Modelling Flood Hazards Impacted by Ungauged River in Urbanised Area Using HEC-RAS and GIS

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ABSTRACT: Ilorin City is located downstream of Asa, Oyun and Awun River Basins. The Asa River is a major river that traverses the city and divides the metropolitan area into east and west, almost equally. The river often overflows its banks to inundate adjacent communities, influencing severe economic damage and impact on human lives. However, efforts to mitigate this have majorly been focused on dredging the Asa River channel which has not solved the problem. For an accurate spatial and temporal understanding of the risks of floods and their potential hazards, it is important to estimate floods using river hydrology. The objective of this study is to model steady flow of the rivers using flow data and to map flood-prone areas in Ilorin using HEC-RAS integrated with GIS. Using the HEC-GeoRAS extension in the GIS environment, the geometric data of the rivers were obtained from the 30 m resolution digital elevation model (DEM) and input into HEC-RAS applying Manning Co-efficient values of 0.04, 0.045, and 0.04. For each river, flow data (Q) was given as the upstream boundary condition while a normal depth of 0.001 was assigned for the downstream condition to model a steady flow and inundation extents. The result of the HEC-RAS model has shown the flood-prone areas along the river channels delineated. The floodplain map produced reveals the spatial distribution and extent of the high flood-risk areas in the Ilorin metropolis. The total flooded area covers approximately 60.95 km^2 (18%) majorly along the river channels. This study has demonstrated that integration of hydraulic modelling using HEC-RAS and GIS process is capable of producing an inundation flood map with good accuracy that will aid in suggesting effective measures to mitigate the impact of flooding.

KEYWORDS: Flood, Hec-Ras, GIS, Disaster risk reduction, Ungauged River.

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I. INTRODUCTION

Flood hazard has been identified as one of the most frequent and destructive threats to urbanization. Apart from its impact on the socioeconomic activities of the urban population, it is reported to claim more lives than any other natural disaster (Yari *et al*., 2019). The frequency and magnitude of its occurrence in many regions of the world have made it a major concern and a serious issue of discussion at national and international fora (Narendra *et al*., 2022). The case is not different in Nigerian cities, including Ilorin the case study of the present study. According to the International Federation of the Red Cross and Red Crescent Society (IFRC, 2020), Ilorin is identified as one of the five most affected cities in Nigeria. In early October 2020, not less than three lives were lost to a flood incident in Ilorin while scores of houses were submerged across the city, particularly in Taiwo and Odota areas communities. The impact of flooding events in Ilorin in recent times can be found in (Idrees *et al*., 2022).

The few studies reported on flood hazards in the Ilorin metropolis (e.g., Ayila & Yinka, 2019, Idrees *et al*., 2022, Mokuolu *et al*., 2022, and Olabode *et al*., 2014) have been linked to the Asa River, a major ungauged river, and its tributaries often overflow their banks to inundate adjacent lowland areas. For example, Oriola and Bolaji (2012) assessed urban flood risk along Aluko River, a tributary of the Asa River using utilizing road and river networks, illegal dump sites, high-resolution Ikonos Imagery, and a topographical map of Ilorin. Using a spatial overlay and buffering analysis, the authors classified the study area into high, moderate, and low flood risk zones, where the high-risk zones are identified at the low land area along the river, particularly around the area where it drains into the Asa River. In another study, Olabode *et al*. (2014) examined the vulnerability status of buildings resulting from flooding events using the GIS technique. The researchers employed Global Positioning System (GPS) and direct observation for their investigation. Their findings revealed that the buildings within 30 m of the Asa River are highly prone to flooding with intense rainfall of between 4 and 6 hours.

In a related study, Iroye (2017) correlates the pattern of Aluko, Agba, Alalubosa and Okun river basin discharge with the degree of urbanization. Utilizing direct measurement, rainfall and river discharge data were collected over one year

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with a standard rain gauge of 20cm, water level collected twice daily with a staff gauge, and stream flow velocity and discharge measured with an OTT HydroMet current meter. The authors discovered that runoff discharge in the basins reflects closely the rainfall pattern; periods of maximum discharge coincided with periods of peak rainfalls. It is also revealed that the Agba drainage basin which has a less urbanized area produced a low runoff percentage during the rainy season; whereas, the Aluko drainage basin which is more urbanized has the highest total percentage of runoff. In their work, Mudashiru *et al.* (2017) investigated the geomorphology of the Asa and Oyun River basins using GIS techniques utilising 30 m resolution Shuttle Radar Topographic Mission (SRTM) DEM to compute and assess how much the geomorphological characteristics of the basins influence flooding. The study inferred that the river basins have fewer structural disturbances resulting in high surface water infiltration and ultimately low river discharge capacity.

Similarly, Shiru and Johnson (2018) employed a physical survey and direct interviews approach to identify the causes of flooding in Ilorin and how to mitigate its impact. Most of the respondents identified poor planning and waste management as responsible for the flooding. The findings of the study also revealed that the structural method of flood control which includes the building of levees, floodwalls, and dredging increases flooding downstream. However, the drawback of these studies is that researchers employed simple spatial overlay and buffering which do not take into consideration the rigorous interdependency of hydrological, climatic, and anthropogenic factors. Besides, some of the results are abstract since they lack spatial content and those that incorporate spatial dimension largely depend on the human judgement which renders them inaccurate and therefore less reliable as decision-making tools.

For accurate and reliable judgement, the impact of river hydrology including the flow rate and discharge, and the interactions between them and other abiotic properties such as the landscape and the river system that shape river ecological communities must be considered (Timbadiya, and Krishnamraju, 2023; Pandey and Das, 2016). The objective of this study is to model the fluvial flood inundation extent and assess the risk it poses to the inhabitants of Ilorin city. Several tools are available for modelling the behaviour of river systems; one such package is HEC-RAS (Adeniran *et al*., 2018; Shivapur, 2017). HEC-RAS is a popular free software widely used in hydraulic and hydrological modelling of one/two-dimensional (1/2D) unsteady flow, steady flow, and temperature. In this study, therefore, HEC-RAS integrated with a geographic information system (GIS) has been applied to modelling the steady flow of the Asa River and its tributaries within the metropolis to predict and map flood hazards.

