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Rising urban flood risk and exposure under shared socioeconomic pathways in Greater Accra Ghana

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This study assesses flood susceptibility in the Greater Accra Region of Ghana, one of West Africa's most flood-prone areas by employing the Frequency Ratio (FR) model. The analysis integrates a range of environmental and meteorological variables alongside non-meteorological factors in the susceptibility mapping. The model yielded an Area Under the Curve (AUC) score of 0.82, indicating reliable flood susceptibility predictions. Various factors such as elevation, slope, geology, distance from urban, and stream power index significantly influence flood susceptibility. The spatial distribution of baseline susceptibility zones reveals coastal and northeastern areas as highly susceptible. Projections under different Shared Socioeconomic Pathway (SSP) scenarios depict a dynamic susceptibility landscape, emphasizing shifts in susceptibility levels. Notably, SSP2 and SSP3 foresee an increase in high and very high susceptibility zones. For district and town-level dynamics, districts like Weija Gbawe and towns along the coastline consistently exhibit very high susceptibility. The spatial distribution of building footprints shows a notable concentration within high and very high flood susceptibility zones, highlighting significant exposure risks to both the population and critical infrastructure. For example, over 780,000 and 810,000 building footprints, representing 3.12 million and 3.24 million people, are projected to experience high flood susceptibility under SSP2 and SSP3, respectively. This comprehensive assessment provides critical insights for flood management decisions in cities, emphasizing the importance of considering various factors in understanding and mitigating flood risks in West Africa and globally.

Keywords Geospatial mapping, Flood susceptibility, Frequency ratio, SSPs, Sustainable cities, Climate change

Flooding, a natural disaster, has been a recurring occurrence from time immemorial up to the present day causing life lost and property damages[1–3]. Hague, in 1997, described flooding as a natural hazard that displaces individuals by causing destruction to their land, residences, and other tangible possessions and assets[4]. Floods act as a force, causing damage to the environmental ecosystem, transportation infrastructure, agriculture, and societal and cultural heritage, ultimately impacting human life[5–7].

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Flooding represents a major developmental challenge, resulting in widespread infrastructure damage, substantial socioeconomic losses, and loss of human lives[8]. It remains one of the most prevalent environmental disasters, ranking closely behind diseases and accidents in terms of impact and frequency. For example, flood events cause significant disruptions to energy, water, communication, and transportation systems, while also impeding public services. They leave lasting impacts on the environment and cultural heritage, contribute to pollution, alter natural habitats, and can lead to population displacement and migration[9]. Annual statistics reveal that floods claim the lives of 100,000 individuals and affect 2 billion people globally with damages amounting to 651 billion U.S. dollars[9].

The frequency of flood events worldwide has exhibited an upward trajectory from 1900 to 2023[10]. Among the past three decades, 2006, 2007 and 2021 stand out with the highest number of recorded flood disasters 228, 226 and 226 respectively[11]. The regional flood report spanning 2020–2023 indicates a higher frequency of flood events in Asia and America[12]. Notably, Asia experienced over 250 flood events in 2020 and more than 150 in 2021. Following closely, Africa saw 155 flood events in 2020, while America recorded 139 in 2021. Nevertheless, America topped the list with the highest number of flood events, reaching 100 in 2022[12].

For country specific events, the world faced a multifaceted challenge involving flooding amid a global pandemic, leading to significant impacts on numerous countries in 2020. For example, in January 2020, unprecedented rainfall totaling 337 mm in 24 h resulted in severe flooding in Jakarta, Indonesia[9]. This catastrophic event claimed the lives of at least 66 people and forced tens of thousands to evacuate from their homes. Jakarta, being the capital of Indonesia, faces additional vulnerability as nearly 40% of its land lies below sea level[9]. Likewise, a torrential rain inundated the village of Dashtiari, triggering devastating floods in Iran's Sistan-Baluchistan region on January 13, 2020. The intense downpours resulted in widespread flooding, causing the closure of approximately 900 roads, disrupting power supply in 877 villages, and causing significant damage to residences and irrigation canal systems[9]. Over 200,000 individuals were directly impacted, and the combined losses in public facilities and agriculture reached a staggering US$ 100 million[9]. Again, 14 rivers flooded seven prefectures due to torrential rains in Japan in July 2020. This event caused power failure to 6,000 homes and caused 77 deaths and about 15,000 buildings damaged[9]. In August 2020, a heavy rain flooded the central region of South korea for 46 days killing 26 people and displacing over 1000 people from their homes[9].

Flooding remains one of the most pervasive and destructive natural hazards across Africa, with profound consequences for livelihoods, infrastructure, and socio-economic development.

West Africa has experienced recurrent large-scale flood disasters over the past two decades. In September 2007, torrential rainfall triggered widespread flooding across approximately 16 African countries, with some of the most severely affected located in West Africa, including Ghana, Burkina Faso, Niger, and Senegal. An estimated 600,000 people were affected during this episode. Subsequent flood events within the same year resulted in approximately 500 fatalities and displaced over one million people across Niger, Burkina Faso, Mali, and Togo, among others[13–15]. The scale of impacts intensified in later years. In 2012, Nigeria experienced one of the most devastating floods in its history, affecting 33 states and impacting approximately 37 million people. The disaster displaced 2.1 million individuals, caused 363 deaths, injured more than 18,200 people, and damaged over 18,000 houses. More recently, in April 2022, at least eight major flood events were recorded in Nigeria and Ghana, resulting in no fewer than 20 fatalities. These events received comparatively limited public and policy attention, as national responses remained heavily focused on the COVID-19 pandemic[16].

East Africa has similarly faced escalating flood risks linked to extreme rainfall and hydrological variability. In 2007, flood events affected Ethiopia and Uganda as part of the broader continental episode, contributing to the estimated 500 fatalities and over one million displaced persons reported that year[13–15]. In March 2020, extensive flooding across East Africa affected more than 13 million people and displaced approximately 981,000 individuals. In Kenya alone, nearly 200 deaths were reported due to overflowing rivers and mudslides, with over 40,000 people displaced. During the same period, Lake Victoria reached its highest recorded water levels in over 120 years, inundating lakeside settlements, displacing thousands, and causing significant damage to roads and other infrastructure[17,18].

Southern Africa has also experienced catastrophic flood disasters, particularly those associated with tropical cyclones. The 2018–2019 southwest Indian Ocean cyclone season culminated in Cyclone Idai, which triggered extensive flooding in Mozambique and Zimbabwe[19]. The disaster resulted in more than 600 deaths, widespread destruction of critical infrastructure, and estimated economic losses of approximately USD 1 billion, underscoring the region's vulnerability to compound hydro-meteorological extremes[19].

In North Africa, extreme rainfall events have similarly produced significant flood impacts. In 2020, heavy rainfall inundated Khartoum, the capital city of Sudan, resulting in approximately 100 fatalities and the displacement of residents from about 100,000 homes, with an estimated 650,000 people affected overall[9].

Perennial floods have long been a significant issue in the Greater Accra region (GAR), persisting from historical times to the present day. Urban flooding, noted as a major concern in Accra since the early 1930s[20], has been punctuated by notable events in 1955, 1960, 1963, 1973, 1986, 1991, 1995, 1999, 2001, 2002, 2010, 2011, and 2015, among others[6,20–22]. On June 3rd, 2015, Accra, the capital of Ghana, witnessed an unprecedented flood event, compounded by an explosion at a Goil filling station, resulting in a death toll exceeding 152 lives. In June 2020 for instance, the capital city of Ghana (Accra) experienced severe flooding in various areas due to heavy rainfall. Numerous homes were submerged, and unfortunate individuals lost their lives, either being carried away or drowning in the floodwaters. Experts attribute the flood to factors such as poor waste management, inadequate structural settlement, and insufficient hydraulic performance of the basins in Accra[6,23]. Despite the establishment of supervisory agencies by the Government of Ghana, such as the Ministry of Works and Housing, City Engineers of Accra Metropolitan Assembly, and the Lands Department, along with commissioned consultants[24,25], the methods employed, including identifying watermarks, media reports, aerial photographic interpretations[26], solid waste management, dredging works on the Odaw river, removal of some illegal structures from waterways, have proven insufficient to fully address or mitigate the periodic occurrence of floods in new areas. The magnitude and dynamic nature of this challenge highlight the imperativeness for policymakers to implement more strategic, forward-looking measures to effectively address both existing and emerging flood risks[27], calling for an innovative approach for the management of flood risk in the region.

This reveals urban flooding as a pressing and escalating development challenge. In the context of rapid demographic growth, intensifying urbanization, and climate change, the underlying drivers of flooding are becoming more complex, while their impacts are growing increasingly severe. Climate change has been one of the major causes of flooding in the world[28–31]. This will make the mitigation and management of flood risk more difficult due to the unpredictable nature of climate change in the 21st century. Anticipated anthropogenic climate change is forecasted to heighten flood risk due to more frequent occurrences of heavy precipitation, heightened catchment wetness, and rising sea levels[28,29]. The "Ten New Insights in Climate Science 2024" highlights the escalating threats that climate change poses to critical infrastructure, particularly in urban settings, where vulnerabilities to extreme weather events such as flooding are intensifying[32]. Integrating Shared Socioeconomic Pathway (SSP) scenarios into urban flood risk modeling, provides a framework for assessing future impacts under varying development and emissions scenarios. This approach enhances the capacity of cities to proactively design mitigation and adaptation strategies that align with both climate and socioeconomic trajectories, thereby strengthening infrastructure resilience and promoting sustainable urban planning.

To better understand the dynamics of the causes of flooding and project future flood occurrences, Geographic Information System (GIS) and Remote Sensing (RS) software techniques are extensively employed due to their capacity to offer a novel perspective in susceptibility assessment, supported by sound justifications. Examining satellite imagery through GIS and RS platforms has yielded satisfactory outcomes for flood susceptibility mapping, delivering accurate information about a given region[33]. It provides a conducive environment for the application of diverse modeling approaches, enabling effective data manipulation and analysis for flood susceptibility assessment, thereby yielding more coherent and reliable results. At present, GIS and RS technologies are being widely and effectively utilized globally for the assessment of flood susceptibility[4,34,35]. A range of models and analytical techniques exist as alternative approaches for flood susceptibility mapping.

The Frequency Ratio (FR) model, as introduced by Lee et al.[36], stands out as a highly reliable technique for assessing hazards with a commendable accuracy rate. This is a bivariate statistical analysis (BSA) that assigns values to each class of individual parameters, assessing their influence on flood occurrence[3,37]. The FR model, known for its simplicity and efficiency, operates seamlessly in a GIS environment, constructing scientifically sound flood susceptibility maps[38–40]. Utilizing sophisticated software like RS and GIS facilitates the straightforward preparation of flood susceptibility maps through the FR model. This study seeks to generate flood susceptibility maps for the GAR using the FR model, under both baseline conditions and future projections based on SSP scenarios. It places particular emphasis on the critical analysis of flood risk potential zones within the region. Furthermore, the influence of climate change significantly shapes the frequency of flooding events. Consequently, evaluating the occurrence of flooding in a specific region under various climate scenarios serves not only to anticipate future risks but also enhances the reliability and accuracy of forthcoming predictions. Only a limited number of studies have applied the Frequency Ratio (FR) model for flood vulnerability mapping in the Greater Accra Region (GAR). For example, some existing studies[41] employed the FR model to assess present-day flood vulnerability in the GAR; however, their analysis did not incorporate future climate projections. To date, no study has integrated SSP scenarios into FR-based flood susceptibility modelling for the GAR, nor has the SSP framework been systematically applied to project how flood susceptibility may evolve under different future climate and development pathways. As such, there is limited empirical evidence to support the use of SSP-informed flood susceptibility assessments in guiding proactive urban flood mitigation and adaptation planning in the GAR. In contrast, recent studies in other geographical contexts have successfully integrated SSP scenarios into flood adaptation and mitigation analyses to inform long-term urban resilience and policy design[42–44].

Numerous studies have extensively documented the occurrence of flooding in the Greater Accra Region (GAR), attributing flood events to a combination of natural and anthropogenic drivers, with the latter often exerting a more dominant influence on flood occurrence and impacts[6,45,46]. While non-meteorological factors such as poor drainage infrastructure, weak solid waste management, construction on waterways, wetland degradation, systemic governance failures, and inadequate green infrastructure are well established in the literature[45,47,48], existing analyses remain largely confined to present-day assessments of flood vulnerability and susceptibility. These drivers are rarely examined within the context of a changing climate, nor are they systematically linked to how future climatic conditions may amplify or reconfigure flood risk patterns in the region. Recurrent flood disasters in the GAR are consistently attributed to urban planning failures and regulatory non-compliance, yet few studies interrogate why these deficiencies persist despite established policies, institutional arrangements, and repeated post-disaster interventions[49–51]. Although institutional fragmentation, weak enforcement capacity, and political interference are acknowledged in the literature, these governance constraints are seldom integrated into flood risk and susceptibility analyses under evolving climate conditions[52–55]. As a result, current scholarship effectively explains *where* floods occur and their proximate causes, but provides limited insight into how flood susceptibility may evolve over time or why flood risks are likely to intensify in the future. Critically, there remains a notable dearth of studies that project flood susceptibility in the GAR under different climate futures, particularly within the framework of the SSPs. The absence of SSP-based flood susceptibility assessments constrains the ability of policymakers and urban planners to anticipate long-term risk trajectories under varying combinations of climatic change, socio-economic development, and urban expansion. This gap underscores the need for a comprehensive investigation that integrates natural and anthropogenic flood-conditioning factors with future climate projections to assess present and future flood susceptibility in the GAR under multiple SSP scenarios.

Materials and methods
Description of the study area
GAR encompasses about 3245 km² (Fig. 1) and has a total population of about 5,455,692[56]. Geographically located between latitudes 5°30’ and 5°53’ North and longitudes 0°03’ and 0°25’ West, the region exhibits a predominantly low-lying topography punctuated by intermittent hills, with an average elevation of approximately 20 m above mean sea level (msl). The topography is predominantly characterized by gentle slopes averaging approximately 11%; however, specific areas such as the McCarthy Hills, Abokobi, and Kwabenya exhibit steeper gradients, with slopes exceeding 22%. The GAR has a water table ranging from 4.80 to 70 m below the surface[57]. Falling within the anomalous dry equatorial climatic region, the region experiences double maxima precipitation and a prolonged dry season with intermittent Harmattan conditions. The peak temperatures are typically recorded between February and March, with average monthly values around 27 °C, while the coolest period spans June to August, featuring mean monthly temperatures of approximately 21 °C[56]. Precipitation in the region displays a bimodal pattern, with a major rainfall season from March to July and a minor season spanning September to November. This rainfall regime contributes to an annual precipitation total ranging between 780 mm and 1,200 mm[58]. The vegetation within the study area is predominantly composed of two major types: coastal shrublands and grasslands, as well as mangrove forests concentrated around coastal lagoon zones. The mangrove areas are typically associated with saline and waterlogged soils. The coastal shrub and grassland zones are interspersed with scattered tree species, notably Baobab (*Adansonia digitata*) and Neem (*Azadirachta indica*). The study area is provided in Fig. 9.

