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Effects of urbanization and deforestation on flooding: Case study of Cap-Haïtien City, Haiti

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Abstract

Cap-Haïtien, the second largest city in Haiti, is highly vulnerable to earthquakes, landslides, and flooding. The rapid pace of urbanization and deforestation has exacerbated the risk of flooding, resulting in disasters in November 2012, 2016, and 2022. This study aims to assess the impact of urbanization and deforestation on river flooding in Cap-Haïtien by applying the hydrological model Soil Water Assessment Tool (SWAT) and the hydrodynamic model Sobek-Rural. We examined the current situation and a scenario of future urbanization and deforestation. Urbanization and deforestation are found to play a pivotal role in the production and deposition of sediment along the lower Haut-du-Cap River reaches. The existing hydraulic capacity of the river and its drainage system cannot handle the estimated peak flows. The mountain ravines west of the city are found to be the primary source of sediment-laden flash floods. We recommend retention basins, drainage extensions, and pragmatic public policies to mitigate flood risk. Comprehensive strategies are needed to address the detrimental effects of urbanization and deforestation on flooding in Cap-Haïtien and similar regions where a lack of water governance has worsened the flooding alongside urbanization and deforestation. We generalize our experiences from Cap-Haïtien into a broader framework for data-scarce areas.

KEYWORDS

Cap-Haïtien, deforestation, flood mitigation measures, floods, Haiti, Sobek-rural, SWAT, urbanization

1 | INTRODUCTION

Haiti's geographic position and topography expose the island to hydro-geological hazards, including floods. Haiti is in the path of frequent storms and hurricanes in the tropical Atlantic system (Farmer, 2003; Gracius & Ozer, 2017; Grigorieva & Livenets, 2022; Monthel et al., 2013). Flood hazards and risk are expected to worsen due to climate change, sea-level rise, and urbanization. In 2015, 53% of the Haitian population lived in and around cities: 12% more than in 1950 and expected to increase to 77% in 2050 (Salomon et al., 2020; Zagatti et al., 2018). The increase can be attributed to overall population growth and migration from impoverished rural areas to cities (Saurav et al., 2021; Zagatti et al., 2018). Newcomers often settle in areas exposed to riverine and coastal flooding (Monthel et al., 2013).

Several studies demonstrate the close relationship between urbanization, deforestation, and increased frequency and severity of floods (CIAT, 2015; Huong & Pathirana, 2013; Ministry of Environment (MDE), 2006; Philippe & Culot, 2009; Saurav et al., 2021; Setegn & Donoso, 2017). Deforestation has been a national issue since colonization (Smith & Hersey, 2008). Most of Haiti's previously forested land is bare of trees (Heinl et al., 1996) because vegetation is the primary energy source.

Economic pressure over natural resources, rapid population growth, and uncontrolled urbanization contribute to increasing flood risk in Cap-Haitien (Gracius & Ozer, 2017). Its industrialization and development as an economic hub puts increasing pressure on fuelwood resources and transforms vegetation cover and land use (Ashiagbor et al., 2019; Chaves et al., 2021; Pramanik & Punia, 2020). Fluvial floods due to torrential rainfall and coastal floods due to storm surges also increase incidents of mudslides and landslides. Most households in Cap-Haitien were affected by flooding in 2017–2020 (World Bank, 2020). Although the effect of anthropogenic actions on flood vulnerability is known in Cap-Haïtien, no study quantifies this effect in hydrological and hydraulic terms.

Rainfall-runoff models are essential for flood risk management in data-scarce regions like Cap-Haitien (Chomba et al., 2021; Finaud-Guyot et al., 2011). Among the various rainfall-runoff models available, SWAT (Soil and Water Assessment Tool) is widely recognized and used extensively (Kiesel et al., 2013). SWAT is a process-based, semi-distributed, and continuous-time hydrological model with a broad range of applications (Arnold et al., 2012; Betrie et al., 2011; Marhaento et al., 2017; Nyeko, 2015; Rafiei Emam et al., 2016; Shrestha et al., 2018; Shuma et al., 2020; Sirisena et al., 2018; Sirisena et al., 2021).

A widely adopted approach to simulate flood hazards is coupling one-dimensional (1D) hydrodynamic models for main river channels with two-dimensional (2D) hydrodynamic models for floodplains (Finaud-Guyot et al., 2011; Patro et al., 2009), often in conjunction with rainfall-runoff models (Thakur et al., 2017). Deltares (2018) developed the 1D-2D Sobek-Rural software (Dhondia & Stelling, 2004; Paarlberg et al., 2010; Yang et al., 2022).

This study aims to quantify the effects of urbanization and deforestation around Cap-Haïtien on flooding to evaluate mitigation measures using process-based hydrological and hydraulic modeling tools. We used SWAT to estimate the impact of deforestation and urbanization on runoff inflow and sediment production from the watershed, and Sobek-Rural to estimate water levels and flooding extent for floods with different return periods and the November 2012 flood. SWAT reproduced river discharges from 2009 to 2012, including two scenarios and the November 2012 flood. We used the latter event as a reference for assessing the impact of structural solutions on flood risk, such as extension of the drainage network and creation of a retention basin. Using the state-of-the-art modeling tools and standard methodology, we emphasise on the practical importance of the results in the case-study area in Haiti and the applicability of the methodology beyond the case-study catchment with similar geographical and climatic settings. In particular, urbanized floodplain areas where the river system receives high influx of flood discharge and sediment from upstream hilly terrains due to high intensity rainfall and deforested landscape. To the best of our knowledge, this is the first application to the specific circumstances in Haiti. We generalize our experiences from this application into a broader framework for assessing fluvial flood risk and mitigation strategies in data-scarce areas.

2 | STUDY AREA

The city of Cap-Haïtien (19°45′3″ N, 72°12′00″ W) is located on the northern coast of Haiti. Its historical significance, picturesque landscapes, and cultural heritage make it a prominent tourist destination in Haiti and the Caribbean. The city covers 52.3 km^2 and comprises three administrative divisions (Bande du Nord, Haut-du-Cap, and Petite Anse) (Figure 1a). Cap-Haïtien is bordered to the west by steep mountains, including the 861 m high Morne du Cap (Figure 1b).

The Haut-du-Cap River originates in the Massif du Nord mountains, crosses the agglomeration of Cap-Haïtien and debouches into the Caribbean Sea. An important tributary is the Any Brios (called Any) River, which passes under the Hugo Chavez International Airport's runway and joins the Haut-du-Cap River in the suburbs of Cap-Haïtien. On the right bank, the river feeds the shallow Rhodo Basin, surrounded by mangroves. On the left side, several mountain streams (ravines) join the river in the central city. The main ones are the Vertières, Zetrier, and Belle Hôtesse (Figure 1c).

The 193.2 km^2 of the catchment consists of 34.4% forest, 15% shrubs, 22.4% urban area, and 24.5%