II. MATERIALS AND METHODOLOGY

A. *Study area and data*

The study is conducted in Ilorin, the Capital City of Kwara State, North-central geopolitical zone of Nigeria (Figure 1). The city covers an area of approximately 765 km2 with a population of about 974,000 based on the Revised World Population Prospects projected by the United Nations Department of Economic and Social Affairs Population Dynamics for 2021, making it the 7th largest city in Nigeria. Ilorin is located at approximately latitude 8° 30' N and longitude 4° 33' E (Shiru and Johnson, 2018). The elevation of the area ranges between 273m to 333m on the western side with an isolated hill (Sobi hill) of about 394m above sea level and ranges on the eastern side from 273m to 364m.

In terms of hydrology, the city is located downstream of Asa, Oyun, and Awun River Basins that drain in the south-north direction. Ilorin is mainly drained by the Asa River which is the major channel that traverses the metropolitan area, dividing it into east and west almost equally (Idrees *et al.*, 2022). The Oyun and Awun Rivers to the city suburbs in the east and west, respectively, constitute major tributaries. Socio-economically, Ilorin is an industrial and education centre; it has food processing and iron industries and is the site of a university and a state polytechnic college. Modern Ilorin is mainly inhabited by Muslim Yoruba people, although its traditional ruler is a Yoruba-speaking Fulani Emir (Babatunde *et al*., 2014). Local handicrafts include pottery making, wood carving, leather working, cloth weaving, and hat and basket weaving. The growing industrial sector now includes sugar refining, food processing, soft drink bottling, and match and soap manufacturing.

This study utilised freely available online geodata resources. This includes the 30 m resolution digital elevation model (DEM) downloaded from the United States Geological Survey (USGS) earth explorer data archive, roads network and railway lines obtained from the geofabric data hub, buildings footprints, population data and schools gotten from the Nigeria GRID3 data resources, and the administrative boundary downloaded from diva-gis geodata resources.

B. *Method*

For the modelling, the DEM is the primary data utilised to extract the river geometry (river centreline, bank lines, flow path and cross sections) and the drainage pattern (flow accumulation and stream order). The methodology involved data pre-processing, model execution, post-processing (flood plain mapping) and risk analysis. Figure 2 presents the data processing and analysis flow chart. GIS-based HEC-RAS and HEC-GeoRAS were used for the processing and flood modelling (Ackerman, 2002; Heydari *et al*., 2013; Merwade, 2016; Yari *et al*., 2019).

1) Preprocessing and derivation of river geometry

During the pre-processing, the DEM was subset to the study area, projected to the Universal Transverse Mercator and sink-filled using the hydrology tools in the Arc map. The pre-processed DEM allowed generating flow accumulation to identify the drainage pattern within the terrain and subsequently the stream order which permitted classifying streams into a hierarchy based on their hydraulic flow capacity (Adeniran *et al*., 2018). The river geometry (centerline, river bank, flow path and cross-section of floodplain areas) was derived in HEC-GeoRAS by digitizing them in the DEM. The cross-section lines are the most important input into HEC-RAS

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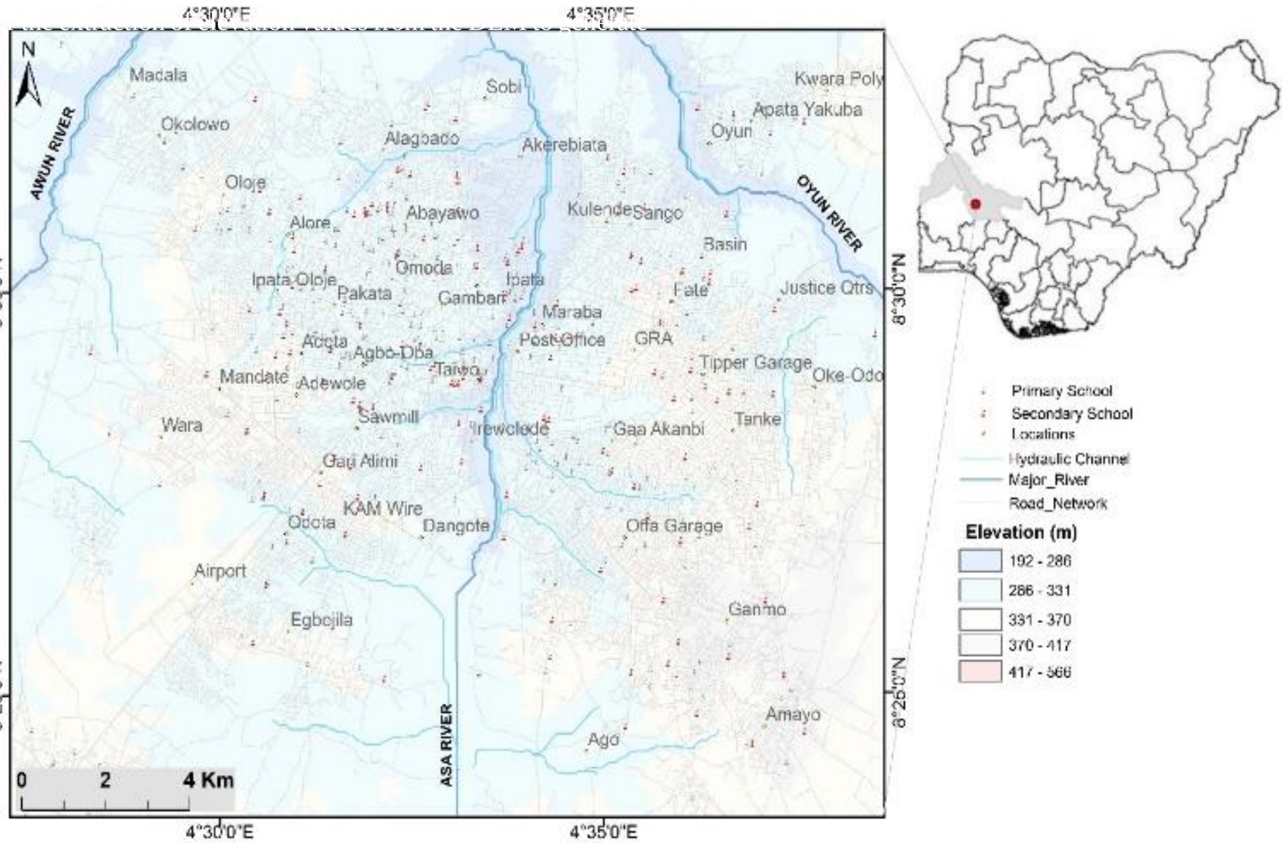

