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Wave Transformation and Propagation under Bathymetric Conditions Using CGWAVE on Kapota Island

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ABSTRACT

The coastal area of Kapota Island, Wakatobi Regency, is potentially vulnerable to coastal changes caused by wave activity, including coastal erosion and sedimentation. Waves propagating from offshore toward the coastal area undergo transformation due to changes in water depth and bathymetric conditions, which may affect wave height, direction, and propagation patterns before reaching the shoreline. This study aims to: (1) analyze wave height and period characteristics in the waters of Kapota Island using the CERC SPM 1984 method; and (2) analyze wave transformation and propagation patterns in relation to the bathymetric conditions of Kapota Island waters using the CGWAVE model operated through the Surface-water Modeling System (SMS) software. This study employs analytical and numerical modeling methods; wind, bathymetric, and other supporting oceanographic data were used as primary and secondary data. The CGWAVE simulation results indicate that the bathymetric conditions of Kapota Island waters influence wave transformation and propagation patterns, with maximum wave velocities from the North, West, and Northwest of 0.58 m/s, 0.56 m/s, and 0.55 m/s, respectively. The findings of this study are expected to provide information on wave transformation and propagation characteristics that can serve as a basis for coastal zone management and the planning of coastal protection structures on Kapota Island.

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INTRODUCTION

The coast is a dynamic coastal zone that may change in response to marine processes and maritime socioeconomic activities. Its seaward boundary is associated with the highest high tide and the lowest low tide, whereas its landward extent is influenced by natural processes and human activities.

Ocean waves are one of the dominant marine parameters affecting shoreline retreat. Waves may be generated by wind blowing over the sea surface, differences in seawater temperature and salinity, and volcanic eruptions occurring beneath or at the sea surface. Shoreline retreat from its original position may be caused by waves and currents as well as by an imbalance between incoming and outgoing sediment.

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The coastal area of Kapota Island is vulnerable to coastal damage, such as erosion and sedimentation, caused by waves approaching from the western side of the island. Large waves may also threaten coastal settlements. The planning of coastal protection structures requires numerous parameters, including soil bearing capacity, currents, and wave height, which can be estimated through wave forecasting or numerical modeling software.

Based on this background, the study attempts to model waves in the coastal area of Kapota Island using the hindcasting method and the Surface-water Modeling System (SMS) CGWAVE software.

This study addresses two questions: (1) how wave height and period at Kapota Island can be determined using the CERC SPM 1984 method; and (2) how wave propagation can be modeled using SMS–CGWAVE.

The objectives are to analyze wave height and period using CERC SPM 1984 and to model wave propagation at Kapota Island using SMS–CGWAVE.

THEORETICAL FRAMEWORK

According to Triatmodjo (1999:1), the coast is a zone forming the boundary between land and sea. The formation of the coastal zone is influenced seaward by the highest high tide and the lowest low tide, while landward conditions are influenced by human activities. The definition of the coastal area is illustrated in the following figure.

The distribution of wind speed above the sea surface is divided into three regions according to elevation. In the geostrophic region, located above 1,000 m, wind speed is constant. Below this elevation are the Ekman region, at elevations of 100–1,000 m, and the constant-stress region, at elevations of 10–100 m. In these regions, wind speed and direction vary with elevation because of friction with the sea surface and temperature differences between air and water (Triatmodjo, 1999:149).

Wind data used for wave forecasting are data at the sea surface within the wave-generation area. These data may be obtained from direct measurements over the sea surface, for example from a vessel, or from land-based measurements, such as at an airport near the forecasting location, which are subsequently converted into marine wind data. Wind speed is measured using an anemometer and is commonly expressed in knots. One knot is equal to 1.852 km/h or 0.514 m/s. Hourly wind records can be used to determine wind duration, maximum wind speed, wind direction, and mean wind speed (Triatmodjo, 1999:151).

Tides are fluctuations in sea level as a function of time caused by the gravitational attraction of celestial bodies, particularly the Moon and the Sun, on the Earth's ocean mass. Although the Moon has a smaller mass than the Sun, its much closer distance to Earth causes its gravitational influence to be greater (Triatmodjo, 2010).

