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Full Length Research Paper

Development of an Operational Satellite-Based Flood Monitoring Model for Tanzania

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ABSTRACT

Timely information during water related disasters is of utmost importance for flood preparedness and risk reduction. However, the conventional ground-based photographic monitoring of flooded areas is an expensive and time-consuming exercise. Satellite remote sensing is a quick and affordable approach that can be used for concurrent floods detection at different scales. This is important as it facilitates timely information for emergency response to disaster management departments, even in scarcely instrumented catchments. This study presents a novel approach for flood tracking using satellite image remote sensing science to map flood affected areas immediately after occurrence of rainfall events. An open-source water detection algorithm is developed that employs readily available satellite images and the Google Earth Engine (GEE) platform. Dar es Salaam and Singida regions in Tanzania were used as the case study for validation of the proposed approach. Use is made of Sentinel-1 satellite images and GEE coding. The after-flood tracking GEE code was validated with the physical flood extent markers and after-event flood extent survey points of the regions provided by the Ministry of Water (MoW). The findings reveal that the approach supports mapping flood extent areas by giving promising results after the satisfaction from validated data. Relevant parameters were then coded in order to develop the flood map of Tanzania. The findings of this study demonstrate the usefulness of open-source GEE in rapid flood inundation mapping.

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INTRODUCTION

Water related disasters, including floods, are expected to become more frequent in the Sub-Saharan Africa due to the global climate change phenomena that is causing hydrologic cycle intensification (WHO, 2020). According to World Health Organization (WHO) statistics, just between 1998 and 2017, more than 2 billion people were affected by floods worldwide (WHO, 2020). Emergency response planning and disaster relief services are usually expected to respond immediately. This, however, is not possible without reliable, accurate and appropriate information on coverage and severity of the floods. The need for tools for generating such operational data in a timely and cost effective manner cannot be over emphasized. Uddin et al. (2019) states that "*natural flood disasters are common and cannot be stopped, however efficient tools for flood inundation mapping and flood damage assessment can be useful for emergency response and disaster management*".

Tanzania is not spared from flood disasters. Flood has brought physical, economic and environmental damages over the past decade. According to Tanzania Red Cross reports, substantial loss of lives, loss of properties, including buildings, infrastructures and livestock, roads inaccessibility and other communication breakdown have been the major aftermath of the floods for many years (Redcross, 2019). Some parts of Tanzania are more severely affected than others. Mara region for example, was affected by floods in October 2019, resulting in displacement of at least 1113 people, 50 of which were injured. More than 370 acres of cropland was destroyed and extensive damage to critical infrastructure like access roads, classrooms and bridges were destroyed or partially damaged (Redcross, 2019). For this reason, it is necessary for the government and disaster experts to monitor and assess the damages. Flood inundation maps provide valuable information towards flood risk preparedness, management, communication, response and mitigation at the time of disaster, and can be developed by harnessing the power of satellite imagery and traditional approaching.

The use of traditional methods such as ground survey and aerial observation in mapping the extents of floods is time consuming, expensive and it accounts for small scale results (Roy and Sarker, 2016). For example, Ramani Huria in 2016 involves the use of many resources in data collection process like Unmanned Aerial Vehicles (UAVs), GPSs and the community for mapping flood prone areas at Dar es Salaam in a big amount of time (Msilanga, 2018). Such resources lead to incur a lot of costs, consume a large amount of time and produce maps whose accuracy is questionable. But satellite image is real time data and its interpretation is very simple, easy and quick method in mapping the extents of flood (Tiwari et al. 2020).

Remote sensing technique came up with consistent reliable technology for satellite data collection using multiple wavelengths of electromagnetic spectrum (Pettorelli et al. 2018). Optical and Synthetic Aperture Radar (SAR) imagery are the main datasets collected from satellites. Its availability has been used as an effective and alternative tool for monitoring flood situation and extent in a particular area (Sivasankar, 2019). Several studies (Sivasankar, 2019, Bioresita et al. 2018, and Cimpianu and Mihu-Pintilie, 2018) have shown the potentiality of SAR imageries in mapping of flood extent. This is because SAR sensors are independent from solar illumination and its signals penetrate through any atmospheric condition (Cimpianu and Mihu-Pintilie, 2018). From this fact, the SAR sensors observe the earth in 24 hours a day and its signals penetrate through clouds, haze or light rain and thus more useful dataset for flood mapping.

Despite the usefulness of SAR sensors, data processing of its satellite images for retrieval of flood signatures on a computer software for large area is cumbersome and time consuming. Large areas require the vast number of satellite images but in a computer, there are resource limitation such as storage capacity and processing speed. However, the latest developed GEE platform has exhibited the capability of rapid processing of big dataset covering a large area (Tiwari et al. 2020). GEE is a cloud computing platform, accessible through a web-based platform interface for planetary scale geospatial science (Gorelick et al., 2017). This cloud-based platform has publicly made available numerous satellite image collections and provides image analysis functionality at large scales (Tiwari et al., 2020). It is also accessed and controlled through an application programming interface (API) accessible by internet browsers and by an interactive development environment (IDE) that enables the creation of prototype and quick visualization of results.

