

Forecasting Trinidad's Evolving Flood Future: A Susceptibility Mapping Approach with Long-Term Rainfall Projections (2010-2100)

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Abstract

Global International Panel on Climate Change (IPCC) models highlight increasing incidence and intensity of rainfall events due to climate change in the Caribbean. However, more granular regional models are needed to guide sector-specific actions. This paper addresses this data gap by using recent remotely sensed data and other geographic information system layers to model flood susceptibility for Trinidad from 2010 to 2100. Data came from the Climate Hazards Group InfraRed Precipitation datasets, and IPCC's mean average rainfall layers (assessed in five-year intervals, generating 19 files). Six layers of elevation, road density, drainage density, land cover and rainfall were integrated into a composite flood susceptibility GIS layer that covered the two main seasons- dry (December to May) and wet (June to November). The composite flood susceptibility layer was subdivided into five classes (very high, high, moderate, low, and very low). Results showed a consistent pattern of high and very high flood susceptibility worsening across both wet and dry seasons, in primarily urban/semi-urban communities. These flooding events, driven primarily by low topography, land cover/land use (urban development decisions), and (inadequate) built drainage infrastructure, will be exacerbated by climate change and short-term weather variations. Policy implications underscore the urgent need for radical mitigation strategies across current flood-prone urban areas in Trinidad, including climate-resilience building designs, redesign of drainage infrastructure, enforceable zoning regulations, community-led warning systems and the design of appropriate adaptation interventions that specifically target these currently flood-prone urban areas.

1. Introduction

Globally, flooding remains one of the most frequent and destructive natural hazards, with small island developing states (SIDS) especially vulnerable due to limited landmass, the concentration of critical infrastructure along low-lying coasts, growing populations, and insufficient funding for disaster resilience strategies. Climate models predict that Caribbean SIDS will experience increased and more intense rainfall events. Studies show that climate change will worsen vulnerabilities, as projections indicate rising intensity and variability of precipitation across the Caribbean (Taylor et al., 2018). Heavy rainfall, combined with poor urban planning and strained drainage systems, significantly raises the risk of flash floods, riverine flooding, and socio-economic damages. As signatories to the United Nations, Caribbean Small Island Developing States have embraced Sustainable Development Goal 11 in pursuit of creating inclusive, safe, resilient, and sustainable cities as articulated in various governance, spatial, socio-economic, and environmental policies (Mycos & Bharath, 2021). Global models indicate that one of the climate change impacts on small island developing states of the Caribbean will be increased and more intense rainfall events. While these global projections have raised awareness of these issues, the design of mitigation and adaptation strategies will require regional and national models. Conducting these detailed analyses will require regional and national specialists working with key informants to detail the spatial dimensions of these negative impacts, to guide policymakers and stakeholders in reducing loss of life, damage, and the undermining of livelihoods. Increasingly, the focus has turned to the role of geographic information system (GIS) tools

and techniques in conducting these types of analyses to update existing flood susceptibility models and integrate up-to-date, remotely sensed, publicly available data.

Recent research highlights the need for locally tailored risk assessments beyond broad global models. General Circulation Models (GCMs) offer long-range projections but lack the spatial detail needed for local planning (Wilby & Wigley, 1997). This has increased interest in statistical and dynamical downscaling, which bridges global models with local realities. When paired with high-resolution datasets such as Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) and geospatial analysis, these approaches enhance flood risk assessments and climate impact modelling (Ritalis et al., 2017).

Across the Caribbean, GIS and remote sensing have become critical tools for flood modelling. These technologies allow the integration of terrain, hydrology, infrastructure, and land cover data into flood susceptibility maps. Several studies have been carried out to assess flood risk in the Trinidad and Tobago region, integrating climatic, geographical, and social data through weighted sums (Roopnarine et al., 2022; Thongs, G. 2019, Roopnarine et al., 2018, Nandi et al., 2016). However, they still rely on historical data and do not incorporate projections of future rainfall, leaving a gap in understanding changing hazard dynamics.

Trinidad and Tobago, like many SIDS, faces rising flood risks from low-lying urban expansion, informal settlements in flood-prone zones, and limited space for redirecting growth. The lack of national-level models that integrate both current and future rainfall patterns undermine effective planning and other forms of decision-making. Bridging this gap will require collaboration

between regional experts and local stakeholders to produce actionable insights.

