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Research Article

Analysis of Sea Surface Dynamics during the Coastal Floods in Manado

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ABSTRACT

Coastal flooding is one of the serious problems facing most coastal areas in the world. On January 17 and December 7, 2021, coastal flooding hit the coastal area of Manado, North Sulawesi, Indonesia. The disaster disrupted economic activities on the coast of Manado Bay. This study analyzed the dynamics of the atmosphere and the sea during coastal flood events using water level data from the Geospatial Information Agency, which was then filtered to separate residual and atmospheric tide, and oceanographic reanalysis data of Wavewatch-III from BMKG Ocean Forecast System (OFS). The results show that events on January 17 and December 7, 2021, coincided with the occurrence of the maximum tide. The residual water level shows a significant value of around 0.2 – 0.3 m, indicating the influence of atmospheric phenomena on sea level rise. According to oceanographical data, the local wind is the main factor of flood occurrence, which is shown by wind speed data which increased wave height significantly to 1,5 m on January 17, 2021, and to 2,0 m on December 7, 2021, around Manado Bay coast. Another factor that might contribute to the event is Manado's land morphology. Further study must be conducted to discover the influence of land morphology on coastal floods.

Keywords: Coastal flood; Water level; Tide

INTRODUCTION

Coastal flooding is one of the important problems facing most coastal areas in the world. Sea level rise, as the result of climate change, can increase coastal flood frequency and its severity (Vitousek et al., 2017; Ghanbari et al., 2019; Kulp & Strauss, 2019; Taherkhani et al., 2020; Bates et al., 2021). However, rather than the periodically increased mean sea level, the temporary increase in water level as well as oceanic and atmospheric processes which influenced the maximum water level such as storms, climate variabilities, and circulation patterns are the significant threats of coastal flooding (Erikson et al., 2018; Anderson et al., 2019; Lang & Mikolajewicz, 2019; Schlef et al., 2019; Kirezci et al., 2020; Liu & Huang, 2021). These factors, combined with the time occurrence of astronomical tide, leading to increased coastal flood risk (Rueda et al., 2017; Marcos et al., 2019; de Lima et al., 2020).

Manado City has a high risk of coastal flooding. Based on research conducted by Wibowo et al. (2018), the Manado reclamation area generally experiences land subsidence accompanied by mass groundwater reduction. This statement is also supported by the research of Triana & Janottama (2021) who projected sea level rise in several coastal cities in Southeast Asia. Manado is one of the cities that has a higher sea level rise rate compared to the global rate with a value of

4.51 mm/year. These two statements meet the requirements of the vulnerability factors causing high coastal flooding based on Nicholls et al. (2021), which consisted of climate-induced sea level rise and vertical land movements.

In 2021, two events of coastal floods occurred on January 17 and December 7 respectively causing the cessation of economic activities, especially in the Manado reclamation area (Wibowo, 2021; Supriatin, 2023). However, even though Manado is one of the cities in Indonesia that is prone to coastal flooding, there is still not much research on coastal flooding in Manado, especially for the analysis of meteorological and oceanographic factors. In fact, this research can be used as a reference to issue early warnings for coastal flooding and prevent the occurrence of a lot of damage caused by the flood.

Research had been conducted to discover the cause of coastal floods in some other areas in Indonesia. Ningsih et al. (2011) examined cases of tidal flooding in Jakarta, Semarang, and Surabaya and discovered a significant correlation between rising sea levels and storms. Pratama (2019) carried out tidal flood modeling in Pekalongan and found that model simulation by considering the effect of land subsidence shows an uplift in tidal flood height up to 14 cm. Saragih & Dafitra (2021) conducted research on tidal flooding in Padang using Wavewatch-III data, tidal data, and JASON satellite data and found that wave formation is supported by surface winds. Meanwhile, Sampurno et al. (2022) analyzed interactions between tides, storm surges, and river discharges in the Kapuas River delta and found that wind speed more than 24 m s-1 will generate storm surge travel more than 150 km upstream, increase the river water level, and then trigger an inundation over the Pontianak floodplain.

In this study, in contrast to previous studies, sea surface currents and wind seas were also considered as addition of other parameters. Therefore, this research aimed to analyze the coastal floods occurrences in Manado in 2021 by using harmonic and spatial analysis. Harmonic analysis is accomplished by identifying the residual water level at the time of the flood event while spatial analysis is carried out by mapping oceanographic parameters.

METHODS

This research was conducted in Manado, North Sulawesi. This area is located in Manado Bay, approximately at 1° 29' N, and 124° 48' E. The research area is shown in Figure 1 below. The data sources in this study consist of oceanographic parameters such as significant wave height, wind and speed directions, primary swell height, current speed and direction, and wind sea height. They were obtained from the reanalysis ocean numerical model of Wavewatch-III from *Badan Meteorologi Klimatologi dan Geofisika* (BMKG) Ocean Forecast System (OFS) with a resolution of 7 km in the format of network Common Data Format (NetCDF). These data were then mapped spatially with the Python application. The processed data are then descriptively analyzed by identifying the significant value of them.

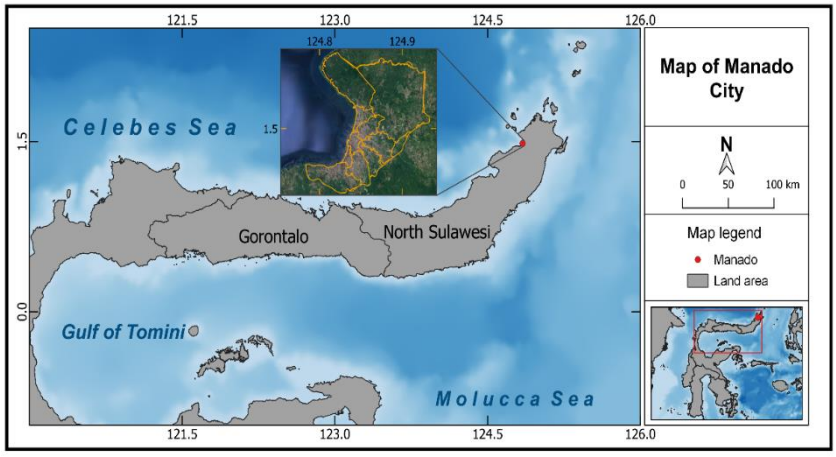


Figure 1. Study area

Meanwhile, two months of sea level data (January and December 2021) were obtained from The Geospatial Information Agency. The data was then filtered into astronomic tides and residual tides using Python re-implementation of the Matlab package UTide (Codiga, 2011) in order to evaluate it harmonically. The astronomic tide is the daily changes in water level which are caused by gravitational interactions between the earth, moon, and sun, while residual tides is a non-astronomic tide caused by other factors besides astronomical factors such as weather (Ningsih et al., 2011). The detail of the process in this study is shown in Figure 2.