Figure 1: Ilorin metropolitan area with the location of primary and secondary schools

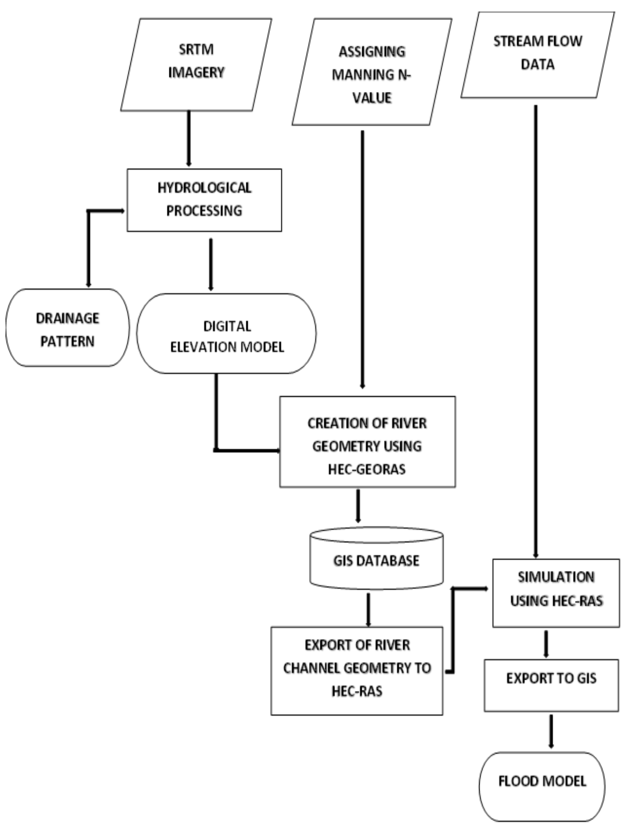

Figure 2: Methodological flow chart

ground profile for computing the channel flow (Shivapur, 2017). In addition, the intersection of the centerline and flow path along with the cross-sections were used to calculate HEC-RAS attributes such as bank stations (locations that separate the main channel from the floodplain) and downstream reach lengths which is the distance between cross-sections. These geometric variables are essential for hydraulic modelling. Meanwhile, before loading the raster grids DEM, it was converted to TIN, a vector data format of terrain data (Adeniran *et al*., 2018). Unlike raster DEM, TIN is available as a gridded surface rather than the point. In addition to storing the elevation of points, TIN also records the planimetric position which is needed in HEC-RAS for geo-referencing of the cross-sections (Riaz *et al*., 2022; Yari *et al*., 2019).

2) Hydraulic Modelling

To model the hydraulic flow, the data layers created in HEC-GeoRAS were imported into HEC-RAS. In the HEC-RAS geometric editor, the imported data layers were examined to ensure they correctly represent the river. For a reliable simulation and derivation of the maximum flood water level, Manning Coefficient values of 0.04, 0.045, and 0.04 were adopted for the left-over bank (LOB), channel and right-over bank (ROB), respectively (Adeniran *et al*., 2018). This is to accommodate the changes in the river geomorphology, geometric, and hydraulic parameters of the channel since they vary along the length of the river (Ali, 2018). In this study, we utilise the flow data gotten from Adeniran *et al.* (2018) to obtain a steady flow simulation, the flow data at the upstream location of each river, tributary and junction, were input for the three profiles. A normal depth of 0.001 (Heydari *et al*., 2013; Merwade, 2016) was assigned at the downstream location of each river and their junction because the boundary conditions are required to establish starting water surface at the ends of the river system. The starting water surface is necessary for the program to calculate the subcritical flow regime (Adefisan & Jummai, 2018). A subcritical flow regime was run since the boundary condition was only applied at the downstream ends of the river system. The simulation results including profile plot, rating curve, general profile plot velocities, and three-dimension (3D) perspective plot were visualised and finally, the resulting model was exported into the GIS environment for further analysis.

3) Floodplain mapping

The floodplain was mapped in the HEC-GeoRAS extension utilizing the water surface elevations generated with the cross-section TIN. For the three profiles, the water surface was converted to a grid and the terrain grid (TIN) was subtracted from it; areas with water surface elevation higher than the terrain elevation had positive values representing inundation depth grid while dry land produced negative value (Abdulrazzak *et al*., 2019). Apart from the water surface elevations, other hydraulic parameters such as the flow velocity, flow rate, channel slope, and flow area were obtained for each cross-section. The water surface profile is computed from one cross-section to another by solving the energy equation (Equation 1) with an iterative procedure called the standard step method (Gary W. Brunner, 2016).

$$Z_2 + Y_2 + \frac{a_2 {V_2}^2}{2g} = Z_1 + Y_1 + \frac{a_1 {V_1}^2}{2g} + h_e \quad (1)$$

where Z_1, Z_2 are elevation of the main channel inverts, Y_1, Y_2 are the depth of the water at the cross-section, V_1, V_2 are average velocities (total discharge/total flow areas), a_1, a_2 is the velocity weighting co-efficient, g is the gravitational acceleration, and h_e is the energy head loss.

C. *Flood risk analysis*

The potential flood risk was estimated using the simulated flood inundation areas. This was done by overlaying the flood extent on the population data, road infrastructure, buildings and schools within the city. In all, there are 540 schools in the metropolis (407 primary and 133 secondary schools) a significant number of which are located within the flood risk zones. Using the Spatial Analysis tools in ArcGIS 10.7, the magnitude of the impact of a potential flood event was examined.

