Spatial analysis of tidal flood in Karawang coastal area using multi-sensor remote sensing

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Abstract. The northern coast of Java, particularly the coastal region of Karawang Regency, is highly vulnerable to tidal flooding, a phenomenon in which seawater inundates low-lying coastal land during high tide. This study aimed to identify and spatially map areas affected by tidal flooding in Karawang's coastal zone using a multi-sensor remote sensing approach. The datasets utilized included Sentinel-1A imagery for land deformation analysis, Sentinel-2A for land cover classification, and data on land slope, sea level rise, tidal patterns, wind speed, rainfall, and tidal flood occurrences. The results indicate that the northern coastal area of Karawang experiences significant land subsidence, reaching up to -6.7 cm per year, with predominantly very gentle slopes (0–8%). Sea level rise was recorded at 5.6 mm per year, compounded by diurnal tidal fluctuations and westerly winds ranging from 3.6 to 8.8 m/s. The spatial analysis revealed that aquaculture pond areas were the most severely affected, accounting for 93.9% of the total inundated land. Among the sub-districts, Cibuaya exhibits the largest extent of tidal flood inundation, covering 57.9% of the total affected area.

Keywords: Coastal, inundation, Karawang Regency, remote sensing, tidal flooding

1 Introduction

1.1 Background of the study

Indonesia, an archipelagic country with the second longest coastline in the world, faces a serious tidal flooding threat, especially in the northern coastal region of Java Island [1]. Tidal flooding is a natural phenomenon that occurs when seawater overflows onto land during high tide, inundating coastal areas that are lower than the high-tide level [2]**.** Tidal flooding not only damages the environment and infrastructure but also threatens the livelihoods of coastal communities [3].

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According to recent news reports, tidal flooding on the north coast of Java threatens 70 industrial areas, five special economic zones, and various vital infrastructures such as airports, ports, and railways, affecting an estimated 50 million people [4]**.** Furthermore, climate change is projected to increase the frequency and intensity of tidal flooding in the future [5], making tidal flooding a major challenge for coastal zone management.

Data from the National Disaster Management Agency (BNPB) indicate that the Karawang Regency is one of the regions in West Java that frequently experiences flooding and ranks eighth nationally in flood disaster vulnerability [6]. The northern coast of the Karawang Regency is one of the coastal areas on the northern coast of Java Island that has been significantly affected by tidal flooding. This area is particularly vulnerable because of its reliance on fishponds and agricultural land, with an average land subsidence rate of 2-10 cm/year [7]. High tides and strong winds also lead to more intense flooding [8]. The vulnerability of this region is also caused by several other factors, such as a relatively flat topography with soil types dominated by lowlands, including alluvial valleys and river bends [9]. In December 2024, tidal flooding affected eight villages across seven sub-districts in northern Karawang, impacting around 2.719 homes and 8.459 residents, with more than 1.000 ha of submerged fish-ponds [10].

Given the extent of the affected area, an approach is needed to identify and map areas prone to tidal flooding on the coast of the Karawang Regency. Multi-sensor remote sensing technology can provide wide coverage and accurate data in the least time [11]. By combining images from various satellite sensors such as Sentinel-1 and Sentinel-2, more accurate information on the distribution of tidal flooding can be obtained [12].

Research in Karawang has shown that its low-lying coastal landscape makes the area highly vulnerable to tidal flooding [13]. This study used high-resolution TerraSAR-X DEM data and Landsat-8 imagery to map flood-prone zones through Topographic Wetness Index (TWI) and Tasseled Cap Transformation (TCT) analyses, showing that the most affected areas are rice fields and fish ponds located near river floodplains and coastal wetlands. Another study applied tidal hydrodynamic modelling using a flexible mesh simulation in MIKE 21 [14]. This study predicted the tidal water levels and estimated the extent of tidal flood inundation, resulting in an inundation area of approximately 38.69 km² along the Karawang coast. However, neither investigated how environmental factors, such as land slope, land subsidence, tidal characteristics, or land use, interact to shape the spatial distribution of tidal flooding.

Through spatial analysis, this study describes the distribution pattern of tidal flooding, as well as the environmental factors that play a role in increasing its vulnerability. Given the limited mapping of tidal flooding phenomena along the coast of the Karawang Regency, the results of this study are expected to provide information on the distribution of tidal flooding.

