


A GIS-based tool for flood damage assessment and delineation of a methodology for future risk assessment: case study for Annotto Bay, Jamaica

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Abstract Flood risk assessments and damage estimations form integral parts of the disaster risk management in Jamaica, owing its vulnerability to hydrometeorological hazards. Although island wide damage and risk assessments have been carried out for major flood events in Jamaica, few studies have been conducted for the creation of damage and risk maps for vulnerable areas. In this study, a risk-based tool was developed by transferring a proven methodology for flood risk assessment in Flanders, called LATIS, to areas with limited data resources. The town of Annotto Bay was chosen as case study due to its vulnerability to coastal and riverine flooding. The model uses input parameters such as flood data, land use, and socioeconomic data and rainfall values to estimate the damage. The flooding of 2001, caused by tropical storm Michelle, as well as a storm surge with a 100-year return period, was input for the model in order to estimate damage from fresh and saltwater for Annotto Bay. The produced maps show the spatial variation of the damage costs, which correlates with the flood depths. The total calculated damage cost from the freshwater flood of 2001 in the study area was estimated just over USD 7 million. Saltwater damages were calculated at USD 30 million. Although validation of the exact damage costs was not possible, the damage spread and number of affected elements were accurate. The model output also shows the potential number of people who would be killed as a result of the event, which was calculated at only 2 casualties for freshwater. Since in reality no one died, this low estimate can be considered accurate. The casualties caused by the saltwater flooding with a return period of 100 years were estimated at 150 people killed. The results of this approach can be extended to other vulnerable areas of the island having topographical and geographical similarities and being affected by similar

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hydrometeorological events. Hence, the method allows damage assessment for data-sparse regions, aiding in planning and mitigation measures for flood-prone communities.

Keywords Flooding · Damage map · Vulnerability map · Risk methodology · Latis · Jamaica

1 Introduction

Globally, floods account for the majority of the natural hazards which have resulted in loss of life and livelihood (Zwenzner and Voigt 2009). Moreover, the frequency of flood events has shown a twofold increase in the decade 2000–2009, as compared to the previous one (Keating et al. 2014). Worldwide, damage from flood events accounted for USD 2.36 trillion between 1980 and 2012 (Munich Re 2013). Of all the different types of flooding, riverine flooding yearly has the largest impact, affecting 21 million people with a cost to society of 96 billion dollars (Deltares 2015). These numbers will further increase due to climate change and socioeconomic development in high-risk areas. Furthermore, the increase in flood risk, observed in past decades, is attributable to an increase in population growth, urbanization and poor land use practices, and the expansion of developments in flood-prone areas (Keating et al. 2014). The United Nations Office for Disaster Risk Reduction (UNISDR) (2011) reported that economic opportunity and poor land use planning are two of the major drivers for development on floodplains, especially for the developing countries of South and East Asia as well as for the islands of the Caribbean. Akew (1997) delineates that floods, primarily of the riverine type, are responsible for one-third of all deaths and damages in Japan. This is even more significant as 10% of the island's entire area is occupied by flood plains, yet these are home to approximately 75% of the population (MLIT 2005).

In the Caribbean, hydrometeorological and tectonic natural hazards account for 77% of the disasters, of which floods and windstorms account for more than three-fourths (Collymore 2011). The majority of floods are attributable to heavy rainfall associated with tropical storms, hurricanes, troughs, and fronts, primarily in the months of May to June and August to November, which is the traditional wet season for the Caribbean. Collymore (2011) reported that the region experiences regular annual losses due to natural hazards in the order of USD 3 billion. This is significant as about 68% of these losses are in the social and production sectors. The loss of life and livelihood is also of significance as approximately 60% of the population resides in coastal areas which represent 70% of the economic activities (Collymore 2011). Carby (2011) reported that 88% of the Small Island Developing States (SIDS) of the Caribbean is affected by floods which range from coastal to riverine to urban runoff. According to the EM-DAT 2015 database that records flood events associated deaths and damages for the Caribbean, the period 1900–2015 shows an occurrence of 138 floods which were responsible for 4983 deaths and a total damage of USD 980,484,000 (EM-DAT 2015).

