Analyzing flood risk in Lagos island local government area of Lagos state

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Key words: Flooding, Modelling, Risk Assessment, GIS

SUMMARY

Lagos Island is a low lying area in Lagos State, plagued by flood on a yearly basis. When intense rainfall occurs, this location is usually flooded, leading to loss and damage of property. In July 2012, extreme rainfall events occurred in this location and this led to severe flooding that caused serious damage to both public and private properties. More extreme flooding occurred in this same location in July 2017. Hence, in this study, the HEC (Hydrological Engineering Centre) modelling packages such as HEC-HMS and HEC-RAS software packages as well as ARCGIS software are used to simulate flood occurrence in Lagos Island. Light Detection and Ranging (LIDAR) and GIS are used for the flood modelling and mapping. LIDAR data, rainfall data, land use maps and GPS points are input data layers in this study. The results indicate that the average flow depths within the study area is 3.2m and over 60% of the Residential and Commercial buildings are at risk. Flood hazard maps are also generated to identify the areas within the city with high risk of flooding. Three-dimensional model of the location with embedded flood inundation map is also generated for a better understanding of the severity of flooding in the location.

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1. INTRODUCTION

Low-lying coastal regions and their populations are at risk during storm surge events and high freshwater discharges from upriver (Wei-Bo Chen & Wen-Cheng Liu, 2014). Over the period 1985 to 2014, flooding in Nigeria has affected more than 11 million lives with a total of 1100 deaths and property damage exceeding US$17 billion (Nkwunonwo, 2016).

Lagos is located on the North Atlantic Ocean. It is one of the major cities in Nigeria that is always greeted with torrential downpours for years. Flooding in Lagos is pluvial (flash, arriving unannounced following a heavy storm) in nature and have been a major cause of concern. While the Lagos State government's efforts towards tackling the hazard have not yielded satisfactory results, they have been criticized as ad-hoc, poorly coordinated, non-generalizable and not well established.

Several efforts have been employed in solving flood related issues; both from industrial and academic points off view. Most of these efforts seemed to be based on the availability of flood data sets; a major problem in analyzing flood risks. A cursory observation of the LIDAR data for the last four years (2014 -2017) revealed that flood, storms, temperature and droughts account for about 30% of total economic losses in the country out of which flood events had caused 5% of all the total losses. Of the naturally occurring hazards in Nigeria, Flood is the highest with resulting effects on humans and properties. While its natural causes are due to heavy rainstorm and ocean storms along the coast, its human causes are as a result of burst water main pipes, lack of effective drainage systems, dam failure and spills.

Various people and researchers in various ways have carried out flood vulnerability assessments. Their methods are tied to the data availability, objectives of the flood vulnerability study as well as the desired results to be obtained (Olayinka and Irivbogbe, 2017). The growing number of flood victims and the constrained sustainable development caused by flooding within the country suggest that much of what is known regarding flooding in the country is deficient on remedies. More critical is the subject-matter of Nigeria being one of the most populated countries of the world with population size estimated at over 170 million people (World Bank, 2013).

The aim of this project is to analyze and model flood risk in an urban environment, Lagos Island Local Government Area, in order to identify and mitigate the menace. It involved modelling and mapping the study area. The HEC-HMS and HEC-RAS models are used for the flood modelling processes with inputs such as land use data, a LIDAR (DEM), precipitation data and building infrastructure information. A two-dimensional representation and three-dimensional representation of the flood modelling results of the study area is produced.

1.1 The Study Area

This study focuses on a naturally dynamic area in the state; Lagos Island. Lagos Island is an adjoining LGA sharing boundaries on the North with the largest coastal lagoon in Western Africa; Lagos Lagoon. It is a densely-populated area with land area of approximately 4.996 square kilometers. It is located within Latitude 6° 26' 34" N and Longitude 3° 24' 30" E on the left and Latitude 6° 27' 8" N and Longitude 3° 22' 42" E on the right. The study area can be described as a place with a variety of land uses. It is notably a commercial area with a mixture of residential and institutional land uses. Figure 1 shows the location of the study area. The Figure vividly describes the water surrounding nature of the study area.

