Nature-Based Solutions 7 (2025) 100236

Contents lists available at ScienceDirect

Nature-Based Solutions

journal homepage: www.elsevier.com/locate/nbsj

A scenario-based analysis of wetlands as nature-based solutions for flood risk mitigation using the TELEMAC-2D model

Kirk B. Enu [a,*], Fabian Merk [b,*], Hao Su [b], Manuel Rauch [c], Aude Zingraff-Hamed [d,e], Karl Broich [b], Kristian Förster [f], Stephan Pauleit [a], Markus Disse [b]

[a] School of Life Sciences, Chair for Strategic Landscape Planning and Management, Technical University of Munich, Emil-Ramann-Str. 6, 85354 Freising, Germany
[b] School of Engineering and Design, Chair of Hydrology and River Basin Management, Technical University of Munich, Arcisstrasse 21, 80333 Munich, Germany
[c] Institute of Geography, University of Augsburg, Alter Postweg 118, 86159 Augsburg, Germany
[d] ENGEES National School for Water and Environmental Engineering, 1 cour des cigarières, CS 61039, 67070 Strasbourg, France
[e] Université de Strasbourg, CNRS, ENGEES, UMR 7362 LIVE (Image, City, Environment Laboratory), 3 rue de l'Argonne, 67000 Strasbourg, France
[f] Institute of Ecology and Landscape, Weihenstephan-Triesdorf University of Applied Sciences, Am Hofgarten 1, 85354 Freising, Germany

ARTICLE INFO

Keywords:
Urban floods
Global South
Sub-Saharan Africa
Peak flow
Rapidly urbanising cities
Wetlands degradation
Floodplains

ABSTRACT

Urban flooding is an escalating threat in rapidly urbanising regions, particularly in sub-Saharan Africa (SSA), where unregulated expansion and climate change intensify risks. Nature-based Solutions (NbS) are increasingly recognised as sustainable and cost-effective, yet empirical evidence to support their strategic planning, especially through high-resolution modelling in data-scarce settings, remains limited. This study presents one of the first integrated applications of spectral indices and TELEMAC-2D hydrodynamic modelling to assess NbS effectiveness in a rapidly urbanising SSA city, the Greater Kumasi Metropolitan Area (GKMA) in Ghana. Focusing on the Aboabo catchment, we analysed wetland ecosystem loss (1986–2023) and evaluated the impact of NbS interventions (floodplain restoration and wetland creation) on flood dynamics. Specifically, we assessed the flood reduction potential of different implementation scenarios and how these scenarios affect the timing and intensity of peak flows under varying storm conditions. Results show that wetland cover declined (59 %) while built-up areas expanded (134 %), leading to reduced cumulative discharge and more intense, shorter-duration floods. The *combined* scenario (floodplain restoration and wetland creation) achieved consistent peak flow reductions (16–19 %) in prolonged storms, while the *ambitious_restoration* scenario (restoring the full floodplain network) performed best (24 %) in short-duration events. In contrast, the *landscape* scenario (wetland creation in available spaces) achieved only modest reductions (1–3 %), underscoring the limited capacity of space-dependent approaches and the importance of spatial targeting. These findings support the case for hybrid approaches that combine NbS with engineering solutions to enhance both immediate and long-term flood resilience. Our approach demonstrates the adaptability of TELEMAC-2D for NbS modelling in data-limited contexts and offers a replicable, decision-relevant framework for integrating NbS into urban flood resilience planning across SSA and similar regions.

1. Introduction

Urban floods are increasing in incidence and severity across the globe due to rapid urbanisation and climate change. From 2000–2018, there were 3798 flash flood events worldwide, which resulted in the loss of over USD 592 billion and claimed about 100 thousand lives [85]. Presently, more than half of the world's population lives in urban areas, and it is projected that this will continue on an upward trajectory, reaching 60 % by 2030 and 68 % by 2050 [110]. With much of the surge in urbanisation processes occurring in the Global South, more people in this region will face high flood risk, which will complicate the ability to cope with extreme weather events, particularly in urban agglomerations [55].

In sub-Saharan Africa (SSA), flood incidences have increased more than tenfold since 2010 [119]. Reflecting this broder trend, Ghana in West Africa has experienced a sharp rise in urban floods [76], with about 1 million people affected yearly by extreme floods since 2017 [10]. This increasing flood situation has been affirmed to be driven mainly by anthropogenic factors rather than climate change [3]. Mintah et al. [78] highlighted the critical impact of the degradation of wetlands and

* Corresponding authors.

https://doi.org/10.1016/j.nbsj.2025.100236
Received 14 January 2025; Received in revised form 10 May 2025; Accepted 17 May 2025
Available online 18 May 2025

floodplains, noting that these areas—essential for stormwater attenuation—are increasingly being converted into residential and commercial development as prime buffer lands become scarce due to rapid urban expansion. Although state institutions are mandated to manage wetland ecosystems sustainably (e.g., Environmental Protection Agency and Spatial Planning departments), they are unable to effectively do so because several internal and external institutional challenges constrain them. Notably, these state institutions do not have direct access to many ecologically sensitive areas because 78 % of land resources in Ghana, including several wetlands, are (in most cases) under the ownership and control of customary institutions and communities, whose interests may not always be to protect them [4]. While some may sell these low-lying lands for financial interests, others lack appreciation of how important they are for flood management [12]. As a result, wetlands, floodplains and other water-related ecosystems continue to dwindle in size [33].

Against this backdrop, conserving and restoring degraded ecosystems like wetlands and floodplains offers a viable pathway for recovering their essential regulatory ecosystem functions, especially flood regulation [38,58,108]. Although rivers are not wetlands, some parts of river ecosystems may function as wetlands if they contain hydric soils, experience consistent or periodic water saturation and support hydrophytic vegetation. Restoring (and creating) wetlands may include enhancing hydrological connectivity between rivers and floodplains, extending water flow paths across floodplains, widening river channels, revegetation and constructing storage basins, among other measures [96]. Besides, conventional engineering solutions traditionally used in flood risk mitigation often provide only immediate short-term effectiveness and fail to adapt to climatic and environmental change [68,123]. For example, numerous cases have shown how levees have been overtopped by waves or failed due to internal erosion and instability shortly after construction [92]. Additionally, conventional engineering solutions are generally capital-intensive and frequently have adverse effects on natural ecosystems, which can make them counterproductive to achieving sustainable and long-term flood resilience [49,90].

On this account, concepts that promote working with nature rather than against it, like nature-based solutions (NbS), are increasingly being prioritised in policy and practice to reverse urbanisation's negative impacts on ecosystems and advance climate adaptation [15,102,124]. NbS are defined as solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience [46,95]. For mitigating flood risk hazards, the restoration of wetlands in river catchments and floodplain restoration is considered as NbS that can effectively restore natural hydrological cycles for regulating runoff [116], enhance environmental quality and biodiversity [88], offer more cost-effective and sustainable outcomes [90], improve urban resilience to climate change and provide significant social and economic co-benefits [125].

In the context of the Greater Kumasi Metropolitan Area (GKMA)–Ghana's fastest urbanizing area and a significant flood-prone zone–there have been numerous calls to apply NbS to address flooding in the city. However, studies that assess the feasibility of such interventions and quantify their potential effectiveness remain largely absent [1,5,78]. It is unclear if wetlands conservation and restoration will be sufficient for mitigating present and future floods or if a landscape-scale approach where wetlands are created will be needed to help significantly reduce stormwater runoff across different storm conditions and durations [83,87]. Thus, studies need to simulate NbS under present land use patterns using different implementation scenarios to precisely understand how they should be planned and implemented on the ground towards flood-resilient cityscapes [40]. Additionally, because most of the earlier studies on flooding in GKMA used qualitative methods, especially in-depth interviews, to arrive at their conclusions, a holistic understanding of flood hazards in the city is missing [43].

In simulating the potential of NbS (and engineered solutions) for flood hazard mitigation, models such as HEC-RAS [120], MIKE Urban and Storm Water Management Models [23] are commonly used. The reliability of depends on the quality of input datasets, well-defined boundary conditions and proper representation of relevant processes. Models can also be computationally expensive and require careful calibration and validation [14]. More so, high-resolution urban flood inundation modelling requires precise information on topography, buildings, narrow watercourses and storm sewer systems [29]. Additionally, such complex models demands make validation difficult when input data are limited [62]. Furthermore, localised conditions can complicate the application of advanced hydrodynamic models, raising concerns about the reliability of flood inundation estimates at the city scale [117]. This challenge is particularly pronounced in data-scarce regions like SSA and cities like GKMA [72].

For this study, TELEMAC-2D was selected due to its proven suitability for simulating flood dynamics in complex and data-scarce environments, such as those found in rapidly urbanising SSA cities. It is a widely used open-source model that solves the 2D shallow water equations without simplifications. TELEMAC-2D has flexible unstructured meshing that allows for fine spatial resolution in critical areas like wetlands, floodplains and vegetated buffers, thereby supporting the representation of hydrological and ecological connectivity—key for assessing NbS effectiveness [56]. TELEMAC-2D also employs advanced numerical schemes that improve flow simulations in dynamic and heterogeneous terrains [105] and it uniquely enables the spatial and temporal variability of wetland features to be captured adaptively [14]. These capabilities distinguish it from more deterministic or rigid models, offering a nuanced depiction of interactions between built-up areas and natural ecosystems. Despite these strengths, applications of TELEMAC-2D in SSA remain limited, partly due to data constraints—particularly the scarcity of high-resolution topographic, hydrologic and infrastructure data—which can introduce uncertainty into scenario-based simulations [17]. To support its wider use therefore, its adaptability and capacity to integrate ecological complexity need to be evaluated.

With this context, we applied the TELEMAC-2D model in the rapidly urbanising and data-scarce SSA setting, focusing on the Aboabo Basin in the GKMA, Ghana, to quantify the effectiveness of NbS (floodplain restoration and wetland creation) in mitigating flood hazards. The study had three main objectives: first, to use remote sensing techniques and spectral indices (Modified Normalized Difference Water Index (MNDWI), Normalized Difference Vegetation Index (NDVI), Normalized Difference Built-up Index (NDBI)) to quantify the spatial and temporal changes in water-related ecosystems and evaluate their influence on hydrological responses, particularly peak discharges and flood duration; second, to evaluate the flood reduction potential of different NbS implementation scenarios; and third, to investigate how these scenarios affect the timing and intensity of peak flows under varying storm conditions. The approach provides a basis for informing strategic and adaptive flood risk management, particualrly in rapidly growing urban contexts with limited data availability.

2. Materials and methods

2.1. Approach

The research approach was quantitative, integrating both descriptive and experimental designs. Remote sensing techniques, specifically spectral indices, were employed to investigate changes in the spatial extent of water-related ecosystems (rivers, floodplains and wetlands) in the Aboabo basin over the years. The effectiveness of wetland NbS for flood hazard mitigation was assessed through geospatial scenario development in ArcGIS Pro 3.2 and flood simulation using the TELEMAC-2D model (Fig. 1). This approach allowed for a comprehensive quantitative analysis of the impact of wetland changes on flood hazard and the potential effectiveness of NbS in mitigating flooding.

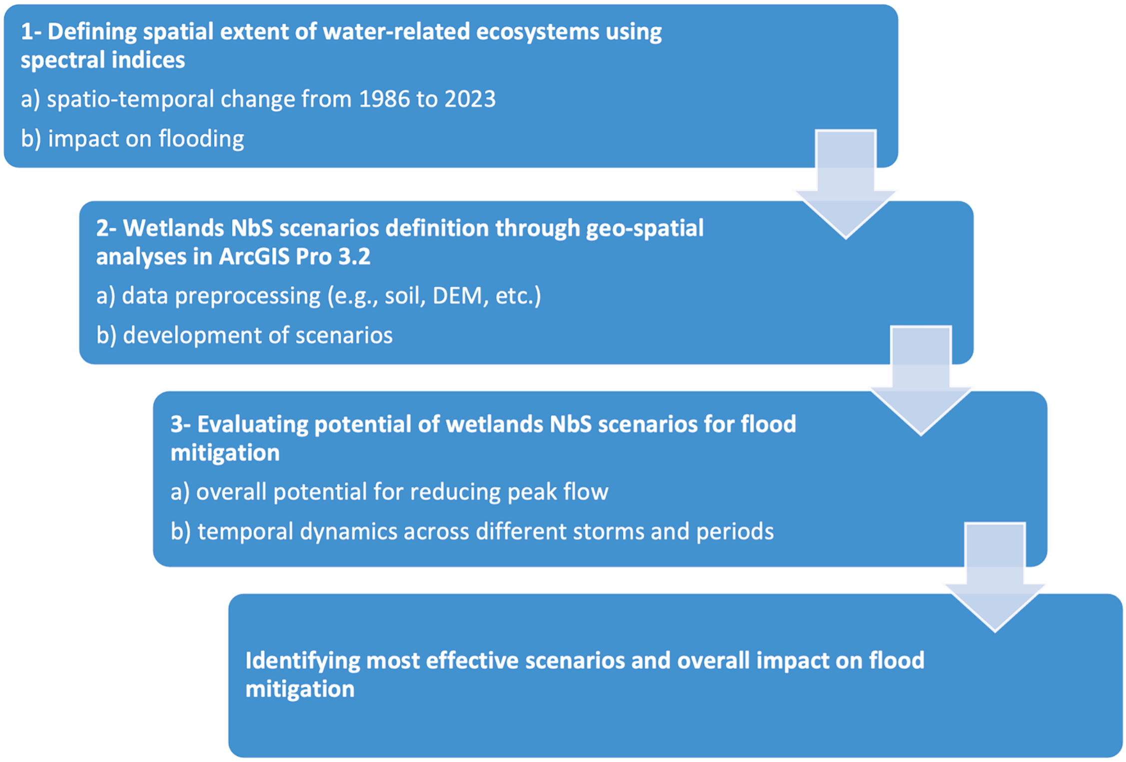

Fig. 1. Overall methodological approach.

2.2. Case study area

GKMA, where the Aboabo catchment is located, is both the administrative capital of the Ashanti Region and the seat of the *Asante* Kingdom in Ghana. It attained metropolitan status in 1987 and has undergone significant urban development, especially since 2000. It is one metro area and six sprawled municipalities. Although the Kumasi Metropolis has a total land area of 254 km^2, GKMA has 2746 km^2 [86]. It has a population of about 3.5 million people [114] who live in over 90 suburbs [51], with about 20 % high-income, 50 % middle-income and 30 % low-income.

The area has a tropical wet-dry (*Aw*) climate according to the Köppen classification. It is located within the forest zone of Ghana and experiences two rainfall seasons [6]. The first rainfall season starts in mid-March and lasts until July, whereas the second starts in September and ends in mid-November. The mean annual rainfall ranges from 1250 to 2000 mm, and the mean number of rainy days is 9.9. Its daily average temperature ranges from 21 °C (minimum) to 31 °C (maximum). The average humidity at sunrise is 84 % and 60 % at sunset [66].

