Flood Mapping and Simulation using Sentinel 2 and SRTM Data

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Abstract

Flood is one of the most devastating natural disasters occurring and affecting lives and economies globally. Hazards associated with floods are linked to storms raging across continents and anomalously high rainfall that impacts largely low-lying terrains. Addressing and managing flood is challenging and these require concerted efforts in technology that is crucial in finding a lasting solution. This require reliable and up to date data which must include accurate topographic information of affected areas. Flood inundation can be mapped and probability of occurrence can be simulated using digital elevation model (DEM). In this work, flood event of November 2019 was mapped and compared with normal water level of River Benue and the adjoining Lakes Gerio and Njuwa using Sentinel 2 MSI. Results show that the flood event engulfed the two lakes and expanded into the riverine wetland covering nearly 450% of area covered by normal water conditions. Simulated results show that at 157m above sea level, flood event can exactly replicate the November 2019 flood, expanding and covering the whole wetland. This result is important in determining rates of inundation by prediction of future events. The simulated results could also serve as a base data for engineering-based hydrologic flood models such as Hydrologic Engineering Centre - Hydrologic Modelling System (HEC-HMS) and Hydrologic Engineering Centre - River Analysis System (HEC-RAS). It is recommended that high resolution DEM would be required to enhance accuracy of flood models such as Light Detection and Ranging (LiDAR), Synthetic Aperture Radar (SAR), and Interferometric SAR (IFSAR) that has resolutions between 1-10m.

Keywords: Flood, Simulation, Sentinel 2, DEM, Mapping, Yola.

INTRODUCTION

The current increase in global climate variability due to aggravated natural disasters as a result of extreme events affects livelihoods and global economies. These events are majorly volcanoes, cyclones/hurricanes, bush fires, avalanches, landslides, floods, earthquakes and tsunamis. Flood, however is the most widely occurring natural disaster that affects livelihoods and cause distress to economies worldwide more than any natural or artificial disaster. It accounts for about one-third of the economic losses and over half of the deaths associated with natural disasters worldwide (Benz, 2000).

The impact and timing however differ from region to region. In the northern hemisphere, it affects societies during the boreal summer when more rainfall is recorded around the monsoonal timescales of June to October. In the southern hemisphere, it affects communities during the austral summer time between January and May.

Tropical rains are generally heavier than in other global regions, hence any continuous rainfall that lasts more than one week tends to cause floods. For example, intense African Easterly

Wave activity on convection, which is purely a tropical even suggests the ability of wave activity in modulating flood-producing rains (Muhammed, 2013).

In the sub-Saharan Africa, ranging from Senegal to Kenya, flood incidences are especially related to anomalous meteorological phenomena such as anomalously high monsoonal rain events. For example, the 2007 floods was associated with late arrival of rains for that particular year (NIMET, 2008; Paeth, 2010), such that heavy rainfall fell on dry soils, leading to a stronger surface runoff and flooding along river basins.

Rainfall pattern changes fairly quickly in low latitudes, exacerbated by monsoonal thunderstorms (Nicholson *et al*, 2003). Hence, floods may be triggered significantly downstream with respect to a different location of precipitation having different local weather conditions. Rivers in some localities may therefore experience increase in water with clear weather above the skies.

Many parts of the sub Saharan Africa are subject to recurrent flooding. In 2012, a record rainfall caused severe flooding that caused lives and substantial economic losses. This flood lasted for four months between July and October, the first of its kind since 40 years (verbal interview). Nkeki *et al.* (2013) showed that the 2012 flood devastated a large part of the northeast, especially along the River Benue trough of Adamawa and Taraba States. Submerged areas in Adamawa affected 6 Local Government Areas (LGAs) with area greater than 1,100km^2, while Taraba with much lower valleys along the Benue had and area of 4,600 km^2 submerged and affected 5 LGAs massively. The probable cause of this flood was attributed by scientist to shifting pattern and intensity of rainfall due to a changing climate (Adnan, 2010; Muhammed *et al*, 2015).

