Drivers of Tidal Flooding and Coastal Vulnerability in the Riau Islands, Indonesia: A Time-Series Analysis (2022-2024)

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Abstract

The Indonesian Maritime Continent is highly vulnerable to climate variability and change, as exemplified by tidal flooding events in the Riau Islands from 2022 to 2024. This study aimed to analyze the characteristics of sea level dynamics and anomalies associated with tidal flooding (rob) and identify the contributing factors. Data on tidal flooding events were gathered from press and online social media reports, while additional information on significant wave height, ocean currents, and wind was obtained from the CMEMS (Copernicus Marine Environment Monitoring Service) Marine Copernicus archives (marine.copernicus.eu). Observational data from tide gauge stations were also accessed via the IOC sea level monitoring system (ioc-sealevelmonitoring.org). The findings revealed a high probability of tidal flooding during the north wind season, particularly in January and February. Notably, tidal elevations during flooding events reached 3.06 m on January 25, 2023, 3.00 m on February 21, 2023, and 3.09 m on February 12, 2024. These events were driven by a combination of oceanographic and atmospheric factors, including high tidal ranges during spring tides, strong wind speeds averaging 19.04 to 21.43 knots in January–February 2023 and 18.65 knots in February 2024, dominant southward current patterns, and significant wave heights reaching up to 1.08 m. The alignment of the sun, moon, and earth during full and new moon phases amplified gravitational forces, causing elevated sea levels. Furthermore, strong winds during the north wind season contributed to higher wave heights, intensifying flooding impacts. Analysis of current patterns indicates that the highest speeds were recorded during the northern wind season, specifically in January and February, which coincides with the tidal flooding events. The currents predominantly moved southward, aligning with the wind direction during this season. This study reveals oceanographic and atmospheric interactions driving tidal flooding, offering insights for mitigation and adaptation to enhance resilience in vulnerable coastal regions.

Keywords: *tidal flooding, Riau islands coastal waters, wind speed, significant wave height, ocean currents*

Introduction

The Indonesian Maritime Continent, is vulnerable to climate variability and change, which often leads to natural disasters. Based on the 2018 disaster risk index calculation for 34 provinces in Indonesia, it was found that 16 provinces (47.06%) fall into the high disaster risk category, while 18 provinces (52.94%) are classified under medium disaster risk, with no provinces falling into the low disaster risk category. According to Harsoyo (2020), the province with medium-low risk is the Riau Islands Province (score 116.40). One example of a natural disaster that occurred was the tidal flooding disaster that affected the coastal areas of the Riau Islands from 2022 to 2024. Several industrial zones and vital infrastructure in the Riau Islands' coastal areas resulted in significant material and non-material

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losses due to tidal flooding. In coastal cities, compound flooding during tropical cyclones often forms under the concurrent effects of storm surges, heavy rains, and enormous waves (Jane *et al*., 2020; Gao *et al*., 2020, 2021; Hsiao *et al*., 2021). Compound floods have more complex flood processes and cause more severe losses to coastal economies (Couasnon *et al*., 2018; Jang and Chang, 2022; Shi *et al*., 2022). According to Setiyono *et al*. (2020), the direct and indirect effects of tidal flooding have hindered various economic and social activities. In addition, several studies have indicated that tidal flooding has adverse effects on coastal areas (Efendi *et al*., 2021; Pasaribu *et al*., 2021; Dusek *et al*., 2022). Floods have an extensive impact range and are among the most severe threats to coastal areas (Fang *et al*., 2020; Matsuba *et al*., 2021).

Egaputra *et al*. (2022), argue that tidal flooding is a flood disaster phenomenon caused by seawater entering and inundating land. Climate change impacts sea level rise, which is one of the contributing factors to tidal flooding. According to Setiyadi *et al*. (2023), sea surface height (SSH) is the distance between the ocean surface and the Earth ellipsoid reference. The relationship between sea surface height and tidal flooding is close and significant. Tidal flooding occurs when the sea level rises above the normal level, resulting in inundation in coastal areas. Overall, higher sea surface height increases the risk of damage due to tidal fluctuations, especially when extreme weather conditions are accompanied by unsustainable coastal development. Coastal flooding frequently occurs for extreme water level events because of simultaneous, combined contributions from astronomic, atmospheric, thermal, oceano-graphic, or geophysical forces (Woodworth *et al*., 2019). The floods induced by the co-occurrence of multiple drivers are com pound flood events that can exacerbate the flood impacts compared to floods under single disaster drivers (Shen *et al*., 2019; Jang and Chang, 2022).

Floods in these regions are influenced not only by local precipitation but also by the combined effects of water or tidal levels from adjacent major rivers (Sadler *et al*., 2020; Gao *et al*., 2023; Zhang *et al*., 2023). Tidal flooding is caused by the overflow of seawater into the surrounding coastal areas. The gravitational pull of the moon and the sun become much stronger compared to other times when the Moon, Earth, and Sun are aligned, or during a full moon or new moon. This is when spring tides occur. The rise in sea level due to tides is a common natural phenomenon and can be predicted. Tidal events are caused by the movements of the sun, earth, moon, and other celestial bodies, as well as the movement of other celestial objects. The tidal waves caused by rising sea levels are influenced by the tidal forces and other external factors such as water surge, swell (waves generated from distant areas), storms, and tropical storms, which are common phenomena at sea. The combination or interaction of all these factors results in sea level anomalies that cause tidal flooding. According to Agustina *et al*. (2025), marine phenomena such as tides, rising sea levels, or external factors such as wind thrusts have a major influence on the formation of tidal floods. Tidal flooding events may also increase due to other factors, such as wind and heavy rainfall during certain periods. During the eastern monsoon season, wind and wave height have a more significant impact on the occurrence of tidal flooding, while in the western monsoon season, high rainfall should also be closely monitored (Budiman and Supriadi, 2019). Thus, from these explanations, there are two types of factors that cause tidal flooding: topographic factors, which are influenced by land subsidence, and sea surface factors, which are influenced by waves, wind, and rainfall.