The topography of the catchment is generally flat, with significant areas of gently undulating slopes rising from 218 to 356 m above sea level. The landscape also features flat-topped interfluvial ridges, with widths ranging from 1500 to 2500 m. The soils are dominated by lithosols, which have limited soil material and typically exhibit a high stone content and high permeability. There are also orthic acrisols, which are characterised by a subsurface horizon with an accumulation of low-activity clays and significant desilication, making them less porous than lithosols [24].

GKMA was selected, focusing on the Aboabo catchment within the area (Fig. 2), because it closely reflects the urban growth dynamics typical of many rapidly urbanising SSA cities. These include the fact that the ongoing rapid growth in the city is unregulated (5.7 % yearly [84]), with, consequently, significant environmental degradation. Also, most ecologically sensitive ecosystems like wetlands are in private or community ownership and poorly managed. These factors have worsened floods in the city. Flood events in the city were sporadic until 2012. By 2014, four main flood events had affected 614 people, increasing to 38 significant flood events by 2017 that affected 3236 people [2]. Since then, devastating floods have become a perennial issue in GKMA, highlighting the urgent need for sustainable interventions.

Flood hazard mitigation efforts in GKMA have been sluggish and predominantly relied on conventional engineering solutions, like large drainage systems [13]. These efforts have not necessarily been informed by comprehensive risk analyses, which calls into question the long-term effectiveness of these current interventions [16]. NbS is plausible for GKMA because the drivers of flood hazards in the city are predominantly human-induced, mainly wetlands degradation and greens depletion [13], juxtaposing the recommendation for wetland NbS against conventional engineering.

2.3. Mapping temporal changes in water-related ecosystems

Remote sensing techniques, particularly the use of spectral indices, provide a reliable and cost-effective means to monitor land cover changes over large spatial and temporal scales. In data-scarce regions like SSA, where consistent ground-based monitoring is often unavailable, spectral indices such as MNDWI, NDVI and NDBI offer critical tools for detecting changes in water bodies, vegetation and built-up areas. These indicators are essential for assessing ecosystem loss and informing spatial planning for NbS.

Building on this, we applied MNDWI to delineate the spatial extent of water-related ecosystems in the Aboabo catchment between 1986 and 2023. Water-related ecosystems were defined as areas directly influenced by water bodies, including wetlands, streams, rivers, ponds and other aquatic habitats that sustain hydrological and ecological functions [121]. MNDWI is a remote sensing technique used to enhance the detection of surface water bodies in satellite imagery [89]. Besides being cost-effective, remote sensing uses a systematic approach that is reproducible and verifiable, unlike manual mapping, which relies solely on on-site visitations. Normalised Difference Water Indices (NDWIs) are

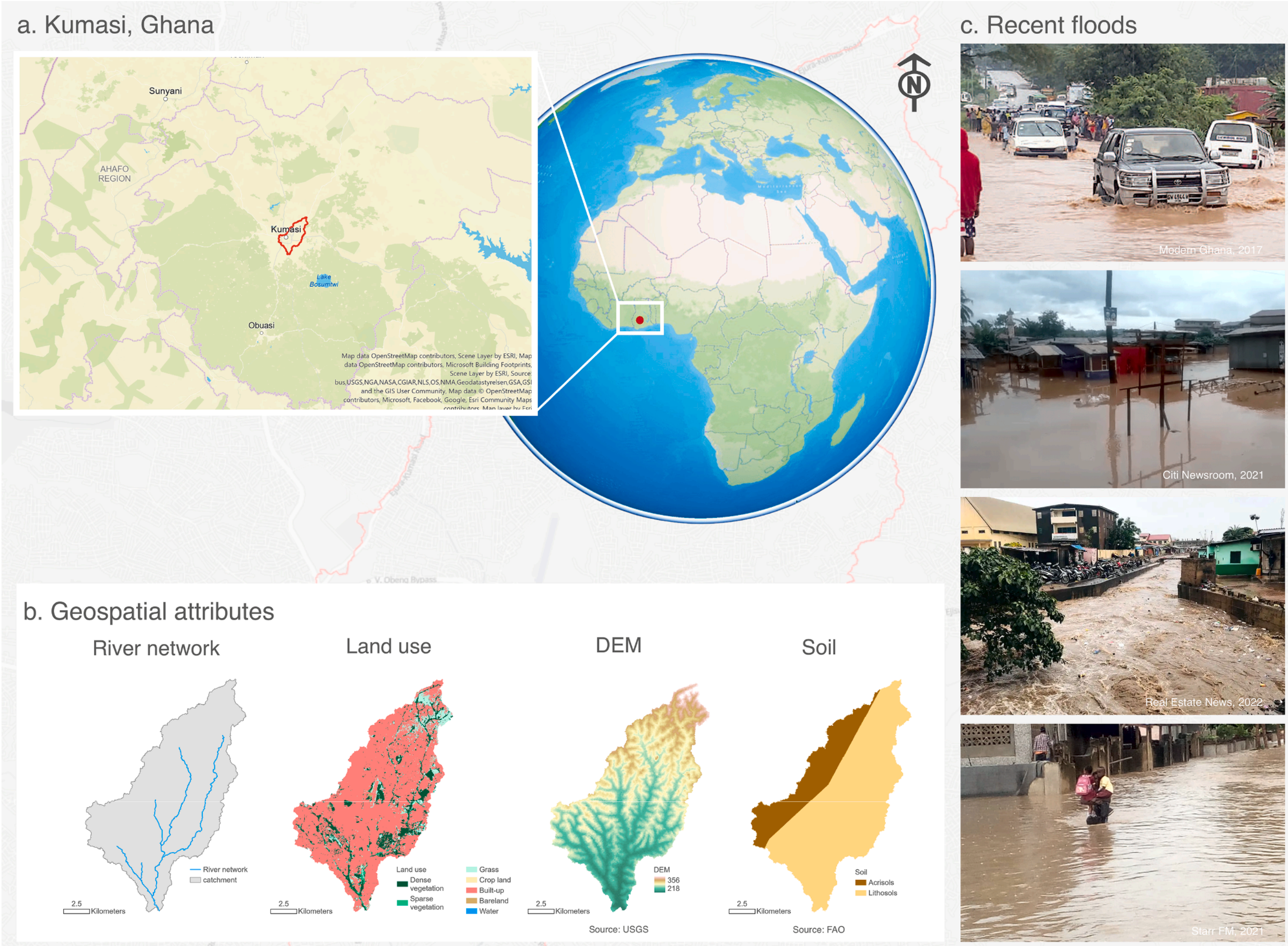

Fig. 2. Case study area description: Aboabo catchment in Kumasi, Ghana. (Sources: (a): OpenStreetMap; (b): USGS and FAO; (c): Sources: Modern Ghana, Citi Newsroom, Real Estate News and Starr FM).

essential in mapping water. The NDWI is an arithmetic operation of two differentiated bands that compare dissimilar reflectance values to improve water signals. NDWIs commonly used include (1), (2) and (3):

$$MNDWI = \frac{Green - SWIR}{Green + SWIR} \quad (1)$$

$$NDWI_{\frac{NIR}{MIR}} = \frac{NIR - MIR}{NIR + MIR} \quad (2)$$

$$NDWI_{\frac{G}{NIR}} = \frac{Green - NIR}{Green + NIR} \quad (3)$$

where *Green* refers to the green spectral band Landsat imagery, which typically corresponds to Band 3 in Landsat 8. *NIR* (Near-Infrared band) in Landsat imagery corresponds to Band 5. *SWIR* (Short-Wave Infrared band) generally corresponds to Band 6 or Band 7 in Landsat 8 and Landsat 7, depending on whether *SWIR1 or SWIR2 is* used. *MIR* (Mid-Infrared band) is often used interchangeably with*SWIR* and typically corresponds to Bands 6 or 7 for Landsat 8, depending on the specific application [33].

The MNDWI was chosen for water mapping because it represents an efficient means of enhancing water signals while suppressing the noise associated with urban land, soil and vegetation. It is considered superior to the NDWI, especially in areas dominated by urban land [82]. The alternative indices were included to provide context on the broader range of variant approaches commonly used in remote sensing. In the MNDWI, the water-related ecosystems were separated from the terrestrial/non-water-related ecosystems based on a threshold value of −0.14, determined by referencing the integrated z-score method [99]. This method involves normalising MNDWI values using the formula (4):

$$z = \frac{x - \mu}{\sigma} \quad (4)$$

where z represents the z-score, x is the MNDWI value, μ is the mean of the dataset and σ is its standard deviation.

Field visitations from March 11 to 15, 2023, helped ground-truth the results and validate the threshold's applicability. Pixels with MNDWI values above the threshold were classified as water-related ecosystems, while those below were identified as non-water-related areas.

In addition, NDVI was used to monitor vegetation changes (5), and NDBI was adopted to assess changes in built-up areas (6). These indices thus provide complementary information on the evolution of urban areas and the state of vegetation to respectively reinforce wetland and water mapping efforts [122].

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (5)$$

$$NDBI = \frac{SWIR - NIR}{SWIR + NIR} \quad (6)$$

Landsat (5 and 8) satellite images obtained from the United States Geological Survey (USGS) were used for these analyses (Table 1).

Table 1
Input data.

Input data	Source
DEM (12 m)	TanDEM-X
Land cover for the current state (2023)	OpenStreeMap
Land cover for the historic state (1986)	USGS
Channel geometry (2022)	Measurements provided by FURIFLOOD project partners at KNUST

Atmospheric correction was carried out in ArcGIS Pro 3.2 using the Dark Object Subtraction method, which reduces atmospheric scattering by assuming that certain surface features (e.g., water bodies) exhibit near-zero reflectance in specific spectral bands [118].

2.4. Assessing the potential effectiveness of wetland NbS

2.4.1. Hydrodynamic modelling using TELEMAC-2D

After assessing the change in water-related ecosystems, hydrodynamic modelling using TELEMAC-2D was performed for 1986 (historical) and 2023 (status quo) to understand the historical context and to establish the baseline conditions, respectively, before the implementation of wetland NbS to evaluate their impact on flood mitigation.

A high spatial resolution of urban flooding and retention effects of wetland structures characterise the flood genesis and the influence of wetlands in urban areas [18]. Roughness impacts through vegetation [26] and infiltration processes in wetland [65]. In the present study, the hydrodynamic model TELEMAC-2D was suitable for addressing the features of wetland NbS and urban flooding.

Simulations with TELEMAC-2D may be driven by precipitation input, inflow boundary conditions, or both. Topography is represented in the computational mesh and retention structures such as ponds can be integrated. Vegetation effects are modelled through land cover-dependent roughness parameterisation using Manning's n [27,63,97,103]. Infiltration was computed using the Soil Conservation Service Curve Number (SCS-CN) method [28,71,106]. Thus, the characteristics of wetlands and their influence on flood genesis in urban areas can be effectively addressed with the application of TELEMAC-2D.

The model was set up based on a 12 m digital elevation model (DEM) with ~1-m vertical accuracy, which generated a computational mesh for the study site of 700,000 nodes. Scenario-specific adjustments were made to land cover representations to reflect changes in surface roughness associated with each NbS intervention. We used the buildings and settlements data from OpenStreetMap (OSM) [25] for its model representation. We followed the suggestion of Merz et al. [77] for the parametrisation and classified the urban area into settlement classes into low, medium and high density. Major roads from OSM were also integrated into the model and parametrised accordingly.

The Manning's n values used for parameterization are listed in Table 2. Infiltration modelling typically requires detailed soil data, which was not available for the GKMA. Therefore, we adopted a conceptual approach where the CNis calibrated against observed variables such as measured streamflow; however, due to the absence of both detailed soil and streamflow data, we applied a representative average CN value for urban areas (CN = 55) [36]. This value reflects the transitional nature of the GKMA, which is undergoing rapid urbanisation but still contains a mosaic of impervious surfaces, vegetated zones, informal settlements and open fields. To verify this assumption, sensitivity testing with higher CN values (e.g., CN = 80) showed only minor differences in flow depth (<0.3 m in 95 % of the floodplain) (Fig. S3), indicating that CN selection has limited impact on the comparative assessment of restoration scenarios—the overarching aim of the study. The wetland features were characterised by a higher infiltration than urban areas [42], i.e., CN = 40 was assigned for the wetlands [36]. We used measured profiles (available upon request) provided by the Kwame Nkrumah University of Science and Technology (KNUST) partners in Kumasi for modelling the river channels from 2022.

Table 2
Scenario modelling and wetland NbS implementation scenarios.

No.	Scenarios	Implementation into the TELEMAC-2D model	Manning' 's n values
1	*Status quo*	Settlement density classes (low, medium, high), major streets from OSM	Low density built-up: 0.04 Medium density built-up: 0.1 High density built-up: 0.15 Streets: 0.01
2	*Floodplain restoration_ambitious*	Removed built-up within 100 m buffer of entire river network and replaced with vegetation	Vegetated buffer: 0.06
3	*Floodplain restoration_prioritized*	Removed built-up within 100 m buffer of river network in selected zones identified as inundation hotspots	Vegetated buffer: 0.06
4	*Landscape*	Created wetlands in suitable locations in the catchment using criteria defined by Mubeen et al. [[79], for details see section 2.4.2.]	Wetlands: 0.1 Sparse vegetation: 0.06
5	*Combined*	Combined *restoration_prioritized* and *landscape* approaches	Vegetated buffer: 0.06 Wetlands: 0.1

The *status quo* was used as the base for all subsequent scenarios in this study, including the wetland NbS described in Table 2 and Table 3, which are implemented as scenarios in the current state.

The design rainfall events for the hydrodynamic model were based on a rainfall disaggregation method that converts daily data into sub-daily information, compensating for the scarcity of high-resolution data in this area (Fig. S2). In urban catchments like GKMA, sub-daily rainfall information is critical due to rapid hydrological response times, as drainage infrastructure is highly sensitive to short-duration, high-intensity rainfall. However, long-term sub-hourly observations are generally unavailable across West Africa, complicating the estimation of the statistical relationships that are essential for flood hazard modelling.

To address this limitation, 384 sub-hourly rainfall events from two stations within the DACCIWA (Dynamics-Aerosol-Chemistry-Cloud-Interactions in West Africa) rainfall network [50,73] were combined with daily data from the Kumasi Airport station (1951-2022), provided by the Ghana Meteorological Agency (GMet). The disaggregation method breaks down daily rainfall totals into 15-minute intervals, using randomly selected weightings from the sub-hourly rainfall events, according to:

$$R_{15min,i} = w_i \times R_{daily} \quad (7)$$

where $R_{15min,i}$ is the rainfall amount for the i-th 15-minute interval, w_i is the weighting factor and R_{daily} is the total daily rainfall.