The exposure of human activities is increasing with the expansion of cities, and there is a motivated suspect that floods are increasing with time (Milly *et al.*, 2002). This is exacerbated by the fact that more and more people live in flood-prone areas (Cutter and Emrich, 2005), be it at the coasts or along riverine areas of lower watersheds, as well as increase in frequency of extreme floods (Milly *et al*., 2002; Fischer and Knutti, 2016). However, due to the increase in perennial floods, governments and other institution-based now priorities their policies and efforts leading to a significant investment efforts in flood mapping and control. Understanding of observational as well as modelling and forecasting of flood events is paramount to curtail the consequences of flood (Krzyzstofowicz, 2001).

Yola is the receiving end of flooded waters of River Benue that originates from the neighbouring Cameroon Republic. Apart from the perennial floods that affect the area, overflow of Lagdo hydroelectric Dam upstream in the Cameroon adds to the dismay of lower Benue settlers, risking lives and properties. The study area focuses on an intra-urban township wetland between Jimeta and Yola Town. The twin towns are combined to be called Yola.

Yola is centred at [9°13′48″N, 12°27′36″E] with an average maximum temperature in Mar and April of 38.9^{o}C. Maximum rainfall is obtainable in August reaching up to 200mm raining for more than 16 days, average relative humidity of 70% in August and mean monthly sunshine hours of 282 hours in November (Adebayo and Tukur 1999). The area has two lakes around the River Benue, Lake Gerio to the northwest and Lake Njuwa to the northeast. The lakes are over-flooded during flood events and loses much water during dry season due to irrigation. The Bagale Hills are also to the northeast.

The main goal of this study is to quantify flood event of November 2019, validating the study with DEM-based flood simulation. This is to examine the normal water extent of River Benue based on DEM extracts of surface water and normal water flow as well as the extent of flood some months after. The paper then compares flooded area from a DEM simulation to examine how the simulation can be reliably employed in extracting flood inundation areas. Simply the paper wants to find out how good the DEM, with a coarse vertical and horizontal resolution can simulate areas of flood inundation based on previous flood events and how these could be used in the absence of flood to show possible inundation areas.

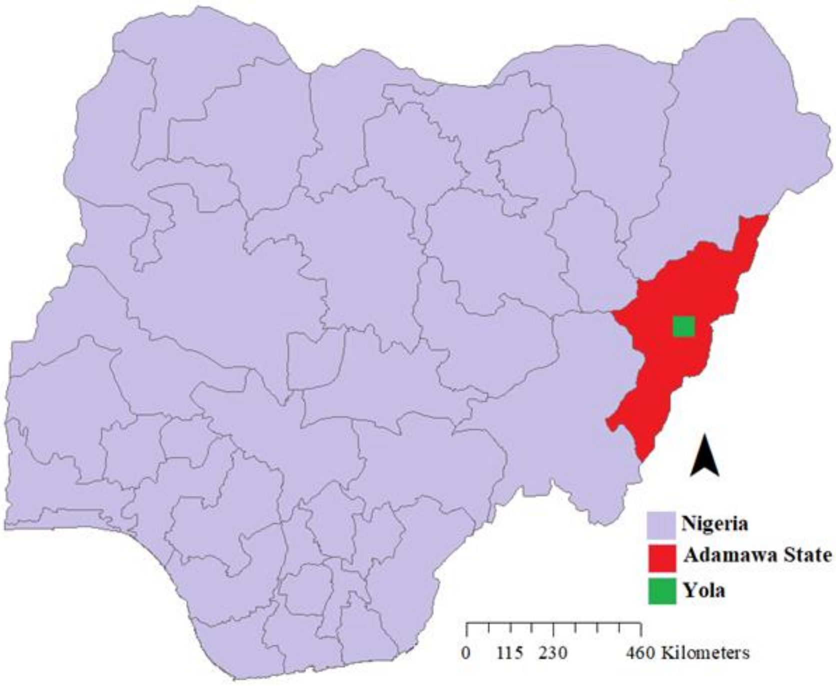

Figure 1: Map of Nigeria showing Adamawa State and Yola the state capital.