Spatial distribution of documented flood occurrences within the study area
In the evaluation of floods, having a historical record of past flood incidents is essential to predict future occurrences[7,60]. Additionally, the flood inventory data serves as a valuable resource for validating the final Flood susceptibility Zone map. The flood inventory map for the GAR was developed by aggregating and extracting historical flood event data from multiple sources, including field surveys, records from the National Disaster Management Organisation (NADMO), academic literature, news reports, archival materials, published studies, and existing maps. A total of 384 historical flood events were identified and geospatially mapped as part of the flood inventory dataset (see Fig. 1). Among the past flood locations, 269 flood points (70%) were randomly

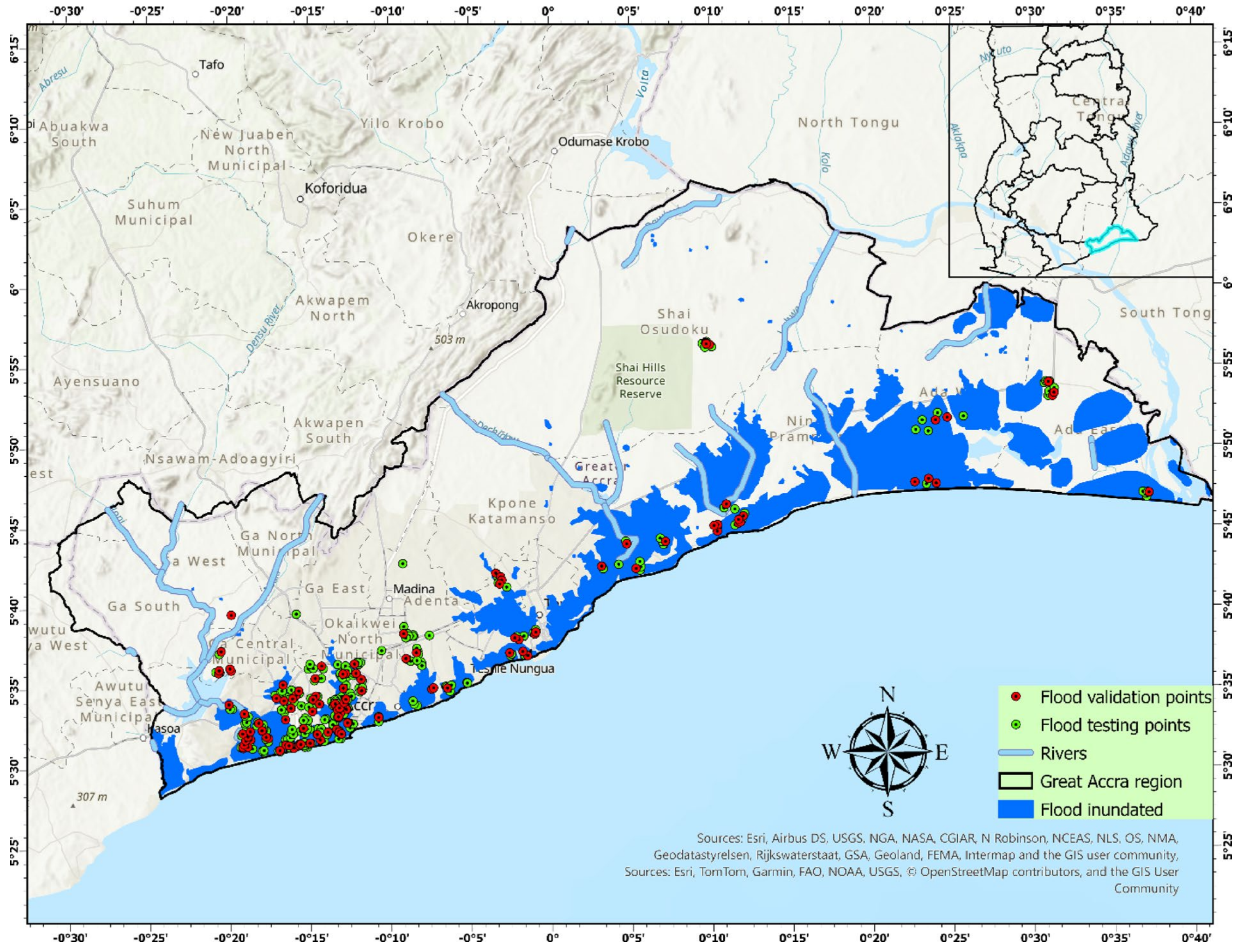

Fig. 1. Study area map showing historical flood inundated areas, flood validation and testing points. Source: Author’s own construct using ARCGIS pro 2.5[59]

allocated to the training dataset, while 115 flood points (30%) were assigned to the validation dataset. The training flood dataset was used to develop the flood susceptibility zone map, whereas the validation dataset served to assess the accuracy of both the generated map and the applied modeling approach. This particular framework has been adopted in the training and validation processes of various studies[60,61]. Nevertheless, there is a lack of explicit guidelines regarding the criteria for partitioning flood points into training and validation sets[37]. To simulate future flood occurrences under the SSP scenarios, all flood conditioning factors were held constant, with the exception of dynamic variables such as precipitation, LULC, and distance to urban areas as shown in Fig. 2.

Climate data

The historical climate data utilized in this study were sourced from the Ghana Meteorological Agency (GMet), as presented in Table 1. Future climate projections were adopted from existing studies[62], which applied bias-correction techniques to CMIP6 datasets under the selected SSP scenarios for the GAR.

These projections provide a refined understanding of the socio-economic challenges associated with climate change adaptation, mitigation, and their broader implications[63]. The Climate Model Intercomparison Project 6 (CMIP6) climate projections are based on an integration of land-use trajectories and emissions scenarios derived from the SSP scenarios, which outline plausible future socio-economic development trends. Furthermore, the projections incorporate updated versions of the Representative Concentration Pathways (RCPs) introduced in the Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment Report[64], enhancing the resolution and relevance of the resulting climate predictions.

The SSP scenarios extend beyond the traditional RCPs by integrating projections of future socioeconomic developments and their potential influence on climate change mitigation and adaptation strategies. Notably,

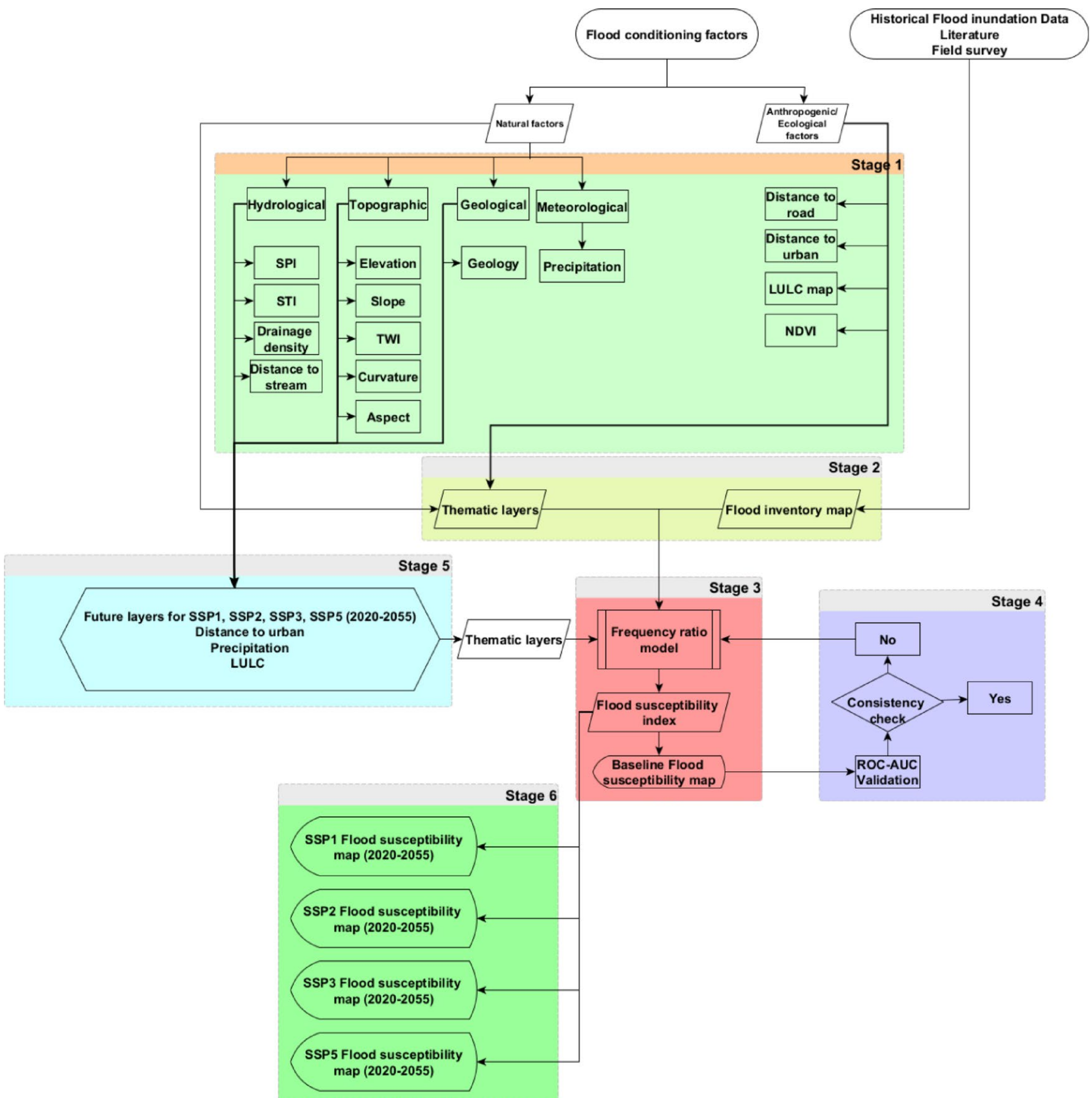

Fig. 2. Flowchart for flood susceptibility mapping. Source: Siabi et al.[74]

Data description	Data resolution/type	Year	Reference/source
Current LULC	30m	2020	Siabi et al.[68]
Future LULC	30m	2020–2055	Siabi et al.[68]
SRTM DEM	90m	2020	USGS
Stream	Raster	2020	Derived from DEM
Road	Raster	2020	Derived from Google open street
Precipitation	Raster	2020	GMet
Future precipitation	Raster	2020–2055	Siabi et al.[62]
Urban data	Raster	2020	Retrieved from LULC map 2020
Future Urban data	Raster	2020–2055	Derived from LULC data 2020–2055
Flood inventory data	Vector	2015–2020	NADMO/Literature/field survey[57,69–73]

Table 1. Data used and sources.

climate projections under CMIP6 differ from those in the earlier CMIP5 phase, not only due to the integration of SSP scenarios into advanced climate models but also because of the introduction of previously unexplored gap scenarios[65]. The IPCC's Sixth Assessment Report outlines five principal SSP scenarios; SSP1-1.9, SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5 which collectively forecast a global mean temperature rise of approximately 1.5 °C in the near future (2021–2040), and a range of 3.3 °C to 5.7 °C by the end of the century (2081–2100), particularly under the highest-emission pathway[64].

These advanced SSP scenarios offer critical insights into the potential evolution of future flood risks. By embedding socioeconomic drivers such as urbanization, population growth, and economic policy directions, the SSP scenarios enable more comprehensive projections of climate-related hazards including increased flooding particularly in vulnerable urban regions.

This study employed both current and future climate datasets focusing on precipitation and temperature under SSP scenarios previously generated in the work of Siabi et al.[62]. For clarity and consistency, four major scenarios are applied in this study: SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5, hereafter referred to as SSP1, SSP2, SSP3, and SSP5, respectively.

The SSP1 scenario represents a world that cooperates effectively to combat climate change, resulting in a projected warming range of 1.3 °C to 2.4 °C and a global population stabilizing around 7 billion by 2100[63]. SSP2 describes a future where countries implement moderate climate actions consistent with current national commitments, leading to warming between 2.1 °C and 3.5 °C, with a population of approximately 9.6 billion[63]. The SSP3 scenario envisions a fragmented world characterized by resurgent nationalism, reduced international cooperation, and prioritization of regional economic agendas. Under this pathway, projected warming falls between 2.8 °C and 4.6 °C, with the global population increasing to about 12.6 billion[63]. In contrast, SSP5 assumes a fossil fuel-intensive future with limited climate mitigation efforts. This scenario projects a warming range of 3.3 °C to 5.7 °C, with the global population peaking at 8.5 billion in the 2050s before declining to around 7 billion by 2100[63].

Key environmental and anthropogenic variables influencing flood susceptibility within the study area

Flood susceptibility mapping involves the challenging task of selecting appropriate flood conditioning parameters, which often lacks consensus[38]. Understanding the various factors influencing flooding in the study region is crucial for choosing suitable parameters to identify potential zones for future flood occurrences[66]. It is essential to establish the relationship between these chosen factors and past flood incidents to conduct an effective flood susceptibility study[67]. The selection of efficient parameters is a key step in generating a Flood susceptibility zone map in any watershed[66]. The present study employed fifteen (15) conditioning variables, selected through a comprehensive review of existing literature on flood susceptibility zone mapping and informed by the distinct characteristics of the study region. These flood conditioning factors include both natural and anthropogenic variables and attained from various sources shown in Table 1. Each flood conditioning factor was processed and reclassified using the quantile classification method. Subsequently, all factors were converted into raster format with a spatial resolution of 30 × 30 m.

Topographic factors

Topography exerts first-order control over runoff generation, flow routing, and inundation potential[75–78].

Aspect, which denotes the compass orientation of a slope, serve a critical topographic driver influencing flood susceptibility in the GAR (Fig. 3A). It influences the spatial patterns of water runoff, soil moisture retention, and solar radiation exposure, all of which affect hydrological responses during rainfall events. By analyzing terrain aspect, it is possible to identify slope orientations that may contribute to differential runoff behavior and, consequently, varying degrees of flood risk. Certain aspects may enhance water accumulation in low-lying areas, particularly during periods of intense precipitation, thereby increasing the likelihood of localized flooding. Conversely, slopes facing directions that encourage rapid surface runoff can expedite water flow toward downstream areas, thereby elevating the risk of flash flooding. Understanding the spatial distribution of aspect across the terrain thus provides critical insight into runoff dynamics and supports more accurate flood risk modeling and mitigation planning.

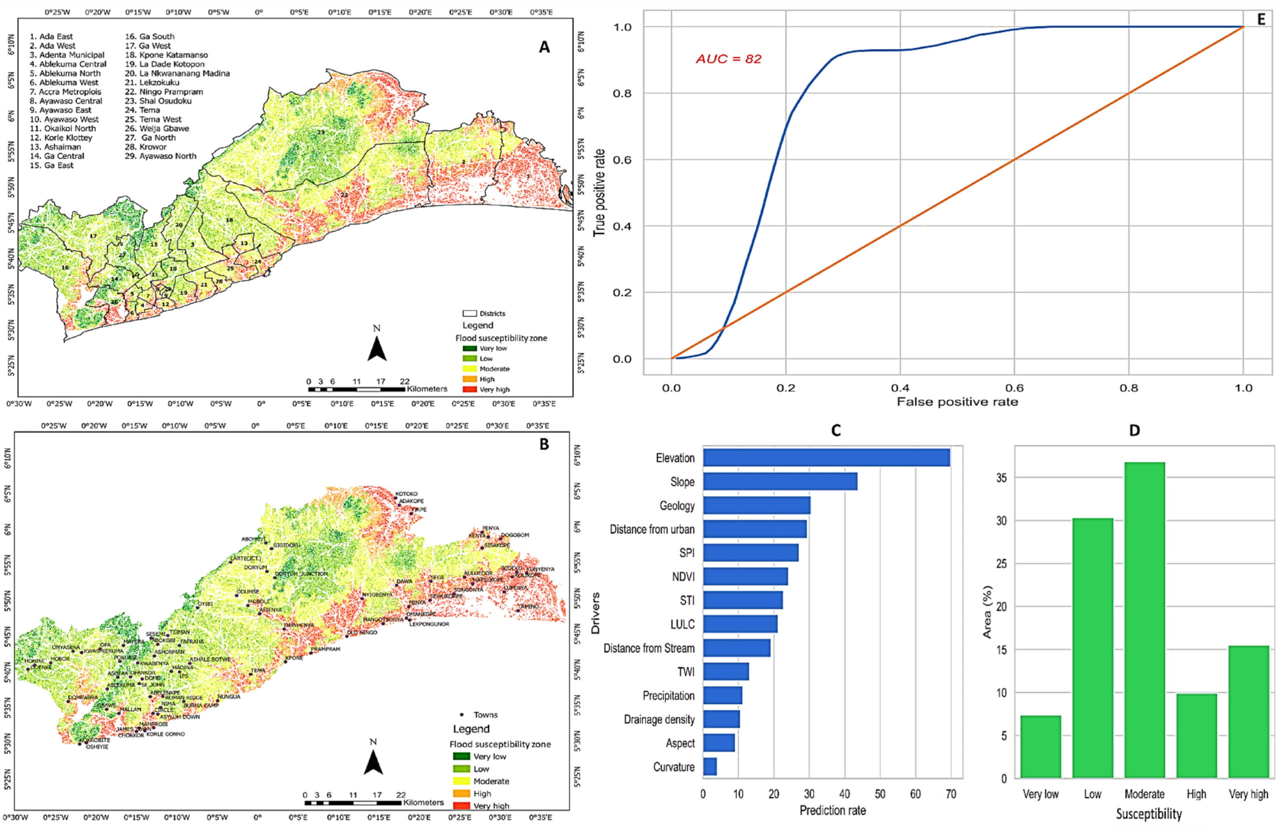

Fig. 3. Flood susceptibility map of GAR showing vulnerable (**A**) districts (Generated using ARCGIS pro 2.5[59]) and (**B**) Towns (Generated using ARCGIS pro 2.5[59]) in the baseline period, (**C**) Prediction rate (Generated using Matplotlib 3.8.0[91]), (**D**) Percentage of flood susceptibility zones (Generated using Matplotlib 3.8.0[91]) (**E**) FR model ROC-AUC (Generated using Matplotlib 3.8.0[91]).

