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Tracing the Urbanisation Factors for Flash Flood Occurrences in Secondary Tanzanian Cities

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Abstract

The largest proportion of the world's urban development and new expansion is not a result of conscientious planning, which increases urban vulnerabilities to disaster risks. Accordingly, SDGs, including Goals 1, 11, and 13, concentrate on minimising vulnerability to disasters like floods and boosting resilience (Anwana & Owojori, 2023). Therefore, there is a need to study the linkages between different patterns of urbanisation and vulnerabilities of cities to climate change-induced disaster risks. This study traces the significance of different urbanisation parameters in contributing to flood disasters in urban sub-catchments in the seven Tanzanian secondary cities. The urbanisation indicators considered are those based on environmental conditions or physical locational qualities and those based on changes in anthropogenic factors. The findings demonstrate a strong correlation of flood occurrences with the fragility of the locations, as indicated by the steep slope and proximity of the built-up areas to a permanent water body. Other urbanisation factors for urban floods are continuous densification through residential land subdivision and a lack of proper stormwater management infrastructure. The findings indicate that regardless of whether the area is planned or unplanned, flood risk is primarily driven by settlement in fragile locations (steep slopes, proximity to water), increased impervious surfaces from densification, and inadequate infrastructure, rather than by changes in precipitation.

Keywords

Resilience, Tanzania, Floods, Urban Sub-Catchment, Urban Green

1. Introduction

The mark of African urbanization reaching fifty per cent of its population is coming with a necessity that the current spatial development patterns, infrastructure development, formal planning, and waste management will need drastic improvements (Henderson et al., 2017; Douglas et al., 2008; Dodman et al., 2017). Among the frequently associated impacts of unsustainable African urbanisation has been the number, frequency, and impacts of flood disaster risks, which are partly contributed to by anthropogenic activities (Douglas et al., 2008; Schipper & Langston, 2015; Borja, 2013; Agbola et al., 2012; EM-DAT, 2015). The urban vulnerabilities are exacerbated by poor socio-economic and environmental conditions (Awuor et al., 2008; UN-HABITAT, 2010).

Planning is an important activity in managing the growth of cities, and it reduces vulnerability to disaster risks, most of which are related to climate change (Meerow & Woodruff, 2020; Alem & Namangaya, 2021). Despite the importance of urban planning, the largest proportion of the world's urban development is not a result of conscientious planning (Angel et al., 2005). Only five per cent of new urban expansion is developed in a planned manner (Zevenbergen et al., 2008). Moreover, planning for management of flood disaster risks may not be the same as general land use or provision of infrastructure because the hydrological processes are conceptually different from the elements of hydraulic systems like street and pipe flow patterns (Mark et al., 2004). In response to the need for planning methods that can reduce urban vulnerability to floods, adaptation planning techniques are emerging, conceptually represented through water-sensitive urban design, spongy city designs, and climate change adaptation planning (Parkinson & Mark, 2005; Macchi & Tiepolo, 2014; Hoyer et al., 2011). These techniques require holistic approaches that consider interdependencies between physical and social systems of anthropogenic activities across space and time (Tsakiris, 2014; Vedeld, 2015; Vedeld et al., 2016). Such holistic analysis helps in understanding how different spatial configurations can influence environmental outcomes, such as surface runoff in the case of new neighbourhood planning (García-Ayllón et al., 2022). Among the direct applications of identifying localised flood vulnerability indicators is the ability to produce flood vulnerability maps or scaled flood sensitivity maps of city areas, depending on the type of development (Afsari et al., 2022; Anwana & Owojori, 2023).

Holistic approaches in managing stormwater in urban areas require selecting various strategies appropriate to a specific location (Hoyer et al., 2011). One area of analysis that can facilitate the choice of appropriate strategies and techniques in managing urban stormwater is identifying a localised and simplified list of vulnerability indicators to inform urban planning and design of urban stormwater management systems (Tsakiris, 2014; Nasiri & Shahmohammadi-Kalalagh, 2013). Therefore, the objective of the paper is to contribute to the knowledge of a simplified list of flood vulnerability indicators that can be used by city development managers in Tanzania and areas of a similar context to evaluate settlements' flood vulnerability and propose appropriate planning solutions.