DATA AND METHOD

Datasets

Sentinel-2 Images

Sentinel-2 satellite was launched in 2015 by the European Space Agency (ESA) to provide high resolution multispectral and radar data for environment studies at a higher resolution. With two satellites, having the same orbital information have a revisit time of 5 days on a global coverage with a wide field of view (290 km), and high pixel resolutions (10 m, 20 m, and 60 m) (Gascon *et al*, 2017). Sentinel-2 data consist of 13 spectral bands in the Visible and Near Infrared (VNIR) and Shortwave Infrared (SWIR) bandwidths with spatial resolutions ranging from 10 to 60 m. VNIR consists of 4 bands (blue, green, red, and near infrared) with 10mspatial resolution, while SWIR includes 6 bands (4 narrow SWIR bands and 2 wider SWIR bands) with 20m spatial resolution, in addition to 3 bands of 60m spatial resolution for atmospheric correction application (Sadek and Li, 2019). Sentinel-2 L1C products are geometrically corrected with respect to the Universal Transverse Mercator map projection (UTM-WGS 84). Sentinel-2 images are freely available through the USGS Earth Explorer web service.

SRTM DEM

The Shuttle Radar Topography Mission (SRTM) was flown aboard the space shuttle *Endeavour* between 11 and 22 February 2000. With a horizontal resolution of 1-arc sec, SRTM represents the best quality, freely available digital elevation models (DEMs) worldwide (Nikolakopoulos, 2006). In addition, RADAR-based height measurements are better than the optical instruments such as ASTER DEM by far. Therefore, their elevation accuracy is high and presence of two antennas looking from different view angles gives a highly accurate horizontal and vertical measurements.

The DEM data are referenced horizontally to WGS84 ellipsoid and vertically to EGM96 geoid orthometric heights (Hoffmann and Walter, 2006). SRTM data vertical accuracy is less than or equal to ±7 meters (Slater *et al*, 2006), while horizontally is about ±20 meters (Huggel *et al*, 2008). It has been developed and then released after using a sophisticated interpolation and hole filling algorithms which allow the use of ancillary data sources when they are available (Jarvis *et al*, 2008).

METHOD

SRTM DEM Water bodies

The SRTM DEM was classified based on the homogenous characteristic of the data to show water level using ArcGIS 10.2. The DEM only show water body based on the period of radar mapping during the mission which was in February 2000. This was extracted and overlaid on the normal terrain map to be compared with the other water surfaces.

Sentinel-2 Water bodies

Surface water bodies were also extracted from the Sentinel-2 data sets. The extraction was based on two periods: before flood (May 2019), and during flood (November 2019). The water surface areas were extracted using Xu (2006) index which was found to be efficient in distinguishing water from all other surface reflectances. This is modified normalised difference water index (mNDWI). It has an advantage over Gao (1996) normalised difference water index (NDWI) that incorporates surface moisture which could not give correct surface area of water (Du, 2016). This method works well due to the extremely high absorption of water throughout the infrared region, particularly relative to the visible region (represented by the green band). This was found to suppress all other features such as land, vegetation, build-up areas, bare lands with the exception of water. It estimate open water extent accurately. This index is as follows:

$$mNDWI = \frac{Band3\ (Green) - Band11\ (SWIR1)}{Band3\ (Green) + Band11\ (SWIR1)}$$

DEM Flood Simulation

The DEM was used to simulate flood models at different mean sea levels (msl) to ascertain how good the DEM performs having vertical accuracy of ±7 meters and horizontally is about ±20 meters. The Area of Interest (AOI) is the flood coverage of November 2019. The simulation is considered at different mean sea levels to see whether it replicates the flood area and at what height (msl). Hillshade is used to help highlight the 3D DEM in ArcGIS.