Elevation plays a critical role in influencing flood risk, with lower elevations generally associated with higher flood susceptibility[75]. The elevation map for the study area was produced using a 90-meter resolution Digital Elevation Model (DEM) derived from the Shuttle Radar Topography Mission (SRTM). Given that the Greater Accra Region spans two SRTM tiles, preprocessing procedures including mosaicking, removal of no-data values, and spatial extraction based on the regional boundary were performed to produce a continuous elevation surface. The processed DEM, with elevation values ranging from – 21 to 398 m above msl, was reclassified into 5 (five) classes. The analysis reveals the predominance of low-lying terrain across the Greater Accra Region, which plays a critical role in exacerbating the area's flood vulnerability (Fig. 3B).

Slope is a critical hydrological parameter, directly influencing surface runoff dynamics and playing a substantial role in flood occurrences[76]. In this study, slope values (in degrees) were derived from the processed Digital Elevation Model (DEM) and subsequently reclassified to assess their spatial distribution and flood implications. Low-elevation areas are generally characterized by gentle or nearly flat slopes, which enhance flood and waterlogging susceptibility due to reduced surface runoff velocity (Fig. 3J). Conversely, steeper slopes facilitate rapid runoff, reducing the likelihood of flood accumulation[77]. As such, low-gradient slopes, particularly in the lower reaches of the study area, demonstrate increased flood susceptibility compared to higher-gradient zones. Both elevation and slope exhibit limited spatial variability across the region, a pattern shaped by the area's historical geomorphological transformation.

Curvature serves as an important geomorphological indicator, offering insights into terrain shape and flow dynamics across a landscape[78]. In this study, plan curvature was derived from the Digital Elevation Model (DEM) and classified into three categories: concave, flat, and convex (Fig. 3N). The spatial distribution analysis revealed that approximately 19.19% of the study area falls within the concave category, 48.63% is characterized as flat, and 32.16% exhibits convex curvature. These curvature classes reflect the terrain's influence on surface flow direction and accumulation, which are essential for understanding localized hydrological behavior and flood susceptibility.

Hydrological factors

Distance to streams was considered a key causative factor in assessing flood susceptibility due to its significant role in influencing flood occurrence. Areas in close proximity to natural drainage features, like rivers and streams, are inherently more susceptible to flooding, as they serve as primary channels for directing surface runoff during rainfall events (Fig. 3C).

Drainage density, defined as the total length of streams and rivers per unit area, was evaluated for its contribution to flood risk modulation (Fig. 3E). High drainage density often indicates a greater propensity for runoff concentration and faster hydrological response, thereby increasing the likelihood and severity of flooding. The spatial representations of both distance to natural drainage and drainage density within the study area are illustrated in Fig. 3E, highlighting their combined influence on regional flood dynamics.

The TWI (Fig. 3H) and SPI (Fig. 3K) are also critical hydrological indicators extensively utilized in flood risk and erosion assessment studies. TWI characterizes the spatial distribution of soil moisture by capturing the effects of topography on surface runoff accumulation and saturation patterns[40]. In contrast, SPI measures the erosive power of flowing water, reflecting the potential impact of surface runoff on landscape degradation[79]. Both indices were derived from the DEM using Eqs. (1) and (2). The spatial outputs of TWI and SPI are presented in Fig. 3, providing essential insights into the hydrological behavior and flood vulnerability across the study area.

$$TWI = \frac{LnA_s}{tan\beta} \tag{1}$$

$$SPI = A_s X tan\beta \tag{2}$$

In the given equation, A_s represents the specific catchment area (m^2/m) and β stands for the slope angle (in degrees).

Geological factors

Geology is identified as a critical causative factor in flood susceptibility assessment, given its direct influence on the infiltration capacity of the subsurface, which is inherently governed by lithological composition[80]. We sourced the geological data from the Ghana geological map. The region consists of 5 (five) geologically distinct units, as shown in Fig. 3I. The geology of the GAR is predominantly characterized by five major lithostratigraphic units. The Dahomeyan (Neoproterozoic) Series comprises predominantly acidic orthogneisses, paragneisses, schists, and migmatites, many of which are enriched in biotite, hornblende, and garnet. The Togo (Neoproterozoic) series consists of silicified limestone, phyllite, quartzite, shale, sandstone, and schist. The Togo Series is characterized by rocks that are mechanically weak, loosely cemented, and poorly consolidated due to sedimentary deposition processes[81]. The Accraian (Mid-Devonian) series underlies the southwestern part of the metropolis and is composed mainly of sandstone, grit, and shale. Spatially, the Accraian series and Togo are predominantly located in the central and western parts of the metropolis, which coincide with gentle slopes and areas experiencing high to moderate perennial flooding[46]. In contrast, the Dahomeyan series is less prone to flash floods due to its steeper slopes and thin overburden, which limits groundwater recharge[82]. Other studies[81] have additionally reported that the Dahomeyan Series is composed of metamorphic basement rocks that are mantled by clay and lateritic deposits. However, this unit is also distinguished by extensive lineament networks (structural geological features) that direct surface runoff toward low-lying areas thereby indirectly exacerbating perennial flooding in parts of the GAR.

Meteorological factors

Precipitation is the primary meteorological trigger of flooding in the GAR, with mean annual totals ranging from 624 mm to 1138 mm (Fig. 3G). Although the annual amounts are moderate, flooding is largely driven by high-intensity, short-duration rainfall events during the major and minor rainy seasons. These events frequently exceed infiltration capacity, generating rapid surface runoff and increasing flood risk.

Spatial rainfall variability interacts with the region's low elevation and gentle slopes, which promote runoff accumulation and prolonged inundation. In urbanized areas, extensive impervious surfaces further amplify rainfall–runoff conversion, lowering the rainfall threshold required to trigger flooding.

Anthropogenic and ecological factors

Proximity to road and urban areas networks represents a key conditioning factor governing flood susceptibility within the GAR. Urbanization and transportation infrastructure substantially alter the region's hydrological regime, increasing the likelihood and intensity of flood events. Urban environments are characterized by a high concentration of impervious surfaces such as roads, pavements, and buildings which restrict natural infiltration and enhance surface runoff during precipitation events. Furthermore, the spatial proximity of urban centers to natural drainage systems often intensifies localized flood risks. The expansion of road networks can also disrupt natural water flow patterns, redirecting runoff toward flood-prone zones. Assessing the distance to urban areas and roads thus provides critical insight into anthropogenic influences on flood dynamics. The spatial distribution maps of proximity to urban areas and road networks are presented in Fig. 3D and L respectively.

LULC is also essential parameter in flood susceptibility mapping, as they offer critical insights into the spatial patterns of human activities and natural land features that influence hydrological responses to rainfall events (Fig. 3F). Urban areas are particularly prone to flooding due to the extensive presence of impervious surfaces, which restrict water infiltration and markedly increase surface runoff[3]. Both current and future LULC datasets employed in this study were sourced from Siabi et al.[68]. These datasets were developed for the GAR using the GeoFLUS model under various SSP scenarios. These data were employed to analyze flood-prone zones across different land cover categories, facilitating a better understanding of the relationship between land use patterns and flood vulnerability.

Within flood susceptibility assessments, the NDVI is a key indicator for characterizing land cover conditions and identifying land use dynamics. NDVI values range from – 1 to 1, with higher values corresponding to denser and healthier vegetation cover (Fig. 3O). Vegetation is essential for soil stabilization, as its root systems minimize erosion and enhance infiltration capacity, thereby reducing surface runoff during periods of heavy rainfall. In flood-prone regions, the presence of robust vegetation cover can significantly attenuate the intensity of flooding by promoting natural drainage and limiting the volume and velocity of overland flow. In contrast, Locations with low NDVI values such as degraded landscapes, barren areas, or densely built-up urban zones exhibit limited infiltration and increased surface runoff, thereby increasing their susceptibility to flooding. NDVI also facilitates the identification and delineation of floodplains, allowing for the detection of ecologically vulnerable or altered areas. The integration of NDVI data into flood susceptibility mapping enables decision-makers to pinpoint high-risk zones and design informed, site-specific mitigation strategies.

FR model

FR serves as a robust bivariate statistical analysis method for quantitatively assess the association between independent and dependent factors[60]. This method has proven successful in Flood Susceptibility Zone mapping in various studies[40,83,84]. In this study, the FR method was utilized to quantify the relationship between historical flood occurrences and the identified flood causative variables within the study area, as represented by Eq. (3)[38]. The FR, which represents the ratio of the probability of occurrence to non-occurrence of an event, is quantitatively defined[85]. A higher determined FR value indicates a greater probability. The FR values corresponding to each causative factor were aggregated to derive the Flood Susceptibility Index (FSI), as expressed in Eq. (3).

The FR method is a widely used bivariate statistical approach for quantitatively assessing the relationship between dependent and independent variables[60]. It has been extensively applied in flood susceptibility mapping, demonstrating its reliability in various hydrological and geomorphological studies[40,83,84]. In this study, the FR method was applied to evaluate the relationship between historical flood events and the identified flood causative variables within the GAR. This relationship is mathematically expressed by Eq. (3), as outlined by previous research[38].

The FR represents the ratio of the probability of a specific factor class occurring in flooded areas to its probability of occurrence in non-flooded areas, thereby providing a measure of its contribution to flood susceptibility[85]. Higher FR values indicate a stronger association with flood events and thus a greater likelihood of contributing to future flood occurrences. The FR values for all causative factors were computed and subsequently integrated to generate the FSI, as expressed in Eq. (4), enabling the spatial delineation of flood-prone zones.

$$FR = \frac{f\left(i\right)/\sum f}{p\left(i\right)/\sum p} \tag{3}$$

Here, $f\left(i\right)$ denotes the number of flood pixels for each class of each variable,
$\sum f$ represents the overall number of flood pixels in the study area,
$p\left(i\right)$ signifies the count of pixels in each class of the variable, and.
$\sum p$ is the overall number of pixels in the study area

$$FSI = \sum FR \tag{4}$$

Here, FSI refers to the flood susceptibility index, and $\sum FR$ represents the summation of FRs for all classes within a variable (i.e., the FR of each factor).

Model performance evaluation

The accuracy of the generated flood map was assessed using the Receiver Operating Characteristic (ROC) curve, a scientifically established method for evaluating the predictive performance of statistical and spatial models. The ROC curve plots the true positive rate (sensitivity) on the Y-axis against the false positive rate (1–specificity) on the X-axis, providing a graphical representation of the model's classification ability. The primary metric derived from the ROC curve is the Area Under the Curve (AUC), which serves as a quantitative indicator of model performance. An AUC value of 0.5 or below signifies a model with no predictive capability, rendering it unsuitable for flood susceptibility mapping. Conversely, an AUC value of 1.0 signifies that the model attains perfect predictive accuracy. AUC values above 0.75 are generally considered acceptable for flood prediction, indicating reliable model accuracy[86–90].

To facilitate interpretability, model performance can be categorized based on AUC values, where ranges of 0.5–0.6, 0.6–0.7, 0.7–0.8, 0.8–0.9, and 0.9–1.0 correspond to poor, average, good, very good, and excellent performance, respectively[86].

Results

Spatial distribution of baseline flood susceptibility zones in the GAR

The spatial distribution of flood susceptibility zones within the GAR is presented in Fig. 4A. During the baseline period (2020), the region is predominantly characterized by areas of moderate flood susceptibility (Fig. 3A). However, areas situated along the coastline and certain sections in the northeastern part of the region predominantly exhibit very high flood susceptibility zones (Fig. 3A). This pattern suggests a reduction in flood susceptibility as the distance from the coast decreases. Consequently, districts (Fig. 3A) and towns (Fig. 3B) along the coastal belt are identified as more susceptible to potential flooding in the region in the baseline period.

Specifically, districts like Weija Gbawe, Ablekuma West, Tema, Ashaiman, Ada West, Ada East, among others, fall within the classification of very high flood susceptibility zones (Fig. 3A). Similarly, numerous towns positioned along the coastal areas of the Greater Accra region exhibit very high susceptibility to flooding during the baseline period. Towns such as Weija Barrier, Accra, La, Kwame Nkrumah Circle, Mallam, Kaneshie,

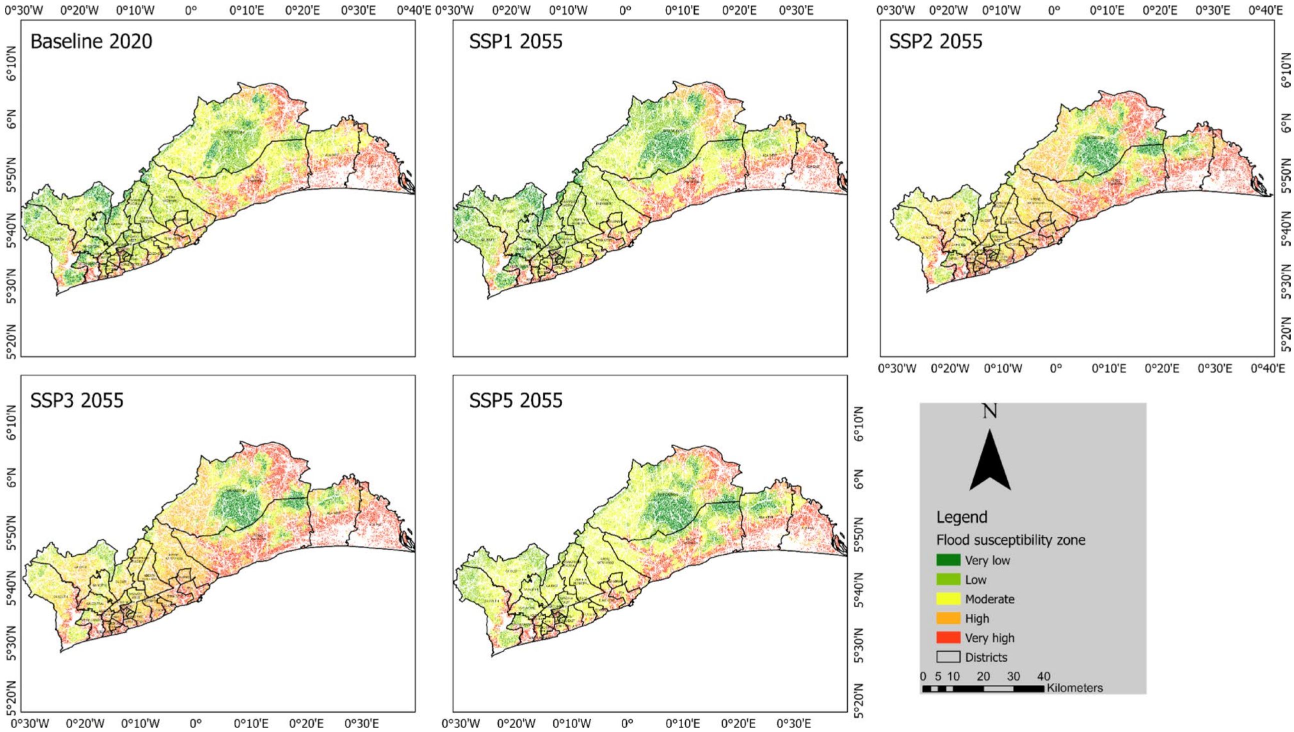

Fig. 4. Spatiotemporal changes in flood susceptibility zones across the SSP scenarios compared with the baseline period (Generated using ARCGIS pro 2.5[59]).