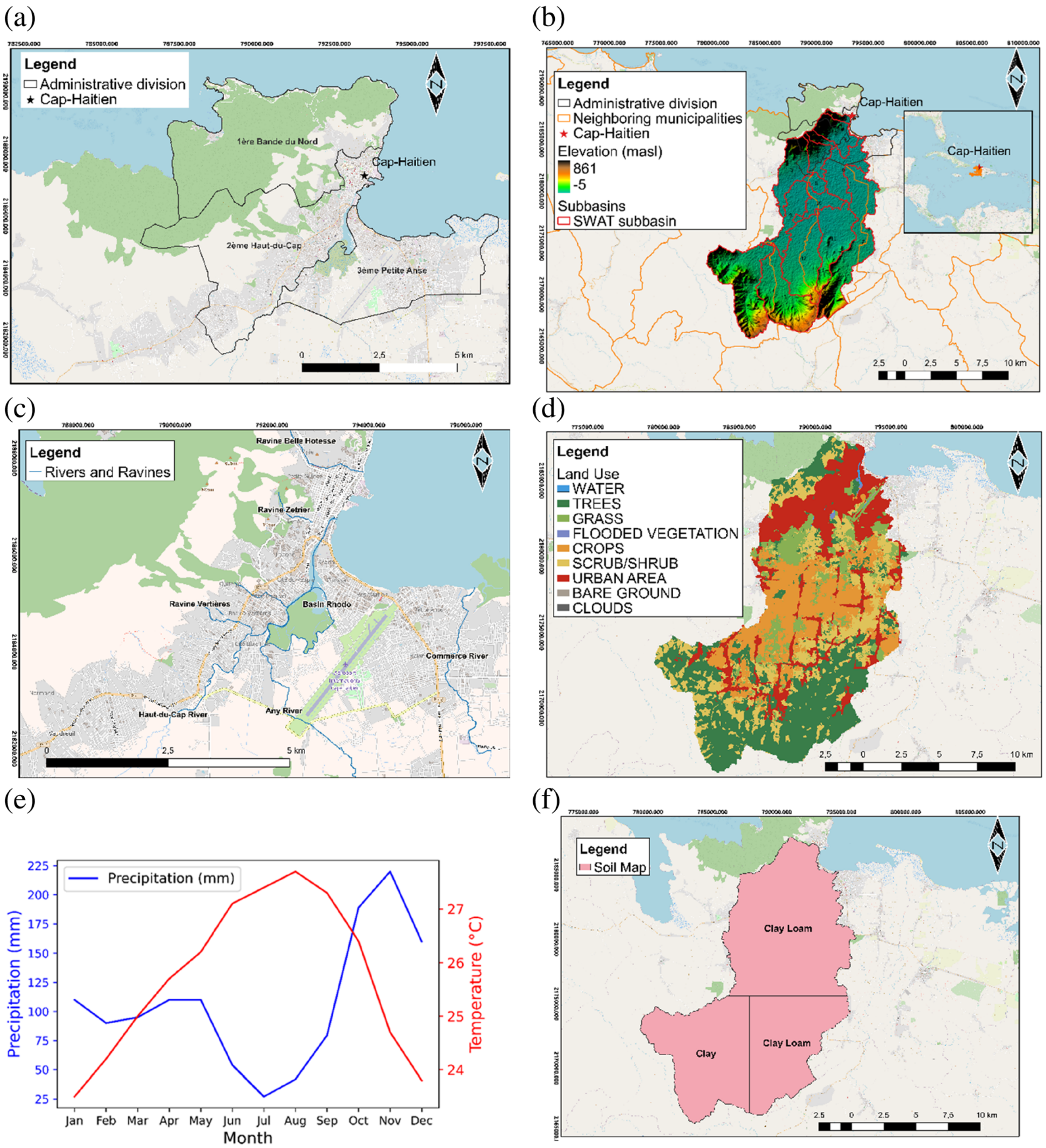

FIGURE 1 Geographical Context of the Study Area, (a) Administrative Subdivisions of Cap-Haitien Municipality, (b) Digital Elevation Model and Catchment Delineation, (c) Hydrographic Network of the Cap-Haitien Metropolitan Area, Encompassing Rivers and Ravines, (d) Land Use Distribution within the Cap-Haitien Catchment, (e) Long-Term Averaged Precipitation and Air Temperature Patterns spanning 1968–2014, (f) Soil Map of the Cap-Haitien Catchment.

cropland-grassland (Figure 1d). The urban area is located near the river mouth at an elevation below 1 m above sea level. The climate is tropical, with an average annual precipitation of approximately 1400 mm and an average temperature of 25°C (Figure 1e). The soil is made of clay and loam (Figure 1f).

Rapid urbanization and deforestation resulted from population growth and expansion of the city, particularly towards Quartier-Morin, Petite Anse, and the northwest mountain slopes (Figure 2a). The population has quadrupled since 1982, reaching 274,000 in 2015 (Centre for International Studies and Cooperation (CECI), 2017). In Cap-Haïtien, urbanization and deforestation are interdependent: urbanization leads to deforestation as energy and space are required for constructing new structures; in turn, deforestation promotes urbanization by providing additional space for structures.

Projected climate change may exacerbate these issues as intense rainfall events are anticipated to increase. For example, in November 2012, 442 mm of rain fell in

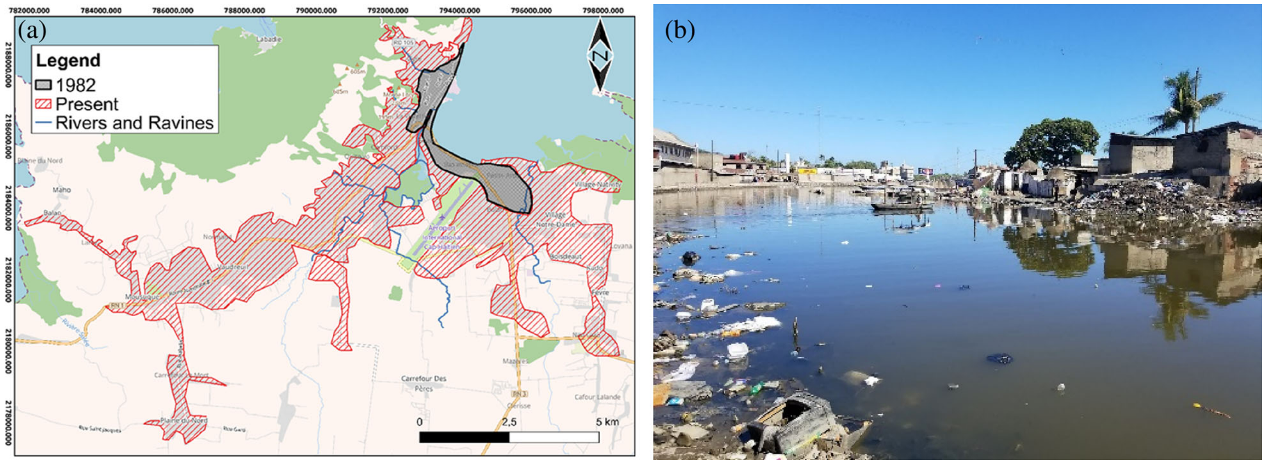

FIGURE 2 (a) Urbanized areas in 1982 and at present, (b) Poor drainage and water body full of waste (field visit December 2021–January 2022).

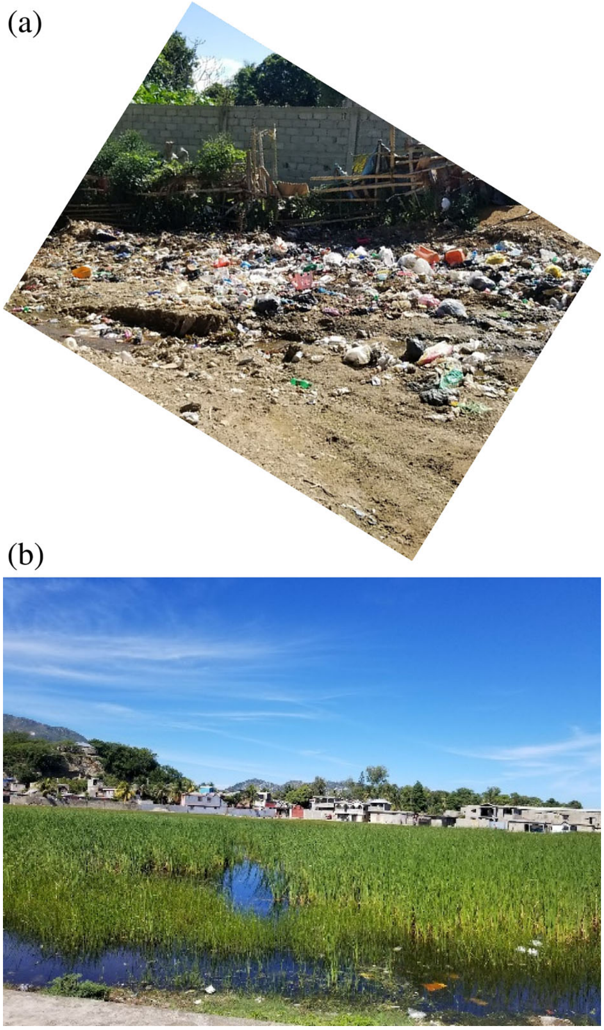

FIGURE 3 (a) Draining canals clogged by waste, (b) High groundwater table near the airport (photos taken during the field visit of December 2021–January 2022).

4 days, with a 50-year event of 282.8 mm on November 8. This peak rainfall was three times larger than the November average from 1968 to 2017. A similar event occurred on November 3 and 4, 2014, with 230 mm of rain recorded at the airport (Townhall, 2014). The number of monthly rainfall events exceeding 300 mm doubled over the 2000s compared to the two previous decades, from 3 to 5 events per decade to 8 (Guillande, 2015).

2.1 | Personal observations

From December 2021 to January 2022, the first author visited Cap-Haïtien to collect data and gather information on the local situation. His observations confirmed the information from scanty literature. The riverbeds, floodplains, eastern coastal mangroves, and ravines are urbanized. In addition, the urban drainage canals are engulfed by waste (Figure 3a). We noted a high groundwater table, which can exacerbate surface runoff during the rainy season, particularly in the airport area (Figure 3b) and in the vicinity of the Rhodo Basin. Bridges such as the Blue Hill Bridge function hydraulically as culverts and generate bottlenecks that can flood upstream communities.

Without holding formal interviews, anecdotes from residents offered valuable insights into the complex interplay between floods, deforestation, and urbanization. Houses in the river's floodplain are more affordable, albeit at the cost of higher exposure to flooding. Despite awareness among residents that construction in these vulnerable zones is ill-advised, the lack of government support and viable alternatives limits their choices. Construction of houses is also more affordable on the steep mountain slopes, causing deforestation and rendering slopes unstable. The absence of law enforcement exacerbates the situation.

The poorest citizens thus face the highest flood exposure. Their actions inadvertently exacerbate their challenges. These interconnected issues require a holistic approach, considering the socio-economic realities behind the community's choices and vulnerabilities.

Access to reliable data is fundamental for studying risk and designing mitigation measures, but there is no comprehensive hydro-climatological database on the rivers and the precipitation regime of the city. Nonetheless, we could find scattered data and knowledge at different local institutions (non-governmental organizations, ministries, the university, and the town hall).

3 | METHODS

3.1 | Hydrological model (SWAT)

The hydrological software can be downloaded from https://swat.tamu.edu/software/plus/. SWAT requires a digital elevation model (DEM), maps of land use or land cover (Figure 1b) and soil type (Figure 1f), and climate data. The model operates with a daily time step. The heterogeneity resulting from the overlay of the DEM and the maps allows SWAT to carry out the hydrological and soil erosion computations at the Hydrological Response Unit (HRU) level.