RESULTS AND DISCUSSION

RADAR and Sentinel Water Levels

The water level (Figure 2) for SRTM 11-22 February 2000 and that of May 2019. It appears that there was still high water level in February during the radar mission before May when the dry season and irrigation did not hit the area much. The changes in the course of water level is due to debris from the weathering rocks and silts upstream that creates a huge sediment covering the large surface area supposedly covered by water. Sedimentation and withholding of water by the Cameroonian Lagdo Dam authorities affect navigation by bigger ships that used to convey goods along the River Benue from the sea to Yola.

The river (green) is the product of sentinel water index. The changes in water course is attributable to increased sedimentation and the likely impact of water holding by Lagdo Dam authorities. The important lakes (Gerio and Njuwa) appear clearly as well as the vast watershed at the centre of the figure.

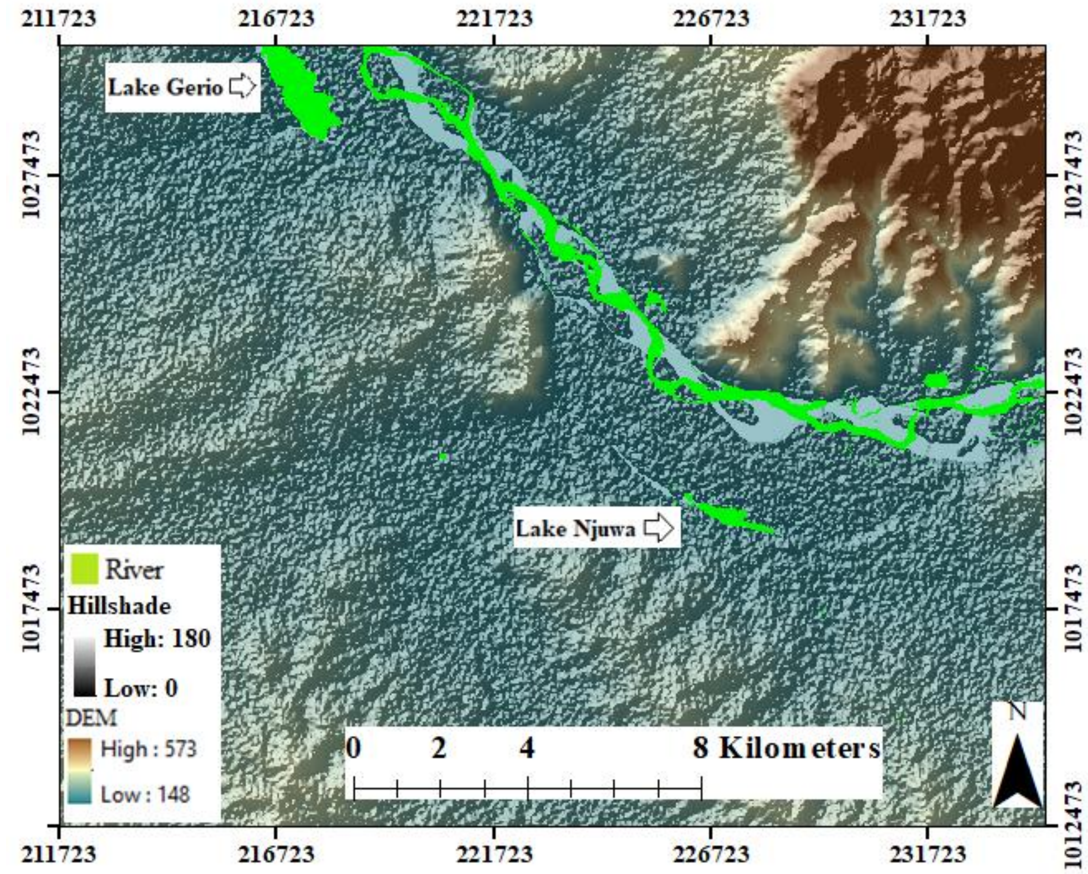

Figure 2: The DEM of the study area showing surface water (grey) during SRTM mapping and current water condition for May 2019 (green) obtained from Sentinel water index. The two important lakes, Gerio and Njuwa are shown while Bagale Hill is broadly seen to the northeast.