Awoshi, Ashaiman, Teshie, Lashibi, Tema, Kpone, Prampram, Mangotsonya, Ahwiam, Totope, Big Ada, Ada Foah, and others were found within the delineation of the very high flood susceptibility zone in the baseline period (Fig. 3A).

Figure 3C shows the prediction rate, revealing the relative sensitivity of different contributing factors to flood occurrences in the GAR. Among the 15 flood-conditioning factors analyzed in this study, Elevation, Slope, Soil type, Distance to urban, and Stream Power Index (SPI) were identified as the top five contributors to flood occurrences within the region. Additionally, other factors such as Distance to roads, NDVI, STI, LULC, among others, were identified as significant contributors to these occurrences.

In terms of flood susceptibility zoning within the GAR, the analysis indicates that the region is primarily characterized by a moderate flood susceptibility zone, covering over 35% of the total area in the baseline period (Fig. 3D). Following this, about 33% of the region's total area is categorized as having low susceptibility to flooding. However, about 10% and 15% of the total area are designated as high and very high flood susceptibility zones, respectively, during the baseline period.

The performance of the FR model is presented in Fig. 3E. The study achieved an AUC value of 0.82, signifying a robust performance in predicting flood susceptibility (Fig. 3E).

Association between causative factors with historical flood occurrence

The FR model evaluated various factors influencing flood occurrence, including SPI, precipitation, distance from stream, distance from urban, NDVI, LULC, drainage density, slope, elevation, amongst others (see Table S1 in Supplementary material (SM)). These factors revealed critical insights into flood susceptibility within the Greater Accra region (Table S1 in SM).

Table S1 in SM provides FR values used to assess flood probabilities, where FR values greater than 1 indicate high flood probability, while values less than 1 suggest lower likelihood. In the case of SPI, two classes (0.21 – 0.04 and 0.03–1.57) exhibited FR values above 1, indicating that higher SPI values associate with increased flood probability in the studied area. These classes produced about 47 and 45% respectively of the total flood pixels (see Table S1 in SM). Similarly, higher precipitation, specifically between 948 and 1018 mm and 1018–1147 mm, yielded FR values around 1.13 (26%) and 1.06 (45%), respectively, signifying heightened flood probability with increased precipitation. Moreover, distance to urban areas displayed significant influence; classes such as 72.56–141.87 m (28%) and 1–72.56 m (63%) indicated higher flood probability as distances to urban areas decreased. Lower NDVI values across various classes demonstrated FR values between 1.27 and 2.04, showcasing a strong positive association between FR and NDVI. Multiple LULC classes notably contributed to flooding probabilities, with classes like Water (7%), bareland (1%), cropland (55%) and built-up (34%) exhibiting FR values greater than 1, indicating high flood susceptibility. Furthermore, drainage density classes, particularly 0.001–13.3 (26%) and 13.3-26.99 (12%), associated with low drainage density, showed FR values higher than 1, implying increased flood likelihood. Furthermore, slope class 0.04°-1.23° recorded an FR value of 1.3 representing about 75% of the total flood pixels. Various factors including curvature, Aspect, TWI, elevation, Soil, distance to roads, and

STI displayed one to three classes demonstrating a strong positive association between FR and these factors, signifying their substantial influence on flood occurrence in the studied area. For instance, most of the low-lying areas between 21 and 47.25 m above sea level representing about 93% of the total flood pixels recorded an FR value of 2.97. This shows the most influential flood causative driver in the study area (see Table S1 in SM).

Spatial distribution of projected flood susceptibility zones

Figure 4 shows the flood susceptibility zones projected for 2055 under different SSP scenarios. The purpose is to compare the spatial distribution of flood susceptibility zones with existing building footprints between the baseline period and the mid-century horizon (2055), to assess potential changes over time. However, the spatial distribution of flood susceptibility zones for 2055 under SSP1 closely resembles that of the baseline period. The dominance of the moderate flood susceptibility zone persists, with an increased presence of the very low flood susceptibility zone compared to the baseline period. Notably, areas along the coastal belt maintain heightened susceptibility, mirroring the patterns observed in the baseline period (Fig. 4). Similarly, the SSP5 scenario exhibits a comparable pattern to the baseline period, yet with distinct variations. In this scenario, the moderate flood susceptibility zone is anticipated to expand in comparison to both the baseline and SSP1 scenario.

Anticipated changes in flood susceptibility zones are foreseen for SSP2 and SSP3 scenarios, indicating a notable shift in the region's susceptibility landscape. These scenarios project a prevalence of high flood susceptibility zones, particularly concentrated in the central part of the region (Fig. 4). Moreover, the projection suggests an expansion of very high flood susceptibility zones from coastal areas towards inland regions compared to the baseline period, resulting in fragmented areas defined by very low and low flood susceptibility zones (Fig. 4). Figure 5 shows spatial variations in flood susceptibility zones under the different SSP scenarios relative to the baseline, indicating significant gains and losses across the region. indicating notable spatial gains and losses. Under the SSP2 and SSP3 scenarios, the proportion of areas characterized as having high and very high flood susceptibility is expected to rise significantly compared to the baseline by about 1% to 20% under SSP2, and 1% to 10% under SSP3. Conversely, there is an expected decrease in low and moderate flood susceptibility zones, ranging from about 1% to approximately 15% and 1% to around 11%, respectively, compared to the baseline. As a result, the projected trends point to a substantial expansion of very high flood susceptibility zones under the SSP2 and SSP3 scenarios by 2055, as depicted in Fig. 4.

With respect to the flood prediction rate in the region from 2020 to 2055, Fig. S1 in the SM identifies elevation, slope, distance to urban areas, soil type, and Stream Power Index (SPI) as the five most influential contributing factors under the SSP1 scenario. However, by 2045, precipitation is projected to replace SPI as the fifth most influential driver of flooding in Greater Accra. Furthermore, in the period from 2050 to 2055 (see Fig. S in SM), precipitation escalates to become the fourth most sensitive driver, indicating its increasing significance in contributing to flooding occurrences, notably under the SSP1 scenario. This may be due to the high levels of precipitation expected under the SSP1 compared to the other scenarios.

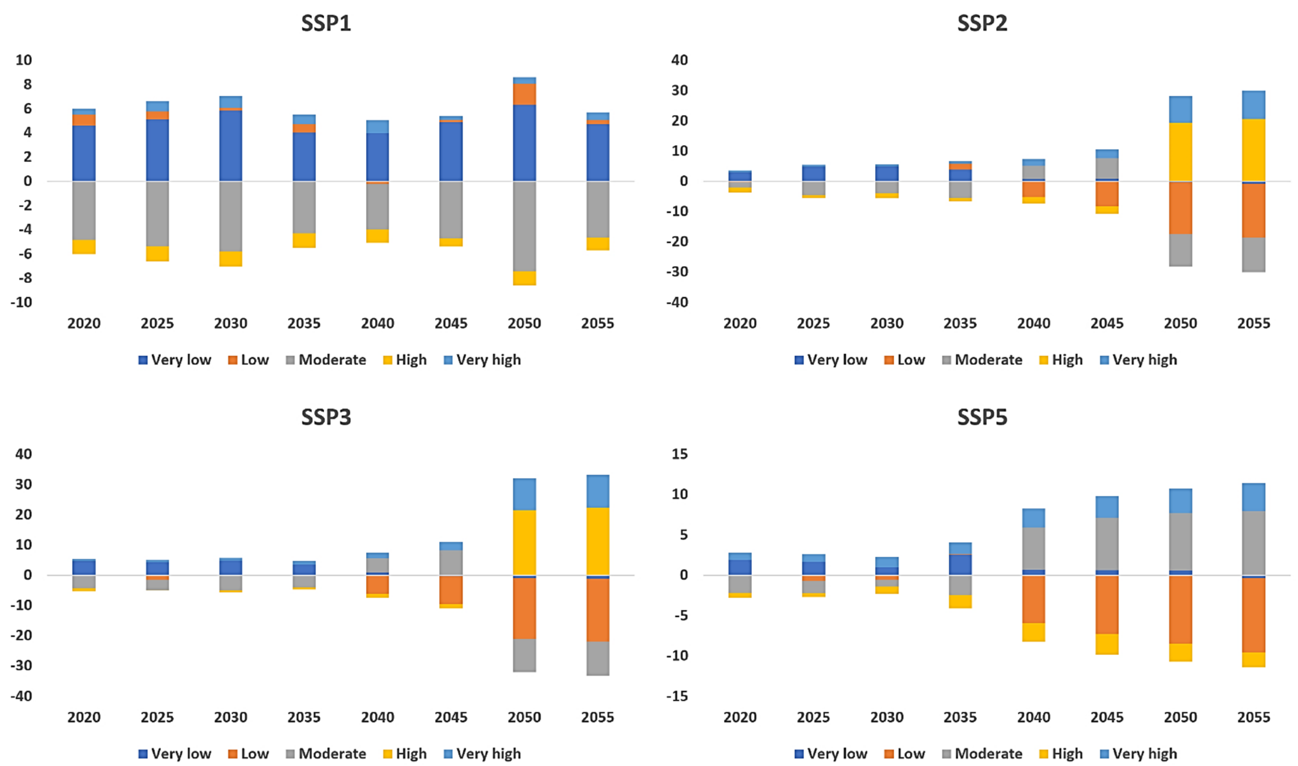

Fig. 5. Percent variation in flood susceptibility zone classification relative to baseline scenario.

For both SSP2 and SSP3 scenarios, elevation, slope, distance to urban areas, soil type, and SPI are projected to remain the five most influential drivers of flood susceptibility between 2020 and 2050 (see Figs. S2 and S3 in the SM, respectively). Notably, in 2055, distance to urban areas is projected to advance to the second most sensitive driver under these scenarios. This emphasizes the anticipated substantial role of proximity to urban areas in influencing flood occurrences, particularly in 2055, within the SSP2 and SSP3 scenarios. Under the SSP5 scenario, precipitation exhibits a variable position within the top five drivers contributing to flooding in the region. In 2025, precipitation is anticipated to rank as the fifth most significant driver, whereas from 2030 to 2040 (see Fig. S4 in SM), it is expected to become the fourth most sensitive driver, highlighting its fluctuating impact on flooding occurrences within the SSP5 scenario.

The Sankey diagram (Fig. 6) visually shows the overall transitions in flood susceptibility zones across the various SSP scenarios. Over time, a decline in very low and low flood susceptibility zones is projected across all SSP scenarios, except for SSP1, which exhibits a relatively higher increase in areas classified as very low flood susceptibility compared to the other scenarios. In contrast, areas classified as high and very high flood susceptibility are expected to expand significantly, with the most pronounced increases occurring under the SSP2 and SSP3 scenarios (Fig. 6). This increase is more pronounced in these scenarios, emphasizing a general escalation in high flood susceptibility zones. Concurrently, there is an expected decrease in moderate flood susceptibility zones across these scenarios. The Sankey diagram provides a visual representation of the anticipated shifts in flood susceptibility zones across different SSP scenarios, revealing a consistent decline in lower susceptibility zones and a notable rise in higher susceptibility zones, especially pronounced in the SSP2 and SSP3 scenarios.

Spatial assessment of flood susceptibility across districts, towns, and building footprints under SSP scenarios in the GAR

At the district level, flood susceptibility zone classifications under the various SSP scenarios for the year 2055 were compared to the baseline conditions (Fig. 7). In general, the spatial distribution of flood susceptibility zones across districts under the SSP1 scenario demonstrates a strong resemblance to the baseline configuration. For example, districts like Adenta Municipal, Tema West, Ashaiman, Ningo Prampram, and Ada West are consistently characterized by moderate flood susceptibility zones in both scenarios (Fig. 7). However, there are instances of notable differences exist between the baseline and the SSP1 scenario. For instance, in the Tema district, the baseline indicates a moderate flood susceptibility zone while the SSP1 scenario predicts a very high flood susceptibility zone in 2055 (Fig. 7). Additionally, while Ablekuma West was classified as a high flood

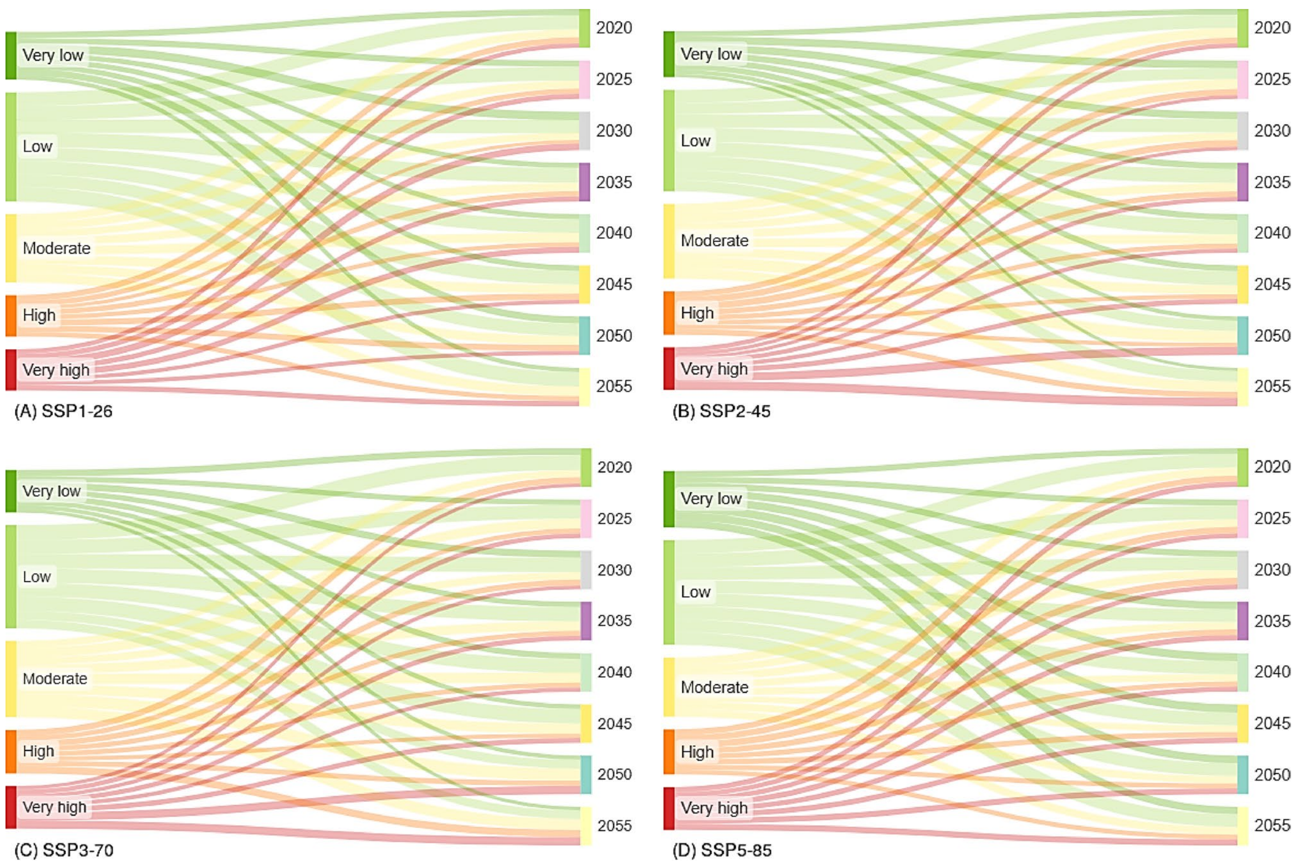

Fig. 6. Sankey diagram showing changes in projected flood susceptibility zones between 2020 and 2055 under SSP scenarios relative to the baseline.