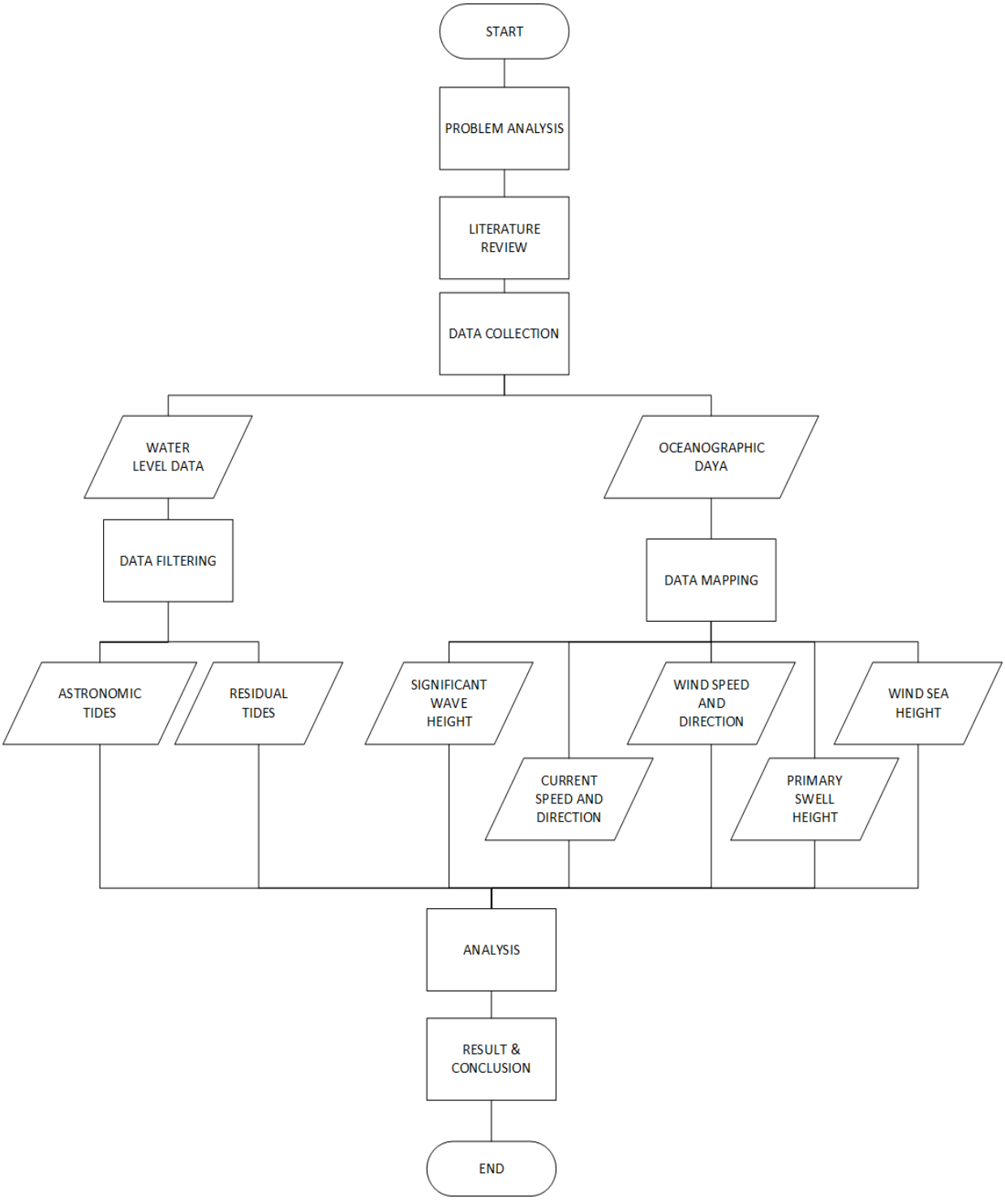


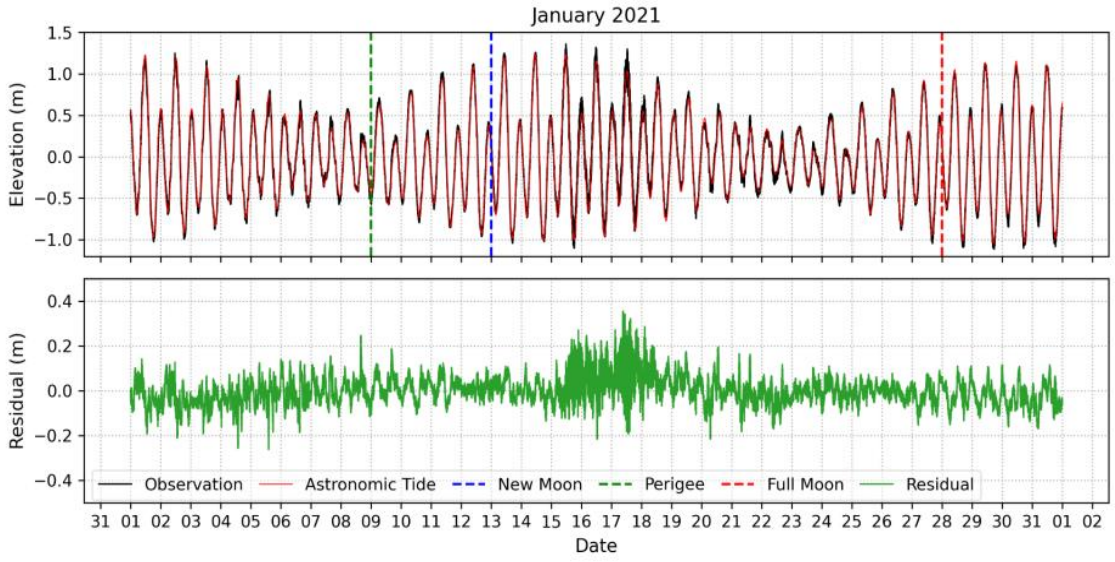
Figure 2. Research flowchart

RESULTS

Sea Tides Analysis

Astronomically, the high tide occurs during the new and full moon phases because both lunar and solar gravitation are aligned to pull in the same direction (McCully, 2006). Based on sea level data taken from The Geospatial Information Agency in Manado, in January 2021 and December 2021, there was about a two-day distance between the occurrence of the new moon / full moon and the maximum tide. Figure 3 shows tidal data in Manado that occurred throughout January 2021 and December 2021. In January, the period when the moon is closest to Earth (perigee) occurs on January 9, 2021, causing an increase in sea level on January 10, 2021, to 0.6 m. Then, the New Moon period occurred on January 13, 2021, which caused an increase in the sea water level to 1.3 m. Likewise when the Full Moon period on January 28, 2021, caused an increase in sea level the next day up to 1.0 m. However, if astronomical factors are separated from non-astronomical factors, it can be seen that there was a significant increase in sea level on January 17, 2021, or during the tidal flood in Manado. This residual sea level rise reaches 0.3 m. Meanwhile, in December 2021, a Super New Moon phase happened on December 4, 2021. This event has had a significant impact on the tides, namely an increase in sea level to 1.4 m. If the astronomical and residual sea levels are separated, the sea level rise due to dominant non-astronomical factors will occur on December 7, 2021, or coincide with the tidal flood in Manado.

The tidal type in Manado is mixed tides prevailing semidiurnal. It is indicated by the presence of two high tides and two low tides in one day, but the height and period are different (Kurniawan et al., 2019). Based on Figure 4, the astronomic tides are in line with observations on January 17, 2021. Manado experiences two high tides in one day, namely at 08.00 – 09.00 LT, which is 0.6 m and at 20.00 – 21.00 LT, reaching 1.5 m. However, after comparing the two tide events, there is an increase in the residual sea water level in the afternoon LT. The height of this residual sea water level ranges from 0.2 – 0.3 m so it indicates that there are factors other than astronomical that cause sea level rise. This is also in line with the tidal value on December 7, 2021 (Figure 4). The observed tidal values are like astronomical tides. However, the residual sea level rise occurs in the afternoon at 16.00 – 17.00 LT along with astronomical tides, causing the tidal value to rise. This residual tidal value is in the range of 0.2 – 03 m. Non-astronomical factors such as weather need to be considered to analyze the causes of the tidal flood.