Several studies (Scientist and Raj, 2013, Sivasankar et al., 2019, Lal et al., 2020, Tiwari et al., 2020, Vanama et al., 2020) have embarked on developing the operational methodology for rapid timely flood mapping in large scale on their affected areas by utilizing SAR images in GEE platform. However, in Tanzania there is no study showing the existing approach ofrapid flood mapping extent using SAR satellite images in GEE platforms. In this study, an algorithm for operational flood mapping using Google Earth Engine is developed. The developed algorithm is for operational use, generating the maps from the present inundated or flooded areas from recent event occurs using available satellite imagery of the affected locations. While this maps the flood inundation extents, its success depends on availability of satellite imagery. This is why this study made use of SAR images that are not hindered by presence of cloud cover, unlike Landsat and MODIS, SAR is able to look through clouds. This study is expected to make significant contribution towards making informed emergence response timely and to future flood events.

METHODS AND MATERIALS

An open-source water detection algorithm that employs readily available satellite images is developed and used together with the GEE platform by utilizing Sentinel-1 satellite images and GEE coding. The after-flood tracking GEE code is validated with the physical flood extent markers and after-event flood extent survey points of the regions provided by the MoW.

Data collection

Primary data was collected and used for validation of the output maps. The primary data in this study was obtained through a survey of recently flooded areas carried out to identify flood markers (high-water-mark indicators). Global Navigation Satellite System (GNSS) survey of high-water-mark indicators, including mudlines on bridges and buildings, tranquil-high-water indicators on stream edges, wash and cut-lines on floodplains, etc., were collected in after floods events. These marks indicate the evidence of inundation extent on the area. GNSS survey data was collected by GNSS receivers.

For Dar es Salaam, ground-truthing was carried out by the research team and complimented by data from Google Earth and Sentinel-1 satellite images. The Tanzania Ministry of Water provided the flood data for Singida region. This data was used to validate this exercise. Other primary data like Digital Elevation Model (DEM) from HydroSHEDS, MODIS land cover, and Tanzania regional shape files were used to improve flood detection algorithm.

Satellite images acquisition

Considerations for sensor limitations were made in the selection of both satellite data and processing tools to be used in this study. Optical and SAR imagery data are both freely available with suitable temporal and spatial resolution for monitoring surface water dynamic changes (Andy, 2016). Despite a vast choice of freely available satellite imagery, multi-temporal SAR imagery from ESA Copernicus was opted over optical imagery due to expected persistent cloudy conditions during floods. These sensors can penetrate fog, rain and cloudy conditions, unlike optical sensors. Specifically, Sentinel-1, with 10-meter resolution, from Copernicus program operating in C band with a revisit time of 12 days were used. Such a short time cycle would allow mapping the inundated areas. Owing to the swath width of the images, a large number of Sentinel-1 images were crucial for monitoring flood evolution and inundation dynamics across all tiles of the pilot areas.

Water extraction algorithm development

GEE is web platform for cloud-based processing of remote sensing data covering large areas. It is a free source code that is flexible and provides quick results using a change detection approach on Sentinel-1 data for mapping flood extent. GEE is suitable for this work as the study is generating a country-wide algorithm, but initially validating it over 2020 flood events and few pilot sites, as previously elaborated.

In mapping flood inundated areas, two sets of satellite data are required for detecting the flood and flood mapping; one set consisting of the image acquired before the event and the other set comprising the image acquired during the occurrence of the flood event. The first image is generally used as a reference (Klemas, 2015). The algorithm for detection of flood inundated areas was written and executed on GEE by utilizing two sets of Sentinel-1 imageries covering the two selected pilot study areas.

Study Area Description

Tanzania country coverage area is estimated to be 945,500 square kilometers with a total population of about 60 million people (Republic et al., 2021). Tanzania experiences two seasons of rainfall, short rains that span between October and December and long rains between March and May (Blocher et al., 2021). According to the report on climate change and migration in the United Republic of Tanzania report (Blocher et al., 2021), abnormal rainfall was reported across the country from October 2019 to May 2020, which was associated with an increase in temperature in the Pacific and Indian Oceans. This occurrence of heavy rains led to tremendous higher levels of water in lakes, rivers and dams. For example, Lake Victoria and Lake Tanganyika reached the maximum levels ever recorded before; all four gates of Mtera dam were opened to prevent it from collapsing due to high amounts of water entering the dam. Also, flows in major rivers (Rufiji, Kagera, Mara, Mbwemkuru, Kikuletwa, Songwe, Great Ruaha, Little Ruaha, Ruvuma, Kagera and Pangani) reached the highest in records
Floods are among water resources management challenges (Fulazzaky, 2014). They fall in the list of natural disasters and they account for about 40% of all-natural disasters occurring worldwide (Abaya et al., 2009). They have significant consequences to economic losses. In Tanzania, it has been observed that frequencies of flood events keep increasing and their impacts prevail. This study was conducted for the whole country Tanzania but only two administrative regions namely Singida and Dar es Salaam, were used for validation as shown in Figure 1.

