

Flooding Hazard Assessment Considering Climate Change in the Coastal Areas of Java / Indonesia Based on Remote Sensing and GIS Data

Data Mining Based on of Free Available Data and Software as Contribution to Hazard Preparedness in Affected Communities

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ABSTRACT

Evaluations of different satellite data and meteorologic data as well as digital elevation data, help to identify critical areas in Java, Indonesia exposed to flooding due to flash floods, storm surge, cyclones, meteo-tsunamis or tsunami waves. Data mining and map creation is the prerequisite for flooding hazard preparedness for every community and for the strengthening of resilience. Case studies from the areas of Surabaya are presented to demonstrate an example how free available geo- and satellite data can be used systematically for flooding hazard preparedness. Sea level rise due to climate change has to be considered and the flooding hazard preparedness adapted according to the actual and future situation. Evaluations of optical satellite data such as Landsat 8 and Sentinel 2 and radar data contribute to a better understanding of the development of currents at the coast and their interactions with the coastal morphology.

Keywords: Remote sensing, GIS, Flooding hazard, Java

1. INTRODUCTION

When catastrophic inundations, flash floods and tsunami hazards happen and affect cities, settlements and infrastructure of Indonesia, immediate and efficient actions are required which ensure the minimization of the damage and loss of human lives [1]. Large floods usually occur in Indonesia due to prolonged rainfall especially in rainy season (usually occurs between October and March). Tropical cyclones such as Dahlia in November 2017 causing extended flooding are another issue. Tsunami hazards and occurrence with extended inundations have been documented to affect the Indonesian coasts [2] Fig.1). Tsunami events have caused significant runup of the high energetic flood waves, exceeding 10 m height level in most parts of Indonesia [3].

In recent years, the impact of flooding has multiplied due to climate change because of rising sea levels, a higher intensity and frequency of storms and cyclones, coastal erosion and salinization [4], even amplified by land subsidence.

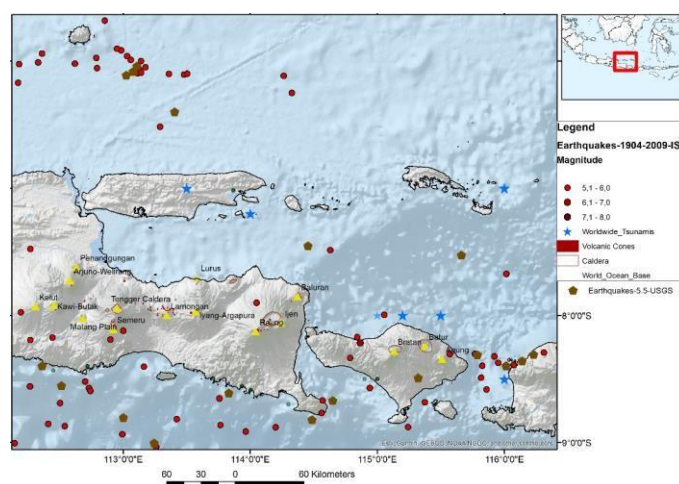


Figure 1. Tsunami events and earthquakes around East-Java and Bali (data source: National Oceanic and Atmospheric Administration-NOAA, US Geological Survey, International Seismological Center-ISC)

Sea level rise related to climate change has to be taken into account when dealing with the detection of areas prone to

potential flash flood and tsunami flooding. Flat and lowest areas with no slopes and curvatures are the most affected locations, such as coastal plains, deltas, muds, estuaries, lagoons and bays [5].

According to climate models a Global Mean Sea Level (GMSL) rise during the 21st century will likely be in the range of 0.29-0.59 m and 0.61-1.10 m. GMSL projections that include the possibility of faster disintegration of the polar ice sheets predict a rise of up to 2.4 m in 2100 and up to 15 m in 2300 [6]. Global mean sea level rise above the likely range – approaching 5 m by 2150 – cannot be ruled out due to deep uncertainty in ice sheet processes [7].

This means that tsunami flooding modeling has to be dynamic as well and to adapt to these sea level changes when calculating the potential inundation extent.

When dealing with the flooding hazard potential along the Indonesian coasts it is necessary to consider meteo-tsunamis as well, often related to cyclones. Destructive meteotsunamis are always the result of a combination of several resonant factors (atmospheric gravity waves, pressure jumps, frontal passages, squalls, etc., Monserrat et al. 2006). As extreme weather events will increase due to climate change [7,8] the occurrence of extreme sea level oscillations associated with meteo-tsunamis and storm surge will be an issue at the Indonesian coasts.

Proper mitigation of damages following disastrous flooding events highly depends on the available information and the quick and proper assessment of the situation. Responding local, national authorities in Indonesia and international institutions like reliefweb / OCHA or Sentinel Asia are provided with information and maps where the highest damages due to unfavourable, local site conditions in case of stronger flooding events can be expected.