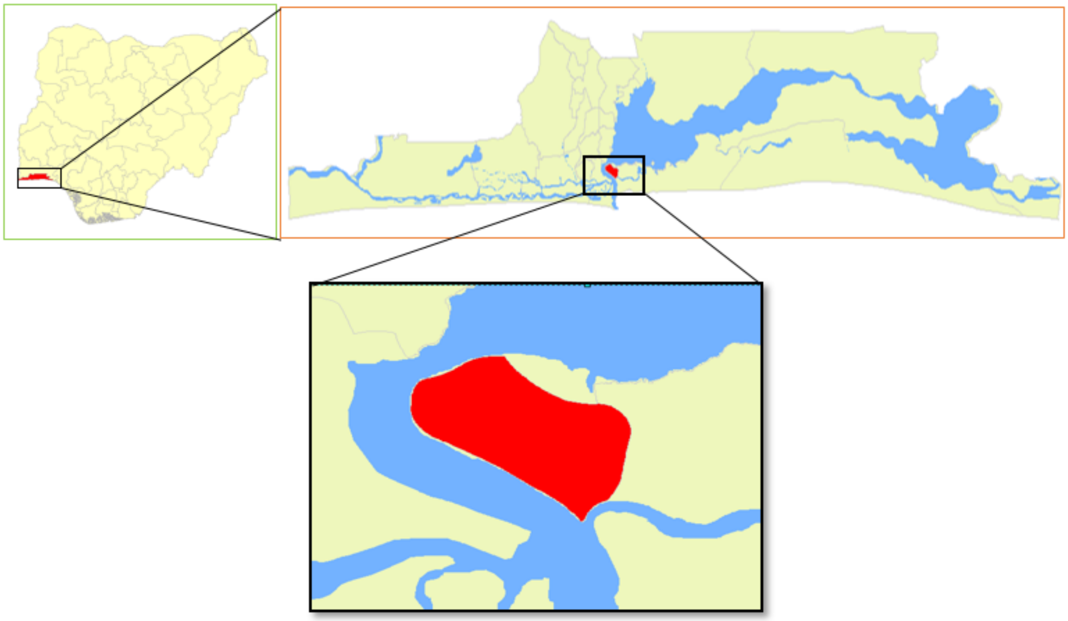


Figure 1: Representation of the study area (Lagos Island in red colour) surrounded by water

2. THE FLOOD MODEL SYSTEMS

Flood model systems are mathematical equations that are too numerous or too complex to solve with pencil, paper, and calculator, they are translated into computer code and an appropriate equation solver (an algorithm) is used. The result is a computer program. Thus, HEC-HMS, HEC-FDA, HEC-FIA, HEC-SSP, HEC-ResSim are computer programs that include a variety of models. The Hydrologic and Hydraulic Model systems are the two Flood inundation models employed in this study. The Hydrologic Models are one of the platforms provided by the United States Hydrologic Engineering Centre (HEC). The models are conducted over two systems provided by HEC viz: the Hydrologic Modelling System (HMS) and River Analysis System (RAS).

Since availability of data is an integral part of model selection, the HEC modelling packages (HMS and RAS), which has been tested and trusted by several hydrologic and hydraulic scientists in the past is employed in this research because of the ease of the parameterization of spatial data available for the study area. The resulting models have compatibility with GIS applications as the platforms maintains a perfectly consistent interaction during the modelling process.
The modelling softwares have demonstrated to be of good practical use in the previous modelling of urban areas in same locality using elevation and land cover data sets, hence suitable for this present work.

2.1 HEC-HMS Model

HEC-HMS is a Hydrologic Modeling System that is designed to describe the physical properties of river basins, the meteorology that occurs on them, simulate the precipitation-runoff processes of dendritic drainage basins and the resulting runoff and stream flow that are produced. The software includes many traditional hydrologic analysis procedures such as event infiltration, unit hydrographs, hydrologic routing and also includes procedures necessary for continuous simulation including evapotranspiration, snowmelt, and soil moisture accounting.

2.1.1 SCS Curve Number (CN) Model

The sub-basin SCS CN rule of thumb, HEC-HMS calculates the incremental precipitation around a hit by re-calculating the infiltration nonfiction at the accomplishment of each predate interim based on the CN and percent secure area of the sub-basin.

The Soil Conservation Service (SCS) Curve Number (CN) model estimates precipitation excess as a function of cumulative precipitation, soil cover, land use, and antecedent moisture, using the following equation:

$$P_e = \frac{(P-I_a)^2}{P-I_a+S} \qquad (1)$$

Where P_e= accumulated precipitation excess at time t;
P= accumulated rainfall depth at time t;

I_a= the initial abstraction (initial loss);
S= potential maximum retention, a measure of the ability of a watershed to abstract and retain storm precipitation. Until the accumulated rainfall exceeds the initial abstraction, the precipitation excess, and hence the runoff, will be zero.

An empirical relationship of I_a and S is developed by SCS from analysis of results from many small experimental watersheds**:**

$$Ia = 0.2S \qquad (2)$$

Thus, substituting Ia and S in equation (2) into equation (1) gives;

$$P_e = \frac{(P - 0.2\,S)^2}{P + 0.8\,S} \qquad (3)$$

The maximum retention, S, and watershed characteristics are related through an intermediate parameter, the curve number (CN) as given by Equations 3 and 4 as follows (Feldman, 2000):

$$S = \frac{1000 - 10\ \mathrm{CN}}{\mathrm{CN}} \qquad (4)$$

$$S = \frac{25400 - 254\ \mathrm{CN}}{\mathrm{CN}} \qquad (5)$$

Equation 3 is used for measurements in foot – pound system while Equation 4 is used for measurements in SI units. The basic definition of CN according to SCS method is CN = 1000/ (10 + S) (Muhammad, Hyung, & Seung, 2017).