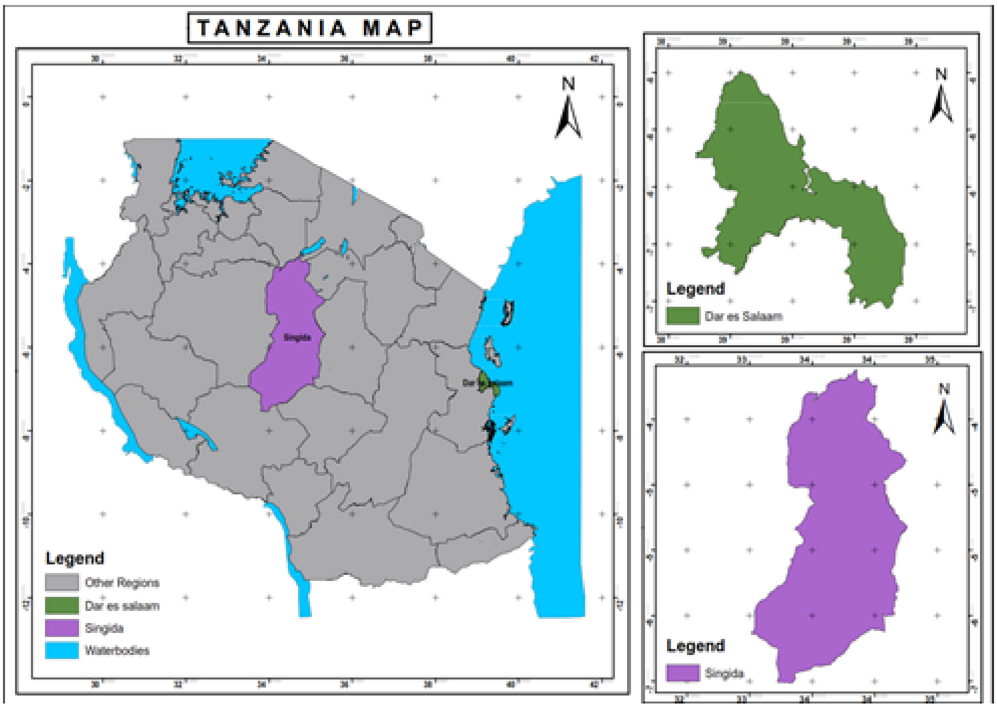

Figure 1: Map of the study area.

Data preparation and analysis

The method used in flood mapping in this study is presented in Figure 2. Specifically, the procedure was carried on the GEE cloud platform with an algorithm which was executed in multiple tasks impeccably, obtaining of Sentinel-1 images concurrent with flood mapping. Dar es Salaam, Singida and Tanzania boundaries shapefiles were used for demarcating selected study site areas where validation of the flood inundation maps as retrieved from Sentinel-1 imagery would also be carried out. From GEE, the predefined parameters of the entire Sentinel-1 Ground Range Detected (GRD) archive, called the image collection, is filtered by the instrument mode, the polarization, pass direction, spatial resolution and are clipped to the boundaries of the area of interest. The filtered Image collection is then reduced to the time frame that represents the time prior to and the time after the flood event. Pre and post flood time frames were defined in such a way that allows for the selection of relevant satellite imagery tiles covering the area of interest. This was done with the understanding that Sentinel-1 imagery is acquired for a minimum of every 12 days for each point on the globe except Europe (ESA, 2012). The time frame for mapping the flood extents in Singida, Dar es Salaam, and Tanzania is as shown on Table 1.

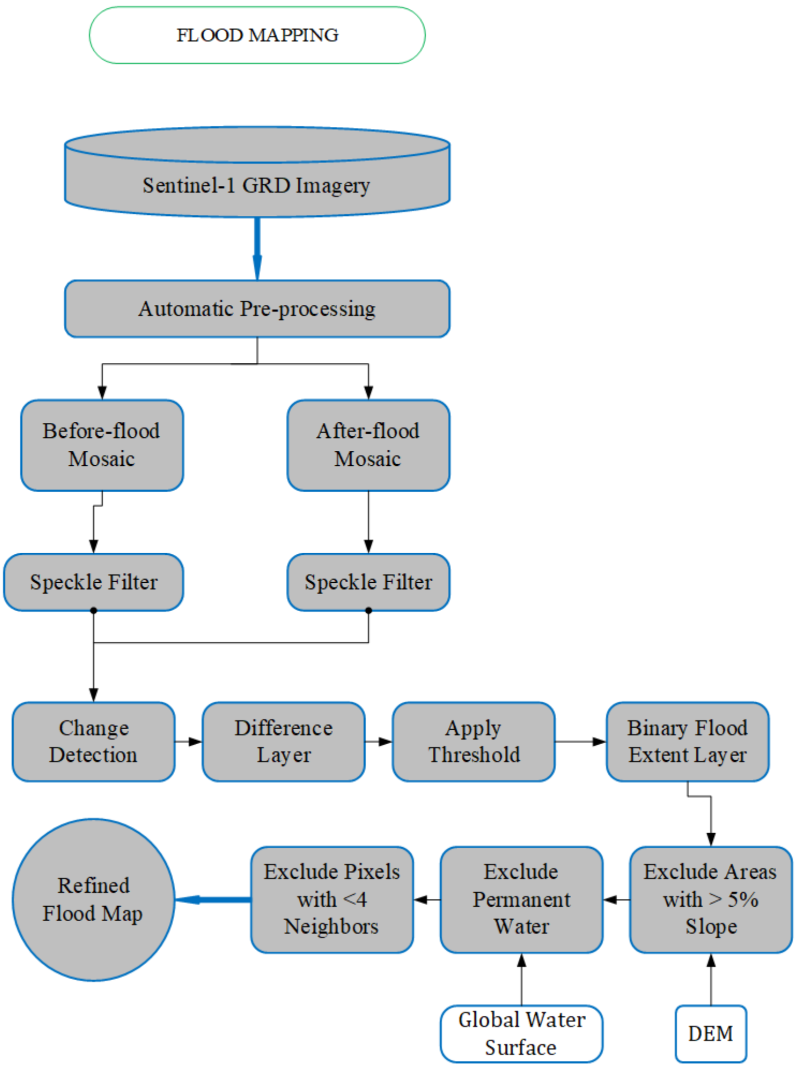

Figure 2: GEE flood mapping workflow.