Research on tidal flooding or tidal surge flooding has been widely conducted by previous researchers, with various methods and models used to analyze tidal flooding events in different locations. Many researchers have studied the joint probability of multiple flood drivers and conducted risk assessments for compound floods in coastal areas in recent years (Kang *et al*., 2019; Li *et al*., 2019; Lin *et al*., 2020; Hsiao *et al*., 2021). In addition, several studies have analyzed the relationship between tides and tidal flooding (Efendi *et al*., 2021; Pasaribu *et al*., 2021; Dusek *et al*., 2022; Guo *et al*., 2025). However, there has been limited research and studies in the Riau Islands Province. Moreover, to effectively predict and manage tidal flooding events, it is crucial to understand the characteristics of sea level dynamics and anomalies, as well as the influencing factors. Effective mitigation and adaptation strategies rely on a comprehensive analysis of the underlying causes, contributing factors, and potential scenarios related to tidal flooding (Jamalludin *et al*., 2016).

This study aims to analyze the characteristics of sea level dynamics and anomalies associated with tidal flooding (*rob*), as well as the factors influencing these events. The understanding of these characteristics and factors is expected to provide useful information for mitigation and adaptation to tidal flooding disasters in the future.

Materials and Methods

This study was conducted between 2022 and 2024 in the Riau Islands region, as shown in (Figure 1). The material used in this study includes secondary data from the results of Jamaludin *et al*.(2016), who analyzed cases of tidal flooding on the North Coast of Jakarta. The data comprised information on tidal flooding events in the Riau Islands area, collected from various sources such as news reports and online social media from 2022 to 2024. Additional information on significant wave height data, ocean currents, and winds was downloaded from the CMEMS (Copernicus Marine Environment Monitoring Service) Marine Copernicus archive (marine.copernicus.eu). Additionally, observational data from tidal stations were downloaded from the IOC sea level monitoring system archive (ioc-sealevelmonitoring.org) for a period of 30 d with an interval of 60 min, downloaded from November 2022 – March 2023 and November 2023 – March 2024. The research workflow is presented in Figure 2.

Wave data

The input model data used in this study came from the downloaded wave data from Marine Copernicus, accessed at https://cds.climate.copernicus.eu/, with a time interval of 3 h, downloaded from November 2022 – March 2023 and November 2023 – March 2024. The data obtained from Marine Copernicus was in .nc format, which was then converted using Ocean Data View (ODV) to the .txt format for use in Microsoft Excel. The Ocean Data View (ODV) application was used to process the records and obtain time series graphs. This method has also been adopted by previous studies (Harmoko *et al*., 2023).

Wind data

The wind data obtained includes wind speed, direction, and time, accessed from the global ECMWF (European Center for Medium-range Weather Forecasts) data site at https://cds.climate.copernicus.eu/. The data period selected is from November 2022 – March 2023 and November 2023 – March 2024, with a time interval of 1 hour. The downloaded data was then imported into the ODV (Ocean Data View) tools for conversion from .nc format to .txt format. The .txt data was then processed in Microsoft Excel to determine the wind direction and speed. The results were processed using WRplot to identify the dominant direction and speed. Wind measurements were also categorized using the Beaufort scale by the WMO (2017) to facilitate analysis.

Current data

The data used to analyze current movements in the Riau Islands region from November 2022 – March 2023 and November 2023 – March 2024 were obtained from CMEMS (Copernicus Marine Environment Monitoring Service) at https://marine.copernicus.eu/. The downloaded data included current data (Vo and Uo), significant wave height data (SWH), and sea surface height above geoid (SSH). Once the data was downloaded, it was processed using software such as ODV (Ocean Data View) or Ocean Data View (Schlitzer, 2025). The data processing in ODV was conducted following the methods outlined in previous research (Setiyadi *et al*., 2023). The .nc files were imported, and the time dimension in the subset was halved. The layout template was adjusted to a single surface window. The next step involved creating an overlay window and changing components with arrows, filling them with X and Y data. After all steps were completed, the processed data was saved.

Result and Discussion

The list of tidal flooding events in the Riau Islands region from 2022-2024, including dates and locations, was compiled exclusively from social media sources. The results showed that the events generally occur in January and February.

Table 1 shows that between November 2022 and March 2024, 3 tidal flooding events occurred, primarily in January and February, during the west season. However, in the Riau Islands, this period is referred to as the north season. The observation was in line with the statement of Nurlianti *et al.* (2023), who stated that the direction and speed of the wind are based on the seasonal wind pattern known among the community of the Riau Islands Province. In this region, the west season is called the north season (December-February). The transition season I is called the east season (March-May) known as the south season (June-August). Meanwhile, the transition season II is called the west season (September-November).

Tidal conditions during tidal flooding events

According to Jasin and Jansen (2019), tides refer to the periodic rise and fall of sea level. The tidal phenomenon is caused by the gravitational forces of the moon and the sun. The rise and fall of sea level occur periodically due to the combined gravitational forces of the sun, earth, and moon. Based on the tidal prediction data from BIG (Badan Informasi Geospasial), a clear correlation exists between tidal flooding events and the full moon phases. During one lunar cycle, two spring tide events occur, one during the new moon and another during the full moon. The position of the full moon can amplify wind activity, which contributes to the severity of tidal flooding. Tidal predictions for the period from November 2022 to March 2023 (Figure 3) show two significant eventsthat coincided with the full moon and the west or north monsoon season. The first event, from January 20-25, saw the highest water level reach 3.06 meters on January 25. The second event, from

February 20-22, recorded a peak elevation of 3.00 meters on February 21. A similar pattern was observed in tidal predictions from November 2023 to March 2024 (Figure 4). The full moon coincided with a flooding event that occurred from February 12-14. The highest water elevation during this period was 3.09 meters, recorded on February 12. This event also took place during the west or north monsoon season, with the full moon's position contributing to intensified winds that influenced the flooding.