This study aims to assess current and future flood susceptibility across Trinidad under changing rainfall regimes by integrating downscaled climate projection data with geospatial flood risk factors. It will apply a statistical downscaling approach to enhance the spatial resolution of IPCC-derived rainfall projections using historical CHIRPS precipitation data for Trinidad and generate composite flood susceptibility maps at five-year intervals from 2010 to 2100, using a GIS-based multi-criteria weighted overlay approach incorporating topographic, hydrologic, and land cover factors.

2.0 Flood Susceptibility Mapping with IPCC Rainfall Data

2.1 The Country Context: Background on the Setting (Related to Flooding in TT)

Trinidad has a tropical maritime climate that experiences distinct dry and wet seasons. The wet season typically spans from June to November. During this period, the island is prone to heavy and intense rainfall often triggered by tropical waves, low-pressure systems and seasonal shifts (Nicholson et al., 2019). The island's natural vulnerability to flooding, combined with rapid urban growth, unregulated land development and limited drainage infrastructure, has resulted in more frequent and severe flooding events in recent years (Williams et al., 2024). This is evident in low-lying and flood-prone areas such as the Caroni and Oropouche river basins, where communities have increasingly experienced the impacts of rising water levels during heavy rainfall events, resulting in damage to property, disruption of transportation networks and loss of livelihoods.

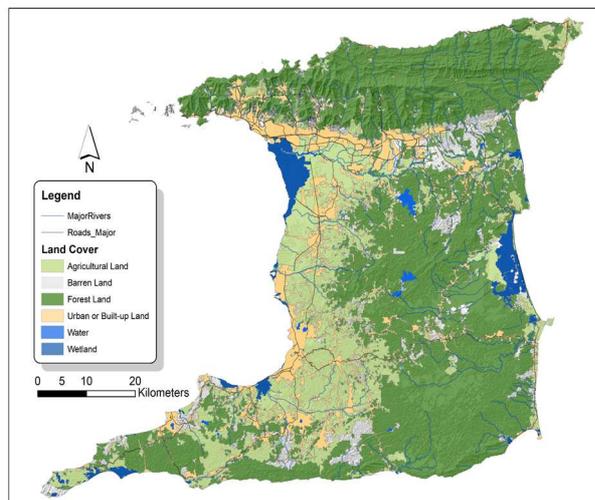


Figure 1: Land Cover Distribution in Trinidad

In the last two decades, there have been considerable flood events that have significantly affected life and caused severe damage which include events in 2008, 2011, 2018 and 2022. The 2018 flood event affected over 100,000 persons with communities inundated, major road networks rendered impassible, and extensive infrastructural damage across north and central Trinidad (Caribbean Disaster Emergency Management Agency, 2018). It is expected that climate changes will compound these

¹https://pmc.ncbi.nlm.nih.gov/articles/PMC4672685/?utm_source=chatgpt.com "The climate hazards infrared precipitation

vulnerabilities and present an increase in the intensity and unpredictability of rainfall patterns, together with rising sea level (Thompson, K. 2023). These effects will exacerbate the existing hydrological vulnerabilities, especially in these flood-prone areas that already pose limited capacity to adapt (Benjamin, C. 2020). As a result, it is imperative that updated susceptibility assessments are derived to guide land use, improve disaster preparedness and support long term climate resilience actions.

2.2 Method and Data Sources

2.2.1 Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS)

Data came from the CHIRPS dataset. Initiated in 1981, CHIRPS is a quasi-global rainfall dataset developed to support drought monitoring, food security assessments, and climate impact studies (Funk et al., 2015). It combines high-resolution satellite imagery with in-situ station data to produce gridded precipitation time series. The dataset spans latitudes from 60°S to 60°N and offers a spatial resolution of 0.05° (approximately 5 km), providing daily, pentadal (5-day), and monthly precipitation estimates. The precipitation values in CHIRPS are expressed in millimeters (mm) per specific time period, such as mm/day for daily data, mm/pentad for 5-day intervals, and mm/month for monthly data. This standardized unit facilitates the comparison and analysis of rainfall patterns over time and across different geographic regions ([\[pmc.ncbi.nlm.nih.gov\]](https://pmc.ncbi.nlm.nih.gov)¹). For this study, monthly precipitation CHIRPS datasets were used, focusing on February and November, which correspond to the dry and wet seasons in Trinidad and Tobago, for the period 1981-2024.

