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An Analytical Hierarchy Process (AHP) and GIS-Based Flood Vulnerability Index and Map for the Tamale Metropolis, Ghana

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Research Article

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Abstract

Defensible, replicable spatial targeting of flood-risk interventions demands a robust, replicable understanding of where flood vulnerability is concentrated, especially where there is limited data and in urban areas throughout sub-Saharan Africa. In this study, the Analytical Hierarchy Process (AHP) and Geographic Information System (GIS) weighted overlay method has been used to develop a Flood Vulnerability Index (FVI) for Tamale Metropolis, Ghana. Nine flood-conditioning factors were compared pairwise using Saaty's nine-point scale based on expert judgement and published literature on flood risk and subsequently combined using the weighted overlay after mapping each spatial layer on a common vulnerability scale of 1–5. Land use/land cover (LULC) and the topographic wetness index (TWI) were the most important flood-conditioning factors (30.46% and 25.65%, respectively), followed by rainfall, drainage density, distance to stream, flow accumulation, elevation, and soil, with slope contributing the least (10.72%). The consistency ratio for the first principal eigenvalue ($\lambda max = 10.81$) was lower than 0.10 Saaty's consistency criterion, which shows that the pairwise judgements were internally consistent. The composite vulnerability map identified 14.41 km² as highly vulnerable, 227.56 km² as moderately vulnerable, 64.02 km² as of low vulnerability and 309.58 km² as of very low or no vulnerability in the metropolis. High vulnerability areas were mainly in the urban built-up areas of the poor road network, Gumani, Gumbihini, Kanvili Tuunaayili, Wurishe, Koblimahigu and Fuo. The mapping of high vulnerability zones correlated well with the areas which have a history of flooding, as revealed during validation with historical flood occurrence data and expert consultation which revealed zones including Tamale Central, Gumbihini, Kakpayili, Vittin and Lamashegu. The findings presented in this report highlight the potential of AHP-GIS integration in providing a powerful tool for selecting priority areas for flood-risk interventions in the Tamale Metropolis and other fast-urbanising cities in West Africa.

1. Introduction

Flood Vulnerability Mapping is a spatially explicit tool that helps decision makers prioritise scarce disaster-risk-reduction resources, but when resources are limited, there is a need to find ways to transform expert and literature-guided judgment into defensible quantitative factor weights (Radwan, Alazba & Mossad, 2019). To meet this need, Saaty (1982) developed the Analytical Hierarchy Process (AHP). AHP organizes complex decisions into pairwise comparisons between the criteria, and uses eigenvector analysis to calculate the relative weights of the criteria and to check for internal consistency. In addition to the mentioned benefits, AHP can incorporate other spatial dimensions, such as rainfall, topography, soils, land cover and drainage properties, through a weighted overlay analysis by Geographic Information System (GIS), which results in a composite vulnerability surface (Zghibi et al., 2020; Castillo, Güneralp, Hales & Güneralp 2020).

This integration of AHP-GIS has been successfully implemented in flood vulnerability/risk mapping in different arid, semi-arid and tropical environments with land cover, topographic wetness and drainage characteristics as key factors in determining flood risk, with the relative importance of these factors varying according to local physiography and land-use context (Radwan et al., 2019; Mishra & Sinha, 2020). In fast-growing urban settlements in West Africa where there are few formal hydrological monitoring stations with sufficient historical records, the integration of AHP and GIS can prove to be a valuable pathway to develop a vulnerability model without the need of a large amount of calibration data (Kasei et al., 2019).

Although the method has proven to be useful in other regions, a validated AHP-weighted GIS-based flood vulnerability mapping has not yet been created for the Tamale Metropolis. This study fills that gap by creating such a map, determining the relative weight of the nine flood-conditioning factors, and outlining the flood vulnerability zones of the metropolis while testing it against historical flood-occurrence data to establish it as an evidence-based tool for targeting flood-risk interventions by local authorities.