We used the model version QSWAT+ in QGIS 3.10. We first delineated the catchment and sub-catchments of the Cap-Haïtien River system, using a stream network from the National Centre of Geospatial Information (CNIGS) alongside the DEM. The catchment outlets were the Haut-du-Cap River, the Vertières Ravine, and the Any Brios River. We defined four slope ranges: 0–10, 10–30, 30–50%, and >50%. The catchment was divided into 14 sub-catchments and 97 channels.

Within SWAT we used the Penman-Monteith component for potential evapotranspiration, the SCS curve number for surface runoff volume, and the variable-storage method for flow routing. The model was run for 5 years (2009–2013), with the first 3 years as spin-up periods. The sediment transport computations of SWAT employ the simplified Bagnold method (Bagnold, 1966) in conjunction with the modified universal soil-loss equation (MUSLE) (Williams, 1975) for erosion caused by rainfall and runoff.

We used a DEM with 1.5 m resolution from a Light Detection and Ranging (LiDAR) survey in 2017 by CNIGS, Haiti, to develop the bed topography of the hydraulic model. In addition, the Shuttle Radar Topography Mission (SRTM) DEM of 30 m resolution (accessible at https://earthexplorer.usgs.gov/) was used to delineate the Cap-Haïtien catchment and sub-catchments, the river network, and catchment characteristics such as slope, surface area, and channel length.

The soil layers were retrieved from the FAO and UNESCO soil database (Batjes, 1997) with a spatial resolution of 400 m. The land use map was the Environmental Systems Research Institute (ESRI) 10 m, with 0.00008980° resolution and 10 classes of land use and land cover, released in 2020 (Karra et al., 2021) and derived from the European Space Agency (ESA) Sentinel-2 imagery.

The catchment has two weather stations. The first one, managed by the Unité Hydrométérologique d'Haiti (UHM), is at the Hugo Chavez International Airport (19.73 N, −72.19 W), 6 m above sea level. The other one, private, is in the Brothers of Christian Instruction (FIC) school (19.76 N, −72.2 W). Although these stations may have reliable data, only rainfall data from 2009 to 2013, including the flood event of November 2012, were available for this study. The analysis by the Climate Forecast System Reanalysis (CFSR) (retrieved from http://www.esrl.noaa.gov/psd/data/) was used for solar radiation, temperature, wind speed, and relative humidity. Data, sources, resolution, and years are provided in Table 1.

Unfortunately, no historical data for proper calibration and validation of the SWAT model were available. Therefore, we used previously calibrated variables and coefficients from the nearby Trou-du-Nord catchment (Setegn & Donoso, 2017) (Table 2), assumed to have the same climatic pattern and soil type as our study area. The model was then validated based on the estimated discharge of the 2012 event.

With the SWAT model, we compared the hydrological variables from the baseline (Figure 1d) with those from an urbanization-deforestation scenario that we derived by extrapolating previous urban expansion from the valley to the upper basin. By changing forest areas into urban areas, we addressed deforestation and urbanization simultaneously. Urban areas in the catchment increased from 22.4% to 32% and forest areas decreased from 34.4% to 24%. We computed water balance variables for both scenarios. The net runoff was converted into discharges, so we reproduced the November 2012 flood event. We quantified the impact of further urbanization-deforestation as a change in peak discharge, which directly influences flood extension, flow depth, and velocity.

3.2 | 1D-2D hydrodynamic model (Sobek-rural)

The drainage network of the city and the adjacent areas, including the Haut-du-Cap River and the streams

TABLE 1 Input data for the SWAT model.

Data	Sources	Resolution	Year
DEM	USGS	30 m × 30 m	2015
DEM	CNIGS	1.5 m × 1.5 m	2017
LULC	ESRI	10 m × 10 m	2020
Soil	FAO-UNESCO	400 m × 400 m	1994
Rainfall	UHM	Daily	2009–2013
Other weather variables	CFSR	Daily	2009–2013

TABLE 2 Calibrated parameters from the Trou-du-Nord catchment SWAT model (Setegn & Donoso, 2017).

Parameter	Description	Final calibrated
CN	Curve number	Reduced by 10%
ESCO	Hydraulic conductivity (mm/h)	35
GW_REVAP	Evaporation soil compensation factor	0.81
REVAMP	Threshold depth of water in the shallow aquifer for revap to occur (mm)	0.02
GWQMIN	Threshold depth of water in the shallow aquifer for return flow to occur (mm)	Reduced by 10%
SOL_AWC	Soil available water content	Increased by 10%
ALPHA_BF	Baseflow alpha factor	0.75
SURLAG	Surface runoff lag coefficient	0.048

discharging from the ravines of the mountains to the west, were modeled using Sobek-Rural (https://www.deltares.nl/en/software-and-data/products/Sobek-Rural-suite/modules/1dflow-rural, Deltares, 2018), 1D for the main channels and 2D for the adjacent floodplains. For this we adapted a model developed by Verwey (2016) in collaboration with the French Anonymous Company for Management and Business Studies (SAFEGE).

The original modeling area covered 33 km^2, from the Colonial Bridge to the Chinese Bridge at the outlet, including the dense urban areas of the west, the international airport, and the Rhodo Basin. It contained the Haut-du-Cap River, the Any River, and the ravines west of the city. We added new physiographic data (area, river length, slope) from the SWAT model. The cross-sections of the rivers were assumed to be rectangular, with width and depth at the different locations derived from in situ and Google Earth estimations. We also added hydraulic structures, including the Colonial, RN3, and Chinese Bridges (Figure 4). The Any River was divided into an upstream part, before crossing the airport, and a downstream part, after crossing the airport. We used Manning's hydraulic roughness values of 0.05, 0.1, and 0.035 s/m$^{1/3}$ for the urban, rural, and riverbed areas, respectively.

The 2D mesh for the areas adjacent to the rivers and the Rhodo Basin had rectangular cells with 50 m × 50 m dimensions, resulting in 20,829 grid cells. We set a constant water level of 0.2 m above mean sea level at the downstream boundary. Figure 4 shows the major structures and branches in the updated model.

We conducted comprehensive data analyses to simulate significant rainfall events, including the 50-year event of November 2012 and events with return periods of 5, 10, 50, and 100 years. We required data inputs for the generalized extreme values (GEV) distribution to initiate these simulations. For this purpose, we turned to a 1940–2009 time series of maximum precipitation data from the UHM. As the availability of sub-daily climate data for the Cap-Haïtien region was limited, we employed a reasonable approximation, assuming that Cap-Haïtien's climatic patterns mirrored those of Southern Florida. We adopted a storm distribution characterized by a 24-h to 15-min type III pattern, a common trait in the Gulf of Mexico and Atlantic coastal areas. This approach, visually depicted in Figure 5a, b, was inspired by similar methodologies employed by Setegn and Donoso (2017). Utilizing the inputs derived from the GEV analysis, we generated a comprehensive set of rainfall storm events with varying return periods ranging from 1 to 500 years (Figure 5c). This set, including the November 2012 event as a reference, culminated in a graph for the peak discharge of different watercourses for different probabilities of occurrence (Figure 5d), a hydrograph for the Haut-du-Cap River and its tributaries during the November 2012 event (Figure 5e), and hydrographs of the Haut-du-Cap River associated with different return periods (Figure 5f).

We used the curve numbers (CN), estimated from the SWAT model, for the different sub-catchments and the expression of Kirpich (1940) to estimate the travel time of flood waves along the rivers. Note that hydrological computations through the SCS module of Sobek-Rural were not linked to the SWAT model.