In Jamaica, the third largest island of the Caribbean, floods are the combined effect of extreme precipitation from tropical storms and hurricanes and poor land use practices and topography. Floods affect primarily the infrastructure sector, as the vulnerable areas are all coastal towns and cities (Burgess et al. 2015; Ishemo 2009; Mandal and Maharaj 2013; Mandal et al. 2013, 2016; Nandi et al. 2016; Taylor et al. 2014). In their compilation of

flood events in Jamaica between 1900 and 2010, Taylor et al. (2014) show that there has been an average of 18 flood events per decade with a total of 103 flood events since 1990. The average number of floods per decade has thus almost tripled in the past century. The Planning Institute of Jamaica (PIOJ) (2002, 2004, 2005a, 2005b, 2007, 2008, 2009, 2010 and 2012) reports that six severe hydrometeorological events occurred in Jamaica during the period 2002–2007 which have resulted in massive floods and damages to infrastructures for a total loss of USD 1.02 billion. Burgess et al. (2015) showed in their compilation of historic flood records from the Water Resources Authority of Jamaica (WRA), the Office of Disaster Preparedness and Emergency Management (ODPEM), and the Meteorological Service of Jamaica that, in 2004, hurricane Ivan accounted for the highest damages and losses, amounting to 8% of the Gross Domestic Product (GDP) in the decade 2000–2009. The major river systems in Jamaica, such as Hope River, Yallahs River, Outram River, Rio Minho, Rio Cobre, and Rio Grande, demand special attention as Jamaica's major infrastructures are located on the floodplains of the above rivers. These floodplains are also the sites of major towns and cities (Kingston, Montego Bay, Ocho Rios, Port Maria, and Annotto Bay, for example). Hydrological modeling to simulate runoff from extreme rainfall events was carried out by Mandal and Maharaj (2013) and Mandal et al. (2013, 2016) for the Hope River watershed and the coastal town of Port Maria, both in Eastern Jamaica. Robinson and Khan (2011) have worked extensively on the physical damage assessments caused by hurricanes, such as Ivan in 2004, Dean and Felix in 2007, Allen in 1980 and Emily, and Wilma in 2005 on the coastlines of Jamaica. The studies involved generating beach profiles pre- and post-hurricane for selected beaches and coastlines across the island and analyzing impacts from storm surges generated by the above-mentioned events. The results showed a maximum run-up of 1000 m, reported for the hurricane Dean for Portland Cottage, a coastal community located in southern Jamaica. A run-up distance of 573 m was also observed for hurricane Ivan for Old Harbour Bay, a community in southern Jamaica (Robinson and Khan 2011). Further work done by Robinson and Khan (2011) on the Negril, Annotto Bay, and Mammee Bay coastline in Jamaica demonstrated that for the period from 1971 to 2003 the coastline of Negril showed a 16-cm retreat compared to the 7-cm shoreline retreat proposed by IPCC (2007).

Risk can be seen as a combination of the hazard, the probability of a disaster, and the consequences, such as economic, human, and material losses. To minimize the cost and the consequences of flooding, governments worldwide have invested in technical flood prevention measures by building dikes, levees, and dams. However, these approaches have only showed limited success (Deckers et al. 2010; Gall et al. 2011), as many technical efforts to decrease risk are wiped out by the growing economic developments in these same areas, increasing the potential losses (Filatova 2014). Therefore, the focus has shifted from flood prevention and control to flood risk management, with a cross-sectorial integration of the flood issue in different sectors, like land use, spatial planning, and nature conservation (Hartmann and Driessen 2013). Informing the inhabitants of flood-prone areas and involving them in the assessment process as a stakeholder in order to reduce risk by influencing their individual behavior, is an important step in this risk analysis (Benson et al. 2016; Filatova 2014). In this new approach, the risk of material, human, and economic losses is calculated and high-risk areas are indicated. This can be done qualitatively, by means of weighted factors to determine a risk scale from low to high (Ortiz et al. 2016), or quantitatively, by multiplying the cost of a certain flood event with the probability of the occurrence of this event (Arrighi et al. 2016). Furthermore, the effect of future prevention measures can be tested using a cost–benefit analysis that calculates the risk before and after the implementation of the measure (Ballesteros-Cánovas et al. 2013). A number of

quantitative GIS (Geographic Information System)-based tools for flood risk assessment already exists, such as the HAZUS-MH Flood Model (FEMA 2009), the HIS-SSM model in the Netherlands (Kok et al. 2005), the LATIS model in Flanders, Belgium (Vanneuille et al. 2005), and the FLEMO model in Germany (Apel et al. 2009). All these models involve estimating damage and risk from flood events and showing a spatial distribution map of the estimated risk

Although floodplain mapping and inundation models have been done for the major river systems in Jamaica for the creation of floodplain maps with a return period of 100 years and Burgess et al. (2015) developed a macroscale flood risk model for Jamaica, based on 198 flood events occurring from 1678 to 2010, not much work has been done on detailed damage and risk assessments from flooding on a microscale level as well as on the creation of flood risk maps for the major watersheds or for other vulnerable coastal towns and communities. Nonetheless, Koks et al. (2015) indicate the importance of a detailed flood risk assessment, taking into account the specific characteristics of local communities and regions in the calculations, instead of using the same flood risk management measures for large areas. Since the climate and water characteristics are region bound, the flood risk governance and risk reduction measures should also be best assessed on city scale (Ward et al. 2013). Therefore, an adequate methodology to estimate location-specific damage and risk from flood events and to create depth damage maps needs to be developed for Jamaica, which can then be extended to the other SIDS of the Caribbean. This will aid local governments and planners in identifying areas prone to increasing flood risk in order to take necessary precautions to minimize material costs and the loss of lives due to future flooding events (Filatova 2014).