2.2 HEC-RAS Model

Where water would flow if it reaches a certain value poses different questions such as what will be the height reached by the flood profile? Whether the surrounding areas will be flooded and extent of the flood? Several factors like the riverbed type, its slope or nature (type of material, presence of vegetation, etc.) as well as water works in the riverbed such as bridges, canalizations etc. are involved. To resolve these questions, powerful and tested softwares such as HEC-RAS have demonstrated their applications over the years. HEC-River Analysis System (RAS), a software in constant process of update is a hydraulic model that calculates one – dimensional steady and unsteady flow. The inputs for this model are the hydrograph output from HMS.

The HEC RAS solves open-channel flow problems and is generally used to compute stage, velocity, and water surface profiles. Computes steady-flow stage profiles, given steady flow rate, channel geometry, and energy-loss model parameters. Computes unsteady flow, given upstream hydrograph, channel geometry, and energy-loss model parameters. HEC-RAS assumes a steady, gradually varied flow scenario and uses iterative computational procedure of the energy equation which states that the total energy at any given location along the stream is the sum of potential energy and kinetic energy. The energy equation is given by (Eric, 1999):

$$H = Z + Y\frac{aV^2}{2g} \qquad (6)$$

Total energy = H
Potential energy = (Z + Y)
Kinetic energy = ($aV^2/2g$)
The Change in energy between two cross-sections (head loss) is called the head loss, h_L
The energy equation parameters are illustrated in the following graphic (Eric, 1999):

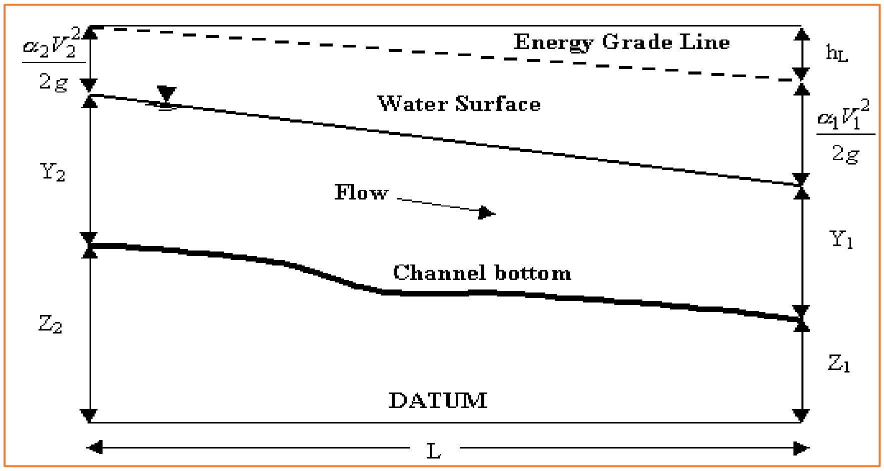


Figure 2: Illustration of energy equation parameters

2.2.1 HEC-GeoRAS

Hec-GEoRAS (Hydrological Engineering Centre – Geospatial River Analysis System) is an improved Arc-View extension (AV-RAS) developed by Hydrologic Engineering Centre together with the Environmental System Research Institute (ESRI). Hec-GEoRAS is a set of procedures, tools, and utilities for processing geospatial data in ArcGIS using a graphical user interface (GUI) that allows the preparation of geometric data for import into HEC-RAS and processes simulation results exported from HEC-RAS.

3. METHODOLOGY

The method adopted in this work is Hec-GEoRAS, which involved the integration of spatial data sets in the hydrological model (HEC-HMS) and the hydraulic model (HEC-RAS) with ESRI's ArcGIS.

3.1 Data Collection

Various Required data have been collected from different sources viz;

- Land use map of study area collected from Ministry of Physical Planning, Lagos State.
- Daily rainfall data for 12 months (1st January – 31st December, 2012) was collected from Tropical Rainfall Measuring Mission (TRMM)
- 2008 LIDAR DEM, in classified text file format, covering *the* study area was obtained from the Office of the Surveyor General of Lagos State. A 5m resolution DEM was created from the text files.
- ESRI vector shapefiles of buildings covering the study area for the year 2009 was obtained from the Office of the Surveyor General of Lagos State.
- Drainage network details of the study area (2012 Drainage network manual).