2. Materials and Methods

2.1 Study Area

The Tamale Metropolis is situated in the Central part of Northern Region of Ghana, bounded by Latitude 9°16' to 9°34' North and Longitude 0°36' to 0°57' West (Ghana Statistical Service [GSS], 2022). The metropolis is mainly flat to gently rolling with elevations between ~ 100m and 200m, and has a distinct rainy season where most flood events take place.

The selection and weighting of flood-conditioning factors will be assessed in relation to the following:

Based on the flood literature and data available for the study area, nine factors were used for flood conditioning: rainfall, topographic wetness index (TWI), slope, drainage density, land use/land cover (LULC), distance to stream, soil, elevation, and flow accumulation. The factors were all produced in ArcGIS using a mix of remotely sensed imagery, digital elevation model, and secondary spatial data, and were reclassified to an ordinal scale from 1 (lowest contribution to vulnerability) to 5 (highest contribution to vulnerability).

After consulting the literature and experts, Saaty's nine-point scale was used to create a pairwise comparison matrix (X) between the nine factors (Castillo et al., 2020; Zghibi et al., 2020). Each entry in this matrix was divided by the column sum and the matrix obtained was denoted as Y. Each row of this matrix was averaged to give principal eigenvector which indicates the relative weight of each factor. The principal eigenvalue (λmax) was calculated from the relationship YW = λmax W and the consistency index (CI) was calculated as CI = (λmax − n) / (n − 1) with n = 9 and RI = Saaty's random index (1.45 for n = 9). As per convention, a CR value of less than 0.10 was deemed as acceptable level of consistency in pairwise judgements, and a value above this would require revision of the weights that would be derived.

2.2 Methods

Expert and resident judgements were collected with the approval of the UDS Graduate School Thesis Review Committee and all participants gave informed consent before taking part.

2.3 Weighted Overlay and Map Validation

The reclassified spatial layers were then weighted overlied in ArcGIS and a composite flood vulnerability surface was derived, which was then classified into four classes of flood vulnerability using natural breaks: very low/no vulnerability, low vulnerability, moderate vulnerability and high vulnerability. The map was validated by comparing the number of recorded flood incidences in the metropolis within each vulnerability class within the map, and upon discussions with experts in the field of disaster management.

3. Results and Discussion

3.1 AHP-Weighted Flood-Conditioning Factors

Land use/land cover and topographic wetness index stood out as the two most influential factors of flood risk in the Tamale Metropolis with their combined weight of over half the total weight for the 9 factors (Table 1). Distance to stream (6.94%), flow accumulation (4.87%), elevation (3.69%) and soil (2.74%) and slope (2.67%) added relatively small amounts of weight. This weighting pattern reflects the physical nature of a low-relief urban context where both the type and the amount of impervious surfaces in the landscape, along with the ability of the land to hold water, have a more pronounced influence on flood outcomes than does slope gradient or soil type (Klemas, 2015; Ružičić et al., 2019).

When the following conditions occur, the Flood-Conditioning Factors are reclassified:

The reclassification scale applied to each spatial layer is shown, as well as the area covered by each class, in Table 3. The factor with the greatest AHP weight (land use/land cover) was assigned the highest vulnerability scale values and the lowest the developed/urban land, which was assigned the lowest vulnerability scale values, as vegetated and water-retentive surfaces help to absorb and slow down the run-off of water compared to impervious cover (Ward et al., 2020). As in the physical sense, the second most influential factor for the topographic wetness index was very-low-TWI zones, for which the highest vulnerability score was assigned reflecting the physical logic that the areas of low TWI in this context correspond to the extensive low-lying poorly drained terrain that dominates the metropolis and is most susceptible to water accumulation.