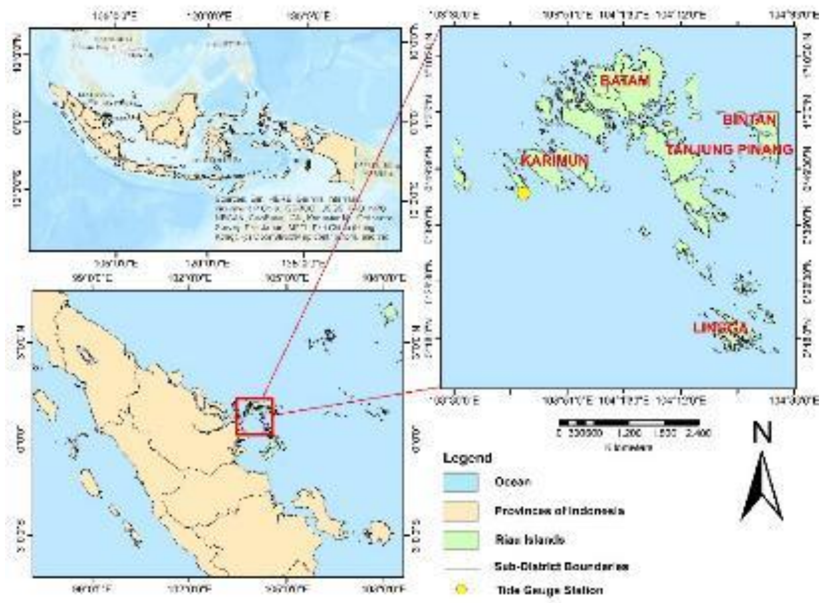

Figure 1. Tidal Flooding Study Location

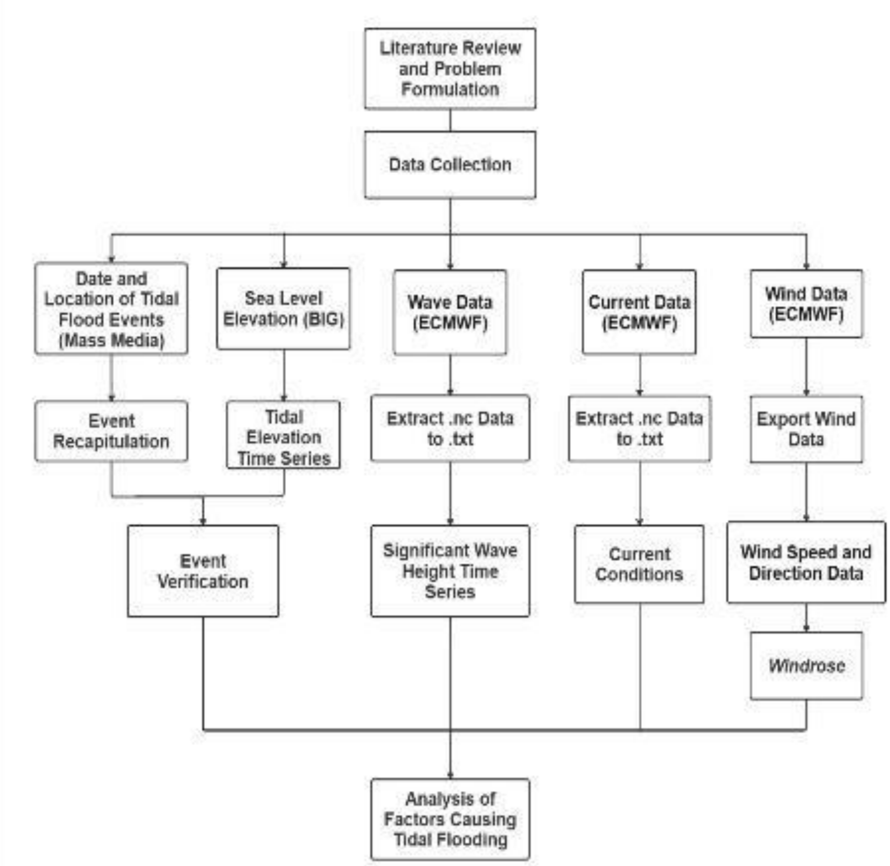

Figure 2. Research workflow

Table 1. List on Tidal Flooding Events Recorded by the Media

No	Date	Location of flooding (recorded in the media)	Source
1.	January 20-25, 2023	West Tanjung Pinang, Tanjung Pinang City	https://youtu.be/
		Karimun Regency (Pamak Village, Tanjung Berlian Village, Pongkar Beach, Tanjung Batu Village)	https://regional.kompas.com/
		Bintan Regency (Kota Baru Village)	https://www.detik.com/
2.	February 20-22, 2023	Karimun Regency, Lingga, Batam to Bintan Island	https://www.mongabay.co.id/
		Tanjung Pinang City	https://mediaindonesia.com/
		Karimun Regency	https://www.kepriheadline.id/
3.	February 12-14, 2024	Tanjung Pinang City, Bintan Regency, Karimun Regency, and Natuna Regency	https://www.mongabay.co.id/
		Karimun Regency	https://youtu.be/
		Bintan	https://sijoritoday.com/
		Tanjung Pinang, Bintan, Karimun, and Lingga	https://www.cnnindonesia.com/