For hydrodynamic simulations, four event durations (2 h, 6 h, 12 and 24 h) were considered. These durations reflect the need to model both short, intense convective storms and longer rainfall accumulations, which are critical drivers of urban flooding. For each event duration (2 h, 6 h, 12 h and 24 h), the 15-min disaggregated values are aggregated to compute total rainfall, assuming uniform intensities within each duration.

To incorporate a design flood scenario, a block maxima approach is applied to the disaggregated rainfall for each event duration to analyse rainfall extremes [35,69,93]. The annual maxima were fitted with a Generalized Extreme Value (GEV) distribution [60], enabling the calculation of return values for different frequencies. For hydrodynamic modelling, we focused on the 100-year return period as a worst-case yet plausible design scenario. This choice also reduced the combinatorial

Table 3
Characteristics of the types of wetlands NbS measures implemented in the model.

Type of wetlands	Number implemented in model	Average surface area (m^2)	Average depth (m)	Average volume (m^3)	Vegetation	Wetness	Drainage
Vegetated stormwater retention wetlands	4	20,000 or less	2	2,000 to 40,000	Vegetated area with low roughness (e.g. bushes and reeds)	Partly dry and partly wet basin (40–60 % wet area)	Drained with a moderate infiltration rate (10–30 cm/day)
Eco-hydrological retention basins	1	20,001 to 100,000	3	60,000 to 300,000	Partly not vegetated area (e.g. some grassland)	Wet basin with minor natural components (>60–70 % wet area)	Well-drained with a high infiltration rate (>30–50 cm/day)

Adapted from Scholz [101].

complexity of the simulations. From the fitted GEV distribution, 100-year return values for rainfall intensity were calculated, providing inputs for TELEMAC-2D simulations. The return values were 72.57 mm/h for 2 h, 26.07 mm/h for 6 h, 13.54 mm/h for 12 h and 6.99 mm/h for 24 h.

Model validation was conducted using observed flood data from the September 2022 flood event, obtained from project partners at KNUST after the initial model setup in 2024. A comparison between observed and simulated flood extents (Fig. S4) demonstrates strong spatial agreement which supports the reliability of the model outputs.

2.4.2. Development of NbS implementation scenarios

The approach to creating the wetland NbS implementation scenarios was strategic, grounded in a tiered approach to how NbS may be implemented based on the degree of ecosystem change (conserve, restore or create) [41]. This tiered approach reflects the real-world continuum of ecosystem degradation in GKMA and the varying potential for intervention. It acknowledges that different parts of the landscape—or urban environments more broadly—exist at different stages of ecological integrity and therefore require contextualised strategies. Moreover, it aligns with the principles of adaptive management that underpin effective NbS implementation.

First, the baseline situation was assessed, focusing on conservation to evaluate how beneficial it would be to prevent further degradation of existing water-related ecosystems in the GKMA. In this study, 'floodplain restoration' refers to reinstating the natural flood-retention functions of existing floodplains by removing encroachments and restoring hydraulic connectivity. Second, a floodplain restoration approach was adopted, grounded in the regulation in Ghana that prohibits development within the 100 m buffer of floodplains in the country [108]. Moreover, previous research has emphasised the importance of defining restoration objectives based on hydrological and spatial connections [112], which has proven vital in mitigating flood hazards [53]. Based on this, two scenarios were examined, one where the entire river network was to be restored to assess the maximum restoration potential and another where the inundation hotspots were to be prioritised to reflect a more realistic implementation strategy. These scenarios were operationalized using the Buffer tool in ArcGIS Pro 3.2 to delineate 100 m buffers along the river network, with restoration constrained to wider river channels [104]. The third approach was the landscape approach, which explored the creation of wetlands. 'Wetland creation' as used here refers to the establishment of new wetland ecosystems in suitable non-wetland areas to enhance flood regulation. In this scenario, a multi-factor criteria framework following methods of Mubeen et al. [79] was used to identify suitable locations for siting the wetlands within the catchment. Suitable locations had to be:

- Non-built-up lands with bare land, grass or sparse vegetation.
- Either of the soil types in the catchment (lithosols and orthic acrisols).
- Be within the lowest 5 % of the elevation of the catchment.
- Be within 1 km proximity of the river network.
- And at least 20,000 m^2 in area.

The Raster Calculator (Spatial Analyst) in ArcGIS Pro 3.2 was used to create an expression to filter areas that meet the defined conditions in the multi-factor criteria framework. Subsequently, a hotspot analysis was performed using the Hot Spot Analysis (Getis-Ord Gi*) tool to identify locations with the highest potential based on statistically significant clustering of suitable sites for wetlands creation (Fig. S1) [52, 75]. Since some of the suitable sites identified were larger than the minimum threshold set (20,000 m^2), different sizes of wetland NbS were created in the *landscape* scenario. The respective characteristics of these wetland NbS measures, including surface area, depth and volume, were represented in the TELEMAC-2D model (Table 3). They included engineered aspects for design purposes but grounded in NbS principles to mimic natural wetland characteristics. Broadly, two distinct measures—vegetated stormwater retention ecosystems and eco-hydrological retention basins—were implemented based on size to ensure the interventions remained as natural as possible while providing effective flood mitigation and water retention capabilities [21,101]. The *combined* scenario involved combining the restoration (*prioritized*) and landscape approaches (Fig. 3).

2.4.3. Evaluating NbS implementation scenarios

Discharge (flow) was used as a primary metric to assess flood dynamics, as it incorporates both water depth and velocity, providing an effective evaluation of flood risks without detailing many parameters. Peak discharges and flood durations were compared for various storm events (Fig. S2) between 1986 and 2023 to examine temporal shifts in flood intensity and dynamics. The TELEMAC-2D model outputs were analysed by comparing these parameters under different scenarios against the *status quo*. Flow curves illustrated the magnitude and timing of peak flows, enabling a thorough evaluation of each scenario's effectiveness in reducing discharges and delaying flows. Heat maps also provided spatial visualisations of peak flow reductions to offer clear representations of each intervention's efficacy. Fixed temporal scales were used across all scenarios to maintain comparability.

3. Results

3.1. Temporal changes in the spatial extent of water-related ecosystems and impact on flooding

The spectral indices (MNDWI, NDVI, NDBI) analysis observed the spatial change in water-related ecosystems and built-up areas between 1986 and 2023 to evaluate the extent of the ecosystem degradation and its implications for flood hazards.

From 1986 to 2023, water-related ecosystems (wetlands, streams and other aquatic habitats sustaining hydrological and ecological functions) in the Aboabo basin decreased from 5.2 % to 2.2 % of the catchment area. MNDWI values narrowed from -0.74 to 0.12 in 1986 to −0.38 to −0.01 in 2023 (fig. 4), reflecting a substantial decline in detectable water bodies likely due to urbanisation, ecosystem degradation and sedimentation rather than climate factors.

NDVI analysis showed a general decline in vegetation, with localised improvements insufficient to offset widespread wetland loss. Built-up

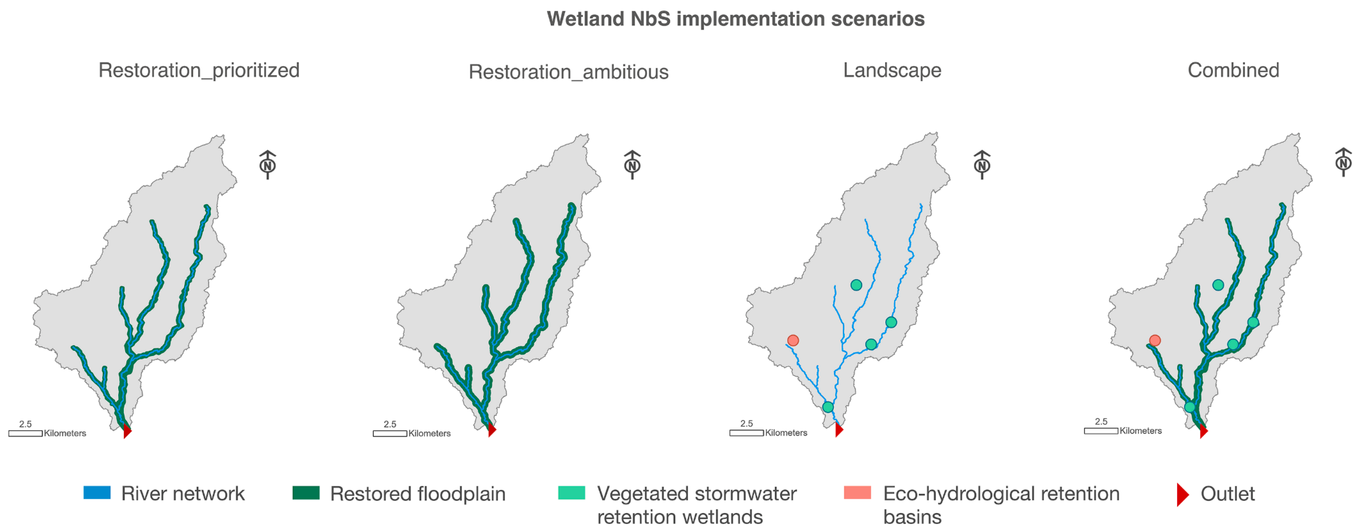

Fig. 3. Wetland NbS implementation scenarios.

areas increased dramatically, from 38.3 % in 1986 to 89.4 % in 2023 (Fig. 5). NDBI values narrowed from -0.21 to 0.67 in 1986 to -0.18 to 0.23 in 2023. This indicates stable or slightly reduced dense urban areas but a significant increase in low-density built-up areas.

On the impact of the ecosystem changes, the hydrological response analysis revealed consistently higher peak discharge values across all storm durations in 2023 compared to 1986. For a 2-h storm, peak discharge increased by 21 % (from 44.2 m^3/s in 1986 to 53.4 m^3/s in 2023). The 6-h, 12-h and 24-h storms saw increases of 16 %, 15 % and 9 %, respectively.

Despite these higher peaks, cumulative discharge — the total volume of water flowing out over the duration of a storm — declined by 17 % to 85 %, with the most pronounced reduction observed during the 2-h constant rainfall event. This suggests that stormwater is being temporarily stored in urban depressions, retained in designated storage areas or infiltrating into modified soils before contributing to surface runoff or drainage discharge. These changes indicate a shift in the timing and pathways of stormwater movement, resulting in faster peak flows but reduced sustained discharge. Consequently, the catchment's diminished drainage capacity increases the risk of flash flooding and local water accumulation. Flood duration curves further illustrate this trend and show shorter but more intense flood events in 2023, characterised by steeper rising limbs and faster recession times (Fig. 6). This shift highlights a flashier hydrological response driven by urbanisation and ecosystem degradation, both of which amplify flood hazards.

3.2. *Flood reduction potential of wetland NbS under different implementation scenarios*

The NbS scenarios were analysed using TELEMAC-2D model outputs, focusing on peak flow reductions and flood timing delays under different storm durations. The results showed that the *restoration_ambitious* scenario consistently stands out as the most effective scenario for reducing both flow and peak flood volume across all storm durations (2 h, 6 h, 12 h and 24 h) (fig. 7). Flow reductions ranged from 7.8 % to 9.5 % across all storm durations, with the most substantial peak flow reductions seen in the 2-h storm, achieving up to 24.4 % reduction. This *restoration_ambitious* scenario achieved the highest reduction across both short and long storm durations. However, its effectiveness decreases slightly during more prolonged storms, though it still maintains the highest reductions compared to other scenarios.

The *combined* and *restoration_prioritized* scenarios also showed substantial flood reduction potential. For instance, the *restoration_prioritized* achieved flow reductions between 5.3 % and 6.6 %, with peak flow reductions ranging from 14 % to 17 % across storm durations. While these reductions are not as high as *restoration_ambitious*, they still offer considerable flood mitigation benefits, especially during prolonged storms.

On the other hand, the *landscape* scenario consistently showed the smallest reductions, with 0.6-1% reductions in flow and peak flow reductions between 2.7 and 5.4 %. Its impact on flood reduction is minimal compared to the other scenarios, highlighting its limited potential for effective flood mitigation (Fig. 8).

The *restoration_ambitious* scenario, thus, offers the best flood mitigation potential across both short and long storm durations, while the *combined* and *restoration_prioritized* scenarios provide significant, albeit lesser, reductions. The *landscape* scenario is the least effective and has minimal impact on both flow and peak flood volume reduction.

3.3. *Temporal dynamics of flow reduction*

Regarding temporal dynamics and the ability to delay and reduce peak flow, the *combined* scenario was the most stable across all storm durations and periods. It maintained steady flow reductions across both short and long-duration storms, making it exceptionally reliable for extended storm events. For example, it achieved a peak flow reduction of 18.7 % in the 12-h storm and 16.6 % in the 24-h storm, particularly during the middle and end stages (Fig. S5).

On the other hand, the *restoration_ambitious* scenario demonstrated the highest peak flow reductions in short-duration storms, especially in the 2-h storm (24.4 %). However, its performance declines more sharply in prolonged storms compared to the *combined* scenario despite maintaining the highest overall flow reduction across all durations. Hence, while the *restoration_ambitious* scenario is highly effective for short, intense storms, its effectiveness is not as strong as the *combined* scenario during more extended events.

The *restoration_prioritized* scenario also offered moderate reductions, with peak flow reductions of 16.33 % in the 12-h storm and 14.3 % in the 24-h storm (Fig. 9). Its effectiveness was more evident during prolonged storms and show a delayed but stable impact on peak flow reduction, particularly in the later stages of the storm.

The *landscape* scenario shows limited capacity to mitigate peak flow, with a 2.3–2.7 % reduction across all storm durations and stages. Its overall effectiveness remains consistently the weakest and offers minimal impact on both peak flow reduction and overall temporal dynamics.