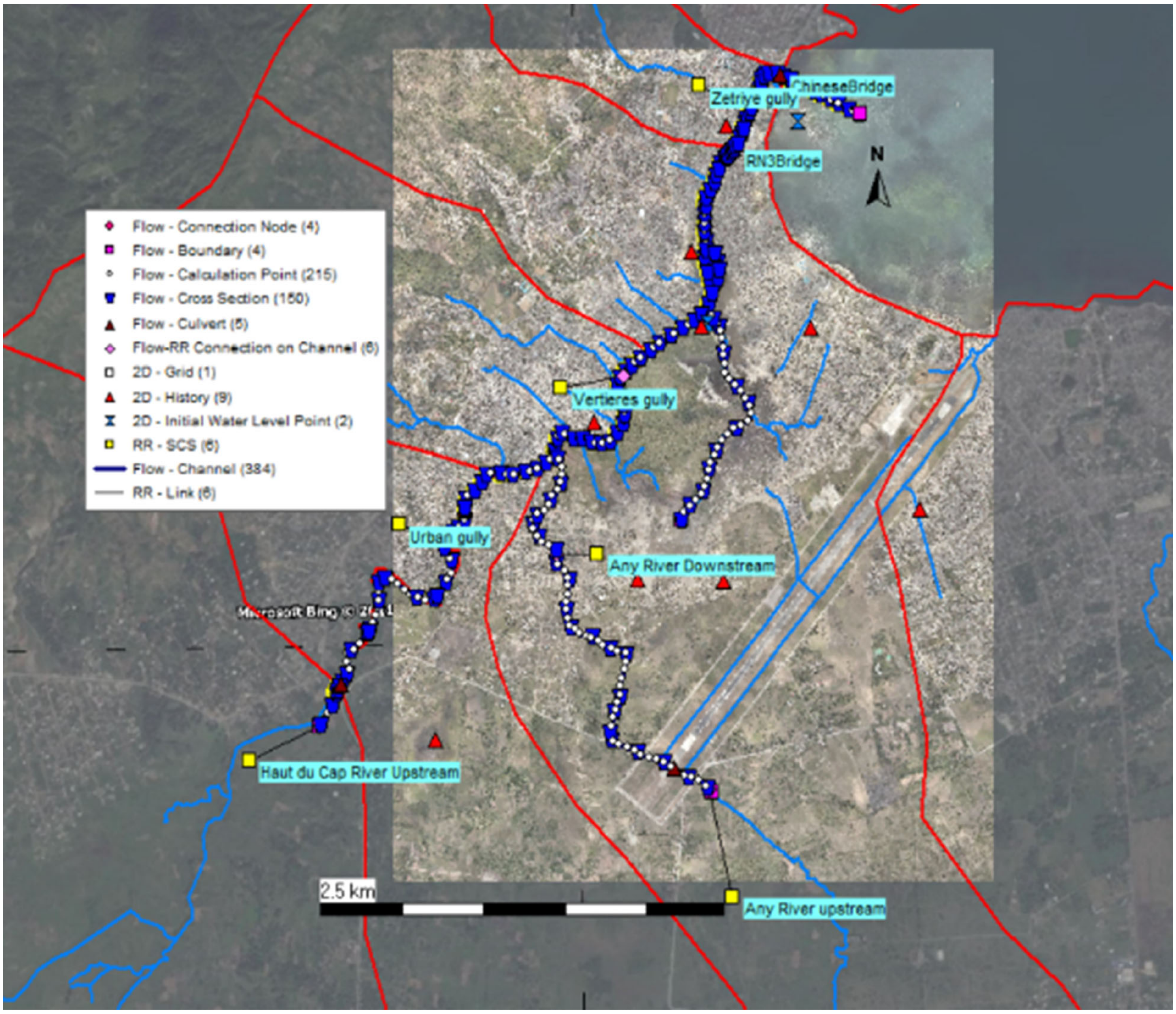

FIGURE 4 River Branches, 2D Domains, Structures, and Boundary Conditions in the Enhanced Sobek-Rural1D-2D Model. The diagram illustrates the key components of the Sobek-Rural1D-2D model in its original configuration. Notably, the model encompasses three primary structures: the Colonial Bridge, the National Road 3 (RN3) Bridge, and the Chinese Bridge located at the Outlet of the Haut-du-Cap River.

Finally, with Sobek-Rural, we analyzed the effects of flood mitigation measures. Effective measures should attenuate the peak discharges upstream before entering the city. An upstream multipurpose dam across the Haut-du-Cap River would be a technically robust solution, but environmental impacts and the required reservoir volume would pose significant limits. Use the Rhodo Basin as a retention pond would be less impacting, but because its retention capacity has been reducing by sedimentation over the years, it would require regular dredging. By deepening it to 1.5 m for an area of 1.5 km^2 and constructing a 55 m wide lateral weir with a threshold sill of 4 m above mean sea level, the basin could store a water volume of 2.25 hm^3. Additionally, an outlet structure should be constructed downstream of the basin to lower the water level before the arrival of the flood.

Extending the drainage network could be an alternative strategy to mitigate floods. Flooding at the airport could be prevented by bypassing the Any River upstream. We proposed a trapezoidal channel of cross-sectional dimensions indicated in Figure 6. We proposed extending the drainage network for the densely urbanized areas of Blue Hills, Vertières, and downstream of the Rhodo Basin. As the extension of the canals would result in the displacement of people and significant socio-economic impacts, we also propose a bifurcation downstream of the Colonial Bridge, with its right branch towards our proposed channel (Figure 6). We proposed extending the

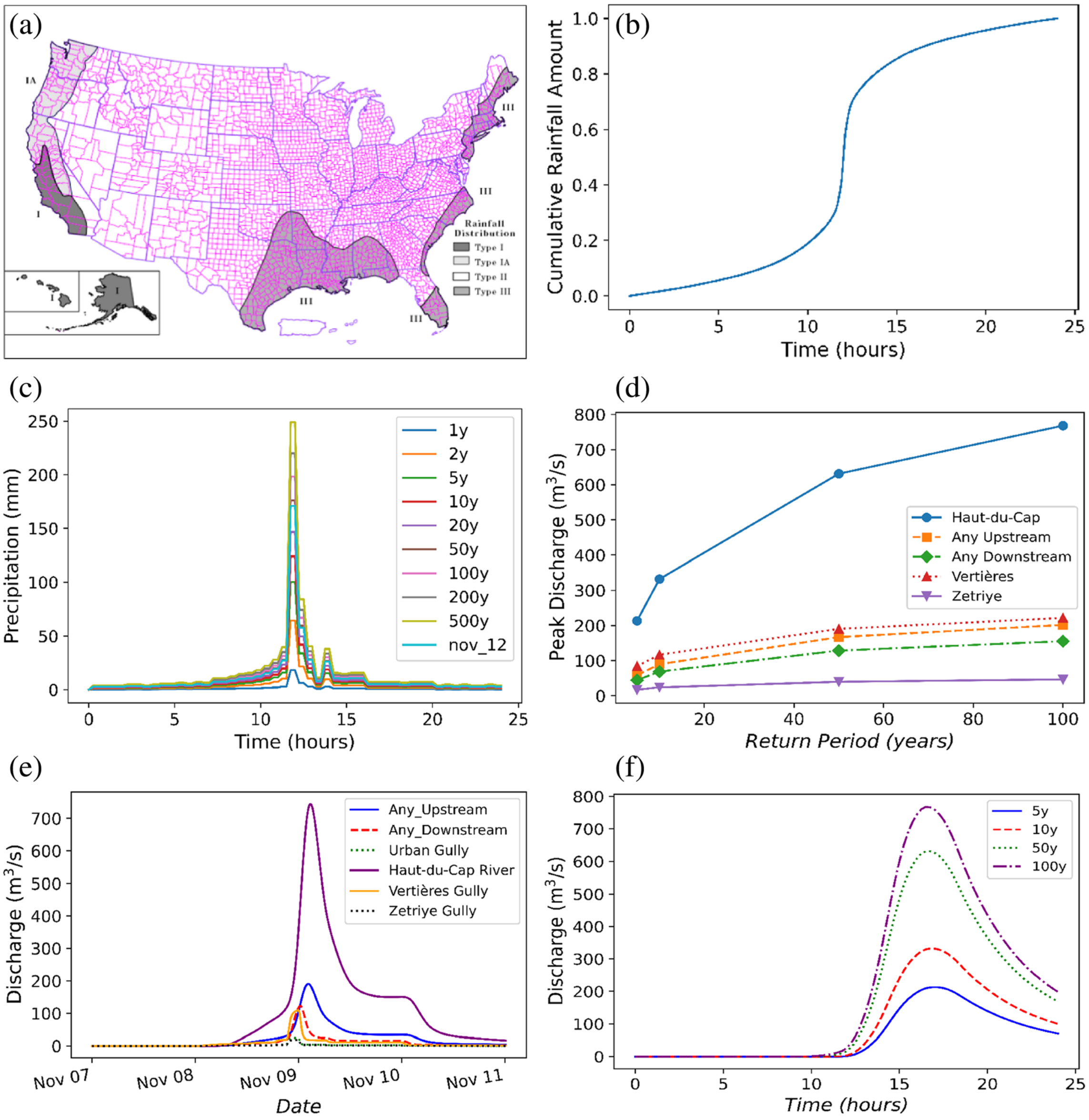

FIGURE 5 (a) Climatic regions of the USA characterized by SCS method rainfall distribution, (b) Distribution of SCS Type III storms, displaying time on the x-axis and cumulative probability distribution on the y-axis, (c) 24-h rainfall patterns for various return periods, alongside the noteworthy November 2012 Cap-Haïtien event, (d) Peak discharge of different watercourses for different probabilities of occurrence, (e) Hydrograph of Haut-du-Cap and Its Tributaries during November 7–11, 2012, (f) Hydrograph of the Haut-du-Cap River for Different Probabilities of Occurrence.

channel east of the Rhodo Basin and the airport and excavating a direct connection from the Rhodo Basin to the ocean. We estimated Manning's roughness coefficient of the extended channels and newly excavated canal for the hydraulic computations at $n = 0.025\ \mathrm{s/m}^{1/3}$. Deepening of the Rhodo Basin was not included in the strategy.

Figure 6 illustrates the proposed strategy (extended drainage network) implemented in Sobek-Rural, whereas Figure 4 depicts the river network in the baseline model. The effects of the interventions were assessed using the 2012 flood as a reference.