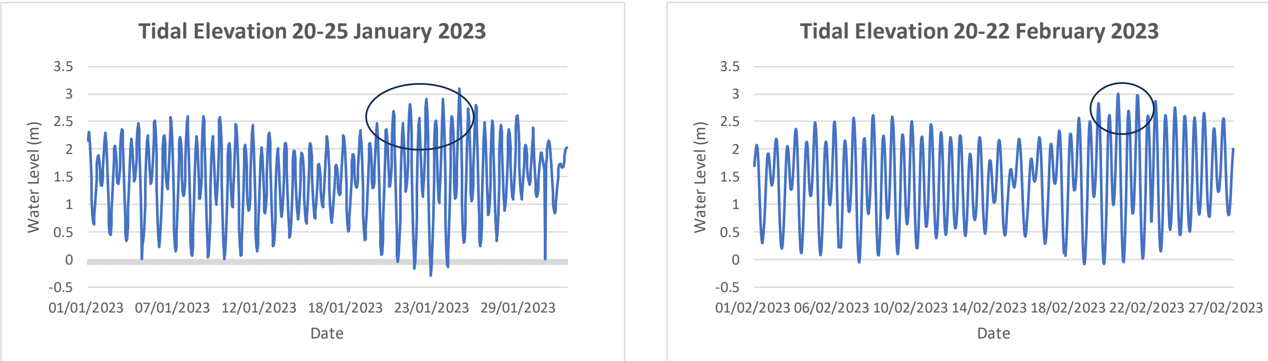

Figure 3. Tides on the dates of tidal flooding events (black circles/ovals) from November 2022 to March 2023.

Gravitational forces cause the rise in sea level and result in the phenomenon of tides. In relation to the tidal flooding events on January 20-25, 2023, February 20-22, 2023, and February 12-14, 2024, these tidal events occurred during the new moon phase. The new moon phase occurs when the moon is aligned between the sun and the earth, a position known as spring tide, where the moon blocks the sunlight. At this time, the moon reaches its closest point to the earth, known as perigee. The strong gravitational force between the moon's center and the earth's center during this alignment generates high tides in the ocean. Analysis of the data reveals that the highest tide events occurred on January 24, 2023, February 22, 2023, and February 12, 2024. Thus, Pariwono's (1989) assertion is proven correct, as the highest tides occur during the spring tide period when the earth, moon, and sun are aligned, according to astronomical factors. In contrast to the full moon, during the crescent moon phase, the positions of the moon, sun, and earth form a right angle, weakening the gravitational forces between the sun and moon, resulting in the lowest sea levels. There are two full moon events each month, during the new moon and the full moon.

Significant wave height conditions

According to Li *et al*. (2019), the estimation of wave overtopping is based on the significant wave height and tide level. The position of the moon influences tidal conditions, leading to high sea levels, known as spring tide events, which superimpose with significant wave heights. High sea levels also trigger elevated waves. The data processing results (Figures 5 and 6) indicate that dominant wave activity contributes significantly to flooding in the Riau Islands region. The analysis shows that during tidal flooding events (indicated by black circles/ovals), the Significant Wave Height also increased, reaching values higher than usual. From the various observed conditions, it can be concluded that key contributing factors include the Significant Wave Height of the Sea Surface (VHM0) and the Significant Wind Wave Height of the Sea Surface (VHM0_WW), both of which were observed to peak during the flooding events (black circles/ovals). The Significant Wave Height of the Sea Surface (VHM0) represents the surface wave height that significantly contributes to tidal flooding. This reflects the highest waves within a specific period, directly impacting the rise in sea levels in the area. Additionally, the Significant Wind Wave Height of the Sea Surface (VHM0_WW) can increase sea levels when interacting with ocean currents, thereby exacerbating tidal flooding conditions.

The study documented several instances of peak wave height during flooding events. From January 20–25, 2023, the highest VHM0 and VHM0_WW values of 1.08 meters were recorded on January 25 in Lingga Regency. During the second event, from February 20–22, 2023, the VHM0 and VHM0_WW peaked at 0.85 meters and 0.82 meters, respectively, on February 21 in Lingga Regency. During the third event, from February 12 to 14, the peak VHM0 was recorded in Tanjung Pinang City on February 12 and 14, with a value of 0.925 m. Meanwhile, the peak VHM0_WW was observed in Lingga Regency on February 12, reaching 0.77 m. These findings support the hypothesis that both oceanic wave activity and wind-induced wave energy play critical roles in the occurrence of tidal flooding in the region, especially when coinciding with spring tides during the full moon phase. This is in line with the opinion of Hanifa *et al*. (2024), who stated that the characteristics of ocean waves are predominantly influenced by winds from the Karimata Strait in the

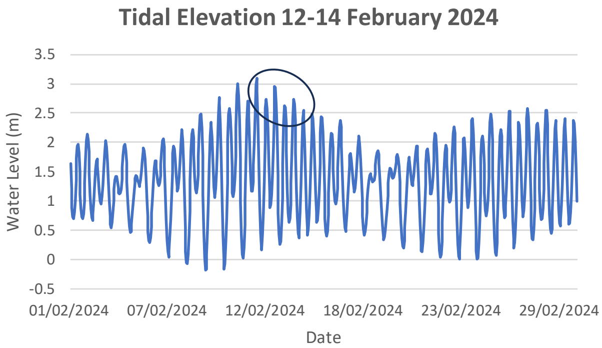

Figure 4. Tides on the dates of tidal flooding events (black circles/ovals) from November 2023 to March 2024.