1.2 Research problem

The coastal area of Karawang Regency exhibits a high level of vulnerability to tidal flooding. Although previous studies have mapped flood-prone zones and modelled tidal inundation, the relationship between tidal flooding patterns and the environmental factors influencing it has not been clearly examined. Therefore, it is necessary to understand the spatial distribution patterns of tidal flooding in the coastal areas of the Karawang Regency and the environmental factors influencing the occurrence of tidal flooding in this region.

1.3 Research objectives

This study aimed to identify and map the areas affected by tidal flooding along the coastal zone of the Karawang Regency. In addition, it seeks to analyze the environmental factors that contribute to the occurrence and severity of tidal flooding in the region.

1.4 Research contributions

The results of this study are expected to provide in-depth information on tidal flooding in the coastal areas of Karawang Regency. In addition, this study can be used as supporting data for further research related to tidal flooding.

2 Methodology

2.1 Time and location

This research was conducted on 16th February 16, 2025, in Karawang Regency, West Java Province, covering nine sub-districts: Cibuaya, Tirtajaya, Tempuran, Rengasdengklok, Cilebar, Pedes, Jayakerta, Kutawaluya, and Rawamerta. Geographically, the region lies between 107°02′00″ E and 107°40′00″ E and 5°56′00″ S and 6°34′00″ S and spans approximately 59,684 ha, characterized by low elevations from 0 to 250 m above sea level, with the northern part having an elevation of only 25 m [15]. Gentle slopes of 0 to 8% make it prone to tidal flooding. **Fig. 1** shows a visualization of the research location in several sub-district areas of the Karawang Regency, West Java Province.

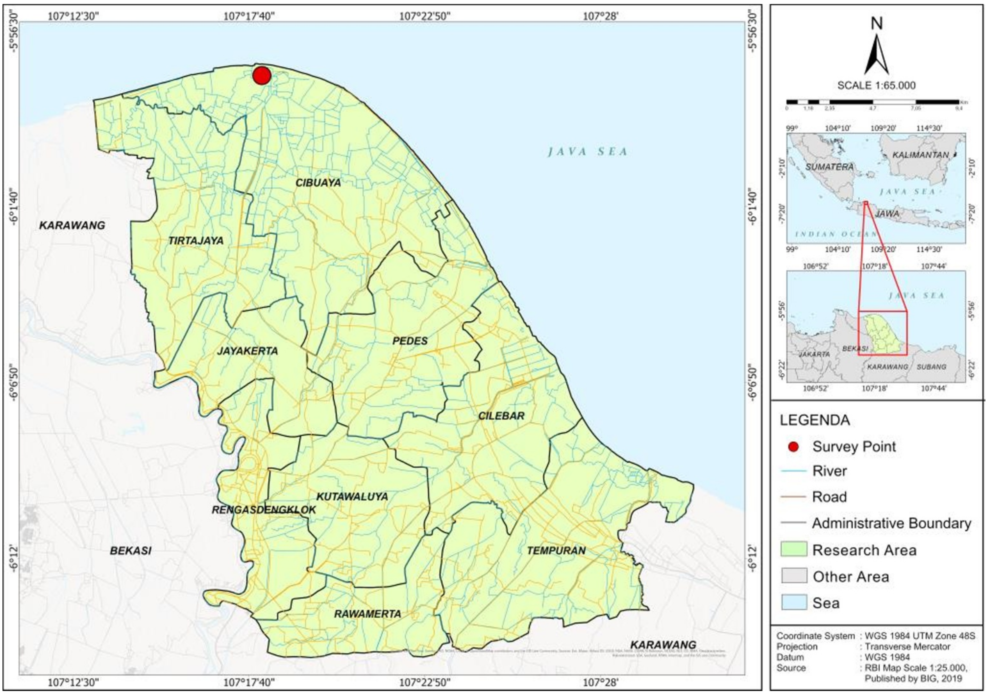

Fig. 1. Research location in Karawang Regency.

2.2 Tools and data

Various tools and materials are used in this study. Key tools included QGIS for data processing, SNAP for handling satellite imagery data, ENVI 5.3 for image corrections, and WRPlot View for processing wind data.