On the selection of flood vulnerability indicators for urban settlements, a wide range of indicators was established by UNESCO (2013)

(21; http://www.unesco-ihe-fvi.org/), but most studies have limited themselves to the crucial ones (Zevenbergen et al., 2008; Balica et al., 2009; Balica & Wright, 2010; Špitalar et al., 2014; Drobot & Parker, 2007; Cutter, 1996; Abdrabo et al., 2023; Cutter et al., 2003). These commonly discussed crucial flood vulnerability indicators are divided into two groups. The first group is the environmental indicators, namely precipitation, proximity (distance) to the permanent water body, and the slope of the area. The second group consists of anthropogenic, specifically urbanisation indicators, namely, population density, road density, level of browning (land use change that increased constructed impervious surfaces), green vegetation coverage, and survey and planning status.

Most of the studies mentioned above evaluate flood vulnerability indicators at a city level and leave out locational-specific analyses that can be used for detailed planning. However, it is known that the spatial pattern of urban development can affect the hydrological connectivity within an urban sub-catchment and, ultimately, the city's stormwater pattern. Therefore, detailing the indicators at the lowest possible level is more useful for neighbourhood planning, housing, and urban infrastructure projects. Consequently, it is recommended that the urban sub-catchment be integrated with the planning control unit in land use and drainage infrastructure (Su et al., 2014). Therefore, the study uses a built-up sub-catchment as the unit of analysis. At that scale, the relationship between changes in urbanisation factors can be related to changes in the surface runoff that precipitates floods.

2. Methodology

The changes in the city-level flood vulnerability indicators were used to benchmark the sub-catchment level analysis in the study. The analysis was done for seven secondary cities in Tanzania, namely Arusha, Dodoma, Kigoma, Mbeya, Mtwara, Mwanza, and Tanga (**Figure 1**).

The seven cities had a population size between 400,000 and 1.2 million and had ongoing infrastructure upgrading projects financed by World Bank loans. The projects enabled the availability of the required data sets for the city-level analysis for the years between 2009 and 2019.

The spatial analysis on changes in the vulnerability indicators was done by the European Space Agency (ESA), which supported the study on *Impact & Effectiveness of Urban Planning on City Spatial Development for Tanzania* (Huang et al., 2018). The study, which was largely based on spatial analysis, used multiple global and local sources. The global source for population changes was the LandScan (http://web.ornl.gov/sci/landscan/). Other spatial data and sources used include land cover data from Landsat and Sentinel-2, Quickbird-2 (pre-2010 data), WorldView-2 (post-2015 data), Open Street Maps, and Google Earth history. These spatial data were deployed in assessing land-use changes, green area coverage, and proximity to water bodies and road density. There were also additional local data sets on administrative boundaries, building use, location of facilities, and road networks.

Figure 1. The location of the studied cities.

The researcher located built-up areas that have experienced flash floods of several hours and are known to cause loss of life or property in 2019 as an initial step in delineating sub-catchments for the analysis. The information was obtained from the respective urban local government offices, whose town planners accompanied the researcher to the sites. The sites were visited, and interviews were conducted with residents and leaders on the extent and depth of floods. The boundaries of commonly affected areas by floods were taken using handheld GPS units. Similar approaches in delineating flood-prone areas in a similar context where data are not readily available are also discussed by Ponte (2014) and Macchi & Tiepolo (2014).

The delineation of boundaries and calculation of the average longest slope of the flooded built-up urban sub-catchment were done using a 30-metre resolution digital elevation model in the Global Mapper software. The 39 built-up sub-catchments in the seven cities were documented to have flooded. A detailed analysis of the patterns of changes in the selected flood vulnerability indicators for the study period was conducted using QGIS and ArcGIS software. The spatial analysis of the indicators generated statistics that were then statistically analysed using SPSS software. Principal Component Analysis (PCA) was used to compare the relationship of the studied vulnerability indicators and the location of different flooded settlements. The PCA analytic tool section is based on its relatively better capacity to demonstrate comparative results (Abdrabo et al., 2023). The precipitation data used was intended to establish whether in the years when land use changes were studied preceding the observation of flooding in the settlements (sub-catchment), there had been any exceptional rainfall patterns. The historical precipitation data were obtained from the online platform of the World Meteorological Organisation (https://worldweather.wmo.int/).

