

Article

Small Island City Flood Risk Assessment: The Case of Kingston, Jamaica

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Abstract: Jamaica has had over 200 floods in the past 50 years, causing significant human and economic losses. Kingston has often caused the most damage due to its high population density and capital exposure. Kingston is crucial to the country's socio-economic stability, and climate change is increasing flood risk, but a local-scale assessment of its flood risk is unavailable. This study fills this gap in the literature by using two models of the integrated Valuation of Ecosystem Services and Tradeoffs (inVEST) suite to qualitatively assess Kingston metropolitan pluvial and coastal flood risk. Key locations like Kingston Container Terminal and downtown Kingston are at high coastal flood risk, according to the results. The study also shows that sea level rise (117%) and habitat loss (104%) will increase the highly exposed area. Instead of hard-engineering coastal protection, this study suggests investing in nature-based and ecoengineering solutions to improve coastal resilience and ecosystem services. The urban flood assessment finds downtown, particularly the Mountview and Minor catchments, at high risk due to poor runoff retention and high population density. To fully address downtown pluvial flood risk, structural social reforms are needed. To reduce short-term flood risk, local authorities should consider targeted adaptation measures. These may include maintaining the drainage gully system and reducing surface runoff in uphill downtown areas. Thus, this study seeks to inform Kingston urban planners about risk distribution and suggest adaptation measures to improve flood resilience.

Keywords: flood risk assessment; pluvial flooding; climate change; nature-based solutions; ecosystem services; Jamaica; inVEST models; urban flooding; habitat loss



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1. Introduction

Small island developing states (SIDS) consist of 39 nations, primarily situated in the Caribbean Sea and the Pacific Ocean [1]. These nations have unique characteristics, and despite contributing a mere fraction (less than 1%) to global greenhouse gas emissions, they are disproportionately affected by the adverse impacts of climate change [2]. Their reliance on the environment for vital sectors like tourism and agriculture makes them particularly vulnerable [3]. The increasing occurrence of natural hazards, such as severe storms, further heightens their challenges [4].

Jamaica, a significant member of the Caribbean SIDS, has frequently experienced these natural adversities. Between 1978 and 2010, the nation endured 198 flood events, causing considerable losses [5,6]. As climate change continues its trajectory, the repercussions for Jamaica, especially in terms of flooding, are expected to escalate. Notably, researchers at UWI Mona have underscored the potential setbacks climate change could pose to Jamaica's developmental aspirations, particularly in sectors like tourism, education, and agriculture [7].

Kingston, as the capital of Jamaica, is not just a bustling urban hub but also a region of critical importance [8]. It houses a significant portion of Jamaica's population and is

a nexus of economic and infrastructural activities [9]. Its airport and port status further bolster its significance in the Caribbean [10,11]. Yet, its geographical positioning makes it susceptible to storm-induced damage [12]. While there is ample research on Jamaica's overall susceptibility to climate change, a distinct void exists when it comes to detailed studies focusing exclusively on Kingston [13,14].

This study seeks to fill this evident gap. By harnessing the capabilities of two models from the inVEST suite, we delve into an in-depth examination of Kingston's flood risks, both from coastal surges and heavy rainfall events. Our research not only presents a detailed flood risk assessment tailored to Kingston but also emphasizes the importance of such city-centric studies. Through our use of the inVEST suite models, we provide a nuanced perspective on Kingston's vulnerabilities, aiming to offer insights that can bolster the city's resilience and mitigation strategies. Furthermore, our findings enrich the broader discourse on climate change impact on urban centres in Small Island developing states and present a methodology that other urban centres, especially in SIDS, might find valuable.

2. History of Flooding in Jamaica and Kingston: Hazards and Impacts

Over the last 30 years, storms and related flood events have caused close to 5000 deaths and about 980 M USD in damage across Caribbean Island states [15]. Being on the main path of Caribbean storms, Jamaica faces a high impact, especially from hurricanes which are the most common natural threat [13]. Jamaica's risk to flooding is heightened because its main towns and industries are located in low-lying coastal areas, which are prone to flooding [16]. This mix of a high risk of flooding and significant human and economic activity in these areas has led to severe losses, with the most damaging five storms since 2004 causing over 1.2 B USD in damages [17].

Kingston, situated on the southern coast between two large river basins (Hope River and Rio Cobre), is no exception to this trend. Its low-lying geography makes it vulnerable to coastal flooding. Important structures like Norman Manley International Airport are less than 10 m above sea level, adding to the city's risk [18,19]. Moreover, the Caribbean Sea levels are projected to rise faster than the global average and are expected to be 1.4 m higher by 2100 in a high emission scenario, which will likely increase coastal flood risk significantly [20]. In addition, the city's layout, with a steep slope from the inner city to the coast, makes it prone to flash flooding during heavy rainfall events [21].

In an attempt to reduce flash flood risks, local authorities have developed a drainage system of gullies and underground channels between the 1930s and 1960s. Today, this system consists of 50 artificial streams that run from the hills around the city to the harbour [22]. However, the gullies have been largely ineffective due to a lack of maintenance and rapid urban expansion around them. The problem is worsened by poor waste management across the city, leading to garbage accumulation in the gullies which obstructs water flow during rains [23]. This issue is particularly severe in poorer, low-lying areas of the city, where garbage from uphill accumulates, heightening the risk of overflow [22].

Flooding has caused severe damage to Kingston throughout the 20th century, with the worst damage often occurring during the hurricane season between September and October [24,25]. In recent times, Hurricane Ivan (2004) and Hurricane Sandy (2012) were particularly destructive for the city. Ivan brought intense rainfall, which was 300% above the average, causing eight deaths and significant damage to over 5000 homes and public buildings [26]. This storm also threatened the Palisadoes sand strip, prompting the government to start sea-defence projects. However, only emergency repair works were completed, leaving Palisadoes and Kingston Harbour vulnerable without the proposed nature-based solutions [27,28]. On the other hand, while hurricane Sandy brought less rain than Ivan, it caused more damage in Kingston as it hit closer to the city. The total losses for Kingston were over USD 45 M, making up 67% of the country's total losses. More than 135,000 people in Kingston were directly affected, with 20,000 left without direct water access and many healthcare facilities, schools, and private homes made inaccessible, which was worse than the aftermath of Ivan [26].

Studies on Flood Risk in Jamaica

The need for a thorough understanding of flood risks in Kingston, particularly at a local level, is underscored by the historical damage the city has endured from flooding. However, there remains a noticeable gap in the literature regarding local-scale flood risk assessments for Kingston. This is largely due to the challenges faced in collecting the detailed data necessary for such assessments in many areas across Jamaica. The complex topography and dense vegetation of the country hinder the collection of high-resolution data on terrain, soil properties, and land cover, which, in turn, makes accurate remote sensing very challenging [29].

For assessing pluvial (rain-related) flooding, Burgess et al. [14] initially crafted a country-scale risk model. This model utilized data from historical extreme precipitation events to classify flood risk across the island, linking them to the damage and fatalities from the ten most severe precipitation incidents recorded in the country. According to this model, areas that were most affected in the past by these events are considered to have the highest flood risk. However, the authors acknowledged a significant limitation in their study, which was the small number of case studies used to build the model. The accuracy of death, damage, and rainfall intensity estimates from historical records was found to be lacking. Furthermore, this model did not consider the physical factors like steepness, soil type, and land cover that influence flood hazards, and instead relied on post-event measurements. This reliance on interpolation to fill in the gaps in damage assessments does not provide an accurate local-scale estimate of flood hazard. Moreover, the model does not offer insights into how flood risk might evolve in the future, especially as local conditions change due to alterations in land-use and other exposure parameters [30,31].

On the other hand, a different method was employed by Nandi et al. [13], who created a country-scale flood hazard assessment based on 14 hydrological, meteorological, and geological parameters. Although this study took a more holistic approach towards understanding flood hazards, it did not incorporate any socio-economic exposure parameters, thus providing only a partial view of the flood risk scenario.

When it comes to coastal flooding, the literature is even more sparse, likely because historically, its impacts have been less severe compared to pluvial flooding. The primary threat to Jamaica's coasts comes from storm surges driven by hurricanes [32]. Ortega et al. [18] carried out a country-scale assessment of coastal flood risk, revealing that a significant portion of Jamaica's coastline is at risk of experiencing 0.5 m flooding events, with an estimated total exposure of about 135 M USD. While this study acknowledged that some bays within Kingston's vicinity, such as Hunts Bay, are highly vulnerable to coastal flooding, the local-scale analysis was focused on other areas.