III. RESULTS AND DISCUSSION

A. *River hydraulic characteristics*

Analysis of channel hydraulic characteristics allows examining the river morphology as a step toward understanding the river flow pattern. Having successfully run the HEC-RAS model, the result of the simulation analysis was viewed and analysed in the profile plot window (Figure 3). The cross-section (Figure 3a) allowed identifying the planar location and the station elevation data being extracted from the DTM along each river course for use in HEC-RAS. As a rule, the cross-sectional lines were drawn perpendicular to the direction of flow (river profile) such that each crosses the flow paths and the two banks, without intersecting one another (Ackerman, 2002; Brunner, 2016). Figure 3(b-e) shows the plot of the river variables against the channel distance. The plots present the channel velocity, hydraulic depth, flow rate (left overbank, main channel, and right overbank), and flow area.

The velocity profile plot (Fig 3b) indicates the laterally distributed velocities in the cross-section. The hydraulic depth (Fig 3c) shows the flow area against the top width. It is generally used for computing either the Froude number or the critical depth of a channel (Heydari *et al*., 2013). The flow distribution plot (Fig 3d) depicts the flow rate of the. Finally, (Fig 4f) gives the 1D representation of the flow area computed with the HEC-RAS 1D flow algorithms (Tazin, 2018). The flow area is defined by laying out a polygon that represents the outer boundary of the 2D flow area (Shivapur, 2017). It can be located at the beginning, the end, or laterally to reach. Certainly, the hydraulic characteristics have shown that there is a more consistent pattern in the structure of the river in terms of flow velocity, hydraulic depth, and flow distribution, unlike the flow area which varies significantly along the river channel. This scenario can be attributed to the basin morphology, the stage of development, an d land use (Brunner, 2016; Heydari *et al*., 2013; Merwade, 2016).

B. *Model outputs*

The hydraulic modelling was obtained by running the HEC-RAS simulation and exporting the results into GIS. In HEC-RAS, there are several simulation options but for this study, steady flow analysis which describes the conditions in which depth and velocity at a specific channel location do not change with time (Riaz *et al*., 2022) was implemented. Using HEC-GeoRAS functionalities, the HEC-RAS hydraulic modelling file (Figure 4 new) was exported into ArcGIS for flood inundation mapping. HEC-GeoRAS converts the water surface to a Grid which is subtracted from the DTM grid to identify areas where the water surface is higher than the terrain (positive) as flood areas while those with negative values are non-flood areas. Variation in the range of blue colour indicates channel depth, the darker the colour the deeper the channel.

In addition to the inundation mapping, the hydraulic modelling simulates the discharge velocity (Figure 5) and quantified the volume of water discharge for three different returns, 30 years, 50 years, and 100 years, at the upper and lower reaches, and the tributary. The discharge velocity ranges from 0.15 m/s to 16.77 m/s. Perhaps the different Manning's roughness co-efficient applied allowed a better representation of the channel depth and velocity but not the flood extent. Channel sections with high velocity (>4.26 m/s) fall along upland areas with steep slopes while the low-velocity channels occur in areas with a relatively flat landscape and low slope. Topography is one of the major factors that significantly contribute to and influence flooding within the flood inundation areas of the city. Idrees *et al*. (2022) stress that the