3. Results and Discussion

The data on the number of days that had average maximum precipitation in each city shows that the days with average maximum rainfall have remained more or less the same. The data also show that the actual quantity of precipitation in each city did not increase or, in some cities, like Mbeya, Mwanza, and Arusha, had fallen, as shown by **Table 1** and **Figure 2**. This enables discounting the increase in precipitation or the number of precipitation days in the studied years as the main contributor to flooding. Hamisi (2013) made the same observation that precipitation in Tanzanian cities did not register a significant change in precipitation for over 30 years.

Table 1. Days of maximum rainfall precipitation in the studied cities.

	Arusha		Mwanza		Mtwara		Kigoma		Dodoma		Tanga		Mbeya	
Year	Days	Precipitation in mm	Days	Precipitation in mm	Days	Precipitation in mm	Days	Precipitation in mm	Days	Precipitation in mm	Days	Precipitation in mm	Days	Precipitation in mm
2009	18	20.153	50	156.12	47	135.66	69	278.04	24	98.82	23	73.21	79	609.4
2010	35	152.82	68	246.24	56	194.73	70	339.48	27	121.46	29	152.13	84	613.97
2011	28	80.84	66	257.92	63	275.41	67	241.97	31	210.61	41	118.6	84	609.93
2012	31	89.7	78	354.58	57	251.71	76	300.41	31	296.23	30	100.97	84	641.4
2013	44	123.06	72	231.27	62	215.14	74	268.01	32	153.94	21	93.08	83	519.03
2014	28	86.5	75	249.84	54	275.17	68	257.52	36	222.72	29	114.05	88	558.51
2015	29	59.18	82	381.53	60	218.74	63	279.83	24	163.22	23	99.49	82	506.38
2016	35	86.31	60	181.6	63	314.83	76	368.56	38	285.38	29	141.5	84	564.98
2017	18	37.3	69	217.98	59	239.17	68	281.58	32	102.66	33	176.07	85	558.42
2018	35	276.4	39	128.26	74	318.95	66	214.97	36	194.48	73	422.5	72	284.67
2019	20	121.87	22	46.4	55	221.73	78	415.16	24	212.13	82	497.49	74	228

Source: Historical data of World Meteorological Organisation (https://worldweather.wmo.int).

Table 2 provides a summary of statistical results at the sub-catchment level analysis for the 39 sub-catchments that had settlements that were observed to experience floods in 2019 (flooded built-up sub-catchments). The slope analysis showed that 30 out of 39 (77%) of the built-up sub-catchments had a permanent water body, be it a river or pond within the small catchment. The study also established a significant positive correlation between the steepness of the slope