3. Materials and Methods

3.1. Study Area

The study area encompasses the metropolitan area of Kingston and parts of Spanish Town; it is bounded southward by the Caribbean Sea and in all other directions by the hill range surrounding the city (Figure 1). The study area of the coastal assessment extends from Fort Clarence Beach on the west [$17^{\circ}54'35''$ N, $-76^{\circ}53'14''$ E] to Bull Bay on the east [$17^{\circ}56'35''$ N, $-76^{\circ}40'2''$ E] and includes the Palisadoes sand strip where NMI is located. In the urban flood risk assessment, the study area is divided into six catchments: three rivers (Hope, Rio Cobre, and Fresh) and three artificial gully systems (Sandy Gully, Mountview Gully, and "Minor" gullies). The "Minor" gullies system comprises six short channels running N-S from Kingston downtown to the sea that are grouped due to data availability and resolution issues (Figure 1). The Palisadoes sand strip is not included in the urban flood assessment as it does not have any water catchments.



Figure 1. Above: Location of Kingston (red star) within the main island of Jamaica. Below: study area for the coastal and urban flooding assessments. The blue lines are a schematic representation of rivers, streams, and gullies sourced from OpenStreetMap. The black lines represent the boundaries of the 6 studied catchments (Cobre, Fresh, Sandy, Minor, Mt. View, and Hope). The orange line highlights the stretch of coastline considered in the coastal flood assessment. Labelled are some key locations mentioned in the study like Kingston Container Terminal (KCT) and Norman Manley International Airport (NMI).

3.2. Assessing Flood Risk Using inVEST Models

In the methodology of our coastal assessment, this study employed the inVEST Coastal Vulnerability (CV) model to produce a relative flood exposure index along Kingston's shoreline. This model, part of a suite designed for qualitative flood risk assessment, integrates both physical and natural habitat factors, which were traditionally considered in isolation [33]. Recognized for its flexibility, the inVEST CV model can accommodate a combination of global and local datasets, making it particularly valuable for regions like Jamaica where data constraints have historically impeded research progression [29].

By design, the inVEST CV model does not provide an absolute quantification of coastal exposure. Instead, it offers a relative assessment within the studied domain. Rather than executing intricate calculations to determine erosion potential or inundation depth, the model contrasts various physical parameters directly linked to flood risk across shoreline segments within a specified region. Consequently, while the model is grounded in quantitative, well-established indicators of coastal exposure, it delivers a qualitative assessment of coastal exposure. The primary objectives are to pinpoint areas with the highest coastal risk and to evaluate how this risk might evolve under different Sea Level Rise (SLR) and habitat extent scenarios. Given that these objectives often align with the requirements of stakeholders and decision makers [34], the model has been widely adopted in the academic literature. Notably, Arkema et al. utilized inVEST CV to gauge coastal exposure across the entire US coastline, underscoring the protective value of coastal ecosystems against erosion and flooding. Their findings significantly influenced the prioritization of natural solutions over engineered interventions in coastal management [35,36]. Similarly, Silver et al. [34] applied the inVEST CV model in the Bahamas, providing crucial insights to national authorities for post-hurricane reconstruction and resilience-building after the 2015/2016 hurricane season.

For our study, the inVEST CV model was deployed to assess coastal exposure along Kingston’s shoreline at a 100 m resolution. It is worth noting that the model’s analysis was confined to physical exposure. Given that the inVEST CV model does not compute the inland progression of storm surges, it was not feasible to directly correlate the hazard impact with parameters of human sensitivity and adaptive capacity, such as assets exposure.

Table 1 delineates the data prerequisites for the inVEST CV model and their respective sources. Notably, the original coastal geomorphology data underwent modifications to better reflect real-world conditions, as corroborated by Google Earth imagery and the literature data. One significant adjustment pertained to the Palisadoes sand strip, where the seaward shore was reclassified as “rock revetment” instead of the originally designated “beach” (Figure S1).

Table 1. Data requirements and sources for the inVEST CV model.

Data	Source	Resolution
Coastal geomorphology	Mao et. al (2022) [37]	10 m
Digital Elevation Model	Shuttle Radar Topography Mission [38]	30 m
Coastal and marine natural habitats	Global Mangrove Watch [39]; Allen Coral Atlas [40]	25 m; 5 m
Sea level rise projections	IPCC AR6 [41–43]	111 km
Exposure to wind and waves	NOAA WAVEWATCH3 (embedded in model)	50 km
Distance from continental shelf (storm surge potential)	Embedded in model	Vector

For each shoreline segment, elements within the same group of variables (Table 1) were ranked from 1 to 5 based on increasing exposure (Table 2). The inVEST model integrates seven variables: wave exposure, wind exposure, surge potential, relief, geomorphology, habitats, and sea level change rates. The five exposure classes of each variable (Table 2) range from 1 (very low) to 5 (very high) [35]. The exposure rank evaluates the extent to which an area is prone to being affected by coastal hazards due to its biophysical attributes. The exposure ranking for natural habitats, shoreline type, and SLR were user-defined, while the model automatically computed it for other parameters.

Table 2. Variables and relative ranks used to calculate the Coastal Exposure Index.

Variable	Exposure Rank				
	1—Very Low Exposure	2—Low	3—Moderate	4—High	5—Very High
Natural habitats	Coral reef, mangroves	-	-	Sea grass	Bare
Shoreline type (geomorphology)	-	-	Bedrock, revetment	Wetland	Beach
Elevation	First quantile	Second	Third	Fourth	Fifth
Wave exposure	First quantile	Second	Third	Fourth	Fifth
Wind exposure	First quantile	Second	Third	Fourth	Fifth
Surge potential	First quantile	Second	Third	Fourth	Fifth
Sea level rise	0–13 cm	13–26 cm	26–39 cm	39–52 cm	52–65 cm

In alignment with other research, wetlands and beaches were designated “high” and “very high” exposure ranks, respectively [44,45]. The final Coastal Exposure Index for each segment was computed as the geometric mean of the ranked variables, with all variables receiving equal weight [46]. This multiplicative approach facilitates a more precise estimate of total exposure, accounting for the non-linear interactions among components of coastal ecosystems [47]. The index was then employed to determine the number of individuals at high risk under each defined scenario, defined as those residing within 100 m of a high-exposure coastal segment [48].

Subsequently, a hotspot analysis was applied to the index to discern the spatial significance of the generated exposure values [49]. The results of this exposure assessment

will be utilized to qualitatively evaluate coastal flood risk, drawing upon the existing literature on Kingston's coastal vulnerability.

In the pluvial assessment of urban flood risk, this study employs the inVEST Urban Flood Risk Mitigation (UFRM) model to evaluate runoff generation and retention at the catchment scale. The UFRM model, previously applied in diverse global contexts ranging from Europe [50,51] to the Middle East [52,53] and Southern Asia [54,55], was pivotal in the Ile-de-France Evaluation Services Ecosystemiques (IDEFESE) project. This initiative, spearheaded by various French national institutions, sought to discern the protective role of ecosystems against flood risk across Paris, thereby informing future urban planning strategies [56].

The six catchments were delineated using the digital elevation model (Figure S2) of the study area, guided by streams and gullies identified via OpenStreetMap [54]. For each catchment, a Flood Vulnerability Index (FVI) was derived, amalgamating both physical and socio-economic exposure parameters (Table 3).

Table 3. Parameters used to calculate the Flood Vulnerability Index.

Data	Source	Resolution
Runoff retention index	inVEST UFRM model [34]	Vector
Building density	OpenStreetMap [57]	Vector
Road density	OpenStreetMap [57]	Vector
Tree cover	Zanaga et al. (2022) [58]	10 m
Population density	Bondarenko et al. (2020) [59]	100 m
Deprivation index	CIESIN (2022) [60]	1000 m

Physical parameters, including building density, road density, tree cover, and runoff retention index, mirror those employed by Kadaverugu, Nageshwar Rao, and Viswanadh et al. [54] in their micro-catchment scale flood risk assessment in Kolkata, India. Building and road densities, which are positively correlated with flood risk, were derived from OpenStreetMap [54], with densities computed by dividing the respective areas by the total catchment area. Conversely, tree cover, sourced from the ESA World Cover database [58], was inversely related to flood risk due to its role in rainfall interception and soil permeability enhancement.

The inVEST UFRM model was instrumental in determining the runoff retention index for each catchment, estimating both generated and retained runoff based on physical parameters and user-defined rainfall intensity values. Two rainfall intensity values were considered: 178 mm, representing a 5-year return period (RP) rainfall event for Kingston, and 342 mm, indicative of a 100-year RP event [5]. The latter intensity aligns with common urban planning practices [61,62], while the former facilitates a comparative analysis of a less intense event's impact on the study area.