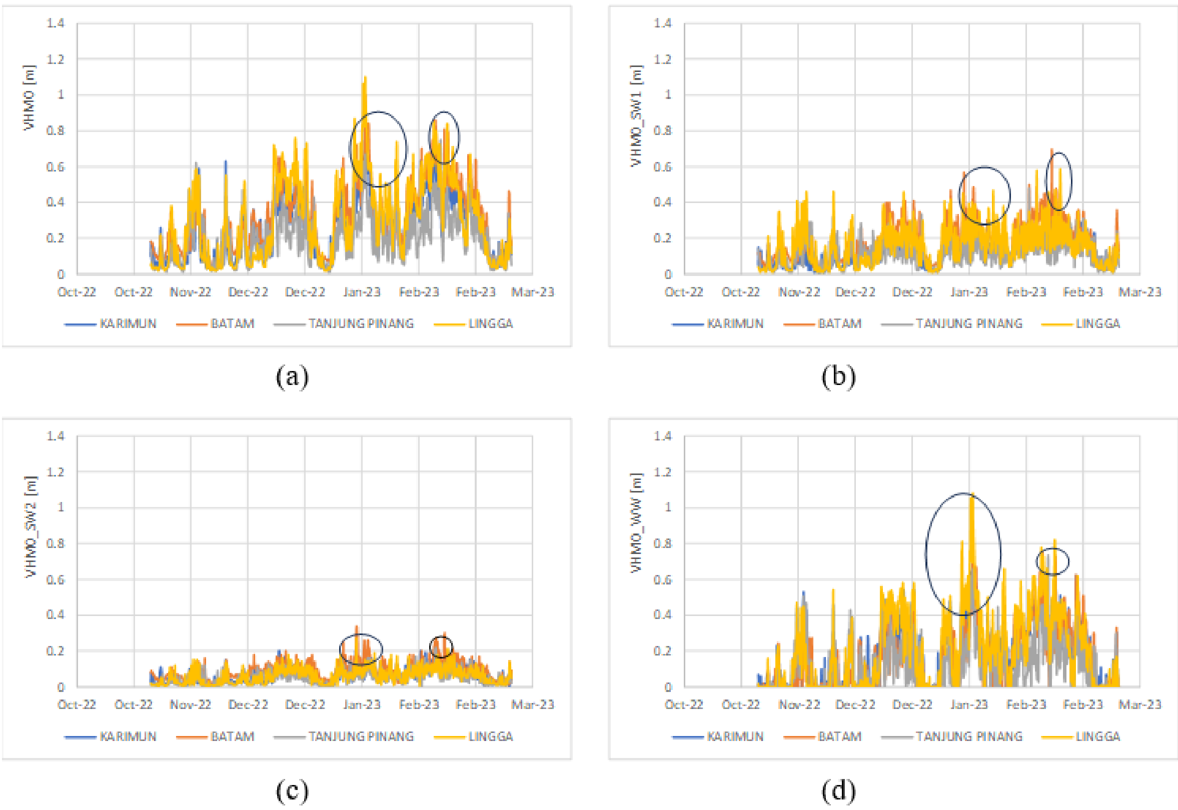

Figure 5. Conditions (a) Sea surface wave significant height, (b) Sea surface primary swell wave significant height, (c) Sea surface secondary swell wave significant height, (d) Sea surface wind wave significant height in November 2022-March 2023.

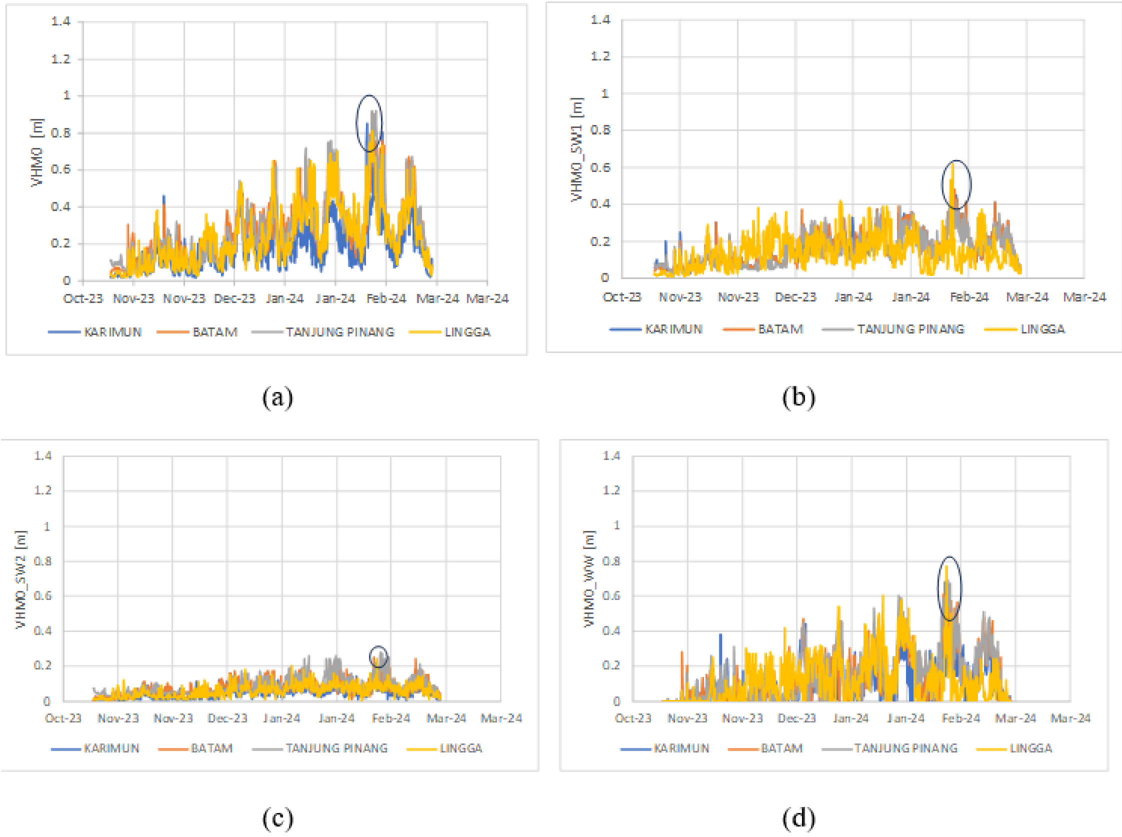

Figure 6. Conditions (a) Sea surface wave significant height, (b) Sea surface primary swell wave significant height, (c) Sea surface secondary swell wave significant height, (d) Sea surface wind wave significant height in November 2023 to March 2024.