Table 1: Time frame before and after the flood events for acquiring Sentinel-1 images.

Area	Dates of acquisitions of Sentinel-1 images	
	Period before floods	Period after and within floods
Dar es Salaam	01-03-2020 to 17-03-2020	02-10-2020 to 16-10-2020
Singida	01-02-2020 to 16-02-2020	02-04-2020 to 16-04-2020
Tanzania	01-07-2019 to 28-07-2019	02-03-2020 to 28-03-2020

Preprocessing of Sentinel-1 collection was already done using sentinel 1 toolbox in GEE catalogue which is updated every week. It involves thermal noise removal, radiometric calibration, terrain correction and conversion of the backscatter coefficient ($\sigma°$) into decibels.

Change detection was carried out where the after-flood mosaic was divided by the prior-the-flood mosaic, resulting in a raster layer showing the degree of change per pixel. The threshold of 1.25 was applied, assigning 1 to all values greater than 1.25 and 0 to all values less than 1.25. The binary raster layer created by this process shows a potential flood extent. The threshold of 1.25 was selected through trial and error as the results were compared with the ground-truthing reference data.

On refining the flood extent layer, several additional datasets were used to eliminate errors in retrieving signals during the flood events. The Joint Research Centre (JRC) Global Surface Water dataset was used to mask out all areas covered by water for more than 10 months per year. The dataset has a resolution of 30m and was last updated in 2018. To remove areas with over 5% slope, a digital elevation model (WWF HydroSHEDS) was chosen, which is based on Shuttle Radar Topography Mission (SRTM) data and has a spatial resolution of 3 arc-seconds. Furthermore, the connectivity of the flood pixels was assessed to eliminate those connected to eight or fewer neighbors. This operation reduces the noise of the flood extent product. This was followed by computing the extent of the inundated flood zone. Notably, it was necessary to overlay and merge the output with the population dataset so as to determine the total number of exposed or vulnerable population.

Furthermore, the assessment of inundated cropland was retrieved by merging the flood inundated maps with MODIS Land Cover satellite images that have a spatial resolution of 500 m and is updated yearly. The Land Cover Type 1 band consists of 17 classes with two cropland classes, class 12 and class 14. For the class 12, at least 60% is cultivated. While class 14, there is only small-scale cultivation of about 40 - 60% with natural tree, shrub, or herbaceous vegetation. Both classes are extracted from the dataset and merged with the flood extent layer.

Similarly inundated urban areas were retrieved as the previously done using the MODIS Land Cover Type dataset. The 'Urban Class 13' of the band Land Cover Type 1 was extracted to assess potentially affected urban areas. It is important to note that difficulties were experienced in separating the spectral signatures of inundated and non-inundated urban areas. It is envisaged that the output is a slightly underestimated due to the difficulties of detecting water in built-up areas.

This study went further in attempt to estimate the population exposed to floods. JRC Global Human Settlement Population maps were used that contain spatially information on the number of people. These data have spatial resolution of 250m and was last updated in 2015.

Validation

Ground-truthing exercise was carried out for the purpose of validating the flood inundation maps. As pointed out earlier use was made of the GNSS receiver during a site survey of the selected areas to collect actual flood extent markers on the ground. Validation was therefore carried out in Envi and ArcGIS to compare the generated satellite derived flood inundation maps and estimates derived from GNSS surveys. Collection of flood extent markers was enhanced by the help of key informant semi structured interview with local leaders and residents of affected areas. This method helps in identifying and further increases the accuracy of the flood markers.

RESULTS AND DISCUSSIONS

This study mapped flood coverage extent during the short rainfall season and during the long season rainfall.

GEE flood mapping of Dar es Salaam

Analysis of flood hydrographs and satellite images revealed that grievous floods occurred on October 13, 2020, as a result of heavy rains on a particular day during a short rainfall season. More than 12 lives were lost as dozens of roadways were disrupted, affecting city transportation. Many urban areas were flooded, with Msimbazi valley being among them. The inundation zones were mapped using imageries from the Sentinel-1 satellite, which were divided into two time periods: The first period was set for 1-17 March 2020, while the second period was set for 2-16 October 2020 as detailed explained in the methods. The date range is specified and varies to ensure that the GEE database retrieve the maximum number of scenes to cover the whole Dar es Salaam area. Assessment carried out from GEE database located the date of 13th October Sentinel-1 scene as actual flood occurrence scene, which was baseline imagery for flood extent mapping. The assessment evidently showed flood occurrence at Msimbazi valley as shown on Figure 3. Total estimation of 1,628 hectares was affected. The analysis also gives an estimate of number of people exposed to the floods, affected cropland and estimation of affected urban areas as shown on the Table 2.