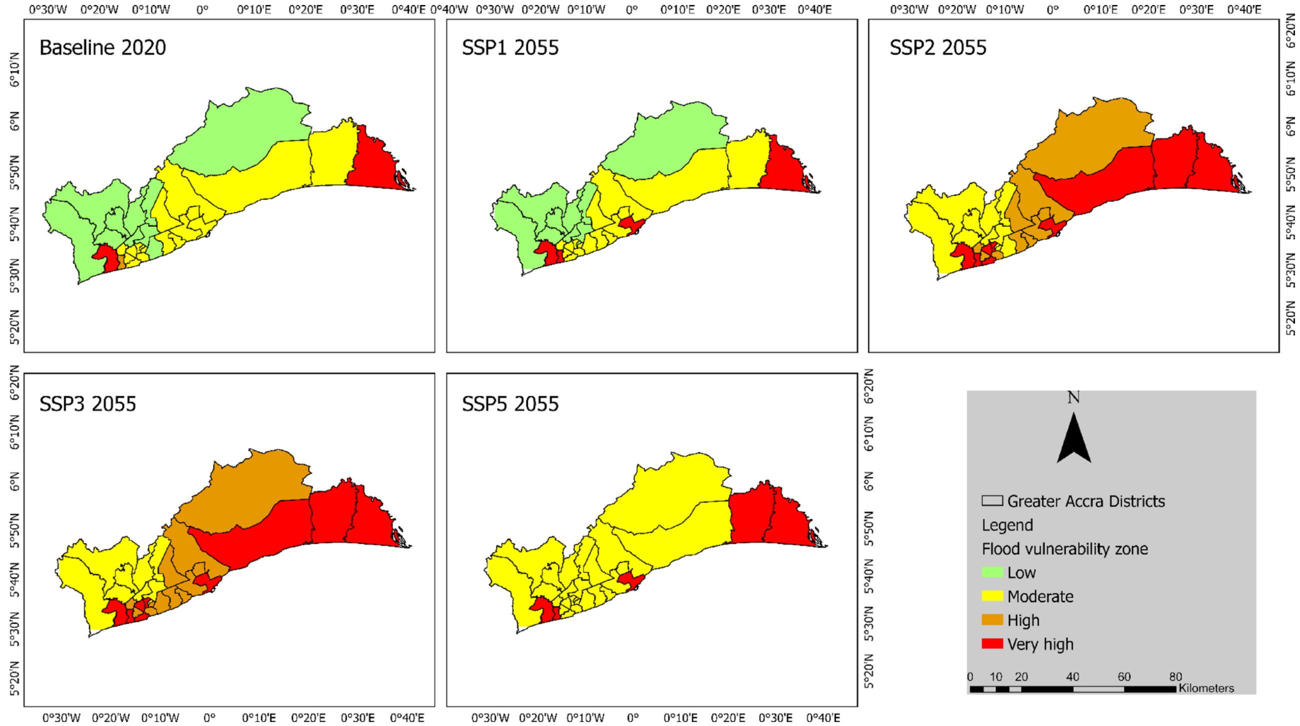

Fig. 7. District-level classification of flood susceptibility under SSP scenarios in 2055 relative to the baseline period (Generated using ARCGIS pro 2.5[59]).

FVI	Baseline	%	SSP1	%	SSP2	%	SSP3	%	SSP5	%
Low	10	34.48	9	31.03	0	0	0	0	0	0
Moderate	16	55.17	16	55.17	10	34.48	8	27.59	24	82.76
High	1	3.45	0	0	10	34.48	12	41.38	0	0
Very high	2	6.91	4	13.79	9	31.03	9	31.03	5	17.24

Table 2. Number of districts per flood susceptibility zones.

susceptibility zone in the baseline period, it is projected to fall into the very high flood susceptibility zone under the SSP1 scenario in 2055. Moderate flood susceptibility zones define 16 (55%) districts, in both the baseline and SSP1 scenarios (see Table 2). However, most districts in the baseline and SSP1 are characterized by low flood susceptibility zones.

The SSP2 and SSP3 scenarios reveal a closely aligned spatial distribution of flood susceptibility classifications across districts within the GAR. For example, districts like Ga South, Ga West, Ga East, Ga North, and others, previously classified in the low flood susceptibility zone during the baseline period, are projected to transition into the moderate flood susceptibility zone under both scenarios (Fig. 7). Similarly, districts like Ningo Prampram, Weija Gbawe, Ablekuma West, Tema, Ada West, and Ada East are anticipated to shift into the very high flood susceptibility zone. The only notable discrepancy between these scenarios pertains to the La Dade Kotopon district. This district displays a moderate flood susceptibility zone under the SSP2 scenario but is projected to experience a high flood susceptibility zone under the SSP3 in 2055 (Fig. 7). In numerical terms, approximately 9 (31%) districts are anticipated to be within the very high flood susceptibility zone under both scenarios (see Table 2). However, the count of districts varies among different flood susceptibility zones. For instance, while 12 (41%) districts are expected to observe high flood susceptibility under SSP3, 10 (34%) districts are projected under SSP2 (Table 2). Hence, most districts are projected to encounter high flood susceptibility under the SSP3 scenario in 2055 (Table 2). Under the SSP5 scenario, most districts (approximately 83%) are projected to fall within the moderate flood susceptibility zone (Table 2).

Concerning town level dynamics, the major towns across the Greater Accra region were assessed based on their susceptibility levels in both the baseline and various SSP scenarios. In the baseline scenario, over 60 towns were situated in the low and very high flood susceptibility zone respectively (Fig. 8). Under the SSP1 scenario, it is anticipated that close to 55 towns will fall under very high flood susceptibility zone with about 28 in the high flood susceptibility zone. However, a significant majority of towns in the Greater Accra region are forecasted to be characterized by the very high flood susceptibility zone under both the SSP2 and SSP3 scenarios. For instance, an estimated 83 and 82 towns are expected to fall into the very high flood susceptibility zone under SSP2 and

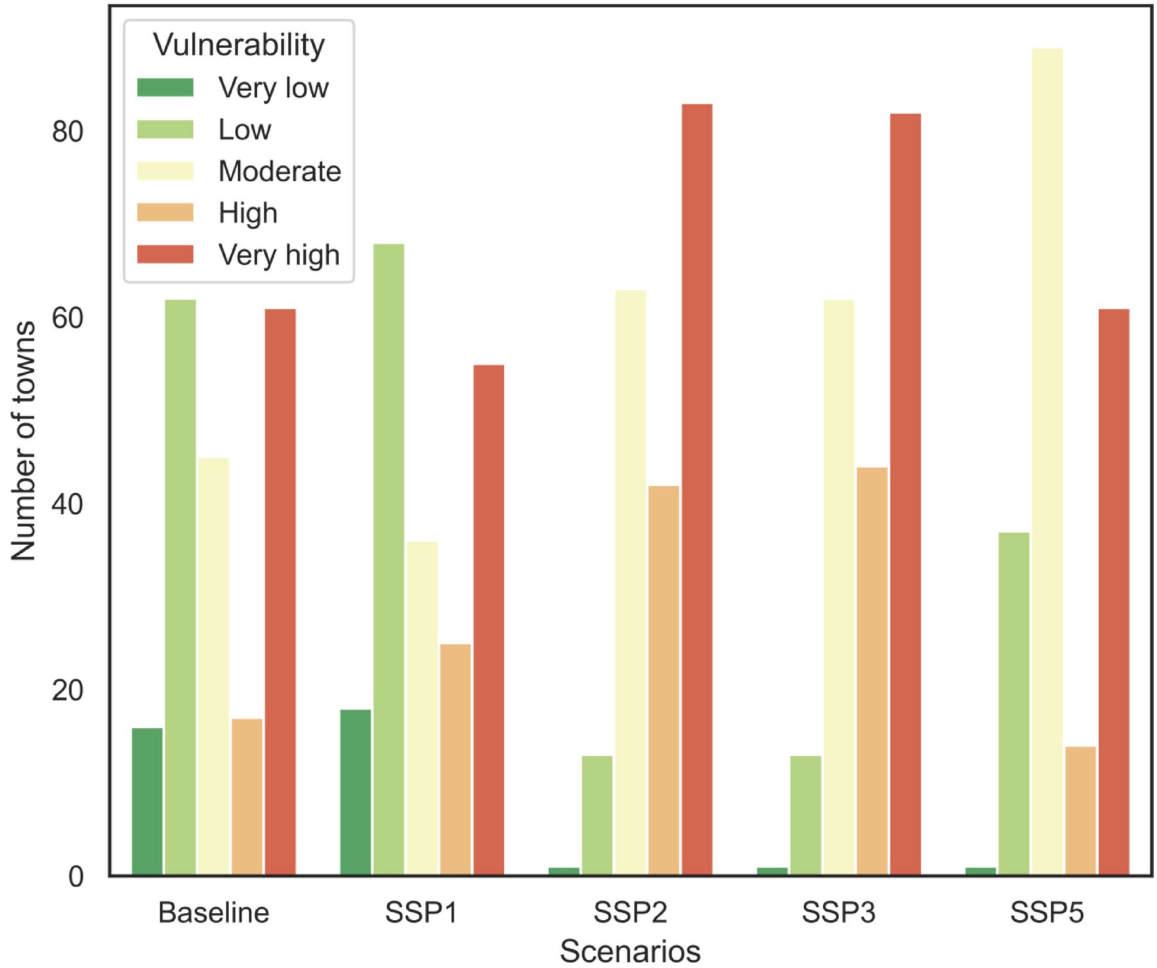

Fig. 8. Number of towns and their flood susceptibility levels in the GAR.

SSP3, respectively (Fig. 8). Similarly, approximately 63 and 62 towns are projected to observe moderate flood susceptibility under SSP2 and SSP3, respectively. In contrast, the SSP5 scenario is projected to be predominantly characterized by towns falling within the moderate flood susceptibility zone, with approximately 61 towns classified under the very high flood susceptibility category (Fig. 8).

Figure 9 depicts the Flood susceptibility of towns due to the elevation in the Greater Accra region. Most towns situated within the very low-lying areas (less than 23 m above mean sea level (msl)) exhibit heightened susceptibility, with approximately 50 to about 80 towns falling within this category. Consequently, these towns experience very high flood susceptibility both in the baseline and under the SSP scenarios (Fig. 9). Notably, SSP1 is expected to register the lowest number (about 50) of towns within the very high flood susceptibility zone, while SSP2 is projected to record the highest number (about 80) of towns in this zone. In areas with low-lying elevations (ranging between 24 and 48 m above sea level), approximately 45 towns are anticipated to observe moderate flood susceptibility under the SSP5 scenario, with around 30 towns expecting low flood susceptibility under SSP1. However, SSP2 and SSP3 scenarios are predominantly characterized by towns facing moderate to high flood susceptibility (Fig. 9). Contrarily, the baseline comprises towns within low to moderate flood susceptibility zones.

Regarding moderately elevated areas (ranging from 49 to 86 m above sea level), both the baseline and SSP1 scenarios predominantly feature towns within low flood susceptibility zones, accounting for about 27 and 33 towns, respectively (Fig. 9). However, SSP2, SSP3, and SSP5 scenarios are dominated by towns facing moderate flood susceptibility. Notably, SSP2 and SSP3 exhibit about 15 and 14 towns within the high flood susceptibility zone, respectively. Towns situated at higher elevations, ranging from 87 to 166 m above sea level, consistently fall within the very low to moderate flood susceptibility zones across both the baseline and SSP scenarios. While the baseline and SSP1 are dominated by towns with very low flood susceptibility, SSP2 and SSP5 consist mainly of towns with low flood susceptibility. In contrast, SSP3 comprises towns predominantly facing moderate flood susceptibility. Finally, the very high areas (ranging from 167 to 398 m above sea level) feature towns primarily categorized under very low and low flood susceptibility zones.

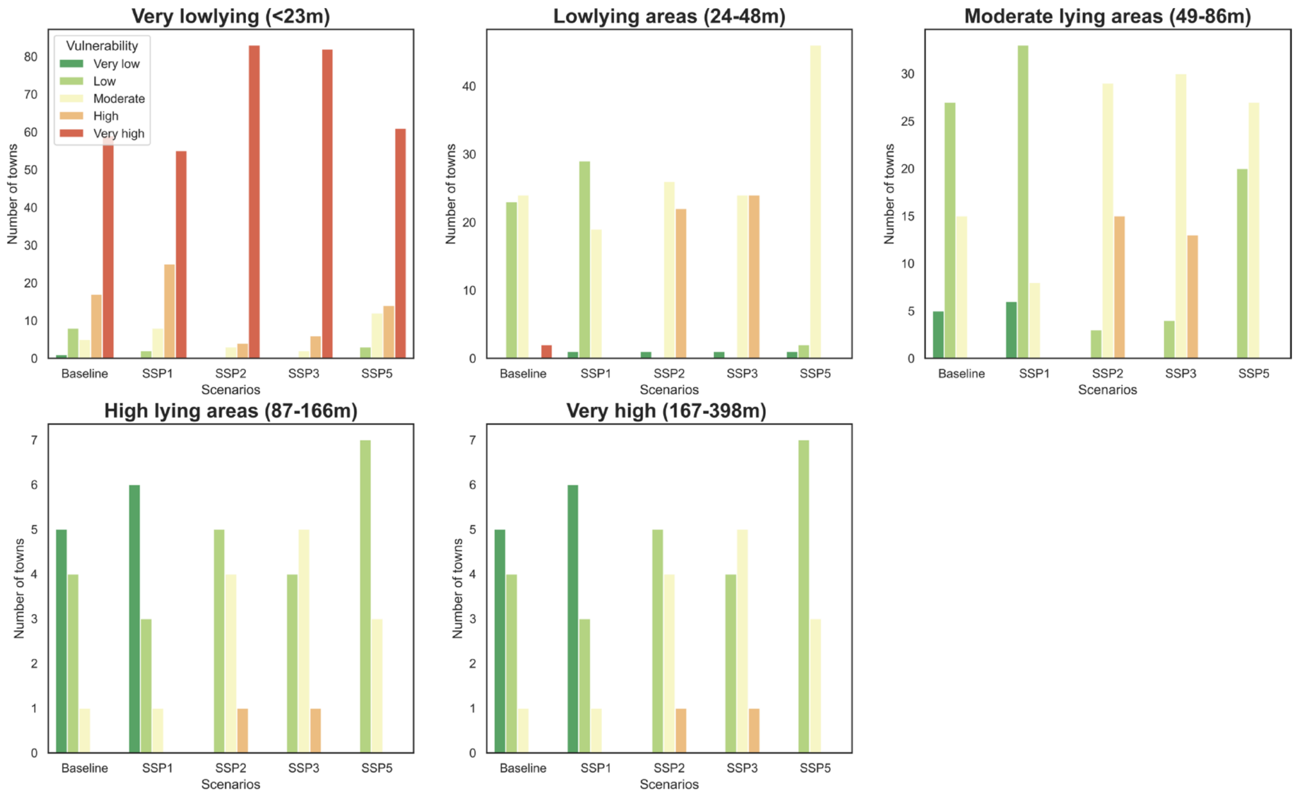

Fig. 9. Flood susceptibility of towns due to elevation.

