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Establishing the Driving Forces and Modeling of flooding in the Lafa River Basin, Accra, Ghana.

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ABSTRACT : *The Lafa River Basin (LRB) experiences increased frequency and magnitude of floods, causing increases in areal and depth of inundation. This translates into huge economic losses and loss of human lives. The effective management of flood disaster of the LRB is hinged on the identification of the factors responsible for the floods, modelling of the flood situations and a quantitative assessment of the hazard zones. Hydrologic Engineering Centre-Hydrologic Modeling System (HEC-HMS) and Hydrologic Engineering Centre-River Analysis System (HEC-RAS) models have been integrated with Geographical Information System (GIS) to identify the driving forces behind the floods, and assess the hazard zones of the Basin. Physiographical characteristics are responsible for the floods and analysis indicate that the LRB is a small urbanised elongated drainage basin of area 27.945 km2 with predominantly steep slopes, and impervious surface soils. The Peak flows produced by 2, 15, 25, 50, and 100 year return period storms have been found to inundate 233.88 ha, 292.92 ha, 298.36 ha, 305.00 ha, and 311.24 ha respectively. 1.68 %, 5.54 %, 5.91 %, 6.41 %, and 6.63 % respectively of total inundation areas were above inundated depth of 2 m and are located around culvert locations on the Lafa stream.*
Keywords*-Basin, Flood plain, Hydrological analysis, Modelling, Peak flows*

I. INTRODUCTION

Urban flooding is generally induced by torrential rains that generate excess precipitation beyond the capacity of river channels and other drainage systems. As the water rises to flood stages, areas along the middle and lower reaches of rivers are flooded resulting in negative impacts on social and economic developments. The Lafa River Basin (LRB) has consistently been affected by floods during rainy seasons (June - July and September - October). The Basin in the past 20 years has been experiencing increased frequency and magnitude of floods causing increases in areal and depth of inundation which translates to huge economic losses to the inhabitants.

The Hydrological Services Department together with the Ga West Municipal Assembly had put in several mitigation measures including desilting the river channel biannually, and pulling down unauthorised buildings within the floodplains. Various portions of the river reaches have also been modified to reduce meandering to ease water flow in the river channel. However, these measures have not yielded the expected mitigation of flooding in the Basin. Increased urbanisation has also led to increasing impervious coverage increasing the flood hazard levels in the Basin. Devastating floods as a result of torrential rainstorms in October 2011 displaced four thousand, four hundred and thirteen (4,413) people from their homes, three (3) corpses were recovered, and properties worth thousands of Ghana cedis were destroyed (Anon., 2011).

The spatial integration of hydrological and hydraulic models into a GIS, enables flood visualisation, animation, and flood hazard levels assessment. Maps of flood situations showing hazards levels are widely used for planning, designing, and forecasting, so that appropriate structural and non-structural measures could be established for efficient flood mitigation and control. It is also used by emergency response personnel to identify safe areas during emergency evacuation exercises.

This paper therefore seeks to identify the driving forces behind the floods in the LRB using GIS technique, model the flood situations, and to assess the flood hazard zones in the Basin. These models will form the basis on which stakeholders would identify the appropriate mitigation measures for effective management of floods in the Basin.

1.1 Location and Assessibility

LRB is located about 9 km to the west of Accra and lie within three administrative jurisdictions of the Greater Accra Region. It can be located between longitudes 0° 18' 33" W and 0° 15' 26" W and latitudes 5° 34' 12" N and 5° 38' 22" N (Fig. 1) and covers an approximate area of 28 km2.

The Basin has evolved from peri-urban into a completely urbanised status due to its proximity to central Accra, as it offers a preferred dwelling place for people who work in the capital city. Pressure has been brought to bear on available space, thus encroaching on the floodplains and stream courses. Such situation causes floods even in short duration high intensity rainstorms. There are numerous socioeconomic infrastructures in the Basin including schools, markets and a power sub-station.

II. MATERIALS AND METHODS

The basic geographical data used for the studies included topographical data comprising of height (contour lines and spot heights), buildings, road lines, and other cultural features were obtained from Survey and Mapping Division of The Lands Commission. Soil data was obtained from the Soil Research Institute (SRI). Culvert locations on the stream were measured on the field using a handheld Geographical Positioning System (GPS) and the specifications measured with a tape.