Table 1
Pairwise comparison matrix of flood-conditioning factors and normalized principal eigenvector (AHP weights)

Factor	**Rainfall**	**TWI**	**Slope**	**Drainage Density**	**LULC**	**Distance to Stream**	**Soil**	**Elevation**	**Flow Accum.**	**AHP Weight (%)**
Rainfall	1	1/5	2	4	1/6	3	3	4	2	12.28
TWI	5	1	7	3	1	4	4	5	7	25.65
Slope	1/2	1/7	1	1/6	1/9	1/3	1	1/2	1/2	2.67
Drainage Density	1/4	1/3	6	1	1/3	3	4	5	2	10.72
LULC	6	1	9	3	1	5	7	8	8	30.46
Distance to Stream	1/3	1/4	3	1/3	1/5	1	3	2	4	6.94
Soil	1/3	1/4	1	1/4	1/7	1/3	1	1/3	1/4	2.74
Elevation	1/4	1/5	2	1/5	1/8	1/2	3	1	1/2	3.69
Flow Accumulation	1/2	1/7	2	1/2	1/8	1/4	4	2	1	4.87

Source: Expert and resident interviews and literature review, 2023

Table 2 presents the estimation of the principal eigenvalue and the resulting consistency ratio. The principal eigenvalue (λmax) was 10.81, yielding a consistency index (CI) of 0.12 and a consistency ratio (CR) of 0.08. Because this value falls below Saaty's (1982) acceptable threshold of 0.10, the pairwise comparisons are considered internally consistent, and the derived weights suitable for use in the composite vulnerability model without requiring revision.

Table 2
Estimation of the principal eigenvalue and consistency ratio (CR)

Factor	Column Sum (Table 1)	Eigenvector	Weighted Sum
Rainfall	14.17	0.115	1.63
TWI	3.52	0.220	0.77
Slope	33.00	0.025	0.83
Drainage Density	12.45	0.131	1.63
LULC	3.204	0.286	0.92
Distance to Stream	17.45	0.084	1.47
Soil	30.00	0.023	0.69
Elevation	27.83	0.046	1.28
Flow Accumulation	25.25	0.063	1.59
Principal Eigenvalue (λmax)			10.81
Consistency Index (CI)			0.12
Consistency Ratio (CR)			0.08
Source: Expert and resident interviews and literature review, 2023			

3.2 Reclassification of Flood-Conditioning Factors

Table 3 presents the reclassification scale applied to each spatial layer, together with the area occupied by each class. For land use/land cover, the factor carrying the greatest AHP weight, vegetation and water bodies were assigned the highest vulnerability scale values and developed/urban land the lowest, reflecting the protective role of vegetated and water-retentive surfaces in absorbing and slowing runoff relative to impervious cover (Ward et al., 2020). For the topographic wetness index, the second most influential factor, very-low-TWI zones were assigned the highest vulnerability score, consistent with the physical logic that areas of low TWI in this context correspond to the extensive low-lying, poorly drained terrain that dominates the metropolis and is most prone to water accumulation.

Table 3
AHP-weighted flood-conditioning factors with corresponding reclassification scale

Map Layer	Classification	Area (km²)	AHP Weight (%)	Scale (1–5)
Soil	Ferric Luvisols	162.65	2.74	1
	Plinthic Luvisols	406.00		2
Slope (%)	0–2	163.48	2.67	1
	2–3	206.80		2
	3–4	158.80		3
	4–5	75.70		4
	> 5	17.20		5
Topographic Wetness Index	Very Low	203.75	25.65	5
	Low	254.68		4
	Medium	127.15		3
	High	32.80		2
	Very High	5.05		1
Drainage Density (km/km²)	Very High	125.398	10.72	4
	High	126.544		3
	Medium	92.300		3
	Low	204.920		2
	Very Low	227.360		1
Elevation	Very Low	130.17	3.69	1
	Low	184.45		2
	Medium	160.03		3
	High	103.29		4
	Very High	42.94		5
Land Use / Land Cover	Water Bodies	29.98	30.46	5
	Developed/Urban	136.45		1
	Bare Land	251.07		3
	Vegetation	135.88		5
	Agric/Cultivated	52.89		4
Flow Accumulation	Land	611.73	4.87	3
	Stream	10.228		1

Rainfall and distance-to-stream classes (weights 12.28% and 6.94% respectively) followed an equivalent five-class scale (Very High to Very Low / Very Low to Very High) but are omitted here for brevity.