The *combined* scenario is generally the most stable and reliable, including for long-duration storms. *Restoration_ambitious*, however, remains the most effective for reducing flow during short-duration storms,

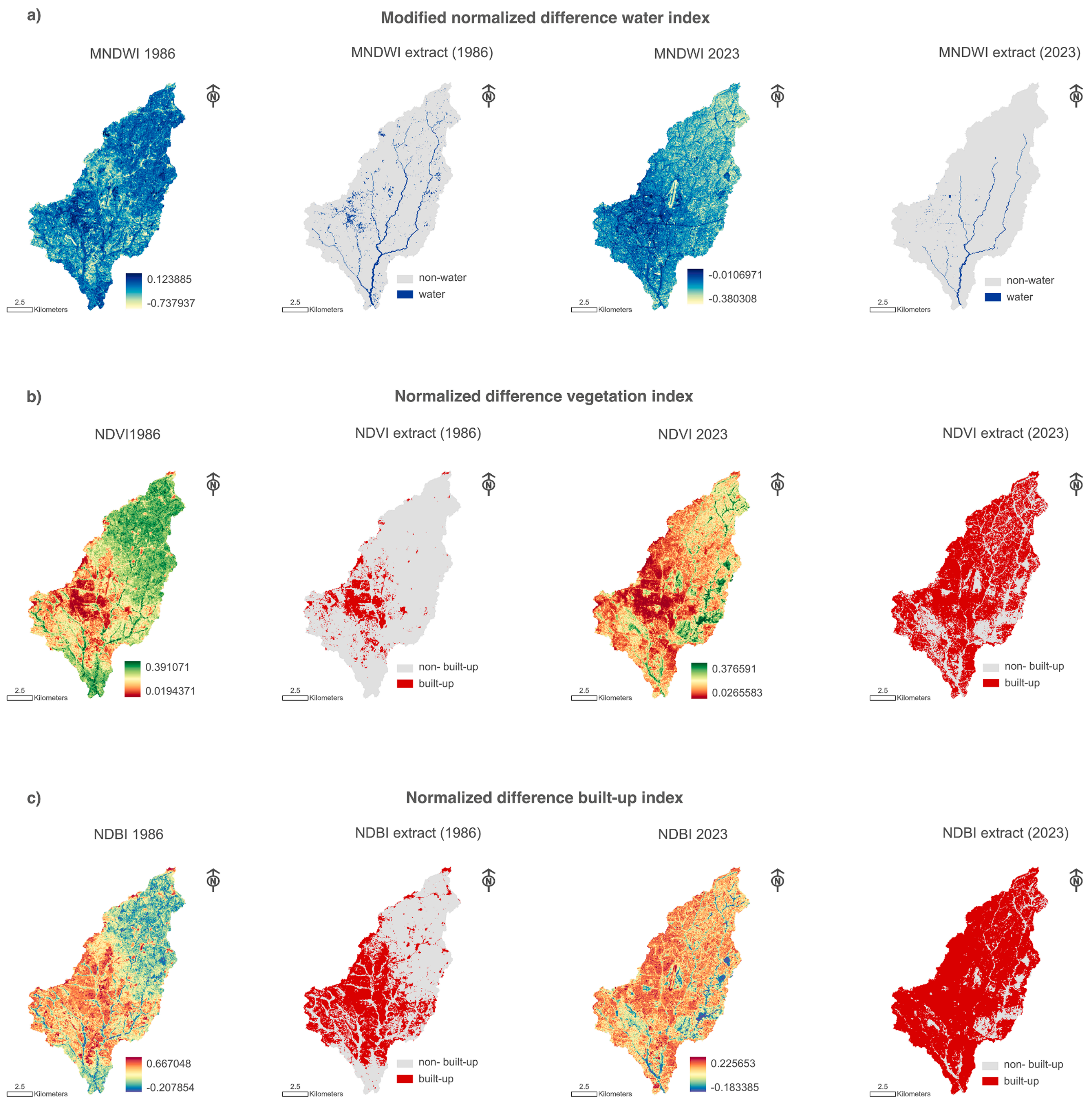

Fig. 4. Spectral indices showing the spatial change in water-related ecosystems, vegetation and built-up areas in GKMA (a) MNDWI (b) NDVI (c) NDBI. (In the case of MNDWI, "extract" represents the areas identified as water, while for NDVI and NDBI, it highlights the built-up areas).

but its effectiveness declines more sharply for longer durations. The *restoration_prioritized* scenario offers a balanced performance between flow reduction and consistency, especially for extended storms, while the *landscape* scenario is the least effective for flood mitigation since it offers limited consistency and reduction potential.

4. Discussions

Our study focused on the Aboabo catchment within the GKMA in Ghana to explore how NbS can reduce flood hazards. We evaluated the spatio-temporal changes in water-related ecosystems and assessed the effectiveness of various NbS implementation scenarios in mitigating flooding. The findings provide insights into the ongoing degradation of water-related ecosystems and other forms of natural capital, as well as the potential of NbS to enhance urban resilience to flooding GKMA and similar rapidly urbanising (SSA) cities.

4.1. Temporal changes in the spatial extent of water-related ecosystems and impact on flooding

Regarding the first objective focused on how water-related ecosystems have changed over time, the results showed a significant and ongoing decline in their spatial extent since 1986 (59 % loss), while built-up areas increased drastically (134 %). These findings align with earlier assessments that used GKMA's boundaries rather than a catchment, which showed that the spatial extent of wetlands reduced from 70

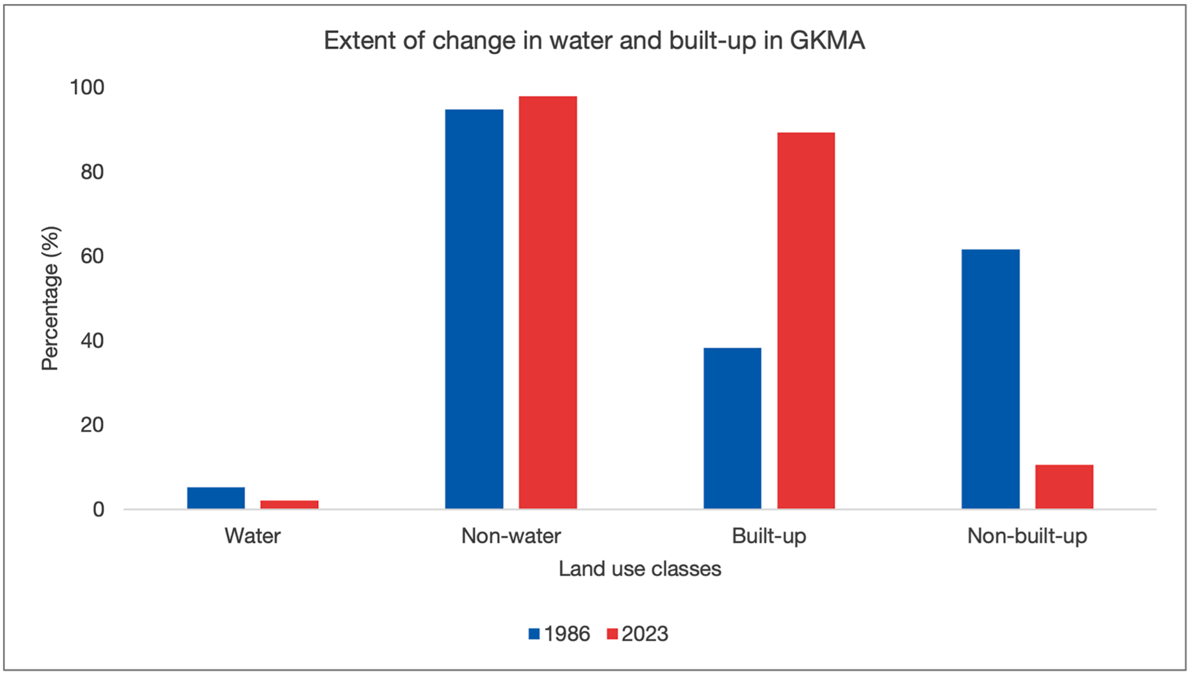

Fig. 5. Percentage change in the spatial extent of water-related ecosystems and built-up areas.

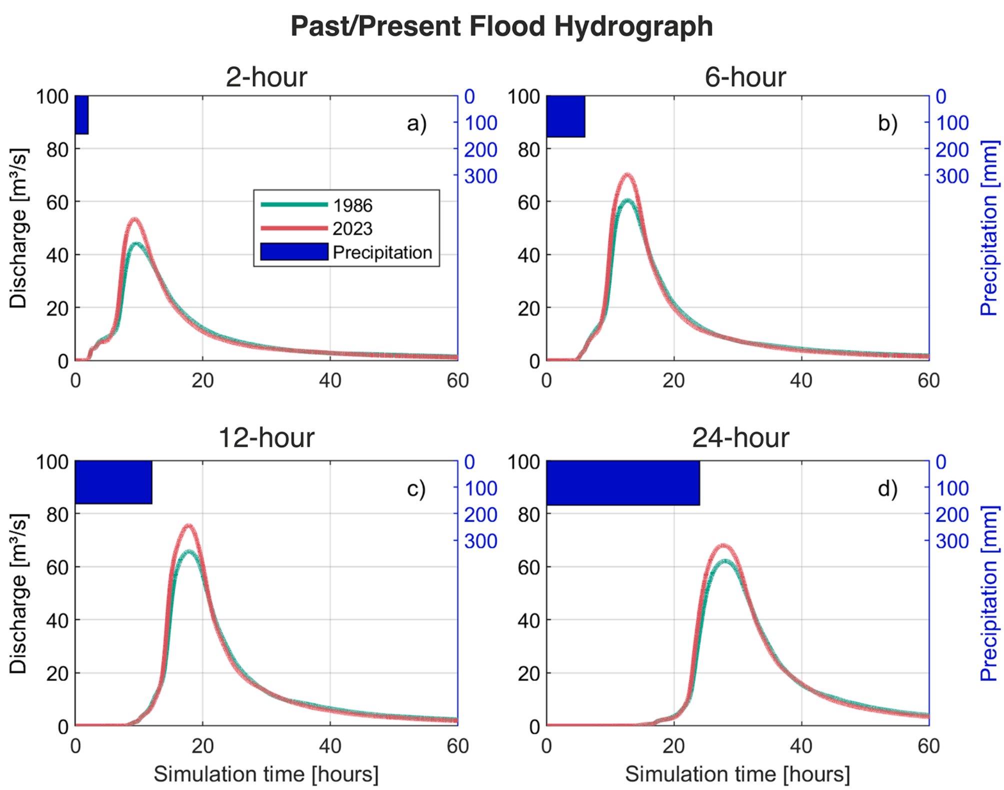

Fig. 6. Flood hydrographs for different storm durations for 1986 and 2023.

km^2 in 1986 to 29 km^2 in 2016 [33] and floodplains severely degraded [108], including 100-year flood zones [91]. The loss of these ecosystems in the city is driven by unregulated urbanisation and encroachment on sensitive areas, and these issues have not been addressed despite being raised several years ago [13]. This further loss of natural capital implies that the window for instituting interventions is closing, and floods may continue to increase in severity.

The results also revealed a narrowing of the NDBI range. This reflects the reality that, although the built-up areas in the catchment area have increased, the urban expansion is occurring through dispersed development rather than through the general intensification of existing built-up areas. This pattern is typical for cities expanding outwards into the surrounding sub-urban or undeveloped areas, such as in most cities in Europe during the mid-1950s, in China between 1990 and 2010 [61]

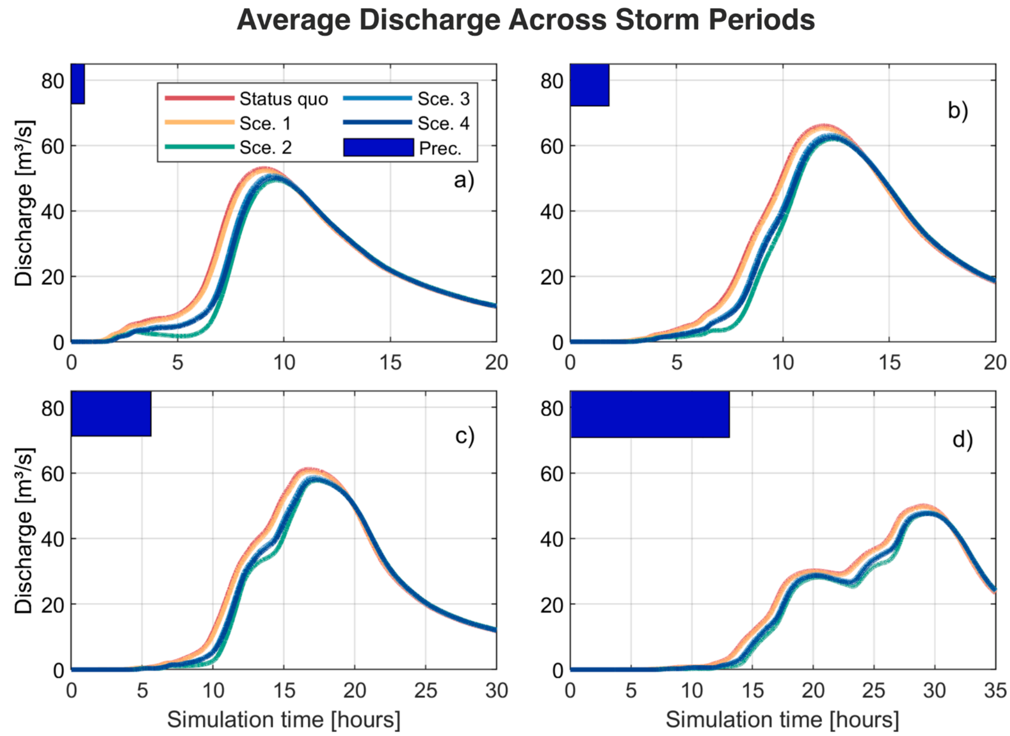

Fig. 7. Flood hydrographs for average discharge across storm periods for each scenario. (NB: "Sce" is the short form of scenario and "Prec." is the short form of precipitation. a) Beginning-rainfall events where precipitation is concentrated near the start of the duration, resulting in an early peak; b–Constant-represents uniformly distributed rainfall across the entire duration (i.e., block rain); c–Middle-indicates a peak in precipitation centred around the midpoint of the duration; and d–Ending-marks rainfall events where the peak intensity occurs toward the end of the duration).

and more recently in SSA cities like Kampala and Dar es Salaam [80,94], giving rise to a more diffused urban footprint. This emergence of dispersed settlements highlights a growing need for a more comprehensive and landscape-based approach to flood control, like wetlands creation, as modelled in the *landscape* scenario.

The TELEMAC-2D model successfully simulated flood dynamics despite data limitations, marking one of the first applications of the model in assessing flood hazards and NbS effectiveness under the specific conditions of rapid urban growth in SSA. The modelling results confirm heightened flood hazard in the GKMA due to rapid urban growth [3,91]. Despite stable rainfall volumes, peak discharges have significantly increased over time, while cumulative discharge has decreased. This indicates temporary stormwater storage within urban depressions, overwhelmed infrastructure or modified soils before eventual runoff or drainage [11,32]. These findings highlight changes in stormwater pathways due to urbanization. Increased built-up areas have reduced infiltration and natural storage, leading to faster runoff and intensified peak flows [19,57]. Meanwhile, reduced cumulative discharge reveals inefficiencies in stormwater systems, with trapped water worsening flooding. Impervious surfaces and degraded ecosystems accelerate water movement and strain hydrological resilience, which creates a flashier flood regime with shorter, higher-intensity events [22]. Such a shift has driven the transition in GKMA from isolated floods before the 2000s to continuous flooding in the past 12 years [1,100]. Without restoring natural water-retaining features like wetlands, GKMA faces worsening flood risks but integrating NbS into urban planning will offer a critical opportunity to prevent such challenges, restore hydrological balance and sustain resilience against future flood hazards.