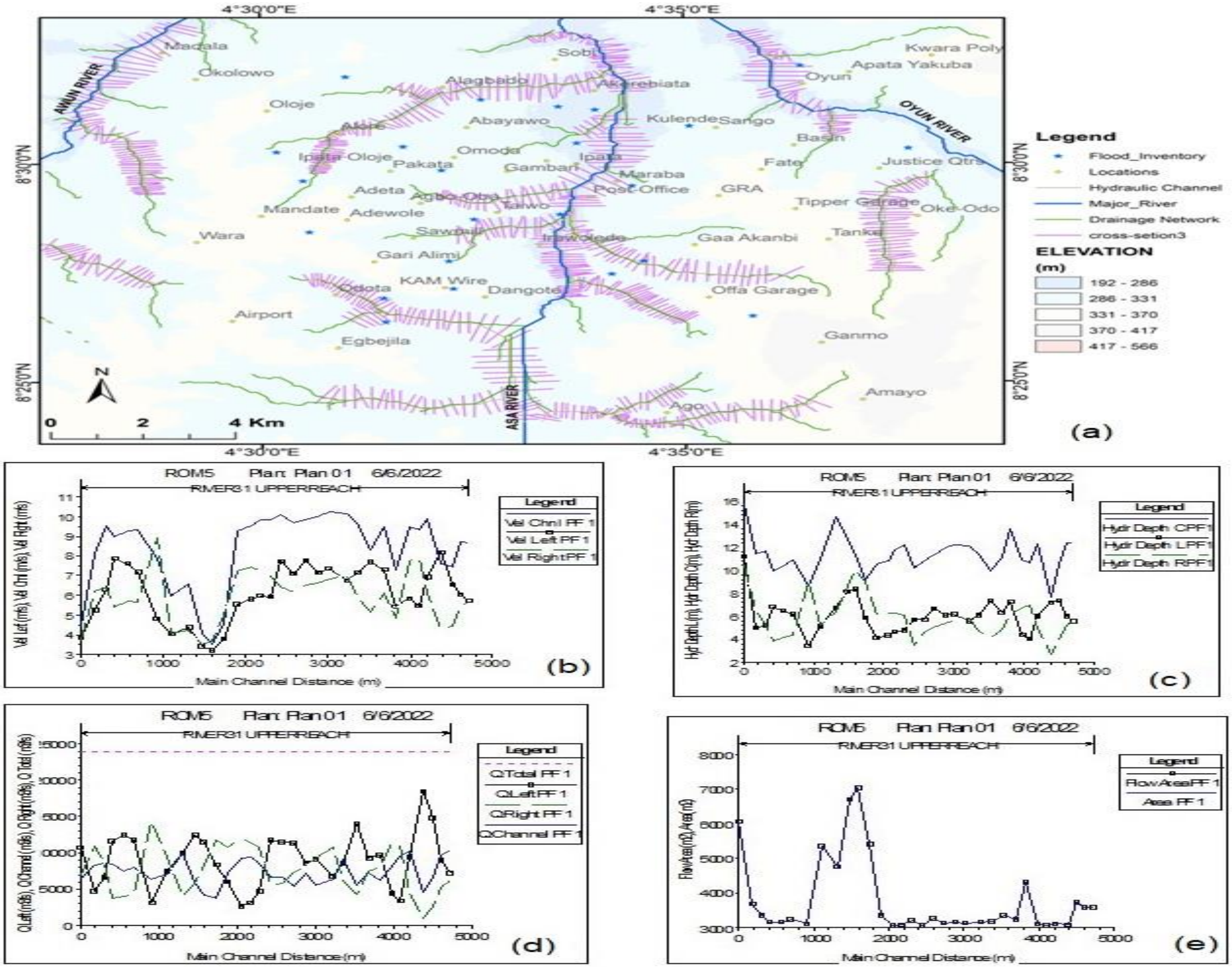

Figure 3: hydraulic model - (a) cross-section (b) flow velocity (c) hydraulic depth, (d) flow distribution (Q) m^3/s, and (e) flow Area m^2.

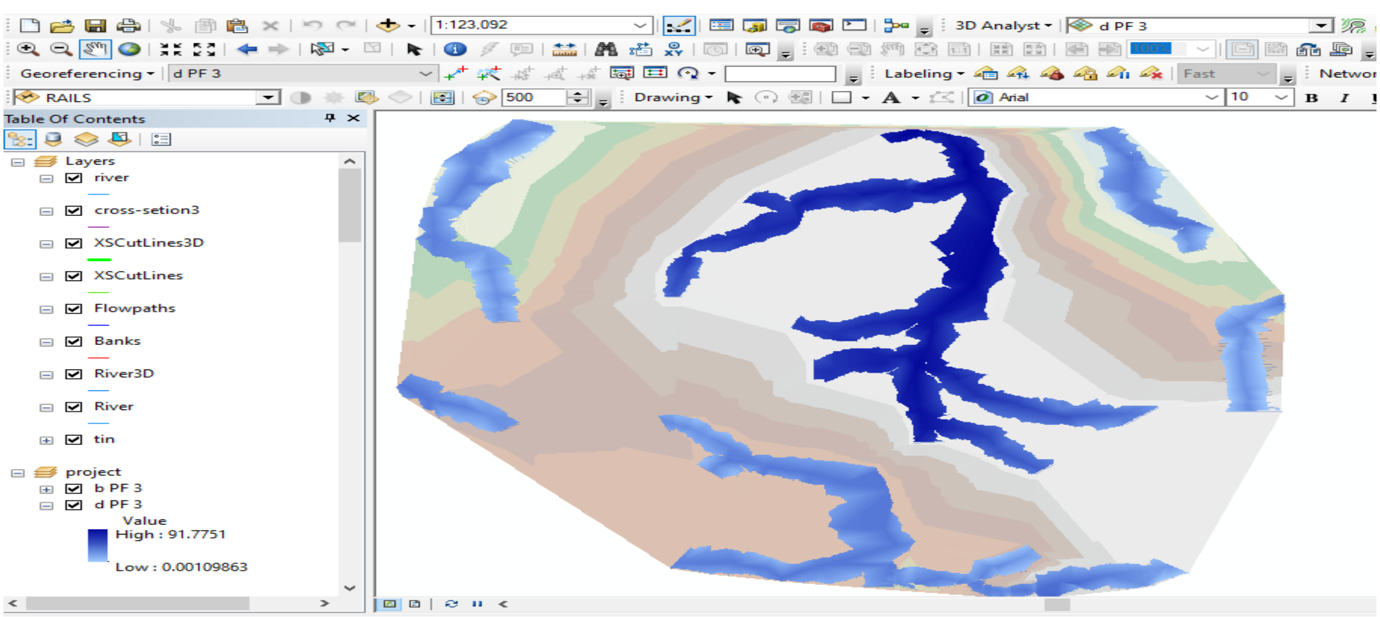

Figure 4 new: HEC-RAS flood inundation model.