Normal River Course and Flood event

The normal area covered by River Benue is shown in green and flood in blue (Figure 3). The normal water surface for May 2019 undulates between high Bagale and Dougirei hills and its course influenced by sediments that accrue over years. The river has never been dredged, and the sediments expanded into the neighbouring watershed to the centre of the study area. During the flood event of 3 November 2019, the flood covered almost the whole watershed and swallowed the Lakes Gerio and Njuwa. The surface area normal river flow and lakes for May 2019 was calculated and found to cover 2, 125Ha while flooded water covered 9, 676Ha. That means surface area of inundation is 455.34 % larger than normal water surface area. As the primary baseline of ground topography, the DEM has a significant influence on the calculated river hydraulics and the extent of inundation areas (Nicholas and Walling, 1997; Horritt and Bates, 2001; Kavetski *et al*, 2006) and is important for determining safety locations for planning, especially along the Benue Valley.

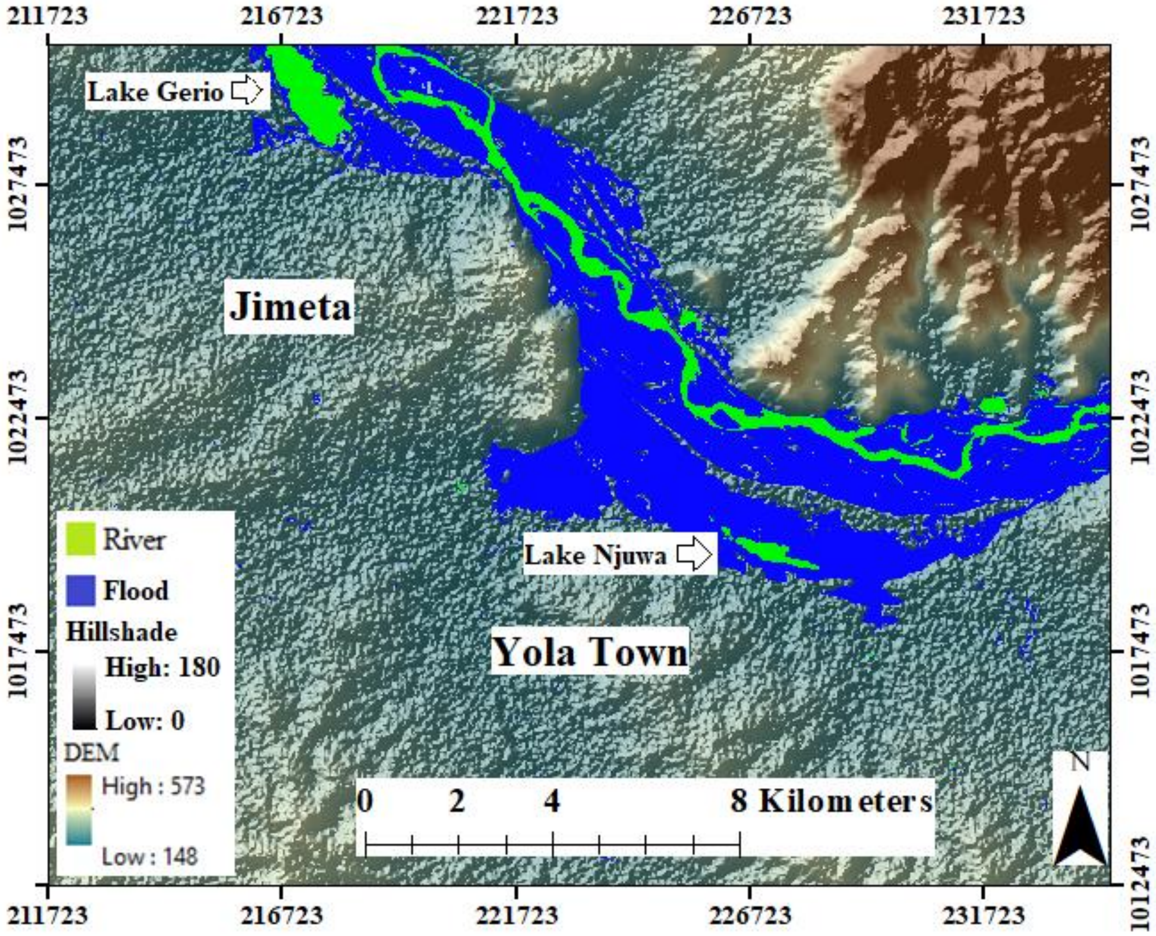

Figure 3: The DEM of the study area with an overlay of normal river flow in May 2019 (green) and flood water of 3 November 2019 (blue). The SRTM DEM shows undulations and valleys with flood water affecting large areas in Yola (Jimeta and Yola Town). Lakes Gerio and Njuwa completely disappeared in the flood. Flood map was computed from Sentinel 2 data using water index.

Flood Simulation

Simulating flood from DEM provides a unique method for projected flood risk mapping and assessment of inundation during flood. The observed flood event (Figure 3, blue) can be compared with simulated flood (figure 4, blue). This correlates well, where hydrological water catchments covers same areas at 157m above msl. The overlay of river shows extent of water in case of flood, indicating the importance of DEM-based flood simulation and determining possible scenarios of flood disaster. These kinds of simulations are important inputs into hydrological models such as Hydrologic Engineering Centre - Hydrologic Modeling System (HEC-HMS) and Hydrologic Engineering Centre - River Analysis System (HEC-RAS) model system that incorporates many variables (Puno and Barro, 2016) and to produce flood hazard maps (Puno *et al*., 2018).