Waves are an important factor in the planning of coastal structures. Ocean waves may be generated by wind (wind waves), the gravitational attraction of the Sun and Moon (tides), volcanic eruptions or earthquakes at sea (tsunamis), moving vessels, and other sources.

In general, naturally occurring waves are highly complex and difficult to describe mathematically because they are nonlinear, three-dimensional, and random, with individual waves having different heights and periods. Existing wave theories therefore describe simplified wave forms as approximations of natural waves.

The simplest theory is Airy wave theory, also known as linear or small-amplitude wave theory, first developed by Airy in 1845. Besides being relatively easy to understand, this theory can be used as a basis for the planning of coastal structures (Triatmodjo, 2010).

$U10 = Uz1/7$ (1)

Where:

U10 = wind speed after elevation correction (m/s)

Uz = wind speed not measured at an elevation of 10 m (m/s)

Z = elevation or height of the measuring instrument above sea level (m).

$t1 =$ det (2)

$=$ (3)

The value of c is determined as follows:

For $0 < t < 3600$

$C1 = 1,277 + 0,296 \tanh (0,9\log)$ (4)

For $t > 3600$

C1 = -0,15 log t1 + 1,5334 (5)

Where:

Ut = wind speed for the desired wind duration (m/s)

t = desired wind duration (s)

UL = RT x Ut (6)

Uw = RL x UL (7)

Where:

RT = amplification ratio (RT = 1.1)

UL = wind speed over land (m/s)

RL = ratio of wind speed over sea to that over land, obtained from the curve

Uw = wind speed over the sea (m/s)

UA = 0,71UW1,23 (8)

Where:

UW = wind speed for the desired duration (m/s)

UA = wind stress factor (m/det).

Fetch is defined as the area over which wind blows with a relatively constant direction and speed. In wave-generation analysis, fetch is limited by the configuration of land surrounding the water body. Waves are generated not only in the same direction as the wind but also at various angles relative to the wind direction. For calculation purposes, a wind direction may be considered constant when its variation is less than 15°, whereas a variation greater than 45° should be treated as a different direction (CERC, 1984).

Feff = (9)

Where:

Feff = effective fetch

Fi = length of the fetch segment measured from the wave observation point to the end of the fetch

α = deviation on both sides of the wind direction, using angular increments up to the specified angle on either side of the wind direction.

Under fetch-limited conditions, wind blows steadily over a sufficient distance for wave height at the end of the fetch to approach equilibrium. Under duration-limited conditions, wave height is limited by the duration of the wind.

Significant wave height (H0) and spectral peak period (Tp) are forecast using the following equations (CERC, 1984):

H0 = 0,0016 1/2   (10)

TP = 0,2857 1/3   (11)

= 68,8 2/3   (12)

7,15 x 104   (13)

The following figure presents the flowchart of the wave forecasting process using the CERC (1984) method:

The waves calculated in the previous section represent deep-water wave heights derived from analyses of wind speed and direction recorded over several years before the construction of coastal protection structures. To determine design wave height, the previously obtained wave heights are analyzed using probability distribution functions. The methods used for calculating design wave height are the Weibull and Gumbel distributions (Fisher–Tippett Type I) (CERC, 1992).

The Surface-water Modeling System (SMS) is environmental modeling software capable of one-, two-, and three-dimensional simulations. It was developed by the Environmental Modeling Research Laboratory (EMRL) at Brigham Young University, in collaboration with the U.S. Army Corps of Engineers Waterways Experiment Station (USACE-WES) and the U.S. Federal Highway Administration (FHWA).

Numerical modeling in SMS can incorporate various types of information. In principle, the application models hydrodynamic conditions in water bodies, including tides and flow velocities for shallow-water problems. The system provides steady and dynamic models and additional applications for seawater intrusion, sediment transport, wave energy dissipation, and wave properties such as direction and amplitude.

Wave transformation modeling is carried out using two-dimensional wave refraction and diffraction software and a coastal wave spectrum model. Model inputs include wave height, direction, period, and wave spectrum parameters, while the outputs include wave height and direction at the coast.

METHODS

This study employs modeling and analytical methods. The modeling method represents natural phenomena using numerical modeling software, while the analytical method is based on the collection and analysis of data relevant to the study. The main objective is to calculate wave forecasts analytically using the CERC (1984) method and to simulate wave propagation using the Surface-water Modeling System.