As many environmental and social data are free available in the internet as well as the necessary software as open source, disaster resilience is nowadays mainly a question of knowledge transfer and training of staff with the focus on how to handle, process and deliver the data to the affected communities. Every community could use the open source data and tools to adapt their strategies to their local conditions and strengthen their resilience. The emergence of new technologies, standards, and multiple data sources has led to the establishment of completely new architectures that provide flexible and scalable solutions for accessing and consuming data. Disaster resilience should be shared responsibility for individuals, households, businesses and communities, as well as for governments [9].

Community resilience is broadly understood as the capacity for a community to be able to recover from a shock such as from a flooding disaster as well as its capability to undergo transformative changes using self-organisation and collective action to deal with the impact and adapt. Building and strengthening resilience within vulnerable communities is a key priority for those working with disaster risk reduction [10].

Thus, hazard preparedness depends on the training and knowledge of the responsible staff such as in fire brigades or the police. The creation of databanks and maps and continuously data mining is the prerequisite for disaster resilience in the hazard prone cities and communities. Spatial planning is a common instrument for disaster management and mitigation measurements. It is urgent to combine the knowledge of flooding hazards with the efforts of urban and regional planning and of social sciences.

Flooding can be one of the partly manageable of natural disasters, if flood prone areas are identified and suitable flood mitigation and emergency strategies are implemented. The detection of coastal areas prone to flooding due to torrential rains, especially during cyclones causing flash floods, can be carried out with the support of remote sensing and GIS tools. This is demonstrated by the example of flooding hazards such as flash floods, storm surge or because of tsunami waves in the next chapters using the area surrounding Surabaya in East-Java as an example.

The aim of this research is focused on a contribution to a flooding hazard geoinformation system with interdisciplinary dynamic content, enabling the communication between local authorities, public organizations and universities. This work approach could be part of a basic risk assessment presenting information for strategic planning on where potential problems may occur in the infrastructure.

This study aims to contribute to the delineation of areas prone to flooding due to their morphometric disposition, mapping of traces of earlier flooding events on the different satellite images, and the influence of different wind directions on current development in the coastal areas and the interaction of currents with the coastal morphology. The inventory of traces of former sea water intrusion is an important step towards the delineation of coastal segments prone to flooding. The potential of volcanic eruptions on the development of tsunami waves has to be investigated as well.

2. METHODS

The interdisciplinary approach used in the scope of this research comprises remote sensing data, geological, geophysical and topographic data and GIS methods. Satellite imageries and Digital Elevation Model (DEM) data were used for generating a GIS data base and combined with different geodata and other thematic maps. Satellite data such as Sentinel 1 – C-Band, Synthetic Aperture Radar (SAR) and optical Sentinel 2 images, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Landsat optical data (Landsat TM and Landsat 8, the Operational Land Imager-OLI) [11]. Digital Elevation Model (DEM) data gained from the Shuttle Radar Topography Mission (SRTM), ASTER DEM data and Advanced Land Badan Informasi Geospasial [12], were downloaded from open-sources such as USGS / Earth Explorer, Sentinel Hub / ESA [13], and Google Earth.

The data were processed using geoinformation systems ArcGIS from ESRI and QGIS. Shapefiles from Indonesia were downloaded from the Geofabrik's download server [14]. Meteorologic data such as about wind directions and wind speeds were downloaded from the 'power regional data access tool' of the 'POWER Data Access Viewer' provided by NASA, Sentinel Asia as well as from earth.nullschool.net [15].

ENVI software from Harris Geospatial Solutions and the Sentinel Application Platform (SNAP) provided by ESA were used for the digital image processing of the optical Landsat 5 and 8, Sentinel 2 and ASTER data. SNAP provided as well the tools for the processing of radar data. The evaluation of Sentinel 1 A and B radar images requires geometric correction and calibration.

2.1. Evaluations of DEM Data

Terrain features can be described and categorized into simple topographic relief elements or units by parameterizing DEMs such as height levels, slope gradients, and terrain curvature. From DEM data derived morphometric maps (slope gradient maps, drainage map, etc.) were combined with meteorologic information in a GIS data base. In the scope of this study DEM data were mainly used to derive information of the lowest and flattest areas prone to flooding. Additionally, the bathymetric DEM data provided by General Bathymetric Chart of the Oceans (GEBCO) [16], International Hydrographic Organization and the Intergovernmental Oceanographic Commission of UNESCO were integrated into the research in order to combine the information of the sea bottom topography with earthquake, tsunami and submarine landslide data. GEBCO bathymetric data were used to derive slope, hillshade and flow accumulation maps from the sea bottom.