The contour lines were edited to ensure line continuity and elimination of overlaps. The river lines were edited for line continuity, and directed towards the outlet. All the datasets were projected using the Projection and Transformation Tools of ArcGIS onto the Universal Transverse Mercator (UTM) reference system (WGS_84_UTM_Zone_30N) to enable integration and analysis. The edited dataset were further organized into a geodatabase for easy access and management. The output maps of the study were thus produced in the UTM reference system. Rainfall data of 1 hour, 2 hour, 3 hour, 4 hour, 5 hour, 6 hour, and 24 hour durations extracted from a 50-year record of the Accra Rainfall Synoptic station was obtained from the Hydrological Services Department.

2.1 Rainfall Frequency Analysis

Rainfall frequency analysis was carried out to relate the magnitude of extreme rainfall events to their frequency of occurrence in the LRB through the use of a probability distribution function. Annual maximum values of each duration records were ranked and fitted to the Gumbel's distribution using the Weibull plotting position. Numerous theoretical and empirical distributions have been proposed by various hydrologists that are generally applicable to annual maximum rainfall series. However, a comprehensive studies of various distributions made by (Hershfield and Kohlar, 1960) revealed that the Extreme Value Type 1 (EV1) or the Gumbel distribution (Gumbel, 1954) is the most suitable (Deshpande et al., 2008).

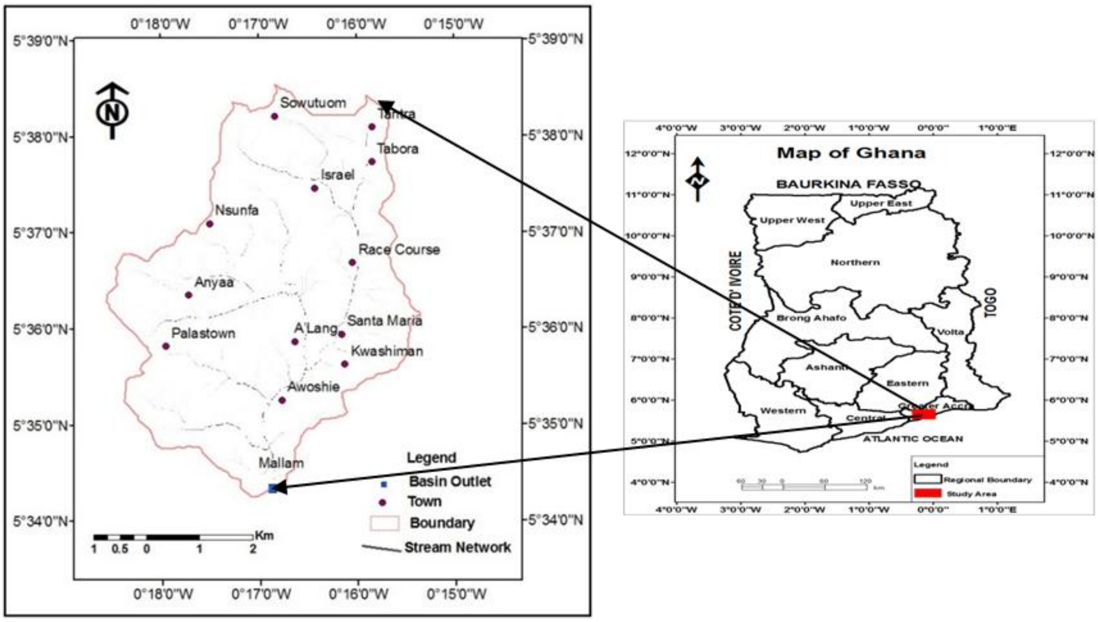

Figure 1 Map showing the Lafa River Basin

2.2 Digital Elevation Model (DEM) Generation

A DEM is a useful source for deriving physiographical variables for hydrological, hydraulic, water resources, and environmental investigations. The DEM of the LRB was generated from the contour data of the Basin using the Topo-to-Raster function in 3D Analyst of ArcGIS 9.3 software. The Topo to Raster interpolator is based on the Australian National University's Digital Elevation Model (ANUDEM) program developed by Michael Hutchinson (Hutchinson, 1989). It was designed specifically for generating hydrologically correct DEMs (Anon., 2009).