The study was conducted on Kapota Island, Wangi-Wangi District, Wakatobi Regency, Southeast Sulawesi Province, at approximately 5°20'26.12" S and 123°30'4.76" E.

The study was conducted in December 2021 and included research preparation, field implementation, data processing, and presentation of the results.

The data required for this study consisted of:

a. Topographic and Bathymetric Surveys

A topographic survey was conducted to determine the land contours of Kapota Island, with approximately 50 steps between prism positions. A bathymetric survey was conducted to determine seabed contours by tracking an area extending approximately 500 m seaward from the shoreline.

b. Tidal Observation

Tidal data were collected through direct field observations for 15 days at 1-hour reading intervals.

a. Wind Data

The wind data covered a 13-year period from 2009 to 2021 and were obtained from NOAA (National Oceanic and Atmospheric Administration) wind data at the BMKG Betoambari Station, Baubau.

b. Administrative Map

The administrative map of Wakatobi Regency was obtained from the official website of the Wakatobi Regency Government.

c. Google Earth Map

The Google Earth map was obtained from the Google Earth application.

The data analysis consisted of tidal analysis, wind analysis for significant wave forecasting, and the integration of bathymetric and topographic maps. These analyses provided the basis for numerical analysis of wave propagation.

The research process began with preparation and the formulation of research objectives, followed by the required stages of analysis until the final results were obtained.

RESULTS

Existing Coastal Conditions at Watubangga

Based on field surveys and direct observations conducted in 2021, the coast of Kapota had experienced shoreline changes caused by high waves. This was evident from considerable sedimentation and accretion at several locations along the coast.

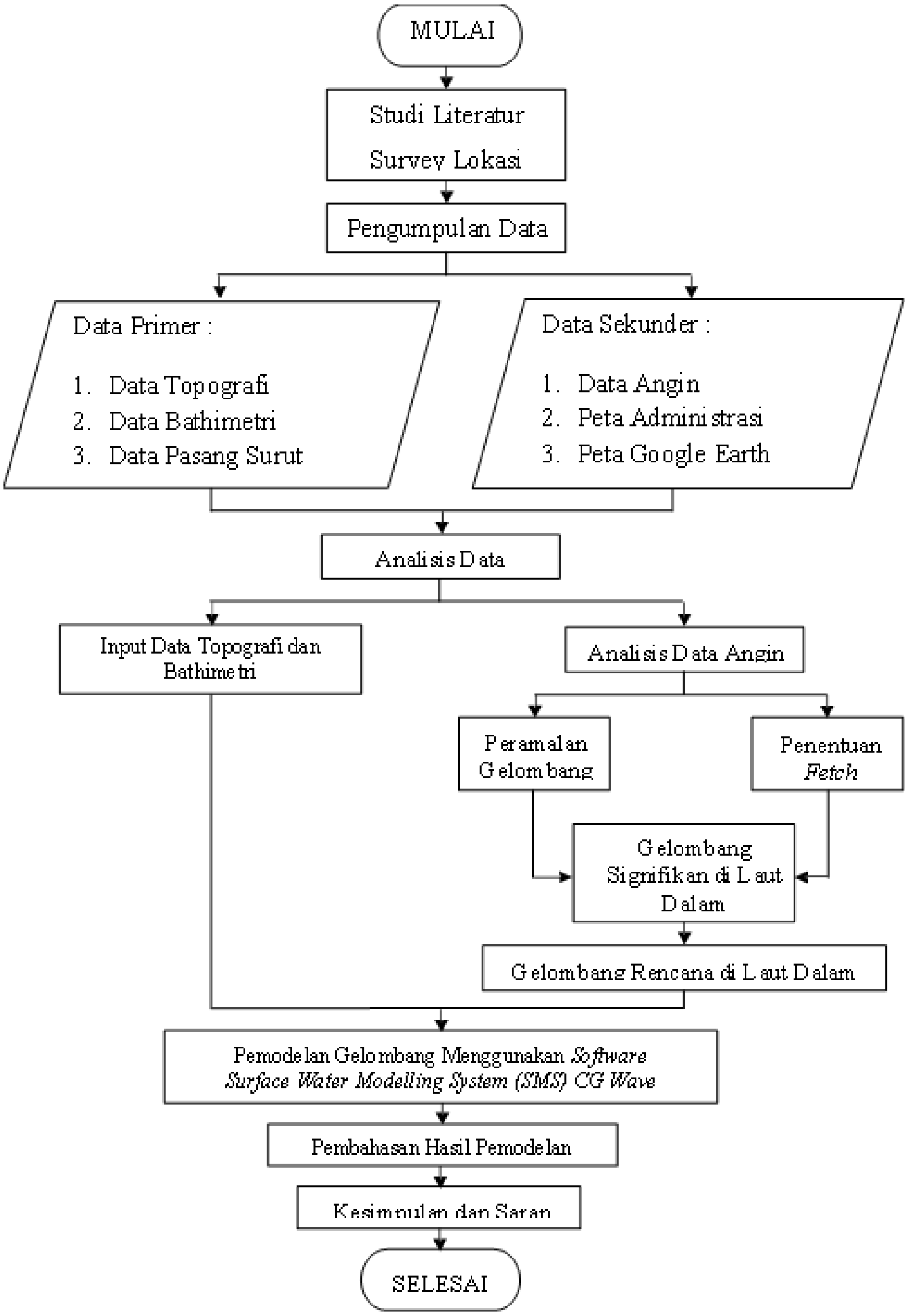
Figure 4. Existing Coastal Conditions on Kapota Island

