Preliminary Flood Vulnerability and Risk Mapping of Koforidua and its Environs using Integrated Multi-Parametric AHP and GIS

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Asante-Annor, A., Ansah, E. and Acherefi K. (2020), "Preliminary Flood Vulnerability and Risk Mapping of Koforidua and its Environs using Integrated Multi-Parametric AHP and GIS", *Proceedings of 6th UMaT Biennial International Mining and Mineral Conference*, Tarkwa, Ghana, pp. 91-102.

Abstract

Certain communities in Koforidua and its environs experiences flooding due to anthropogenic and natural causes. There is the need for better understanding of the spatial extent and demarcation of flood prone areas for effective management of flood risk in the municipality. This study aims at providing flood vulnerability and risk map of Koforidua and its environs for planning purposes. The Analytical Hierarchy Process (AHP) integrated into GIS has proven to be an effective and cost-effective method. This paper integrated Remote Sensing Data, Geographic information System (GIS) and Analytical Hierarchy Process (AHP). This technique enabled the hydrological mapping of the study area. The study utilised six flooding causative factors that are relevant to the study area and their respective percentages; rainfall intensity (35 %), drainage density (9 %), elevation (9 %), slope (11 %), soil media (24 %), and land use (12 %). About 20% of the area is highly vulnerable to flooding, concentrated in North-western part of Koforidua and Asokore township. Other areas of Koforidua, Koforidua Ada, and Okorase are found in moderate flood risk zones of about 60% of the area. Low flood risk areas constitute about 20% of the study areas and includes towns such as Nyerede and Okorase. A consistency index (CI – 0.023) and the consistency ratio (CR – 0.018) obtained ascertain and confirms high accuracy for the flood vulnerability and risk assessment.

Keywords: Flood Vulnerability, Remote Sensing, Geographic information System (GIS), Analytical Hierarchy Process (AHP), Koforidua

1 Introduction

Among all kinds of natural hazards of the world, flood is probably the most devastating natural hazard which frequently impact the livelihood and the economy throughout the world (Ouma and Tateishi, 2014). Research has shown that the risk of flooding will not decrease in the coming years and that with the onset of climate change, the intensity and frequency of flooding will threaten many parts of the world (Jonkman and Dawson, 2012).

Floods can occur in the form of an overflow of water from water bodies in which the water exceeds its boundaries, so that much of this water escapes from its usual limits. The frequency of flooding is a problem in the field of hydrological and natural hazard science, as these events are more important in natural disasters in terms of the number of people affected worldwide and the proportion of individual deaths (Borga *et al.*, 2011). The potential for flood and damage victims is also increasing in many areas due to social and economic development, which puts pressure on land use, for example through urbanisation. The risk of flooding is expected to become more frequent and more severe due to the effects of global change on climate, severe weather events in the form of heavy rain and river flow conditions (Dihn *et al*., 2012). The current trend and future flood risk scenarios therefore require precise spatial and temporal information on the potential flood hazards and risks.

Ghana experienced its first flood in 1968, affecting approximately 25,000 people, including loss of property and life (Asumadu-Sarkodie *et al*., 2015a). Floods are one of the most natural disasters that annually affect Ghana. Asumadu-Sarkodie *et al*. (2015b) in their report presented a table which indicates that, floods are number two after the epidemics when it comes to loss of life by natural disasters and risks in Ghana. About 409 out of almost 3.9 million people were killed because of the floods between 1968 and 2014 (Asumadu-Sarkodie *et al*., 2015a). According to Asumadu-Sarkodie *et al*. (2015b), economical loss caused by flood in Ghana is roughly US$ 780,500,000.

Koforidua, the capital town of the Eastern Region of Ghana is not left out in the perennial floods which occurs in the country. Such an occurrence can still occur if no flood management strategy is defined. It is therefore necessary to examine new ideas and approaches that can be integrated into existing structures to solve this problem. This article proposes new approaches to deal with this environmental problem which constantly puts some populace of Koforidua in danger. This approach will serve as a guide for urban and rural planners to determine suitable areas for new developments and to develop solutions for the most vulnerable areas. The objectives of the current study are: (i) to determine parameters that contribute to flooding; ii) to map the relative flood risk using AHP in a ArcGIS environment; (iii) to integrate these two methodologies and apply them to Koforidua and its environs; and (iv) produce a flood risk map and to determine vulnerable areas of flooding at various levels.

1.1 Study Area

1.1.1 Location and Accessibility

Koforidua is located in the Eastern Region of Ghana. Koforidua is located approximately at 803392 m to the East and 674375 m to the North according to the Universal Transverse Mercator, in Zone 30 degrees North. It is the regional capital of the Eastern Region and the municipal capital of the New Juaben Municipality. The municipality shares boundaries with East-Akim Municipality to the northeast, Akwapim North District to the east and south, and to the west Suhum-Kraboa-Coaltar District. The community is well connected to road networks as shown in Fig. 1.