Disaster risk management requires adequate data collection, related to costs and damages with regard to events and locations (Deckers et al. 2010). This is significantly lacking for developing countries, such as Jamaica and other SIDS of the Caribbean, due to a lack of data related to location-specific costs and damages (ODPEM 2013). In other study areas, this limited data availability has led to the use of other types of input data for flood damage and risk assessment. For example, a rice crop damage map was generated for the Cambodian floodplain using remote sensing data, a DEM, and land use data (Kwak et al. 2015). Satellite imagery was also the input data for a flood risk assessment of the Kashmir Valley in India, performed by Kumar and Acharya (2016).

In this study, vector data, acquired by ODPEM (2013) for a flood risk assessment for Annotto Bay, was used as a base for the generation of a new quantitative damage map. Annotto Bay is a town with many informal settlements with little to no information available. Therefore, it was important to use a quantitative approach based on all elements at risk present in the study area (ODPEM 2013). Furthermore, by taking into account the cost of the elements at risk and not only the probability of a disaster, the risk is calculated more adequately (Filatova 2014). This new risk assessment methodology is based on the risk assessment tool LATIS, developed by Flanders Hydraulics Research in cooperation with the Department of Geography at Ghent University, Belgium. It creates a risk map which shows the economic risk, expressed in euro/m²/year, as well as a map which visualizes the human risk, expressed as people killed/year. These maps are generated by combining flood maps with different return periods, depth damage functions, land use, and land cover maps together with replacement values for all elements at risk, such as buildings, roads, crops and cars (Deckers et al. 2010). LATIS allows for the processing of changes in land use, for example new water defense structures, and predicts the consequences for the risk in the region. The tool has helped Flemish policy makers in choosing the most effective risk reducing approach and the areas to protect, showing a clear decrease

in the cost due to flooding in the assessed regions in Belgium (Deckers et al. 2010). Not only does the LATIS methodology and goal fit the aim of this study, but, since the tool was developed in cooperation with Ghent University, it was also possible to look into the internal processes and formulas of the tool, enabling the adaption of the methodology to fit the study area of Annotto Bay and testing the possibility to transfer a detailed and proven methodology for flood risk assessment to new areas with limited resources. Although the methodology in this study also includes the creation of a risk map, this step could not be executed in the present study, due to a lack of flood data. However, the other steps of the methodology were implemented and a damage map of one flood event in 2001 was created. This was the first of its kind being tested for Jamaica and can be extended to other test sites, as well as to other similar flood-prone communities in the Caribbean, showing occurrences of similar hydrometeorological events, as well as physiographic features.

2 Study area

The island of Jamaica, covering an area of 10,990 km², is located in the Atlantic hurricane belt which makes it vulnerable to hurricanes and tropical systems (storms and atmospheric depressions). Annotto Bay is a small coastal town located in the parish of St Mary, in the northeastern part of the island, made up of small shops, residential buildings and a few small factories. Since there is no well-known cultural heritage, the town does not accommodate tourists. Moreover, the town experiences economic challenges since the heavy decline of the sugar and particularly the banana industries. The elevations of the entire area (Annotto Bay and surrounding communities) range from 200 m above sea level in the interior to 20 m above sea level near the coast line, but the urban area of Annotto Bay lies lower than 3 m above sea level (ODPEM 2013). The coastal town is located on an alluvial fan drained by the Annotto River, Wagwater River, Mother Ford Drain, Pencar River, and the Crooked River as shown in Fig. 1; all these rivers, except for the Mother Ford Drain, originate in the highlands. The Mother Ford Drain is a stream which has been channelized with concrete sides and floor to allow drainage of water in the town. Majority of the buildings are wooden structures and lie in a linear strip bordering the coast and along