GEE flood mapping of Singida

Singida region experienced above-average rainfall throughout the long rainy season of 2020, resulting in exceptionally high level of water in Lakes Singidani, Kindai, and Munang, leading to the confluence of Kindai and Munang, causing flooding in the surrounding communities. Because of these incessant rains flood occurred on April 1, 2020. On mapping the flood extent area, the start and finish dates of the pre-flood period, as well as the start and end dates of the post-flood period were identified as from 1-13 March 2020 and 1-12 April 2020 respectively, for acquiring Sentinel 1 imagery. This study was able to map the entire Singida region by utilizing imageries in the database from span of 2-14 April 2020. Lakes' Kindai, Munang and Singidani were inundated as seen on Figure 4. The estimates show a total flooded area of about 28,556 hectares. further, this study estimated the exposed number of people, inundated cropland and estimation of inundated urban areas as shown in the Table 2.

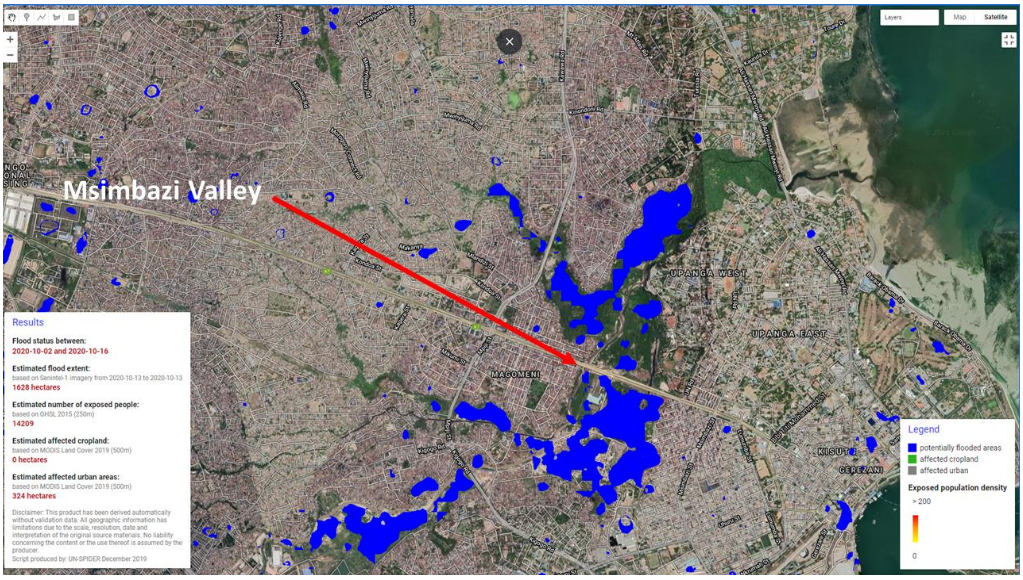

Figure 3: GEE flood map of Dar es Salaam.

Figure 4: Flood extent on GEE of Lake Munang and Kindai in Singida region.

Table 2: GEE's estimation of exposed number of people, affected cropland and estimation of affected urban areas

Area	Flood status in (2020)	Estimated flood extent (hectares)	Estimated number of exposed people	Estimated affected cropland (hectares)	Estimated affected Urban area (hectares)
Dar es Salaam	2 – 16(October)	1628	14209	0	324
Singida	2 – 16 (April)	28556	2175	0	0
Tanzania	2 – 28 (March)	229484	202187	18273	10677

Dar es Salaam Validation Data: The results from the Dar es Salaam city inundation map were plotted against the spatial extent data for validation purposes, as shown in the Figure 5. Ground surveys to collect actual flood extents were collected on the outskirts of Jangwani, Msimbazi, and Mkwajuni, which are known to be flood prone areas in the Msimbazi valley and not the entire flooded area. Due to heavy rain, transportation facilities were halted, and conducting a manual survey over a large area was difficult because it required enormous resources such as skilled labor, financial, and computational resources. The ground location points were used to validate the study outputs of the generated flood inundation maps to ascertain their position with respect to actual flooded areas in the study area (Figure 5).

Lakes Singidani, Kindai and Munang Flood Extents Validation

Figures 6 and 7 are maps derived from data made available by the MoW. Figure 6 depicts Lake Singidani before and after flooding, while Figure 7 depicts Lake Kindai and Munang before and after flooding. In this study, the generated GEE flood map was compared to with the ground-based data from MoW that were used to construct the maps in Figures 6 and 7. The result of the validation shows that the GEE algorithm successfully mapped the flood extents as indicated by Figure 8.