Source

Expert and resident interviews and literature review, 2023

3.3 Composite Flood Vulnerability Map

A composite flood vulnerability map was created by assigning weights to all the nine reclassified factors and overlaying them as shown in Fig. 1. The Tamale Metropolis was divided into four flood vulnerability zones to illustrate the composite map. This is the high-vulnerability classification of 14.41 km² or about 2.3 per cent of the metropolis, which is mostly occupied by bare-soil and urban built-up land use, very high population density, and very low provision of the infrastructure road network in the Gumani, Gumbihini, Kanvili Tuunaayili, Wurishe, Koblimahigu and Fuo localities. The moderate vulnerability class covers an area of 227.56 km2 (36.1%) spread across Sogunayili, Gbalo and Jisonayili. The remainder of the metropolis (10.1% and 49.0% respectively) is covered by low vulnerability and very-low/no-vulnerability classes, respectively, due to more favourable geographic and environmental conditions, especially in the areas with higher vegetative cover and better natural drainage.

The issue of high vulnerability within certain built up communities instead of it being spread uniformly over the metropolis is in line with the previous observation that indiscriminate dumping of refuse materials into drains and water bodies, building in environmentally sensitive areas and the release of water from dams upstream combine with the lack of the systematic forecasting and planning of evacuations to increase flood vulnerability in these particular areas (Kasei, Kalanda-Joshua & Benefor, 2019). It has the analytical value that it shows that a significant amount of risk reduction can be achieved in a large part of the Tamale Metropolis from a smaller portion of the metropolis' total land area, as opposed to having to invest metropolis-wide.

3.4 Validation of the Flood Vulnerability Map

The vulnerability map was checked using historical records of flood occurrence and expert consultation (Fig. 2), where there was good correlation between the mapped high vulnerability areas and the areas where floods have been recorded, such as Tamale Central, Gumbihini, Kakpayili, Vittin, and Lamashegu. The areas that were classified as moderately vulnerable marked about 6 historical flood events on average, and the areas of low vulnerability marked only 1, reflecting a gradient expected to be in accordance with the map's classification scheme, and thus giving confidence to the map's predictive validity. The pattern is similar to vulnerability distributions in other cities in Ghana, such as Accra, Kumasi and Sekondi-Takoradi, where flood risk is also higher in low-lying and heavily built up areas with limited drainage capacity.

This correspondence between the AHP-GIS model and independent historical flood records offers an important, mostly data-light form of validation for the approach, and ensures the reliability of the AHP-GIS approach as a tool to identify priority zones for flood-risk intervention in the Tamale Metropolis and in similar data-limited urban contexts throughout West Africa where comprehensive hydrological monitoring networks are lacking.

4. Conclusion

This study aimed at developing and validating an AHP weighted GIS-based Flood Vulnerability Index and map of the Tamale Metropolis. Land use/land cover and the topographic wetness index were identified as the important flood-conditioning factors as they comprised over half of the total weight of all factors and their consistency ratio was 0.08, indicating good internal consistency of the pairwise comparisons on which the model was based. The resulting vulnerability map highlighted 14.41 km² in the metropolis to be highly vulnerable, mostly in specific urban built-up communities, which are poorly equipped with road infrastructure, such as Gumani, Gumbihini, Kanvili Tuunaayili,

Wurishe, Koblimahigu and Fuo, while the areas found to be highly vulnerable matched well with historical flood records. The results provide the basis for prioritized investments in the Tamale Metropolis for flood hazard, with a focus on specific areas of high vulnerability depicted by the model, as well as land-use and land-cover management responses to the main physical contributors to vulnerability identified in the analysis. The approach developed and validated here using the AHP-GIS is replicable and defensible for other Metropolitan & Municipal Assemblies in Ghana and other cities in the West African data-poor region in need of flood-risk investment priorities.

5. Recommendations

The following recommendations are made on the basis of the results of the present study to facilitate effective flood-risk management and spatial planning in the Tamale Metropolis:

First, it is suggested that the interventions for flood-risk reduction should be geographically prioritized to those areas considered to be highly vulnerable by the AHP-GIS model. It is important to consider vulnerable communities like Gumani, Gumbihini, Kanvili Tuunaayili, Wurishe, Koblimahigu and Fuo, which showed relatively high flood vulnerability. The Tamale Metropolitan Assembly and other relevant actors should draw on the vulnerability map as a planning-support tool for prioritising the drainage improvement, maintenance of existing drainage infrastructure, management of stormwater associated with roads, and other suitable flood-risk reduction measures.