2.3 Watershed Extraction from DEM

The LRB extraction from the DEM was carried out using the hydrology analysis tools of the ArcGIS suite. The DEM was preprocessed using the flow direction, sink identification and sink filling tools to produce a smooth or depressionless DEM. The Flow Accumulation function was used to compute accumulated flow which is the accumulated weight of all cells flowing into each downslope cell in the output raster. The flow accumulation threshold or the pour point was set at the Basin outlet. The pour point and the flow accumulation raster were used in the watershed function to extract the LRB.

A drainage basin's physical characteristics play a critical role in the hydrological response of the basin. The physiographical parameters of the LRB were determined using ArcGIS Suite based on the LRB DEM. These include slope, aspect, and morphometric parameters. The slopes and aspect of the LRB were determined using the Spatial Analyst tool of ArcGIS. The slopes were further classified into five (5) categories namely; Flat (0-2 %), Undulating (2-8 %), Rolling (8-16 %), Hilly (16-30 %), Mountainous (>30%). Linear and areal morphometric parameters of the LRB were also determined and computed. The linear aspects of the drainage network included; stream order (Nu) and stream length (Lu). The areal aspects of the Basin considered included basin area (A), basin perimeter (P), basin length (Lu), elongation ratio (Re), circularity ratio (Rc), and form factor ratio (Rf).

2.4 Rainfall-Runoff Modelling

The US Army Corps of Engineers Hydrological Engineering Center's HEC-HMS was adopted for the rainfall-runoff simulation for the study due to its simplicity and availability on the internet. The Natural Resources Conservation Service (NRCS), Curve Number (CN) loss method was used to compute rainfall losses. SCS Unit Hydrograph, and Muskingum routing methods were adopted for transform and flow routing estimation respectively. The resulting landuse grid was also used to prepare a percentage impervious surface grid based on the percent impervious values of the corresponding landuse classes.

The landuse/landcover (LULC) of the LRB was generated from the topographic data with Google earth image of the LRB as backdrop. The map was delineated in four classes (Table 1) based on the United States Geological Survey Land cover Institute classification system (Anon., 2012)

2.5 Hydraulic Modelling

Hydraulic model of the U.S. Army Corps of Engineers, Hydrological Engineering Center River Analysis System (HEC-RAS), and Hydrological Engineering Center-Geospatial River Analysis System (HEC-GeoRAS) were selected for this study due to their extensive application for floodplain analysis and free accessibility on the internet. HEC-GeoRAS application was developed specifically to process geospatial data for use with HEC-RAS.

2.6 Flood Hazard Mapping

The hazard assessment in the LRB involved the estimation of two vital parameters: the probability of occurrence or the return period of the hazard, where the Probability of occurrence P and the Return period T over a Period n are mathematically related by:

$$P = 1 - \left(1 - \frac{1}{T}\right)^n \qquad (1)$$

The hydraulic model output for the various return periods were exported to HEC-GeoRAS and classified for flow depth (d) indicated on Table 2.

The inundated depth classes were computed for hazard levels assessment for each return period.

Table 1 LRB Inundated depth classification

Inundated Depth Class (d)	Hazard Level
d < 0.5 m	Very Low
0.5 m < d < 1 m	Low
1 m< d< 1.5 m	Medium
1.5 m< d < 2 m	High
d > 2 m	Very High

Table 2 Delineated LULC Classes of the Lafa River Basin

LULC Class	Class Number	Percent Impervious	Area (m2)
Low Intensity Residential	21	20	21809196.100
High Intensity Residential	22	25	4583915.180
Herbaceous	71	5	1137815.296
Bare rock	31	85	414038.847

III. RESULTS

3.1 Rainfall Frequency Analysis

A plot of the maximum rainfall against the reduced variate followed a linear trend (Fig. 2) indicating consistency in the data and justified the use of the Gumbel distribution (Reddy, 2011). The result of the Gumbel distribution frequency analysis performed for 1, 2, 3, 4, 5, 6, and 24 hour duration rainfall corresponding to 2 year, 15 year, 25 year, 50 year, and 100 year return period is summarised in Table 3 and Fig. 3.