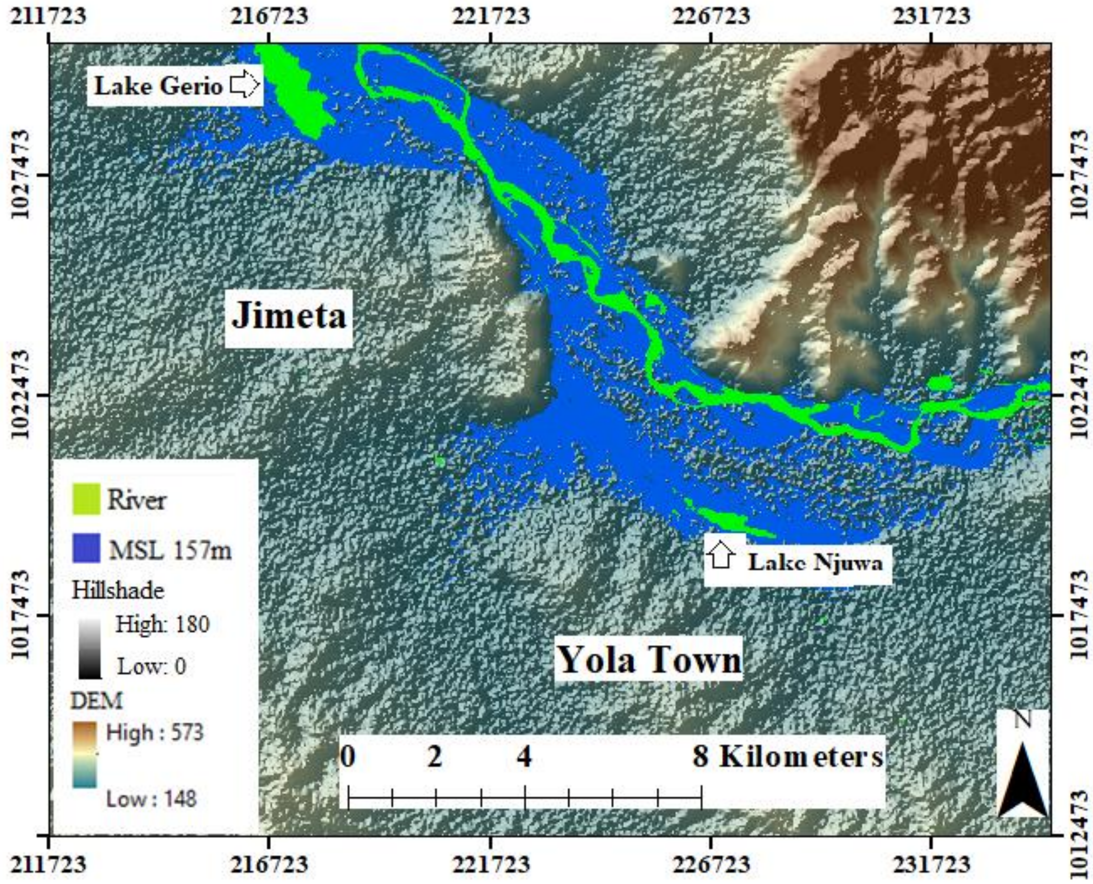

Figure 4: The DEM of the study area showing surface water (grey) during SRTM mapping and current water condition for May 2019 (green) obtained from Sentinel data using water index. The DEM simulation shows at 157m above msl, the November flood inundated a vast area as shown. Note figure 3 and 4 show similar pattern.

Comparison Observed and Simulated Floods

The satellite observed flood inundation of November 2019 is compared with simulated results of 157m above mean sea level. Results demonstrates that simulated flood using DEM as compared to normal flood provides a very good correlation. It also shows the variation and structure of surface water arising from the presence and shifting pattern of sediments across time, which is a good determinant of sediment condition during dredging.

This research corroborates with previous studies, showing that DEM with higher resolution produces more accurate flood maps compared to coarser resolution DEM which over-predict the flood extents (Werner, 2001; Brandt, 2005; Cook and Merwade, 2009). DEM represents the general topography of the river bank (Weepener *et al*., 2012), floodplain and adjoining hills as an important aspect of hydraulic flood modelling. Hence, high accuracy and high resolution data estimates flood damage and inundated areas better. White many researchers develop their

DEM from low resolution contour maps, this work uses higher resolution DEM of 30m resolution.

CONCLUSION

The importance of DEM in flood inundation mapping has been studied, allowing smaller lakes like Gerio and Njuwa to be mapped. While we employ satellite optical instruments to map out flood inundation, we could as well employ DEM to simulate conditions of flood for the purpose of predictability. SRTM DEM simulation gives good result for predicting flood disaster in a safer inland water ways devoid of storms. For very small urban areas, a better resolution DEM such as IFSAR and LiDAR with less than 10m should be employed.

DEM-based flood mapping provides the best approach to a cost-efficient strategy in delineating flood-prone areas. The idea is based on the ability to map areas of low and high lands using radar-based satellite DEM via geo-mathematical and computing processing techniques. These methods rely solely on morphological characteristics of river basin as conditions of having all features controlled by hydrology and watersheds. Changes in these areas of hydrologic characterisation may depend on soil, geology and climate. Therefore, modelling these require a complete and inclusive applications of these data. These data and the DEM can be incorporated into hydrological models such as HEC-RAS and HEC-HMS to model flood in municipal or urban areas. A complete modelled flood analysis in this region is necessary for making inundation maps which institutions such as National Emergency Management Authority (NEMA) of Nigeria would require to show specific risks during disaster events.

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