Secondly, land-use and land-cover management in flood-prone regions must be improved. Consideration should be given to changes in land use/land cover, particularly where this relates to land being built upon, and where land use may have an impact on the natural drainage and movement of surface water, as this has been given the highest weight during the AHP assessment. Spatial planning authorities should use flood-vulnerability information as a tool in their decision-making process when granting development permissions, when designing urban development and when extending urban expansion, thereby reducing development in flood-vulnerable areas.

Third, there should be an enhancement of stormwater drainage system in sensitive areas of the metropolis. The results show the critical role of topographic wetness, drainage and surface water accumulation in the determination of spatial variation in flood vulnerability. Existing drainage infrastructure should thus be part of the regular inspection, desilting and maintenance schedule for the metropolis and appropriate measures taken in identified vulnerable locations for stormwater management should be part of this programme.

Fourth, the AHP-GIS vulnerability map should be incorporated into the disaster-risk management and urban development planning process. The map can serve as a spatial basis to identify specific areas that need more attention, and can aid the Metropolitan Assembly, disaster-management organizations, planning bodies and others in making decisions to allocate scarce resources. As the land use, infrastructure, drainage, and other factors that affect the vulnerability of the community change, a vulnerability map should be updated periodically.

Fifth, enhance flood monitoring and local level data collection. Relevant institutions should create and continuously maintain records of flood events, damaged location, flood extent, infrastructure damage, and relevant indicators. This information would help to better validate and refine existing flood vulnerability models and inform the development of new ones. Greater coordination between the Metropolitan Assembly, the National Disaster Management Organisation (NADMO), planning authorities, researchers and communities would also ensure better gathering, management and use of information about floods.

Finally, the AHP-GIS framework developed in this study could be replicated in other municipalities in Ghana and West Africa that rapidly urbanising and have limited data resources. The factor weights and vulnerability thresholds should be reviewed and tested locally before using in other areas as the relative importance of the factors of flood-conditioning

may be different depending on local topography, land use, drainage characteristics, rainfall patterns, and settlement. Further research is needed to include more detailed historical flood data, more detailed spatial data and more socio-economic and hydrological data to further improve the accuracy of flood vulnerability assessment and increase the reliability of spatial flood-risk planning in the future.

Declarations

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Ethics approval and consent to participate

This study involved human participants, namely disaster-management experts and residents of the Tamale Metropolis, all of whom were adults aged 18 years and above. All experimental protocols were reviewed and approved by the University for Development Studies (UDS) Graduate School Thesis Review Committee, chaired by Professor Paul Kwame Nkegbe, which served as the institutional ethics review body for this study. Before this, the study protocol was reviewed and endorsed by the Department of Environment and Sustainability Sciences, UDS, through the Head of Department, Professor Ebenezer Owusu-Sekyere, in line with the UDS Graduate School Handbook, Guidelines and Regulations. All procedures involving human participants were carried out in accordance with the relevant institutional guidelines and regulations and with the ethical principles of the Declaration of Helsinki and its later amendments.

Consent to participate

Informed consent was obtained from all participants before data collection. Participants were told the purpose of the study, that their participation was voluntary and that they were free to withdraw at any time without any consequence. They were also assured that their responses would be treated confidentially and used for research purposes only.

Affiliation

This study forms part of the author's Doctor of Philosophy graduate research at the University for Development Studies, Ghana, where ethical review and approval were obtained. The author is currently affiliated with the Department of Architecture and Real Estate, Sunyani Technical University, Ghana.

Competing interest

The author declared that he has no competing interests.

Clinical Trial Number

Not applicable

Consent to Publish

Declaration: Not applicable

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Author Contribution

Justice Agyei Ampofo had the concepts of the study, developed the methodology, did the systematic literature search and review, analysed and synthesized the findings, and wrote the original draft. Justice Agyei Ampofo made the manuscript revisions and edited it, as well as reviewing and approving the final version and accepting responsibility for the content of the work.

