Extreme Coastal Flood Inundation Mapping Based on Sentinel 1 Using Google Earth Engine

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Abstract. Coastal flooding frequently occurs along the Northern Coast of Java due to the continuous land subsidence and rising sea level. Tidal floods routinely occur on the North Coast of Java during high tides, disrupting the livelihood activities of surrounding communities [1][2]. Additionally, land subsidence continuously happens due to natural and anthropogenic processes [3][4][5][6]. The coastal area of the North Coast of Java consists of alluvial deposit, making it susceptible to land compaction and expansion [7][8]. The impact of land subsidence might also expand the inundation area caused by tidal floods along the coast [9][10]. One of the tidal flood events that had a significant impact on the North Coast of Java occurred on May 23rd, 2022 [11][12]. This tidal flood caused inundation that was relatively higher than usual. As an example, during the normal spring tide, the water surface elevation around Semarang is around 180 cm on the high tide [13] according to local vertical datum. However, on May 23rd, 2022 the sea water elevation reached 210 cm as recorded by the same tidal gauge [14]. This event had affected many areas on the north coast of Java.

Regarding disaster mitigation, the simulation and prediction of future events and their impacts are crucial. However, the evaluation, calibration, and verification to these models are often limited due to the lack of available data of coastal flood extent [15]. Post event surveys are commonly used to capture the past flood extent as used in [16]. Nevertheless, conducting such surveys over large areas can require substantial resources. Therefore, this paper seeks to identify a more cost-effective alternative for delineating flood extents. One method which recently has been frequently used is the use of satellite imagery [17][18].

Several researchers have carried out inundation mapping using various methods in the north coast of Java. Most researchers carried out the mapping locally focusing on one or two districts, such as in Demak [19][20], Semarang [21], Pekalongan [22][23], and West Java [24]. There were also those who did the inundation mapping in one study on the north coast of Java which was conducted with data around 2000-2015 [25]. Spatial mapping has been carried out by previous researchers using data on Landsat [26] or Sentinel [27][28]. One of the latest processing tools is Google Earth Engine [29][30][31][32][33] which enables user to access satellite imagery without having to download and save the images to their local drive.

The extent of inundated area around Semarang due to the tidal flood that occurred on May 23rd, 2022 has been mapped locally [34]. Local mapping is usually done to maintain the accuracy. However, it often necessary to assess the overall inundation extent in larger area, for example in case of general coastal flood numerical simulation calibration. Therefore, this study was conducted to estimate the coastal flood impact around the Northern coast of Java, specifically from...
Cirebon to Demak (see Fig. 1). The decision to limit the study domain was based on the variations in tidal phases along the Northern Coast of Java [35]. This variation of tidal phases may also account for the differing flood impact at various locations during the same tidal event.

Objective of the study is to evaluate the usability of Sentinel-1 in mapping the flood extent over vast areas. Furthermore, the results of the study can serve as data calibration or verification of hydraulic coastal flood models.

### 2 Data and method

This study was conducted in three main steps: (1) understanding the flood extent through e-news data mining and utilization of field observation data from previous research; (2) flood extent extraction based on Sentinel-1 images; and (3) verification on the extracted flood extent.

This work began by collecting past flood events from January to July 2022 from the news to understand the flood frequency and the extent of their damage. Within those six months, there were 36 reported events across the study domain, with 16 cases (44%) were caused by coastal flooding. Furthermore, we utilized the ground check data from previous researches at two selected locations: Pekalongan [36] and Semarang [37], as verification data.