4.2. Flood reduction potential of wetland NbS under different implementation scenarios

We explored different implementation scenarios for wetland NbS, comprising conservation (*status quo*), *restoration* (ambitious and prioritised), wetland creation (*landscape* approach) and a *combined* scenario (comprising floodplain restoration and wetlands creation). This provides a pioneering quantitative assessment of the potential of NbS for reducing flood risks in urban SSA contexts—a region with limited NbS research [31,45] —filling a critical gap in understanding their role in such rapidly urbanising areas. Also, unlike most scenario-based studies, which predominantly assess NbS under varying climate conditions (e.g., [74]), our research focused on implementation scenarios for NbS, focusing on their spatial configurations and effectiveness in reducing flood risks. Hence, this study also makes a meaningful contribution to the emerging global body of scenario-based NbS analyses (e.g., [116, 126]).

The results of the scenario analysis from GKMA were compelling: *restoration_ambitious* and *combined* scenarios emerged as the most effective strategies. Specifically, the *restoration_ambitious* scenario performed best in managing shorter, high-intensity storms. This indicates that ambitious restoration efforts focused on restoring floodplains and other degraded water-related ecosystems can offer benefits for addressing flood events. This will be important for addressing the present high flood risk that has impacted all suburbs of GKMA [43]. Based on sustained peak flow reductions, the *combined* scenario outperformed the other scenarios. Understandably, the *combined* scenario offered room for stormwater runoff regulation across all storm durations, both in the floodplain and the landscape, significantly enhancing flood resilience [98]. Thus, adopting an ambitious approach to NbS implementation and utilising both large-scale and decentralised small or medium-scale measures (effectiveness of localised measures demonstrated by Wübbelmann et al. [116] and Zölch et al. [126]) like wetlands in the *combined* scenario will be the most effective approach for peak flow mitigation for both short and long-duration flood hazards. This finding suggests that achieving long-term flood resilience in GKMA and rapidly urbanising cities may require more than simply restoring degraded ecosystems. Given the rapid urban environmental change, creating new

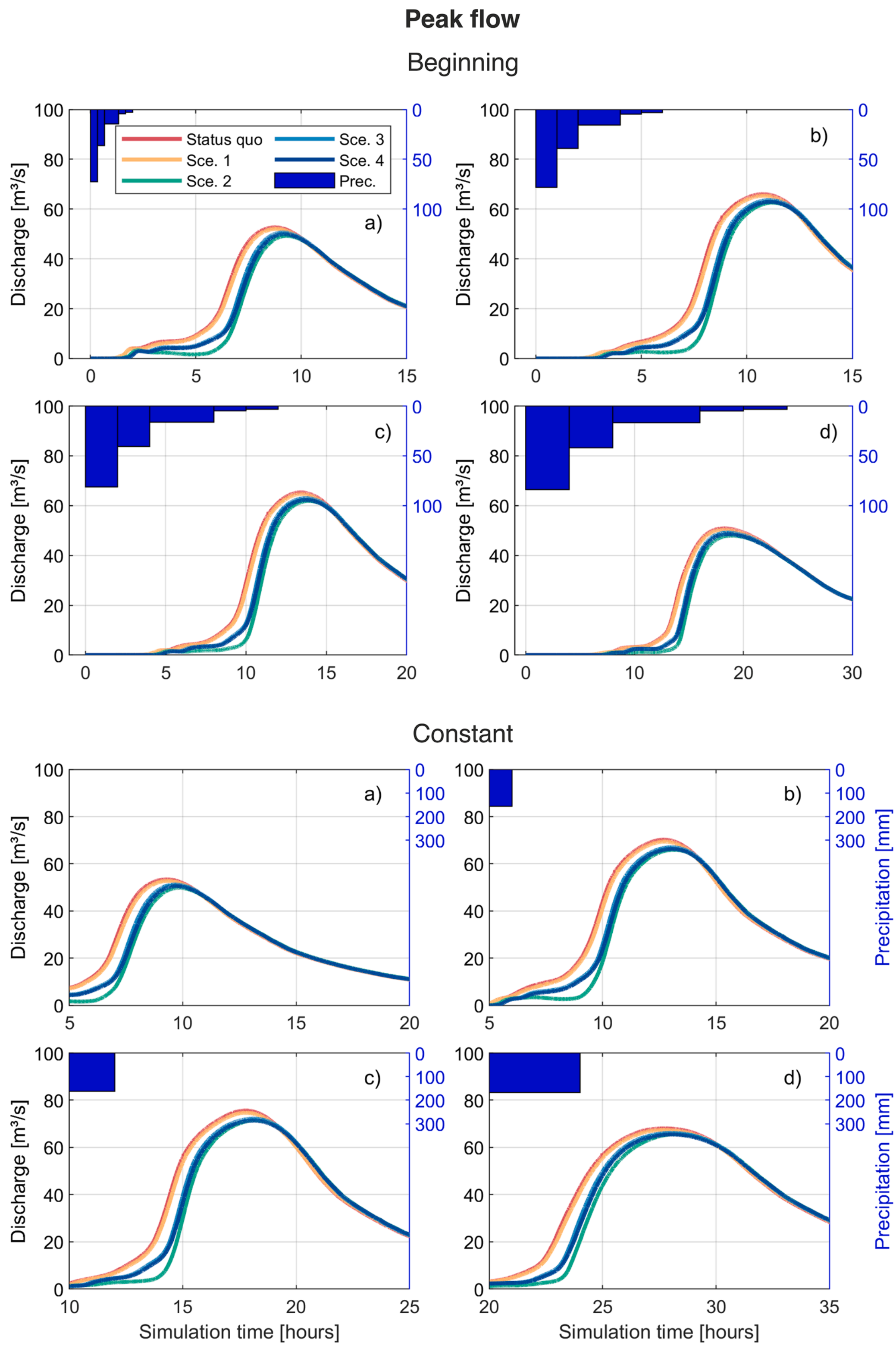

Fig. 8. Hydrographs of peak flow reduction potential for the different scenarios and storm durations. (NB: a) Beginning-rainfall events where precipitation is concentrated near the start of the duration, resulting in an early peak; b–Constant-represents uniformly distributed rainfall across the entire duration (i.e., block rain); c–Middle-indicates a peak in precipitation centredaround the midpoint of the duration; and d–Ending-marks rainfall events where the peak intensity occurs toward the end of the duration).

ecosystems and restoration efforts should be seriously considered. Moreover, the more ambitious these efforts are, the more effective they will enhance flood resilience.

Contrary to initial expectations, the *landscape* scenario, which involved the creation of wetlands based on land availability and physical conditions, was the least effective scenario for peak flow reduction

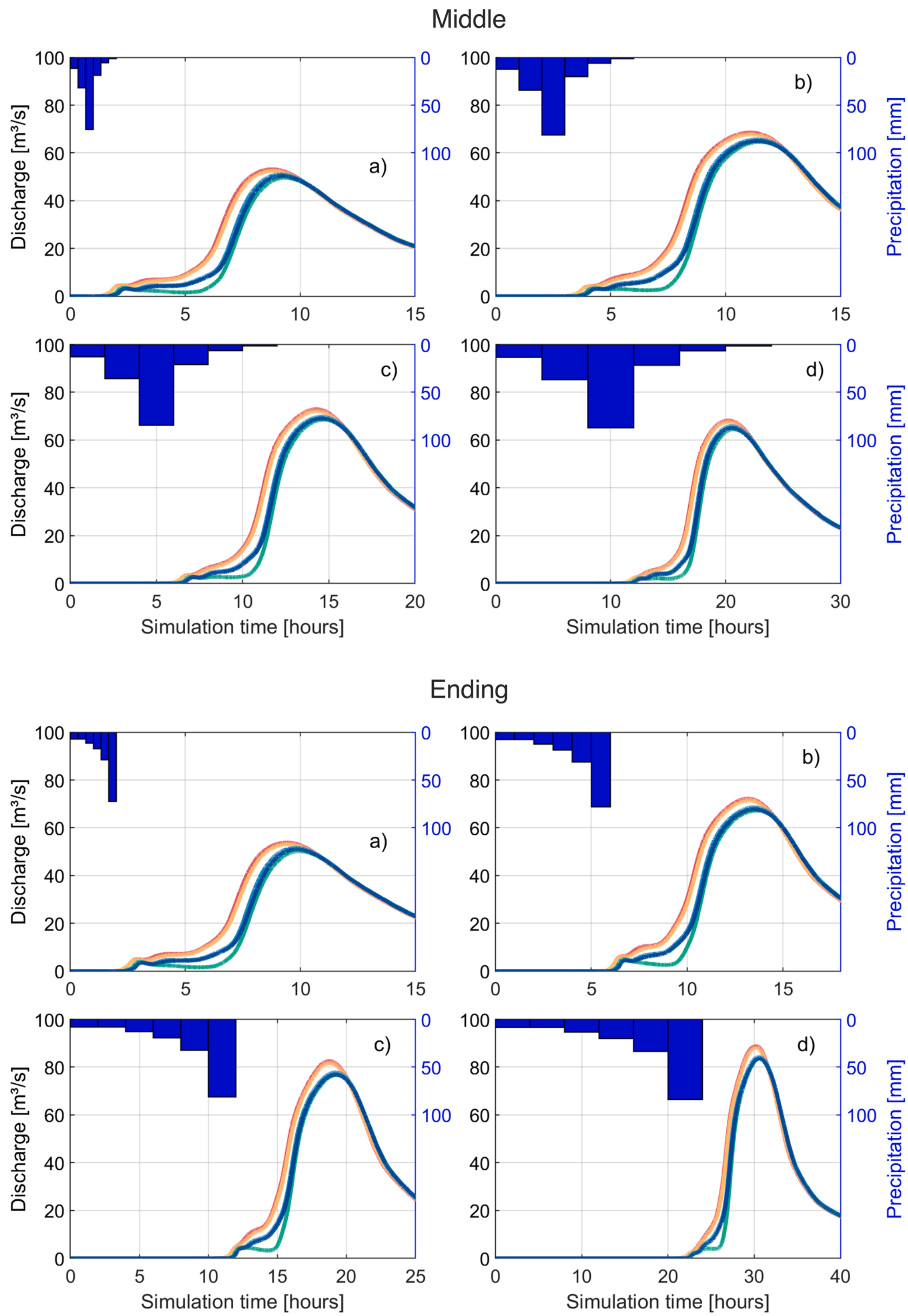

Fig. 8. (*continued*).

across all storm durations and stages. This outcome appears to result from a combination of site selection criteria, limited spatial scale and the implementation strategy itself. In this scenario, we applied a novel multi-criteria framework to identify suitable sites for implementing these measures, mainly based on land availability and physical conditions (slope, soil and proximity to rivers) and also considered hotspot areas [79]. The implementation was, thus, limited to few dispersed locations where sufficient space was available within the landscape. Besides, the nature of urban expansion in the catchment—characterized more by sprawl than densification—made such an approach justifiable. Hence, we expected better results than were reported in the *landscape* scenario. This finding implies that to achieve flood resilience using NbS, following an opportunistic approach where measures are implemented solely in locations where there is space may not be sufficient, even if this may be the most feasible way to implementing NbS in the real-world sense (Castellanos [30]). However, it is important to note that the *landscape* approach could potentially be more effective in other catchments with different characteristics, such as more uniform topography,

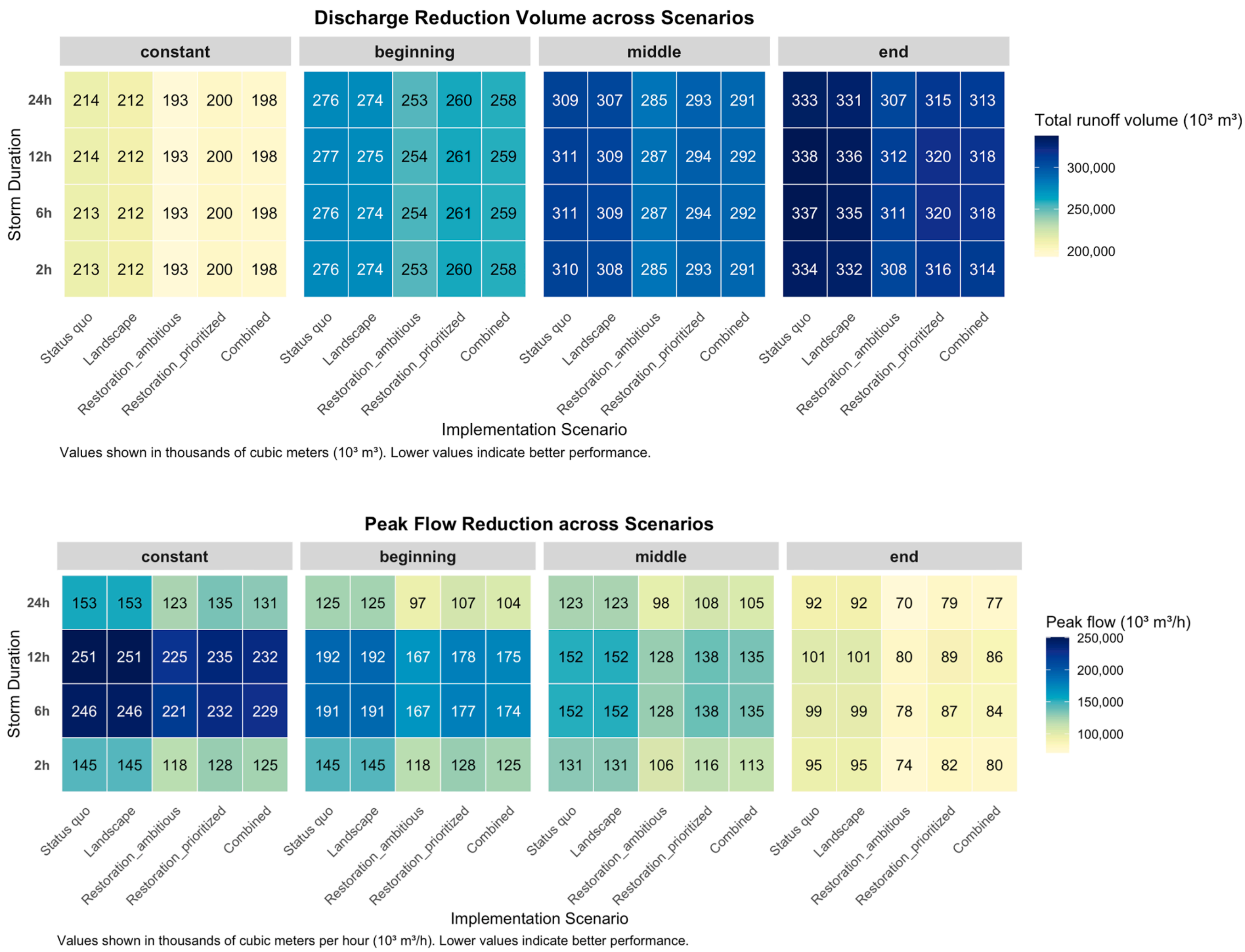

Fig. 9. Heat map showing (peak) flow reduction for each scenario and storm duration. (NB: "Constant" represents uniformly distributed rainfall across the entire duration (i.e., block rain); "Beginning" refers to rainfall events where precipitation is concentrated near the start of the duration, resulting in an early peak; "Middle" indicates a peak in precipitation centred around the midpoint of the duration; and "End" marks rainfall events where the peak intensity occurs toward the end of the duration).

lower urbanisation levels or those with a higher capacity for large-scale wetland implementation or when implemented across the entire catchment area rather than a few isolated sites[109].