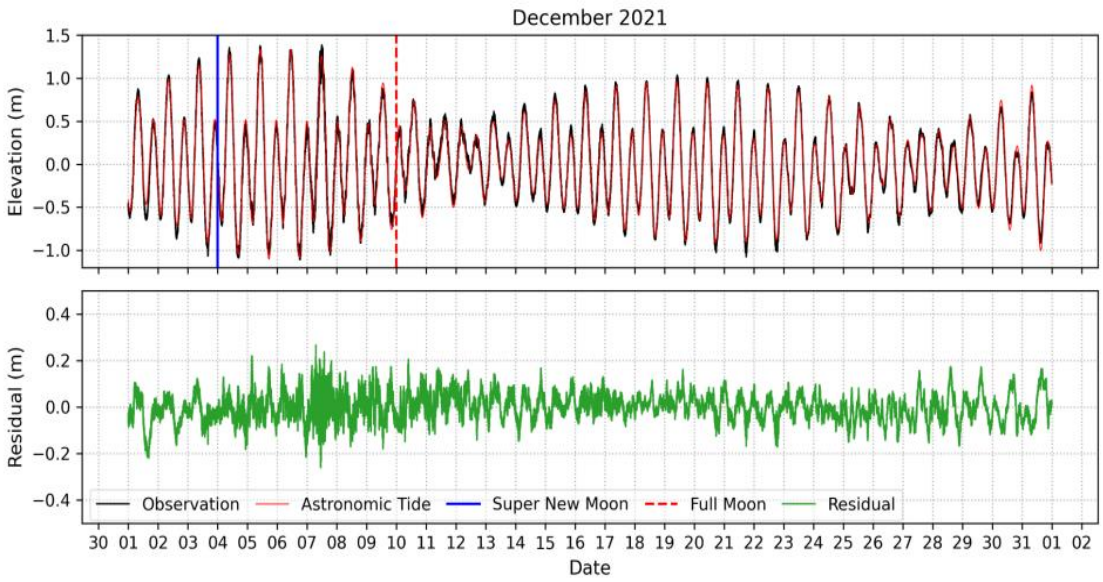


Figure 3. Sea water level data in Manado in January 2021 and December 2021

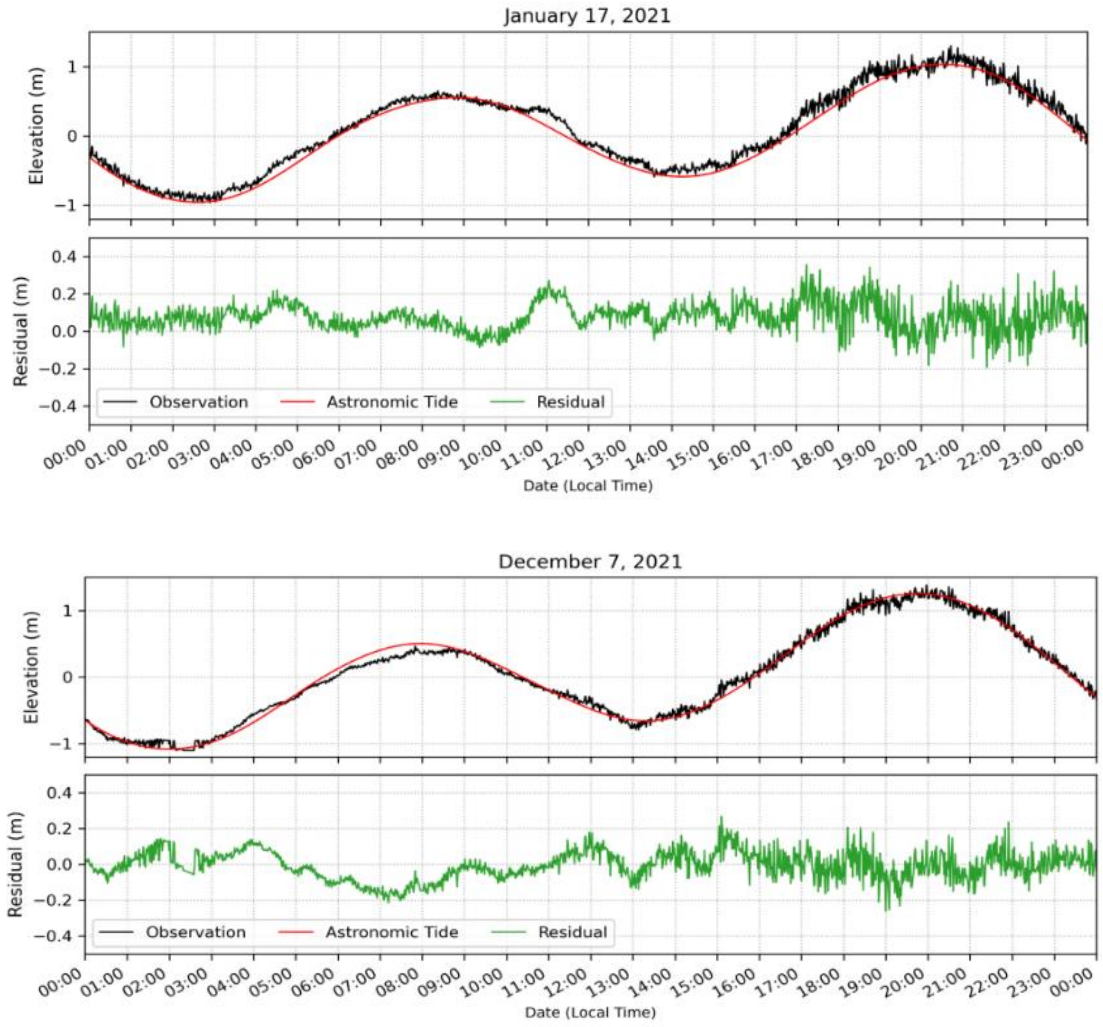


Figure 4. The daily sea water level in Manado on January 17, 2021, and December 7, 2021.

Oceanographic Parameter Analysis

January 17, 2021

Figure 5 shows significant waves that occurred around the waters of North Sulawesi on January 17, 2021. At 08.00 LT, the waves around Manado Bay still showed slight value (0.50 – 1.25 m) with the direction of the waves from West - Northwest. At the same time, the waves from the Sulawesi Sea were already in the moderate category (1.25 – 2.00 m). The waves were getting higher at 20.00 LT, where the waves in Manado Bay were already in the range of 1.25 – 2.00 m with the direction of the waves from West – Northwest. Meanwhile, waves in the Sulawesi Sea also showed an increase in wave height of up to 3.5 m from the Southwest - Northwest or towards the Manado area.