3.2 Developing the Hydrological Model (HEC-HMS Modelling)

Four main components are required which are created for developing a HEC-HMS project are basin model manager, meteorological model manager, control specifications manager, LIDAR DEM which served as foundation data. The basin model was created using the Hec-GEoHMS, an ArcGIS extension of HEC-HMS, Hec-GeoHMS.

The hydrological model (HEC-HMS) was used to analyze the rainfall water volume and the amount of runoff water volume that was generated. The Basin model manager contains the hydrologic elements (Sub-basin, reach, junction, reservoir, diversion, source and sink) and their connectivity that represents the movement of water through the drainage system (Scharffenberg & Fleming, 2006). A terrain preprocessing was carried out on the DEM (Figure 3). A DEM reconditioning process and a final production of the hydrologically corrected DEM was carried out. Further operations to prepare the DEM for use in HEC-HMS were carried out. A final basin processing was carried out in HEC-HMS after a project generation in the same modeling package.

A meteorological model was developed in which meteorological data (such as observed discharge, evapotranspiration, wind speed, humidity and sunshine hour) and daily precipitation data were spatially and temporally distributed over the river basin within six months period (1st July – 31st December, 2012) were added to the HEC-HMS project generated. The daily precipitation data was to provide the model with adequate amount of rainfall data to be used in the model calculation process.

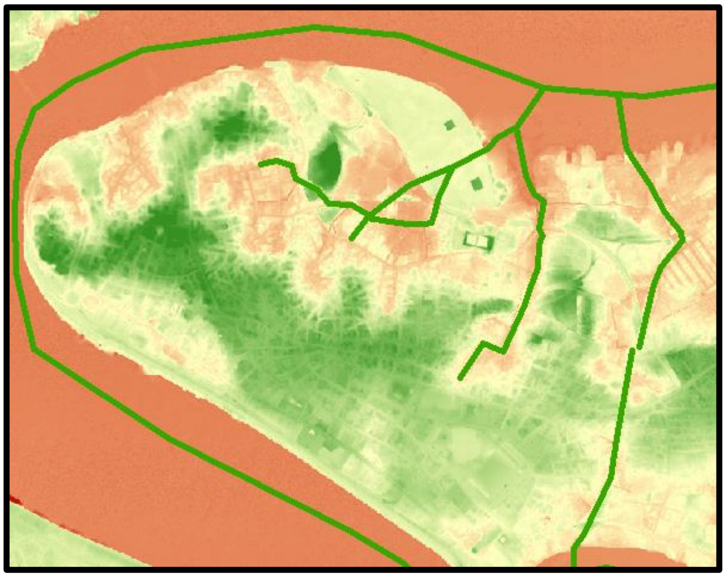
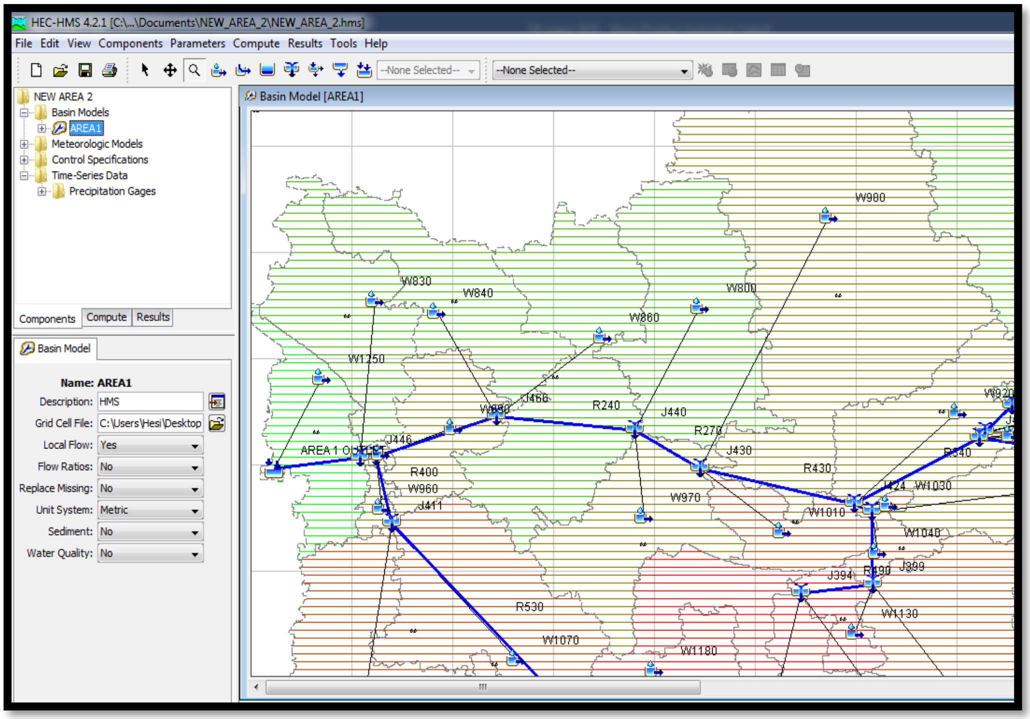


Figure 3: DEM of project area with Drainage Network

Since daily precipitation data was acquired for the study, a time interval of 24 hours was created, using the control specification manager and this was used to control time interval of simulation window for which the model calculates discharges.