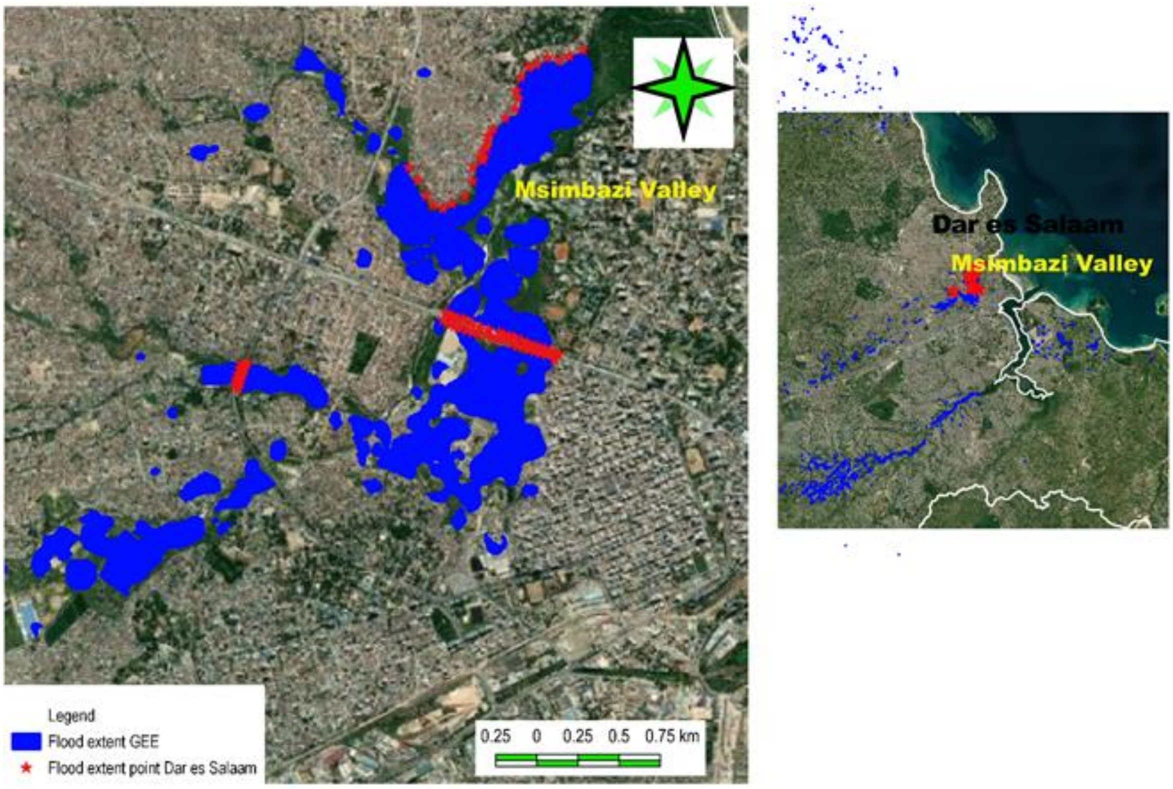

Figure 5: Comparison of the ground-based flood marks information collected across Msimbazi and the GEE satellite derived flood inundation map of Msimbazi valley in Dar es Salaam.

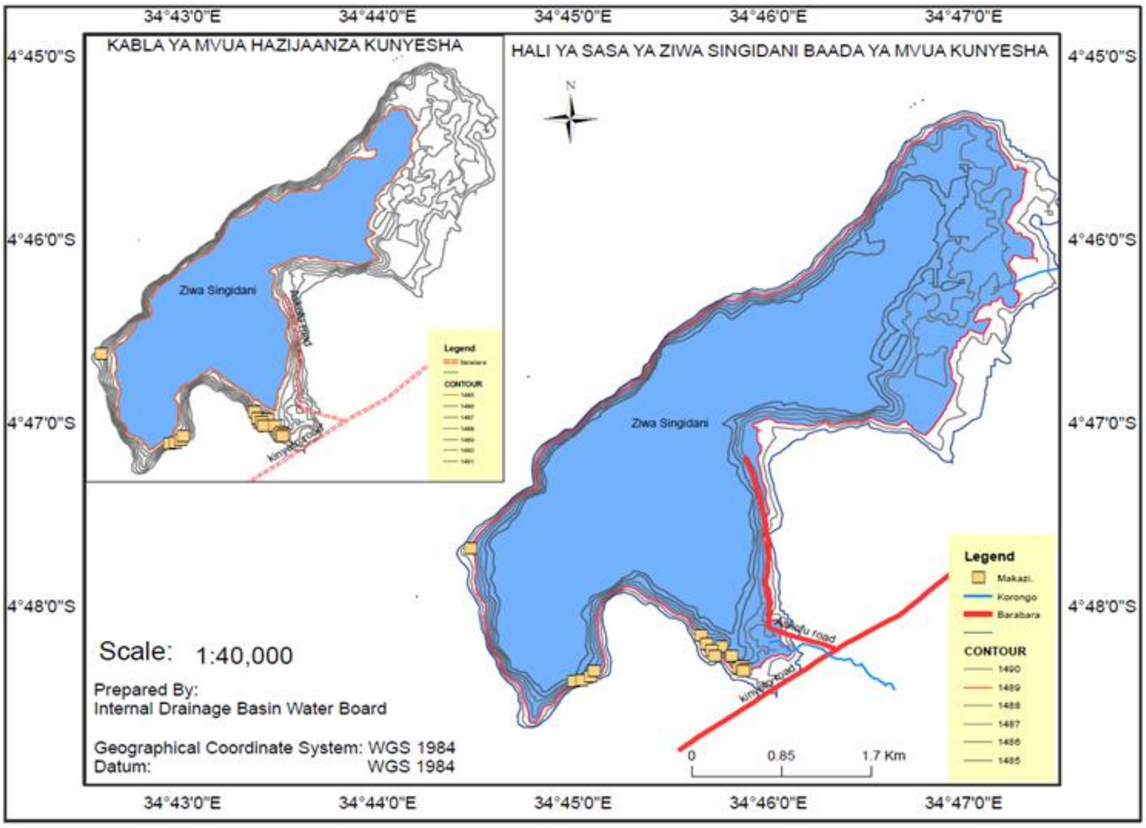

Figure 6: Lake Singidani's extents before and after heavy rainfall, (MoW).