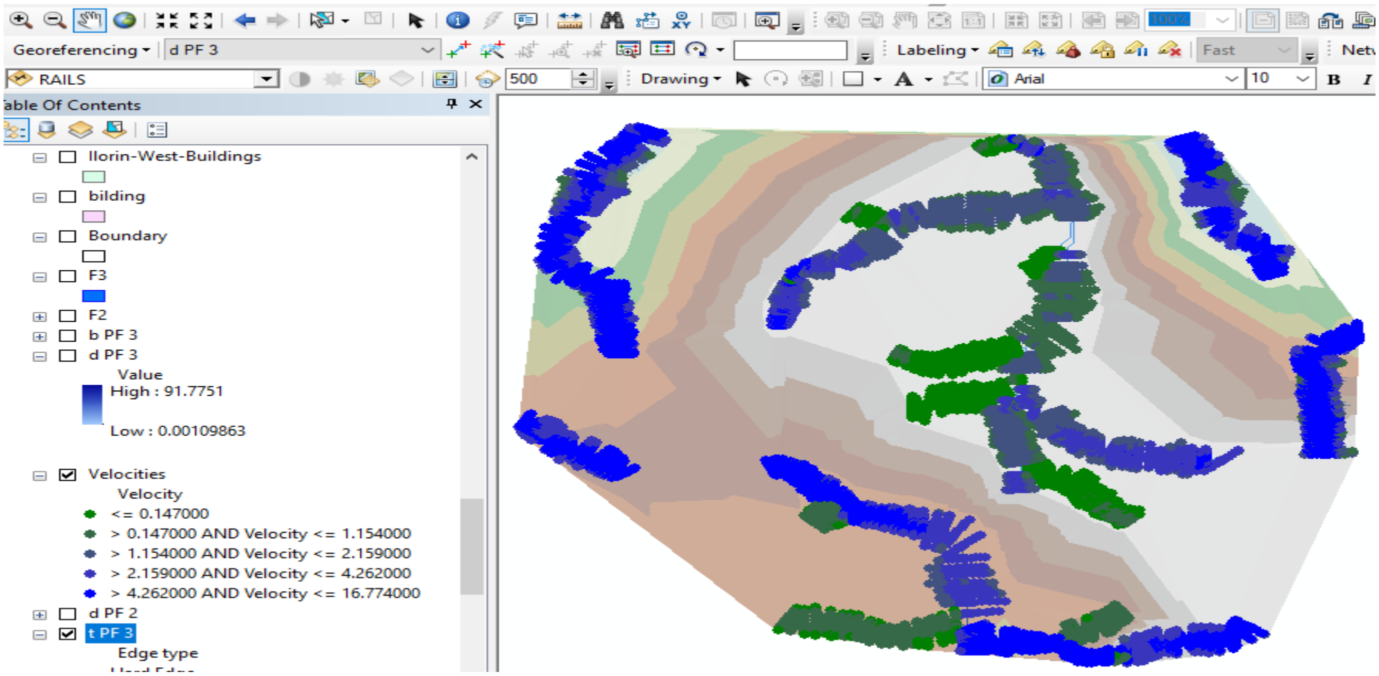

Figure 5: Steady flow discharge velocity

Lowland and relatively plain surfaces within the floodplain are more likely to be inundated during flood events. Across the returns and the river reaches, the volume of water discharge increases geometrically (Table 1).

Table 1: Steady flow water discharge volume

Return period (Years)	30	50	100	Reach
Flood discharge (m^3/s)	24000 25000 1000	48000 50000 2000	96000 100000 4000	Upper Lower

C. *Flood vulnerability and analysis of the impact*

The flood hazard map of Ilorin generated using a combination of different GIS techniques and RAS packages are presented in Figure 6. The flood risk areas are identified in dark blue colour while the extent of the maximum flood is shown in red colour. In Ilorin, flood risk is mainly from the rivers at the lower regions of the Asa, Oyun, and Awun rivers that converge and discharge into River Niger. The map clearly shows that areas highly vulnerable to flooding in Ilorin are found around the river channel areas. It is more critical because the city is located downstream of drainage basin areas of the three river basins. In particular, Asa being the primary drainage channel in the metropolitan area accumulates runoff in and around the city that flows through the city into the pour point of the catchment areas where the other two major rivers also discharge. Historically, most of the areas identified as high flood risk in this study had also experienced significant flood occurrences over the past decades. In terms of area coverage, the flood risk extent occupies approximately 17.7% (58.2 km^2) of the 328.5 km^2 area investigated and has been identified as high flood risk (Table 1). This could extend by 1% during extreme rainfall events (maximum flood extent).

Given that the study is focused on the urbanized area, it is essential to assess the potential risk. The flood risk maps generated reveal the flood behaviour and characteristics of floodplain areas of the study areas. For impact analysis, we employ overlay and query analysis methods in GIS to interpret and analyse the flood risk areas within the study area and their possible consequences. The flood risk map indicates that high flood risk areas are found around the flood plain of the river channels most of which have been converted to residential areas. In addition to an extreme rainfall event, the topography of the study area is more likely a major factor that significantly contributes to the extent of flooding in the city. Overlaying the buildings and road layers allowed for assessing the household and roads/rail at the risk of flooding. It is estimated that about 12,872 buildings representing about 5% of the buildings in the city are at risk of flooding (Figure 7). Among these buildings, 100 school locations made up of 75 (18.4%) primary and 25 (18.8%) secondary schools fall within the flood risk zones.

In addition to the building, the trunk of road infrastructure that could be affected totals 395.53 km (Figure 8). The road segments comprise residential service lanes and secondary, tertiary, and unclassified roads. Other hydraulic structures associated with the road infrastructures which are also under threat of flood hazards are the bridges and culverts across the rivers and water channels.

The combination of HEC-RAS and GIS permitted the simulation of flood inundation in two-dimensional (2D) space resulting from rivers overflowing their banks. The basic dataset required for the modelling DEM was obtained from freely available online geodata resources. The map has shown that floods could extend up to an average of 500 m on both sides of the river channels. The flood prediction map allowed examining the key facilities at risk. Most of the predicted floodable areas occurred in the densely populated urban areas