Building footprints and flood susceptibility zones

Building and construction footprints used in this study were extracted using AI from high-resolution remote sensing data provided by NextGIS[92]. The dataset incorporates the most recent outputs from Microsoft and Google models, along with building data from the basemap. This analysis aimed to estimate the number of buildings and households potentially affected by flooding under various SSP scenarios. It is noteworthy that this assessment was based on the current distribution of building footprints, assuming constant population dynamics across the different scenarios.

A total of 1,323,661 building footprints in the Greater Accra region were superimposed onto both the baseline and SSPs flood susceptibility maps to evaluate the building dynamics relative to flood susceptibility zones (see Fig. S5 in SM). Along the coastline, a significant number of building footprints were observed within the very high flood susceptibility zone during the baseline period (see Fig. S5 in SM). Similar trends persisted across the various SSP scenarios, with most building footprints anticipated to fall within the high and very high flood susceptibility zones under SSP2 and SSP3 (see Fig. S5 in SM).

Figure 10 offers an overview of the number of building footprints within each flood susceptibility zone across the different SSP scenarios. The baseline period and SSP5 scenario predominantly feature buildings within the moderate flood susceptibility zone. For instance, over 600,000 building footprints were situated in the moderate flood susceptibility zone during the baseline period, increasing to approximately 960,000 under SSP5. Under the SSP1 scenario, most building footprints over 676,000 are projected to lie within the low flood susceptibility zone, while more than 437,000 are expected to fall within the moderate susceptibility zone (Fig. 10).

The trends observed under SSP2 and SSP3 scenarios are quite similar, with a dominance of building footprints expected in the high flood susceptibility zone, followed by those in the moderate and very high flood susceptibility zones. However, there are slight numerical differences between these scenarios. For instance, while more than 780,000 building footprints are projected to experience high flood susceptibility under SSP2, this number increases to over 810,000 under SSP3. Similarly, around 346,000 and 304,000 building footprints are expected to face moderate flood susceptibility under SSP2 and SSP3, respectively (Fig. 10).

Population estimates were generated by applying the average household size reported by the Ghana Statistical Service (GSS)[56] to the number of building footprints identified across the baseline and SSP scenario periods. Using an average household size of 3.55 people in the GAR, the population was estimated under the assumption of a constant population across all scenarios. This approach provides an indicative assessment of the number of individuals potentially exposed to varying levels of flood susceptibility under each SSP scenario.

In the baseline period, over 2.44 million people were situated in the moderate flood susceptibility zone, with approximately 1.6 million in the low flood susceptibility zone (Fig. 10). A smaller population of about 26,000 people was recorded in the very high flood susceptibility zone during this period. Under the SSP5 scenario, projections indicate that more than 3.43 million people might reside within the moderate flood susceptibility

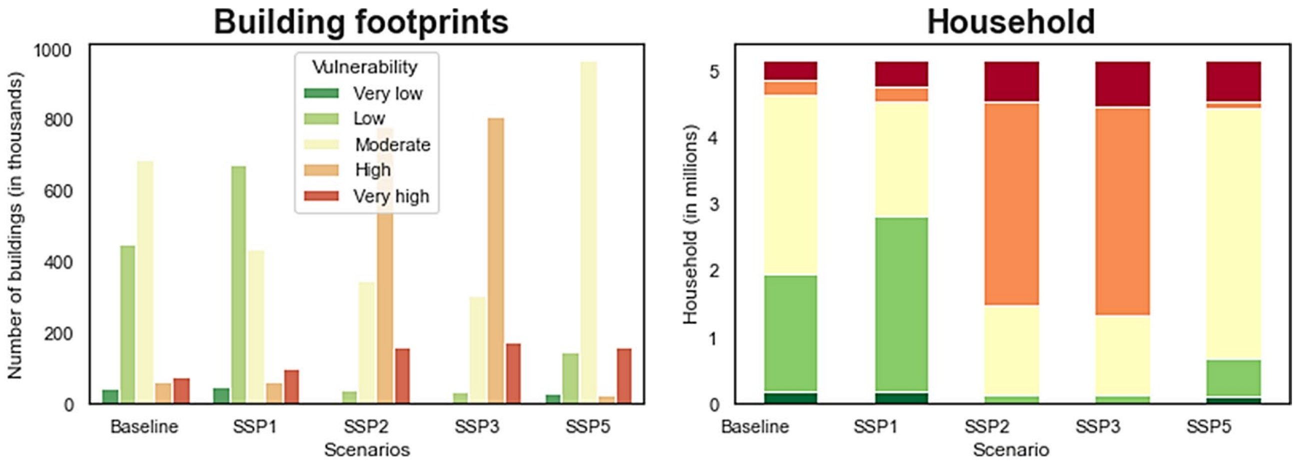

Fig. 10. Building footprints and their flood susceptibility levels (left) and household population and their flood susceptibility level (right).

zone, while 511,000 and 567,000 people could be situated in the low and very high flood susceptibility zones, respectively (Fig. 10). The SSP2 and SSP3 scenarios present similarities in terms of the population distribution across various flood susceptibility zones. These scenarios are predominantly characterized by populations within the high flood susceptibility zone, followed by those in the moderate and very high flood susceptibility zones. For instance, over 3.12 million and 3.24 million people are anticipated within the high flood susceptibility zone under SSP2 and SSP3, respectively. Similarly, approximately 635,000 and 683,000 people might reside within the very high flood susceptibility zone under SSP2 and SSP3, respectively (Fig. 10).

Discussion
Overview
This section interprets the results of the flood susceptibility assessment for the GAR by first evaluating the performance of the FR model, followed by an examination of the dominant environmental and anthropogenic drivers of flooding. It then discusses the spatial distribution of flood susceptibility under baseline conditions and future SSP scenarios, highlighting district- and town-level vulnerabilities. The section concludes by situating the findings within broader urban flood risk management and policy frameworks, with implications for climate adaptation in coastal West Africa.

Model performance and implications
The ROC-AUC value obtained for the study shows that the FR model is appropriate for flood susceptibility mapping in the study area. The ROC-AUC metric measures the performance of the FR Flood Model, which evaluates the likelihood of flood occurrence against non-occurrence. A value of 0.822 indicates that the model has shown strong discriminatory power in distinguishing between flood and non-flood events. Moreover, a value greater than 0.75 is widely recognized as demonstrating strong predictive performance in flood susceptibility mapping, as validated by numerous studies[86,87,90]. Therefore, the demonstrated performance of the Frequency Ratio (FR) model confirms its suitability as a cost-effective decision-support tool for flood risk planning in data-limited urban environments. Moreover, the methodological framework is readily transferable to other West African cities facing comparable constraints in hydrometeorological data availability.

Nonetheless, several limitations should be acknowledged. The model depends on historical flood inventories, which may underrepresent undocumented or small-scale flood events. In addition, the FR approach assumes conditional independence among driving factors, an assumption that may oversimplify the complex, non-linear interactions governing urban hydrological processes.

Influential flood contributing factors
About the underlying causes of flooding in the GAR, elevation emerged as the most influential contributing factor. Notably, areas situated between 21 and 47.25 m above mean sea level (msl) were identified as particularly vulnerable, revealing the increased flood susceptibility of low-lying zones across the region. Despite the region's elevation not being uniformly flat, low-lying areas, particularly within the Accra metropolis[46], contribute to its designation as one of Ghana's naturally flood-prone regions. Given its low-lying nature, runoff waters from neighboring regions, such as the Eastern region and Lower Volta, drain towards the region. Slope emerged as the second most critical factor influencing flood occurrence, with approximately 75% of flooding observed in areas with a slope between 0.04°-1.23°. This implies that location and topography expose the region to flood risk. Additionally, the low-lying nature of parts of the region, with elevations reaching about 5 m above sea level, exacerbates flooding risks in the region[46,93,94]. Climate-induced heavy rains, sea-level rise and tidal surges may even worsen the case of the region especially in informal settlement areas such as Mpoase, Gbegbeyise and Glefe[94,95].

As such, flood risk in the GAR is fundamentally conditioned by geomorphology, making structural flood control alone insufficient. Similar low-elevation coastal cities in West Africa (e.g., Lagos, Abidjan, Lomé, Cotonou) are likely to experience comparable flood dynamics under increasing rainfall variability and sea-level rise.

However, coastal processes such as storm surges and tidal backflow were not explicitly modelled.

Additionally, proximity to urban areas and SPI played significant roles. Areas close to highly urbanized zones exhibited greater susceptibility to flooding due to reduced percolation and infiltration rates resulting from compact concretization. The recurrent waterlogging and frequent flooding, even with minimal rainfall, underscore the near-zero levels of infiltration and percolation in key districts such as Accra metropolis, Weija Gbawe, Korley Klottey, Ablekuma West, Tema, Ashaiman, etc. The rising population in Accra has contributed to an expansion of impervious surfaces through increased pavement and building construction[22,96]. For this region, the urban factors that causes flooding goes beyond just impervious surfaces. For instance, large engineering projects (e.g. the construction of water supply dams and irrigation systems), production activities (e.g. beach sediment mining) and improper disposal of municipal waste accelerates the risk of flooding especially in the western part of the region[97]. Urban areas are characterized by non-meteorological drivers including inadequate drainage systems, construction in waterways, inappropriate waste disposal, limited implementation of roof-top rain harvesting in urban areas, alterations in land cover, scarcity of green spaces, and a lack of tree planting which increase the propensity of the occurrence of floods. Previous research has similarly affirmed that concentrated and unplanned human settlements in flood-prone regions significantly contribute to elevated flood risks, as observed in various parts of Accra such as Avenor, Kaneshie, Weija etc[6,23]. For instance, related studies[98] attributed this phenomenon to settlers acquiring land parcels unlawfully without proper documentation. Primarily, squatters in slum areas, concentrated in low-lying regions where major drainage networks are prevalent, contribute to this trend[98].

Other factors such as distance to road, distance to stream, NDVI, LULC, TWI, precipitation, drainage density etc. were found to be drivers for the occurrence of floods in the region. One of the major issues currently in the region that causes flooding is that a significant number of the drainage systems within the study area have experienced compression and concealment beneath transportation infrastructures. Additionally, many drainage channels are either obstructed by solid waste or have been converted into open sewers, further impeding the effective flow of stormwater. Consequently, the elevated FR values concerning drainage density can be attributed to these factors, rendering these areas highly prone to flood susceptibility. The association with previous flood locations reveals that 71% of these sites are situated in areas with rainfall ranging from 948 to 1147 mm. This suggests that while rainfall intensity serves as a fundamental underlying factor for flooding, though, it cannot solely account for flood situations in regions like GAR. For instance, Ansah et al.[45] observed that most of the majority of rainfall during the flood events remained below the established threshold (> 50 mm per 24 h) in Accra. A major factor complicating flood management efforts for both residents and urban planners in the region is the high variability in rainfall patterns. As noted by Gaisie and Cobbinah[94], substantial month-to-month fluctuations in precipitation make it challenging to accurately predict the timing and occurrence of flood events, thereby limiting the effectiveness of preparedness and response strategies.

Therefore, flooding in the GAR is not solely rainfall-driven but strongly shaped by non-meteorological, human-induced factors. The findings reinforce the need for integrated urban planning, enforcement of building regulations, and waste management reforms across rapidly urbanizing West African cities.

Nonetheless, key limitations remain. Informal settlement dynamics and behavioral drivers such as waste disposal practices were not quantitatively represented in the modelling framework. In addition, institutional and governance factors were addressed qualitatively rather than being explicitly integrated into the flood susceptibility model.

Spatial patterns of flood susceptibility (baseline)

During the baseline period, the Greater Accra Region is primarily dominated by moderate flood susceptibility zones, with low and very high susceptibility zones occurring to a lesser extent. These findings align with the classification of the region as medium, according to the findings of ThinkHazard[99]. The study further identified numerous towns falling within the very high flood susceptibility zone. The study of Asumadu-Sarkodie[6] highlighted specific towns in the region, including Accra, Awoshi, Adabraka, Mallam, Kwame Nkrumah, Dansoman, etc., as being susceptible to flooding. Communities located along major rivers and their tributaries within the region are particularly prone to flooding, especially in the aftermath of intense rainfall events. For these settlers and their dwellings, flooding has become a recurring problem[22,96]. Previous studies have noted the reluctance of many residents in the capital city to address flooding caused by siltation as a significant factor[100]. However, more work is needed to carefully examine this relationship and also to thoroughly investigate the reasons behind such reluctance. The improper disposal of waste into drains diminishes their capacity to effectively channel runoff into the sea[100]. Notably, the Korle Lagoon, Odaw River, and Onyasia River are among the principal water bodies within the Accra metropolitan area[6,23]. Unfortunately, these water bodies have become dumping sites for many, receiving runoff from their catchment areas and carrying it to the sea. This issue culminated in a tragic event on June 3, 2015[6,23]. Alarmingly, this event added to the total count of 567 lives lost between 1968 and 2015 due to flooding incidents.

As such, flood risk is spatially persistent rather than episodic, highlighting the need for long-term adaptation strategies in place of reactive, event-driven responses. Moreover, coastal urban flood risk in the GAR reflects a broader regional pattern observed across West African coastal cities, including Lagos and Lomé.

It is important to note that flood susceptibility mapping does not directly quantify flood depth or inundation duration, and socioeconomic vulnerability at the household level was not explicitly assessed in this study.

Future flood susceptibility under SSP scenarios

The projected flood susceptibility levels under SSP1 are like those of the baseline. However, the very low susceptibility zone under the SSP1 is projected to increase compared to the baseline. The SSP1 scenario is the sustainability scenario where sustainable development is attained with focus on ecofriendly technologies. Here, the GAR is expected to be marked by a blend of low societal susceptibility and low forcing level with significant landuse change (especially increased worldwide forest areas). This is expected to reduce the level of flood susceptibility in the region under SSP1 as revealed by the results. The dominance flood susceptibility zones under the SSP2 and SSP3 were revealed to be high flood susceptibility zones. Although SSP5 is largely dominated by moderate flood zone, almost the entire region is marked by moderate flood zones except four districts with very high flood susceptibility zones. This may be attributed to the projected increase in population under these scenarios. For instance, global economy is expected to expand rapidly with urban expansion rate faster under SSP2, SSP3 and SSP5 scenario. Anticipated population growth, accompanied by subsequent urban expansion and inadequate solid waste disposal practices are likely to elevate the likelihood of flooding incidents is expected to intensify in the future under these scenarios in the Greater Accra region.

Multiple contributing factors to flood occurrences in the GAR have been identified across the various scenarios. Notably, elevation, slope, distance to urban areas, soil type, and SPI are anticipated as the five most sensitive drivers contributing to flooding under SSP2 and SSP3. Numerous studies have linked the incidence of flooding in the region to environmental factors including elevation, slope, drainage density, precipitation, and contour[46]. Conversely, other researches have pointed to non-meteorological factors[6,45], as previously discussed. Nevertheless, the outcomes emphasize the interconnected nature of factors influencing the occurrences flooding under the different SSP scenarios.