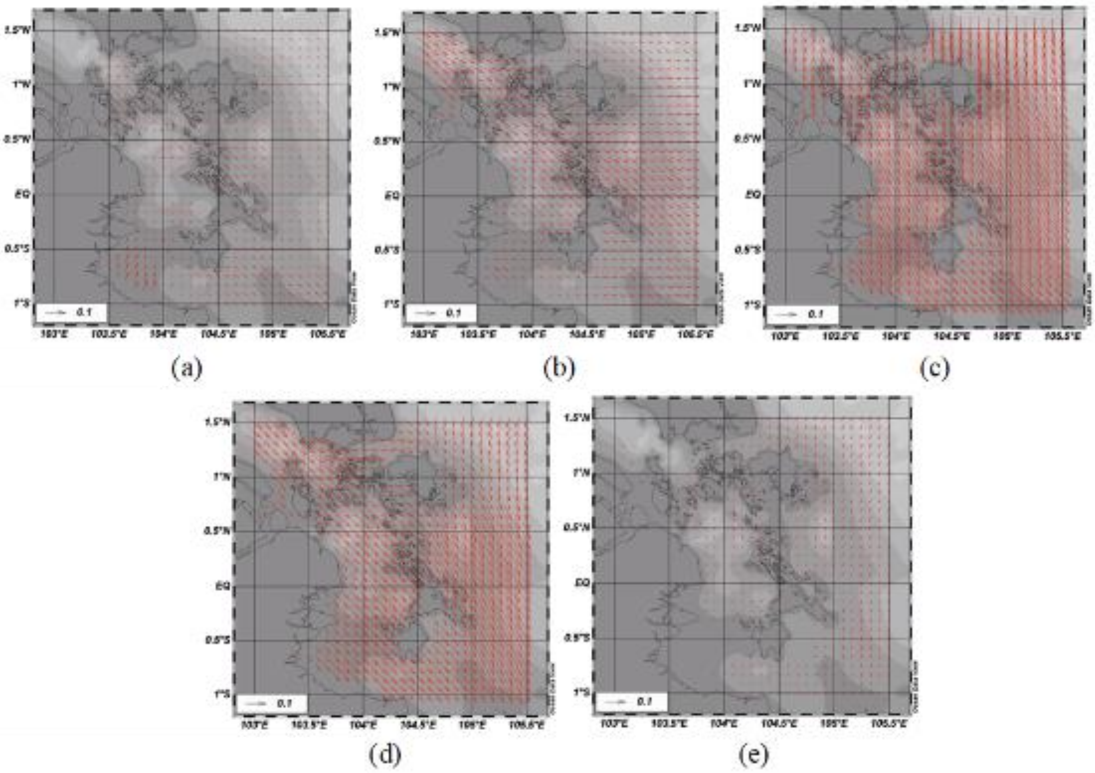

Figure 7. Horizontal Current Conditions in the Riau Islands in the months of a) November 2022 (b) December 2022, (c) January 2023, (d) February 2023, (e) March 2023.

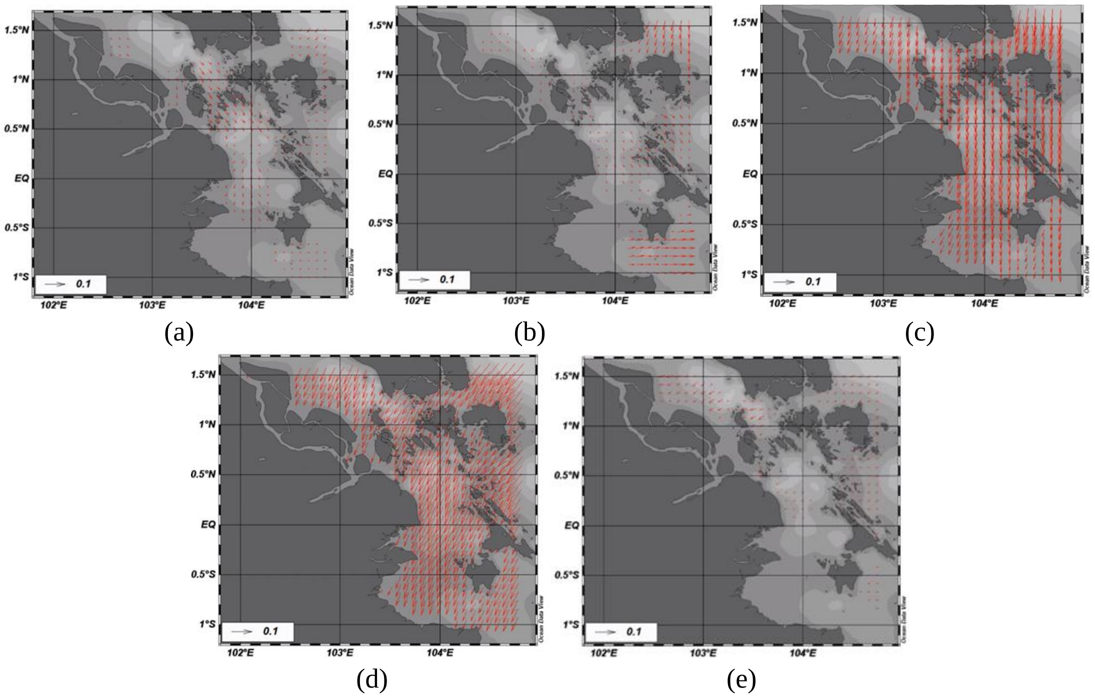

Figure 8. Horizontal Current Conditions in the Riau Islands in the months of a) November 2022 (b) December 2022, (c) January 2023, (d) February 2023, (e) March 2023.

eastern part of the southern waters of Batam City and the northern waters of Lingga Regency, which is an open sea area with no obstructions. A study on wave characteristics based on wind data conducted by Afriady *et al*. (2019) also showed that wind speeds in the Natuna waters reach their peak during the west or north monsoon season. This phenomenon is caused by the monsoonal wind circulation that moves from high-pressure areas in the northern subtropical latitudes toward low-pressure areas in the southern subtropical latitudes (Tjasyono, 2004).