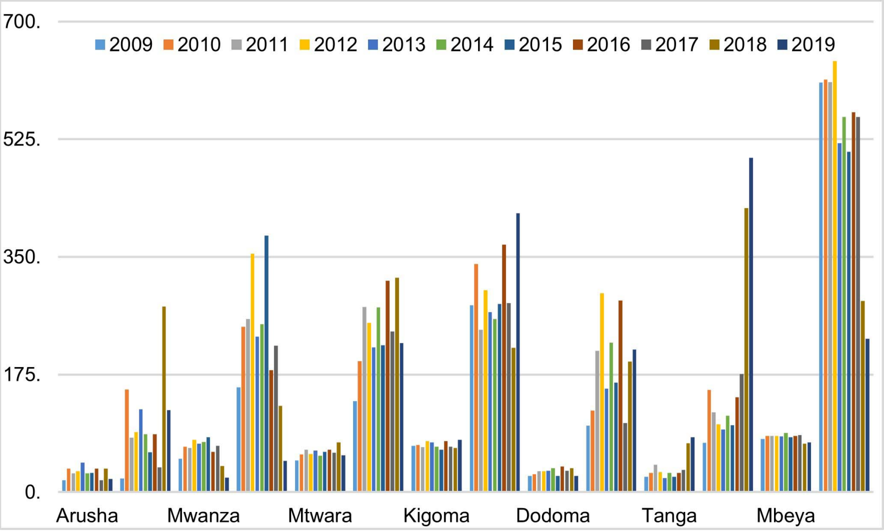

Figure 2. Number of days with maximum precipitation and the amount of precipitation in mm in the studied cities.

and the presence of a permanent water body. Areas that have steep slopes and permanent water bodies are naturally the fragile areas that should only be built on if necessary development conditions have been adhered to, which is hardly the case in these cities. Noteworthy, over 70% of the cities' land has not been planned and surveyed.

Table 2. Sub-catchment statistics from spatial analysis.

City name	Sub catchment by an mtaa/sub ward name	Sub catchment area km^2	Proportion of water body coverage	Average longest slope	Proportional change in					
					Population size	Population density	Areas covered by impervious surface	Areas covered by buildings	Planned built-up area	Green area coverage
Arusha	Orien	0.63	0.01	0.04	0.21	0.32	0.19	0.76	0.00	−0.03
	Nguseru	0.49	0.01	0.03	0.11	1.07	0.18	0.75	0.00	−0.07
	Kimandolu	0.79	0.00	0.02	0.09	0.16	0.03	0.81	0.04	−0.03
	Elerai	0.75	0.00	0.04	0.39	−0.46	0.18	0.65	0.00	−0.03
	Baraa	1.79	0.00	0.03	0.25	2.52	0.01	0.73	0.00	−0.02
Mwanza	Pasiansi	9.71	0.00	0.02	0.13	0.46	0.13	0.49	0.38	−0.02
	Nyamanoro	10.65	0.02	0.02	0.00	−0.21	0.05	0.70	0.34	−0.08
	Nyakato	5.28	0.00	0.03	0.16	1.28	0.31	0.51	0.30	−0.02
	Nyakato1	3.70	0.00	0.04	0.05	0.20	0.12	0.66	0.22	−0.11
	Mkuyuni	6.00	0.18	0.08	0.05	0.28	0.06	0.38	0.06	0.03
	Mahina_1	4.45	0.00	0.01	0.16	3.93	0.17	0.23	0.02	0.00
	Mahina	5.62	0.00	0.03	−0.07	0.45	0.13	0.55	0.37	−0.08
	Isamilo	13.65	0.17	0.01	−0.03	−0.08	0.04	0.45	0.31	−0.05
	Ilemela	15.75	0.00	0.01	0.33	4.41	0.13	0.18	0.36	0.00
	Ilemela_2	2.94	0.13	0.09	−0.08	−0.06	0.07	0.27	0.40	−0.06
	Butimba	12.61	0.07	0.02	0.07	−0.40	0.04	0.01	0.00	0.00