Socio-economic parameters, namely population density and the deprivation index, are frequently incorporated in FVI-based flood risk assessments [63,64]. Population density, a direct measure of exposed human capital, was computed using QGIS [65] by counting the total population [59] within catchment boundaries and then normalizing by the catchment area. The deprivation index, a composite metric encapsulating various socio-economic indicators, is directly associated with flood vulnerability due to its impact on population resilience and adaptive capacity [66].

To ensure comparability, all parameters were normalized on a 0–1 scale. These scaled parameters were then ranked from 1 to 5 based on increasing flood exposure (Table S1). The FVI for each catchment was computed as the geometric mean of these ranks, with all variables given equal weight. Similar to the Coastal Exposure Index, the FVI was categorized qualitatively as “low,” “medium,” or “high” based on specific value thresholds [34].

The FVI approach, distinct from conventional flood risk assessment methods, allows for the integration of socio-economic exposure parameters alongside physical determinants of hazard magnitude [67]. Such indices simplify complex variable interactions into a singular metric, enhancing understandability for stakeholders and policymakers [63].

The accuracy of an FVI hinges on the chosen indicators and their respective weightings. While some advocate for differential parameter weighting based on perceived importance [68], the inherent subjectivity and lack of a universal weighting scheme often lead researchers to adopt an equal weighting approach [61]. This method, while straightforward, is deemed as technically valid as any other, given the empirical indeterminacy of any specific weighting scheme [63,69].

3.3. Coastal Exposure

The inVEST CV model was used to assess coastal exposure along the Kingston shoreline at 100 m resolution. The model provides a relative assessment of coastal exposure to flooding and erosion based on several physical parameters [34]. The analysis was limited to physical exposure as the inVEST CV model does not estimate the landward propagation of storm surge, so the hazard impact could not be directly related to parameters of human sensitivity and adaptive capacity (i.e., assets exposure).

Table 1 shows the data requirements for the inVEST CV and the sources from which they were collected for this study (Figures S1–S4). The original coastal geomorphology data have been modified to adjust for real-world conditions based on Google Earth images and the literature data. The only change applied was on the Palisadoes sand strip, in which seaward shore has been classified as “rock revetment” rather than “beach” as assigned in the original file (Figure S1).

For each shoreline segment, elements within the same group of variables listed in Table 1 were ranked from 1 to 5 in order of increasing exposure (Table 2). Exposure ranking was user-defined for natural habitats, shoreline type, and sea level rise, while the model computed it automatically for the other parameters.

Coral reefs and mangroves were both assigned a “very low” exposure rank (Table 2) as extensive evidence exists for the significant coastal protection services offered by these ecosystems [18,35,70,71]. Seagrass beds were assigned a “high exposure” rank (Table 2) as they offer some protection against low-intensity waves at high density but have limited effect against stronger waves [72]. For coastline segments with more than one habitat, the model computed a composite rank score so that the presence of multiple habitats ensured higher protection than any of them alone [34] (Figure S1 for the habitats distribution).

In agreement with other studies, wetlands and beaches were assigned “high” and “very high” exposure ranks (Table 2), respectively [45,52]. Bedrock and revetment shoreline segments were ranked 3 (moderate exposure) following Silver et al. [35]. Other studies assigned rocky shoreline rankings of 1 or 2 [45,46], but as shown by sensitivity analysis, the choice of this ranking does not significantly affect the final coastal exposure results (Figure S3). Following Silver et al. [34] and Zhang et al. [45], sea level rise ranks were assigned by dividing the sea-level rise curve for Kingston Harbour into five ranges as shown in Table 2. The first quantile (0–13 cm) represents the current sea level and was assigned rank 1; the fifth quantile (52–65 cm) represents end-of-century sea level rise under a moderate emissions mitigation Shared Socioeconomic Pathway scenario (ssp245) [41] and was assigned rank 5. The ssp245 scenario, in which some measures for climate change mitigation are taken but are not sufficient to keep global average temperatures below 2 °C [73], was chosen as it is in line with the most recent projections [74].

The final Coastal Exposure Index for each segment was calculated as the geometric mean of the ranked variables, with all variables having equal weighting [46]. A multiplicative model allows for a more accurate estimate of total exposure as it accounts for the non-linearity of the interactions among components of coastal ecosystems [47]. The index was calculated for four scenarios of different SLR and habitat extent: (1) current sea level and habitat extent, (2) current sea level and complete habitat loss, (3) end-of-century sea level and current habitat extent, and (4) end-of-century sea level and complete habitat loss. Figure 2 provides a schematic summary of the steps used to calculate the Coastal Exposure Index. In line with the inVEST risk ranking guidelines and other studies using inVEST CV, including Silver et al. [34] and Hopper [49], the index was expressed in the qualitative

categories of “low”, “medium”, and “high” for values lower than 2, between 2 and 3.5, and greater than 3.5, respectively [33].

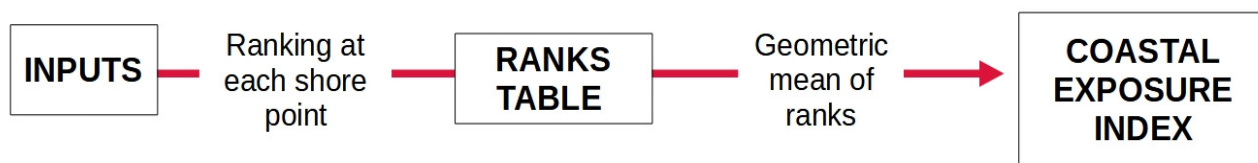


Figure 2. Flow chart graphically summarizing the key steps for calculating the Coastal Exposure Index. For each shoreline segment, input data (Figures S1–S4) are ranked 1–5 according to their increasing contribution to exposure. The geometric mean of the ranks is then taken to calculate the final Coastal Exposure Index.

The index was then used to calculate the number of highly exposed people under each scenario, defined as the number of people living within 100 m of a high-exposure coastal segment [75]. A distance of 100 m was chosen to provide a conservative estimate of the affected people consistent with the limited computational capacity of the model and to account for the steep elevation gradient between the seaside and inner areas (Figure S3). The numbers refer to the current total population in all scenarios and do not account for future projections [34]. This choice was made as while the total Jamaican population is projected to decrease by a third by 2100 [9], it is not possible to predict over such a long horizon how people would redistribute on the island and how many would live in proximity of coastal areas.

Hotspot analysis was then applied to the index to determine the spatial significance of the exposure values produced [49]. The hotspot analysis was performed using the hotspot analysis plugin in QGIS [76]. The tool calculated the G_i^* z-scores and p -values for each datapoint, with positive (negative) Z-scores indicating a cluster of high (low) values of coastal hazard. A statistically significant hotspot (coldspot) is identified when a positive (negative) feature is surrounded by other of the same value [45].

The results of the exposure assessment were used to qualitatively evaluate coastal flood risk using the literature evidence on Kingston’s coastal vulnerability.

3.4. Urban Flood Risk

Urban flood risk was assessed at the catchment scale. The six catchments were delineated using the digital elevation model (Figure S2) of the study area as a guideline, with the streams and gullies identified through OpenStreetMap [57]. For each catchment, an FVI was calculated from both physical and socio-economic exposure parameters (Table 3). A schematic summary of the methodology followed to compute the FVI is shown in Figure 3.

The physical parameters (i.e., building density, road density, tree cover, and runoff retention index) are the same used by Kadaverugu, Nageshwar Rao, and Viswanadh [77], who assessed flood risk at the micro-catchment scale in Hyderabad (India). Building density and road density are positively correlated to flood risk, as they reduce water infiltration rates and increase surface runoff generation [78]. Building footprints and the road network were extracted from OpenStreetMap [57] (Figures S7 and S8). The road and building densities were calculated by dividing the area of roads and buildings in each catchment by the total catchment area. Tree cover is anticorrelated to flood risk since trees contribute to rainfall interception (depending on species) and improve soil permeability [79]. Tree cover was extracted from the ESA World Cover database (Figure S5) [58].

The runoff retention index for each catchment was calculated using the inVEST Urban Flood Mitigation (UFRM) model. The model estimates generated and retained runoff based on physical parameters and a user-defined rainfall intensity value using the SCS curve number method (Figures S5 and S6). In this study, two values of rainfall intensity were considered: 178 mm and 342 mm. The former represents the 24 h intensity of an average historical (1895–2010) 5-year return period (RP) rainfall event for Kingston, and the latter

represents the same quantity for a 100-year RP event [5]. The 100-year RP intensity was selected for this study as it is a commonly used time horizon in urban flood planning, aligning with conventional practices as documented in references [58,59]. Conversely, the 5-year RP was chosen to evaluate the impact of a less severe event on the studied area. This event, characterized by the 5-year RP, is more frequent with a 20% chance of occurrence annually. Comparing these two RPs offers a framework to analyse how flood events of varying magnitudes affect the area under study.