4.3. *Temporal dynamics and implications for flood mitigation planning*

As seen in this study, although the effectiveness of NbS may depend on multiple factors [107], the level of ambition in their implementation plays a significant role. For the case of GKMA, this may mean relocating squatter settlements and removing structures built within floodplains. 67 % of the structures in most floodplains in GKMA are slums built with wooden materials. In comparison, 33 % are permanent structures used for residential and commercial purposes (e.g., scrap metal dealing, auto mechanics and grocery shops) [7,34]. Even more, advancing the *combined* scenario where wetlands are created alongside floodplain restoration will likely require compensating private landowners to use their lands for flood regulation besides the actual costs of NbS implementation (e.g., removing concrete channels, revegetation) [125]. These realities are complex to manage due to the social justice implications and impact on transformative socio-economic development [9]. Hence, in the interim, adopting a strategic approach to implementing NbS for flood risk mitigation in GKMA and similar rapidly growing cities through ecosystem conservation and restoration efforts can yield immediate significant results for addressing flooding [111]. This will be more feasible financially in the short term. But as it will not be sufficient for addressing flooding, it can then be complemented by the phased introduction of payment for ecosystem services schemes to also support the creation of new ecosystems like wetlands in non-state-owned lands. Payment for ecosystem services schemes are financial mechanisms in which beneficiaries of ecosystem services compensate landowners or resource stewards for sustainably managing, restoring or making their lands available for ecosystem creation, including areas designed to be intentionally flooded, in ways that sustain or enhance those services [70]. To ensure inclusivity, these schemes should also address the needs of squatters or informal settlers who may be most affected by relocation but do not hold formal land ownership, potentially through livelihood restoration programs or other forms of equitable compensation. As 78 % of lands are non-state owned in GKMA and Ghana [4], such schemes could offer sustainable ways for promoting NbS to create more room for stormwater regulation and to help improve flood resilience in the long term.

The analysis showed that even the most promising NbS implementation scenarios (*combined* and *restoration_ambitious*) would not be sufficient for providing adequate flood protection across all storm durations, as highlighted by reports in the literature. While the *combined* scenario, involving floodplain restoration with wetland creation, achieved reductions of up to 19 % for 12-h storms and 17 % for 24-h storms, these reductions remain below the 24–42 % discharge reductions cited in other regions (e.g., [59,115]) (see section 4.4 for more details). In contextualizing this result from GKMA within the broader SSA region, we observe for instance that, a study in Kampala, Uganda, utilizing the PCSWMM model to evaluate blue-green infrastructure options, reported a 10–20 % reduction in pluvial flood peaks [81]. Our findings therefore align with regional studies. It is important to note, however, that this study's analysis focused on (peak) flow reductions and did not directly quantify overall flood risk, which includes vulnerability and exposure [40]. As such, although NbS offer practical flood mitigation benefits, their ability to address flooding in GKMA across diverse storm scenarios remains uncertain and warrants further investigation, particularly with more ambitious and coordinated interventions.

In this regard, there is an imminent need for a hybrid approach toward integrating NbS with conventional engineering measures to effectively manage the present runoff volumes within the GKMA for immediate flood risk reduction. Furthermore, the temporal lag in wetland NbS effectiveness reinforces the need for a phased approach to flood mitigation. NbS, like wetlands, typically take years to realise their full capacities of managing stormwater and flood mitigation benefits [20,113]. In such a case, conventional engineering solutions, such as retention basins and stormwater channels, could provide immediate protection against floods, reducing vulnerability by allowing some time for NbS to come into maturity [54,68]. Moreover, this dual approach is vital in the GKMA context given the urgent need for effective flood risk management. However, implementing such hybrid approaches would realistically involve combining strategically located engineered retention basins and stormwater channels with targeted floodplain restoration and wetland creation. While technically feasible, the success of this integration is challenged by high land acquisition or compensation costs, fragmented governance structures and the need for sustained community buy-in, especially from customary landowners and informal settlers. Consequently, the feasibility of hybrid approaches depends not only on technical capacity but also on aligning financial resources, institutional coordination and equitable stakeholder engagement mechanisms.

Lastly, the link between urbanisation and land cover changes driving increased flooding in the GKMA highlights the urgent need for integrated planning to effectively manage urban sprawl. Land-use policies must prioritise the preservation of wetlands, vegetative buffers and other water-retaining natural assets, while balancing these effectively with development needs. Strategies like promoting green belts and higher-density development in suitable areas can help prevent unchecked sprawl [37]. Existing legal frameworks, such as the Buffer Zone Policy, Wetland Management Regulation and National Land Policy [47]), already support nature conservation and restoration, and the growing public acceptance of wetland NbS in GKMA offers promise for such efforts [44]. However, robust enforcement mechanisms are essential to prevent further ecosystem degradation and ensure the implementation of NbS. Broad stakeholder engagement will be central to advancing NbS adoption. Community involvement can foster stewardship and ensure the long-term sustainability of flood mitigation measures [64]. Other stakeholders, including government agencies, non-profits and research institutions, can provide the necessary expertise to advance NbS [8]. Also, meaningful engagement with customary land-owning institutions will be crucial to address their apprehensions and financial interests (e.g., with payment for ecosystem services and recreational benefits which are highly valued in GKMA [39]).

4.4. Potentials and limitations of the methodology

While the use of spectral indices (MNDWI, NDVI, NDBI) provides a systematic and cost-effective approach to land cover mapping, several limitations potentially affect the accuracy of model outputs. Spectral confusion—particularly in urban areas where impervious surfaces or dense vegetation may resemble water signals—alongside the moderate spatial resolution of Landsat imagery (30 m), can lead to misclassification, especially for small or fragmented water-related ecosystems. Seasonal variability, such as temporary flooding or dry conditions, also introduces uncertainty, as ground-truthing was limited to a specific period (March 2023). Although atmospheric correction (e.g., Dark Object Subtraction) and field validation were applied [89,118], some classification errors may persist. Additionally, hydrological parameters such as roughness coefficients and CN values were derived from literature and conceptual assumptions due to limited soil and runoff data; but sensitivity checks confirmed only minor influence on peak flow, supporting the reliability of the results for comparative scenario assessment. Rainfall inputs were derived using a robust disaggregation method validated through the FURIFLOOD project and comparable studies in other SSA cities (e.g., [80]). Still, the analysis does not currently quantify the uncertainty of rainfall extremes. In future studies, rainfall uncertainty could be addressed through extreme value analysis with bootstrapping techniques to estimate confidence intervals for precipitation return levels. Despite these limitations, the scenario-based comparison of NbS strategies remains robust for assessing relative effectiveness under a consistent framework for informing policy and guiding further research.

The effectiveness of wetlands for mitigating peak flow was quantified using the TELEMAC-2D model, with the highest peak flow mitigation potential reaching about 24 % under the *restoration_ambitious* scenario. While the model was constrained by limited input data—particularly the absence of observed river discharge and detailed soil information—it was partially validated using a documented flood event to improve confidence in its predictive performance. The scenarios, however, did not account for unanticipated land-use changes driven by socio-economic dynamics. Comparatively, studies using TELEMAC-2D in the Eagle Creek watershed in the United States, where more extensive input data were available, reported reductions of 42 % in peak flow, 55 % in flood areas and 15 % in water velocities [59]. Other models, such as the 1D stormwater management model and the Delft3D FLOW and WAVE models, showed reductions in peak flow of 23 % and 37 %, respectively [48,67]. The results of our model align with these findings and demonstrate TELEMAC-2D's utility in evaluating NbS under data-scarce conditions.

The study also did not establish the extent of inundated urban areas under different scenarios, such as how changes in peak and total discharge translate into changes in flood risk. This limitation arose from the focus on hydrological modelling to evaluate the relative effectiveness of NbS scenarios. Due to the significant computational and data requirements, incorporating detailed inundation modelling and exposure analysis was beyond the study's scope [62]. However, the discharge-focused analysis provides an essential first step for planners in understanding the potential of NbS strategies for peak flow reduction and serve as a precursor to more detailed risk assessments. Altogether, while subject to certain uncertainties that may affect absolute predictions, the results provide a reliable basis for comparative analysis.

While discharge data offers a strong foundation for evaluating NbS effectiveness by focusing on flow magnitude and timing, future research should also explore spatial variations in flood depth and velocity to better understand how NbS influences flood dynamics. Incorporating these hydrodynamic parameters would provide a more comprehensive understanding of interactions between landscape elements and floodwaters. To enhance model robustness, future studies should prioritise validation using deployed water loggers in critical catchment areas and compare the performance of TELEMAC-2D with alternative 2D hydrodynamic models, such as HEC-RAS 2D. Furthermore, integrating inundation modelling and exposure assessments would provide planners and policymakers with clearer insights into the spatial and socio-economic implications of NbS implementation. Participatory research involving local stakeholders in co-assessing the suitability and acceptability of NbS locations could further improve the feasibility and local relevance of interventions. Finally, combining adaptive modelling frameworks like TELEMAC-2D with real-time hydrological and land-use data could enhance the optimisation and resilience of NbS interventions in rapidly urbanising areas. These advancements would improve flood mitigation outcomes and deepen understanding of the interplay between urbanisation, ecosystem degradation and flood resilience and offer a roadmap for sustainable and context-specific strategies.

5. Conclusions

In this study, we applied the TELEMAC-2D model to evaluate the effectiveness NbS—specifically floodplain restoration and wetland creation—in mitigating flood hazards in the rapidly urbanising GKMA, with a focus on the Aboabo basin. This research provides one of the first quantitative assessments of NbS for flood mitigation in SSA and contributes to the growing body of scenario-based NbS studies by testing diverse, context-sensitive implementation approaches. Between 1986 and 2023, the Aboabo catchment experienced a 59 % decline in water-related ecosystems and a 134 % increase in built-up areas, leading to a substantial loss of natural flood-regulating capacity (17–85 %). These changes have intensified flood hazards, marked by steeper peak flows, faster runoff and a more abrupt hydrological response. This highlights the urgent need to restore ecological buffers and integrate NbS into urban planning to re-establish hydrological balance.

Beyond their technical value, spectral indices (MNDWI, NDVI, NDBI) were instrumental in quantifying long-term land cover changes and visualising urban encroachment. In a context where consistent ground-based monitoring is limited, these indices offered a strategic, replicable means of identifying ecosystem loss and informing spatial priorities for NbS implementation. The study also demonstrates the value of coupling remote sensing with hydrodynamic modelling, like TELEMAC-2D, to capture the dynamics of flood hazards and evaluate the performance of NbS under varying scenarios. TELEMAC-2D proved highly adaptable to the data-limited and complex urban conditions of SSA cities and can serve as a robust tool for planners and hydrologists for simulating interactions between natural and built environments.

Overall, the findings demonstrate that NbS can significantly reduce peak flows, particularly when applied in a coordinated manner across both floodplain and urban landscapes. Their effectiveness, however, is influenced by scale, spatial integration and catchment-specific conditions. Opportunistic, space-driven implementation is unlikely to deliver sufficient impact on its own, whereas ambitious restoration—especially when combined with targeted wetland creation—offers a more consistent and adaptable strategy. These results support a phased, hybrid approach that combines NbS with conventional infrastructure to provide both immediate protection and long-term resilience in rapidly urbanising cities like the GKMA. By restoring degraded ecosystems and enhancing flood resilience, the study supports progress toward Sustainable Development Goals 11 (Sustainable Cities), 13 (Climate Action) and 6 (Clean Water and Sanitation).

Finally, the findings offer transferable insights for other SSA cities facing similar pressures of urban expansion and ecosystem degradation. They can inform local authorities and communities in shaping land-use regulations, enhancing risk preparedness and integrating NbS into municipal planning frameworks using tools such as zoning and payment for ecosystem services.

Funding

The authors thank the BMBF (Bundesministerium für Bildung und Forschung) for funding the FURIFLOOD (Current and future risks of urban and rural flooding in West Africa) research project with grant no. 01LG2086B, and the Andrea von Braun Stiftung for funding the project "Wetlands as Nature-based Solutions for Climatic Extremes Mitigation in Ghana" [grant no. 2021/006].

NbS impacts and implications

Environmental: Ambitious floodplain restoration effectively reduces peak flood discharge, mitigating flood risks.

Economic: Integrating floodplain restoration with decentralised, targeted wetland creation could deliver cost-effective and stable flood mitigation across varied storm durations.

Social: Wetland restoration and creation efforts should equitably address the needs of displaced squatters through compensation or livelihood restoration programs.

CRediT authorship contribution statement

Kirk B. Enu: Writing – original draft, Visualization, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Fabian Merk:** Writing – original draft, Visualization, Validation, Project administration, Investigation, Formal analysis, Data curation, Conceptualization. **Hao Su:** Investigation, Formal analysis, Data curation. **Manuel Rauch:** Writing – original draft, Methodology, Data curation. **Aude Zingraff-Hamed:** Writing – review & editing, Supervision, Funding acquisition. **Karl Broich:** Writing – review & editing, Validation, Methodology. **Kristian Förster:** Writing – review & editing, Validation, Methodology. **Stephan Pauleit:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Markus Disse:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nbsj.2025.100236.

Data availability

Data will be made available on request.

References

[1] K. Abass, Rising incidence of urban floods: understanding the causes for flood risk reduction in Kumasi, Ghana, GeoJournal (2020) 1–18.

[2] K. Abass, D. Buor, K. Afriyie, G. Dumedah, A.Y. Segbefi, L. Guodaar, E. K. Garsonu, S. Adu-Gyamfi, D. Forkuor, A. Ofosu, Urban sprawl and green space depletion: implications for flood incidence in Kumasi, Ghana, Int. J. Disaster Risk Reduct. 51 (2020) 101915, https://doi.org/10.1016/j.ijdrr.2020.101915.