Continued

Mtwara	Bwawani	4.64	0.01	0.01	0.16	0.24	0.15	0.59	0.26	−0.02
	Kiyangu	3.86	0.06	0.01	−0.03	0.16	0.03	0.53	0.83	−0.01
	Matopeni	13.13	0.02	0.04	0.49	0.26	0.20	0.52	0.29	−0.02
	Nabwada	2.43	0.05	0.01	0.00	0.00	0.04	0.55	0.83	−0.04
Kigoma	Katubuka	6.99	0.00	0.02	0.09	0.61	0.03	0.91	0.62	0.09
	Kibirizi	3.17	0.03	0.03	0.26	1.79	0.22	0.64	0.03	0.01
	Kibirizi 1	1.99	0.18	0.10	0.19	1.15	0.11	0.54	0.05	0.02
Dodoma	Ipagala	2.07	0.01	0.01	0.21	2.45	0.16	0.30	0.55	0.03
	Makole	0.88	0.00	0.01	−0.01	0.24	0.06	1.00	0.60	0.16
	Viwandani	6.65	0.00	0.01	0.01	0.25	0.02	0.03	16.40	0.04
Tanga	Gezaulole	8.34	0.01	0.01	0.01	0.13	0.02	0.66	0.81	−0.06
	Magoani	5.04	0.00	0.01	0.02	0.13	0.03	0.73	0.86	−0.10
	Magomeni	4.14	0.01	0.01	0.43	0.07	0.20	0.51	0.31	−0.05
	Magomeni_Border	11.43	0.00	0.01	0.07	0.13	0.04	0.05	0.37	0.00
	Magomeni_Dampo	4.34	0.03	0.01	0.08	0.10	0.09	0.47	0.30	−0.07
Mbeya	Itezi	2.93	0.00	0.01	0.06	1.60	0.49	0.79	0.00	−0.15
	Iyunga	6.54	0.00	0.04	0.00	0.00	0.08	0.15	0.00	0.00
	Iziwa	13.00	0.00	0.07	0.00	0.00	0.09	0.03	0.29	0.00
	Kalobe	10.06	0.01	0.02	0.01	0.38	0.13	0.19	0.18	−0.04
	Nzovwe	4.81	0.00	0.06	0.03	0.21	0.13	0.61	0.44	−0.06
	Sinde	4.09	0.00	0.05	0.05	0.23	0.27	0.81	0.14	−0.11
	Swaya	7.00	0.01	0.03	0.01	0.48	0.11	0.16	0.01	−0.03
	Uyole	4.08	0.00	0.05	0.05	0.34	0.14	0.29	0.00	−0.07

Source: Spatial analysis of various spatial data from 2009 to 2019.

On the indicator of population density, the study established that in 25 out of 39 cases (64%), there has been an increase in population density of more than 50 per cent; the average increase in density measured across the cities is 46 per cent. Six (6) out of 39 have registered a reduction in population density, having experienced some resettlements. Therefore, although these flooded sub-catchments increased population density, almost the same proportional increase is also felt across cities in the same period. Therefore, the observed increase in population in the settlements cannot exclusively explain the occurrence of floods.

On the indicator of road density in the studied period, 25 out of 39 (65%) sub-catchments have less than a 10 per cent increase in road density, while at the city level, the average is a 25 per cent increase in road density. Therefore, there is a comparatively lower improvement in infrastructure in the studied settlements. Since most drains are provided as roadside drains, this implies inaccessibility and the inability to drain the excess water.

On the land-use change, 38 out of 39 (97%) sub-catchments registered an increase in impervious surfaces, while the mean increase for the cities for the same indicator was 24 per cent. Lived-in structures that existed previously in the sub-catchments seem to have undergone more browning by 49 per cent, indicating that residents' ongoing efforts to increase pavements or build other structures within their plots.

On the planning status of the sub-catchments, 38 out of 39 (97%) have at least some part which is developed informally (unplanned and un-surveyed), which includes 14 cases (36%) that are wholly informal settlements. For those cases with mixed planned and unplanned areas, 10 out of 39 (25%) cases have more than 50 per cent of the land formally developed. Therefore, about 30 per cent of the flooded built-up sub-catchments may be classified as planned (and surveyed) settlements, which equates with the cities' average coverage of formal planned land, which is about 31 per cent. The correlation analysis established that as the slope increases, the proportion of planned becomes smaller with a negative, significant correlation coefficient of −0.356. Further, there is a significant negative correlation between the increase in built-up spaces and the increase in coverage of informality, with a coefficient of −0.401. These results imply that most flooded areas are mature informal settlements, and some of the flooded areas are planned.