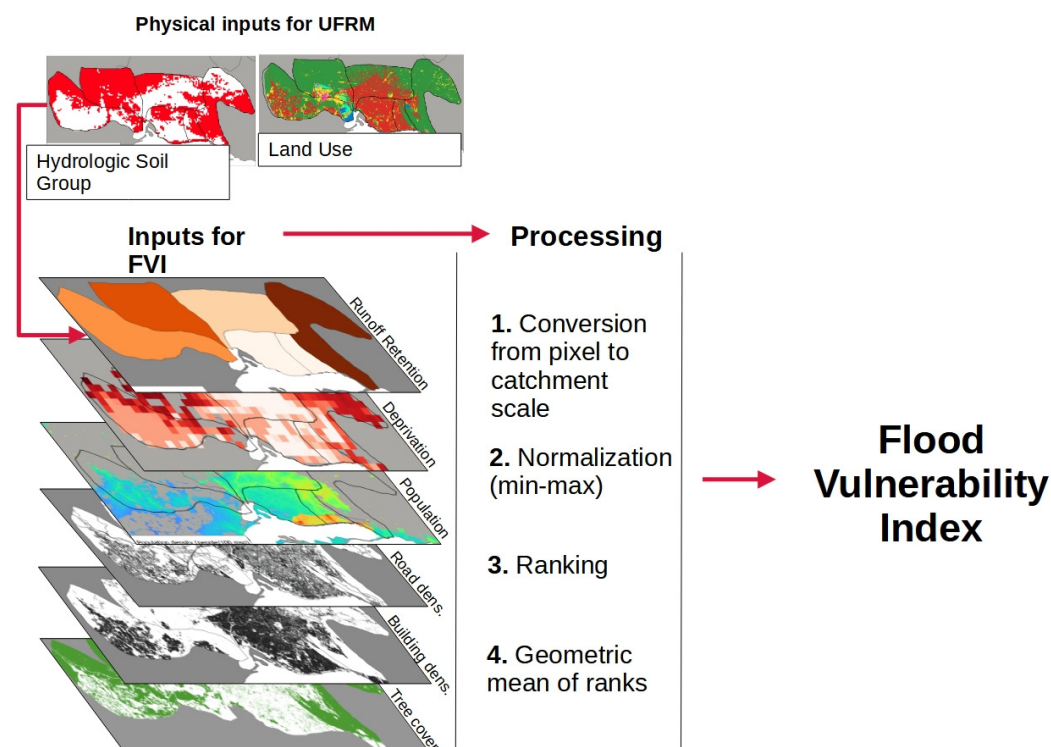


Figure 3. Flow chart graphically summarising the key steps for calculating the urban Flood Vulnerability Index. First, the inputs for running the inVEST UFRM model (Figures S5–S10) were collected and processed to calculate the runoff retention index for the six studied catchments. The runoff retention index was then combined with the other datasets used to calculate the Flood Vulnerability Index. The data used to calculate the FVI were converted from pixel to catchment scale, normalised, and ranked at catchment scale. Finally, the FVI was calculated as the geometric mean of the ranks for each catchment.

The selected socio-economic parameters (population density and deprivation index) are among the most used in flood risk assessments using FVIs [63,64]. Population density is positively correlated with flood risk, as it is a direct measure of the human capital exposed [80]. In each catchment, the population density (people/m²) was calculated using the field calculator function in QGIS [65] to count the total number of people [63] within the catchment boundaries and then divide this quantity by the catchment surface area (Figure S9). The deprivation index used in this study (Figure S10) is a composite indicator of deprivation encompassing child dependency ratios, infant mortality rates, a subnational human development index, building footprints per square kilometre, and nighttime lights [60]. All the individual variables composing the index are commonly used indicators in flood risk assessments [63]. Deprivation is directly correlated with flood vulnerability as it significantly reduces the resilience and adaptive capacity of the impacted population [66]. The reader is referred to the Centre for International Earth Science Information Network for a detailed description of the index composition.

In each catchment, the aforementioned parameters were then normalized to a common decimal scale (from 0 to 1) to be comparable with each other. The scaled parameters were

then used to assign a 1–5 rank to each catchment in order of increasing flood exposure (Table S1). Finally, the FVI for each catchment was calculated by taking the geometric mean of the ranks, with all variables assigned equal weighting. As for the Coastal Exposure Index, the FVI is expressed in the qualitative categories of “low”, “medium” and “high” for values lower than 2, between 2 and 3.5, and greater than 3.5 [34]. The methodology to compute the FVI is schematically summarized in Figure 3.

4. Results

4.1. Coastal Exposure

Figure 4 shows the distribution of the Coastal Hazard Index along the Kingston shoreline under different SLR scenarios and assuming current habitats extent. In the current scenario, the highest exposure was found in downtown Kingston, Hunts Bay, and on the seaward side of Port Royal (Figure 4a). In contrast, the lowest exposure was observed on the harbour side of the Palisadoes tombolo and on the eastern side of Kingston harbour. A sharp increase (104%) in the number of coastline segments showing high exposure was found in the future scenario (Figure 4b), in which all the studied coastline is highly exposed except for the eastern side of Kingston harbour and some points along the harbour side of Palisadoes.

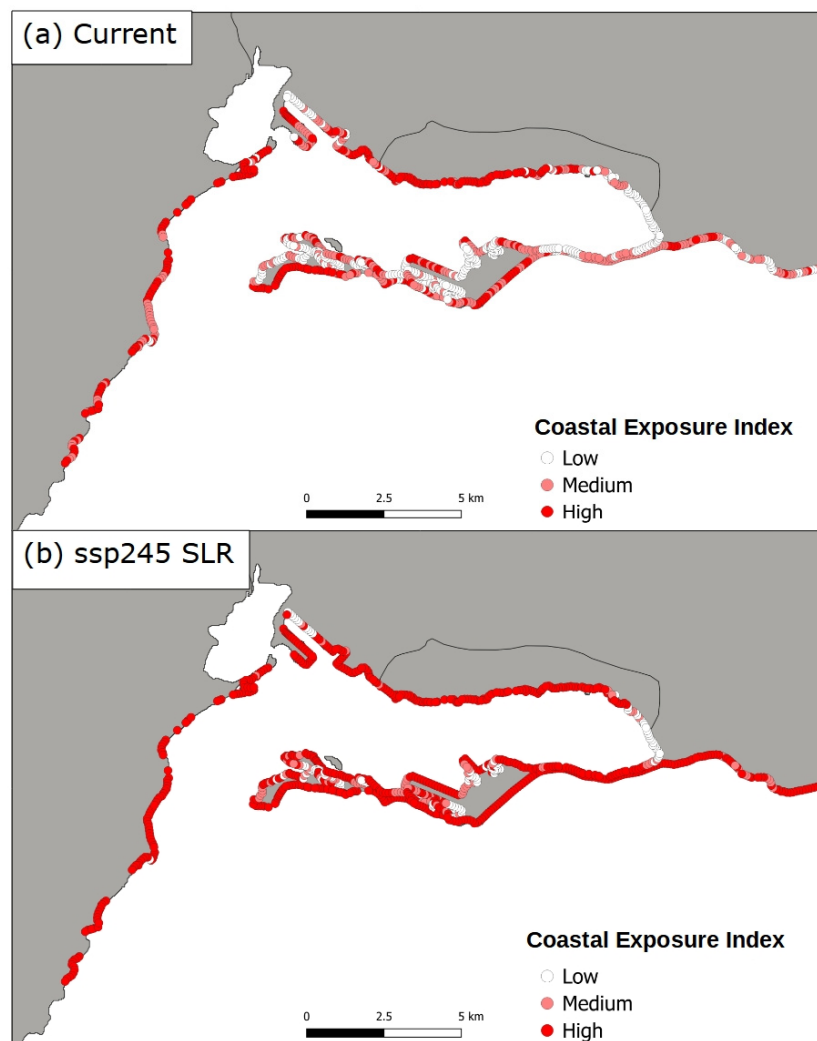


Figure 4. Costal Exposure Index for Kingston coastline under (a) current and (b) ssp245 end-of-century sea level assuming current habitat extent. Each dot represents a 100 m segment of coastline. White dots indicate low exposure, pink dots medium exposure, and red dots high exposure to flooding.