[3] K. Abass, G. Dumedah, F. Frempong, A.S. Muntaka, D.O. Appiah, E.K. Garsonu, R. M. Gyasi, Rising incidence and risks of floods in urban Ghana: is climate change to blame? Cities 121 (2021) 103495.

[4] B. Adjei-Poku, S.K. Afrane, C. Amoako, D.K. Inkoom, Customary land ownership and land use change in Kumasi: an issue of chieftaincy sustenance? Land Use Policy 125 (2023) 106483.

[5] E.B. Agyapong, G. Ashiagbor, C.A. Nsor, L.M. van Leeuwen, Urban land transformations and its implication on tree abundance distribution and richness in Kumasi, Ghana, J. Urban Ecol. 4 (1) (2018) juy019.

[6] J. Agyekum, L.K. Amekudzi, T. Stein, J.N. Aryee, W.A. Atiah, E.A. Adefisan, S. K. Danuor, Verification of satellite and model products against a dense rain gauge network for a severe flooding event in Kumasi, Ghana, Meteorol. Appl. 30 (5) (2023) e2150.

[7] A. Ahmed, R.D. Dinye, Impact of land use activities on Subin and Aboabo rivers in Kumasi Metropolis, Int. J. Water Resour. Environ. Eng. 4 (7) (2012) 241–251.

[8] A. Ahmed, J.A. Puppim de Oliveira, Integration of biodiversity in urban planning instruments in developing countries: the case of Kumasi Metropolitan assembly, Ghana, J. Environ. Plan. Manag. 60 (10) (2017) 1741–1764.

[9] I. Ajibade, Can a future city enhance urban resilience and sustainability? A political ecology analysis of Eko Atlantic city, Nigeria, Afr. Urban Risk Resil. 26 (2017) 85–92, https://doi.org/10.1016/j.ijdrr.2017.09.029.

[10] A. Almoradie, M.M. de Brito, M. Evers, A. Bossa, M. Lumor, C. Norman, Y. Yacouba, J. Hounkpe, Current flood risk management practices in Ghana: Gaps and opportunities for improving resilience, J. Flood Risk Manag. 13 (4) (2020) e12664.
[11] M.A. Al-Zahrani, Assessing the impacts of rainfall intensity and urbanization on storm runoff in an arid catchment, Arab. J. Geosci. 11 (2018) 1–14.
[12] M. Amo, F.K. Bih, A. Agyeman, T. Adu-Gyamfi, T. Mensah, Investigation into the acquisition and development of Wetlands built environment industry: a case study in Kumasi Metropolis, Int. J. Civ. Eng. Constr. Estate Manag. 5 (4) (2017) 1–20.
[13] P. Amoateng, C.M. Finlayson, J. Howard, B. Wilson, A multi-faceted analysis of annual flood incidences in Kumasi, Ghana, Int. J. Disaster Risk Reduct. 27 (2018) 105–117, https://doi.org/10.1016/j.ijdrr.2017.09.047.
[14] A. Andrei, B. Robert, B. Erika, Numerical limitations of 1D hydraulic models using MIKE11 or HEC-RAS software–case study of Baraolt River, Romania 245 (7) (2017) 072010.
[15] B. Arheimer, C. Cudennec, A. Castellarin, S. Grimaldi, K.V. Heal, C. Lupton, A. Sarkar, F. Tian, J.-M. Kileshye Onema, S. Archfield, The IAHS science for solutions decade, with hydrology engaging local people IN one global world (HELPING), Hydrol. Sci. J. 69 (11) (2024) 1417–1435.
[16] J.B. Asiedu, Reviewing the argument on floods in urban areas: a look at the causes, Theor. Empir. Res. Urban Manag. 15 (1) (2020) 24–41.
[17] Assila, L., Secher, M., Viard, T., Blancher, B., & Goeury, C. (2020). *Uncertainty propagation in T elemac 2D dam failures modelling and downstream hazard potential assessment*. 465–480.
[18] K. Banach, A.M. Banach, L.P. Lamers, H. De Kroon, R.P. Bennicelli, A.J. Smits, E. J. Visser, Differences in flooding tolerance between species from two wetland habitats with contrasting hydrology: implications for vegetation development in future floodwater retention areas, Ann. Bot. 103 (2) (2009) 341–351.
[19] O. Barron, A. Barr, M. Donn, Effect of urbanisation on the water balance of a catchment with shallow groundwater, J. Hydrol. 485 (2013) 162–176.
[20] T. Bendor, A dynamic analysis of the wetland mitigation process and its effects on no net loss policy, Landsc. Urban Plan. 89 (1–2) (2009) 17–27.
[21] Berkowitz, J. E., & Hurst, N. R. (2022). *New initiatives improve wetland restoration outcomes: engineering with nature and the use of natural and nature-based features*.
[22] P. Bhola, J. Leandro, M. Disse, Framework for offline flood inundation forecasts for two-dimensional hydrodynamic models, Geosci. (Switz.) 8 (2018) 346, https://doi.org/10.3390/geosciences8090346.
[23] D.S. Bisht, C. Chatterjee, S. Kalakoti, P. Upadhyay, M. Sahoo, A. Panda, Modeling urban floods and drainage using SWMM and MIKE URBAN: a case study, Nat. Hazards 84 (2) (2016) 749–776.
[24] H.-P. Blume, D. Kuhn, M. Bölter, Soils and soilscapes. Geoecology of Antarctic Ice-free Coastal Landscapes, Springer, 2002, pp. 91–113.
[25] G. Boeing, Exploring urban form through openstreetmap data: a visual introduction. Urban Experience and Design, Routledge, 2020, pp. 167–184.
[26] B. Braskerud, The influence of vegetation on sedimentation and resuspension of soil particles in small constructed wetlands, J. Environ. Qual. 30 (4) (2001) 1447–1457.
[27] J.D. Bricker, S. Gibson, H. Takagi, F. Imamura, On the need for larger Manning's roughness coefficients in depth-integrated tsunami inundation models, Coast. Eng. J. 57 (2) (2015), 1550005–1.
[28] Broich, K., Pflugbeil, T., Disse, M., & Nguyen, H. (2019). *Using TELEMAC-2D for hydrodynamic modeling of rainfall-runoff*. 15–17.
[29] D.T. Bulti, B.G. Abebe, A review of flood modeling methods for urban pluvial flood application, Model. Earth Syst. Environ. 6 (3) (2020) 1293–1302.
[30] C. Diaz, L. A., Bonin, O., Antoine Versini, P., & Tchiguirinskaia, I. (2021). *Analysis of spatial dimensions and explicit multifractal modelling for the deployment of green areas in an urban agglomeration.* EGU21-10732.
[31] C. Choi, P. Berry, A. Smith, The climate benefits, co-benefits, and trade-offs of green infrastructure: a systematic literature review, J. Environ. Manag. 291 (2021) 112583, https://doi.org/10.1016/j.jenvman.2021.112583.
[32] M.F. Chow, H. Haris, Y.X. Leong, The effect of temporal resolution of input rainfall data in hydrological modelling at urban catchment, in: *AIP Conference Proceedings* 2339, AIP Publishing, 2021. No. 1.
[33] P.B. Cobbinah, P.I. Korah, J.B. Bardoe, R.M. Darkwah, A.M. Nunbogu, Contested urban spaces in unplanned urbanization: wetlands under siege, Cities (2021) 103489, https://doi.org/10.1016/j.cities.2021.103489.
[34] P.B. Cobbinah, M. Poku-Boansi, C. Peprah, Urban environmental problems in Ghana, Environ. Dev. 23 (2017) 33–46.
[35] S. Coles, J. Bawa, L. Trenner, P. Dorazio, *An Introduction to Statistical Modeling of Extreme Values* (Vol. 208), Springer, 2001.
[36] R. Cronshey, *Urban Hydrology for Small Watersheds* (Issue 55), US Department of Agriculture, Soil Conservation Service, Engineering Division, 1986.
[37] C. Cuiyun, G. Chazhong, Green development assessment for countries along the belt and road, J. Environ. Manag. 263 (2020) 110344.
[38] G. Daily, Mainstreaming the Values of Nature for People into Decision Making, Pontifical Academy of Sciences and the Pontifical Academy of Social Science Joint Workshop on Sustainable Nature: Our Responsibility, 2014.
[39] S.K. Diko, Urban green space planning in the Kumasi Metropolis, Ghana: A prioritization conundrum and its co-benefits solution, Socio-Ecol. Pract. Res. (2022) 1–14, https://doi.org/10.1007/s42532-022-00135-5.
[40] M. Disse, T.G. Johnson, J. Leandro, T. Hartmann, Exploring the relation between flood risk management and flood resilience, Water Secur. 9 (2020), https://doi.org/10.1016/j.wasec.2020.100059, 100059–100059.
[41] H. Eggermont, E. Balian, J.M.N. Azevedo, V. Beumer, T. Brodin, J. Claudet, B. Fady, M. Grube, H. Keune, P. Lamarque, Nature-based solutions: New influence for environmental management and research in Europe, GAIA-Ecol. Perspect. Sci. Soc. 24 (4) (2015) 243–248, https://doi.org/10.14512/gaia.24.4.9.
[42] Eli Robert N, Lamont Samuel J, Curve Numbers and Urban Runoff Modeling? Application Limitations. Low Impact Development 2010, 2012, pp. 405–418, https://doi.org/10.1061/41099(367)36.
[43] K.B. Enu, A. Zingraff-Hamed, D.O. Appiah, S. Pauleit, Narrowing down the drivers of flood risk in medium-sized sub-Saharan African cities: Insights from the Greater Kumasi Metropolitan Area, Ghana, Hydrol. Sci. J. (2024), https://doi.org/10.1080/02626667.2024.2401605.
[44] K.B. Enu, A. Zingraff-Hamed, Y.A. Boafo, M.A. Rahman, S. Pauleit, Citizens' acceptability and preferred nature-based solutions for mitigating hydro-meteorological risks in Ghana, J. Environ. Manag. 352 (2024) 120089, https://doi.org/10.1016/j.jenvman.2023.120089.
[45] K.B. Enu, A. Zingraff-Hamed, M. Rahman, L. Stringer, S. Pauleit, Review article: potential of nature-based solutions to mitigate hydro-meteorological risks in sub-saharan Africa, Nat. Hazards Earth Syst. Sci. 23 (2023) 481–505, https://doi.org/10.5194/nhess-23-481-2023.
[46] European Commission & Directorate-General for Research and Innovation, Towards an EU Research and Innovation Policy Agenda for Nature-Based Solutions & Re-naturing Cities: final Report of the Horizon 2020 Expert Group on "Nature-based Solutions and Re-naturing Cities": (Full version) (2015), https://doi.org/10.2777/479582.
[47] M. Everard, National Wetland Policy: Ghana, in: C.M. Finlayson, M. Everard, K. Irvine, R.J. McInnes, B.A. Middleton, A.A. van Dam, N.C. Davidson (Eds.), The Wetland Book: I: structure and Function, Management, and Methods, Springer Netherlands, 2018, pp. 785–788, https://doi.org/10.1007/978-90-481-9659-3_158.
[48] T.P. Fairchild, W.G. Bennett, G. Smith, B. Day, M.W. Skov, I. Möller, N. Beaumont, H. Karunarathna, J.N. Griffin, Coastal wetlands mitigate storm flooding and associated costs in estuaries, Environ. Res. Lett. 16 (7) (2021) 074034.
[49] C.S.S. Ferreira, K. Potočki, M. Kapović-Solomun, Z. Kalantari, Nature-based solutions for flood mitigation and resilience in urban areas. Nature-based Solutions for Flood Mitigation: environmental and Socio-Economic Aspects, Springer, 2021, pp. 59–78.
[50] A. Fink, *Dacciwa_kumasi_raingauges* [Dataset], 2024, https://doi.org/10.6096/BAOBAB-DACCIWA.1772. Baobab.
[51] D. Forkuor, P. Kyei, J. Forkuor, Land usage changes and its effects on the provision of social facilities to residents of the Kumasi Metropolis of Ghana, Ethiop. J. Environ. Stud. Manag. 6 (3) (2013) 324–332.
[52] A. Getis, J.K. Ord, The analysis of spatial association by use of distance statistics, Geogr. Anal. 24 (3) (1992) 189–206.
[53] B. Gumiero, J. Mant, T. Hein, J. Elso, B. Boz, Linking the restoration of rivers and riparian zones/wetlands in Europe: Sharing knowledge through case studies, Ecol. Eng. 56 (2013) 36–50.
[54] T. Hartmann, L. Slavíková, S. McCarthy, Nature-based solutions in flood risk management. Nature-based Flood Risk Management on Private Land, Springer, Cham, 2019, pp. 3–8. https://link.springer.com/chapter/10.1007/978-3-030-23842-1_1.
[55] B.T. Hassan, M. Yassine, D. Amin, Comparison of urbanization, climate change, and drainage design impacts on urban flashfloods in an arid region: Case study, New Cairo, Egypt, Water 14 (15) (2022) 2430.
[56] J.M. Hoch, R. van Beek, H.C. Winsemius, M.F. Bierkens, Benchmarking flexible meshes and regular grids for large-scale fluvial inundation modelling, Adv. Water Resour. 121 (2018) 350–360.
[57] E. Igun, E. Sanganyado, J.L. Igben, Local drying climate magnified by urbanization in West Africa, Int. J. Climatol. 43 (12) (2023) 5317–5326.
[58] IPCC, Climate change 2022: Impacts, adaptation and vulnerability, in: H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (Eds.), *Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 2022, p. 3056, https://doi.org/10.1017/9781009325844.
[59] A. Javaheri, M. Babbar-Sebens, On comparison of peak flow reductions, flood inundation maps, and velocity maps in evaluating effects of restored wetlands on channel flooding, Ecol. Eng. 73 (2014) 132–145.
[60] A.F. Jenkinson, The frequency distribution of the annual maximum (or minimum) values of meteorological elements, Q. J. R. Meteorol. Soc. 81 (348) (1955) 158–171.
[61] L. Jiao, Urban land density function: a new method to characterize urban expansion, Landsc. Urban Plan. 139 (2015) 26–39.
[62] A. Kadaverugu, C. Nageshwar Rao, G. Viswanadh, Quantification of flood mitigation services by urban green spaces using InVEST model: a case study of Hyderabad city, India, Model. Earth Syst. Environ. 7 (1) (2021) 589–602.
[63] A.J. Kalyanapu, S.J. Burian, T.N. McPherson, Effect of land use-based surface roughness on hydrologic model output, J. Spat. Hydrol. 9 (2) (2009) 51.
[64] B. Kiss, F. Sekulova, K. Hörschelmann, C.F. Salk, W. Takahashi, C. Wamsler, Citizen participation in the governance of nature-based solutions, Environ. Policy Gov. 32 (3) (2022) 247–272.
[65] T. Kiss, J. Nagy, I. Fehérváry, C. Vaszkó, (Mis) management of floodplain vegetation: the effect of invasive species on vegetation roughness and flood levels, Sci. Total Environ. 686 (2019) 931–945.
[66] C. Koranteng, B. Simons, D. Nyame-Tawiah, Green to grey: an urban heat assessment of Kumasi, Ghana, Int. J. Environ. Clim. Change (2019) 751–763.