(Source: Field Survey, 2021)

Analysis of Bathymetric and Topographic Data

Bathymetric and topographic data consisting of corrected X, Y, and Z coordinates (Zkr) for Kapota Island, Wakatobi Regency, referenced to mean sea level (MSL), were processed using Surfer Version 13.

Figure 5. Bathymetric and Topographic Contour Map of Kapota Island Coast



(Source: Data Analysis Results, 2022)

The figure above shows the seabed and land-surface conditions along the coast of Kapota Island, Wakatobi Regency. The coastal area is very gently sloping and is characterized by numerous sand mounds around the shoreline.

Figure 6. Three-Dimensional Contour of Kapota Island Coast

(Source: Data Analysis Results, 2022)

Analysis and Development of the Wind Rose

Wind speed and direction data from 2009–2021, obtained from NOAA at the BMKG Betoambari Station, were used to analyze and construct the wind rose. The data were grouped according to wind speed and direction, after which the frequency and percentage of each group were calculated. The results were then used to develop the wind rose, as presented in the following table.

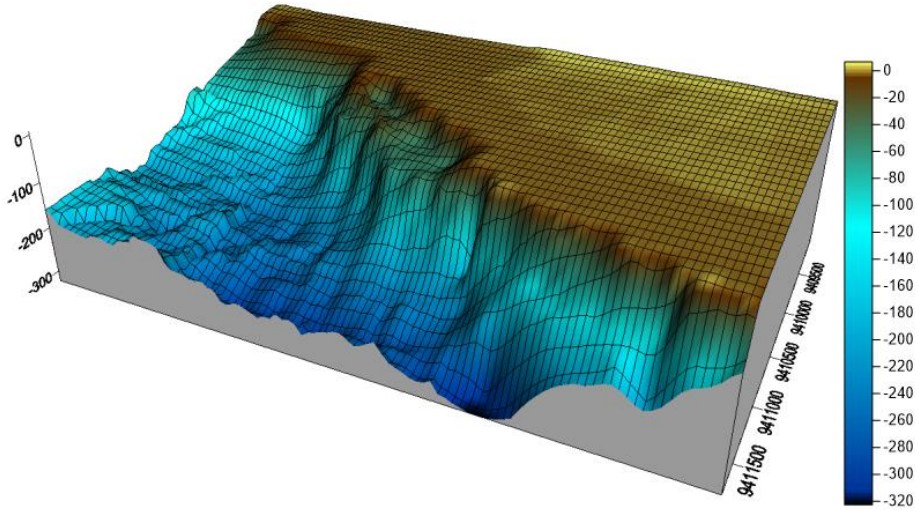
Table 1. Frequency of Wind Occurrence

FREQUENCY OF WIND OCCURRENCE									
Wind Speed (m/s)	Wind Direction								Number of Occurrenc
	U	TL	T	TG	S	BD	B	BL	
0.3<UZ≤1.5	897	1978	4013	1952	1707	954	872	608	12981
1.6<UZ≤3.3	560	1381	2841	796	1107	1402	1838	578	10503
3.4<UZ≤5.4	75	275	1144	345	429	455	694	111	3528
5.5<UZ<7.9	4	31	183	40	58	36	63	11	426
UZ>8	5	2	9	2	4	5	5	2	34
Total Wind Occurrences	1541	3667	8190	3135	3305	2852	3472	1310	27472