1.1.2 Topography, Drainage and Weather

Koforidua generally has an undulating topography, which ranges between 151 m and 198 m above mean sea level. The highest point in Koforidua is located at Obuotabiri, a suburb which is the mountain belt along the eastern border (Fordjour, 2016). The area falls within the Densu basin with the Densu River and its tributaries being the key means of drainage in the area. Open and closed culvert serves as other key artificial drainage in the study area. The river is retained in Densuano to supply the municipality of Koforidua and its suburbs with treated drinking water. There are few waterfalls in different sections of the Densu River (Fordjour, 2016).

The climate of the study area is humid and dry tropical climate. The average temperature in March is 27.3 °C, the hottest month, and in August, 24.2 °C, the coldest month of the year. It has an average rainfall of 1407 mm/year, with the lowest rainfall in January and the highest in June (Fordjour, 2016).

1.2 Geology

The study area consists of the Voltaian sandstone, granitoid and dolerite dyke rocks as shown in Fig. 2. The Cape Coast granitoid complex includes a heterogeneous group of rocks occupying the western parts of the study area. They are mostly granitic to quartz dioritic gneiss, which gradually develops in the field from gneiss to fine-grained foliated biotite-quartz-diorite to exclusively hornblende-quartz-diorite gneiss (Ahmed, 1997). The Voltaian rocks belong to the Kwahu Group which is divided into three main formations; Mpraeso Formation, Abetifi Formation and Anyaboni Formation and each formation is subdivided into two different units (Coueffe and Vecoli, 2011). The Mpraeso and Abetifi Formation are made up of sandstones, thickly bedded to crossbedded, quartzose, locally poorly sorted, becoming finer grained and micaceous towards base (Coueffe and Vecoli, 2011). The area is controlled by tectonic structures (faults, fractures, and lineament) trending Northeast-Southwest, Northwest-Southeast, East-West and North-South as shown in Fig. 2.

1.3 Hydrology and Flooding Problems

The Densu River serve as one of the important utilisation resource in Ghana. It serves as the main source of water supply for many communities to which the river traverses. In Koforidua and Nsawam, the River is impounded, treated, and supplied to towns for commercial, domestic, and industrial use (Alfa, 2010). The groundwater resource of the basin also serves as a source of water supply to the communities within the basin. Groundwater exploitation is persistent in the basin, especially in areas that lack access to portable surface water. The groundwater in the basin occur due to the development fractures, joints, shearing and deep weathering (Akudago, 2007; Banoeng-Yakubo and Skjernaa, 2000) with a variable yield (Ganyaglo *et al.*, 2010).

Koforidua has been experiencing yearly torrential rainfall, however, since 2012 there has been an increase according to the meteorological agency of Ghana. There was a flooding incident on September 29, 2016 and September 14, 2018 which resulted in the loss of life, destruction of many homes and properties thereby leaving about two thousand people homeless (Anon., 2019). The affected areas included Koforidua-Zongo, Yaw Kyeremakrom, Abrewa-Nkwanta, Nsukwao, Asokore, Oyoko and Effiduase (Anon., 2019). An attempt to solve this flooding problems should include the consideration of hydrological networks, factors influencing flooding, delineation of flood risk zones, urban and landuse planning.

2 Materials and Methods Used

The AHP employs a comparison technique which aid in deriving priorities for the criteria taking into consideration its importance in achieving the aim (Ouma and Tateishi, 2014). Similarly, the alternative priorities (i.e., the choices competing under consideration) are also derived in the comparison technique in terms of how one performs to the criterion. With respect to that, Saaty (2008) suggested three principles when considering AHP, which are, decomposition, comparative judgment, and synthesis of priorities. By organising and evaluating alternatives to a multifaceted hierarchy of attributes, AHP provides