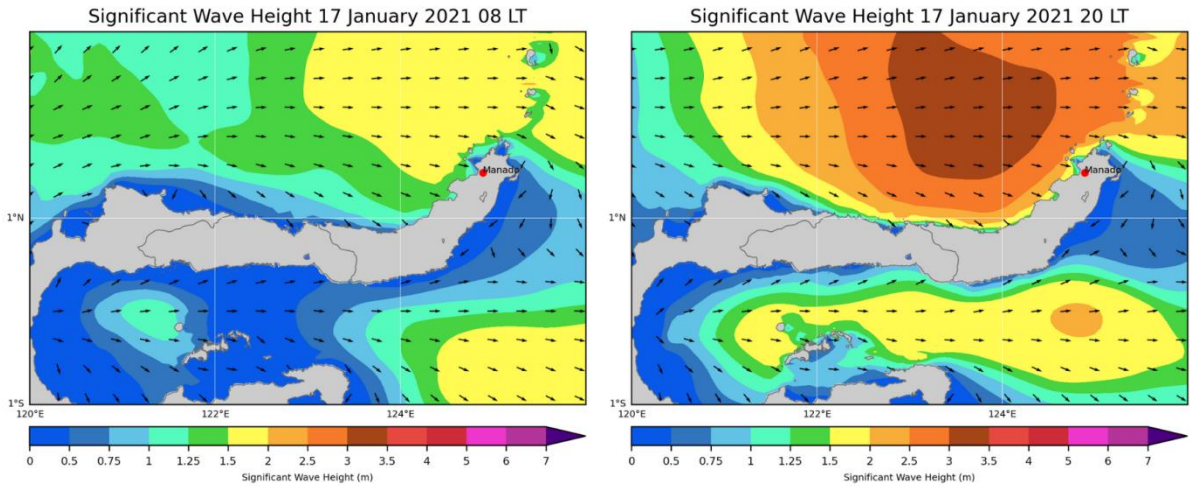


Figure 5. Significant wave height around Manado on January 17, 2021

As one of the wave generating factors, the values of wind direction and speed are also considered to see if these factors have a major effect on coastal floods. Figure 6 shows the direction and speed of the wind on January 17, 2021. At 08.00 LT, the wind around Manado Bay was in the range of 6 – 10 knots and blowing from the Southwest – West. Meanwhile, the wind in the Sulawesi Sea, especially in the western part of the Sulawesi Sea, has shown a speed of 15 – 30 knots and blown from the Southwest – Northwest. The wind speed in Manado Bay increased at 20.00 LT with a speed of 15 – 20 knots blowing from the Southwest – West. The wind speed in the Sulawesi Sea at that hour was also in the same range.