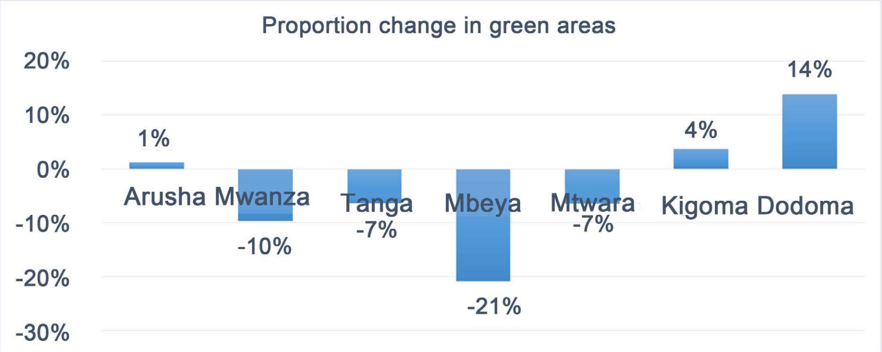

Figure 3. The trend in green area coverage across the cities. Source: Spatial analysis of various data in Tanzania by ESA for the years 2009-2019.

On the indicator of change in green areas, it was established that there had been a marginal decrease in the proportion of coverage of green areas by about 1.7 per cent across the flooded built-up sub-catchments. About 7 out of 39 (18%) of flooded built-up sub-catchments have increased green area coverage with an average increase of 5.6 per cent. Five cities have lost much of the green in the period, while Dodoma has registered a substantial increase in green areas (Figure 3). In Dodoma, there are planned and surveyed built-up sub-catchments that have registered a substantial increase in green area coverage, yet they are flooded frequently (Figure 4).

Figure 5 presents a principal component analysis for associating different flood vulnerability indicators in the study's urban sub-catchments. The analysis

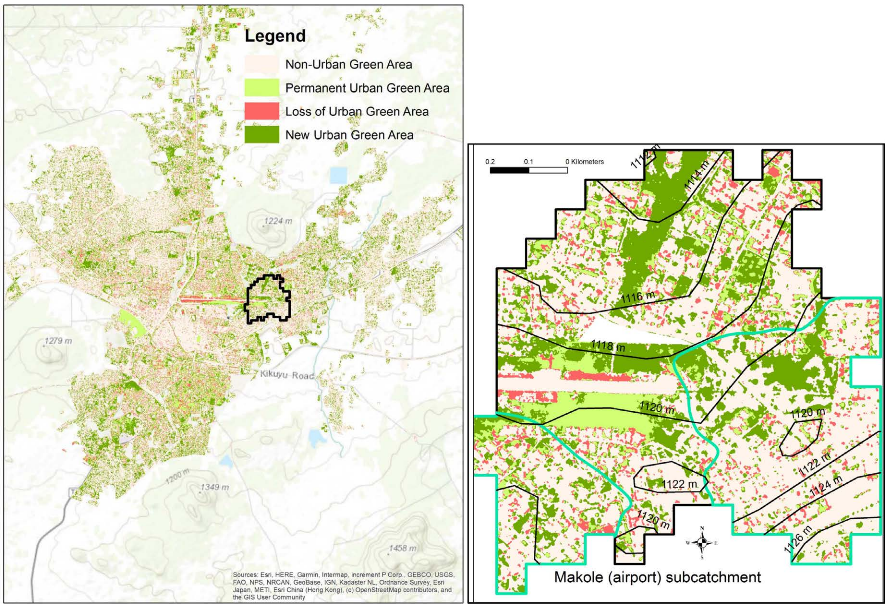

Figure 4. Makole, an example of a planned flooded built-up sub-catchment, which has registered an increase in green area coverage. Source: A spatial analysis of various data in Tanzania for the years 2009-2019.