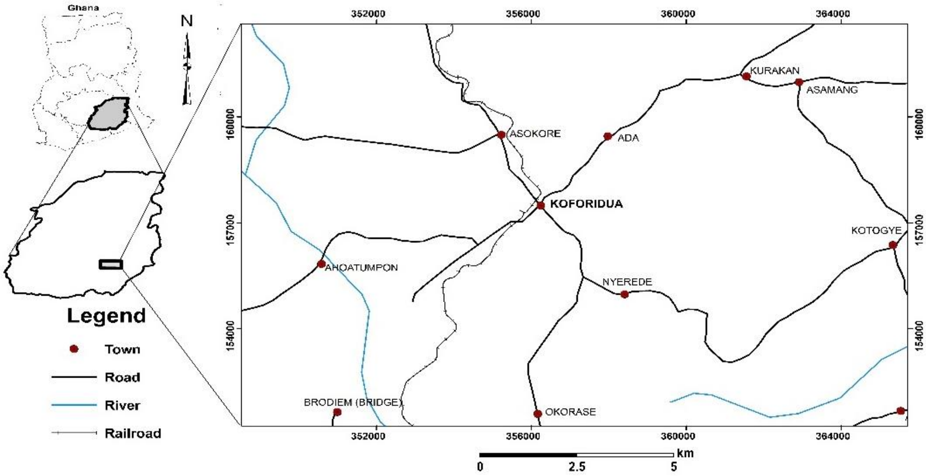

Fig. 1 Location Map of Koforidua and its Environs

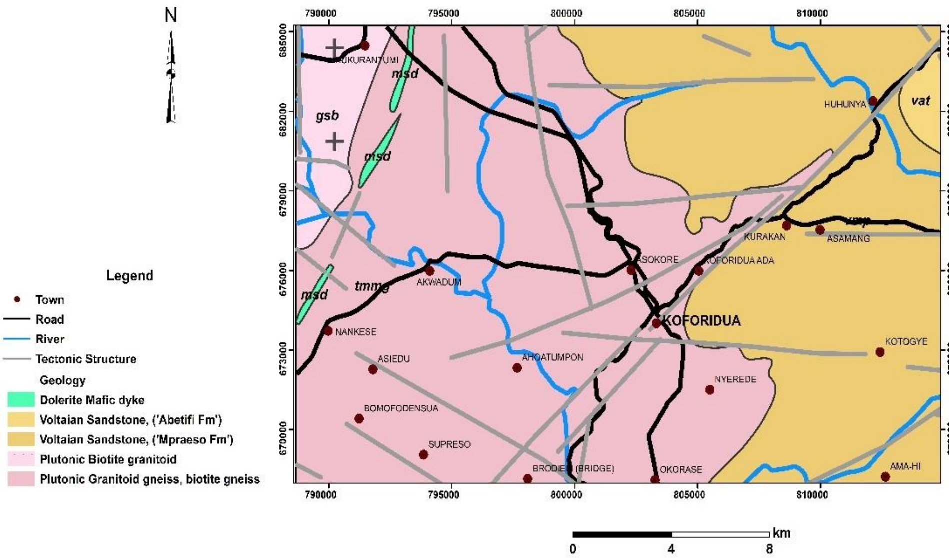

Fig. 2 Geological Map of Koforidua and its Environs

Table 1 Nine-point Intensity of Importance Scale

1	**Requirement k and l are of equal impact/effect**
3	Requirement k has a slightly higher impact/effect than j
5	Requirement k has a strongly higher impact/effect than j
7	Requirement k has a very strongly higher impact/effect than j
9	Requirement k has an absolutely higher impact/effect than j
2,4,6,8	These are intermediate scales between two adjacent judgments
Reciprocals	If requirement k has a lower value than l

Modified after Ouma and Tateishi (2014)

an effective quantitative decision tool for dealing with complex and unstructured problems (Ouma and Tateishi, 2014). Bojovic and Milenkovic (2008) added that AHP provides a better, simpler, and more efficient framework to identify selection criteria, to calculate their weights, and for analysis. Therefore, the procedure allows judgments on intangible qualitative criteria to be incorporated into specific quantitative criteria. Once the hierarchy is established, experts and participants use AHP to prioritise all their nodes and this is processed mathematically. In AHP, multiple pair comparisons are based on a standardised nine-level comparison scale (Table 1). The nine points are chosen because psychologists conclude that nine objects are the most that an individual can simultaneously compare and classify. Pair trials are based on the best information available and on the knowledge and experience of the decision maker.

The data used for the study area map comprise of topographical and geological shapefiles from the Survey and Mapping Division Department of the Lands Commission of Ghana and Ghana Geological Survey Department, respectively. Remote sensing data from United States Geological Survey (USGS) website was used to develop elevation and drainage models. Landuse map was developed using google maps and rainfall data obtained from the Ghana Meteorological Agency.

2.1 AHP as a Multi-Criteria Decision Analysis Tool

The AHP process can be summarised in four stages: structure of the decision hierarchy; determine the relative importance of the attributes and sub-attributes; evaluate each alternative and calculate their total weight in relation to each attribute and check the consistency of the subjective evaluations (Schoenherr *et al.,* 2008). In the first step, the decision is broken down into its independent elements and presented in a hierarchical diagram which must have at least three levels (objective, attributes and alternatives). Second, the user is asked to subjectively assess the attribute pairs on a nine-point scale. In the third step, a weight is calculated for each attribute (and sub-attribute) based on pairwise comparisons. Since the assessments are subjectively submitted by the user, the logical consistency of these assessments is checked in the last step. The result of the AHP is a relative score for each decision alternative that can be used in the subsequent decision process. AHP has been used successfully in various fields and disciplines (Ouma and Tateishi, 2014; Ishizaka and Labib, 2011).