Name: AREA1
Description: HMS
Grid Cell File: C:\Users\Hesi\Desktop
Local Flow: Yes
Flow Ratios: No
Replace Missing: No
Unit System: Metric
Sediment: No
Water Quality: No

Figure 4: HEC-HMS modeling Process

3.3 Developing the Hydraulic Model (HEC-RAS Modelling)

The resultant hydrological model (rainfall runoff volume) created from HEC-HMS was used as input in HEC-RAS to analyze the way the water moves on the study area and the places where it concentrates, thereby creating inundation problems.

The next step was creating RAS layers that was used for developing geometric data and extraction that were used in the hydraulic modelling. The geometric layers that were created are the river center lines, cross section bank stations, flow path centerlines and cross sections cut lines and surface lines, downstream reach lengths for the left over bank main channel and right over bank. These layers were extracted from the LIDAR DEM by use of the Hec-GEoRAS extension in the ArcGIS 10.2.

Having created the geometric layers, proper preprocessing (preparation and entering the necessary inputs to the model, importing GIS data and defining the model output) was carried out using Hec-GEoRAS. Once the hydraulic computations are performed, exported water surface and velocity results from HEC-RAS are imported back to GIS using Hec-GEoRAS for spatial analysis.

A polygon layer (with a field to reference for N values) is created from the land cover data and was used to estimate roughness coefficient (Manning's N values) along each cross sectional cut line in HEC-RAS. The intersection of the cut lines with other RAS layers will determine bank station locations, downstream reach lengths, manning's values, ineffective areas, blocked obstructions and levee positions (Ackerman, 2011). All geometric data were imported into the HEC-RAS modelling environment. The steady flow data was added with analysis applying a time series of discharge rates at each river reach in the computation of cross sectional hydraulic flow. The discharge rates are fed into columns (profiles) in the steady flow data workspace. A DSS (data store) connection was made to the location of the data store of results from the HMS model run so that profiles can read information from the HMS discharge model results at specified time steps.

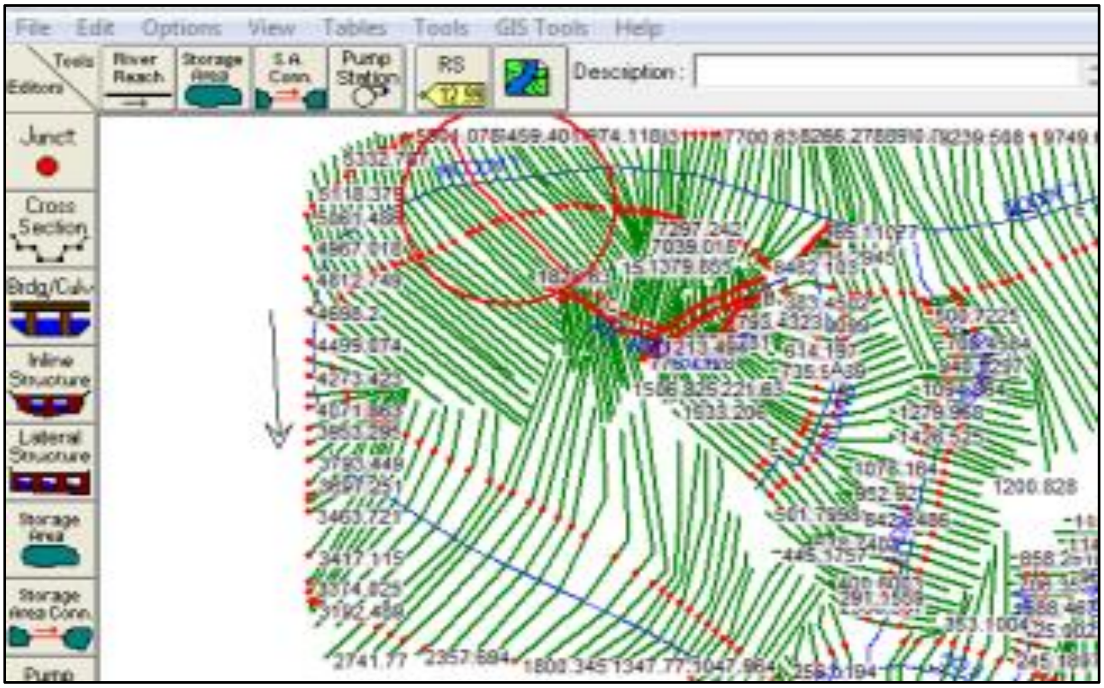


Figure 5: Geometric data of the hydraulic model in HEC-RAS

The RAS export file generated from model run in HEC-RAS was imported into the GIS using Hec-GEoRAS for the further processing and flood mapping of the model results. The post process results such as the water surface generation, flood plain delineation grids are saved into output directory and the subsequent flood inundation map was produced, while the vector data generated in post processing are saved into the dataset within the specified geodatabase. The cross sectional cut lines and bounding polygon that were created are used for building flood plain data sets.