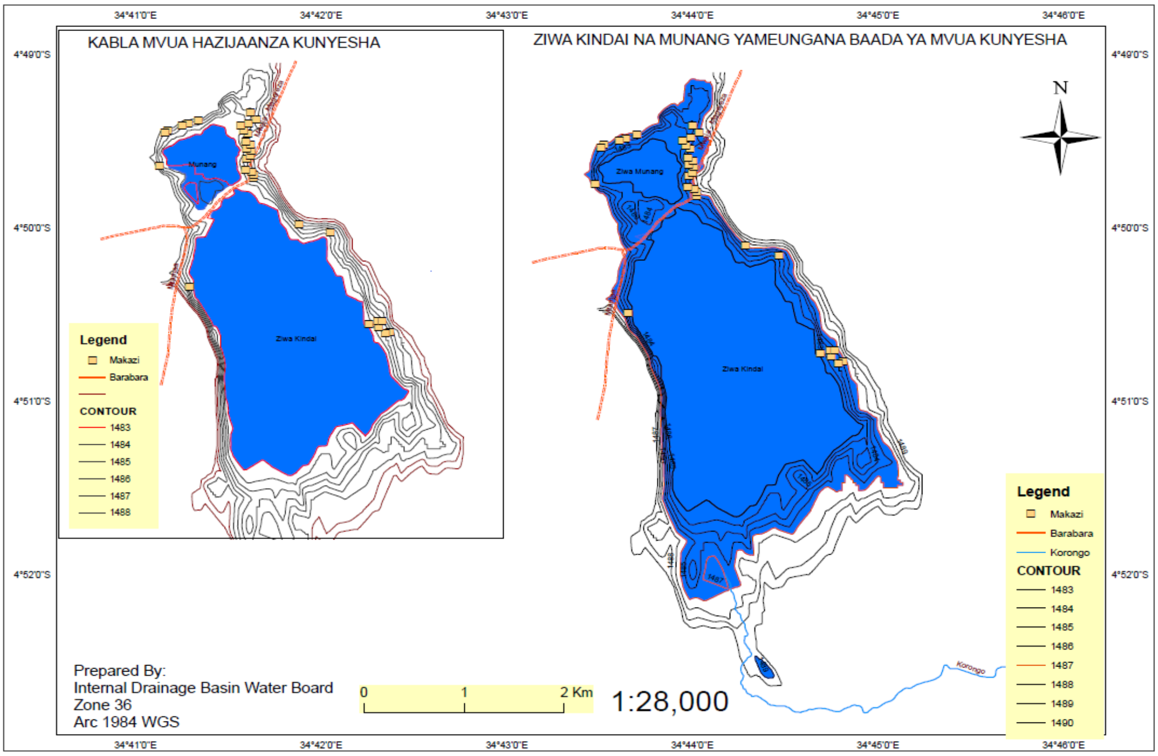

Figure 7: Lake Munang and Kindai's extents before and after heavy rainfall, (MoW).