The ability to process both qualitative and quantitative data makes AHP an ideal method for certain prioritisation problems when different criteria are considered. The result of the pairwise comparison on *n* criteria can be summarized in an (*n* _ *n*) evaluation matrix *A* in which every element a_{kl} (*k*, *l* = 1, 2... *n*) is the quotient of weights of the criteria, as given in Equation (1).

$$A = \begin{pmatrix} a_{11} & a_{12} & a_{1n} \\ a_{21} & a_{22} & a_{2n} \\ a_{31} & a_{32} & a_{3n} \end{pmatrix}, a_{kk} = 1, a_{lk} = \frac{1}{a_{kl}}, a_{kl} \neq 0 \qquad (1)$$

The fundamental scale of absolute number for the pairwise comparisons in AHP ranges from 1 to 9 (Saaty, 1977). The scale 1 is of equal importance whilst 3, 5, 7 and 9 are of moderate, strong, demonstrated, and extreme importance respectively as shown in Table 1.

At the last step of AHP, the mathematical process commences to normalise and find the relative weights for each matrix. The relative weights are given by the right eigenvector (*w*) corresponding to the largest eigenvalue (λmax) as in Equation (2). Ouma and Tateishi (2014) states that the quality of the output of the AHP is strictly related to the

$$Aw = \lambda_{\max} w \qquad (2)$$

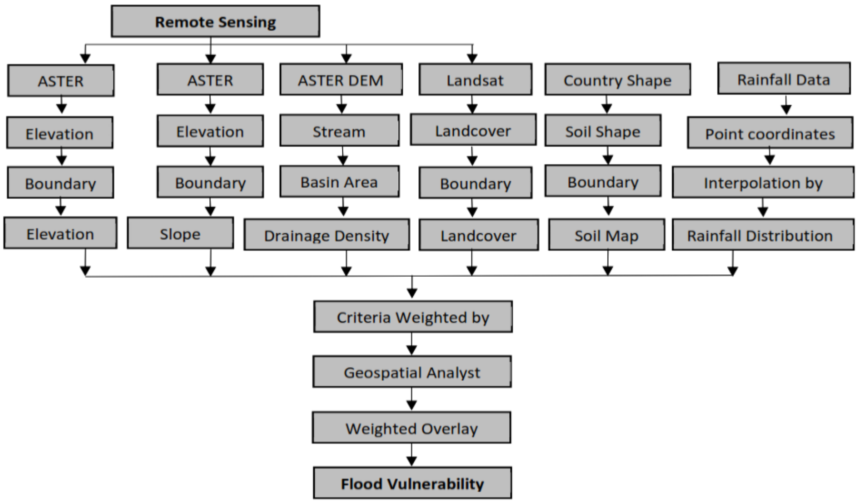

Fig. 3 Flow Charts of Methods Used

consistency of the pairwise comparison judgments. The consistency is defined by the relation between the entries of *A*. The consistency index *CI* is given below in Equation (3):

$$CI = \frac{(\lambda_{\max} - n)}{(n-1)} \quad (3)$$

The final consistency ratio (*CR*), usage of which lets the user to conclude whether the evaluations are sufficiently consistent, it is calculated as the ratio of the *CI* and the random index (*RI*), as expressed in Equation (4) (Saaty, 1977). The maximum threshold of CI is ≤0.1 and CR ≤10%; the rational value is when the CI and CR have fulfilled the maximum threshold value.

$$CR = \frac{CI}{RI} \quad (4)$$

2.2 AHP-GIS Implementation Strategy in Urban Flood Vulnerability Mapping

Based on the decision maker's preferences, three risk classes were used for classification with each criterion considered. To generate criteria values for each assessment unit, each factor was weighted based on the estimated importance for the occurrence of floods. The reverse order has been applied to some of these factors, with weights 1 the least important and 5 the most important. For the different criteria maps to be comparable, standardisation of raw data is generally required (Ouma and Tateishi, 2014). The resultant comparison is transferred into an AHP excel sheet to determine the weighted averages for the overlaying of the maps to develop the flood hazard map. The six maps used lead to 15 pairwise comparisons as shown in Equation (5).

$$\text{Number of Comparison} = \frac{n(n-1)}{2}; n = 6 \quad (5)$$

Once the weight in each factor is determined, the multi-criteria analysis is performed to produce a flood-vulnerable area using ArcGIS. To compute the vulnerable area, a weight linear combination was applied in ArcMap 10.4 to produce the Vulnerability Index (VI) using the Equation (6). Figure 3 gives a schematic diagram of all the processes to go through to obtain a flood vulnerability map combining five criteria.

$$\begin{aligned} VI = & (\text{Rainfall weight} * R) + (\text{Soil weight} * S_o) + \\ & (\text{Slope weight} * S) + (\text{Drainage density weight} * D) + \\ & (\text{Landcover weight} * LC) + (\text{Elevation weight} * E) \end{aligned} \quad (6)$$

3 Results

The classification and prioritisation process are the main objective of decision making based on several AHP criteria. The quality of the prioritisation has a direct impact on the efficiency of the resources available, which in most cases is the judgement of the decision maker. The results of the pairwise comparison and ranking of the criterion are presented in Table 3. Table 4 shows the normalised matrix converted to percent contributions, from which the average priority vector is derived.