3.2 Physiographical Parameters Analysis

The contour and river lines data were used to generate the DEM, from which LRB DEM was delineated (Fig. 4). From Fig. 4, the minimum elevation on the LRB is 2 m at the outfall and the maximum is 160.232 m located on the north-easterly trending hills at the western fringe of the basin. Based on the DEM, the morphometric parameters of the basin were also derived.

3.2.1 Morphometric Parameters

The morphometric parameters of the LRB are summarised in Table 4. The study showed that the Lafa Stream is a 3rd Order stream with 53 total numbers of streams and a total stream length of 34.390 km.

For a relatively large basin, the order number is directly proportional to the size of the contributing watershed, channel dimensions, and the stream discharge at any section in the system (Strahler, 1964). The area of a drainage basin is very critical in hydrological design. It is a direct function of the volume of water that can be generated from an effective rainfall. The area of the LRB is 27.945 km^2 (Table 4). According to Reddy's watershed classification, a watershed is considered to be small if its area is less than 250 km^2 (Reddy, 2011). Small watersheds tend to have a shorter time of concentration and therefore prone to floods. This criterion therefore characterizes LRB as a small basin.

Basin shape is not applied directly in hydrological computations, however, it supposedly reflects the way runoff will 'bunch up' at the basin outlet and has a significant effect on the hydrological character of the basin. The shape indices considered in this study included elongation ratio, circularity ratio, and form factor ratio.

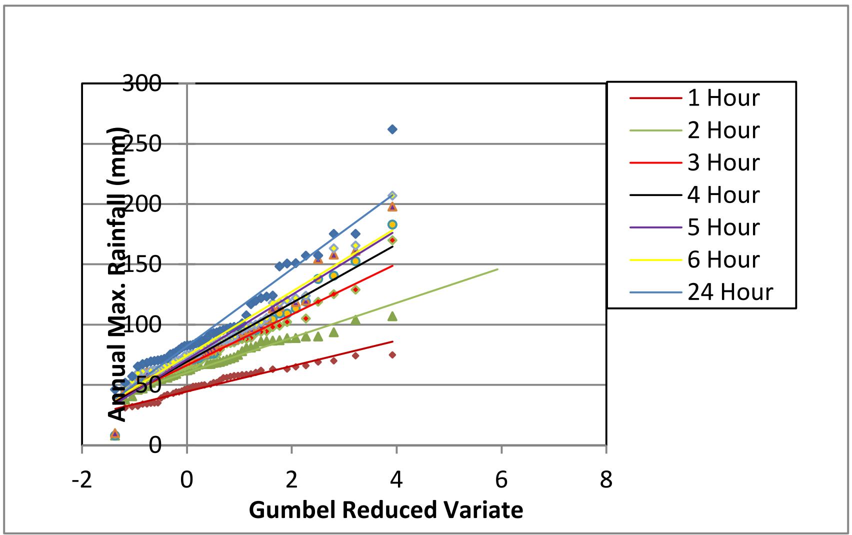

Figure 2 A Graph of Maximum Rainfall versus Gumbel Reduced Variate

Table 3 Summary of Rainfall Frequency Analysis

	Rainfall Magnitude (mm)				
Duration	2 Year	15 Year	25 Year	50 Year	100 Year
1 hour	48.3	74.3	80.2	88.1	96.0
2 hour	65.3	100.8	108.8	119.7	130.4
3 hour	73.8	124.2	135.7	151.1	166.3
4 hour	77.7	136.1	149.4	167.2	184.9
5 hour	80.6	144.8	159.4	178.9	198.4
6 hour	83.8	147.4	161.9	181.3	200.5
24 hour	93.6	171.0	188.6	212.2	235.6