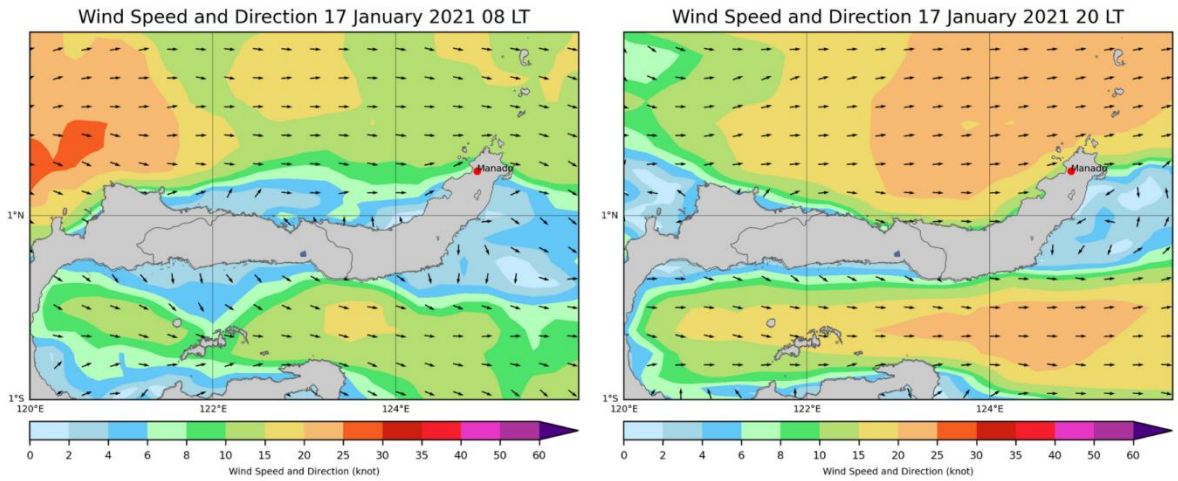


Figure 6. Wind speed and direction around Manado on January 17, 2021.

Figure 7 shows the movement of ocean currents around the waters of North Sulawesi on January 17, 2021. The ocean currents around Manado Bay ranged from 5 – 45 cm/s and headed towards the Northeast – East. Meanwhile, at 20.00 LT, the sea currents around Manado Bay did not experience significant changes, both in direction and speed.

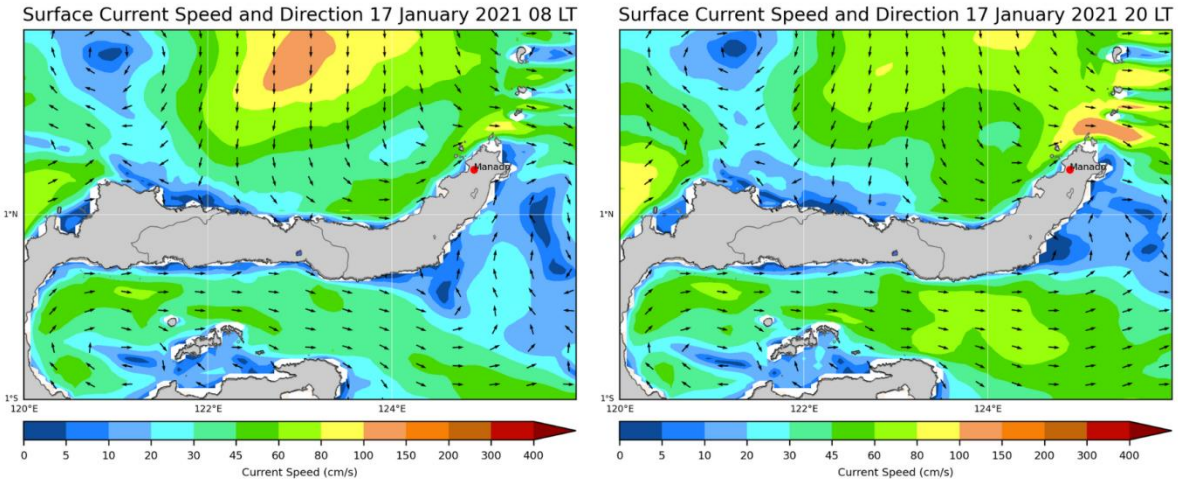


Figure 7. Surface current speed and direction around Manado on January 17, 2021.

Figure 8 shows the primary swell height around the waters of North Sulawesi on January 17, 2021, where at 08.00 LT, the swell in Manado Bay reached 1 m. However, at 20.00 LT, the swell was in a state of calm or less than 0.5 m high.

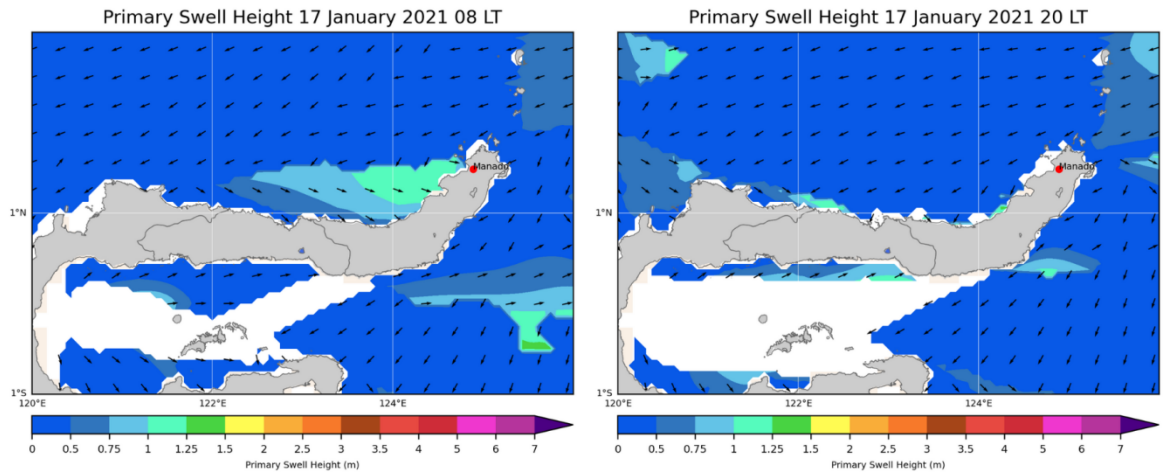


Figure 8. Primary swell height around Manado on January 17, 2021.