4. RESULTS AND DISCUSSION

The flood inundation map, which shows the flood depth and extent, was prepared in ArcGIS environment. This is shown in figure 7. A polygon for the inundation extent was created and the area for this polygon was calculated. **The total area covered by this polygon was 2.006 sq. kilometres.** This value excludes the area covered by the water body present in the project.

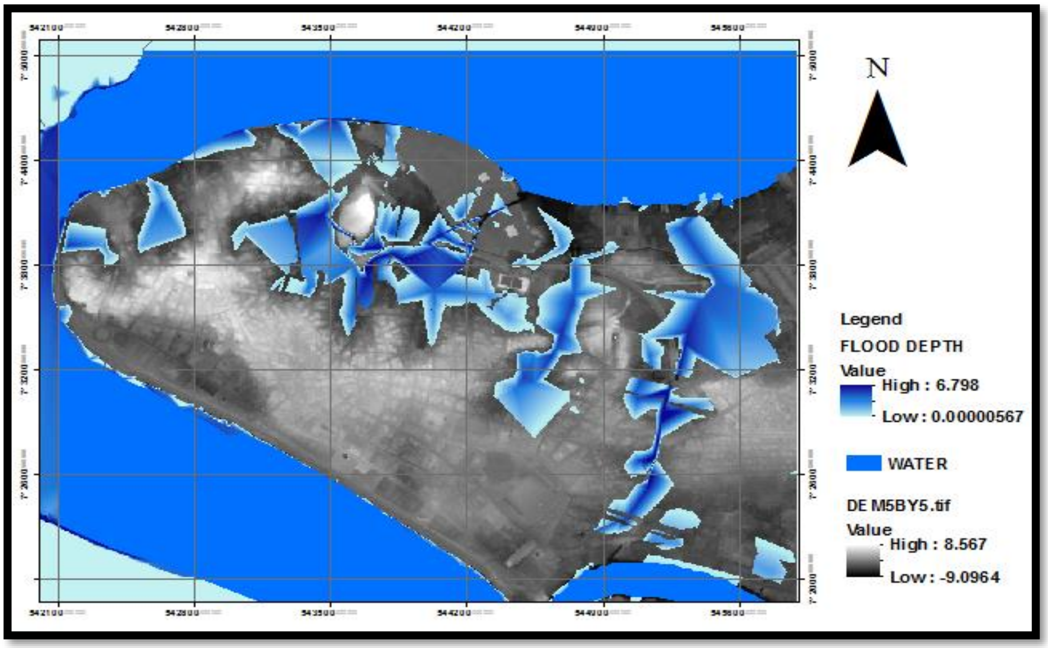


Figure 7: Flood inundation map showing flood depth and extent

4.1 Flood Risk Assessment on Parcels of Land and Buildings

Parcels of lands that fall within the inundation zones are at the greatest risk during flooding. The severity of the flood will tell the level of destruction on the lives and properties in each parcel. It is against this backdrop that it becomes imperative to make a count of the building types that lie within these areas. This will help us to know the structures that are at risk and the threat this poses on the lives of people and even the environment at large. Buildings of various types within the inundation extent were counted. The result in percentage is given in Table 1. The buildings at risk (within the flood inundation [polygon) in the study area are shown in a map in Figures 8.

Table 1: Percentage number of building types at risk

Building Type	Percentage Coverage at Risk (%)

Residential	25.45
Commercial/Business	36.56
Institutional	16.56
Other uses	6.87
Recreational	14.56