A flooding susceptibility map of coastal areas, that predicts the probable locations of possible future inundation due to flash floods or to tsunami occurrences, is required which takes into consideration as well the potential morphodynamic consequences of these events at the coasts such as, abrasion, sedimentation and landslides. DEM data help to identify those areas that are most likely to be flooded due to their morphometric disposition and properties [1]. As river mouths are forming an entrance for intruding water waves from the sea a systematic assessment of larger river mouths prone to flooding will contribute to hazard preparedness.

The integration of different morphometric factors in a GIS environment using weighting procedures plays an important role in the GIS application in the frame of this study. The basic pre-requisite for the use of weighting tools of GIS is the determination of weights and rating values representing the relative importance of factors and their categories. The weighted overlay method takes into consideration the relative

importance of the parameters and the classes belonging to each parameter (ESRI, online support in ArcGIS). The application of a weight-linear-combination in susceptibility assessment has been identified as a semi-quantitative method, involving both expert evaluation and the idea of ranking and weighting factors. The efficacy of the weighted overlay-method lies in the fact that human judgments can be incorporated in the analysis. The weights and ratings are determined using the expert's subjective knowledge. The method starts by assigning an arbitrary weight to the most important criterion (highest percentage), as well as to the least important attribute according to the relative importance of parameters. The sum over all the causal factors/layers that can be included into GIS provides some information about the susceptibility to flooding and the extent of inundation. By extracting first morphometric factors like slope degrees below 10 ° from the slope gradient map, by deriving from the drop raster the areas with values below 50.000 units using the hydrology-tools in ArcGIS (flow direction), by extracting from curvature maps areas with terrain curvature = 0 and from the aspect map the flat areas (-1), the flattest areas are highlighted. In the weighted overlay procedure these selected morphometric data were summarized, merged with different percentages of influence and represented in a map. thus, enhancing and accentuating the visibility of areas prone to flooding. The flattest areas with lowest slope degrees and curvatures are classified by values from 0 to 6, thus, enhancing and accentuating the visibility of of areas prone to flooding.

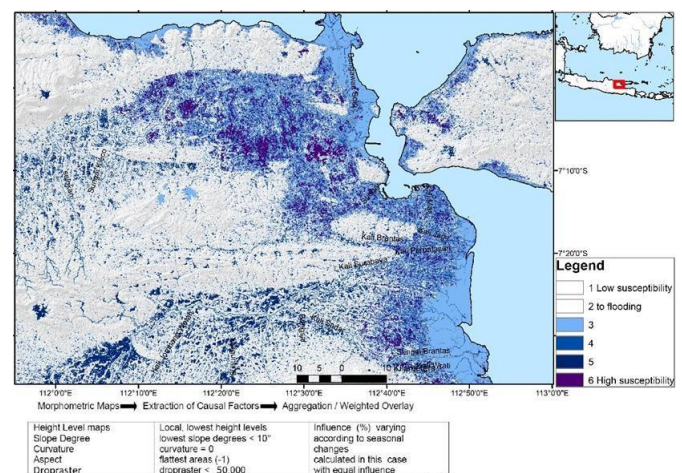


Figure 2. Weighted overlay workflow in ArcGIS to derive information about areas susceptible to flooding due to their morphometric disposition based on SRTM DEM data (dark-blue - highest susceptibility / disposition to flooding)

This susceptibility is calculated by adding every layer, as described below, to a weighted influence and summing all layers. After weighing (in %) the factors according to their probable influence, susceptibility maps can be elaborated, where those areas are considered as being more susceptible to

flooding, where “negative” causal factors occur aggregated and are interfering with each other (Figure 2). When combining the weighted overlay results with morphological watersheds and actual precipitation data it can be derived quickly which areas are prone to higher surface runoff and which areas might be affected by flash floods in case of torrential rains (Figure 3). The monitoring of the conditions within the catchment area of the Brantas and Surabaya and Porong rivers belonging to the Delta Brantas System becomes even more important for flood management when dealing with flooding disasters downriver due to increasing river discharge such as the mud flood disasters [17].

The amount of the sea level rise is still in discussion and in research. In a worst case scenario, it will comprise more than several meters as mentioned before. Therefore, flooding susceptibility maps of coastal areas should include the future sea level rise. Based on the current free available DEM data the areas below 10 m height level are delineated to show which areas might be prone in future to flooding, whether by sea level rise, storm surge or by flash floods.