4 | RESULTS

4.1 | Present situation

The November 2012 peak discharges estimated by SWAT were 360 and 90 m^3/s for the Haut-du-Cap (Figure 7a) and Any Rivers (with an upstream portion of 55 m^3/s) (Figure 7b), respectively, whereas the peak of direct Vertières Ravine inflow into the Rhodo Basin was estimated at 6 m^3/s (Figure 7c). Despite all the uncertainties in the model setup and calibration, the estimates seem

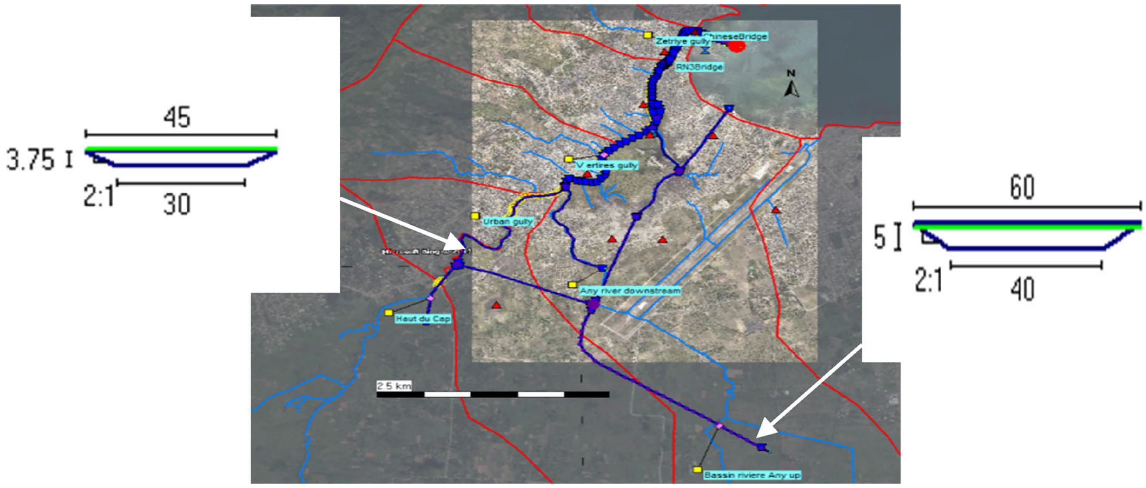

FIGURE 6 Extended drainage network for flood mitigation in Cap-Haïtien City, featuring cross-sectional dimensions of new drainage channels.

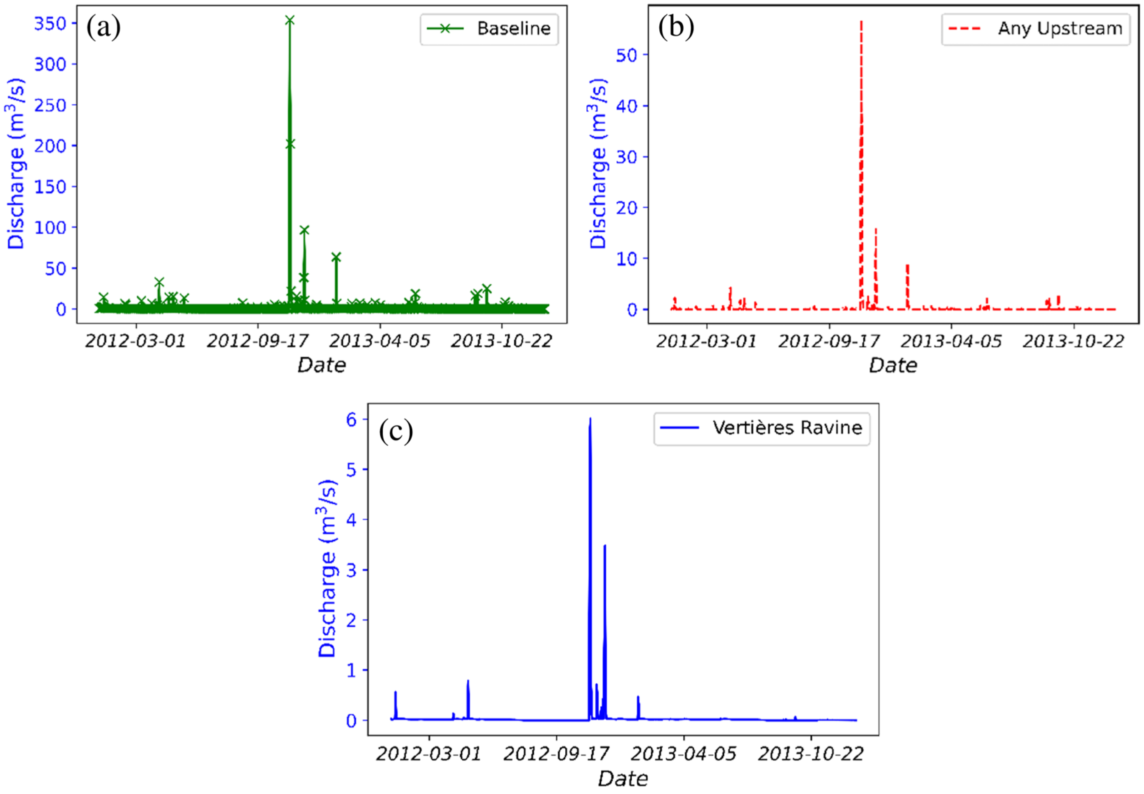

FIGURE 7 SWAT model results for the period January 2012 to December 2013, (a) flow discharges of Haut-du-Cap River under the baseline conditions, (b) flow discharges of any upstream under baseline conditions, and (c) flow discharges of Vertières Ravine under baseline conditions.

sufficiently accurate if we consider the peak discharge of 400 m^3/s reported by Guillande (2015).

Figure 8 presents the total sediment yield at the outlets of the Vertières Ravine and the Any River upstream, whereas Figure 9a shows the sediment transport of the Haut-du-Cap River (red dotted line). The computed values did not consider any potential backwater effect from the ocean or tides. For the 2012 event, the peak sediment transport rate was 516 tons/day for the Haut-du-Cap River. This value is based on sediment transport capacity, which is also significant for the steeper Vertières Ravine and Any River. We noted an imbalance between the Vertières

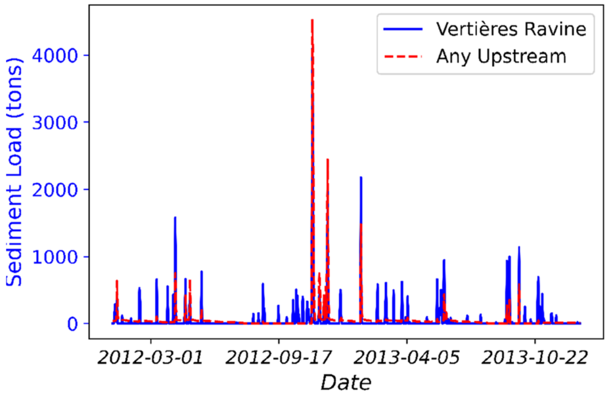

FIGURE 8 Sediment transport of the main tributaries for the urbanization-deforestation scenario.

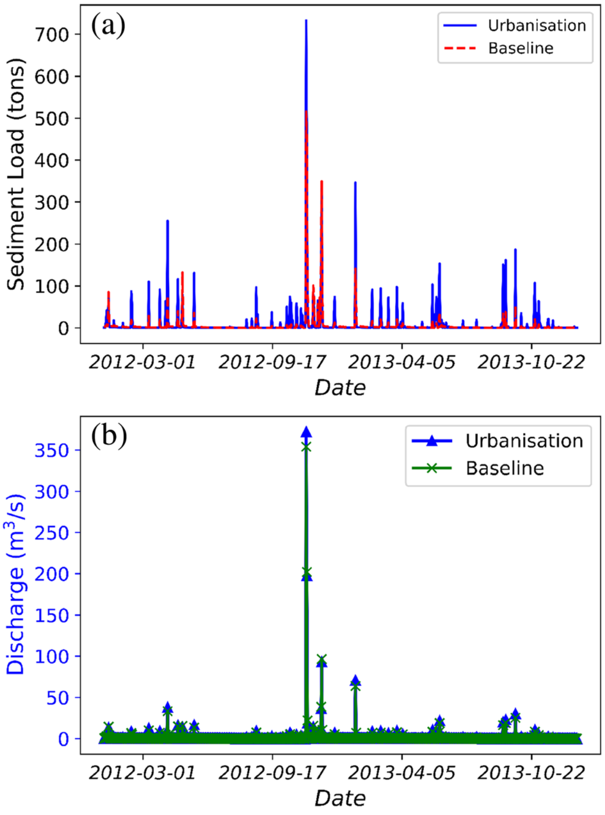

FIGURE 9 Results of SWAT for the period 2012–2013. (a) Sediment transport of the Haut-du-Cap River for the baseline and urbanization-deforestation scenarios. (b) Flow discharges of the Haut-du-Cap River for the baseline and urbanization-deforestation scenarios.

TABLE 3 Annual average basin water balance of Cap-Haïtien (2009–2013).

Water balance component	Yearly average (mm)
Precipitation	1227
Surface runoff	310
Return flow	29
Percolation to the shallow aquifer	37
Revap (shallow aquifer ≥soil/plants)	28
Deep aquifer recharge	18
Total aquifer recharge	55
Total water yield	376
Actual evapotranspiration	896
Potential evapotranspiration	2156

Ravine's sediment yield and the Haut-du-Cap River's outlet, which complies with sediment deposition within the Rhodo Basin or, more likely, with overbank flows during floods that spread out and contribute to the formation of floodplains. The overarching long-term trend in riverbed development is sedimentation, as evidenced by the partial burial of the Colonial Bridge upstream of the city. Alterations in the morphology of the urban area's channels do not depend on upstream sediment yield but on local variations in flow speed, both acceleration and deceleration (Mosselman, 2017).