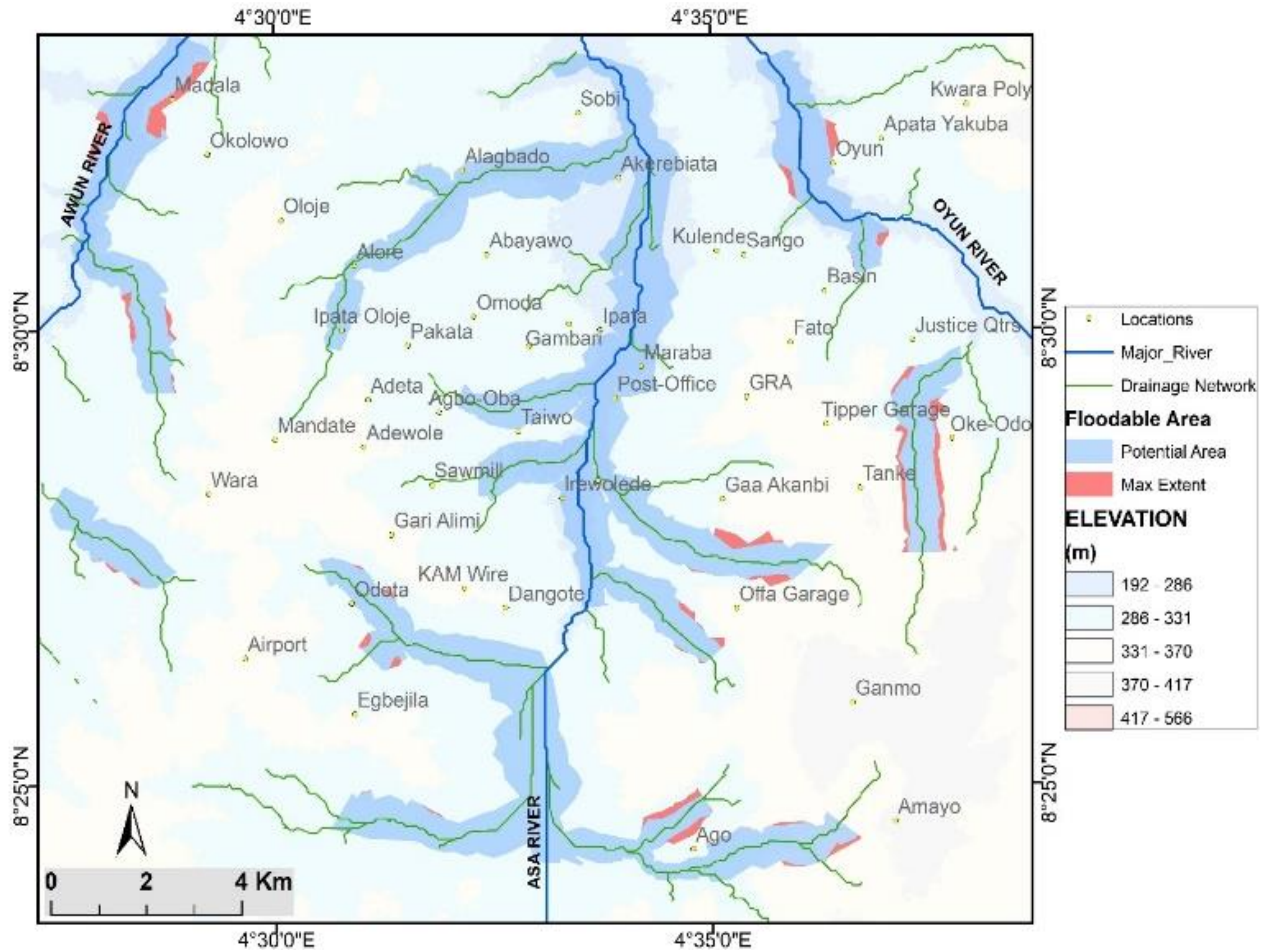

Figure 6: Predicted flood area extent

Table 2: Statistics of flood and non-flood risk areas

Area type	Areas (km^2)	% Area
High flood risk area	58.23	17.73%
Max flood extent	0.72	0.22%
Total flood risk area	58.95	17.95%
Non-flood prone area	269.55	82.06%

in the low land adjacent to the river channels, similar to recent findings of (Idrees, *et al*., 2022). The number of buildings within the flood risk zones revealed the degree to which households are prone to flood hazards. The closeness of the buildings to the river equally revealed noncompliance with the urban development plan with most of the river flood plains converted to residential areas. Certainly, an increase in population without improving refuse disposal and management which results in blockage of water channels also worsens the chance of flooding events (Shiru and Johnson, 2018). The weakness of the present study is the non-availability of accurate population and household data which prevents estimating the actual number of people that could be impacted. Also, the prediction becomes more frightening considering the age bracket of the students that attend the schools identified within the flood hazard zones. The finding also highlights the road section at risk which is significant to emergency response and evacuation planning in the event of flood incidence. HEC-RAS hydraulic model and ArcGIS allowed improved detection and analysis of flood risk within the city which will be useful for floodplain management, flood disaster planning and mitigation.

IV. CONCLUSIONS

This study has shown that the HEC-RAS model integrated with GIS is vital for hydrologic analysis, including flood inundation mapping and flood plain delineation. The present work, utilising a digital elevation model, provided an accurate estimation of water discharge, flow velocity, and flood inundation extent due to flood events. Analysis of the hydrology of the Ilorin metropolis with the HEC-RAS model using geometric data and discharge data provided water surface profiles for various three return periods. Overlay of the high flood risk area on the road network and building footprints revealed the degree of risk to the inhabitant and road infrastructure. The results of the study will help urban planners and policymakers suggest effective measures to mitigate flood during flood season thereby reducing the impact of the flood on the inhabitants and damage to infrastructure.