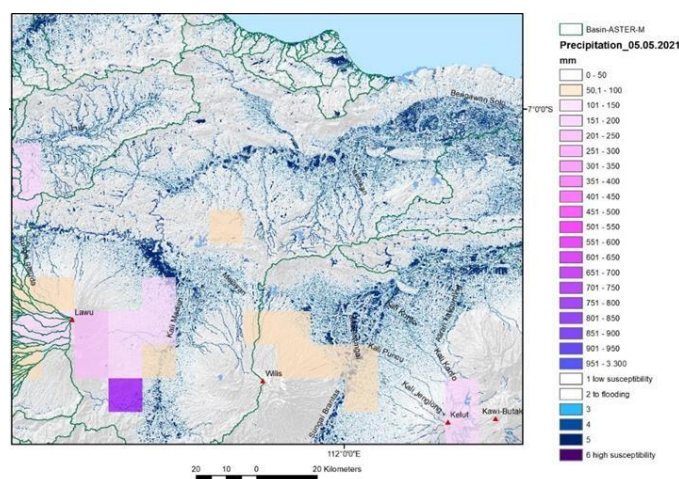


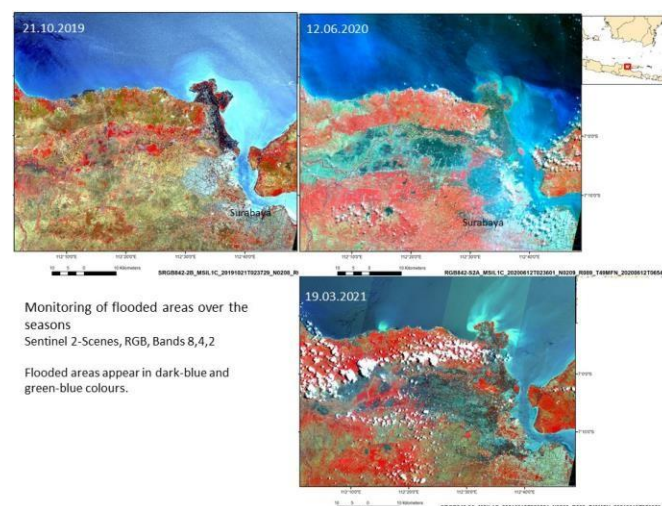
Figure 3 Merging the weighted overlay map and morphological watersheds with actual precipitation data

2.2. Evaluations of optical and Radar Satellite Data

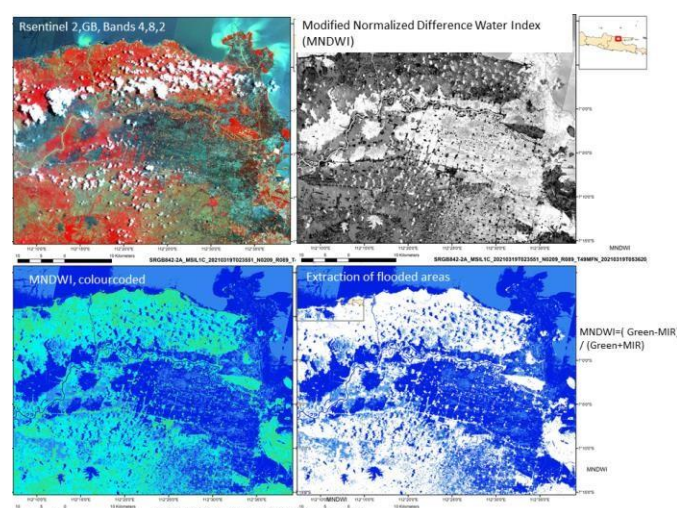
Areas that have been flooded in the past will most likely be flooded in future again. Therefore, a careful monitoring of satellite data revealing flooded areas is required. A systematic inventory of flooded areas, backwater areas, of coast-near lakes and ponds and their seasonal water level and volume changes as a prerequisite for flooding preparedness can be carried out with the support of remote sensing. With regard to climate change the systematic monitoring of those seasonal changes (water volume, outline, etc.) gets an increasing importance. Fig. 4 provides an example of Sentinel 2-scenes of the dry and humid seasons. Flooded areas become clearly visible. During the humid season with high water

levels in the lakes and ponds the extent of flooded areas will be larger than during a dry season with low water levels or dried-up streams and lakes (Figure4).

Digital image processing methods are used to visualize the flooded areas. Classification of the satellite data according to the specific spectral characteristics of the water surfaces helps to delineate the flooded terrain. By creating water indices like the Modified Normalized Difference Water Index (MNDWI) calculated from the green and Shortwave-Infrared (SWIR) bands of Sentinel 2 data using the open-source SNAP software provided by ESA areas covered by surface water can be identified and extracted to be presented in maps. (Figure 5).