These results were generally confirmed by the Gi* hotspot analysis (Figure 5), which highlights the areas along the Kingston shoreline with the highest and lowest exposure independently of SLR. The hotspot analysis does not consider the change in exposure given by the increased sea level, but only identifies hotspots of exposure within the same set of conditions. The hotspot analysis generally agreed with the raw exposure assessment, showing how downtown Kingston, the seaward shore of Port Royal, and parts of Hunts Bay all qualify as hotspots of coastal exposure (Figure 5). Accordingly, the eastward side of Kingston harbour and the harbour side of the Palisadoes sand strip are identified as “coldspots” of low exposure (Figure 5). The main discrepancy was observed for the seaward side of NMI Airport, which was not identified as a statistically significant hotspot despite showing high exposure in both scenarios (Figure 4).

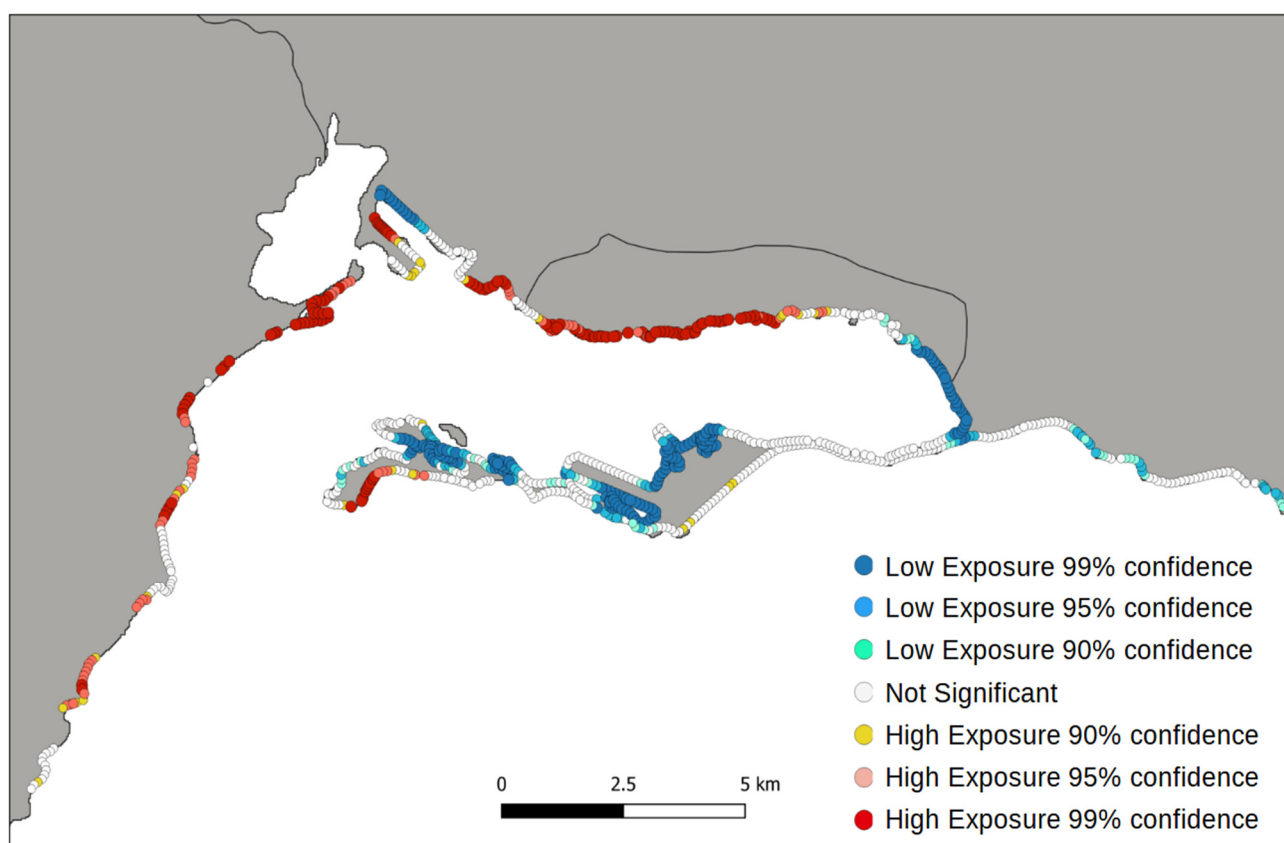


Figure 5. Hotspot analysis of coastal exposure along Kingston coastline. Each dot represents a 100 m segment of coastline. The warm (cold) colours indicate hotspots (coldspots) of exposure with darker colours indicating higher statistical confidence.

The combined effects of SLR and habitat loss on coastal and population exposure are shown in Figure 6. Ecosystems provide a significant contribution towards coastal protection, with the complete loss of habitats under current sea level conditions causing a 104% and 64% increase in the length of highly exposed coastline and the number highly exposed people, respectively. Yet, SLR appears to be a stronger risk factor, with end-of-century conditions producing a 117% and 89% increase in highly exposed coastline and population assuming the preservation of current habitats extent (Figure 6).

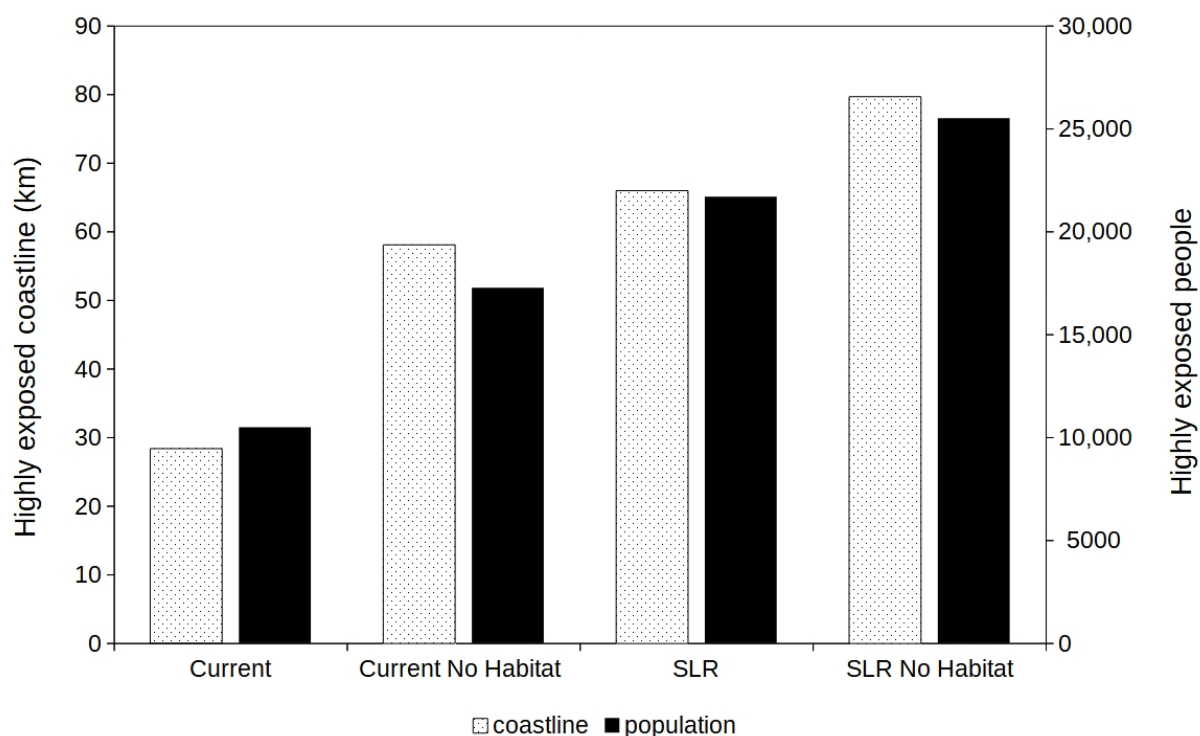


Figure 6. Kilometres of highly exposed coastline (dotted) and number of highly exposed people (black) under four different SLR and habitat extent combinations: current sea level and habitat extent, current sea level and complete loss of habitats, end-of-century SLR and current habitat extent, and end-of-century SLR and complete habitat loss.

4.2. Urban Flood Risk

In assessing the urban flood risk in Kingston, it is vital to consider a spectrum of determinants that influence the city's susceptibility to flooding events. These determinants encompass (1) rainfall intensity, represented by varying RP events; (2) the spatial distribution patterns that spotlight consistently vulnerable regions; (3) the prevailing urban land use patterns, distinguishing between built-up and forested areas; and (4) the diverse soil types and their corresponding water absorption capabilities. Figures 7 and 8, along with the associated Supplementary Materials, visually and analytically represent these factors, offering an integrated perspective on the city's flood dynamics.

Figure 7 illustrates Kingston's runoff retention capacities during two distinct rainfall scenarios: the 5-year RP event and the 100-year RP event. A notable decline in the runoff retention index as we transition from the 5-year to the 100-year event underscores the city's heightened vulnerability in the face of intensified rain events. Additionally, Figure S11, provides a deeper insight into the increase in runoff generation, especially during the more intense 100-year event.