Using SWAT, we derived the water balances of the Cap-Haïtien catchment for the 5 years 2009–2013. Table 3 indicates the total precipitation, actual evaporation, and the net amount of water routed to direct streamflow (water yield). Table 4 presents the monthly water balance for the Cap-Haïtien catchment.

Around 75% of the annual total precipitation in the area was lost by evapotranspiration. The amount agrees with the average of 68 years of evapotranspiration as derived by Hargreaves and Samani (1983).

The high-rainfall season runs from September to November, with a peak in November, and the lowest precipitation period is from May to August, with July as the driest month (Table 4). The peak runoff is expected in November and the peak evapotranspiration in April. Surface runoff in Cap-Haïtien has a high correlation with rainfall. Groundwater influences the runoff too, which we confirmed during fieldwork in December 2021 when we observed a high groundwater table level near the airport in the upper part of the city (Figure 3b).

4.2 | Impacts of urbanization and deforestation

We used the results of SWAT to estimate the impacts of urbanization and deforestation. These impacts were particularly pronounced in the Vertières Ravine, where sediment production and transport rates were significantly affected. For a November 2012 event with increased urbanization-deforestation, the Vertières Ravine and the upstream part of the Any River would transport an average of about 4100 (2500 in the baseline scenario) and

TABLE 4 Monthly water balances of the Cap-Haïtien catchment (2009–2013).

Month	Rain (mm)	Runoff (mm)	Lateral flow (mm)	Water yield (mm)	Evapotranspiration (ET) (mm)	Potential evapotranspiration (PET) (mm)
Jan	100	24	4	28	88	126
Feb	51	6	3	9	83	146
Mar	100	14	3	15	97	169
Apr	113	18	4	22	118	202
May	90	13	3	16	77	213
Jun	64	9	3	12	69	221
Jul	16	1	2	3	35	240
Aug	41	4	0	4	46	225
Sep	107	19	0	19	67	197
Oct	126	12	0	12	88	175
Nov	329	159	3	161	92	129
Dec	99	36	3	39	65	130

TABLE 5 Maximum sediment transport rates for both the baseline and the urbanization-deforestation scenarios.

Peak sediment transport rates (10^3 kg/day)		
Rivers	**Baseline**	**Urbanization-deforestation**
Haut-du-Cap	516	733
Any	4509	4522
Vertières	2500	4094
Urban ravine	3	33

4500 tons/day of sediment, respectively (Table 5). Ongoing urbanization-deforestation of the Vertières Ravine can therefore be expected to fill the Rhodo Basin with tons of fluvial sediments, especially during wet periods. Consequently, the channel bed and water levels will keep rising, further deteriorating the low hydraulic capacity of the Cap-Haïtien system.

Figure 9b shows the peak discharges for the baseline and the urbanization-deforestation scenarios. Urbanization-deforestation was found to increase the peak discharge from 360 to 380 m^3/s. Although the relationship is not linear, this result provides insights in the potential effects of future urbanization of the southern part of the Cap-Haïtien plain. More significant discharges might be expected due to further deforestation of the mountains and acceleration of uncontrolled urbanization.

4.3 | Flood simulation and flood mitigation measures

The 50-year event of November 2012 had extraordinary flood extents and depths. Despite uncertainties in the measurements, we could rudimentarily calibrate the Sobek-Rural model on observed flood extent and depths. According to the calibrated model, the 2012 event covered an area of 17 km^2, in line with simulation results by SAFEGE (SUEZ, 2017) which reported a flood extent of 17 km^2 and a flood depth of more than 1 m at the eastern part of the airport. Our calculated flood extent agreed sufficiently with values reported by Guillande (2015), despite some discrepancies in measured water depths.

Figure 10 shows the computed flood extent and maximum water depths during the 2012 event. The computed flooded area included the Rhodo Basin, the areas of Vertières and Blue Hills, and the airport. The water levels were estimated to be 1.50 to 4 m above mean sea level. Filling of the Rhodo Basin with rubbish and fine sediments increased the water level. Furthermore, the bottleneck downstream of the RN3 (national road number 3) Bridge created backwater that flooded the upstream communities. At the airport, the capacity of the Any River culverts was insufficient for the magnitude of flooding. Drainage being blocked by the airstrips, the airport's eastern communities of Petite Anse were entirely flooded. The flooding of the agricultural area upstream of the Colonial Bridge and the Blue Hills area was mainly due to the Haut-du-Cap River's overflow since the peak flow substantially exceeded the bankfull discharge. The central area downstream of the Rhodo Basin was primarily flooded by water from the ravines, mainly the urban ravine and the Vertières Ravine. The discharge capacity of the outlet from the Rhodo Basin was computed to be around 200 m^3/s.

We also applied Sobek-Rural to floods with return periods of 5, 10, 50, and 100 year. Table 6 presents the corresponding peak discharges. Current hydraulic

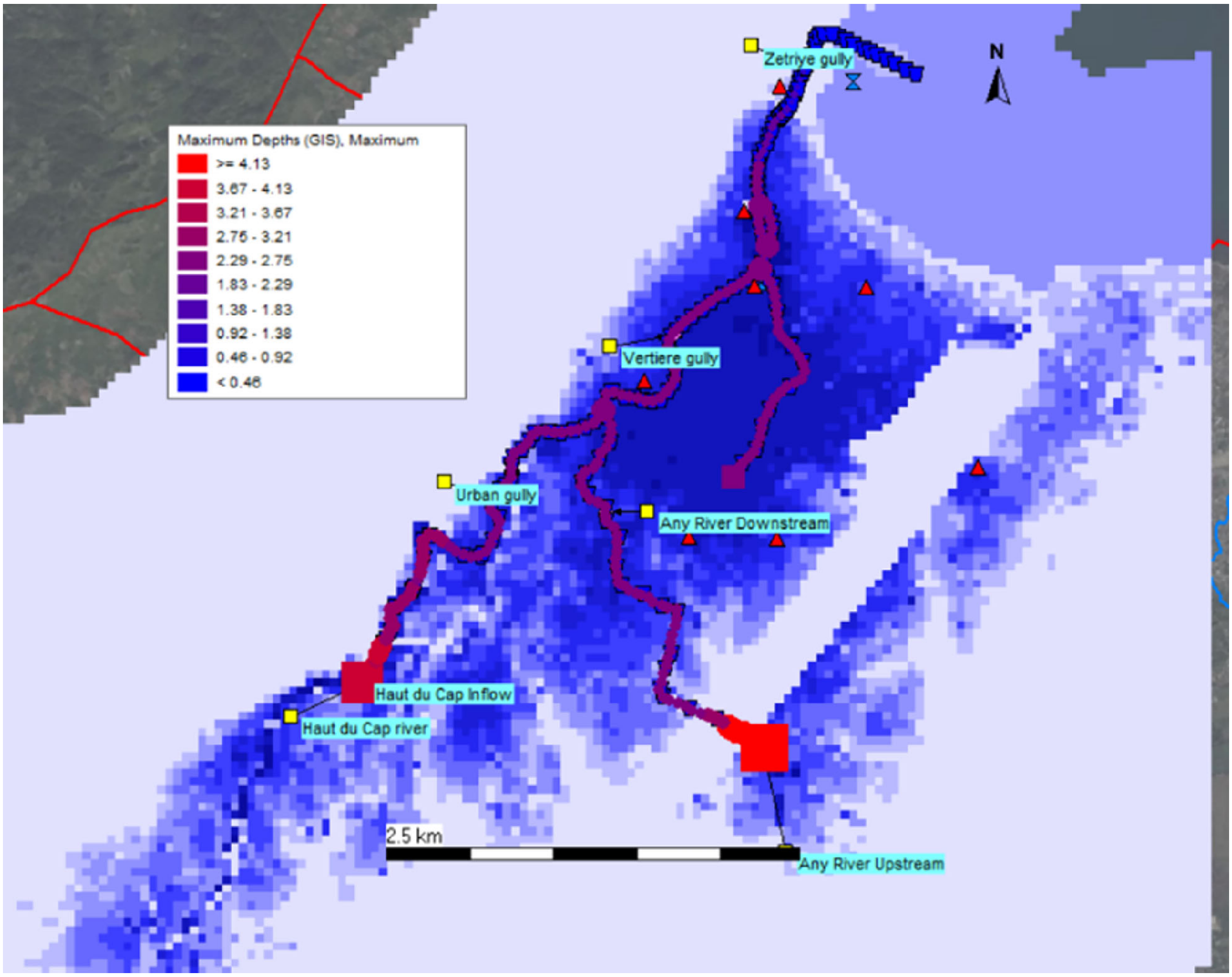

FIGURE 10 Computed flood extent and maximum water depths at the peak discharge of the 2012 event.

TABLE 6 Peak discharges of the major watercourses for events having different return periods.

Return period (year)	Haut-du-cap (m^3/s)	Any upstream (m^3/s)	Any downstream (m^3/s)	Vertières (m^3/s)	Zetriye (m^3/s)
5	213	59	44	84	17
10	332	90	69	117	24
50	631	167	129	190	40
100	768	202	155	222	46

capacities of the Haut-du-Cap and Any Rivers are approximately 200 and 87 m^3/s, respectively. For the Haut-du-Cap River and its structures this is significantly lower than the estimated peak discharge of even the 5-year event (SUEZ, 2017). Inevitably flooding will occur frequently. Records confirm this since Cap-Haïtien was flooded in 2012, 2014, 2016, 2019, and 2022 (Ellsworth & Thomas, 2014; Geffrard, 2016; Sénat, 2021).