Based on the wind sea height on January 17, 2021 (Figure 9), at 08.00 LT there was no significant height around Manado Bay. However, the wind sea height increased at 20.00 LT when the value around Manado Bay was in the range of 1.25 – 1.50 m.

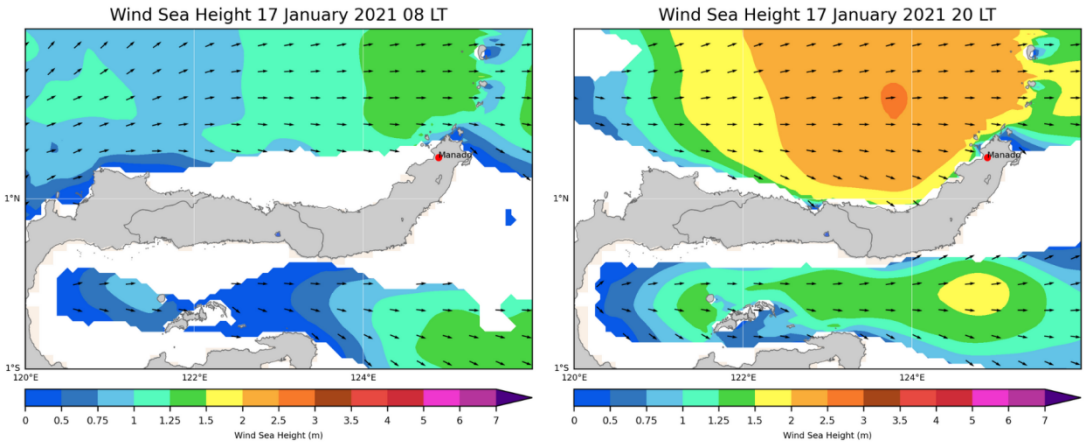


Figure 9. Wind sea height around Manado on January 17, 2021.

December 07, 2021

It is shown in Figure 10 that significant waves on December 07, 2021 at 08.00 LT in Manado Bay showed calm conditions (0.25 – 0.5 m). However, it has been seen that there was significant high waves of up to 2.5 m moving from the West – Northwest or from the Sulawesi Sea. This wave increased at 20.00 LT when a significant wave in Manado Bay showed a value of 1.50 – 2.50 m from West – Northwest.

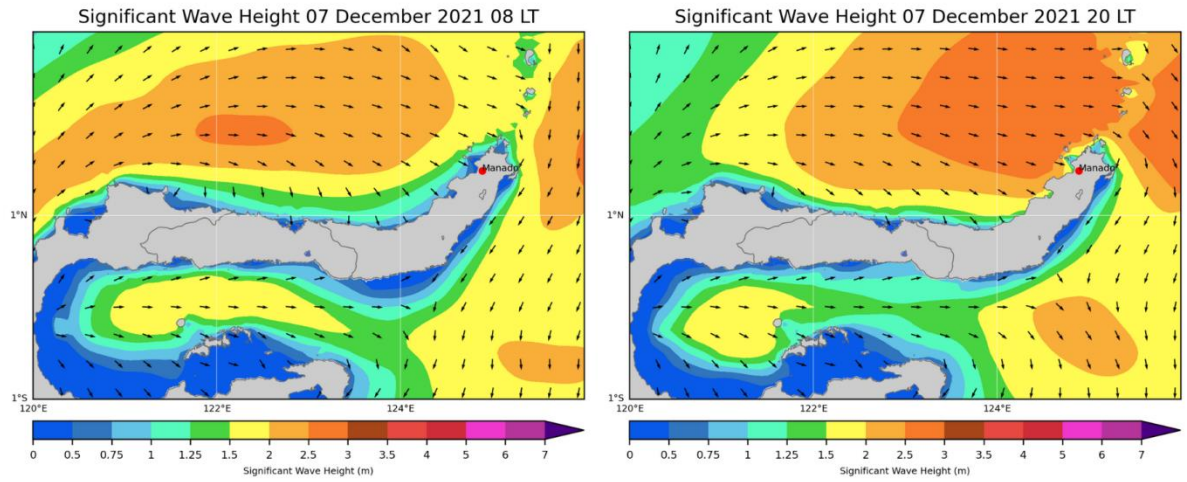


Figure 10. Significant wave height around Manado on December 07, 2021.

Meanwhile, the conditions of wind direction and speed around the waters of North Sulawesi on December 7, 2021, are shown in Figure 11. Around Manado Bay, the wind speed ranged from 6 – 10 knots and blew from the West-Northwest. The wind speed then increased at 20.00 LT, which was in the range of 15 - 20 knots and blew from the Southwest - Northwest.