Data materials included Sentinel-1A satellite imagery was used to detect land deformation (search.asf.alaska.edu), DEM SRTM data for topographic reference, and Sentinel-2A data for land-cover analysis (dataspace.copernicus.eu). Sea level anomaly data were analyzed to assess sea level rise (cds.climate.copernicus.eu), tidal data to examine tidal patterns (srgi.big.go.id), rainfall data to evaluate rainfall distribution (bmkg.go.id), and wind data to analyze wind direction and speed (climate.copernicus.eu). Finally, interviews and field observation data were used to enrich information regarding tidal flood events. This study employed a multi-sensor remote sensing approach using data from Sentinel-1 and Sentinel-2 satellites. Sentinel-2 maps land cover affected by flooding with its optical sensors, while Sentinel-1 uses Synthetic Aperture Radar (SAR) to monitor land deformation.

2.3 Data processing

Various data processing methods were used in this study to identify areas affected by tidal flooding and to determine environmental factors. For land deformation detection, this study used the Differential Interferometry Synthetic Aperture Radar (DInSAR) technique. DInSAR combines two radar images (master and slave) to identify changes in land by analyzing phase information. The basic calculation principles of the DInSAR method are presented in Equations 1 and 2 [16].

$$\Delta\varphi_{int}=\varphi_s-\varphi_m \qquad (1)$$

Several components contained in this phase:

$$\Delta\varphi_{D\text{-}int}=\varphi_D-\varphi_{Topo_{res}}+\Delta\varphi_{Atm}+\Delta\varphi_{Orb}+\varphi_{Noise}+2k\pi \qquad (2)$$

The interferometric phase difference ($\Delta\varphi_{int}$) represents the difference between the slave image phase (φ_s) and master image phase (φ_m). The total deformation phase value ($\Delta\varphi_{D\text{-}int}$) consists of several components, namely, the deformation phase (φ_D), residual topographic error ($\varphi_{Topo_{res}}$), atmospheric disturbance error ($\Delta\varphi_{Atm}$), orbital error ($\Delta\varphi_{Orb}$), noise phase (φ_{Noise}), and phase ambiguity expressed as multiples of $2k\pi$.

For land slope analysis, elevation data were sourced from the National Digital Elevation Model (DEMNAS) covering the entire study area. After combining and cropping the data, land slope percentages were calculated. These percentages indicate how prone the area was to tidal flooding. Tidal data were processed using Microsoft Excel with the Least-Squares method, calculating various tidal components to determine the Highest High Water Level (HHWL) and Formzahl values and classifying tides accordingly [17]. Equation 3 was used to obtain the Formzhal values [18].

$$F=\frac{K_1\text{-}O_1}{M_2+S_2} \qquad (3)$$

According to [19], tidal types can be classified based on the Formzahl values. If 0,00 $< F \leq 0.25$, the tide is categorized as a semidiurnal tide. If $0.25 < F \leq 1.50$, it is classified as a predominantly semidiurnal mixed tide. For values of $1.50 < F \leq 3.00$, the tide is categorized as a mixed tide predominantly diurnal. Finally, when F exceeds 3.00 (F > 3.00), the tide was classified as diurnal.

To calculate the annual rate of sea level rise, a linear regression method was applied from sea level anomaly data using Equations 4 and 5 as follows [20]:

$$y=ax+b \tag{4}$$

$$\text{Annual trend}=\frac{Y_{max}-Y_{min}}{\text{months}}\times 12 \text{ months} \tag{5}$$

Coefficient a denotes the offset value, and x refers to the time expressed in months. Parameter b indicates the rate of increase or trend.

Wind data for this research were obtained from the Meteorology, Climatology, and Geophysics Agency (BMKG) for the Karawang area and will be processed using WRPlot and classified according to the Beaufort scale [21]. Rainfall data were also collected from the Meteorology, Climatology, and Geophysics Agency (BMKG), focusing on the daily rainfall during the rainy season. Land use analysis utilized Sentinel-2A imagery with supervised classification methods such as Maximum Likelihood Classification (MLC) to create a land use map for further tidal flood analysis. Finally, data on the flood height and duration were collected through interviews and field observations.