2.2.2 IPCC-WGI AR6 Interactive Atlas Gridded Monthly Dataset

The IPCC-WGI AR6 Interactive Atlas Gridded Monthly Dataset, provides comprehensive climate projection data supporting the International Panel on Climate Change (IPCC) Sixth Assessment Report's Interactive Atlas (C3S 2023). This dataset includes monthly gridded data from global models (CMIP5 and CMIP6) and regional models (CORDEX), covering 22 climate variables and indices relevant to climatic impact-drivers (Iturbide et al, 2022; Gutiérrez et al., 2021). Spanning from 1850 to 2100, it offers spatial resolutions of 2° for CMIP5, 1° for CMIP6, and up to 0.25° for European CORDEX domains. The data, formatted in NetCDF4, are designed for users seeking to develop customized climate analyses at various scales. For this study, monthly precipitation data derived from the Coordinated Regional Climate Downscaling Experiment (CORDEX) model were used, covering the period 2006 to 2100, with a spatial resolution of 0.5° (approximately 50 km). The selected months were also February and November, as done with the CHIRPS dataset.

2.2.3 Method for Downscaling of IPCC data

Due to the coarse spatial resolution of the IPCC dataset, a statistical downscaling was applied using historical CHIRPS data. For this purpose, the mean CHIRPS monthly precipitation was computed for November and February, leading to two raster summary grids with a spatial resolution of 0.05°. Then, for each monthly IPCC grid of the period 2006-2100, these CHIRPS summary maps were used for downscaling in the following way: For each low-resolution IPCC grid cell i,j a corresponding

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high-resolution CHIRPS block, called B_{ij} , is defined and adjusted so that:

$$\text{mean}(B'_{ij}) = V_{IPCC}(i,j) \quad (1)$$

Where B'_{ij} are the downscaled values to be computed, $V_{IPCC}(i,j)$ is the IPCC precipitation value in that cell, and $\text{mean}(B'_{ij})$ is the mean CHIRPS value in the block B_{ij} . To compute the block B'_{ij} a scale factor must be used to scale the values of B_{ij} to the total amount of the IPCC cell. This scale factor is calculated as:

$$\text{scale_factor} = V_{IPCC}(i,j) / \text{mean}(B_{ij}) \quad (2)$$

And finally, B'_{ij} is calculated as $\text{scale_factor} \times B_{ij}$. Figure 2 depicts an example of the downscaling on one of the IPCC grids.

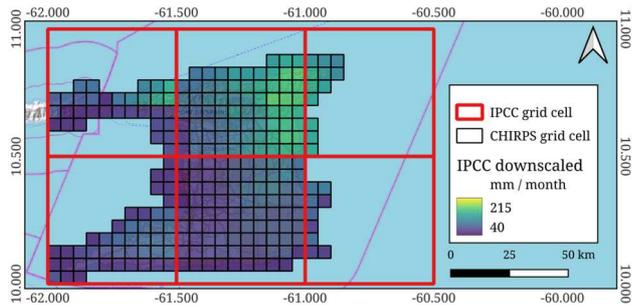


Figure 2. Sample IPCC raster grid downsampled to the resolution of CHIRPS. The red polygons represent the original resolution cell, while the dark polygons represent the downsampled pixels.

2.2.4 Flood Susceptibility Analysis

A flood susceptibility analysis was conducted using a methodological progression that integrated a series of GIS tools and techniques. The analysis was conducted in five sequential steps:

1. Selection of inundation factors
2. Classification of factors
3. Weighting of factors
4. Reclassification of the flood susceptibility output layer
5. Validation of the susceptibility model

Selection of inundation factors:

Further, six key factors and their contribution to flood impact were considered, namely:

- elevation
- slope
- road density
- drainage density
- land cover (2007)
- rainfall

Each of these datasets was derived by either remotely sensed techniques, such as supervised classification of satellite imagery, or in-person land surveying techniques. The use of these six factors was based on literature, analyzing past flood incidents and key expert knowledge of the respective island (Roopnarine et al., 2022; Thongs, G. 2019, Roopnarine et al., 2018, Nandi et al., 2016).

The GIS technique is mathematically expressed as:

$$SM = f(I(HR_{2010-2024}, PR_{2025-2100}), \text{Topography, Elevation, Land Cover, Drainage Density, Road Density})$$

Where SM = Susceptibility Mapping, $PR_{2010-2100}$ = projected rainfall from 2025 -2100, and $HR_{2010-2100}$ = historical rainfall from 2010 -2024.