Figures 4 Documentation of a dry season situation (upper left) and of flooded areas using Sentinel 1 and 2 satellite data of the Surabaya area



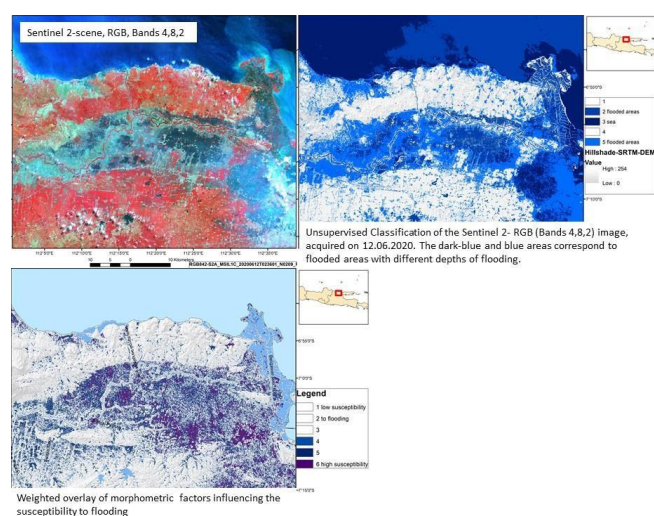
Figures 5 Modified Normalized Difference Water Index (MNDWI) based on Sentinel 2 data (blue-water surfaces) calculated from the green and Shortwave-Infrared (SWIR) bands.

3. RESULTS AND DISCUSSION

The different causes of flooding such as torrential rains, storm surge or tsunami or tidal waves require an adapted approach.

3.1. Monitoring Flooding related to torrential Rains

When combining the satellite data with the weighted overlay results based on DEM data that are summarizing the morphometric factors influencing the disposition to flooding, it can be stated that the areas most susceptible to flooding on the map (dark-blue) are in deed those flooded in the past (Figure 6). The weighted overlay approach in ArcGIS can contribute to the detection of those lowlands, that could remain longer time flooded than the environment.



Figures 6 Combing the weighted overlay results with the classification results of Sentinel 2 data. Supervised und unsupervised classifications of the satellite data help to extract and visualize the flooded areas. The information of flooded areas gained from the satellite data are compared with the weighted overlay results. The coincidence of flooded areas with those areas with high susceptibility to flooding due to their morphometreic disposition is obvious.

Whereas optical satellite data of this area often show cloud covers and, thus, are not available for a continuously flood monitoring, radar images have the advantage to be nearly weather-independent. Flooded areas can be detected on radar images due to their “mirror-like”, radar-smooth reflection of radar signals, appearing black on the radar image. Figure 7 provides an example how Sentinel 1 A radar scenes support the mapping of flooded areas that nearly correspond to areas below 10 m height level.

Merging the information of the extent of areas flooded in the past with infrastructural data such as buildings and roads it can be derived which buildings will be affected by future

flooding events and sea-level rise near the coast, see Fig.8. Buildings situated in height levels below 5 m are indicated in red colours on Fig.8 as well as roads below 5 m height level. These areas can be considered as vulnerable to flooding [18]. In case of emergency the responsible authorities involved in disaster management are able derive quickly which road segments in the affected area could not be used anymore.

3.2. Contribution of Landsat and Sentinel 2 Satellite Data to the Monitoring of Water Currents and high energetic Flood Waves (tsunami, tidal)

The monitoring of water currents in the Java Sea and the straits of Surabaya and Madura is essential for flooding hazard preparedness related to high energetic flood waves.

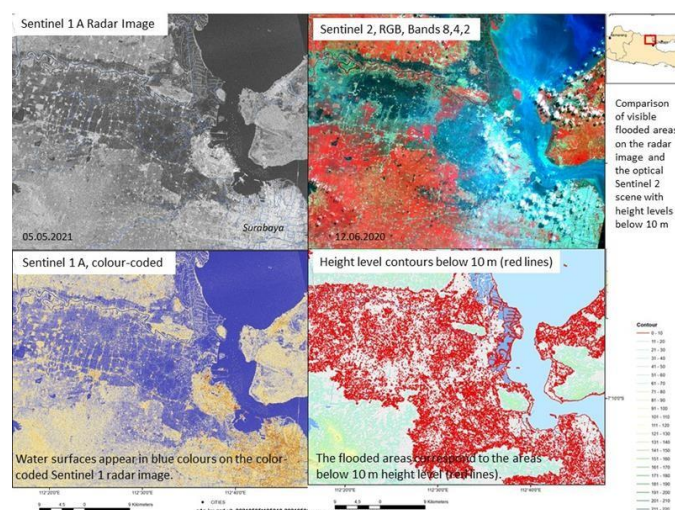


Figure 7 Sentinel 1 A radar and Sentinel 2 scenes in comparison with the height level map