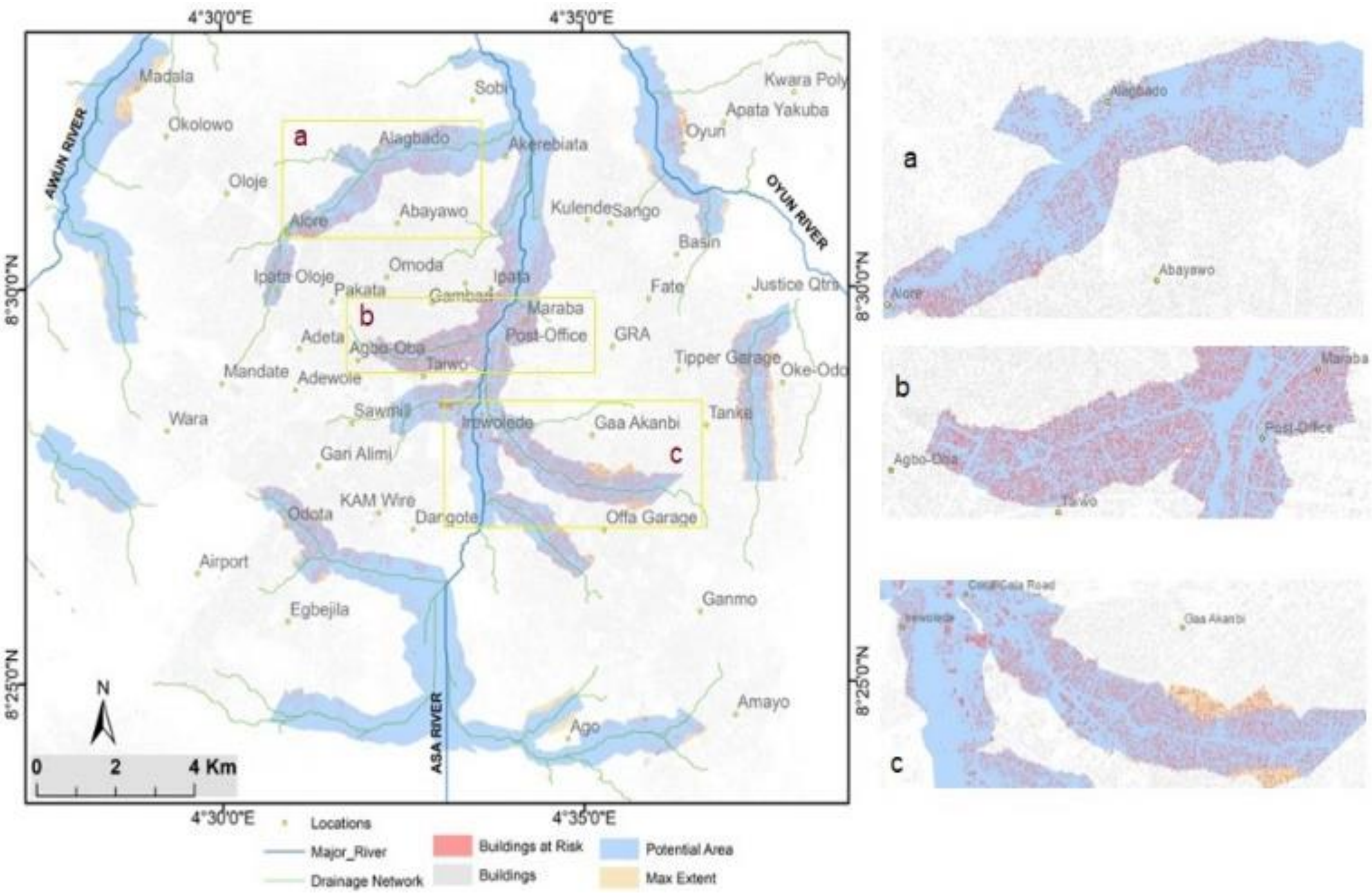

Figure 7: Households at risk of flooding

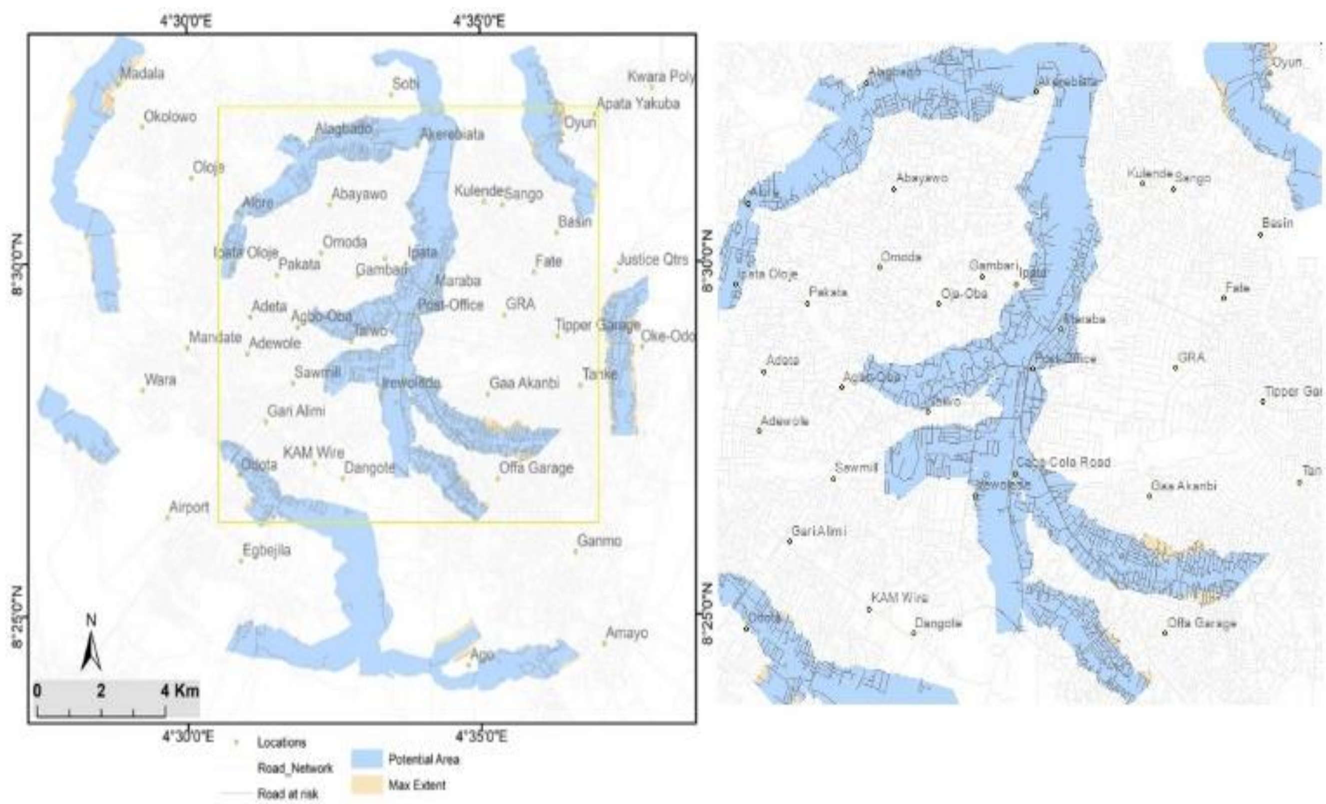

Figure 8: Road sections at risk of flooding

AUTHOR CONTRIBUTIONS

A. Yusuf: conception, supervision, analysis and reporting; **M.O. Idrees**: conceived and manage the project, designed the research, edited and approve the final draft; **R. Ojo**: data processing, prepared the figures and tables; **A. Balogun**: research design, provided software, revised the draft manuscript; **I.B. Salami**: Prepared the first draft of the manuscript; **O.S. Sani**: revised the draft manuscript.

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