We assessed the effects of the proposed mitigation measures by simulating the 2012 event with and without their implementation. Extension of the drainage network (without dredging the Rhodo Basin) was found to significantly decrease the water levels to between 0.69 and 2.35 m above mean sea level (Figure 11).

The interventions attenuated the 600 m^3/s peak discharge by around 400 m^3/s (Figure 12), and they considerably decreased the flood extent and the water depth in the dense communities of Blue Hills and its agricultural area in the south (Figure 13).

Apart from fluvial flooding, Cap-Haïtien is also threatened by coastal flooding from storm surges generated by strong winds. We analyzed the potential effects of

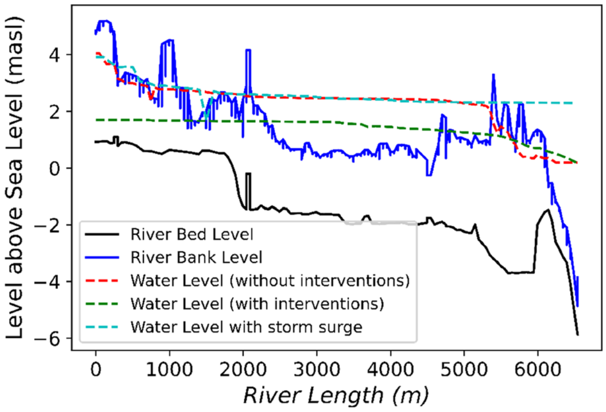

FIGURE 11 Maximum water levels in the Cap du River before and after the proposed flood mitigation interventions: extension of draining network, bypass by the airport.

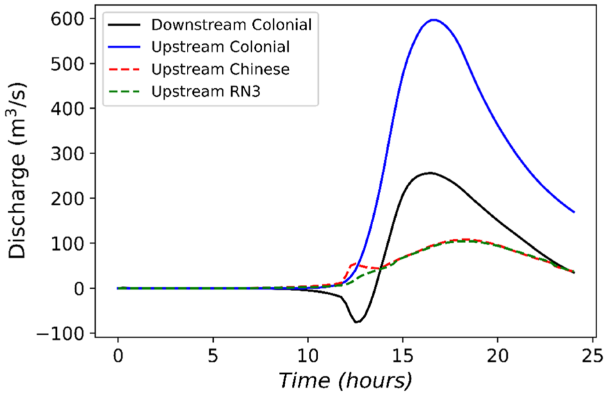

FIGURE 12 Peak discharges near the Colonial and Chinese Bridges with and without the proposed interventions.

the proposed interventions by imposing a storm surge level of 0.6 m above mean sea level at the downstream boundary of the Sobek-Rural model. The effects on flooding were only minor compared to the effects of high river discharges (Figure 11).

5 | DISCUSSION

The peak discharges of the 2012 event estimated by the SWAT model (360 m^3/s) and by Guillande (2015) (400 m^3/s) differ significantly from the peak discharge of 600 m^3/s for a 50-year return period according to the SCS method in Sobek-Rural. The difference can be attributed to 1) the assignment of a 50-year return period to the 2012 event (SUEZ, 2017), which would be 10–20 years instead according to our results; 2) the setup and simplifications of the SCS method that overestimate runoff; 3) the uncertainties linked with the input data of the SWAT model, mainly the digital elevations with 30 m resolution, which may underestimate peak runoff in steep terrain. In any case, these contrasting results highlight the inherent uncertainties associated with peak discharge estimates. Therefore, the designing of scenarios and the implementation of flood management strategies calls for caution and for accounting for these uncertainties.

The hydrodynamic model results depend much on the cross-sections assigned to the drainage network (rivers and ravines). The cross-sectional profiles in our model stem from a preliminary survey within the SUEZ study (SUEZ, 2017) for the World Bank in Cap-Haitien. These measurements were supplemented by estimates derived from Google Earth, which also introduced uncertainties. Moreover, during our on-site field assessment, we observed that the channels are obstructed by debris of waste, sediment accumulations, and proliferating riparian vegetation in the city's upper reaches. The morphology of cross-sections was not updated in the hydrodynamic Sobek-Rural model. Differences between model geometry and the dynamic real geometry were hence inevitable.

Cap-Haïtien grapples with challenges in waste management (Figure 2b), including issues with clogged river channels, sedimentation, and inadequate drainage. Even existing morphological models would not account properly for the transport and accumulation of waste because of its heterogeneous nature. Approximately 50% of the estimated 0.7 kg daily waste per capita is organic and 50% non-organic. This results in an annual waste production of 77,000 tons, calculated as 0.7 kg/(day. inhabitant) × 300,000 inhabitants × 356 days/year × 0.001 ton/kg. Part of it is transported in suspension, settling if flow decelerates, and part of it floats (e.g., plastic bottles), accumulating along riverbanks, trapped in mangroves or deposited on floodplains as floods recede. This is illustrated by the photographs of Figures 2b and 3a, taken during fieldwork. Waste reduces river conveyance capacity, raises bed levels, and exacerbates flood extent and levels. Consequently, computed water levels might substantially deviate from reality. Transport and deposition of waste is an emerging frontier in science, and our study shows this is not only environmentally relevant but also important for flood risk management.

In our approach, it was inevitable that we had to use both SWAT and Sobek-Rural. This revealed two fundamental methodological inconsistencies. First, return periods for SWAT regard precipitation data, whereas return periods for Sobek-Rural regard discharge data. Differences in the corresponding statistics imply that a single extreme event has different return periods, depending on the perspective taken. Second, sediment yields

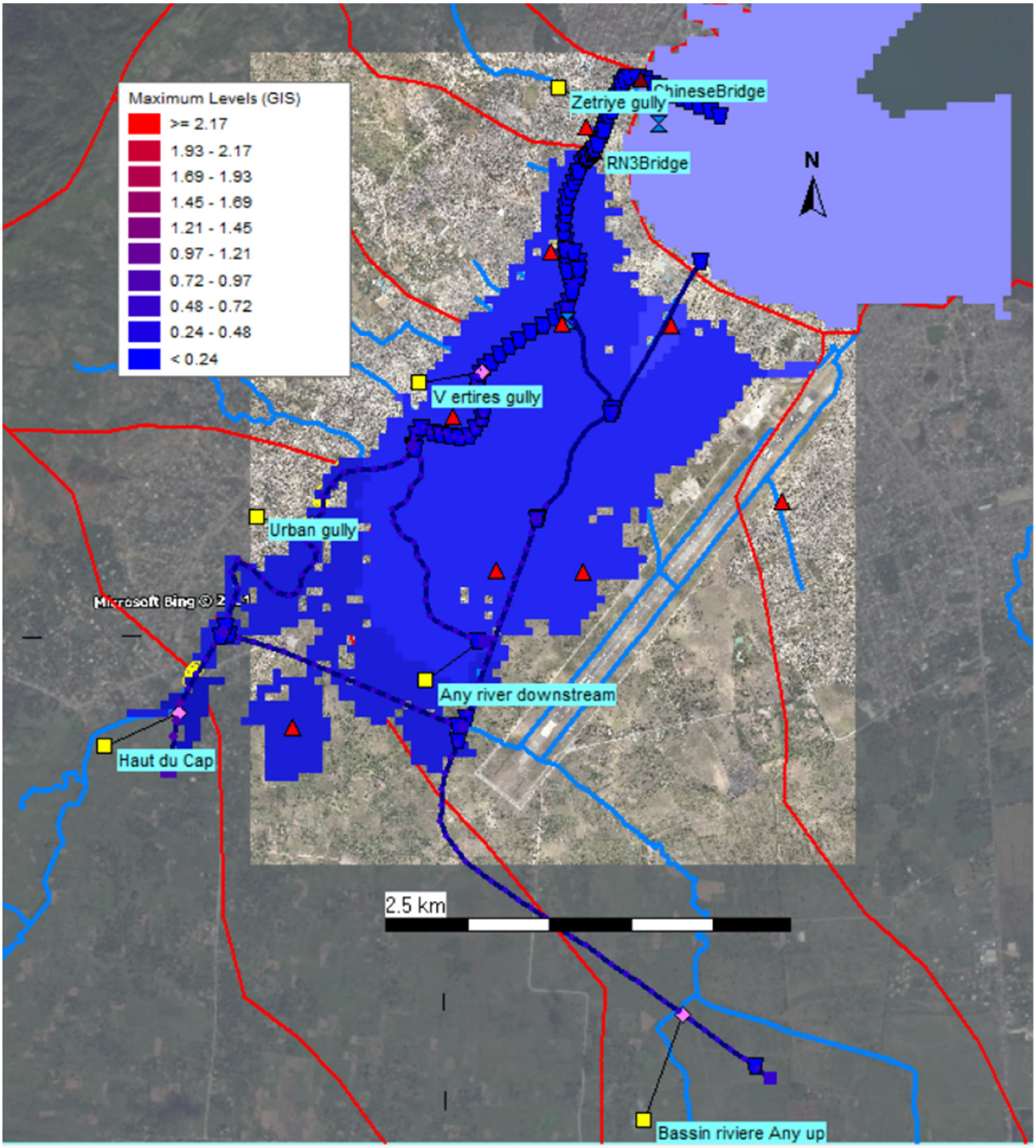

FIGURE 13 Flood extension with maximum water depths with interventions at the peak discharge of the 2012 event.

predicted by SWAT are based on soil erosion in the catchment, a function of rainfall energy (Neitsch et al., 2011), whereas Sobek-Rural is a mere hydrodynamic model. Part of the sediment in SWAT becomes a supply limited washload that is flushed through the river without being affected by flow strength until it settles in the stagnant Rhodo Basin or flocculates in contact with salty sea water in the estuarine reach. The rest of the sediment in SWAT joins the capacity-limited bed-material load that contributes to morphological changes according to the Exner Principle (Exner, 1925). The first-order streams in the upper catchment create a gap in sediment transport representation, as erosion of riverbeds and riverbanks along these streams is inadequately accounted for in the universal soil loss equations of SWAT (Wischmeierr & Smith, 1978).