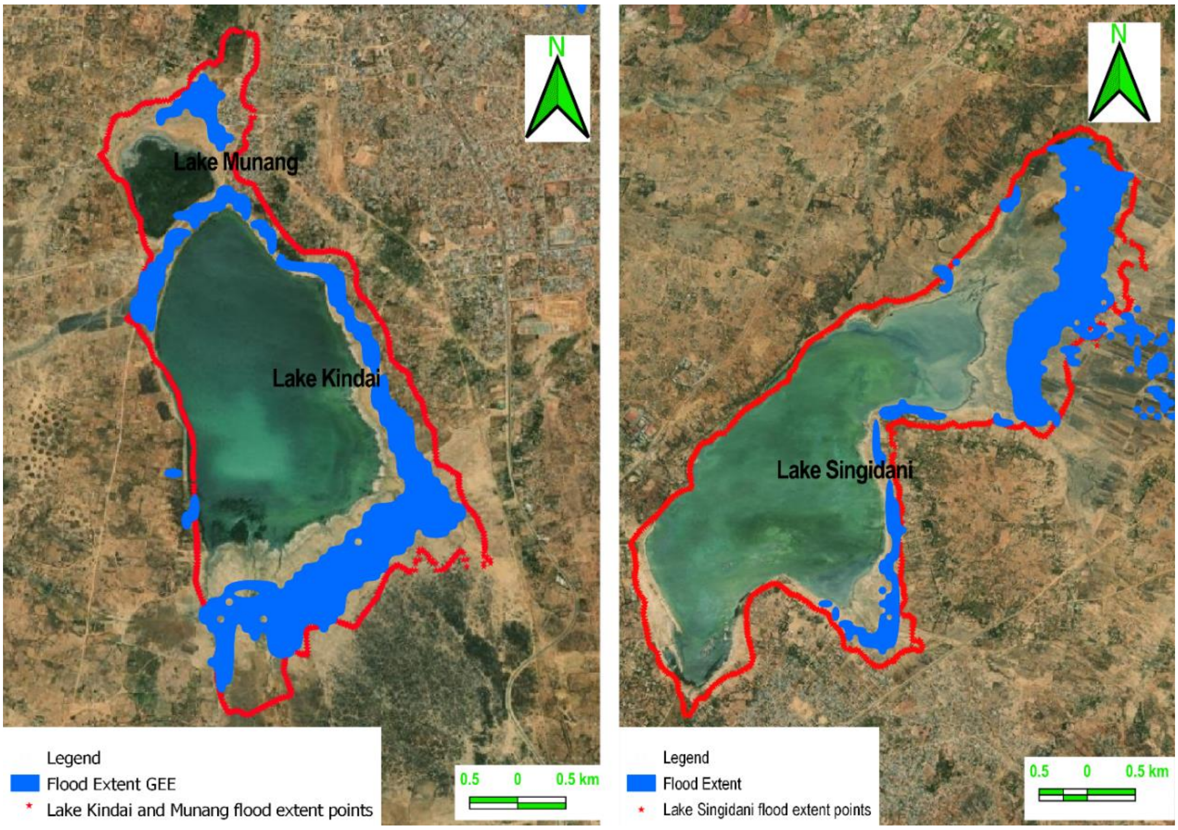

Figure 8: Lake Singidani, Munang and Kindai flood data extents vs GEE flood extents.

GEE Flood Mapping of Tanzania

Flood mapping across the country was carried out in considerations of the rainfall seasonality and their differences across the country. This also informed the image acquisition dates. Tanzania experiences unimodal rainfall pattern in the southern and western to central areas with one rainy season from November to May, while bimodal seasonality is experienced in the northern and Eastern parts of Tanzania i.e., two rainfall seasons. First season termed as long rains, begins in March, and ends in late May and the second season termed as short rains begins in September and ends in November. Upon attempting to detect flood inundated areas across the country, the date of image acquisition was selected in a range 1-28 July 2019 as prior-flood-period area and 2-28 March 2020 as post-flood area. The inundation areas were mapped based on Sentinel-1 of 2-27 March 2020, resulted with an estimation of total area of 229484 hectares, 202187 number of people were exposed, 18273 hectares of crops were affected, and 10677 hectares of urban area affected as shown on Table 2. The most affected areas were southern western part of Morogoro, eastern part of Mbeya and areas in close proximity to water bodies such as lakes and rivers. Areas around River Rufiji, Lake Singidani, Lake Kindai, Lake Munang, are shown to be potential flood areas during heavy rainfall. These has been shown in Figure 9.

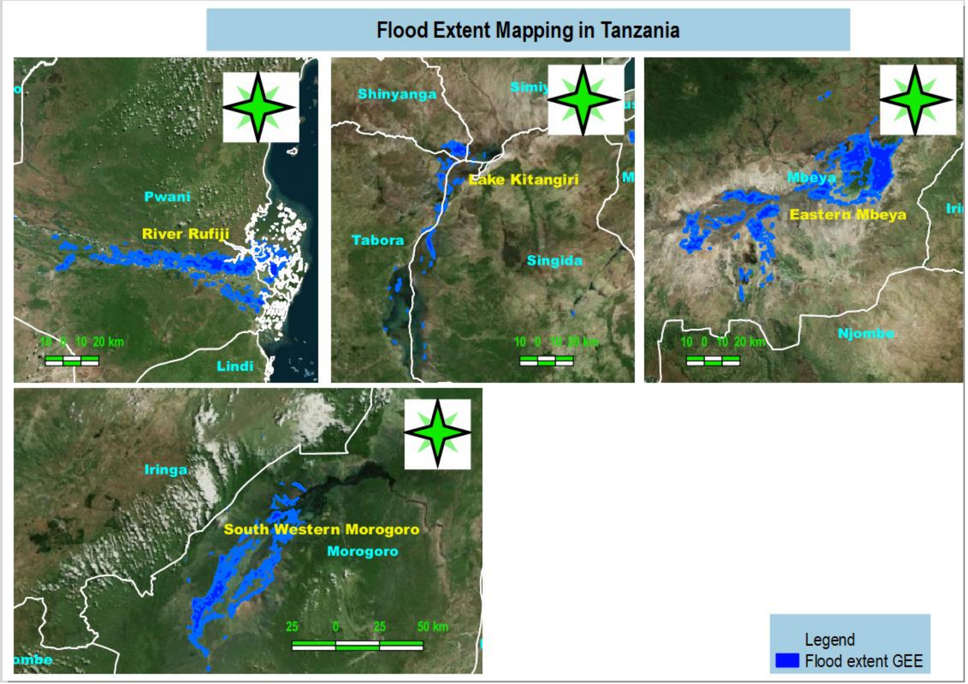

Figure 9: GEE Flood Mapping of Tanzania.

CONCLUSION

The comparison between the flood extents shown by the MoW data and those shown by GEE for Jangwani, Msimbazi, and Mkwajuni in Dar es Salaam and lakes Singidani, Kindai and Munang in Singida showed matching results as expected but more importantly the GEE platform used less time and minimal costs. Due to the results, it is evident that these mapping technologies can assist local councils and disaster management groups to improve their disaster management, land use planning and help in mitigation measures by utilizing free satellite images which are essential in determining and estimating the extent of flood on a large scale. The GEE platform can act as an operational tool for rapid timely mapping of floods at any area of a country. This method would be a basis for coordinating appropriate flood damage assessment activities, providing relief to the victims and construction of drainage infrastructure. Simply by recording data from presently flooded areas would also be useful when identifying areas at risk of future flooding.

Also, the use of this approach will enable the formulation of an atlas for past and present flood events, which would serve as a useful resource of information for policy makers, planners and civil society groups, specifically on the possibility of planning and monitoring development activities ongoing on flood prone and floodplain areas.

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