The spatial distribution of tidal flooding was analyzed by integrating several parameters, including land slope, land subsidence, sea level rise, tidal high water level (HHWL), and land cover. The analysis was conducted in QGIS Pro using Raster Calculator and Reclassify to distinguish between flooded and non-flooded areas. Land subsidence values were adjusted relative to slope conditions, whereas HHWL values were corrected for sea-level rise. The final output was a spatial map showing the extent of tidal flood inundation in the Karawang Regency coastal areas.

3 Results and discussions

3.1 Environmental factors influencing tidal flooding

Land deformation in the Karawang Regency experienced a decline of -0.6 to -6.7 cm/year. The most severe land subsidence, reaching -3.7 to -6.7 cm/year, occurs in the northern coastal areas such as Cibuaya, Tirtajaya, and parts of Pedes and Cilebar Districts. Areas with lower subsidence levels, between -0.6 to -2.7 cm/year, are located near urban regions like Banyusari, Rengasdengklok, and Rawamerta. Local residents report subsidence rates of approximately -5 cm/year in the Cibuaya and Tirtajaya sub-districts. This is because the Karawang region is one of the areas where excessive groundwater extraction occurs due to the high intensity of groundwater use for agriculture and aquaculture use[22]. This condition is also exacerbated by the type of soil that dominates Karawang Regency, namely alluvial soil and partly regosol, which do not absorb water very well, causing water to easily stagnate on land [23].

Research indicates that the Karawang Regency consists mainly of gently sloped land ranging from 0-8%, particularly in rice and pond areas. Areas with steeper slopes (8-15% and 15-25%) were limited to the central and southern parts. Meanwhile, areas with high slopes ranging from 25% to 45% are very limited in several sub-districts and are only located in areas far from the coast. This gentle slope is due to the fact that most of the land cover consists of lowlands with slopes of less than 2%, namely rice fields and ponds. Land with a gentle slope can slow the tide from flowing back into the sea, causing the seawater to remain longer and expand the flooded area [24].

Tidal data indicates that the highest tide recorded on December 15, 2024 at 03.00 WIB with a height of 0.66 m, coincided with flooding in the northern coast of Karawang. The Formzhal value was F = 4.86 with an HHWL value of 0.72 m. The tidal pattern is classified as diurnal, meaning that there is one high tide and one ebb each day. This is in accordance with the results of a previous study [25], in which the tidal type found on the Karawang coast was a single or diurnal type. Diurnal tides cause longer durations of high sea levels, particularly during full moons. This causes the northern coastal areas of the Karawang Regency to be flooded by seawater for longer periods than areas with double tidal types, which also face delayed water drainage due to numerous ponds and rivers.

The rate of sea level rise on the northern coast of the Karawang Regency over a 10-year period (2014-2024) reached 5.6 mm/year, reflecting a consistent upward trend. This increase is influenced by global warming, which causes polar ice to melt and contributes to rising sea levels. According to the latest data from the BMKG, the rate of sea level rise in Indonesian waters is currently around 4-6 mm/year, with local conditions in Karawang, including flat seabed topography. The gentle coastal morphology and low elevation of the area increase the risk of infrastructure damage from flooding and tidal events [26].

The wind conditions in 2024 in the Karawang Regency show that the highest wind intensity occurs in the west monsoon period, ranging from 3.6 to 8.8 m/s. The most frequent wind speeds are between 3.6 and 57 m/s, and the wind generally blows from west to east. On the contrary, in the east monsoon, the wind speed is indicated by lower wind speeds, primarily from the east. During the transition seasons, the wind direction varied more widely, leading to generally lower speeds. Based on research [27], wind patterns can influence tidal flooding, as strong winds can push tidal waves toward the coast. Based on the Beaufort Scale, the dominant wind speed in the Karawang Regency is classified as Scale 3 (light wind), which ranges from 3.3 to 5.5 m/s. If this wind pattern blows consistently during high tides, it can increase the risk of tidal flooding.

Rainfall patterns in Karawang were analyzed over a three-month period from October to December. The highest rainfall occurred in the first ten days of December, reaching 138.6 mm. However, the tidal flooding phenomenon on the coast of Karawang Regency occurred in the second ten days of December, even though the accumulated rainfall did not fully correlate with this event. This indicates that the tidal flooding that occurred was not only influenced by rainfall but also by other factors such as sea tides, land subsidence, land slope, and sea level rise.