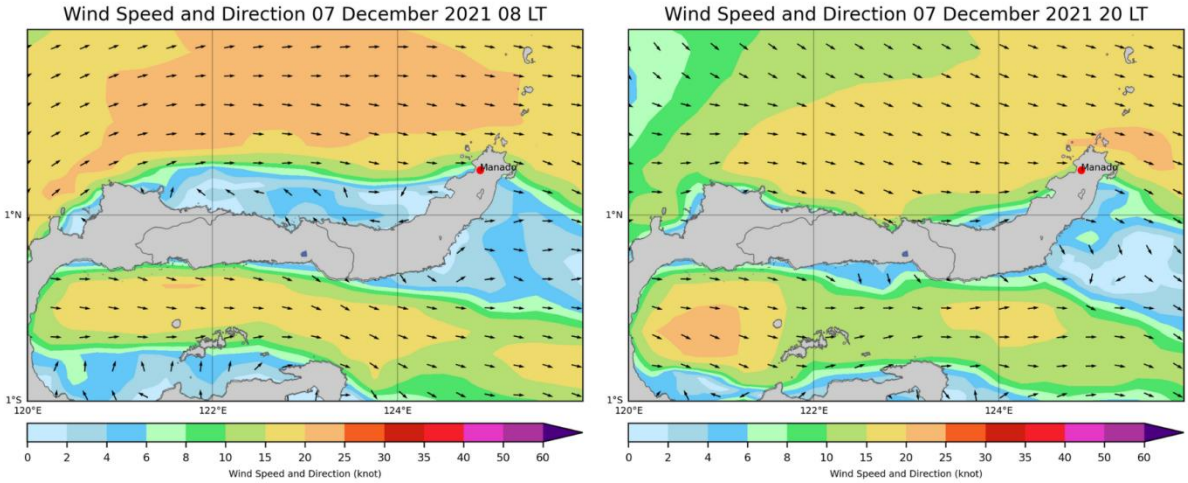


Figure 11. Wind speed and direction around Manado on December 07, 2021

The sea current conditions in the waters around North Sulawesi are shown in Figure 12. At 08.00 LT and at 20.00 LT, there was no significant change in the direction or speed of the current around Manado Bay, which was only in the range of 5 – 45 cm/s and headed towards Northeast - East.

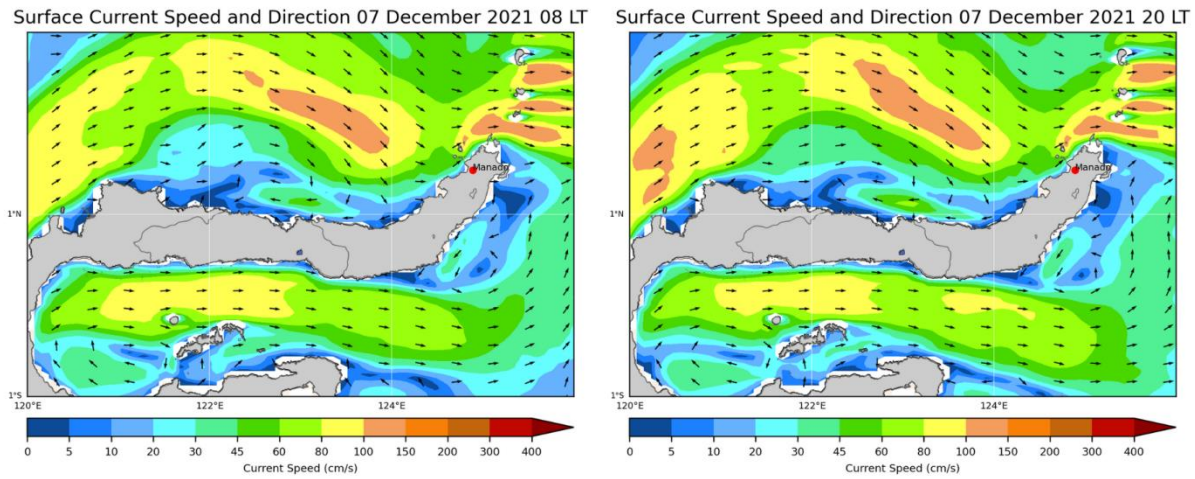


Figure 12. Surface current speed and direction around Manado on December 07, 2021.

The condition of the primary swell around Manado Bay is shown in Figure 13. Based on the processed data, the primary swell on December 7, 2021, at 08.00 UTC was in the range of 0.25 – 0.5 m. However, no swell was detected in Manado Bay at 20.00 LT.

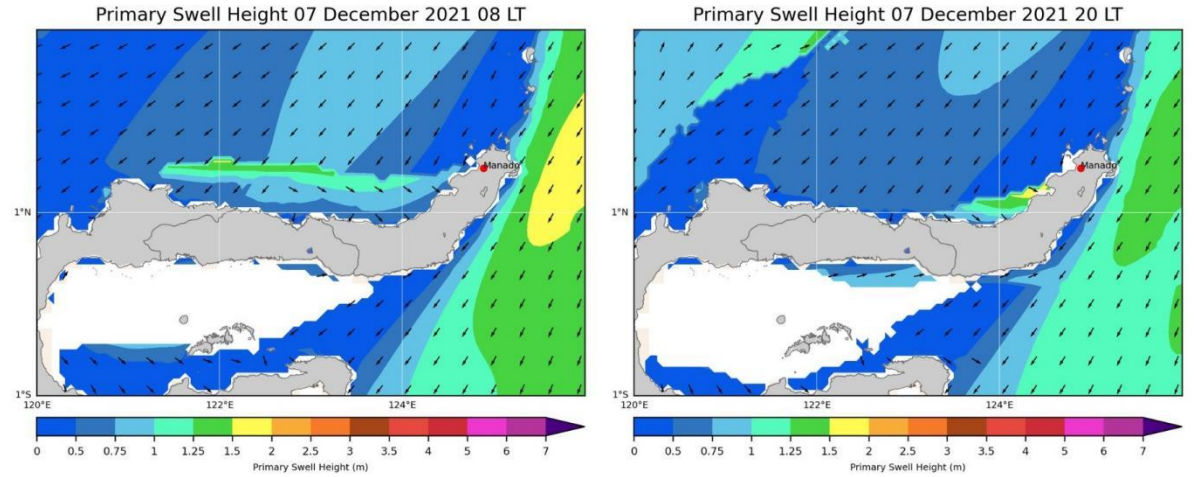


Figure 13. Primary swell height around Manado on December 07, 2021.

Based on the condition of the wind sea height in Manado Bay on December 7, 2021, there was no significant height around there at 08.00 LT. However, the wind sea height then increased significantly at 20.00 LT, in the range of 1.5 m – 2.0 m, as shown in Figure 14.