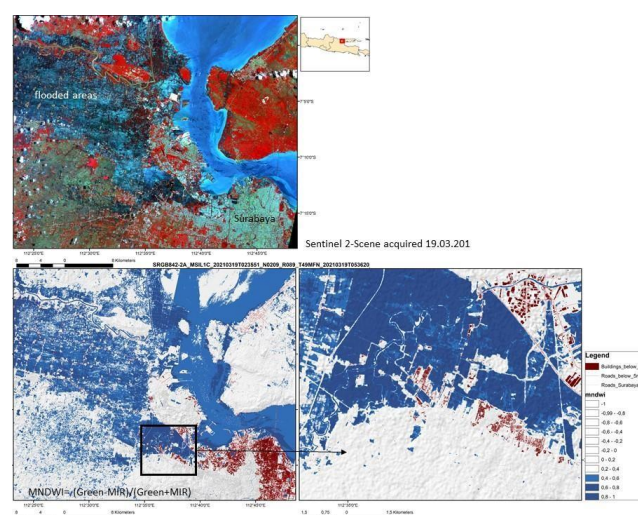


Figure 8 Merging of the extent flooded areas derived from the Sentinel 2-image (acquisition: 19.03.2021) with infrastructural data (streets and buildings below 5 m height level)

Satellite images contribute to a better understanding of the interactions of the coastal morphology and the development of water currents, of course, depending on meteorologic and tidal conditions at the acquisition time of the images. Tsunami events have been recorded from this part of the sea and in the Basin of Bali (Figure 1) related to earthquakes, volcanic eruptions, and submarine landslides. The source of tsunamis, the direction of the incoming waves, their height and energy cannot be predicted. However, when analysing the influence of the coastal morphology on the streaming pattern in relation to wind and wave directions, it supports a better understanding of what might happen in case of high energetic flood waves.

Given that coastal flow is the product of a complex mix of factors (for example freshwater discharge, tides, temperature, salinity, winds in various frequency bands and heights and the influence of motions imposed from seiche movements), coastal dynamics may be regarded here as regional. The low depth of the sea below 100 m might increase these effects. The tide amplitude at the time of a potential tsunami directly affects the inundation height as well and, hence, the impact of the tsunami on the coastal areas. Even in the case of small amplitude tsunamis, the combination of the tsunami with a higher tide might result in a higher wave height [19].

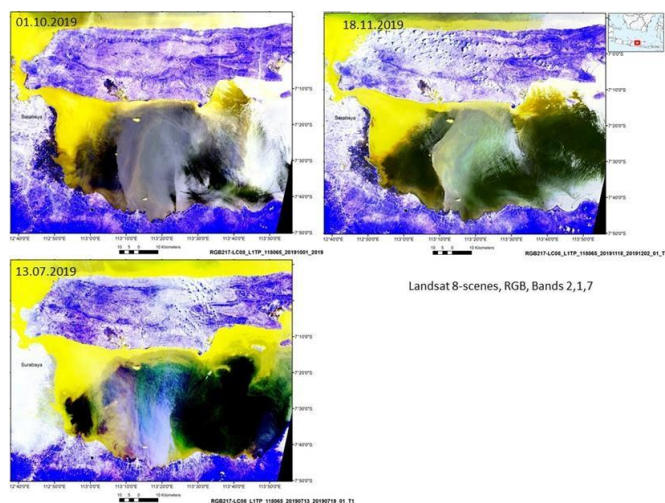


Figure 9 Streaming patterns in the Strait of Madura visible on Landsat 8 scenes (wind directions from south)

Figure 9 shows Landsat 8-senes (RGB band combination 2,1,7) of different acquisition times with different wind and streaming conditions from the Strait of Madura. Islands in front of the coast line are influencing and modifying the wave patterns, their densities and sizes, often causing turbulent flows. Depending on the wind direction waves are interfering each other within the area of the islands. The islands situated in front of the coast line might slow down high energetic flood waves directed towards the coast. Due to the u-shaped outline of the coasts in this part of the Java Sea seiche development can be expected enhancing upwelling and downwelling

currents and interfering waves (Figures 9 and 10). Upwelling and downwelling occurs along coastlines are related to the main wind directions. However, these up-and downwelling processes cannot be monitored directly by remote sensing due to the low penetration depth of the sensors only up to several centimeters. Thermal bands of Landsat 8 help to identify current patterns that might be related to these currents.

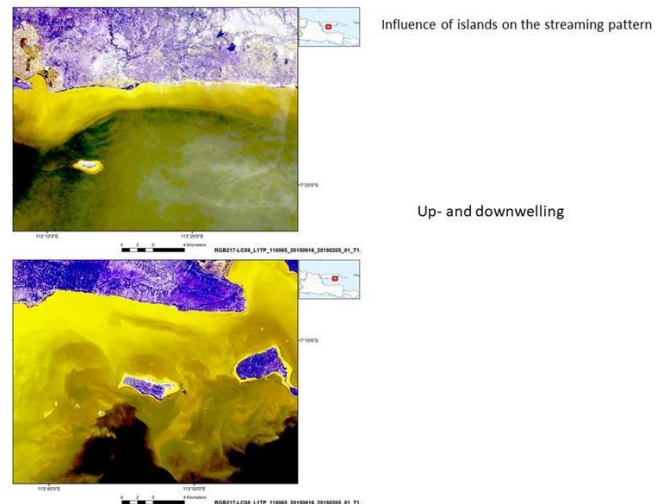


Figure 10 Landsat 8 scenes revealing the current pattern along the coast

The Landsat 8 scene acquired on 23.11.2015 shows high-energetic waves directed towards west to the coast of Surabaya by creating longitudinal waves parallel to the coast (Figure 11).