The second phase of the study was the extraction of flood extent based on Sentinel-1 using the Google Earth Engine (GEE). Sentinel-1 is a satellite launched by the European Space Agency (ESA) in the Copernicus Program. Sentinel-1 offers several products for different applications. Sentinel-1 products include SLC, GRD at level 1, and OCN at level 2. Accurate flood inundation mapping is one of the applications of using Sentinel-1 products, namely GRD (Ground Range Detected). GRD is a product of Sentinel-1 that has a reference to the WGS84 ellipsoid equipped with multilook amplitude and intensity information. Sentinel 1 has a good level of accuracy because Sentinel 1’s spatial resolution is 10 m. This high spatial resolution allows for large-scale geographic analysis, including for analysing flood inundation in an area. GEE cloud is a cloud platform well known for its cloud-based large-scale computation capabilities [38]. Some data such as Sentinel 1, Global Surface Water (GSW), and the Area of Interest (AOI) would be used to extract the surface water and water body area before proceeding to further calculation.

The Sentinel-1 analysis was divided into two conditions, namely before flood (flood extent in April 2022) and after flood (flood extent in May 2022), as a comparison of study area. Values obtained from the Sentinel-1 were monthly averaged. Therefore, two months period were selected to distinguish the flood extent. We selected the VH band polarization and the IW (Interferometric Wide swath) instrument mode for the analysis. The speckle filter was then applied to the selected images. The data were then be smoothened and classified into flood and water classification before being exported to shapefile (*.shp). The process were scripted in the GEE cloud.

The resulting shapefile data of surface water, flood area, and water body area were then further processed by eliminating the overlapping data. This step was used as a data correction, for example flood correction. All results of the analysis would be compiled as one data basis of water level changes. The results were presented based on district or city boundaries in a WebGIS. Detail workflow is displayed in Fig. 2.

The extracted flood extents were then compared to the available ground check data based on [36] and [37].

### 3 Results and discussion

This study explored the possibility of using satellite image data to delineate flood extent over large area. We focused on the flood event which occurred around the end of May 2022. Thus, we focused on the differences between tidal flood extent on May 2022 (as the extreme event) and April 2022 (normal flood event) to emphasize the magnitude of the extreme flood event. This was calculated based on the difference in the area of the detected water body of April 2022 and that of May 2022. The result was then presented in the WebGIS.
which can be accessed through the following link: rob-pantura.netlify.app.

Several sample results at a district level were displayed in Fig. 3, covering overall the North Coast of Java from Cirebon, Brebes, Tegal, Pemalang, Batang, Kendal, Semarang, and Demak. All mapping results area were displayed on the WebGIS as one of the benefits of this research to provide initial information regarding flood-prone areas. However, it should be noted that local verification are still needed to obtain the accuracy of this data extraction.

Local inundated area for each region along the Northern Coast of Java were also shown at a district level, namely Cirebon (Fig. 6), Brebes (Fig. 7), Tegal (Fig. 8), Pemalang (Fig. 9), Pekalongan (Fig. 5), Batang (Fig. 10), Kendal (Fig. 11), Semarang (Fig. 12), and Demak (Fig. 13), which are shown in Table 1.

Field observation was carried out in Pekalongan by visual survey [36]. As seen in Fig. 9, the flood inundation of Pekalongan, both in normal (April 2022) and extreme (May 2022) reached almost the entire area of Pekalongan. The most impacted area was around the northern parts which have low ground elevation. Several researches shows that Pekalongan has also been influenced by land subsidence, especially in North Pekalongan since 2017 of around 24.13 cm/year [39]. At Pekalongan city, the inundation mostly appeared in the north to eastern area around Banger River.

Groundcheck was taken in normal condition while the flood has reduced. Some points included in the inundation map are shown in Fig. 4. Firstly, the western side of Banger River was the Panjang Wetan region which was quite dry though the drainage channels were full (Fig. 4. (a,b,c,d,e)). On the other hand, the eastern one always wet, so the area was mainly changed into fishponds, and certain buildings were elevated or being abandoned (Fig. 4. (f)). The location conditions are quite suitable compared to the result because the dominant inundations appeared in the eastern area of Banger River.