No-Wind Occurrences	8942
Total	36414

(Source: Data Analysis Results, 2022)

Figure 7. NOAA Wind Rose Data at BMKG Betoambari Station



(Source: Data Analysis Results, 2022)

Determination of Wave Generation Length Using Effective Fetch

In wave-generation analysis, fetch is limited by the configuration of land surrounding the sea. Within the wave-generation area, waves are generated not only in the same direction as the wind but also at various angles relative to the wind direction.

The effective fetch can be determined using the following equation:

Feff =

Where:

Feff: mean effective fetch

Xi (Fi): length of the fetch segment measured from the wave observation point to the end of the fetch

α: deviation on both sides of the wind direction, using 5° increments up to 45° on either side of the wind direction.

The map used to calculate effective fetch length was obtained from Google Earth. Fetch calculations were performed for the northwest, west, and southwest directions.

48.129 km

48128.88 m

Table 2. Calculation of Effective Fetch for the Northern Direction

EFFECTIVE FETCH – NORTHERN DIRECTION			
α (o)	cos α	Fi (km)	cos α × Fi (km)
45	0.000	0.000	0.000
40	0.000	0.000	0.000
35	0.000	0.000	0.000
30	0.000	0.000	0.000
25	0.000	0.000	0.000
20	0.000	0.000	0.000
15	0.000	0.000	0.000
10	0.000	0.000	0.000
5	0.996	149.700	149.130
0	1.000	149.200	149.200
5	0.996	149.700	149.130
10	0.985	6.100	6.007
15	0.966	5.200	5.023
20	0.940	5.100	4.792
25	0.906	4.100	3.716
30	0.866	4.100	3.551
35	0.819	3.800	3.113
40	0.766	3.700	2.834
45	0.707	3.200	2.263
Σ	9.947	483.900	478.760
Feff	=	48.129	Km
		48128.88	m

(Source: Data Analysis Results, 2022)

Wave Forecasting Using the CERC 1984 Method

Most ocean waves are generated by wind, and the resulting wave height and period are influenced by wind speed (U), wind duration (t1), and fetch (F). The following is an example of wave-generation analysis for 1 January 2009 from the western direction.

1) Elevation Correction

Wind Speed (Uy) = 4.086 knots = 2.10 m/s

Height of the measuring instrument above sea level (y) = 10 m

2) Duration Correction

Wind duration at speed U10

Determination of C1

Determination of U3600

Calculation of Ut

3) Stability and Observation Location Corrections

Stability correction

Observation location correction

4) Drag Coefficient Correction

5) Fetch

Feff = 89,896.975 m (West); therefore:

6) Wave Height and Period Forecasting (Hindcasting)

Wave Height

= 0.2433 x

= 0.262 m

Wave Period

= 8.138

= 2.693 s

Table 3. Calculation of Maximum Annual Wave Height and Period

Tahun	U		BL		B	
	H0 (m)	Tp (detik)	H0 (m)	Tp (detik)	H0 (m)	Tp (detik)
2009	1.547	5.440	0.468	3.600	0.559	3.936
2010	1.541	5.433	0.470	3.609	0.561	3.942
2011	1.824	5.748	0.461	3.574	0.562	3.948
2012	1.515	5.403	0.478	3.641	0.561	3.942
2013	1.604	5.507	0.404	3.345	0.619	4.141
2014	1.543	5.435	0.530	3.831	0.559	3.936
2015	1.765	5.684	0.530	3.833	0.597	4.068

2016	1.543	5.435	0.404	3.345	0.651	4.249
2017	1.733	5.650	0.541	3.873	0.559	3.936
2018	1.543	5.435	0.397	3.319	0.559	3.936
2019	1.543	5.435	0.397	3.319	0.559	3.936
2020	1.523	5.411	0.397	3.319	0.559	3.936
2021	1.733	5.650	0.397	3.319	0.559	3.936