Regarding district susceptibility levels, some districts consistently fall between moderate to very high flood susceptibility zones in both the baseline and under the SSP scenarios. Notably, districts such as Ada East and Weija Gbawe persist in the very high flood susceptibility zone in both the baseline and the various SSP scenarios, identifying them as consistently high-risk areas in the GAR. However, under critical scenarios like SSP2, SSP3, and SSP5, all districts in the region are expected to be within the moderate to very high flood susceptibility zones. Moreover, approximately 60–83 towns are identified within the very high flood susceptibility zone during the baseline period and under the SSP scenarios, with peaks in SSP2 and SSP3 scenarios. The spatial distribution reveals that towns along the coastal belt are particularly susceptible. Consequently, towns situated in very low-lying areas (< 23 m above mean sea level) are found to be most vulnerable in both the baseline and SSP scenarios. Likewise, a significant portion of building footprints is concentrated along the coastlines in the baseline, with an anticipated increase in the number of building footprints falling within the high and very high flood susceptibility levels under SSP2 and SSP3. For example, more than 780,000 and 810,000 building footprints, representing 3.12 million and 3.24 million people, are projected to experience high flood susceptibility under SSP2 and SSP3, respectively. This emphasizes the critical susceptibility of the region's inhabitants to floods, both presently and in the future under the SSP2 and SSP3.

For instance, the Greater Accra region's average elevation is just 62 m above sea level. Some places sit at or below zero elevation, making them natural flood plains. The Akuapem-Weija Ridge acts like a funnel, pushing runoff waters at terrifying speeds into low-lying communities such as Adabraka, Kaneshie, Madina, Ablekuma. Slope gradients between 0.04° and 1.23° dominate flood-prone zones—gentle enough to stagnate water, steep enough to accelerate flooding downstream. However, urbanization worsens it all. Paved compounds, tiled walkways, and vanishing vegetation make infiltration almost impossible. When it rains, the water has nowhere to go. Squatter settlements in slum areas, particularly those located in low-lying regions with extensive drainage networks, combine to increase susceptibility levels in the region. According to the West Africa Network for Peacebuilding (WANEP)[101], widespread non-compliance with building regulations has led to the proliferation of informal settlements within designated greenbelt zones. This has resulted in significant vegetation loss and increased the vulnerability of these areas to flooding. In parts of Accra, several structures are built in close proximity to rivers and drainage channels some as near as a few meters from streambeds or even directly across natural watercourses further elevating the flood risk faced by these communities.

According to the UNCT Ghana (2015) report, approximately 8,470 settlement structures are constructed on waterways throughout various parts of the Accra Metropolis (see Fig. S6 in the SM). Notably, communities such as Circle, Nima, Alajo, Old Fadama, and Agbogbloshie are located within major drainage corridors, making them particularly vulnerable to frequent flood incidents. In addition, Nima, Old Fadama, and Agbogbloshie are identified as some of the most densely populated and slum-dominated areas in the city[98,102]. Owing to the existing susceptibility to flooding in low-lying areas, another critical issue that the region may face under the SSP scenarios such as SSP2, SSP3 and SSP5 is the expansion of urban areas into moderate to high-lying areas. It is anticipated that moderate to high-lying areas will be affected as population rapidly expands in the region, especially under the SSP2, SSP3 and SSP5. This is likely to exacerbate flood events in the region, as the expansion of hardscapes in high-lying areas is expected to facilitate rapid runoff in the region.

Consequently, effective flood mitigation in the Greater Accra Region requires a holistic, system-based approach that encompasses all districts, with particular emphasis on those most at risk under critical scenarios. This approach should address the interdependencies across spatial and temporal scales and integrate the full spectrum of disaster risk management phases including pre-disaster mitigation and preparedness, emergency response and recovery during flood events, and long-term adaptation strategies to enhance resilience to future climate change impacts[94]. Special attention is warranted for specific districts, especially those along the coast, such as Accra Metropolis, Weija Gbawe, Tema, Ablekuma West, Ningo Prampram, Kpone Katamanso, Ashaiman, Adenta Municipal, Lekzokuku, La Dade Kotopon, and Korle Klottey.

Various studies, such as Gaisie et al.[94], critique the predominant top-down approach to managing flood events. This method often fails to consider local flooding factors or develop community-centered, bottom-up responses.

The prevailing practice of expressing sympathy and providing relief items to flood victims is largely reactive and superficial, offering temporary relief without addressing the root causes of flooding or strengthening community resilience to future events. Likewise, interventions such as clearing waterways and desilting blocked drains, though important, are often short-term fixes that fall short of delivering sustainable flood risk management solutions. In areas like Accra, this often involves evicting flood-affected individuals and demolishing informal structures deemed to obstruct water flow[55].

Foreign donors have played a significant role in enhancing flood resilience in vulnerable areas by funding the development of critical drainage infrastructure. These efforts aim to mitigate the impacts of flooding on lives, property, and livelihoods. Notable recent interventions include the construction of sea defense walls and the expansion of drainage systems to address the growing threats of coastal and flash flooding. However, these measures have exposed flaws in current flood management strategies, as they often overlook local flooding factors and rely on a top-down approach that fails to address future risks under changing climate conditions. Additionally, unclear institutional responsibilities complicate flood management. The region is divided into numerous districts and municipalities, each with its own National Disaster Management Organization (NADMO), leading to fragmented authority and unclear accountability for citywide flood challenges[103]. Flood management measures are typically led by central government ministries with backing from international partners. However, their effectiveness is undermined by institutional limitations, including insufficient logistical, technical, and financial resources, as well as weak community engagement and fragmented coordination among stakeholders[104].

Rapid, unplanned urbanization in regions like Greater Accra exacerbates flooding issues, and inadequate institutional resources for stormwater management further complicate the situation. Although flooding is recognized as a significant climate impact requiring broader mitigation and adaptation efforts, policymakers in Accra have predominantly employed a top-down approach focused on international frameworks and national policies rather than tailored, local strategies. Ghana's 2012 national urban policy emphasized climate change as critical for a sustainable urban future[105], and various other policies outlined strategies for addressing climate impacts, including flooding. However, there remains a significant gap between these policies and the practical causes of flooding, which are expected to worsen with future climate scenarios.

International frameworks and national policies often stress the importance of knowledge dissemination and coordination, yet there is little evidence connecting these factors to the specific causes of flooding in Accra[104]. The lack of a contextual understanding of local flooding factors and a reliance on top-down approaches have contributed to the shortcomings of recent flood management efforts, despite support from international organizations. Accra's flood management largely focuses on top-down control measures and post-disaster relief, while rapid urbanization and climate impacts likely intensify flooding. Implementing a systems-based, context-sensitive resilience approach, as advocated by Zevenbergen et al.[106], offers a more comprehensive and effective strategy for managing flood risks. This framework focuses on minimizing exposure while enhancing adaptive and response capacities across multiple spatial scales from the city level to neighborhoods and individual buildings. In the case of Accra, a nuanced understanding of local flood dynamics could substantially strengthen urban resilience and guide the development of more effective, locally tailored response strategies. However, these critical insights have yet to be fully incorporated into existing flood management frameworks.

Conventional flood management strategies in addressing the evolving challenges anticipated under the SSP scenarios, which project increasing levels of flood susceptibility in the GAR are currently inadequate. Presently, the region faces a range of flood-related issues, including severe erosion, unregulated settlement expansion, limited drainage capacity, poor waste management practices, and intensifying urbanization. These compounding factors necessitate a more responsive and forward-looking approach, one that embraces an integrated flood risk management strategy within the broader framework of Integrated Water Resources Management (IWRM).

A holistic IWRM-based strategy is critical for optimizing the use of floodplains while minimizing the associated risks to lives and property. Embedding the study's findings within this framework enhances their practical applicability and provides a pathway for actionable policy development. In the context of Greater Accra, where rapid urban growth intersects with climate variability and institutional fragmentation, the implementation of tailored, locally adapted IWRM strategies becomes imperative. Such an approach would include the promotion of decentralized rainwater harvesting and storage systems to reduce reliance on centralized water infrastructure and to mitigate urban flooding particularly in informal settlements that are highly vulnerable to runoff. Furthermore, integrating urban planning with blue-green infrastructure through the inclusion of permeable surfaces, green spaces, and the restoration of wetlands can improve groundwater recharge and reduce stormwater impacts, thereby aligning land use with hydrological functions. Equally important is the strengthening of institutional coordination among key agencies such as the Water Resources Commission (WRC), Environmental Protection Agency (EPA), Hydrological Services Department, and metropolitan authorities. Enhanced collaboration will facilitate data sharing, policy coherence, and joint monitoring of urban water systems. Moreover, community-based monitoring and early warning systems, developed through active stakeholder engagement, can improve local-level adaptive capacity and risk preparedness.

Finally, the application of scenario-based decision support tools that incorporate SSP scenarios will be instrumental in simulating future water demand, flood risks, and infrastructure pressures. These tools can provide spatially and temporally explicit guidance for urban planning and policy interventions. Collectively, these strategies serve to operationalize IWRM principles at the urban scale, advancing more adaptive, participatory, and resilient water governance in the face of climate change.

Therefore, development pathways exert a strong influence on future flood risk, in many cases outweighing the effects of climate forcing alone. In the absence of sustainable urban planning, flood risk is likely to intensify across West African cities facing comparable demographic growth and urbanization pressures.

However, SSP projections are subject to uncertainty arising from assumptions related to population growth and land-use change. In addition, adaptive responses and prospective infrastructure investments were not dynamically represented in the modelling framework.

Conclusion

This study applied a Frequency Ratio–based flood susceptibility framework combined with SSP scenarios to evaluate present and future flood risks in the Greater Accra Region under changing climatic and urbanization conditions. The FR model's performance was rigorously assessed using the ROC-AUC metric, confirming its reliability and accuracy in predicting flood susceptibility. The model achieved an AUC value of 0.82, indicating robust predictive capabilities. By evaluating 15 flood causative factors, critical insights into flood susceptibility in the GAR were uncovered. The analysis of FR values revealed the influence of different factors on flood probabilities, with classes like Elevation, Slope, distance from urban, SPI, precipitation etc. showing a high positive association with increased flood probability. Notably, towns along the coastal belt and low-lying areas were identified as highly susceptible. Examining the spatial distribution of flood susceptibility zones, the baseline period predominantly featured moderate susceptibility, with coastal areas exhibiting very high susceptibility. Projections under different SSP scenarios indicated dynamic shifts in susceptibility zones. SSP2 and SSP3 scenarios foresaw an increase in high and very high susceptibility zones, especially in the central part of the region, while SSP1 and SSP5 scenarios showed variations in the prevalence of moderate susceptibility. District-level dynamics illustrated changes in flood susceptibility zones, with districts such as Weija Gbawe consistently classified as very high susceptibility areas. Town-level assessments revealed that under SSP2 and SSP3, most towns would fall into the very high susceptibility category, emphasizing the need for targeted mitigation strategies. Analyzing flood susceptibility concerning elevation levels demonstrated that low-lying areas faced heightened susceptibility, particularly in the very high flood susceptibility zone. Examining building footprints in flood susceptibility zones indicated a concentration of buildings, especially along the coastline, within high and very high susceptibility zones with millions residing in high and moderate susceptibility zones, emphasizing the importance of comprehensive flood risk management strategies. These findings highlight the intricate relationship between environmental and meteorological elements to the non-meteorological factors in influencing flood susceptibility in GAR. Therefore, this comprehensive assessment provides valuable understanding into flood susceptibility in the GAR, offering a basis for informed decision-making and the development of effective mitigation measures to safeguard communities from the escalating risks of flooding. As climate change and urbanization continue, this research provides a foundation for ongoing efforts to enhance resilience and reduce the impact of flooding in mega cities as well as address SDG 11. Future studies could strengthen the modelling framework by explicitly incorporating coastal processes such as storm surges, as well as integrating informal settlement dynamics and behavioral drivers, including waste disposal practices, institutional and governance conditions, and household-level socioeconomic vulnerability.

Data availability

Current and projected flood susceptibility maps have been deposited in Zenodo (https://zenodo.org/records/10631312) with DOI: https://doi.org/10.5281/zenodo.10631311.

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References

1. Youssef, B. et al. The contribution of the frequency ratio model and the prediction rate for the analysis of landslide risk in the Tizi N'tichka area on the national road (RN9) linking Marrakech and Ouarzazate. *CATENA* **232**, 107464 (2023).
2. Du, J., Fang, J., Xu, W. & Shi, P. Analysis of dry/wet conditions using the standardized precipitation index and its potential usefulness for drought/flood monitoring in Hunan Province, China. *Stoch. Environ. Res. Risk Assess.* **27**, 377–387 (2013).
3. Shafapour Tehrany, M. et al. GIS-based spatial prediction of flood prone areas using standalone frequency ratio, logistic regression, weight of evidence and their ensemble techniques. *Geomat. Nat. Hazards Risk*. **8**, 1538–1561 (2017).
4. Haque, C. E. *Hazards in a Fickle Environment: Bangladesh* **10** (Springer Science & Business Media, 1997).
5. Rahmati, O., Haghizadeh, A., Pourghasemi, H. R. & Noormohamadi, F. Gully erosion susceptibility mapping: the role of GIS-based bivariate statistical models and their comparison. *Nat. Hazards*. **82**, 1231–1258 (2016).
6. Asumadu Sarkodie, S., Owusu, P. A. & Rufangura, P. Impact analysis of flood in Accra, Ghana. *Adv. Appl. Sci. Res.* **6**, 53–78 (2015).
7. Sarkar, D. & Mondal, P. Flood vulnerability mapping using frequency ratio (FR) model: a case study on Kulik river basin, Indo-Bangladesh Barind region. *Appl. Water Sci.* **10**, 17 (2020).
8. GFDRR. Global Facility for Disaster Reduction and Recovery. https://www.gfdrr.org/en.
9. Flash flood program. A Compilation of 20 20–20 21 Global Flood E Vents and International Experience in Flood Management. (2022).
10. Processed by Our World in Data. Number of recorded natural disaster events. EM-DAT, EM-DAT CRED / UCLouvain & UCLouvain, C. R. E. D. Natural disasters. (2023).
11. Statistica Number of flood disasters worldwide from 1990 to 2022. https://www.statista.com/statistics/1339730/number-of-flood-disasters-worldwide/ (2023).
12. Bruna, A. *Global Number of Reported Flood Events 2020–2022, by Region*. (2022).
13. Di Baldassarre, G. et al. Flood fatalities in Africa: From diagnosis to mitigation. *Geophys. Res. Lett.* **37**, (2010).
14. Kellens, W., Terpstra, T. & De Maeyer, P. Perception and Communication of Flood Risks: A Systematic Review of Empirical Research. *Risk Anal.* **33**, 24–49 (2013).
15. Carrick, J. et al. Is planting trees the solution to reducing flood risks? *J. Flood Risk Manag.* **12**, e12484 (2019).
16. Echendu, A. J. Relationship between urban planning and flooding in Port Harcourt city, Nigeria; insights from planning professionals. *J. Flood Risk Manag.* **14**, (2021).
17. Aliyu, A., Liman-Hamza, K. & Lawal, A. Floods in Sub-Saharan Africa; causes, determinants and health consequences. (2023).
18. Eastern Africa Region. Regional Floods and Locust Outbreak Snapshot. https://www.unocha.org/publications/report/south-sudan/eastern-africa-region-regional-floods-and-locust-outbreak-snapshot-january-2020 (OCHA, 2020).