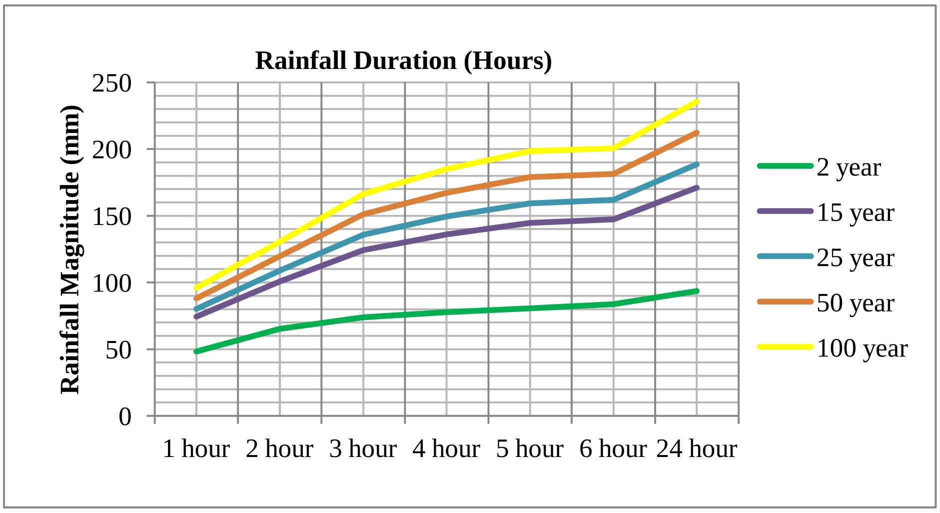

Figure 3 Relationship between Magnitude, Duration and Return Period

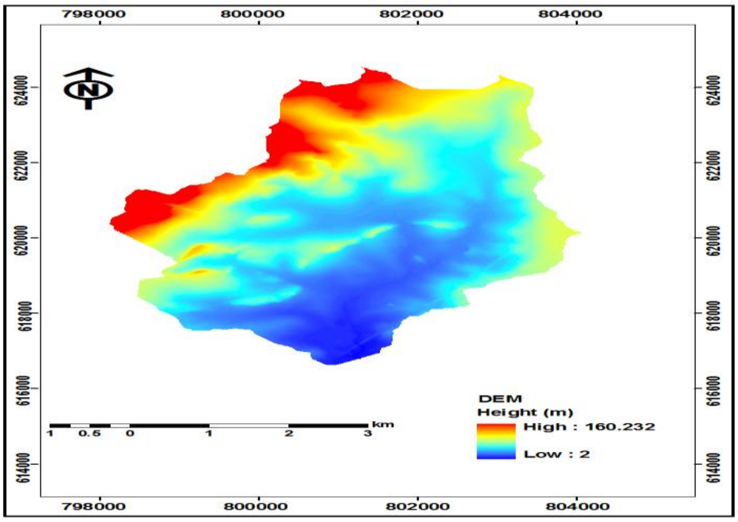

Figure 4 DEM of the Lafa River Basin

Shumm (1956) defined elongation ratio (Re) as the ratio of diameter of a circle of the same area as the basin to the maximum length. The Re values generally ranges between 0.6 and 1.0 over a wide variety of climate and geologic types. Values near to 1.0 are characteristics of region of very low relief, while values in the range of 0.6-0.8 usually occur in the areas of high relief and steep ground slope (Chow, 1964).

These values are further categorised as circular (Re>0.9), oval (0.9-0.8) and strong elongated to less elongated (0<Re<0.7), (Yusuf et al., 2011). The computed Re of the LRB is 0.609. The Circularity ratio (Rc) is a dimensionless factor that indicates the measure of circularity of the basin. The computed Rc value of 0.521 (Table 4) indicates that the LRB is elongated. A form factor value (Rf) of 0.291 further indicates a lower value of form suggesting that the LRB is not circular or oval in shape but an elongated basin.

3.2.2 Lafa River Basin Slopes

The slopes of the LRB created from the DEM ranges between 0 and 56 %. These percentage slopes were further classified into five categories based on (Sreenivasulu and Pinnamaneni, 2010) classification illustrated on (Table 5).

Flat slopes cover 22 % of the basin area and are located along the main stream channel which constitutes the floodplain of the basin. The undulating, rolling, hilly, and mountainous areas which constitute the steep slopes cover 78 % of the Basin. The velocity and volume of runoff depends on the slope of the land. Steeply sloped basin characteristics induce faster stream response to precipitation. It produces higher peak flows and shorter time of concentration due to reduced time for infiltration and shorter travel time to the stream channel and outfall. Channel slope affects the magnitude of the peak and the duration of runoff. A steep channel produces greater velocities and allows faster removal of runoff from the watershed and produces shorter times to peak. A mild or low channel slope produces lower velocities and slow removal of runoff, resulting in higher peaks and therefore influences frequent flood occurrence.