[67] S. Kumar, A. Agarwal, V.G.K. Villuri, S. Pasupuleti, D. Kumar, D.R. Kaushal, A. K. Gosain, A. Bronstert, B. Sivakumar, Constructed wetland management in urban catchments for mitigating floods, Stoch. Environ. Res. Risk Assess. 35 (2021) 2105–2124.
[68] R. Lafortezza, J. Chen, C.K. Van Den Bosch, T.B Randrup, Nature-based solutions for resilient landscapes and cities, Environ. Res. 165 (2018) 431–441, https://doi.org/10.1016/j.envres.2017.11.038.
[69] P. Laux, E. Weber, D. Feldmann, H. Kunstmann, The robustness of the derived design life levels of heavy precipitation events in the pre-alpine Oberland region of Southern Germany, Atmosphere 14 (9) (2023) 1384.
[70] T.-A.T. Le, K. Vodden, J. Wu, R. Bullock, G. Sabau, Payments for ecosystem services programs: a global review of contributions towards sustainability, Heliyon (2024).
[71] Ligier, P.-L. (2016). *Implementation of a rainfall-runoff model in TELEMAC-2D. 11*.
[72] M.B. Malgwi, S. Fuchs, M. Keiler, A generic physical vulnerability model for floods: review and concept for data-scarce regions, Nat. Hazards Earth Syst. Sci. 20 (7) (2020) 2067–2090, https://doi.org/10.5194/nhess-20-2067-2020.
[73] M. Maranan, A.H. Fink, P. Knippertz, L.K. Amekudzi, W.A. Atiah, M. Stengel, A process-based validation of GPM IMERG and its sources using a mesoscale rain gauge network in the West African forest zone, J. Hydrometeorol. 21 (4) (2020) 729–749.
[74] E.G. Martin, M.M. Costa, S. Egerer, U.A. Schneider, Assessing the long-term effectiveness of nature-based solutions under different climate change scenarios, Sci. Total Environ. 794 (2021) 148515.
[75] S.J. Medland, R.R. Shaker, K.W. Forsythe, B.R. Mackay, G. Rybarczyk, A multi-criteria wetland suitability index for restoration across Ontario's mixedwood plains, Sustainability 12 (23) (2020) 9953.
[76] H. Mensah, D.K. Ahadzie, Causes, impacts and coping strategies of floods in Ghana: a systematic review, SN Appl. Sci. 2 (5) (2020) 1–13.
[77] B. Merz, H. Kreibich, R. Schwarze, A. Thieken, Review article" Assessment of economic flood damage", Nat. Hazards Earth Syst. Sci. 10 (8) (2010) 1697–1724.
[78] F. Mintah, C. Amoako, K.K. Adarkwa, The fate of urban wetlands in Kumasi: An analysis of customary governance and spatio-temporal changes, Land Use Policy 111 (2021) 105787.
[79] A. Mubeen, L. Ruangpan, Z. Vojinovic, A. Sanchez Torrez, J. Plavšić, Planning and suitability assessment of large-scale nature-based solutions for flood-risk reduction, Water Resour. Manag. 35 (10) (2021) 3063–3081.
[80] R.O. Muchelo, T.F. Bishop, S.U. Ugbaje, S.I. Akpa, Patterns of urban sprawl and agricultural land loss in Sub-Saharan Africa: the cases of the Ugandan cities of Kampala and Mbarara, Land 13 (7) (2024) 1056.
[81] S.N. Mugume, L.P. Nakyanzi, Evaluation of effectiveness of Blue-Green Infrastructure for reduction of pluvial flooding under climate change and internal system failure conditions, Blue-Green Syst. 6 (2) (2024) 264–292.
[82] Mwakapuja, F., Liwa, E., & Kashaigili, J. (2013). *Usage of indices for extraction of built-up areas and vegetation features from landsat TM image: A case of Dar es Salaam and Kisarawe peri-urban areas, Tanzania*.
[83] S. Namirembe, B. Leimona, M. van Noordwijk, F. Bernard, K.E. Bacwayo, Co-investment paradigms as alternatives to payments for tree-based ecosystem services in Africa, Curr. Opin. Environ. Sustain. 6 (2014) 89–97.
[84] S.N. Narh, S.A. Takyi, M.O. Asibey, O. Amponsah, Garden city without parks: an assessment of the availability and conditions of parks in Kumasi, Urban For. Urban Green. 55 (2020) 126819, https://doi.org/10.1016/j.ufug.2020.126819.
[85] NatCatSERVICE, NatCatSERVICE analysis tool. https://natcatservice.munichre.com/, 2020.
[86] Oduro, C. Y., Ocloo, K., & Peprah, C. (2014). *Analyzing growth patterns of Greater Kumasi metropolitan area using GIS and multiple regression techniques*.
[87] J. Ommer, E. Bucchignani, L.S. Leo, M. Kalas, S. Vranić, S. Debele, P. Kumar, H. L. Cloke, S. Di Sabatino, Quantifying co-benefits and disbenefits of nature-based solutions targeting disaster risk reduction, Int. J. Disaster Risk Reduct. 75 (2022) 102966, https://doi.org/10.1016/j.ijdrr.2022.102966.
[88] H.V. Oral, P. Carvalho, M. Gajewska, N. Ursino, F. Masi, E.D.van Hullebusch, J. K. Kazak, A. Exposito, G. Cipolletta, T.R Andersen, A review of nature-based solutions for urban water management in European circular cities: a critical assessment based on case studies and literature, Blue-Green Syst. 2 (1) (2020) 112–136.
[89] I.R. Orimoloye, A.M. Kalumba, S.P. Mazinyo, W. Nel, Geospatial analysis of wetland dynamics: Wetland depletion and biodiversity conservation of Isimangaliso Wetland, South Africa, J. King Saud Univ.-Sci. 32 (1) (2020) 90–96.
[90] O. Ourloglou, K. Stefanidis, E. Dimitriou, Assessing nature-based and classical engineering solutions for flood-risk reduction in urban streams, J. Ecol. Eng. 21 (2) (2020) 46–56.
[91] J.K. Owusu-Ansah, The influences of land use and sanitation infrastructure on flooding in Kumasi, Ghana, GeoJournal 81 (4) (2016) 555–570.
[92] I.E. Özer, M. van Damme, T. Schweckendiek, S.N. Jonkman, On the importance of analyzing flood defense failures, E3S Web Conf. 7 (2016) 9, https://doi.org/10.1051/e3sconf/20160703013.
[93] G. Panthou, T. Vischel, T. Lebel, J. Blanchet, G. Quantin, A. Ali, Extreme rainfall in West Africa: a regional modeling, Water Resour. Res. 48 (8) (2012).
[94] S. Pauleit, A. Coly, S. Fohlmeister, P. Gasparini, G. Jorgensen, S. Kabisch, K. Yeshitela, Urban vulnerability and climate change in Africa, Futur City 4 (2015).
[95] S. Pauleit, T. Zölch, R. Hansen, T.B. Randrup, C.K van den Bosch, Nature-based solutions and climate change–four shades of green. Nature-Based Solutions to Climate Change Adaptation in Urban Areas, Springer, Cham, 2017, pp. 29–49, https://doi.org/10.1007/978-3-319-56091-5_3.
[96] R. Pérez-Ceballos, A. Zaldívar-Jiménez, J. Canales-Delgadillo, H. López-Adame, J. López-Portillo, M. Merino-Ibarra, Determining hydrological flow paths to enhance restoration in impaired mangrove wetlands, PloS One 15 (1) (2020) e0227665.
[97] S. Petryk, G. Bosmajian III, Analysis of flow through vegetation, J. Hydraul. Div. 101 (7) (1975) 871–884.
[98] F. Pugliese, G. Caroppi, A. Zingraff-Hamed, G. Lupp, C. Gerundo, Assessment of NBSs effectiveness for flood risk management: The Isar River case study, AQUA—Water Infrastruct. Ecosyst. Soc. 71 (1) (2022) 42–61, https://doi.org/10.2166/aqua.2021.101.
[99] Y. Qi, H. Dou, Z. Wang, An adaptive threshold selected method from remote sensing image based on water index, J. Phys. Conf. Ser. 2228 (1) (2022) 12001, https://doi.org/10.1088/1742-6596/2228/1/012001.
[100] A.K. Sarfo, E. Owusu-Sekyere, A. Toku, N.N N-Yanbini, Geographically induced and the spatially differentiated dimension of flood vulnerability in Greater Kumasi Metropolis, Ghana, Int. J. Urban Sustain. Dev. 16 (1) (2024) 73–92, https://doi.org/10.1080/19463138.2024.2321218.
[101] M. Scholz, Classification methodology for sustainable flood retention basins, Landsc. Urban Plan. 81 (3) (2007) 246–256.
[102] N. Seddon, S. Sengupta, M. García-Espinosa, I. Hauler, D. Herr, A.R. Rizvi, Nature-based solutions in nationally determined contributions: Synthesis and recommendations for enhancing climate ambition and action by 2020, Gland Switz. Oxf. UK: IUCN Univ. Oxf. 48 (2019), https://doi.org/10.2305/IUCN.CH.2019.07.en.
[103] S. Shih, G. Rahi, Seasonal variations of Manning's roughness coefficient in a subtropical marsh, Trans. ASAE 25 (1) (1982) 116–0119.
[104] M. Singh, R. Sinha, Integrating hydrological connectivity in a process–response framework for restoration and monitoring prioritisation of floodplain wetlands in the Ramganga Basin, India, Water 14 (21) (2022) 3520.
[105] S. Smolders, P. Meire, S. Temmerman, F. Cozzoli, S. Ides, Y. Plancke, A 2Dh hydrodynamic model of the Scheldt estuary in 1955 to assess the ecological past of the estuary, TUC 2013 (2013) 137.
[106] Soil Conservation Service, *National Engineering Handbook: Section 4: Hydrology*. U. S, Dep. Agric. (2004).
[107] B. Sowińska-Świerkosz, J. García, A new evaluation framework for nature-based solutions (NBS) projects based on the application of performance questions and indicators approach, Sci. Total Environ. 787 (2021) 147615.
[108] S.A. Takyi, O. Amponsah, G. Darko, C. Peprah, R. Apatewen Azerigyik, G. K. Mawuko, A. Awolorinke Chiga, Urbanization against ecologically sensitive areas: Effects of land use activities on surface water bodies in the Kumasi Metropolis, Int. J. Urban Sustain. Dev. 14 (1) (2022) 460–479.
[109] F.Y. Teo, F. Aziz, S. Di Francesco, K. Förster, Potential and limitations of Nature-based Solutions (NbS) to global water challenges, Front. Water 5 (2023) 1278462.
[110] UN, World Urbanization Prospects 2018, Department of Economic and Social Affairs, 2018. Webpage.
[111] R. Van Coppenolle, S. Temmerman, Identifying global hotspots where coastal wetland conservation can contribute to nature-based mitigation of coastal flood risks, Glob. Planet. Change 187 (2020) 103125.
[112] J.T. Verhoeven, M.B. Soons, R. Janssen, N. Omtzigt, An operational landscape unit approach for identifying key landscape connections in wetland restoration, J. Appl. Ecol. 45 (5) (2008) 1496–1503.
[113] Z. Vojinovic, A. Alves, J.P. Gómez, S. Weesakul, W. Keerakamolchai, V. Meesuk, A. Sanchez, Effectiveness of small-and large-scale nature-based solutions for flood mitigation: the case of Ayutthaya, Thailand, Sci. Total Environ. 789 (2021) 147725.
[114] World Population Review, Kumasi Population. https://worldpopulationreview.com/world-cities/kumasi-population, 2021.
[115] Y. Wu, G. Zhang, A.N. Rousseau, Y.J. Xu, É. Foulon, On how wetlands can provide flood resilience in a large river basin: a case study in Nenjiang river Basin, China, J. Hydrol. 587 (2020) 125012.
[116] T. Wübbelmann, K. Förster, L.M. Bouwer, C. Dworczyk, S. Bender, B. Burkhard, Urban flood regulating ecosystem services under climate change: how can nature-based solutions contribute? Front. Water 5 (2023) 1081850.
[117] E. Yalcin, Assessing the impact of topography and land cover data resolutions on two-dimensional HEC-RAS hydrodynamic model simulations for urban flood hazard analysis, Nat. Hazards 101 (3) (2020) 995–1017.
[118] Yan, L., & Li, J. (2018). *A Case Study of Dark-objects Subtraction based Atmospheric Correction Methods for GF-1 Satellite Images*. 1–4.
[119] A. Zeufack, C. Calderon, M. Kubota, V. Korman, C. Cantu Canales, A. Kabundi, Africa's Pulse, No. 24: October, World Bank, 2021. https://openknowledge.worldbank.org/bitstream/handle/10986/36332/9781464818059.pdf?sequence=10&isAllowed=y.
[120] K. Zhang, M.H. Shalehy, G.T. Ezaz, A. Chakraborty, K.M. Mohib, L. Liu, An integrated flood risk assessment approach based on coupled hydrological-hydraulic modeling and bottom-up hazard vulnerability analysis, Environ. Model. Softw. 148 (2022) 105279.
[121] Y. Zhang, Editorial riparian ecology and conservation: the home of cutting-edge research on riparian biophysical processes, biodiversity, ecosystem functions and services, Riparian Ecol. Conserv. 1 (2013) (2013) 1–2.
[122] Y. Zheng, L. Tang, H. Wang, An improved approach for monitoring urban built-up areas by combining NPP-VIIRS nighttime light, NDVI, NDWI, and NDBI, J. Clean. Prod. 328 (2021) 129488.
[123] Zhongming, Z., Linong, L., Xiaona, Y., Wangqiang, Z., & Wei, L. (2018). *Many African countries are flooding, risking decades of development if they do not adapt*.

[124] A. Zingraff-Hamed, F. Hüesker, C. Albert, M. Brillinger, J. Huang, G. Lupp, S. Scheuer, M. Schlätel, B. Schröter, Governance models for nature-based solutions: seventeen cases from Germany, Ambio 50 (8) (2021) 1610–1627.
[125] Zingraff-Hamed, A., Lupp, G., Bäumler, K., Huang, J., & Pauleit, S. (2023). *The Isar River: Social pride as a driver of river restoration*.
[126] T. Zölch, L. Henze, P. Keilholz, S. Pauleit, Regulating urban surface runoff through nature-based solutions–an assessment at the micro-scale, Environ. Res. 157 (2017) 135–144.