This aligns with the findings of Jainur *et al*. (2024), which observed that flooding along the coast of Baubau City intensifies during the western monsoon season, the maximum sea wave heights in Baubau waters typically occur during the peak of the western monsoon (December-February) due to strong winds blowing from the west to the east. The highest wave height occurs during the western monsoon, reaching 1.89 m with a period of 6.49 seconds. The significant wave heights during the western monsoon are greater compared to those during the second transitional season and the eastern monsoon, owing to the bay topography of the studied region (Setiyadi *et al*., 2023).

Current and wind conditions

The measurement of currents in the Riau Islands waters was conducted to gather information on the current movement conditions in the region. By analyzing current direction and speed data using the Ocean Data View (ODV) application, wind vectors over the Riau Islands waters were obtained. This aligns with the study by Mustikasari and Rustam (2019), which stated that current circulation is represented by arrow vectors indicating the direction of the current, with the length of the arrow vectors serving as a scale for current speed.

From the research findings (Figure 7 and 8), it was observed that during the tidal flooding events in January 2023, February 2023, and February 2024, the currents consistently moved southward. This observation aligns with the findings of Puspitasari *et al*. (2020), who stated that the northern wind season along the northern coast of Bintan Island generally occurs during winter, when the currents also move southward. Therefore, it can be concluded that during the northern wind season, both wind and currents move in the same direction, from north to south. According to the literature by Anisa *et al*. *(*2023), during the north season the current vector moves towards the south.

The analysis of ocean current data from November 2022 to March 2023 indicates that the highest current speeds occurred around January to February (during the northern wind season). These high current speeds can lead to a rise in sea level, particularly when accompanied by significant wave heights and strong winds. These months have been identified as part of the northern wind season, which is known as a period with a high likelihood of coastal flooding.

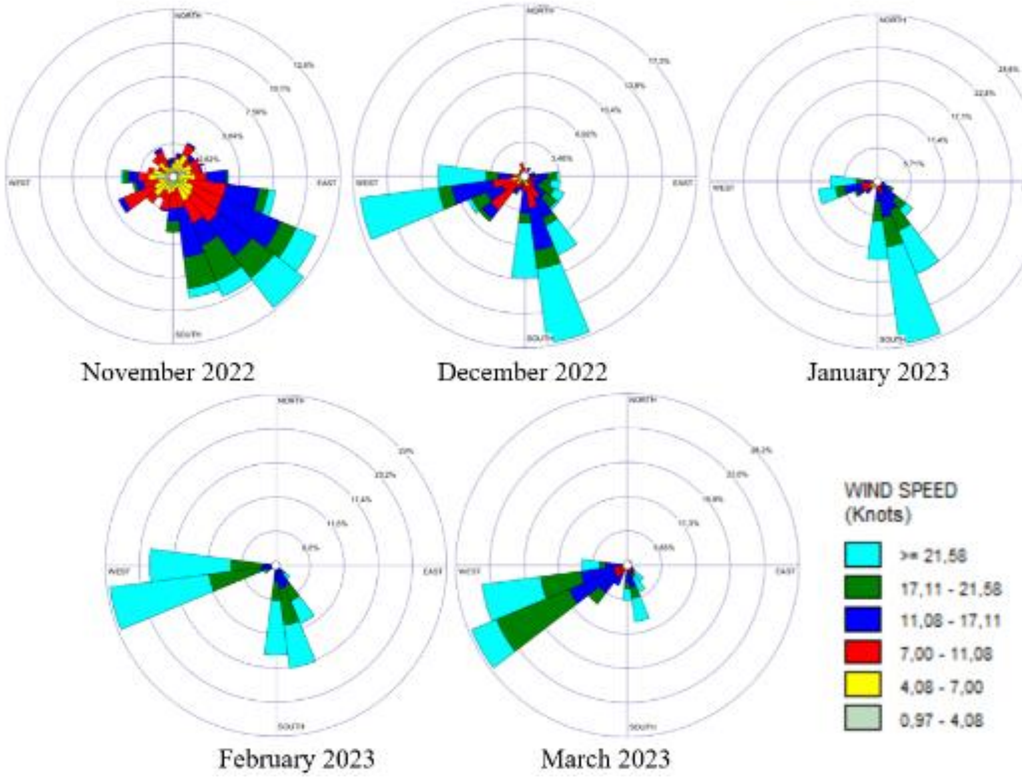

Figure 9. The wind rose (read: direction coming from) from November 2022 to March 2023