2.2.4.1 Flood Susceptibility Analysis using IPCC Rainfall Layers

A critical component of this flood susceptibility model was the use of the IPCC rainfall layers. These rainfall layers were crucial to analysing not only past rainfall patterns, but also facilitated the characterisation and progression of the spatial distribution of predicted rainfall. Thus, allowing the assessment of existing and future flood susceptibility. In order to achieve this, mean (average) rainfall layers at five-year intervals ranging from 2010 to 2100 were used. For example, 2010, 2015, 2020, 2025 and so on. A total of 19 files were generated from the 2010 to 2100 period.

2.2.4.2 Justification for Land Cover Dataset Selection

Initially, the 2022 global land cover dataset was intended for use in this flood susceptibility analysis. The respective land cover files lacked the detailed spatial data needed to analyse local-level flood modelling in a small island state like Trinidad. The global file was generally too coarse and did not accurately replicate the critical land cover classes. As such, although the locally derived and verified 2007 land cover layer is older than the 2022 land cover file, it more accurately portrays locally relevant land characteristics, particularly the barren land, agricultural areas, and smaller built developments. This degree of specificity is essential for accurately mapping and analysing flood

susceptibility in a small island state. For this reason, the 2007 land cover data was used in this flood susceptibility analysis.

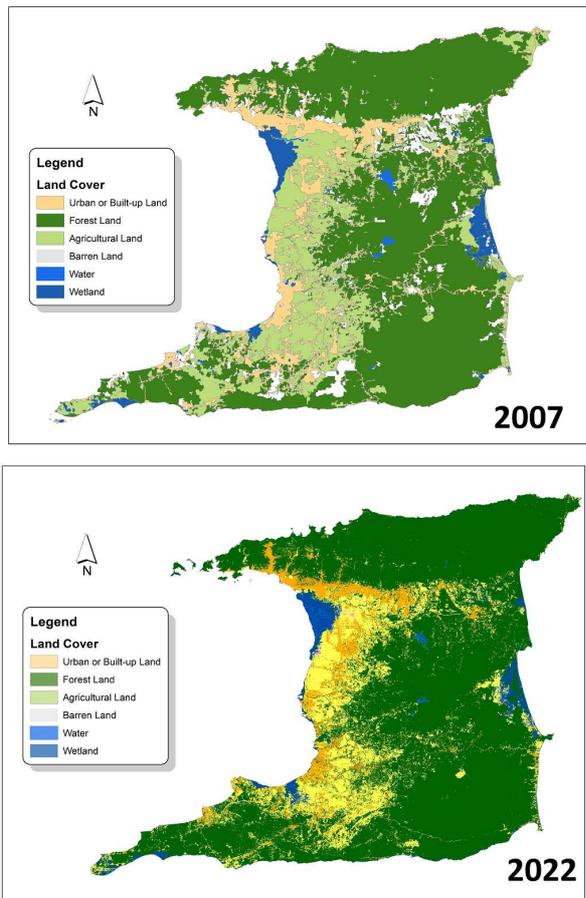


Figure 3: Comparison of land cover layers (2007 and 2022)

2.2.4.3 Building the Cartographic Model

Subsequent to the selection of the flood susceptibility factors, a cartographic model was built in order to automate the classification, overlaying and reclassification of each factor. Using model builder, each factor was classified into a five-point scale based on its relative contribution to flooding within the study area. Every category of the six factors was assigned weights to reflect their impact on flood susceptibility. A five-point scale was used primarily because five-point scales pose no difficulty in differentiating among very high, moderate, and low impacts to flooding. Moreover, it more easily spatially displays meaningful differences across a relatively small island. For example, areas with low elevation were categorized with the highest weight of five, since these locations are more prone to water accumulation. Similarly, areas with gentle (low) slopes, high rainfall, high road density, high drainage density and high densities of impervious land cover surfaces were also assigned higher weights, since flatter terrain tends to impede runoff, significant precipitation, reduced infiltration, and dense river networks all increase the likelihood of flooding. This classification approach was consistently applied across all factors to produce a composite flood susceptibility map.