Upon closer examination of the spatial intricacies in Figure 7, it is evident that specific areas, especially built-up zones like Minor, Mountview, and Sandy Gully, face a continual challenge with low runoff retention. This contrast with the forested regions highlights the significant influence of urban land use in shaping flood risks. Urban areas, characterized by dense infrastructure and concrete terrains, inherently hamper rainwater absorption, positioning them as perennial flood hotspots. Conversely, forested regions, endowed with their natural permeability, act as protective shields, reducing flood risks. Another layer to this analysis is introduced by the variations in soil types. While their influence might seem nuanced, it becomes more apparent in regions near the Hope and Sandy catchments, as hinted in Figure S6. Different soil types, with their unique absorption properties, add depth to the understanding of the flood determinants.

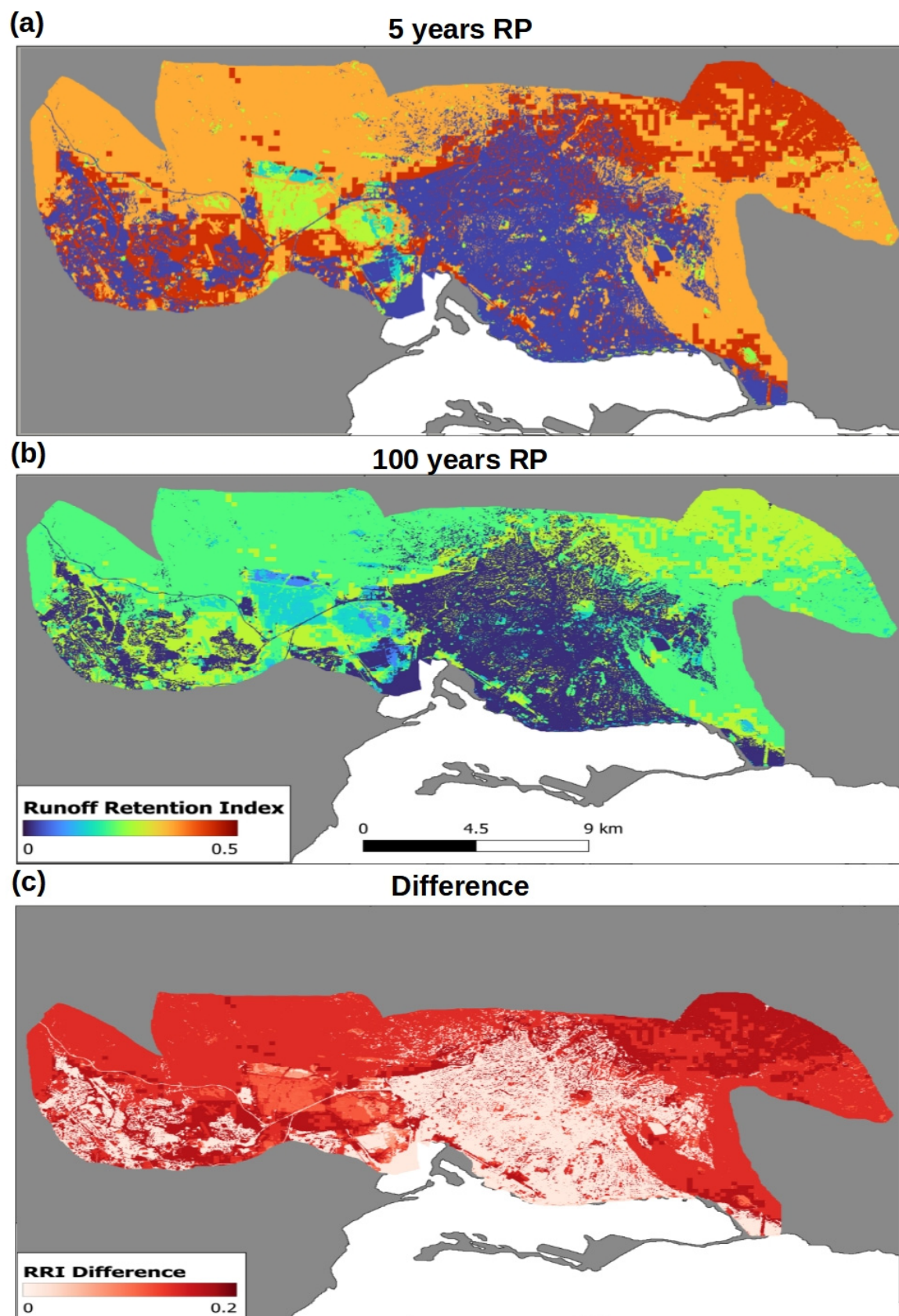


Figure 7. Runoff Retention Index for (a) 5-year RP storm (178 mm rainfall/24 h) and (b) 100-year RP storm (342 mm rainfall/24 h), with the difference between the two scenarios shown in (c).

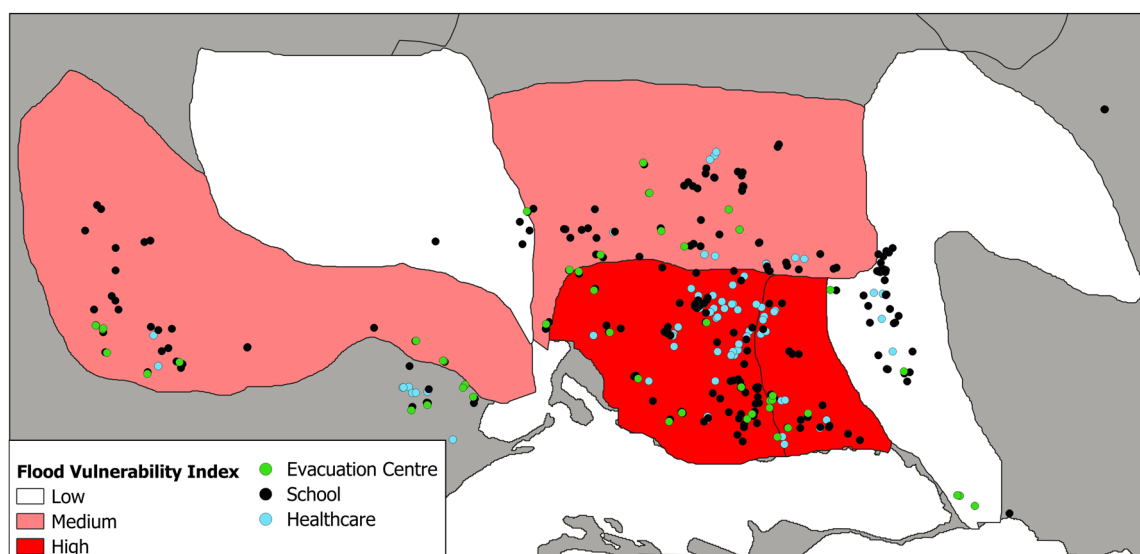


Figure 8. Flood Vulnerability Index of the six studied catchments. Low flood risk ($FVI < 2$) is shown in white, medium risk ($2 < FVI < 3.5$) in pink, and high risk ($FVI > 3.5$) in red. The location of schools (black dots), healthcare facilities (cyan dots), and evacuation centres (green dots) across the six catchments is also highlighted.

Figure 8 takes this narrative forward, presenting the Flood Vulnerability Index. This index melds the insights from Figure 7 and the associated Supplementary Materials to offer a comprehensive risk assessment. Notably, geographically sensitive areas like the Minor and Mountview catchments, while inherently vulnerable, also house a significant portion of Kingston’s essential infrastructure, emphasizing the compounded risk. In summary, Figures 7 and 8, complemented by the detailed Supplementary Materials, craft a holistic story of Kingston’s flood risk landscape, shaped by rainfall intensity, urbanization, soil variations, and critical infrastructure.

5. Discussion

5.1. Coastal Flood Risk

The coastal assessment shows how most areas hosting major infrastructures are highly exposed. Medium–high exposure is found around the Kingston Container Terminal (KCT) in Hunts Bay (Figure 4a), with the hotspot analysis confirming the result at a 99% confidence level (Figure 5). Exposure increases to high around KCT with end-of-century SLR (Figure 4b). These findings are consistent with the analysis by Monioudi et al. [11], who mapped the potential of coastal inundation around KCT under different SLR scenarios and found significant portions of the terminal to be at risk of flooding under ssp245 SLR as soon as 2050. They also found that risk would significantly increase in a higher emission scenario, in which almost half of the KCT area would be exposed to inundation by 2100. The risk faced by KCT is also highlighted by [17], who point out how several portions of KCT lie less than 1 m above sea level, making them vulnerable to flooding even in low emission scenarios, with Caribbean SLR reaching 0.5 m. The KCT is a crucial infrastructure for Kingston and Jamaica: it controls most of the national imports and exports and, being the 8th largest port in Central and South America for throughput, it is a hub of strategic relevance for the entire region. Thus, it is of paramount importance for Jamaican stability that adaptation measures are implemented to make the KCT able to withstand future climate change forcings. However, despite multiple studies agreeing on the fundamental importance of implementing such resilience measures [11,17] and the considerable investments recently made to increase the terminal capacity [81], there is currently no evidence for a climate change adaptation plan being developed for KCT.