Table 2 Weighted Comparison

		l					
		Rainfall	Drainage	Elevation	Slope	Soil	Land-use
k	Rainfall	1	5	2	3	7	2
	Drainage	0.2	1	0.5	0.33	0.25	3
	Elevation	0.5	2	1	0.5	0.25	0.5
	Slope	0.33	3	2	1	0.25	0.5
	Soil	0.14	4	4	4	1	3
	Land-use	0.5	0.33	2	2	0.33	1

Table 3 Weighted Flood Hazard Factors

	Rainfall	**Drainage**	**Elevation**	**Slope**	**Soil**	**Land-use**	**Criteria Weight**
Rainfall	0.37	0.33	0.17	0.28	0.77	0.20	0.35
Drainage	0.07	0.07	0.04	0.03	0.03	0.30	0.09
Elevation	0.19	0.13	0.09	0.05	0.03	0.05	0.09
Slope	0.12	0.20	0.17	0.09	0.03	0.05	0.11
Soil	0.05	0.26	0.35	0.37	0.11	0.30	0.24
Land-use	0.19	0.02	0.17	0.18	0.04	0.10	0.12

Table 4 Consistency Ratio Results

Weighted Sum Value (WSV)	**Criteria Weight (CW)**	**WSV/CW**
2.995	0.354	8.470
0.302	0.090	3.344
0.561	0.088	6.373
0.735	0.111	6.646
1.446	0.240	6.021
0.684	0.117	5.833
λmax	6.115	
CI	0.023	
CR	0.018	

From the percentages, rainfall is the highest contributor to flooding. It also depicts the contribution of each map to the flood risk map. The normalised values for the pairwise comparison produced weighted averages which were used to overlay the produced maps. The CR is designed in such a way that if CR < 10%, the ratio indicates a reasonable level of consistency in the pairwise comparison. Since the CR is less than 10%, the ratio shows a reasonable consistency in this analysis, and implies that the determined weights for the generation of the vulnerability maps are acceptable.

3.2 Weighting and Ranking of the Model Input Factors

A summary of the flood causative factors or variables development showing the various factors, their respective weights and how they are ranked according to their influence on flood events in the study area is presented in Tables 2 to 4. In the weight and ranking calculation step, the pairwise comparison matrix and the various maps are used.

The use of a weighted linear combination implies that the weights sum to 1.

3.3 Ranking of Flood Mapping Criteria

3.3.1 Elevation Map

The resultant elevation map for the study area is developed as shown in Fig. 4. It can be identified that the study area lies in a region of fair elevation distribution as majority of elevations lies between 61m to 551m. The surrounding environment has higher elevations suggesting that the area is mountainous. This means that the higher surrounding elevation will have it runoff gathering in the lower elevation regions hence increasing flooding potential.

Table 5 AHP Parameters Constructed from the Datasets

Parameters	Weight	Weight (%)	Decision Sub-factors	Reclass/Ranking
Elevation (m)	0.087983471	9%	61-152	5
			152-188	4
			188-255	3
			255-354	2
			354-551	1
Slope (%)	0.110658501	11%	0-8	5
			8.0 -15	4
			15.0 - 28	3
			28.0 - 47	2
			47.0 -100	1
Drainage Density (pixel)	0.090286819	9%	2.23 - 2.77	5
			1.67 - 2.22	4
			1.12 - 1.66	3
			0.556 - 1.11	2
			0 - 0.555	1
Landuse	0.117299591	12%	Settlement	4
			Mixed Vegetation/Farmland	2
			Vegetation	1
Monthly Precipitation	0.35353846	35%	231 - 236	5
			227 - 230	4
			223 - 226	3
			220 - 222	2
			216 - 219	1
Soil	0.240233158	24%	Lixisols	5
			Luvisols	4
			Arenosols	3
			Leptosols	2
			Fluvisols	1

3.3.2 Slope Map

The slope affects the direction and amount of surface runoff or underground drainage that reaches a location. The slope has a dominant influence on the contribution to precipitation to stream flow. The combination of slope angles essentially defines the shape of the slope and its relationship to lithology, structure, soil type and drainage. A flat surface that allows the water to flow quickly is a disadvantage and causes flooding while a higher surface roughness can slow down the flood response.

The slope map developed is shown in Fig. 4. It is observed that Nkurakan, Asokore, Koforidua Ada, Koforidua, Nyerede and Okorase are lying in a lower steep region. The surrounding environment has steeper slopes indicating that run off will accumulate in the lower steep regions and hence having a higher vulnerability to flood.