Table 4 Morphometric Parameters of the LRB

Drainage Basin Parameter	Symbol/Formula	Parameter Value
Stream Order	Nu	3
Stream Length	Lu	34.390 km
Total Number of Streams	Ns	53
Basin Length	Lb	9.800 km
Basin Area	A	27.945 km2
Basin Perimeter	P	25.957 km
Elongation Ratio	$R_e = \frac{2}{L_b}\sqrt{\frac{A}{\pi}}$	0.609
Circularity Ratio	$R_c = \frac{4\pi A}{p^2}$	0.521
Form Factor Ratio	$R_f = \frac{A}{{L_b}^2}$	0.291

The computed mean channel slope of the LRB is 1%, which does not influence a quick removal of runoff from the stream channel resulting in water overtopping the banks causing floods in the basin. The aspect grid created indicated that the slopes of the basin are directed towards the stream channel indicating less travel time for runoff to reach the stream channel, and thus enhance flooding in the Basin.

Table 5 Slope Classes on the LRB

Slope Class	Class (%)	Area (Km^2)
Flat	0-2	6.302
Undulating	2-8	16.799
Rolling	8-16	3.850
Hilly	16-30	0.831
Mountanous	> 30	0.162

3.3 Soil Data Map

The classified soil map is illustrated in Figure 6 shows that the Korle series is the only soil with relatively high infiltration rate. However, the Korle series only constitutes 17 % of soils in the LRB. The remaining soils, including; Chuim-Gbegbe, Fete-Bediesi, Nyigbenya-Haacho, Oyarifa-Manfe, Oyibi-muni, and Songaw constitutes 83 %. These soils have clay content soils that impede vertical transmission of water resulting in low infiltration rates and higher runoff volume.

3.4 Landuse/land cover Map

The result of the LRB landuse data preparation is indicated on Fig. 7. It could be observed that the residential landuse characteristic covers a total of 94 % of the LRB, a marginal herbaceous characteristic of 4 %, and 2 % bare rock surface located in the abandoned quarry sites. These percentages indicate that the landuse type of the LRB is residential and urban in nature. Urbanisation, with the accompanying loss of vegetation, replacement of soil with impervious surfaces, and routing storm water runoff directly to stream channels, has significant impact on many of the processes that control streamflow in a drainage basin (McCuen, 1998).

3.5 Hydraulic Modelling and Hazard Assessment

The Geometric data output from HEC-GeoRAS and the flow rates were used to compute the water surface profiles (flood models) corresponding to 2 year, 15 year, 25 year, 50 year, and 100 year return period in HEC-RAS.

From the hydrological analysis and the hazard maps, it was observed that the peak flows produced by 2 year, 15 year, 25 year, 50 year, and 100 year return period storms are 43.0 m3/s, 98.0 m3/s, 112.4 m3/s, 132.6 m3/s, and 153.5 m3/s respectively. These flows inundated 233.88 ha, 292.92 ha, 298.36 ha, 305.00 ha, and 311.24 ha respectively of the LRB. The area inundated with respect to peak flows show that inundated area increased rapidly between the 2 year and 15 year peak flows, increased moderately between 15 and 25 year flows, and slight increases beyond 25 year flows (Fig. 8).A relationship between the return period and the inundated areas showed a rapid increase of inundated area from 2 to 15 year and moderate increases between 15 and 25 year return periods. Slight increases occurred beyond 25 years return period (Fig. 9).

3.5.1 Flood Hazard Assessment

The result of the flood hazard assessment based on the hazard maps is summarised in Table 6. It could be observed that inundated area decreases with increasing depth for all return periods. For inundation depth $d<0.5$ designated low hazard level, inundation extent for 2 year, 15 year, 25 year, 50 year, and 100 year is 139.16 ha, 145.16 ha, 143.60 ha, 139.36 ha, and 136.36 ha respectively, which covers 59.50 % , 49.6 %, 48.13 %, 45.64 % and 43.81 % of total inundated area respectively. This indicates that low hazard flood is approximately 50 % of total inundated area for all flood intensities. For inundation depth $d>2$ designated very high hazard level, the inundated areas for 2 year, 15 year, 25 year, 50 year, and 100 year flood are 3.92 ha, 16,24 ha, 17.64 ha, 19.56 ha, and 20.64 ha respectively. These areas cover 1.68 %, 5.54 %, 5.91 %, 6.41 %, and 6.63 % respectively of total inundation extent of each return period flood. This indicates that area above inundation depth $d>2$ also increases with increasing flood intensity.