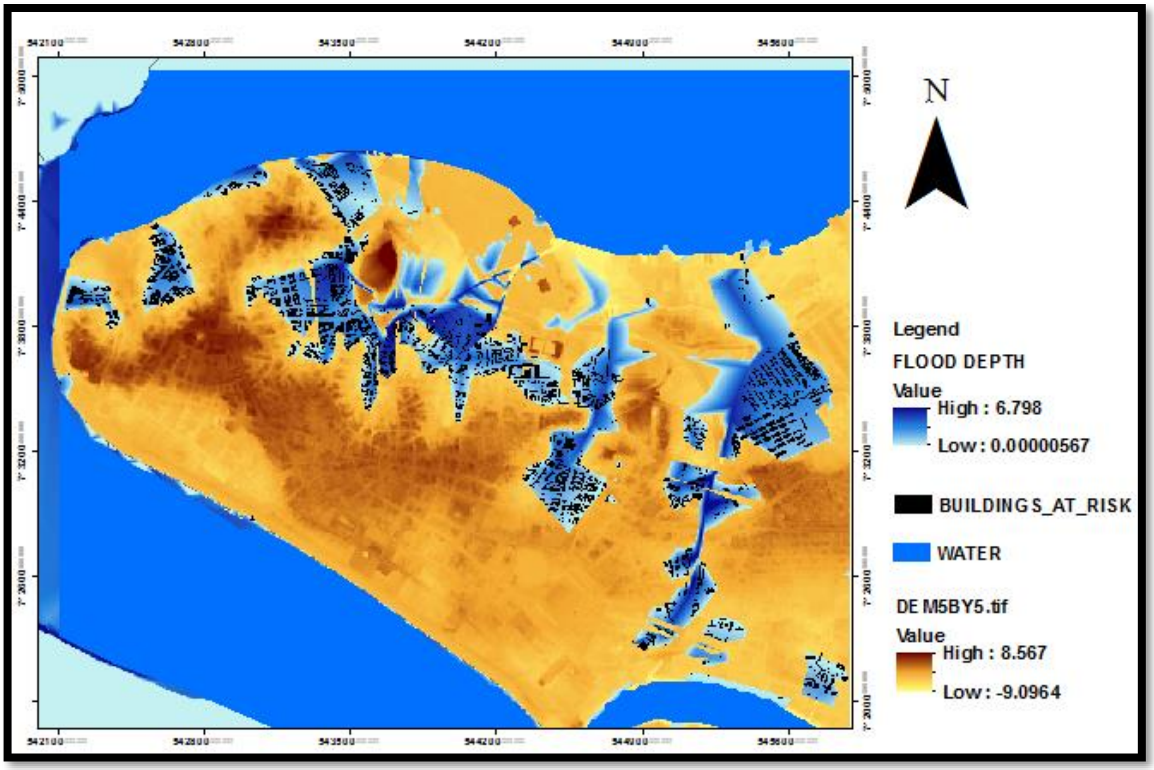


Figure 8: Plot parcels and Buildings with flood inundation in study area

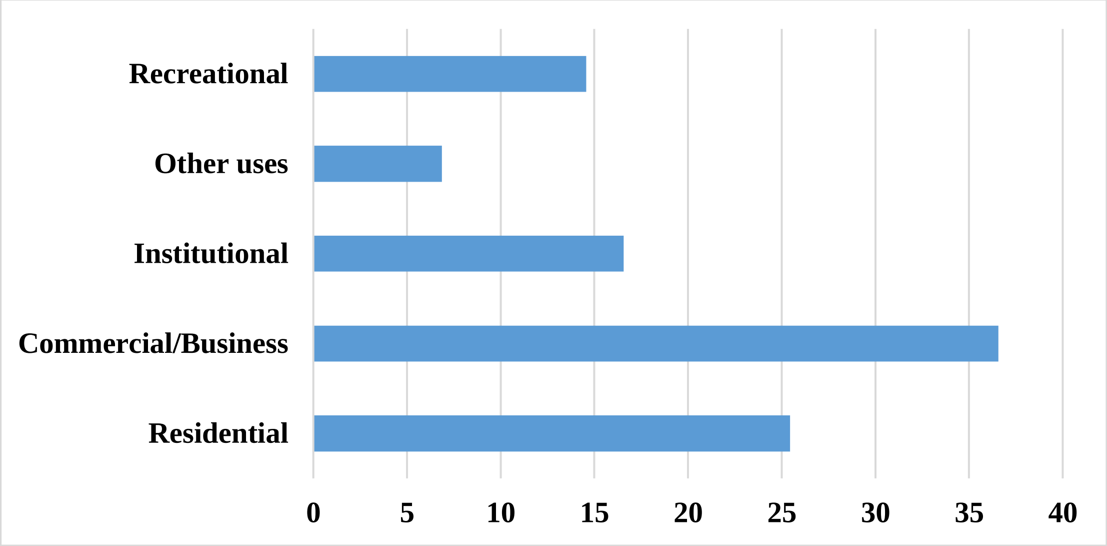


Figure 9: Percentage Coverage of building types at risk

4.2 Validating the Modelling Operation

Model validation involves comparing the results of the flood model with actual flood occurrence in the study area to check the ability of the model to accurately predict flooding at the selected locations in the study areas. Photographic images (pictorial representations of flood event after rainfall at the selected locations) with their corresponding GPS locations as well as names of the selected locations in the study area were collected in the field. These locations were plotted on the flood map and the photographic images of the flood events after the rainfall at each selected locations where hyperlinked to the map.