(Source: Data Analysis Results, 2022)

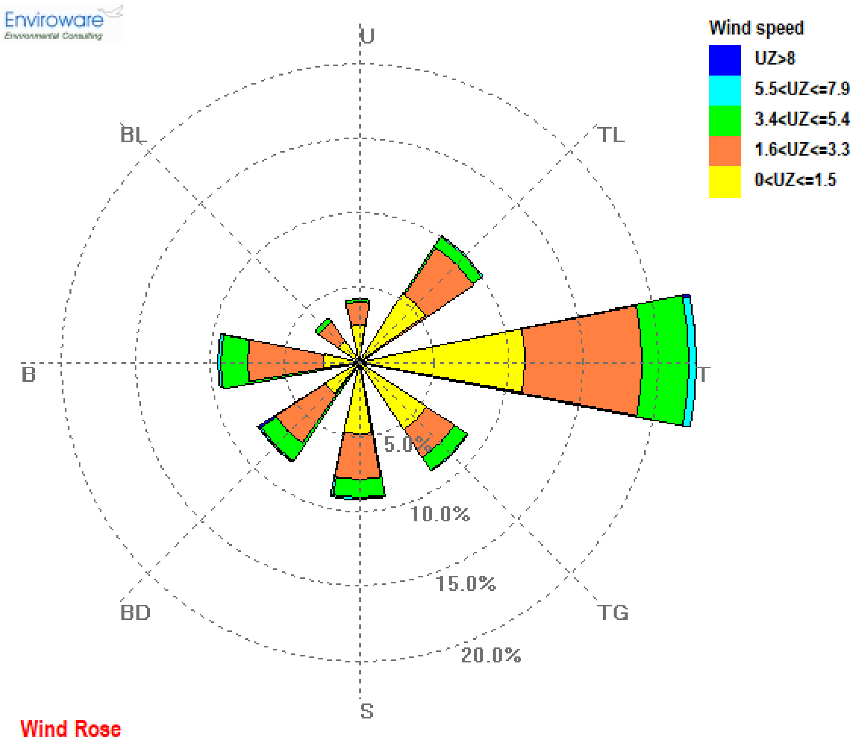
Analysis and Development of the Wave Rose

The analyzed wave forecasting results were subsequently summarized in the table below.

Table 4. Percentage Frequency of Wave Occurrence

Wave Height (m)	Percentage of Wave Occurrence (%)								Number of Occurrences (%)
	U	TL	T	TG	S	BD	B	BL	
$0 < H0 \leq 0.1$	6.03	0.00	0.00	0.00	0.00	0.00	4.44	4.10	14.57
$0.1 < H0 \leq 0.2$	13.11	0.00	0.00	0.00	0.00	0.00	21.48	8.97	43.56
$0.2 < H0 \leq 0.3$	4.79	0.00	0.00	0.00	0.00	0.00	11.50	4.41	20.70
$0.3 < H0 \leq 0.4$	0.00	0.00	0.00	0.00	0.00	0.00	10.04	2.97	13.02
$H0 > 0.4$	0.44	0.00	0.00	0.00	0.00	0.00	7.45	0.27	8.16
Jumlah	24.37	-	-	-	-	-	54.91	20.72	100.00
Total									100.00

(Source: Data Analysis Results, 2022)



(Source: Data Analysis Results, 2022)
Figure 9. Wave Rose

Design Waves in Deep Water

Table 5. Calculation Results of Wave Height for Specific Return Periods in the Northern Direction

Return Period (Tr)	Yr (years)	Hsr (m)	σnr	σr	Hsr-1.28σr (m)	Hsr+1.28 σr (m)
2	5.466	1.582	0.610	0.067	1.497	1.668
5	6.384	1.687	0.278	0.030	1.648	1.726
10	7.077	1.766	0.525	0.057	1.692	1.839
25	7.994	1.870	1.045	0.114	1.724	2.017
50	8.687	1.949	1.460	0.160	1.745	2.154
100	9.380	2.028	1.879	0.205	1.765	2.291
1000	11.683	2.291	3.283	0.359	1.831	2.750

(Source: Data Analysis Results, 2022)