![Fig. 3. Results of the tidal flood area across the study domain (Cirebon to Demak).](image)

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**Table 1. Result of the flood extent area: area of inundation and the inundation difference between the normal flood (April 2022) and the last extreme flood (May 2022).**

<table>
<thead>
<tr>
<th>No.</th>
<th>Region</th>
<th>Inundation Area (ha) April 2022</th>
<th>Inundation Area (ha) May 2022</th>
<th>Increase (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Cirebon</td>
<td>13,809</td>
<td>14,589</td>
<td>780</td>
</tr>
<tr>
<td>2.</td>
<td>Brebes</td>
<td>14,139</td>
<td>14,500</td>
<td>361</td>
</tr>
<tr>
<td>3.</td>
<td>Tegal</td>
<td>1,922</td>
<td>2,653</td>
<td>731</td>
</tr>
<tr>
<td>4.</td>
<td>Pemalang</td>
<td>4,534</td>
<td>5,812</td>
<td>1,278</td>
</tr>
<tr>
<td>5.</td>
<td>Pekalongan</td>
<td>3,579</td>
<td>3,811</td>
<td>232</td>
</tr>
<tr>
<td>6.</td>
<td>Batang</td>
<td>1,683</td>
<td>2,487</td>
<td>804</td>
</tr>
<tr>
<td>7.</td>
<td>Kendal</td>
<td>7,063</td>
<td>7,860</td>
<td>797</td>
</tr>
<tr>
<td>8.</td>
<td>Semarang</td>
<td>3,296</td>
<td>3,381</td>
<td>85</td>
</tr>
<tr>
<td>9.</td>
<td>Demak</td>
<td>18,908</td>
<td>19,402</td>
<td>494</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td>68,933</td>
<td>74,495</td>
<td>5,562</td>
</tr>
</tbody>
</table>
Fig. 4. (a) Jl. WR. Supratman, (b) Crematorium, (c) Student Dormitory of UIN Pekalongan, (d) Panjang Wetan Housing, (e) SDN Panjang Wetan 04, and (f) Parking Lot of SMPN 9 Pekalongan in January 2023. Yellow lines indicate flood extent in the area during the May 2022 flood event. Photos were taken a few months after the flood.

Fig. 5. Flood inundation in Pekalongan (left: inundated area in April 2022, middle: inundated area in May 2022, and right: inundation difference).
Fig. 6. Flood inundation in Cirebon (left: inundated area in April 2022, middle: inundated area in May 2022, and right: inundation difference).

Fig. 7. Flood inundation in Brebes (left: inundated area in April 2022, middle: inundated area in May 2022, and right: inundation difference).

Fig. 8. Flood inundation in Tegal (left: inundated area in April 2022, middle: inundated area in May 2022, and right: inundation difference).
Fig. 9. Flood inundation in Pemalang (left: inundated area in April 2022, middle: inundated area in May 2022, and right: inundation difference).

Fig. 10. Flood inundation in Batang (left: inundated area in April 2022, middle: inundated area in May 2022, and right: inundation difference).

Fig. 11. Flood inundation in Kendal (left: inundated area in April 2022, middle: inundated area in May 2022, and right: inundation difference).
Flood extent mapping based on Sentinel-1 generally appears to be effective, as seen in the delineation of inundated area around Pekalongan (Fig. 14-a). However, this method encounters challenges when mapping the inundated area around high density population district as Semarang (Fig. 14-b). This might be due to the image resolution relative to the urban coverage. For urban areas in particular, additional measures might be required as outlined in a previous study [31].

4 Conclusions
Options on the flood extent mapping through satellite imagery was done in this exploratory study. The results of the mapping revealed that there was an increase in the inundated area from approximately 5,562 hectares in
April 2022 to May 2022, indicating a significantly wider extent of flooding in May 2022 compared to the usual tidal floods. Data from Sentinel-1 processed in the Google Earth Engine (GEE) cloud appears to be promising to delineate flood extent over a large area. Nevertheless, to validate the mapping results, ground verification or high-resolution aerial photography is essential.

It is important to note that mapping in densely populated urban areas presents certain challenges with this method. The resolution of satellite images may prove to be relatively low when compared to the detailed urban landscape. Therefore, additional steps should be considered in the analysis for more accurate results.

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