There are locations were the model returned considerable amount of flood and those locations that had little or no flood returns. Field observations were made at these locations to test for locations that were over-predicted, under-predicted or where there was no prediction for flood inundation (Figures 10). An inspection of the modelled inundation against the pictorial representations was then conducted at each location and a comparison between the modelled inundation and actual inundation illustrates a close agreement between the simulated and observed inundation.

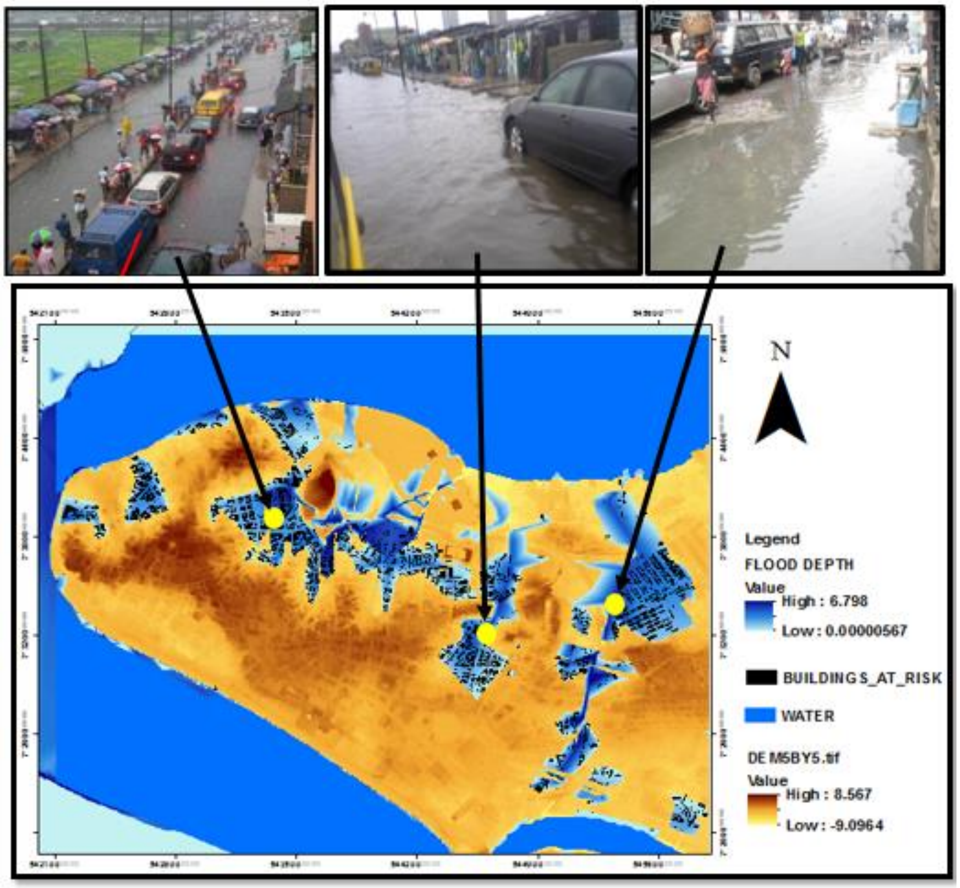


Figure 10: Geo-location of GPS coordinates of selected locations in the study area

4.3 Three Dimensional Model of Result

The three-dimensional floodplain view is very useful for flood mapping and inundation extent visualization. Arcscene was used for the three dimensional representation of ***the terrain, the flood inundation extent and the building features that are within the flood extents***. With the specification of proper extrusion values, base heights and Arcscene exaggeration properties, the features were properly represented.

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The use of GIS and Remote sensing alone as demonstrated to map flood events in previous flood studies are not enough to adequately measure the intensity and the extent of flood and its impacts. Further research on the use of the state of the art flood models available across countries, some of which are open source are necessary to improve the flood risk analysis in the country, hence, the use of HEC (Hydrological Engineering Centre) modelling packages such as HEC-HMS and HEC-RAS software packages as well as ARCGIS software. The hydrological model (HEC-HMS) was used to analyze the rainfall water volume and the amount of runoff water volume that was generated. This was used as input in HEC-RAS to analyze the characteristic movement of water on the study area and the places where it concentrates, thereby creating inundation problems.

Figure 11: Three-dimensional Representation of features in ArcScene (A) ***(Depicts areas in*** Lagos Island LGA and Osborne Estate areas that are highly at risk and within the flood extents)

5.2 Recommendation

It is important to bear in mind that flooding cannot be constrained within human environment and the menace will worsen in the future, and as such there is the need to create social systems that are resilient to hazard. Several other local government areas in the country are lacking flood data to carry out flood mapping. This study recommends developing of a repository of flood data to be useful for future investigations.

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