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Data Availability

The datasets generated during the course of the study are included in this published article.

Code availability:

Not applicable

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Figures

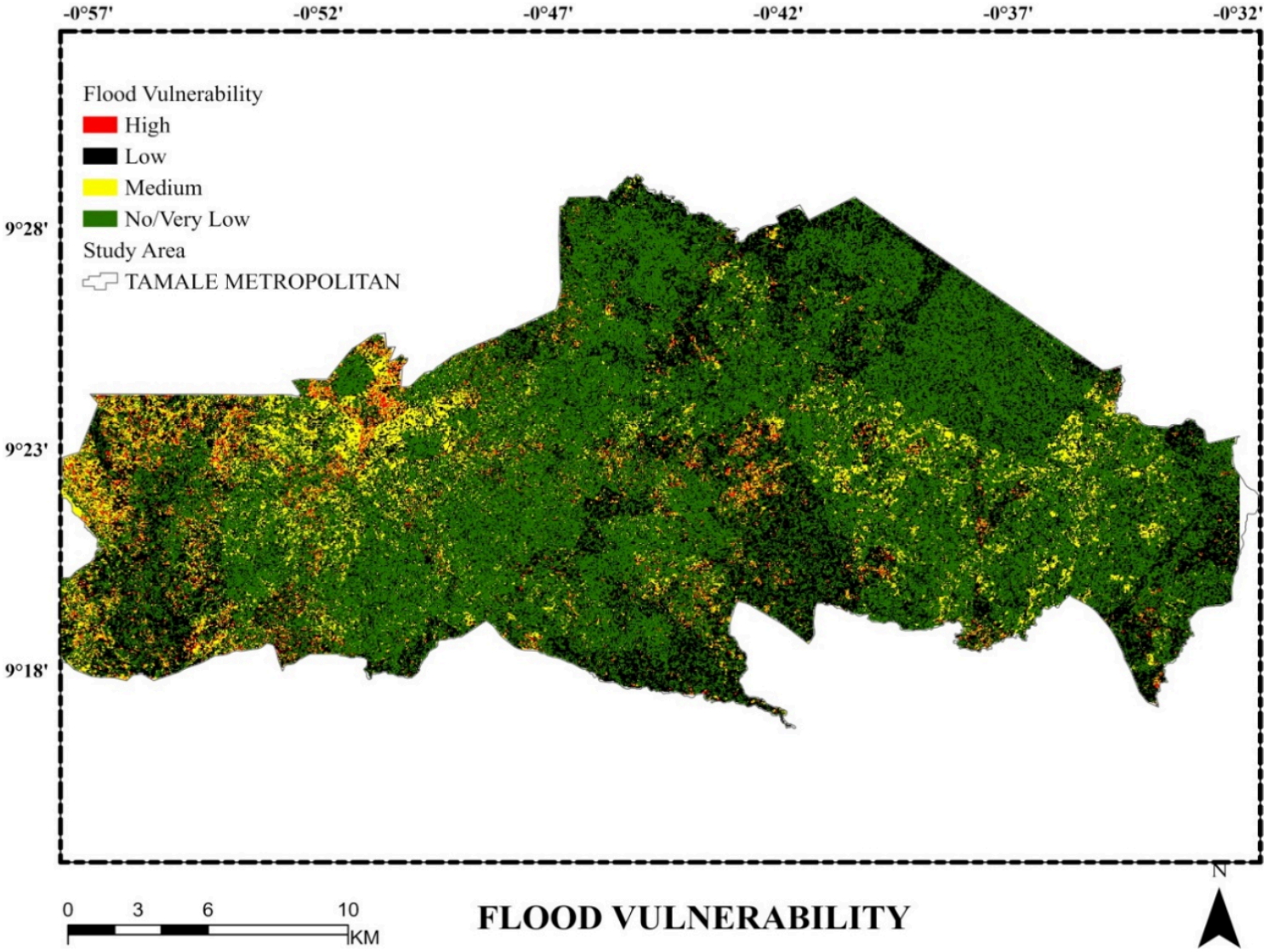

Figure 1

Composite flood vulnerability map of the Tamale Metropolis

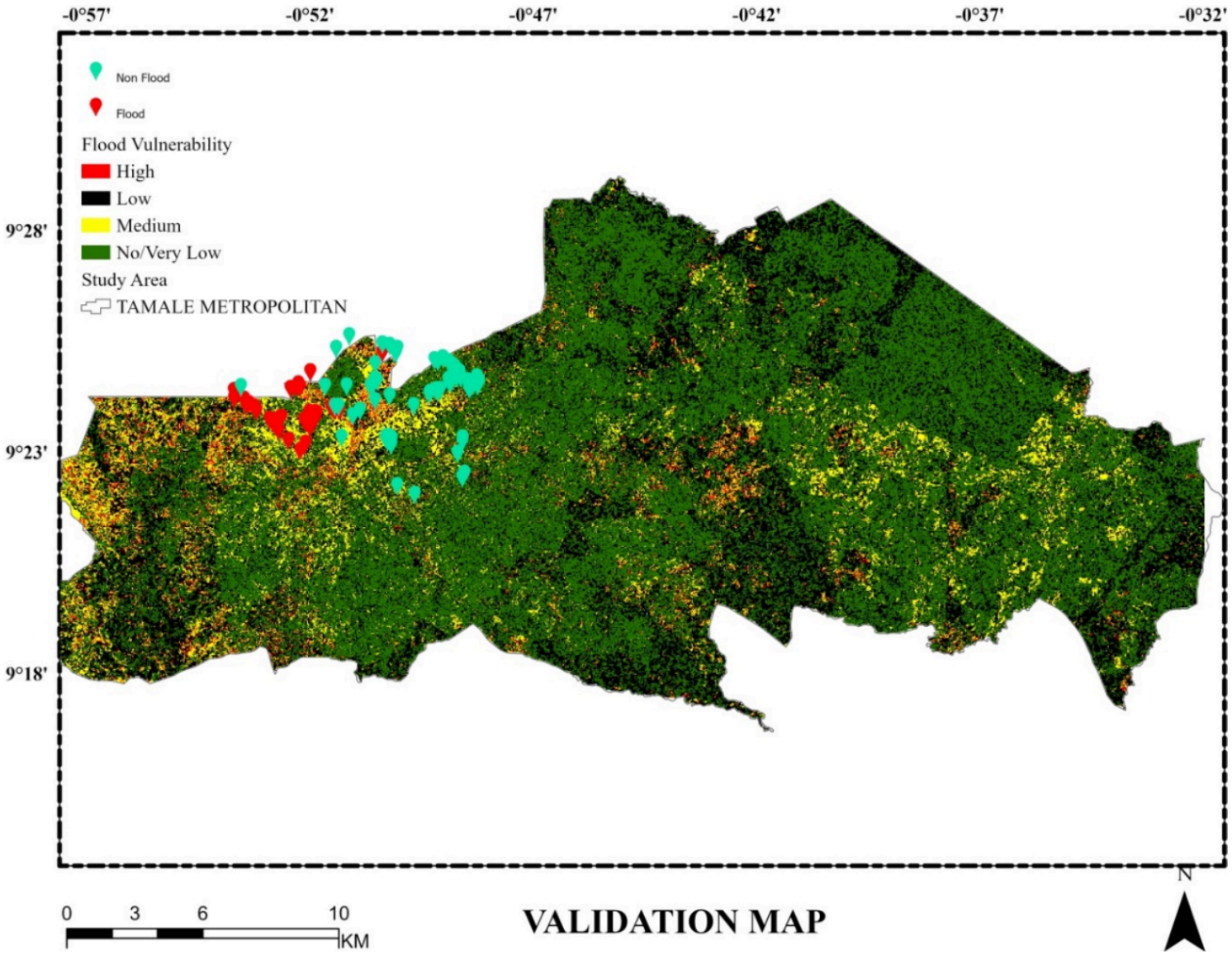

Figure 2

Validation map of flood vulnerability against historical flood occurrence in the Tamale Metropolis