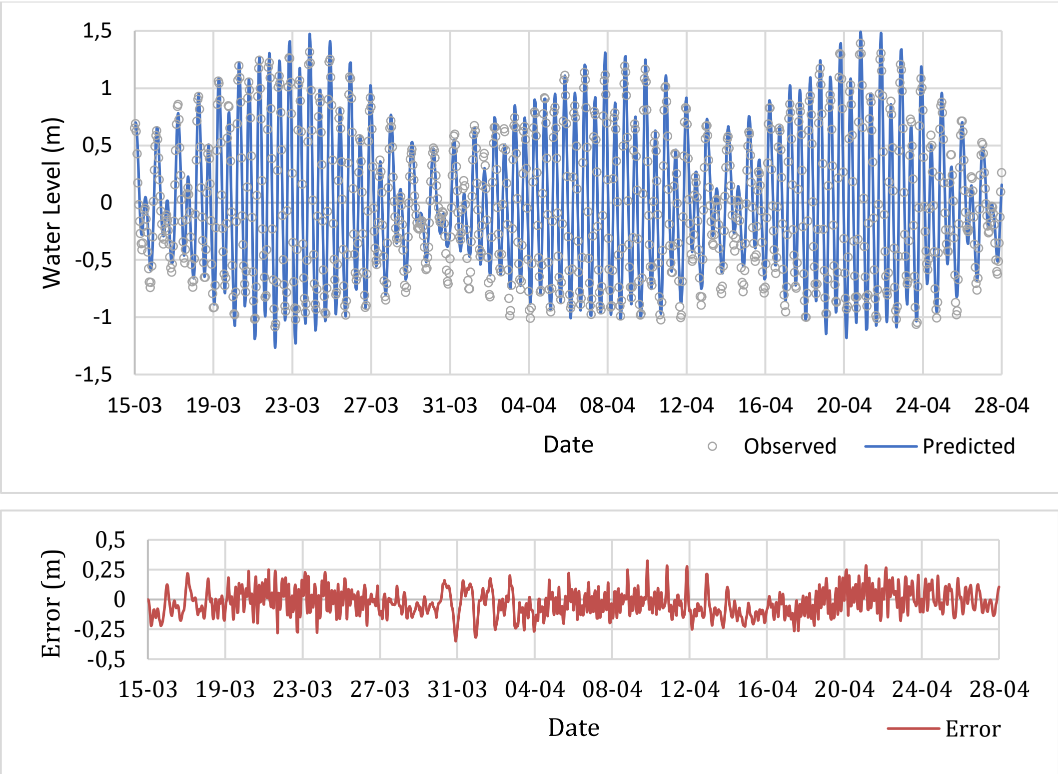
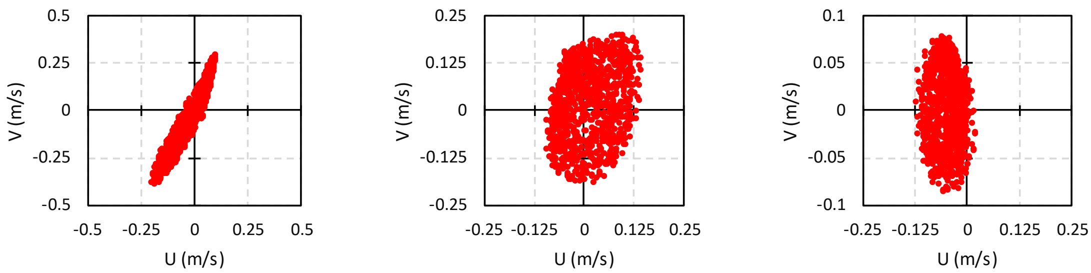


Figure 6. Time Series of Predicted and Observed Water Level

Tidal Current

Horizontal movement is the dimension that involves the tidal current. The current vector is represented by a single dot of an U,V plot vector. This dot will project the flow component to show flow orientation. The U,V components from A1, B1 and C1 monitoring stations are shown in the figure below.



(A1) (B1) (C1)

Figure 7. Tidal Current

From the figure above, some form a sharp shape, such as A1. These types of current, called reversing current which caused by the flow direction is constricted. For B1, the type of current is rotary current, where water flow direction is not restricted and usually occurs in offshore areas. The C1 is a combination of reversing and rotary.

The motion of the water flow in the figure above also shows two maximum velocities in opposite directions. These two are peak floods and peak ebbs of high and low water. The scale of the velocity for flood and ebb currents is shown in positive and negative values. A summary of these maximum velocities is shown in the table below.

Tabel 1 Floods and Ebbs Velocities

No	Monitoring Location	Floods (m/s)	Ebbs (m/s)
1	A1	0,295	-0,389
2	A2	0,147	-0,200
3	A3	0,109	-0,163
4	B1	0,202	-0,187
5	B2	0,227	-0,151
6	B3	0,219	-0,161
7	C1	0,079	-0,125
8	C2	0,109	-0,163
9	C3	0,147	-0,200
10	Velocity Obs	0,480	-0,583
	Average	0,210	-0,232

As the result shown in the tables above, average current velocity for flood movement is 0,210 m/s and for ebb movement is -0,232 m/s.

CONCLUSION

The Formzahl number obtained is 0.377. The type of tide is mixed predominantly semidiurnal, in which there are two daily high and low waters. The difference in the water level is 27 mm at spring tide and 0.4 mm at neap tide. The most significant difference in water level occurs in zone A. The shape of the tidal current in the nearshore area is mostly reversing current. On the offshore, there is a combination of rotary and reversing current, but it is still dominated by reversing current. The averaged magnitude of the tide current in flood movement is 0,210 m/s and in ebb movement it is -0,232 m/s.

ACKNOWLEDGEMENT

The authors acknowledge the Center for Peatland and Disaster Studies (CPDS), (“Pusat Unggulan Iptek Gambut & Kebencanaan” or “PUI-GK”), University of Riau (UNRI), as part of the research scheme in the "JSPS-DGHE Bilateral Exchange Project" for supporting tide and velocity data to make this research possible.

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