High hazard exposure was also found along most of downtown Kingston's shoreline in both simulated scenarios (Figure 4), with the hotspot analysis confirming the results (Figure 5). These findings are consistent with the simulation produced by the Coastal Dynamics Modelling Laboratory at UWI Mona, which shows how the main coastal road connecting Kingston to Spanish Town would be submerged with 1 m SLR [7]. Similar results were also achieved by Ortega et al. [18], who identified areas along downtown Kingston among the most vulnerable in the country to coastal hazards.

Coastal Protection: Current State and Recommendations

Natural habitats provide a significant contribution towards Kingston coastal protection, with the loss of corals and mangroves inhabiting Kingston Harbour having similar effects on coastal exposure to end-of-century SLR (Figure 6). These findings confirm the hypothesis advanced by Monioudi et al. [11] about the critical contribution offered by mangroves to decrease the coastal flood vulnerability of NMI (Figure 4). At the same time, they confirm the concern expressed by UWI scholars C. Burgess and M. Webber about the importance of strengthening the Palisadoes revetment works with mangrove planting on the harbour side of the tombolo [28].

Despite their vital role, coastal ecosystems across Kingston Harbour remain mostly degraded. The creation of the "Port Royal Marine Protected Area" in 1998 contributed to the tombolo experiencing lower mangrove loss rates than other parts of the country, with some gains registered around Port Royal. However, the expansion of the NMI airport and the road leading to it still caused significant ecosystem losses, with an estimated reduction in the historical mangrove area of 10–15% [18]. Another threat to coastal ecosystems in the harbour is the pollution produced by the port and shipping operations [82]. As reported by the National Environment and Planning Agency [83], waters in Kingston Harbour are heavily polluted by sewage and industrial effluents, with the wastewater treatment facilities opened in recent decades unable to cope with the diffuse waste pollution sources [84,85]. Fish and invertebrate communities, which play a fundamental part in preserving the health of coral reefs and mangroves, have also been negatively impacted by the macro and micro-plastic pollution reaching the bay [86]. Some promising signals have recently come from the mangrove restoration and planting projects implemented around Kingston Harbour [87]. However, such initiatives are still lacking the resources necessary to have significant large-scale impacts [28]. Moreover, the already critical situation of water quality in the area will probably soon worsen, as further dredging of the shipping canal entering the harbour is planned by 2030 [81].

The efficacy of nature-based solutions against flooding and coastal erosion is now widely recognized in the literature, with these approaches also providing a range of co-benefits, including biodiversity, recreational value, and water quality improvement [72]. Thus, the coastal adaptation strategy should first focus on supporting the coastal habitats where these are already producing tangible benefits, like Hunts Bay and around NMI.

However, nature-based approaches are unsuitable for protecting the downtown Kingston coastline due to the limited stretch of shore available and the depth of the harbour water. So far, the principal intervention to protect this area has been the reinforcement of 1 km of shoreline stretching east from Rae Town with a sea wall and armoured boulder revetment [88]. The minister of Economic Growth and Job Creation has recently stressed the importance of expanding these reinforcement works to a longer stretch of the downtown Kingston shoreline, with a total of 28 km needing renovation to save it from the increasing damages produced by storm surges and wave erosion [89]. Contrasting views exist about this approach to coastal defence. On the one hand, artificial barriers offer a rapid solution to the issues they are designed to address. Thus, they are generally considered the most suitable approach when emergency adaptation works are urgently required, as they are immediately effective upon completion [90]. However, several studies point out the limitations of artificial structures when not combined with nature-based solutions [91–93]. Artificial solutions are not adaptive, so they can only withstand the climate forcing they

are designed for and become obsolete when this is exceeded. While it is possible to build artificial barriers to resist even the most extreme scenarios, such works would require an unsustainable expenditure of resources and carry the risk of damaging the local ecosystems and the aesthetic value [94].

Various eco-engineering solutions exist to mitigate the negative impacts on biodiversity produced by traditional hard-engineering and create some of the co-benefits offered by habitat restoration [95,96]. Such approaches, including seawall stairs, seawall texturing, and habitat benches, promote the development of micro-habitat communities on the existing concrete structures [97]. While promoting biodiversity and providing ecosystem services, recent studies found that these retrofitting solutions also improve the defence performance, providing a significant reduction (up to 100%) in seawall wave overtopping risk [98,99]. Therefore, local authorities should consider the implementation of eco-engineering measures on the already built infrastructure and integrate them into the design of the Kingston Harbour Walk Project aimed to protect the 10 km of shoreline between Rae Town and Harbour View and expected to commence in 2024/2025 [100]. As with habitat restoration, eco-engineering measures should be developed accounting for the disturbances that coastal habitats will inevitably experience over the next few decades, like ocean warming and acidification, with priority given to climate-resilient practices [101].

5.2. Urban Flood Risk: Spatial Gradients and Causes

The runoff retention index (Figure 7) and the FVI (Figure 8) show how downtown Kingston is the area with the highest pluvial flood risk. The risk results from a combination of physical and socio-economic factors. On the one hand, the Minor and Mountview catchments are prone to high surface runoff generation due to the abundance of impervious surfaces limiting water infiltration (Figure S5). On the other, these catchments show high human exposure to flooding since they have the highest population density across the studied area (Figure S9). In addition, these catchments also host the highest relative proportion of schools, healthcare facilities, and evacuation centres in the Kingston metropolitan area (Figure 8). Thus, implementing flood adaptation measures seems paramount for the social stability of the city.

The common trait of these three sources of flood risk is the poor urbanistic development of the city, which is identified by multiple studies as the main threat to its resilience against natural hazards [22,23,102]. Kingston's urbanization issues find their roots in colonial domination time and have worsened with the uncontrolled urban sprawling registered in the second half of the 20th century. While thousands of Jamaicans started moving from the rural areas to the city to seek livelihoods, Kingston authorities could not meet the housing needs of such an influx of people [102]. As a result, people were forced to find shelter in informal settlements and practice squatting, with $\approx 20\%$ of the Jamaican population still living this way [103]. In Kingston, most informal settlements are in the downtown area, roughly corresponding to the Minor and Mountview catchments identified in this study (Figure 8) [104]. Despite the efforts that have been made to address the crisis, most people still cannot escape their squatting condition due to the lack of affordable state housing [102].

The abundance of informal settlements contributes to people's vulnerability to flooding in multiple ways. First, as they were not built under government approval, informal settlements are often located in areas unsafely exposed to natural hazards. As reported by Altink [22], the inadequate location of housing led hundreds of residents of Kingston to lose their shelter in 2008 after the passage of Hurricane Gustav caused the overflowing of McGregor Gully (i.e., one of the Minor gullies). Second, lack of recognition from the government also means that these settlements do not receive the public services granted to the rest of the city, including waste collection. Thus, gullies running through informal settlements suffer the highest rates of illegal waste disposal and, at the same time, the lowest maintenance. Moreover, as informal settlements often host artisanal practices, gullies also receive high influxes of dangerous, bulky waste from metal smelting and garage shops [23].

Mitigating Urban Flood Risk

Due to the complexity of the issues described above, addressing the human dimensions of flood exposure in Kingston would require a radical, multi-faceted set of interventions addressing the housing crisis, poverty, and political corruption permeating the city. Moreover, due to their magnitude and the nature of the problems they would address, such solutions would only reap concrete benefits in terms of flood risk mitigation in decades, leaving the population exposed to the consequences of climate change in the meantime. As such, identifying solutions to these problems lies beyond the scope of this study. However, to complement the systemic transformations required by Kingston to tackle flood risk, authorities should start investing in targeted initiatives of urban adaptation to decrease flood vulnerability in the short term (3–7 years).

The most straightforward intervention to decrease vulnerability entails investing in a structured cleaning and maintenance service for the gully system. Currently, gully cleaning is not performed routinely, with garbage removal campaigns occasionally being organised during the election season or right before the passage of tropical storms [22]. However, as testified by the multiple instances of overflow, these sporadic interventions are insufficient to ensure safety [105,106]. Waste blockage is not the only problem with the gully system, with several occurrences of structural damage identified. The current degraded state, combined with the outdated design (>75 years old), makes the gully system a source of flood risk for Kingston that would probably worsen over time with climate change [22]. Indeed, examples worldwide demonstrate how inefficient, poorly maintained structures for climate change adaptation represent a double threat for the affected areas: while not providing the service they are designed for, they also create the illusion of protection, making adaptation improvements less likely to be implemented [107,108].