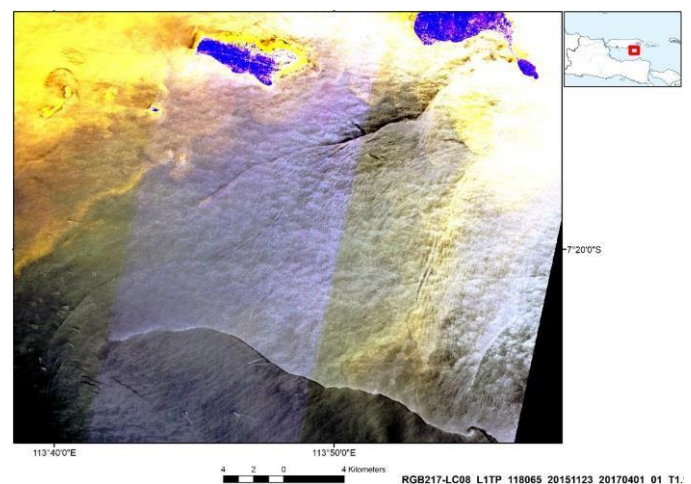


Figure 11 Landsat 8 scene (23.11.2015) showing high-energetic waves (enlargement in the next figure) westward moving waves (ships in front) towards the Strait of Surabaya

When including information of the wind pattern at the acquisition time of the Landsat image as well as of the ocean current flow directions there is no visible explanation for the wave front visible on the Landsat scene directed towards west.

As the main wind direction was coming from SE to SSE on 23.11.2015 this wave front is obviously not related to the main wind direction. The main direction of the ocean streaming pattern was directed towards east at the acquisition time of the Landsat data (Figure 12).

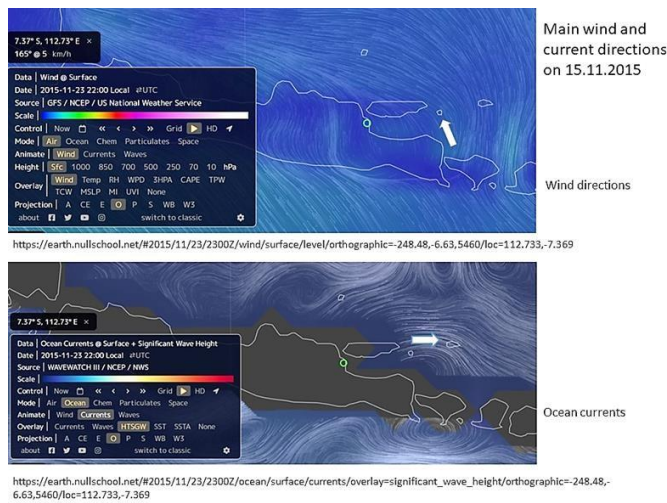


Figure 12 Main wind and sea current directions on 15.11.2015

The coastal morphology might be one of the reasons for these waves as the passage through the islands might focus the water flow and energy. Another explanation for origin of the waves visible on the Landsat 8 scene could be highly energetic tidal stream currents. Further reasons for such waves might be subaqueous volcanic eruption, submarine mass movements or stronger earthquakes triggering the development of sea waves.

In this part of the Java Sea volcanic activity seems to be a probable source (Fig.13), when considering the amount of active volcanoes in the southeast of Surabaya. However, the strong earthquakes along the plate boundaries in the north of Bali might be another important source.

The sea bottom topography, especially slope gradient maps derived from General Bathymetric Chart of the Oceans (GEBCO) bathymetric data provide an idea where stronger earthquakes, submarine volcanic eruptions and volcanic activities at the land surface (often related with earthquake swarms) might trigger secondary effects like submarine landslides and turbidity currents and, thus, tsunami waves.

The next figure shows the slope gradient map of the sea bottom of the Strait of Madura in about 50 to 100 m depth (Figure 13). A north-south orientation and parallel arrangement of the flat valleys is clearly visible. Whenever there might be further volcanic activity in the south of the Strait of Madura the N-S-orientation of the sea valleys could have an effect on resulting flood waves? In case of volcanic eruptions from the volcanic chains aligned in N-South direction such as from of Iyang Agapura to Lurus volcano near the coast the subaquatic flow of volcanic material could cause tsunami waves, directed

especially towards the southern coastline of the Madura Island (Figure 14).