Table 6. Calculation Results of Wave Period for Specific Return Periods in the Northern Direction

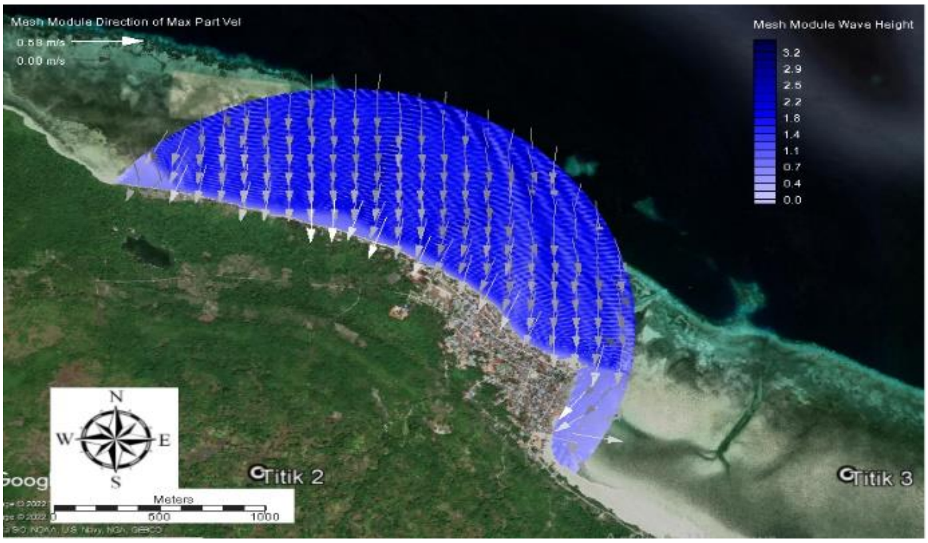
Return Period (Tr)	Yr (years)	Tsr (det)	σnr	σr	Tsr-1.28σr (det)	Tsr+1.28σr (det)
2	5.466	5.479	0.610	0.075	5.384	5.575
5	6.384	5.596	0.278	0.034	5.553	5.640
10	7.077	5.685	0.525	0.064	5.603	5.767
25	7.994	5.802	1.045	0.128	5.638	5.966
50	8.687	5.890	1.460	0.179	5.661	6.119
100	9.380	5.978	1.879	0.230	5.684	6.273
1000	11.683	6.272	3.283	0.402	5.757	6.787

(Source: Data Analysis Results, 2022)

Wave Modeling

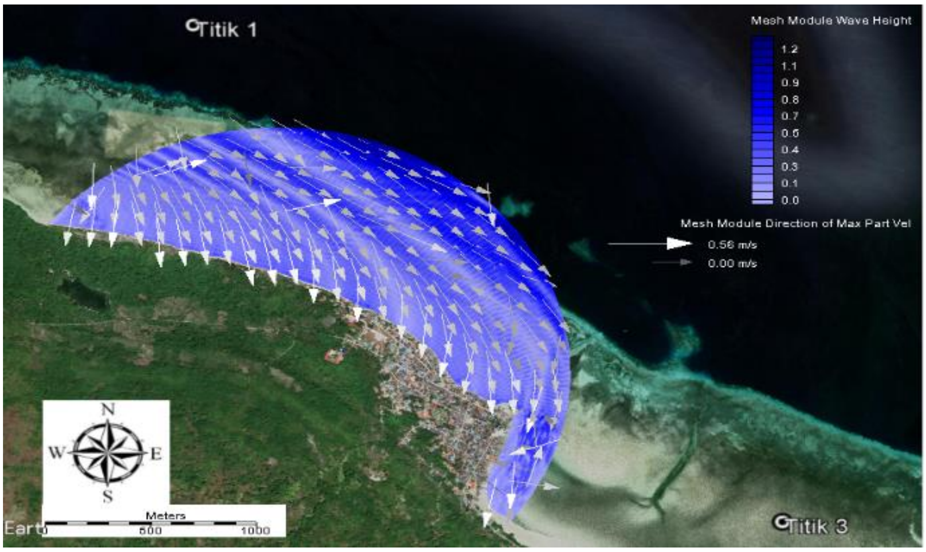
Based on the CGWAVE model simulations, the wave propagation patterns shown by the vector plots for waves approaching from the North, Northwest, and West exhibit maximum wave velocities of 0.58 m/s, 0.56 m/s, and 0.55 m/s, respectively.