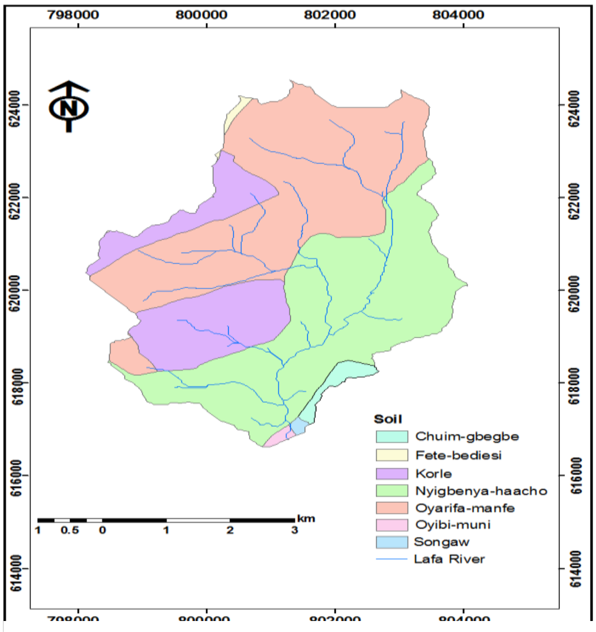

Figure 5 Soil Map of the Lafa River Basin

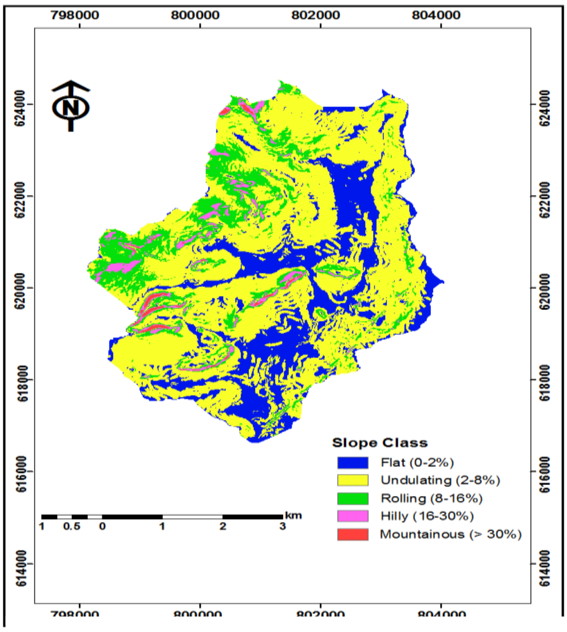

Figure 6 LRB Classified slope grid

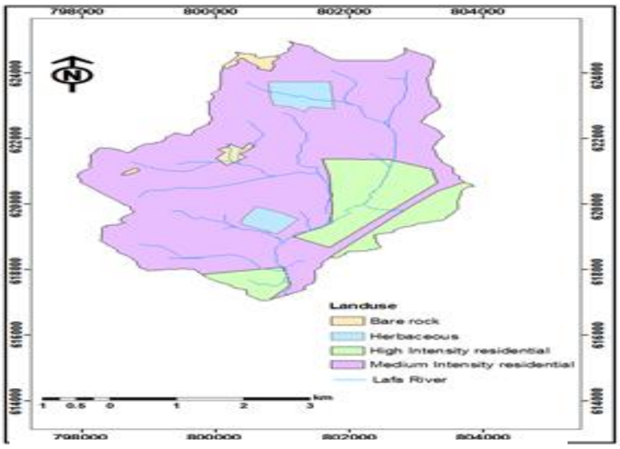

Figure 7 Landuse Map of Lafa River Basin

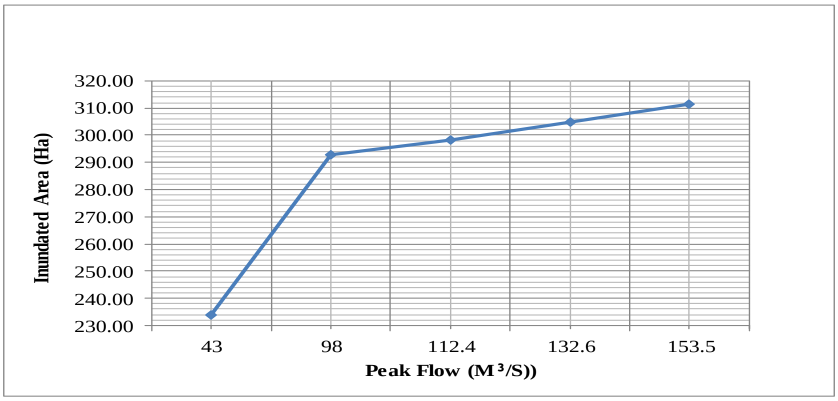

Figure 8 Peak Flow and Inundated area relationship

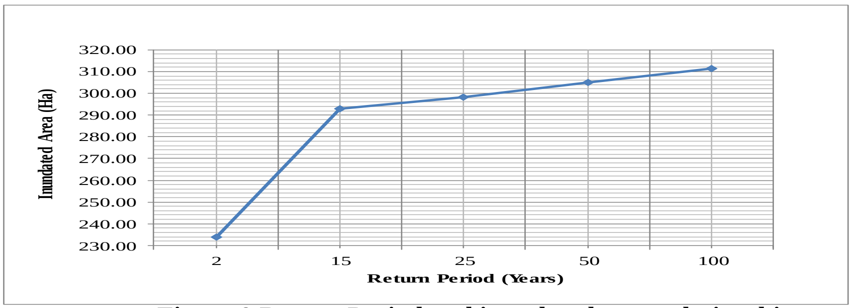

Figure 9 Return Period and inundated area relationship

Table 6 Summary of Flood Hazard Assessment

Water Depth (d) (m)	TOTAL FLOODED AREA (Ha)									
	2 Year Flood		15 Year Flood		25 Year Flood		50 Year Flood		100 Year Flood	
	Area	%	Area	%	Area	%	Area	%	Area	%
d < 0.5	139.16	59.50	145.16	49.56	143.60	48.13	139.20	45.64	136.36	43.81
0.5 < d < 1	57.56	24.61	74.60	25.47	78.68	26.37	85.56	28.05	90.96	29.23
1 < d < 1.5	22.96	9.82	36.12	12.33	37.40	12.54	37.28	12.22	38.76	12.45
1.5 < d < 2	10.28	4.40	20.80	7.10	21.04	7.05	23.40	7.67	24.52	7.88
d > 2	3.92	1.68	16.24	5.54	17.64	5.91	19.56	6.41	20.64	6.63
Total	**233.88**	100	**292.92**	100	**298.36**	100	**305.00**	100	**311.24**	100

IV. CONCLUSIONS

Results from this study show that a combination of hydrological and hydraulic model integrated with GIS is an invaluable tool for flood analysis and management in drainage basins where limited hydrometeorological data exist. The results indicate that the driving forces behind the floods in the LRB are inherently natural physiographical characteristics that include the following:

- The Basin consists of a 3rd order stream with a drainage area of 27.945 km2. It has an elongated shape characterised by high relief and steep ground indicated by an elongation ratio (Re) of 0.609, circularity ratio (Rc) of 0.521, and form factor value of 0.291.
- 78 % of the Basin is characterised by steep slopes that produce higher peak flows and shorter time of concentration due to reduced time for infiltration and shorter travel time to the stream channel and outfall.
- 83 % of the soils in the LRB impede vertical transmission of water resulting in low infiltration rates, and higher runoff volume in the basin.
- 94 % of the landuse characteristic in the basin is residential, indicating an urban setting and therefore predominantly impervious.

The flood models produced by the hydraulic analysis corresponding to 2 year, 15 year, 25 year, 50 year, and 100 year return period storms inundated 233.88 ha, 292.92 ha, 298.36 ha, 305.00 ha, and 311.24 ha of the LRB flood plain respectively. These inundation extents give an indication of the potential flood situations in the Basin.

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