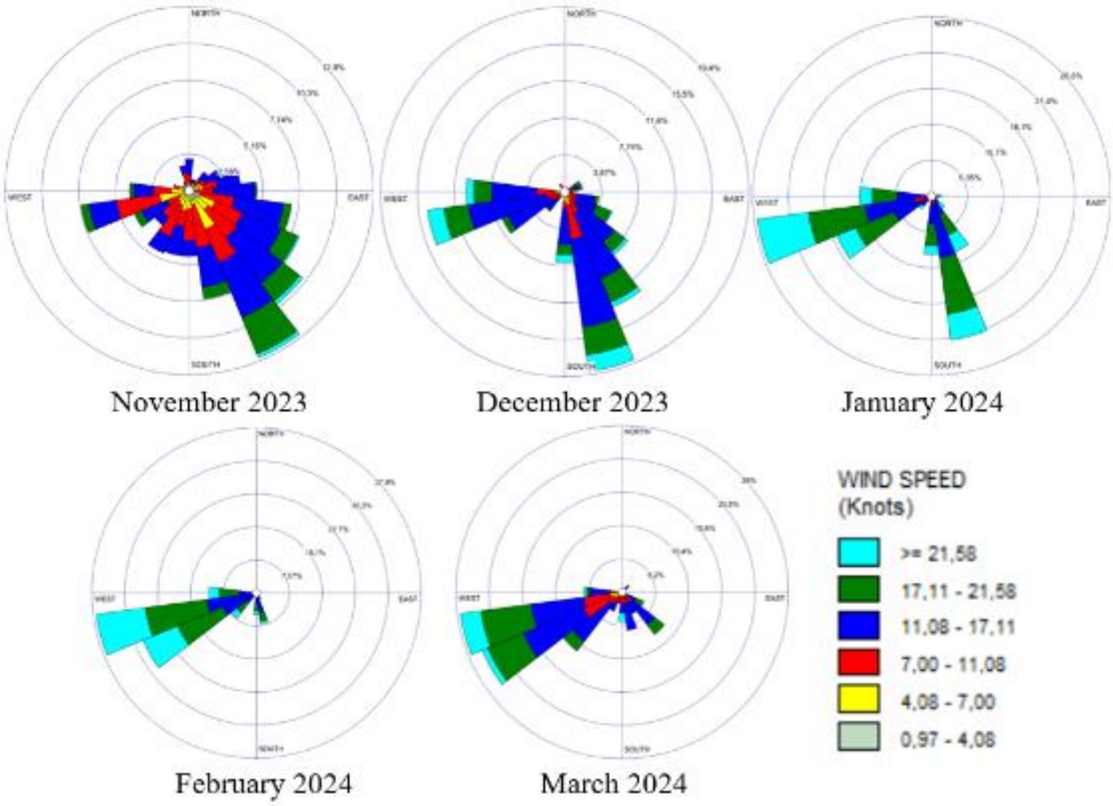

Figure 10. The wind rose (read: direction coming from) in November 2023- March 2024

Based on data from wind processing, the north season period has previously been identified as a time with a high probability of tidal flooding. The results obtained from ECMWF wind data processing using the ODV, Excel, and WRplot applications, are in the form of a wind which can be seen in Figures 9 and 10. The wind rose analysis for November 2022 to March 2023 shows that the highest speeds occur in January and February, coinciding with tidal flooding in the Riau Islands. During the north season (December-February), which is known as the west season in other regions, there is a high likelihood of tidal flooding in the Riau Islands. Wind data analysis from November 2022 to March 2023 showed that the highest wind speeds occurred in January and February, coinciding with tidal flooding events. Specifically, the average wind speed in January 2023 was 19.04 knots, and in February 2023, it was 21.43 knots. Both speeds are categorized as a fresh breeze on the Beaufort scale, capable of producing waves 2 to 2.5 meters high. The Riau Islands region, located in the northern hemisphere (BBU), experiences wind direction and speed patterns greatly influenced by the dominant monsoon system in Southeast Asian waters (Wyrtki, 1961).

Wind patterns in the Riau Islands, located in the northern hemisphere, are influenced by the dominant Southeast Asian monsoon system. This aligns with the findings of Prawirowardoyo (1996), who noted that the western monsoon occurs from October to April, with its peak in December to January, while the eastern monsoon prevails from April to October, peaking in June to August. Wind rose analysis from November 2023 to March 2024 (Figure 10) indicates that the highest wind speeds occurred in February, coinciding with tidal flooding events in the Riau Islands. The analysis showed that average wind speeds reached 18.65 knots, categorized as fresh winds, which are capable of generating waves of 2 to 2.5 meters. These strong winds, predominantly from the west and southwest, are typical of the western monsoon. The interaction between strong winds and high tides, particularly during full moon phases, is believed to intensify flooding events. Tidal flooding heights are further amplified when accompanied by extreme waves generated by strong winds, commonly referred to as storm surges. Hanifah and Ningsih (2018) also emphasized that tidal flood levels become more severe when combined with extreme waves driven by strong winds.

From the overall windrose results, it was identified that the three occurrences of tidal flooding were associated with wind in the fresh breeze category. The significant influence of wind speed can be observed during tidal flooding events in the western season, where strong winds, classified as fresh breeze typically occur and come from the west during tidal flooding events from December to February. These two wind categories are capable of generating high waves. This is different from the first transition season and the eastern season, where wind speeds are generally slower, falling under the gentle breeze and light breeze categories, and coming from the east. According to Satriadi and Prayogi, (2017), wave generation in the Semarang waters is heavily influenced by winds during the western season. This is because, during the western season, winds are unobstructed, unlike in the eastern season, where the wind direction comes from the southeast and is blocked by islands. As a result, significant wave heights during the eastern season are not as large as those in the western season.

Conclusion

In conclusion, this study records three tidal flooding events in the Riau Islands waters that occurred on January 20–25, 2023, February 20–22, 2023, and February 12–14, 2024. These events consistently took place during the new moon or full moon phases (spring tides), when the alignment of the sun, earth, and moon amplifies gravitational forces, causing a significant rise in sea levels. Time series analysis revealed that the highest recorded tidal elevations reached 3.06 m, 3.00 m, and 3.09 m during these events, respectively. The influential wave factors identified were the Significant Wave Height of the Sea Surface (VHM0) and the Wind Wave Height of the Sea Surface (VHM0_WW), with peak values recorded at 1.08 m for both parameters in Lingga Regency on January 25, 2023. Increased wave heights, driven by strong winds, contributed to higher sea levels along the coast, exacerbating the impacts of tidal flooding. Analysis of current patterns indicated that the highest current speeds occurred in January and February, consistently moving southward, aligning with the wind direction during this northern wind season. Wind rose analysis confirmed that wind speeds ranged between 18.65 to 21.43 knots, categorized as 'fresh breeze' on the Beaufort scale, capable of generating waves between 2 to 2.5 m. In January and February 2023, dominant wind directions came from the south and west, while in February 2024, the winds shifted to the southwest. The consistent alignment of high tides, strong winds, southward currents, and elevated wave heights magnifies the impacts of tidal flooding in the Riau Islands region. Therefore, these events are influenced by a combination of oceanographic and atmospheric factors, including high tidal ranges, strong wind speeds, dominant southward current patterns, and significant wave heights. This study offers valuable insights into the interactions driving tidal flooding and provides a crucial basis for the development of future mitigation and adaptation strategies to enhance resilience in vulnerable coastal areas.

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