Along with maintaining existing structures, authorities could further strengthen the system by building new physical barriers to surface runoff, like swales, infiltration trenches, or pervious pavements [109]. Above-ground interventions are fundamental to increasing Kingston flood resilience, as the low soil permeability of the area (Figure S6) naturally reduces water infiltration rates [110]. However, evidence from other cities shows that only building new infrastructure is insufficient to reduce vulnerability if the general living conditions are not improved [111,112]. Thus, the abundance of informal settlements and the generally precarious socio-economic conditions of downtown Kingston might compromise the construction of new physical measures in the Minor and Mountview catchments. Indeed, any new adaptation measure implemented would soon become obsolete, like the existing gullies system, without a dedicated maintenance service. Moreover, social unrest would likely arise if implementing such measures entailed land reclamation, as land tenure rights are poorly defined in the context of informal settlements [102].

In contrast, higher benefits would likely stem from developing flood risk adaptation infrastructure in the more affluent neighbourhoods of uptown Kingston (i.e., northern Sandy Gully). As those areas are uphill from the highly vulnerable settlements downtown, reducing surface runoff generation around there would significantly lower the volume and speed of water entering the gullies system downhill [113]. Construction and maintenance would also be easier, as services provision in uptown Kingston is better than anywhere else in the city. It is fundamental that every step in the development of the system, from design to construction, is aimed to maximise benefits for both the uptown and downtown communities. Indeed, a poorly implemented, scattered intervention in the uptown neighbourhoods would not increase the overall flood resilience of the city but widen the already alarming socio-economic gap with the downtown areas [104].

A more effective strategy to increase urban flood resilience in downtown Kingston in the short term might entail the implementation of an early warning system combined with public awareness campaigns to make people better understand the risks of flooding [114]. While this approach is not foolproof, with its effectiveness depending on correct system functioning and an adequate response from the population [115], its functionality in Kingston would be improved by the storm-related nature of flooding, which makes events

predictable on a daily to weekly timescale and the small spatial extent covered [116]. Implementation costs would also be relatively low, with advancing research making warning system chains easy to implement and accessible to people even in highly deprived conditions [117]. Ideally, the warning system should be designed in collaboration with members of local communities to improve awareness and reactivity in case of emergencies [115].

5.3. Limitations of the Study

To the author's knowledge, this study is the first attempt to assess the coastal and pluvial flood risk for the Kingston metropolitan area, hence representing the first step in the resilience-building strategy of the city against flood hazards. Yet, the results produced should not be considered a definitive quantification of flood risk, and further research will be needed to confirm them and overcome the weaknesses of the methodology used.

The limitations of the coastal assessment mainly derive from the design of the inVEST CV model. As discussed in the methods section, this model only provides a relative estimate of coastal exposure, so it cannot be used to quantify the impacts of any real-world event. Moreover, as thoroughly discussed by Silver et al. [34], the model has some structural limitations affecting the accuracy of the results. For example, using the continental shelf distance as a proxy for storm surge potential might lead to oversimplification of the complex storm dynamics leading to surge generation, causing a misrepresentation of exposure in certain areas. Furthermore, the model only provides an approximative estimate of the habitat's contribution to coastal protection since exposure ranks and protective distances are based on the literature data and should be confirmed by empirical validation in the studied area. Nevertheless, as argued in the literature review and methods section, while these limitations need to be accounted for when using this coastal exposure assessment for further purposes, evidence from previous works demonstrates how inVEST CV results generally agree with observations and provide solid predictions for coastal flood adaptation [75].

On the other hand, involving local stakeholders in selecting and weighting indicators for the FVI could improve the urban flood risk assessment. While the equal weighting approach used here is widely applied, recent studies highlight how the participation of local stakeholders in the design of the FVI can increase the accuracy of the assessment and the likelihood of local authorities engaging with the results [63,68]. Moreover, interviews with local stakeholders could be used to source additional data for non-publicly available FVI parameters, like literacy rate or sanitation access, and further increase the robustness of the results.

Further limitations of the urban flood risk assessment arise from comparison with observed flooding events. In this study, the Hope River catchment shows low risk if compared with the other studied catchments. However, settlements on the Hope River, like Kintyre and Harbour View, have been among the most severely affected by flooding events following the passage of tropical storms [118,119]. This discrepancy does not discredit the accuracy of the results, as risk not only represents the probability of a flood event to occur but also the exposure and vulnerability of humans and assets [120]. However, it highlights how the assessment performed here might underestimate the importance of sub-catchment characteristics, like river morphology and steepness, for flood risk [121]. At the same time, it shows how averaging risk indicators over entire catchments might oversimplify the results, even for small streams such as those studied here. For instance, while most of the Hope River catchment has very low population density and high tree cover (Figures S5 and S9), hence low overall risk [120], these characteristics do not apply to the urban setting of Harbour View, which would have probably shown a higher FVI if considered alone.

6. Conclusions

The present study provided the first local-scale, qualitative assessment of pluvial and coastal flood risk across the Kingston metropolitan area. The coastal exposure assessment highlighted how several areas of the Kingston shoreline, including KCT and the downtown

area, are currently at high flood risk and will be increasingly threatened with SLR. While the adaptation strategy has, so far, revolved around hard-engineering solutions, the present study highlights the potential of natural habitat restoration and eco-engineering approaches to provide higher coastal protection and a range of fundamental ecosystem services.

In the urban flood component, the present study finds the Minor and Mountview catchments in downtown Kingston to be the most exposed due to the high population and building density. The elevated exposure of these areas stems from their poor urban development, with many residents still living in informal settlements located in precarious locations next to the gullies. While structural societal reforms would be necessary to address flood risk entirely in downtown Kingston, authorities can still invest in short-term adaptation measures to reduce vulnerability in the most exposed areas. In agreement with other studies, the highest priority should be given to cleaning and repairing the gully system, which currently represents a threat more than a deterrent to flooding. Auxiliary interventions could entail developing an early warning system implemented in the most exposed catchments and building some physical barriers to runoff generation in uphill areas.

As the first of its kind, the results of this study will need to be confirmed by further research. Empirical verification of the habitat protection role and local stakeholder engagement are two suggested ways of improving the methodology of the coastal and urban assessments, respectively. Nevertheless, this study represents an unprecedented resource to inform the implementation of flood resilience measures in Kingston according to the pledges included in the “Vision 2030 Jamaica” development program for making cities inclusive, safe, resilient, and sustainable in line with SDG 11.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w15223936/s1>, Figure S1: Distribution of coastal habitats across the studied area. Coral and sea grass distribution sourced from Allen Coral Atlas [39], mangroves distribution sourced from Sayre et al., [40]. Figure S2: Shoreline geomorphology classification of the studied area sourced from Allen Coral Atlas [39]. Figure S3: Digital Elevation Model for the studied area extracted from the Shuttle Radar Topography Mission [38]. The six studied catchments are delineated in black with blue lines representing the streams and gullies sourced from OpenStreetMap [57]. Figure S4: Coastal exposure index under current SLR calculated with bedrock exposure ranks of (a) 3 (as for Figure 4) and (b) 1. Figure S5: Land cover classes for the studied area sourced from the ESA World Cover database [58]. Figure S6: Hydrologic soil type in the studied area sourced from the HYSOG 250 m dataset [122]. Figure S7: Building footprint of the studied area sourced from OpenStreetMap [57]. Figure S8: Road network of the studied area sourced from OpenStreetMap [57]. Figure S9: Population density (people/100 m²) calculated with QGIS field calculator [65] dividing the total population data [59] for the surface area of area of each catchment. Figure S10: Deprivation index sourced from CIESIN [60]. The scaling of the index is relative to the national context of Jamaica, with a value of 100 (0) representing the highest (lowest) relative deprivation. The index is composed of six indicators of deprivation: child dependency ratios, infant mortality rates, a subnational human development index, building footprints per square kilometer, and nighttime lights (both current and recent changes). Figure S11: Runoff generation (mm/10 m²) for (a) 5-year RP storm (178 mm rainfall/24 h) and (b) 100-year RP storm (342 mm rainfall/24 h), with the difference between the two scenarios shown in (c). Table S1: Normalization and ranking of the original deprivation index data for all the studied catchments. Table S2: Curve Numbers of the land covers relevant for this study for each hydrologic soil type. A higher number represents a higher runoff generation potential.

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