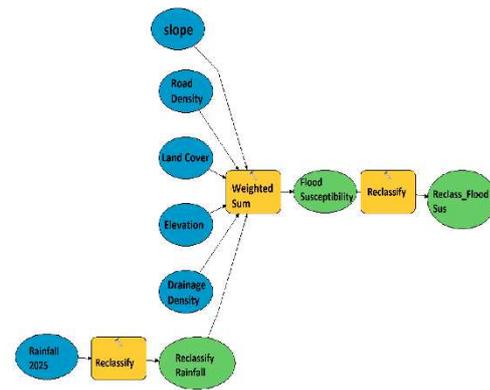


Figure 4: Cartographic Model of Flood Susceptibility Analysis

2.2.4.2 Undertaking a Weighted Overlay Analysis

Subsequent to this classification process, the weighted sum tool was used to undertake a weighted overlay analysis. The six categorized layers of elevation, road density, drainage density, land cover and rainfall were integrated into a composite flood susceptibility GIS layer. Each of the earlier flood analyses applied different weighting schemes. Thus, making it difficult to select a single weighting approach. As such, in the weighted sum tool, each layer was equally weighted, and this was based on the simple assumption that each of these factors would equally contribute to flooding within the context of Trinidad.

This composite layer displays the variations of flood susceptibility across Trinidad. To improve clarity and interpretation, the composite flood susceptibility layer was further classified into five categories of flood susceptibility classes. The five classes were, namely, very high, high, moderate, low, and very low. Doing this enhances the ability to spatially identify the locations (and communities) of highest and lowest susceptibility, thereby supporting efforts to target specific communities for flood resilience strategies.

2.3 Results

Results for the 19 5-year flood susceptibility layers which facilitated the analysis of both short and long-term trends under changing rainfall conditions, showed consistency in their high to very high flooding susceptibility. Further, results showed that while there were differences in the rainfall that occurred in February (dry) versus November (wet), spatial patterns in flood susceptibility remained consistent across the two distinct seasons of the year (dry and wet). Figure 5 shows two of the generated layers for November 2025 and 2030.

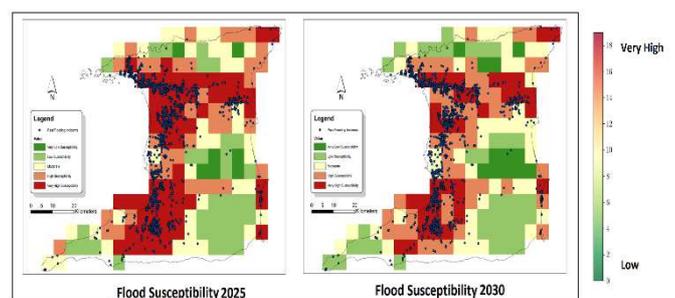


Figure 5: Modeled susceptibility map for November, 2025 and 2030. Coordinate System: WGS84 - UTM Zone 20N

Across the 38 5-year flood susceptibility layers (19 for Feb, 19 for Nov) generated, the same communities consistently experienced high susceptibility to flooding. The analysis demonstrated that the high population and building density locations within flood-plain zones, in areas such as the capital of Port of Spain and environs, the east-west corridor and the growing residential areas in Valencia consistently ranked as either high susceptibility or very high susceptibility. In the more rural spaces, the low-lying areas of South Oropouche emerged as a persistent flood-prone area.

Figure 6 depicts spatial and temporal trends for the month of November. It shows using a pixel-based map the count of years with a predicted susceptibility score of 4 or greater, during the period 2010-2100. Additionally, it shows the temporal trend of the average susceptibility score computed for all the pixels of Trinidad and the locations of past flood incidents, respectively.

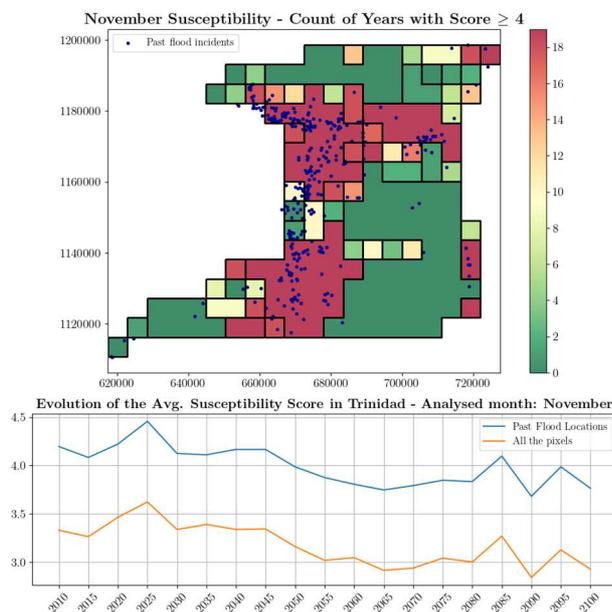


Figure 6: Count of years with a score of 4 or greater (top), and temporal evolution of the susceptibility score (bottom).
 Coordinate System: WGS84 - UTM Zone 20N

There is, therefore, a consistent and growing pattern of chronic flood susceptibility across multiple communities in Trinidad. For this reason, it can be suggested that chronic flood susceptibility in Trinidad is driven by low topography, land cover/land use (urban development decisions), and (inadequate) built infrastructure, rather than short-term weather variations alone.