3.3.3 Land Cover Map

Ouma and Tateishi (2014) in their report pointed out that the land cover and its use management are the main concerns in the mapping of flood risks. In fact, it is a factor that reflects not only the current land use, model and type of use, but also the importance of its use in relation to soil stability and infiltration. Soil cover, as well as the vegetation cover of soils, whether they are permanent meadows or the cover of other crops, has a significant impact on the capacity of the soil to act as a water reservoir. Rainwater runoff is much more likely in bare fields than in those with good vegetation cover. The presence of thick groundcover slows the path of precipitation to the ground and reduces the amount of runoff. Likely, impermeable concrete hardly absorb water which most likely contribute to flooding.

The resultant land cover map is shown by Fig. 5. The study area is highly urbanised and enveloped by vegetation. The crowded nature of the study area makes it vulnerable to floods.

3.3.4 Drainage Density

Drainage density map was developed with the aim of determining the drainage density. After the geometry calculation the drainage density was determined to be 1.1 signifying that the drainage density is low. A lower drainage density will imply that drainage contributes little to flooding events in the study area (Fig. 5).

The resultant map shows that rainfall is channelled through the path designated by the stream network which will make it more susceptible to flooding should the stream network overflow its boundary.

3.3.5 Rainfall Distribution Map

Floods are most common due to heavy rainfall when natural rivers and streams are unable to carry excess water. Also, water that cannot penetrate the ground immediately at heavy downpour flows down slope as runoff. The amount of runoff depends on the amount of rain in a region.

The water level in rivers, streams or lakes rises due to heavy rainfall. When the water level rises above riverbanks or dams, the water begins to overflow, causing the river to flood. Water overflows into areas next to rivers, streams, lakes or dams and causes floods.

It was observed that rainfall amounts on the upstream catchments contribute to flood hazard and risk caused by the rivers and some streams. Therefore, much consideration was given to rainfall during the integration in the analysis. A mean monthly rainfall for thirty years (1982–2012) was considered and interpolated using Kriging method of interpolation to create a continuous raster rainfall data within and around the study area. The resulting raster layer was finally reclassified into the five classes using an equal interval. The reclassified rainfall was given a value 1 for least rainfall to 5 for highest rainfall. Figure 6 shows the results of the raster rainfall layer kriging interpolated data layer and the reclassified rainfall data.

3.3.6 Soil Map

Soil texture and moisture are the most important components and properties of soils. Soil textures have a major impact on flooding, as sandy soil absorbs water at an early stage and only drains off little. In contrast, clay soils are less porous and retain water longer than sandy soils. This means that areas with clay soils are more affected by flooding. Soil moisture increases when there is enough rain to overcome losses to streams and groundwater and is important for soil erosion, slope stability, plant growth and crops. Nicholls and Wong (1990) highlighted in their report that, the soil types in an area are important because they control the amount of water that can enter the soil, and therefore the amount of water that becomes runoff.

The boundary layer clipped unto the soil shape file of Ghana produces the soil map of the study area. It is observed that Asokore, Koforidua Ada and Koforidua are luvisol. Luvisol are characterised by a surface accumulation of humus overlying an extensively leached layer that is nearly devoid of clay and iron bearing minerals. The infiltration rate at these areas are good. Nyerede is found in leptosol environment. Leptosol are soils with very shallow profile depth and they contain large amount of gravel. They typically remain under vegetation and are susceptible to erosion and waterlogging. This indicate that water can easily accumulate in Nyerede area. Okorase is characterised by the lixisol soil (Fig. 6). Generally, it can be concluded that the soil has little influence on flooding event in the study area.

3.3.7 Flood Risk Map

Once the weights for the factors were determined, a multi-criteria evaluation was performed by utilising the specific weights for each factor, the factors themselves, and the constraint maps for each factor to produce the flood vulnerability map. The various maps in their raster format were reclassified using the reclassify tool in the spatial analyst tool according to their respective ranking values (Table 5). The six maps developed were overlaid to produce the flood risk map in ArcGIS. The resulting flood Vulnerability and risk map was generated as shown in Fig. 7. Asokore and North-western (NW) part of Koforidua are found in high flood risk zones (20% of area). Other areas of Koforidua, Okorase and Koforidua Ada are in a