Figure 10. Distribution of Wave Propagation Patterns from the North



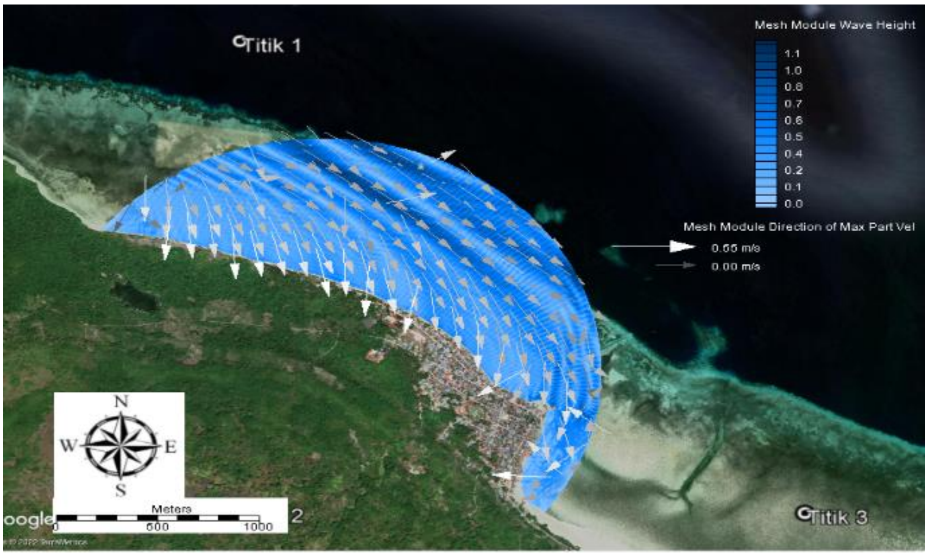
(Source: Data Analysis Results, 2022)

Figure 11. Distribution of Wave Propagation Patterns from the Northwest



(Source: Data Analysis Results, 2022)

Figure 12. Distribution of Wave Propagation Patterns from the West



(Source: Data Analysis Results, 2022)

DISCUSSION

The results show that bathymetric conditions influence the transformation and propagation of waves approaching the coast of Kapota Island. Variations in water depth alter wave characteristics and produce different propagation patterns for waves approaching from different directions.

The wave analysis identified maximum significant wave heights from the North, West, and Northwest of 1.870 m, 0.582 m, and 0.643 m, respectively. The corresponding maximum significant deep-water periods were 5.802 s, 4.035 s, and 4.223 s.

The CGWAVE simulations indicate different propagation responses under the three incident-wave directions, with reported maximum wave velocities of 0.58 m/s from the North, 0.56 m/s from the West, and 0.55 m/s from the Northwest. These findings support the use of bathymetric information and numerical wave modeling as a basis for coastal-zone management and coastal-protection planning on Kapota Island.

CONCLUSIONS

Based on the results and discussion presented in this study, the following conclusions can be drawn:

The maximum significant wave heights were 1.870 m for the northern direction, 0.582 m for the northwest direction, and 0.643 m for the western direction. The corresponding maximum significant deep-water wave periods were 5.802 s from the North, 4.035 s from the Northwest, and 4.223 s from the West.

Based on wave vectors, the maximum wave velocities were 0.58 m/s for waves approaching from the North, 0.56 m/s from the Northwest, and 0.55 m/s from the West.

RECOMMENDATIONS

Based on the results of this study, the following recommendations are proposed:

1. In Surface-water Modeling System simulations, the model geometry should be adjusted to represent the actual existing conditions at the study site.

2. Further studies are required so that the results obtained using the software more closely represent the wave forecasting results obtained through analytical methods.

3. To support and improve student competencies, training related to the use of specialized software and the provision of instructional modules should be developed to assist students in completing final projects involving software applications in the field of Ocean Engineering.

FURTHER STUDY

Further investigations may extend the present modeling by incorporating additional seasonal wave conditions, longer observational records, and more detailed validation data to strengthen the assessment of coastal processes and protection needs on Kapota Island.

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