2.4 Discussion

The consistent and worsening flood susceptibility issues highlight the urgent and sustained need for flood preparedness, mitigation and adaptation strategies across the urban areas in Trinidad. This includes, but should not be limited to, improved drainage infrastructure, enforceable zoning regulations and community-based and community-led adaptation strategies that specifically target flood-prone areas.

These findings are especially more alarming as Trinidad is a small island developing state. With its fixed coastal boundary, a

steadily increasing population, and continuous growth for residential development, Trinidad is confronted with heightened difficulty in its capacity to reconfigure urban growth. If major interventions are not immediately implemented, the island will continue to be in a particularly vulnerable position where chronic floods will impact public safety and long-term socio-economic resilience.

The presented approach has limitations, particularly for small countries situated in tropical regions, such as the Caribbean. First, the coarse resolution of the IPCC climate scenarios might not be enough for regions like Trinidad, where the whole island fits in only six pixels (see Fig. 2). To compensate for this, a CHIRPS-based statistical downscaling has been applied to achieve a resolution of ~5 km. This could be further improved by integrating precipitation data coming from weather stations installed on land. The Caribbean region has a reasonably good network of installed weather radars, with two located in Trinidad and Tobago, respectively. Another limitation comes from the evolving nature of the IPCC scenarios, as they rely on emission projections (Girod et al., 2009). This means that a risk map derived from them can quickly become outdated as new information or updated scenarios become available. This highlights the opportunity to move from the static mapping approach presented in this work to a dynamic one, using web-GIS layers that are updated semi-automatically to reflect changes in the input data.

Another significant constraint was the unavailability of an independent dataset to undertake a quantitative validation of the findings. This is a common challenge for SIDS, which are data-scarce regions. With this in mind, this research sought to be the foundational first step towards generating valuable predictive outputs that inform urban planning and disaster management.

Moreover, the flood patterns generated by this research are consistent with the flood history of Trinidad and Tobago. These patterns have remained relatively stable over the last 10 years. As national and regional environmental and GIS experts, familiarity with the surroundings and these established patterns supports high confidence in the reliability of the patterns generated by the model.

The primary aim of the paper was to underscore the current scarcity of high-resolution hydro-meteorological data in SIDS the Caribbean. The absence of this data impacts disaster resilience planning in a region that needs it the most. This research results show that even with minimal data, meaningful analyses are possible, but at the same time, point to the transformative potential of enhanced data availability.

Despite the data scarcity, the model integrated long-term rainfall projections with local biophysical data in order to generate a forward-looking flood susceptibility map for a country that is regularly impacted by recurrent flash and riverine flooding. Building such a model shifts emphasis away from reactive disaster management to anticipatory and proactive resilience planning. Thus, shaping an improved evidence-based future drawing on the historical lessons of the past, while also using forward-thinking scenario-driven modelling that captured a diverse range of potential futures.

7. Conclusions

This study is the first to provide granular remotely sensed data and geographic information systems to conduct a flood susceptibility assessment. The scientific contribution of this research is that it builds on previous work but also provides a new approach to analyzing future flood risk.

These findings bring into question the use of limited national resources (payments such as flood relief grants) to help maintain residents in these high and very high flooding susceptibility communities. There is urgent need for enforceable zoning plans to ensure that the requisite data is available to support land use and planning decisions in Trinidad and Tobago. It is expected that these findings supported by regional remote sensing experts as well as local key experts can play a key role in other studies that spatially display the current and future patterns of natural hazards. These studies will be essential in supporting the national decision-making process as it relates to climate change mitigation and adaptation strategies. Current urban development, hazard mitigation and future infrastructure plans can be informed/integrated in a meaningful way by use of these data-driven insights. This is a significant scientific contribution which is especially important in the Caribbean context, where land is a limited fixed asset that heavily drives socio-economic growth. Moreover, the opportunity to align these findings with development decisions will have long-lasting and permanent consequences.

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