19. Cyclone Idai Reveals Africa's Vulnerabilities. https://www.cfr.org/articles/cyclone-idai-reveals-africas-vulnerabilities (Council on Foreign Relations, 2019).
20. Karley, N. K. Flooding and physical planning in urban areas in West Africa: situational analysis of Accra, Ghana. (2009).
21. Twumasi, Y. A. & Asomani-Boateng, R. Mapping seasonal hazards for flood management in Accra, Ghana using GIS. In *IEEE International Geoscience and Remote Sensing Symposium* **5** 2874–2876. (IEEE, 2002).
22. Rain, D., Engstrom, R., Ludlow, C. & Antos, S. Accra Ghana: A city vulnerable to flooding and drought-induced migration. (2011).
23. Asumadu-Sarkodie, S. Situational Analysis of Flood and Drought in Rwanda. *Int. J. Sci. Eng. Res.* **6**, 960–970 (2015).
24. Gyau-Boakye, P. & Adinku, S. Flood control measures: hazard mapping. *Water Res. Inst. CSIR Accra Unpubl.* (1997).
25. Adinku, S. Disaster preparedness: A sociological study of the flood problem in the Odaw catchment in Accra. *Unpubl. Thesis Present. Dept Sociol. Univ. Ghana* (1994).
26. Kuma, D. Use of Maps, Aerial Photographs and other Remote Sensed data for engineering geology evaluation of flood prone disaster areas of Accra. *Ghana. Eng.* **15**, 1–12 (1996).
27. Jha, A. K., Bloch, R. & Lamond, J. *Cities and Flooding: A Guide to Integrated Urban Flood Risk Management for the 21st Century* (World Bank, 2012).
28. Wilby, R. L. & Keenan, R. Adapting to flood risk under climate change. *Prog Phys. Geogr. Earth Environ.* **36**, 348–378 (2012).
29. Singh, S. *Global Climate Change* (Elsevier, 2021).
30. Liu, W. et al. A probabilistic assessment of urban flood risk and impacts of future climate change. *J. Hydrol.* **618**, 129267 (2023).
31. Shu, E. G. et al. Integrating climate change induced flood risk into future population projections. *Nat. Commun.* **14**, 7870 (2023).
32. Achakulwisut, P. & Persson Å. 10 new insights in climate science 2023/2024 (Global Solutions). https://doi.org/10.1017/sus.2023.25 (2023).
33. Ali, S. A., Khatun, R., Ahmad, A. & Ahmad, S. N. Application of GIS-based analytic hierarchy process and frequency ratio model to flood vulnerable mapping and risk area estimation at Sundarban region, India. *Model. Earth Syst. Environ.* **5**, 1083–1102 (2019).
34. Khosravi, K., Nohani, E., Maroufinia, E. & Pourghasemi, H. R. A GIS-based flood susceptibility assessment and its mapping in Iran: a comparison between frequency ratio and weights-of-evidence bivariate statistical models with multi-criteria decision-making technique. *Nat. Hazards*. **83**, 947–987 (2016).
35. Dewan, A. M., Islam, M. M., Kumamoto, T. & Nishigaki, M. Evaluating Flood Hazard for Land-Use Planning in Greater Dhaka of Bangladesh Using Remote Sensing and GIS Techniques. *Water Resour. Manag.* **21**, 1601–1612 (2007).
36. Lee, M. J., Kang, J. & Jeon, S. Application of frequency ratio model and validation for predictive flooded area susceptibility mapping using GIS. In *IEEE International Geoscience and Remote Sensing Symposium* 895–898. https://doi.org/10.1109/IGARSS.2012.6351414 (IEEE, 2012).
37. Jebur, M. N., Pradhan, B. & Tehrany, M. S. Optimization of landslide conditioning factors using very high-resolution airborne laser scanning (LiDAR) data at catchment scale. *Remote Sens. Environ.* **152**, 150–165 (2014).
38. Tehrany, M. S., Lee, M. J., Pradhan, B., Jebur, M. N. & Lee, S. Flood susceptibility mapping using integrated bivariate and multivariate statistical models. *Environ. Earth Sci.* **72**, 4001–4015 (2014).
39. Liao, W. et al. Projections of land use changes under the plant functional type classification in different SSP-RCP scenarios in China. *Sci. Bull.* **65**, 1935–1947 (2020).
40. Samanta, R. K., Bhunia, G. S., Shit, P. K. & Pourghasemi, H. R. Flood susceptibility mapping using geospatial frequency ratio technique: a case study of Subarnarekha River Basin, India. *Model. Earth Syst. Environ.* **4**, 395–408 (2018).
41. Forson, E. D., Amponsah, P. O., Hagan, G. B. & Sapah, M. S. Frequency ratio-based flood vulnerability modeling over the greater Accra Region of Ghana. *Model. Earth Syst. Environ.* **9**, 2081–2100 (2023).
42. Behzadi, F., Javadi, S., Hafezi, S., Vasheghani Farahani, E. & Golmohammadi, G. Flood risk projection in Iran using CMIP6 models and frequency analysis of precipitation. *Stoch. Environ. Res. Risk Assess.* **38**, 4843–4861 (2024).
43. Kimura, Y., Hirabayashi, Y. & Yamazaki, D. Reduction of the uncertainty of flood projection under a future climate by focusing on similarities among multiple SSP-RCP scenarios. *Sci. Rep.* **15**, 31614 (2025).
44. Koubodana Houteta, D. et al. Flood frequency and amplitude analysis under changing climate scenarios in the Mono River Basin, West Africa. *Sustain. Water Resour. Manag.* **11**, 47 (2025).
45. Ansah, S. O. et al. Meteorological Analysis of Floods in Ghana. *Adv. Meteorol.* **2020**, 1–14 (2020).
46. Dekongmen, B. W. et al. Flood vulnerability assessment in the Accra Metropolis, southeastern Ghana. *Appl. Water Sci.* **11**, 134 (2021).
47. Mensah, H. & Ahadzie, D. K. Causes, impacts and coping strategies of floods in Ghana: a systematic review. *SN Appl. Sci.* **2**, 792 (2020).
48. Clemenz, N., Boakye, R. & Parker, A. Rapid Climate Adaption Assessment (RCAA) of water supply and sanitation services in two coastal urban poor communities in Accra, Ghana. *J. Water Clim. Change*. **11**, 1645–1660 (2020).
49. Cobbinah, P. B., Poku-Boansi, M. & Asomani-Boateng, R. Urbanisation of Hope or Despair? Urban Planning Dilemma in Ghana. *Urban Forum*. **27**, 415–432 (2016).
50. Poku-Boansi, M., Amoako, C., Owusu-Ansah, J. K. & Cobbinah, P. B. What the state does but fails: Exploring smart options for urban flood risk management in informal Accra, Ghana. *City Environ. Interact.* **5**, (2020).
51. Cobbinah, P. B. & Poku-Boansi, M. Towards resilient cities in Ghana: Insights and strategies. *Futures* **101**, 55–66 (2018).
52. Owusu-Ansah, J. K. The influences of land use and sanitation infrastructure on flooding in Kumasi. *Ghana. GeoJournal.* **81**, 555–570 (2016).
53. Amoako, C. & Boamah, E. F. The three-dimensional causes of flooding in Accra, Ghana. *Int. J. Urban Sustain. Dev.* **7**, 109–129 (2015).
54. Cobbinah, P. B., Poku-Boansi, M. & Peprah, C. Urban environmental problems in Ghana. *Environ. Dev.* **23**, 33–46 (2017).
55. Amoako, C. & Cobbinah, P. B. Mensah Darkwah, R. Complex twist of fate: The geopolitics1 of flood management regimes in Accra, Ghana. *Cities* **89**, 209–217 (2019).
56. GSS. Ghana 2021 Population and Housing Census General Report. (2021).
57. Nyarko, B. K. Flood risk zoning of Ghana: Accra experience. *Part B* **12** (2002).
58. Nyarko, B. K. Application of a Rational model in GIS for flood risk assessment in Accra, Ghana. **14** (2014).
59. Desktop, G. I. S. Software | Mapping Analytics | ArcGIS Pro. https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview.
60. Rahmati, O., Pourghasemi, H. R. & Zeinivand, H. Flood susceptibility mapping using frequency ratio and weights-of-evidence models in the Golastan Province, Iran. *Geocarto Int.* **31**, 42–70 (2016).
61. Manandhar, B. Flood plain analysis and risk assessment of Lothar Khola, Nepal. *Unpubl. Ph Thesis Tribhuvan. Univ. Nepal* (2010).
62. Siabi, E. K. et al. Assessment of Shared Socioeconomic Pathway (SSP) climate scenarios and its impacts on the Greater Accra region. *Urban Clim.* **49**, 101432 (2023).
63. O'Neill, B. C. et al. The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci. Model. Dev.* **9**, 3461–3482 (2016).

64. IPCC. Summary for policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. 3–32. https://doi.org/10.1017/9781009157896.001 (Camb. Univ. Press Camb. U. K. N. Y. NY USA, 2021).
65. Rogelj, J. et al. Paris Agreement climate proposals need a boost to keep warming well below 2°C. *Nature* **534**, 631–639 (2016).
66. Kia, M. B. et al. An artificial neural network model for flood simulation using GIS: Johor River Basin, Malaysia. *Environ. Earth Sci.* **67**, 251–264 (2012).
67. Liu, Y. & De Smedt, F. Flood modeling for complex terrain using GIS and remote sensed information. *Water Resour. Manag.* **19**, 605–624 (2005).
68. Siabi, E. K. et al. Future land use simulation modeling for sustainable urban development under the shared socioeconomic pathways in West African megacities: Insights from Greater Accra Region. *J. Environ. Manage.* **376**, 124300 (2025).
69. BBC news. Million hit by floods in Africa. (2007).
70. Twumasi, Y. A. & Asomani-Boateng, R. Mapping seasonal hazards for flood management in Accra, Ghana using GIS. In *IEEE International Geoscience and Remote Sensing Symposium* **5** 2874–2876. (IEEE, 2002).
71. Rain, D., Engstrom, R., Ludlow, C. & Antos, S. Accra Ghana: A city vulnerable to flooding and drought-induced migration. (2011).
72. Amoako, C. & Frimpong Boamah, E. The three-dimensional causes of flooding in Accra, Ghana. *Int. J. Urban Sustain. Dev.* **7**, 109–129 (2015).
73. OCHA Situation Report on floods. in Ghana No.1. https://www.unocha.org/publications/report/ghana/ocha-situation-report-floods-ghana-no1 (OCHA, 2007).
74. Siabi, E. K. et al. Flood risk assessment under the shared socioeconomic pathways: a case of electricity bulk supply points in Greater Accra, Ghana. *Discov Water*. **4**, 76 (2024).
75. Choubin, B. et al. An ensemble prediction of flood susceptibility using multivariate discriminant analysis, classification and regression trees, and support vector machines. *Sci. Total Environ.* **651**, 2087–2096 (2019).
76. Meraj, G., Romshoo, S. A., Yousuf, A. R., Altaf, S. & Altaf, F. Assessing the influence of watershed characteristics on the flood vulnerability of Jhelum basin in Kashmir Himalaya. *Nat. Hazards.* **77**, 153–175 (2015).
77. Tehrany, M. S. & Kumar, L. The application of a Dempster–Shafer-based evidential belief function in flood susceptibility mapping and comparison with frequency ratio and logistic regression methods. *Environ. Earth Sci.* **77**, 490 (2018).
78. Rahmati, O. & Pourghasemi, H. R. Identification of Critical Flood Prone Areas in Data-Scarce and Ungauged Regions: A Comparison of Three Data Mining Models. *Water Resour. Manag.* **31**, 1473–1487 (2017).
79. Khosravi, K. et al. A comparative assessment of flood susceptibility modeling using Multi-Criteria Decision-Making Analysis and Machine Learning Methods. *J. Hydrol.* **573**, 311–323 (2019).
80. Haghizadeh, A., Siahkamari, S., Haghiabi, A. H. & Rahmati, O. Forecasting flood-prone areas using Shannon's entropy model. *J. Earth Syst. Sci.* **126**, 39 (2017).
81. Addo, K. A. Changing morphology of Ghana's Accra coast. *J. Coast Conserv.* **15**, 433–443 (2011).
82. Erdélyi, M. The hydrogeology of Ghana. *Int. Assoc. Sci. Hydrol. Bull.* **10**, 44–52 (1965).
83. Tehrany, M. S., Pradhan, B. & Jebur, M. N. Flood susceptibility mapping using a novel ensemble weights-of-evidence and support vector machine models in GIS. *J. Hydrol.* **512**, 332–343 (2014).
84. Cao, C. et al. Flash Flood Hazard Susceptibility Mapping Using Frequency Ratio and Statistical Index Methods in Coalmine Subsidence Areas. *Sustainability* **8**, 948 (2016).
85. Bonham-Carter, G. *Geographic Information Systems for Geoscientists: Modelling with GIS* (Elsevier, 1994).
86. Saha, S. Groundwater potential mapping using analytical hierarchical process: a study on Md. Bazar Block of Birbhum District, West Bengal. *Spat. Inf. Res.* **25**, 615–626 (2017).
87. Ozdemir, A. & Altural, T. A comparative study of frequency ratio, weights of evidence and logistic regression methods for landslide susceptibility mapping: Sultan Mountains, SW Turkey. *J. Asian Earth Sci.* **64**, 180–197 (2013).
88. Akgun, A., Dag, S. & Bulut, F. Landslide susceptibility mapping for a landslide-prone area (Findikli, NE of Turkey) by likelihood-frequency ratio and weighted linear combination models. *Environ. Geol.* **54**, 1127–1143 (2008).
89. Egan, J. P. Signal detection theory and ROC analysis. (1975).
90. Pradhan, B. Landslide susceptibility mapping of a catchment area using frequency ratio, fuzzy logic and multivariate logistic regression approaches. *J. Indian Soc. Remote Sens.* **38**, 301–320 (2010).
91. Matplotlib — Visualization with Python. https://matplotlib.org/.
92. Custom area. buildings AI— download building footprints from Microsoft and Google and buildings from OpenStreetMap. *NextGIS Data* https://data.nextgis.com/en/region/custom/msbld/.
93. Accra Metropolitan Assembly (AMA). Accra Climate Action Plan. (2019).
94. Gaisie, E. & Cobbinah, P. B. Planning for context-based climate adaptation: Flood management inquiry in Accra. *Environ. Sci. Policy*. **141**, 97–108 (2023).
95. Siabi, E. K. et al. Quantifying future climate extreme indices: implications for sustainable urban development in West Africa, with a focus on the greater Accra region. *Discov Sustain.* **5**, 167 (2024).
96. Okyere, C. Y., Yacouba, Y. & Gilgenbach, D. The problem of annual occurrences of floods in Accra: an integration of hydrological, economic and political perspectives. *Theor. Empir. Res. Urban Manag.* **8**, 45–79 (2013).
97. Appeaning Addo, K., Walkden, M. & Mills, J. P. Detection, measurement and prediction of shoreline recession in Accra, Ghana. *ISPRS J. Photogramm Remote Sens.* **63**, 543–558 (2008).
98. Oppong, B. E., Asomani-Boateng, R. & Fricano, R. J. Accra's Old Fadama/Agbogbloshie settlement. To what extent is this slum sustainable? *Afr. Geogr. Rev.* **39**, 289–307 (2020).
99. ThinkHazard!- Greater Accra. ThinkHazard - Greater Accra.pdf. (2022).
100. Tabiri, M. O. Perennial problem of floods in Accra: What is the way forward? *Int. J. Adv. Res.* **2**, (2015).
101. NEWS Quick Update. - Flooding in the Greater Accra Region claims 12 lives on April 15, 2019 – West Africa Network for Peacebuilding (WANEP). https://wanep.org/wanep/news-quick-update-flooding-in-the-greater-accra-region-claims-12-lives-on-april-15-2019/ (2020).
102. Owusu, A. B. & Agbozo, M. Application of Geographic Information Systems for Flood Risk Analysis: A Case Study from Accra Metropolitan Area. *Present Environ. Sustain. Dev.* **13**, 81–97 (2019).
103. Gaisie, E., Kim, H. M. & Han, S. S. Accra towards a city-region: Devolution, spatial development and urban challenges. *Cities* **95**, 102398 (2019).
104. Frick-Trzebitzky, F. *GIS-What Can and What Can't It Say about Social Relations in Adaptation to Urban Flood Risk?* (Universität Trier, 2019).
105. Government of Ghana. National urban policy framework. Accra. (2012).
106. Zevenbergen, C., Veerbeek, W., Gersonius, B. & Van Herk, S. Challenges in urban flood management: travelling across spatial and temporal scales. *J. Flood Risk Manag.* **1**, 81–88 (2008).

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Declarations

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