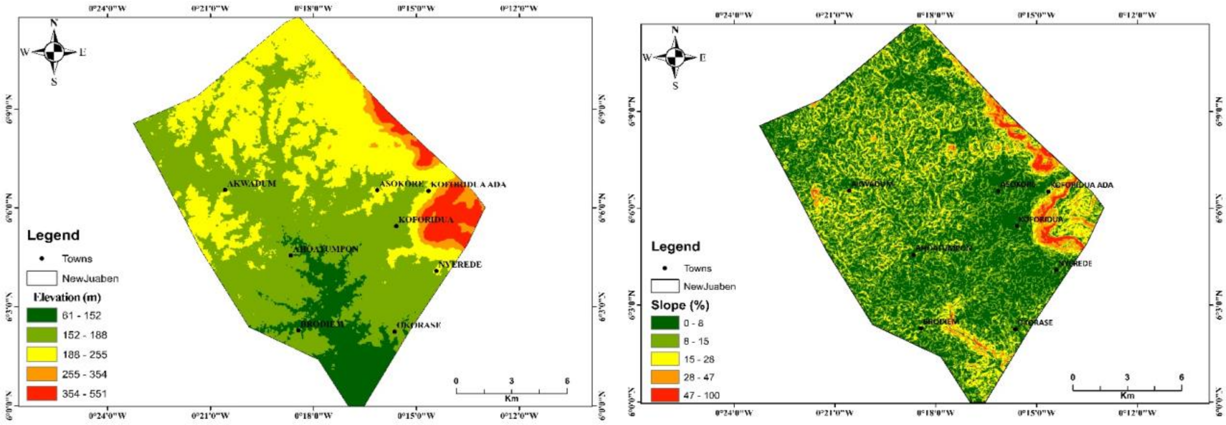

Fig 4 Elevation Map and Slope Map of the Study Area

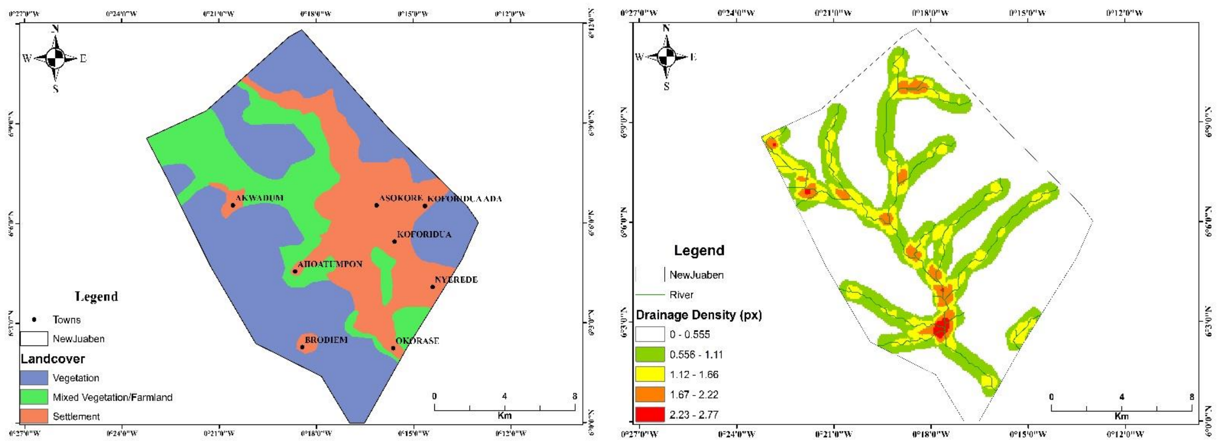

Fig. 5 Land Cover and Drainage Density Map of the Study Area

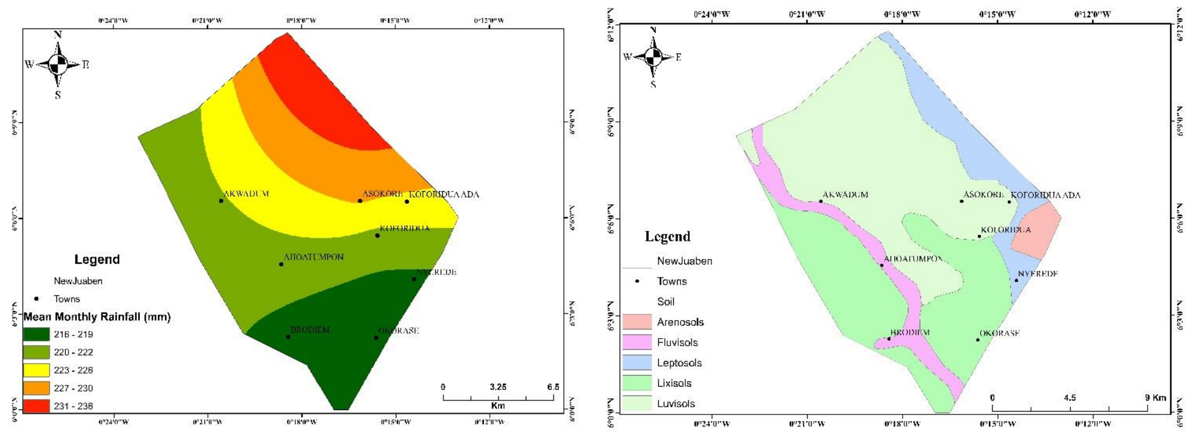

Fig. 6 Rainfall Distribution and Soil Map of the Study Area

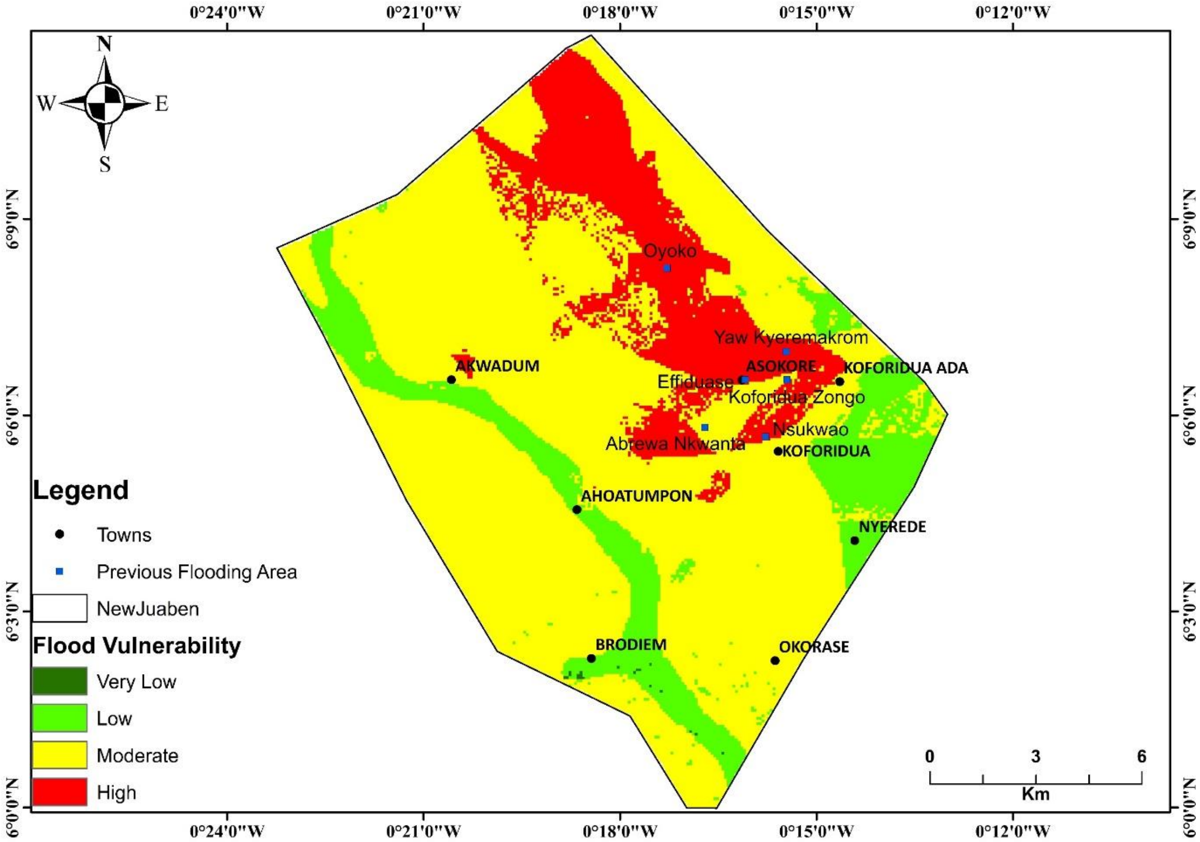

Fig. 7 Flood Vulnerability Map of the Koforidua Area

moderate-risk flood zone (60% of area). Low flood risk areas constitute about 20% of the study areas and includes towns such as Nyerede and Okorase.

4 Conclusions and Recommendations

4.1 Conclusions

The study confirms that using a remote-controlled ASTER DEM and GIS approach to create hydrological and topographic maps is effective. The drainage network in the region has dendritic patterns and has a moderate drainage density. The watershed and watershed map are very useful for planning the use of rainwater and watershed management.

Asokore and NW part of Koforidua are in an area at high risk of flooding. Other parts of Koforidua, Koforidua Ada, and Okorase also have a moderate risk to flooding. Low flood risk areas include towns such as Nyerede and Okorase. Parameters that control flooding were precipitation, altitude, land cover, hillsides, drainage, and soil type. A high precipitation in a short time can lead to flooding especially with negative landcover changes, increase in urbanization and lack of adequate drainage channels. Areas of previous flooding mapped was within the high to moderate flood vulnerability zones in Figure 7. The consistency ratio of 0.018 is acceptable.

This study has shown that AHP and GIS technology provides an efficient and cost-effective tool for flood parameter geospatial data analysis. This generated data is an excellent tool for water resource management, disaster management and urban planning.

4.2 Recommendations

It is recommended that land cover changes are monitored, to curb activities that deplete green zones. Drainage channels should be desilted regularly to accommodate increase in precipitation. High flood prone areas should have building codes that can withstand flooding. Enforcement of policies that prevent the development of unsuitable structures within flood plains.

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