3.2 Height and duration of tidal flooding

Interviews with residents revealed that the height and duration of tidal flooding vary according to the location and intensity of the event. Flooding typically lasts between 3 h and half a day and occurs every 2-3 months, peaking in January, May, and December. Mild floods last 2-3 hours, whereas extreme flooding can continue for several days. **Fig. 3** shows an example of a peak tidal flooding event that lasted for three consecutive days on December 13, 14, and 15, 2024. Differences in tidal times can affect flood characteristics, with the western region experiencing tides more frequently in the early morning (10:00 p.m. to 6:00 a.m.), whereas the eastern region experiences them in the afternoon to evening (6:00 p.m. to 10:00 p.m.).

(a) (b) (c)

Fig. 2. Tidal flood in Karawang Regency on December 13–15, 2024: (a) December 13, (b) December 14, (c) December 15, December 2024.

Reports indicate that tidal flooding in Karawang is increasing yearly, with heights rising by about 20 cm every five years due to 5 cm/year land subsidence and coastal erosion. The flooding intensity is also affected by high waves and strong winds, particularly during the monsoon season. This also impacts the productivity of fishponds and the activities of coastal residents, especially fishermen. Although residents have attempted mitigation measures such as stacking bamboo and stones, these attempts have not shown significant results in holding back the tide.

3.3 Spatial distribution of tidal flooding in Karawang coastal area

Karawang Regency is a coastal region directly adjacent to the Java Sea, characterized by a low-lying topography that makes it highly susceptible to tidal flooding. Spatial analysis of tidal flood events in December 2024 indicated that inundation predominantly occurred in the northern sector of the regency, particularly in areas proximal to the shoreline. The delineation between the flooded and non-flooded zones is represented by a red boundary line on the map (**Fig. 2**). The map also classified the extent of tidal flooding based on land use categories, revealing that rice fields, aquaculture ponds, agricultural fields, and residential areas were among the most affected.

Fig. 3 presents land cover data in Karawang Regency, with fishponds being the area most affected by tidal flooding, with a flood area of 11,902 ha (93.9%) of the total fishpond area of 12,671 ha. This is because fishponds have very low land slopes and elevations (0-2 meters above sea level), which makes it easier for tidal water to flood inland and takes a long time to return to the sea [28]. Other types of land cover that were also affected by tidal flooding were rice fields with a flooded area of 1.097 ha (3.6%), followed by fields with 695 ha (6.2%), and settlements with 506 ha (11.4%). Although the total area covered by these three types of land cover was smaller, they still caused quite high losses, especially in the lives of the community. **Table 1** presents detailed data on the land areas affected by flooding.

Table 1. Land use areas and regions affected by tidal flooding.

Land Use	Total Area (ha)	Flood-Affected Area (ha)	Flood-Affected Percentage
Rice fields	30,833	1,097	3.6%
Fish Ponds	12,671	11,902	93.9%
Land Use	**Total Area (ha)**	**Flood-Affected Area (ha)**	**Flood-Affected Percentage**
Dry Fields	11,149	695	6.2%
Settlements	4,426	506	11.4%