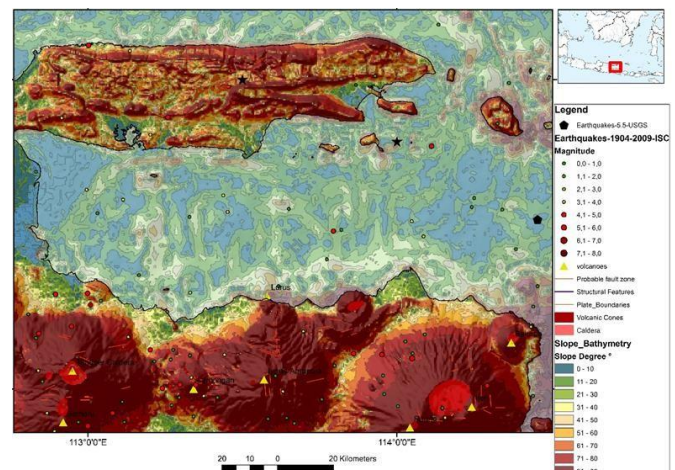


Figure 13 Slope gradient map of the sea bottom in the Strait of Madura

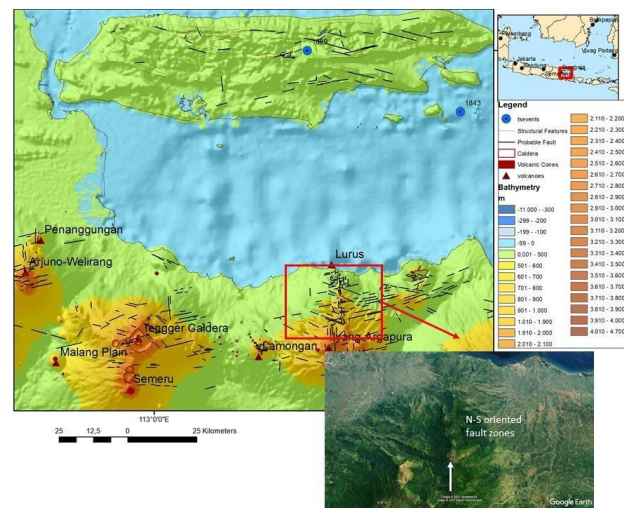


Figure 14 Height level map of the Strait of Madura based on GEBCO 2020 bathymetric data including volcanic features and probable faults mapped based on satellite data

Monitoring of potential sites for volcanic eruptions (lahar flow, lava flow) that might influence water currents and water quality in the Strait of Madura is essential for the fishery and aquaculture.

4. CONCLUSION

The impact of increasing flooding on society because of climate change requires preparedness and adaption strategies. These have to rely on a solid data base that has to be updated regularly. Coastal risk is dynamic and related to a change in coastal infrastructure, community livelihoods, land use, agriculture and habitability. Actual satellite data support the

documentation of these changes. Areas flooded in the past can be mapped by using Landsat, Sentinel 2 and Sentinel 1 radar images. This is a very important issue when dealing with flooding hazard preparedness by supporting local authorities with methods to collect and manage information used for risk estimation, analysis, assessment and finally management. The collection of basic data is of prime importance, and should be carried out by staff from the municipality in collaboration with local institutions and the local communities (van Westen, 2004) [20].

The input of remote sensing and GIS can be considered only as a small part of the whole “mosaic” of flooding research approaches and efforts to strengthen disaster resilience. Nevertheless, it offers a low-cost to no-cost approach (as the used DEM and satellite data are free), that can be used in any community, providing a first basic data stock for emergency preparedness. Summarizing factors influencing flooding susceptibility (such as relatively low height levels, terrain curvature corresponding to flat terrain, or slope gradients $<10^\circ$) by using the weighted-overlay tools in ArcGIS, help to detect areas with higher flooding susceptibility due to their geomorphologic disposition. This approach is suited to obtain a first basic overview on susceptible areas according to a standardized approach. The GIS integrated evaluation of the different data sets helps to identify areas vulnerable to flooding. The free available data and software could be used in every community, provided that the training of the staff is given. Using these tools strategies for flooding management adapted to the local needs can be elaborated and actualized continuously.

The impact of storm surge or tsunami waves on the coastal areas depends not only on the source of the high energetic flood waves, but also on the geomorphological settings of the coast. Evaluations of satellite images in combination with meteorological data contribute to a better understanding of the local influence on the waves and their interactions with the coastal morphology.

Disaster resilience requires an interdisciplinary approach and a strong cooperation and data exchange between different disciplines and institutions. One of the tasks to strengthen of disaster resilience should be improving the interdisciplinary knowledge transfer, co-operations and alignments between disaster involved institutions and to provide the legal and technical infrastructure. The exchange of data between different institutions often needs the support of laws.

It is urgent to combine the knowledge of flooding hazards with the efforts of urban and regional planning and of social sciences. Urban and regional planning in Indonesia has to adapt more and more to the impacts of natural hazards and of climate change.

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