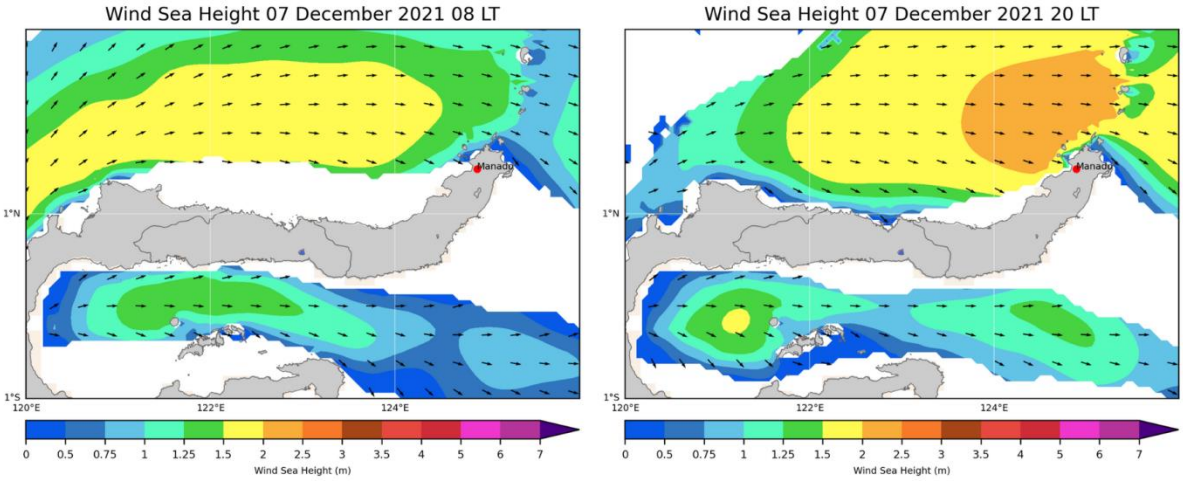


Figure 14. Wind sea height around Manado on December 07, 2021.

DISCUSSION

After seeing the results of sea water level data processing, non-astronomical factors or residual water level, or in this case meteorological and oceanographic factors, is the main factor causing tidal flooding in Manado. This was also supported by astronomical factors, namely the new moon phase, which caused the sea water level to be at the maximum tide. The detail of parameters is shown in Table 1.

Table 1. Significant oceanographic parameter value in Manado Bay during coastal floods

Occurrence Date	Significant Wave Height	Wind Speed and Direction	Current Speed and Direction	Primary Swell Height	Wind Sea Height	Other Factors
17 January 2021	1.25 – 2.00 m from West - Northwest	15 – 20 knots from Southwest - West	5 – 45 cm/s to Northeast – East	0.25 – 1.0 m	1.25 – 1.5 m	New Moon phase
07 December 2021	1.50 – 2.00 m from West - Northwest	15 – 20 knots from Southwest - Northwest	5 – 45 cm/s to Northeast – East	0.25 – 0.5 m	1.25 – 2.0 m	Super New Moon phase

Based on the sea surface dynamics data that has been analyzed, there are similarities in conditions for the two events, namely wind speeds of up to 20 knots from the west, also supported by surface currents moving from the Sulawesi Sea to Manado Bay. In addition, the strong winds also caused waves to rise up to 2.5 m. The increase in wave height can be seen from the analysis of wind sea height, where it can be seen that the number of waves generated by the wind reached 2.0 m around Manado Bay. In this analysis, the swell did not significantly influence the occurrence of coastal flooding.

Previous studies such as Ningsih et al. (2021) and Xu et al. (2022) stated that tropical cyclones can also have an indirect impact on tidal flooding. However, in the two tidal floods in Manado, no tropical cyclones were recorded that hit the area around the area. Nevertheless, those two events have similar weather conditions. According to rainfall intensity data taken from Sam

Ratulangi Meteorological Station (Table 2), on January 17, 2021, continuous rain happened from 12.00 LT to 16.00 LT, resulting in 10.1 mm total rain measurements at 14.00 LT and 17.00 LT. Meanwhile, on December 07, 2021, intermittent light rain happened between 08.00 LT and 09.00 LT. It then became continuous light rain from 10.00 LT until 14.00 LT, resulting in 10.5 mm total rain measurements at 14.00 LT.

Table 2. Rainfall intensity in Manado before coastal flooding events

Time (LT)	Rainfall Intensity (mm)	
	Jan 17, 2021	Dec 07, 2021
08:00	0	1.5
11:00	0	7
14:00	10	3.5
17:00	0.1	0.2
20:00	0	0

Extremely high intensity and persistent rainfall may result be the driver of coastal flooding (Sutrisno et al., 2020). Both coastal flooding events in Manado satisfied the continuous rainfall condition. However, according to the BMKG rainfall intensity threshold (Gustari et al., 2012), the rainfall during coastal floods in Manado is categorized as light rain with intensities less than 20 mm/day and less than 5 mm/hour. Thus, rainfall did not impact significantly coastal flood events in both cases.

Another factor that causes the high risk of coastal flooding around the Manado area is the change in land morphology which is also accompanied by the urbanization of coastal cities. Bilskie et al. (2014) discovered that the storm surge response to sea level rise is dynamic and sensitive to changes in the landscape. Manado area had a similar situation where the land morphology keep changing over the years due to the presence of coastal protection buildings and land reclamation (Manginsela et al., 2016). Moreover, according to Xu et al. (2021), reclamation is an important contributor to coastal floods because it has substantially increased population exposure, so it is essential to incorporate reclamation into the assessment process of future coastal flooding impacts.

CONCLUSION

Meteorological and oceanographic factors were the main factors causing coastal flooding in Manado on January 17 and December 07, 2021. At the time of the incidents, the wind speed was blowing up to 20 knots from west around Manado Bay, increasing sea level in that area. This was also supported by astronomical factors, namely the new moon phase, which caused the water to be at the maximum tide. It should also be noted that the Manado reclamation area is vulnerable to flooding due to the land morphology. Further study must be conducted to discover the influence of land morphology on coastal floods in Manado.

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DECLARATIONS

Conflict of Interest

The authors declare that in the research and preparation of this article, there are no conflict of interests related to certain organizations, institutions, and individuals or groups.

Ethical Approval
On behalf of all authors, the corresponding author states that the paper satisfies Ethical Standards conditions, no human participants, or animals are involved in the research.

Informed Consent
On behalf of all authors, the corresponding author states that no human participants are involved in the research and, therefore, informed consent is not required by them.

DATA AVAILABILITY

Data used to support the findings of this study are available from the corresponding author upon request.

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