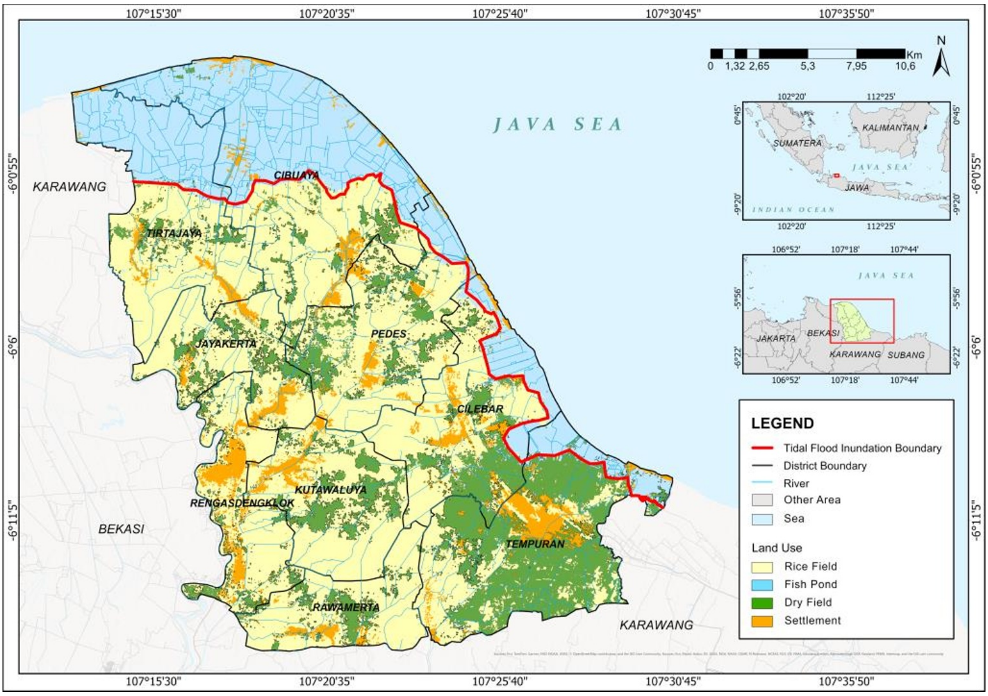

Fig. 3. Spatial distribution of tidal flood inundation in Karawang Regency, December 2024.

The spatial distribution of tidal flooding in the study location shows that five sub-districts were affected, namely Cibuaya, Tirtajaya, Pedes, Cilebar, and Tempuran. These results are in line with a report by Jabar [29], which stated that the tidal flooding that hit the coast of Karawang Regency submerged 1,153 houses in eight subdistricts of Karawang, including Tirtajaya, Cibuaya, Pedes, Cilebar, and Tempuran. Based on **Table 2**, Cibuaya District is the most affected area, with a flooded area of 6,845 ha, or 57.9% of the total area of the district. Tirtajaya also faced significant flooding, namely 2,984 ha (38.9%), while Cilebar, Tempuran, and Pedes experienced considerable impact, although to a lesser extent than Cibuaya.

Table 2. Land use areas and regions affected by tidal flooding.

Subdistrict	Total Area (ha)	Flood-Affected Area (ha)	Flood-Affected Percentage
Cibuaya	11,827	6,845	57.9%
Tirtajaya	7,677	2,984	38.9%
Jayakarta	4,144	0	0.0%
Pedes	6,858	601	8.8%
Cilebar	7,032	1,326	18.9%
Rengasdengklok	4,090	0	0.0%
Kutawaluya	5,222	0	0.0%
Rawamerta	3,761	0	0.0%
Tempuran	9,073	1,076	11.9%

Tidal flooding in the Karawang Regency is caused by various natural factors such as global warming, leading to rising sea levels, land sinking, and gentle coastal slopes. High tides combined with strong westerly winds worsen flooding. Economically, this flooding affects farmers and fishermen as their lands and ponds are often inundated. Research has shown that tidal flooding damages infrastructure and homes near coasts and rivers, while contaminated floodwaters can lead to health issues such as itching and diarrhoea [30]. Therefore, local governments and communities need effective plans to mitigate and adapt to such floods. Actions such as building higher sea walls, managing groundwater use, and planning for risks are essential for reducing future impacts.

4 Conclusion and suggestions

Tidal flooding in the Karawang Regency predominantly affects five coastal sub-districts: Cibuaya, Tirtajaya, Pedes, Cilebar, and Tempuran. Among these, Cibuaya exhibits the highest level of inundation, with a flooded area reaching 6,845 ha, which is equivalent to 57.9% of its total land area. Land cover analysis revealed that aquaculture ponds were the most severely affected, accounting for 11,902 ha or 93.9% of the total pond area. Rice fields and residential zones have also experienced substantial flooding.

The severity of tidal flooding in this region is driven by a combination of environmental factors, including pronounced land subsidence at a rate of -6.7 cm/year, very gentle topographic slopes (0–8%), and ongoing sea level rise of approximately 5.6 mm/year. These conditions were further exacerbated by diurnal tidal patterns and prevailing westerly winds during the monsoon season, with wind speeds ranging from 3.6 to 8.6 m/s.

The use of multi-sensor satellite data has proven effective for spatial monitoring and analysis of tidal flood dynamics. For future research, it is recommended to incorporate long-term observational datasets to enhance trend analysis and integrate real-time measurements of tidal fluctuations, wind velocity, and sea-level changes using continuously accessible in-situ sensors.

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