Additionally, these streams do not align with the resolution of the Sobek-Rural river schematization. For this second inconsistency, we recommend development of a method that bridges the gap between sediment transport calculations in SWAT and other modeling suites capable of incorporating morphological changes (Delft3D, SOBEK-RE, etc.).

Hydrological and hydraulic models are essential tools in simulating rainfall-runoff processes. However, their utility in ungauged and poorly gauged catchments is limited by the quantity and quality of the available data. The length of available data series is an essential factor in the accuracy of model results. The dynamic nature of the river cross sections in Cap-Haïtien City poses an obstacle to validation. Cross-sections evolve rapidly by multiple factors, including construction activities on the floodplains, settlement of waste including plastic materials, and sand mining. Insufficient data and absence of documentation of past flood events and hydraulic conditions in the region has hindered the possibilities of validation based on observed data.

The rainfall probabilities in our analysis agree with a study by Hargreaves and Samani (1983). We used 5 years of precipitation data from a single station. Accurate results would require longer data series and a higher spatial resolution. The lack of data necessitated several assumptions, such as calibrating the model using parameters from a neighboring basin (Garcia & Wiralles-Wilhelm, 2017) and employing the SCS Type III method for 24-h precipitation distribution over time. A comparable methodology for a nearby Haitian catchment has nonetheless yielded strong agreement in the outcomes ($r^2 = 0.95$) (Garcia & Wiralles-Wilhelm, 2017).

The analysis of urbanization dynamics in Cap-Haïtien reveals insights into the intricate relationship between urban development and flood vulnerability. These findings are similar to those from coupled hydrologic and hydrological models by Cheng et al., et al. (2020), where urbanization created higher surface runoff discharge rates, shortened times to reach peak runoff and discharge, and increased the occurrence of flash floods. Also, Hodgkins et al. (2019) found that for highly urbanized basins, which are concentrated in the Northeast and Midwest of the US, increases in the magnitude of peak flow were significantly correlated with the amount of basin urbanization. Existing urban planning policies thus play a pivotal role in shaping the susceptibility of urban areas to flooding. Demographic trends and socio-economic factors influencing settlement patterns contribute to the vulnerability of specific communities based on population density and necessitate targeted interventions.

The impact of infrastructure development on altered water flow patterns calls for sustainable solutions that enhance flood resilience while minimizing environmental repercussions such as disease breakouts, polluting drinking water, and damaging the living environment (Chen et al. 2017). Community engagement in decision-making processes and integrating sustainable urbanization practices emerge as key factors in mitigating flood risks, highlighting the importance of a holistic and environmentally conscious approach to urban development in flood-prone regions. In regions facing similar challenges, such as highly urbanized areas, non-engineering management is the avenue to mitigate urban flood risk. Examples of such approaches include flood risk warnings (Chen et al. 2017), alternative land use planning, and flood management practices (Sheng and Wilson 2009), but also the creation of programs like flood insurance, as argued by (Ntelekos 2010), could work in the Cap-Haitien context.

Political crises, public insecurity, migration, and a generalized governance problem plague Haiti. These issues inevitably have repercussions in Cap-Haïtien too. Floods are essentially a governance issue, apart from their natural causes. People live on the banks of the rivers, areas at risk where the quality of buildings is below all structural standards. There is no solid waste management system in the city. All rubbish is thrown into the streets, the ravines, and the river. This clogs the already poor drainage system and reduces the hydraulic conveyance capacity of the Haut-du-Cap River. An integrated solution to the flooding problem requires better urban planning, law enforcement, an urban environment management system, qualified policies, systemic approaches, stakeholder involvement, public awareness, and participation.

The methodologies employed in this study have been assembled to collect the maximum of information possible in a data-scarce environment. Together, they constitute a transferable framework for assessing fluvial flood risk and mitigation strategies in areas grappling with urbanization, deforestation, and flooding challenges. It consists of (i) utilizing global datasets on elevations, precipitation, temperature, and land cover for hydrological modeling; (ii) enriching and calibrating the hydrological model with data from nearby or similar catchments; (iii) informing hydraulic modeling with hydrological model outputs; (iv) calibrating the hydraulic model with a variety of local evidence and knowledge such as flood marks, historical flood records, local observations during flood events, and anecdotal evidence; and (v) scenario-based simulations of system response to different forcings and interventions such as land cover change, climate change, and river network enhancement. We believe that the explicit delineation of the steps of this framework provides valuable guidance to researchers and practitioners in regions facing analogous issues.

6 | CONCLUSIONS AND RECOMMENDATIONS

This study has significantly enhanced our understanding of the hydrological dynamics in Cap-Haïtien. Our findings demonstrate that the primary cause of the Haut-du-Cap River overflow is its inadequate hydraulic capacity to safely accommodate water flow, even during ordinary events with a return period of 5 years. The current hydraulic capacity of the Haut-du-Cap and Any Brios Rivers is approximately 200 and 87 m^3/s, respectively. However, the peak discharges estimated by the SWAT model for the Haut-du-Cap River during the 2012 event were on the order of 400 m^3/s (360 m^3/s for SWAT and 400 m^3/s according to Guillande, 2015), and the 5-year-event peak discharges estimated by the SCS method in Sobek-Rural already exceed 200 m^3/s. We have identified urbanization and deforestation as key drivers of flooding in Cap-Haïtien. Following the current expansion pattern, our study suggests that a 10% increase in urban area leads to a 5% increase in surface runoff. The impacts of urbanization and deforestation are particularly pronounced in the Vertières Ravine, where sediment production and transport mechanisms are significantly affected. During the 2012 event, the Vertières Ravine and the Any River transported an average of 4500 and 4100 tons/day of sediments, respectively. We proposed and analyzed a strategy to mitigate flooding in Cap-Haïtien. It includes extending the city's drainage network by constructing a bypass around the airport and a canal from the Rhodo Basin to the sea via the MTPTC premises. Connecting the Haut-du-Cap River downstream of the Colonial Bridge to the bypass would reduce water levels for communities such as Blue Hills. An elaborate maintenance plan must accompany these measures. Constructing a cascade of small retention basins in the catchment upstream of the river's entry into the city could further attenuate peak flows. These measures would also render the system more resilient in face of climate change, although corresponding scenarios of increased volume and frequency of flooding were beyond the scope of our study.

To sustainably mitigate Cap-Haïtien's flooding challenges, we recommend:

(i) Data acquisition and bathymetric surveys: Implementation of a comprehensive data acquisition program is imperative. Collaborate with local and international stakeholders to conduct detailed bathymetric surveys, ensuring accurate mapping of riverbed topography. Establish a centralized database to monitor and update hydrological parameters to enable timely decision-making continuously. (ii) Structural measures: Structural interventions should be strategically implemented, including retention basins and drainage extensions. Collaborate with engineering experts to design and construct resilient infrastructure that can withstand varying flood scenarios. Ensure community engagement in the planning phase to address local needs and concerns. (iii) Organizational framework: Establish an organizational framework dedicated to flood management. Formulate a multidisciplinary task force comprising hydrologists, engineers, urban planners, and community representatives. Clearly define roles, responsibilities, and communication channels to streamline coordination and response efforts during flood events. (iv) Maintenance: Regular maintenance of existing infrastructure is paramount for sustained effectiveness. Develop a routine maintenance schedule and allocate resources for inspections, repairs, and upgrades as needed. Implement preventive measures to address potential vulnerabilities identified through ongoing monitoring and evaluation. (v) Participatory approach: Adopt a participatory approach that involves local communities in decision-making processes. Facilitate workshops, awareness campaigns, and training programs to empower residents with knowledge of flood risks and mitigation strategies. Foster a sense of community ownership, encouraging responsible behavior and cooperation during emergencies.

Our study introduced avenues for future research. The identified mountain ravines as the primary source of sediment-laden flash floods warrant in-depth exploration. Future studies could delve into the specific dynamics of these areas, providing insights into the complex interactions between deforestation, urbanization, and flash flood occurrence. Exploring the effectiveness of the recommended mitigation measures in real-world implementation scenarios will further contribute to refining flood risk management strategies. This study unveils the intricacies of flooding dynamics in Cap-Haïtien and serves as a blueprint for integrated assessments and actionable policies in global regions grappling with similar challenges. The synthesis of scientific progress, methodological transferability, policy implications, and future research directions underscores our work's broader impact and significance.

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DATA AVAILABILITY STATEMENT

All data and models supporting this study's findings are available from the corresponding author upon reasonable request.

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