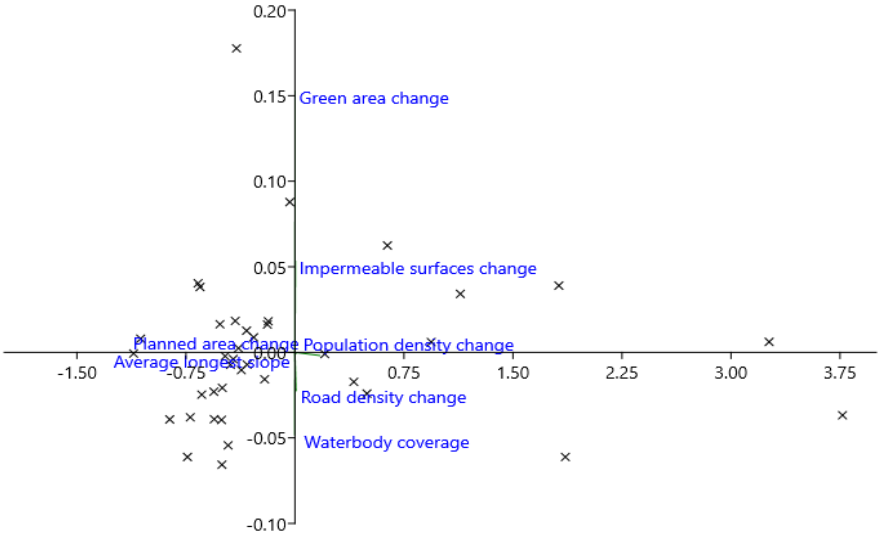

Figure 5. The principal component analysis for the most influential relationships among flood vulnerability indicators. The "×" denotes the graphical placement of the built-up urban sub-catchment. Therefore, the more "×" marks are concentrated, the more settlements are located in relation to the marked flood vulnerability indicators.

established that the presence of steeper slopes, decrease in permanent water coverage, increased planned area coverage, increase in population density, decrease in road density, and increase in impermeable surfaces correlated well with flood occurrence in the studied built-up sub-catchments. In contrast, the observed increase in green area coverage is not associated with flood occurrence in many of the studied sub-catchments (**Figure 5**). It should be noted that the form of planning in many of the studied sub-catchments is a land regularisation, which mostly take place in mature or relatively densely developed informal settlements that developed without layout or land ownership registration, to undertake land parcels ownership identification, designation of streets and minimum passable spaces, cadaster survey and ownership registration of land parcels leading to issuance of land titles. This form of planning is usually not coupled with upgrading services such as paved roads, drainage or insertion of nature-based solutions to manage stormwater (Sakijege, 2025; Nuhu et al., 2023).

4. Conclusion

The study has established contextually relevant flood vulnerability indicators that can be used to generate flood maps and indices to inform urban planning for flood risks. The study has also established that the flood vulnerability indicators generate patterns, which are observable in all flooded built-up urban sub-catchments. The study demonstrated that floods tend to affect mostly mature settlements whose building development rates are much higher than the rate of improvement of line infrastructures like drainage, and there has been a continuous subdivision of land for new buildings and haphazard development of impervious surfaces. Floods are also experienced in fragile areas characterised by steeper slopes and where people are drying up urban wetlands for building development; naturally, these areas are in the bottom parts of sub-catchments. The study has shown that a settlement's susceptibility to floods does not depend on whether the land has been surveyed or not. The same conclusion was reached by Balica & Wright (24) that it is not the status of land surveying, but the 'planning' that considers the location of buildings in relation to the physiography of the area, infrastructure provision, control of plot coverage and adherence to building density, which reduces vulnerability to flooding disasters. The observation was also made that in these flooding built-up sub-catchments, the changes in the proportion of green area coverage did not have a direct directional influence on flood risk. Therefore, green areas development can only have the desired effect on flood control if provided in a planned manner, meaning they are a part of land use organisation, particularly at the city or a wider ecosystem level, rather than at the neighbourhood level.

The findings imply that urban planners need to undertake flood vulnerability assessments as a part of hydrological assessments into subdivision, approvals and land regularisation schemes, and enforce implementation of appropriate measures to manage storms water in the process of urban development management. These measures could enable urban communities to be safe and sustainable while also adapting to climate change as provided by Sustainable Development Goal (SDG) 11 and 13 respectively. Since many of the flooded and unplanned inner city areas are occupied by poor people whose predicaments are exacerbated by flash floods, such interventions form part of ending poverty in urban areas, as provided by SDG 1.

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Conflicts of Interest

The author declares that there is no conflict of interest in the study.

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