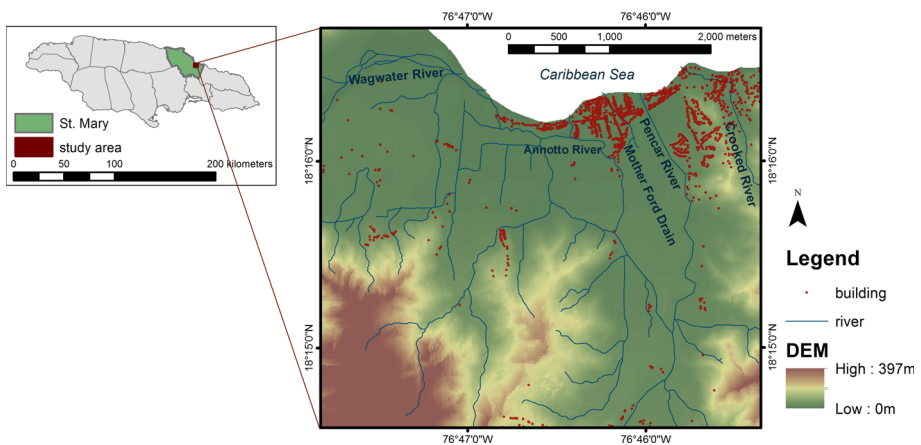


Fig. 1 Situation map of Annotto Bay, St. Mary, Jamaica, with the drainage network (Data source: WRA), DEM (Data source: NSDMD, resolution of 6,18 m), buildings and parishes (Data source: ODPEM)

the banks of Annotto River, Pencar River, and Mother Ford Drain. Vegetation ranges from shrubs to mixed cultivation.

Annotto Bay in Jamaica has been affected by both riverine and coastal floods from tropical storms, hurricanes and storm surges. Aside from this, the town of Annotto Bay also is home to many informal settlements, located in flood-prone areas due to the lack of adequate building regulations and drainage as well as the low building costs in these areas (ODPEM 2013). The Community Disaster Risk Management Plan for Annotto Bay, prepared by ODPEM between 2010 and 2012, reports that most of the communities are located in areas of high susceptibility to floods due to its high drainage density and location on the low lying alluvial fan. Floods and hurricanes rank highest in the list of hazards affecting the town and its surroundings, causing damage to the roads, drains and buildings (most of which are made of wood and thus susceptible to damage). Some of the major events which have affected the town and its surroundings were from hurricane Allen in 1980, which was recorded as “devastating” by ODPEM (2001). This was followed by coastal flooding and no passage of vehicular traffic for a week after the occurrence of hurricane Gilbert in 1988. Other significant ones are from hurricane Ivan in 2004, Emily in 2005, Dean in 2007, tropical storm Gustav in 2008, as well as heavy rainfall in late October 2001, which all resulted in loss of lives and destruction of socioeconomic goods.

Khan (2006) studied the hazard impact for Annotto Bay by using baseline data obtained by studying 40 years of coastline changes and a combination of aerial photographs, as well as GPS (Global Positioning System)-based field surveys. The study involved storm surge mapping for hurricane Ivan of 2004, as well as a flood assessment from hurricane Michelle of 2001. Further studies were conducted by the ODPEM with regard to preliminary flood damage assessment for Annotto Bay based on floods resulting from hurricanes and tropical systems. Although these studies identified the extent of the hazards, a detailed in depth damage assessment was still lacking for the study area (Glas et al. 2015).

3 Methodology and data

In the present study, both damage calculations for fresh and saltwater were carried out, since Annotto Bay suffers from riverine flooding as well as from storm surges. The damage calculations were executed separately due to the different characteristics of the hazards. The freshwater damage estimations were carried out by using data of riverine flooding caused by hurricane Michelle in the year 2001, while the saltwater calculations used a storm surge map with a return period of 100 years as input. ODPEM (2013) created this 100-year storm surge map which visualizes the impact of such a storm surge on the coastal town, by using an IKONOS 2001 satellite image, a DEM (6 m horizontal and 1 m vertical resolution), bathymetric data, historical storm tracks from NOAA, and wind-wave model JONSWAP. Both damage estimations were carried out for buildings, agriculture, a quarry present in the study area, and roads. The methodology is divided into two steps: (i) calculating the maximum damage based on replacement values, resulting in a maximum damage map, and (ii) calculating the estimated damage based on depth damage functions, through the combination of the flood map and the maximum damage map. Casualties are estimated through a similar method, by using population data coming from census of 2001 and a drown factor as input data. An overview of the data used is shown in Table 1.

Table 1 Overview of the data used in the methodology of the flood risk assessment

Data	Type	Source
Landuse	Polygon	By National Spatial Data Management Division (NSDMD) (2001) + update based on WorldView-2 satellite (2010)
Roads	Polyline	By ODPEM (2013)
Buildings	Point	By ODPEM (2013)
Population density	Polygon	By Statistical Institute of Jamaica (STATIN) (2011)
Average crops values	Table	By Food and Agriculture Organization of the United Nations FAOSTAT (2012)
Average building values	Table	By ODPEM (2013)
Strategic buildings	Point	By ODPEM (2013)
2001 flood extent	Polygon	By WRA (2001)
100-year storm surge map	Polygon	By ODPEM (2013)
Depth damage functions	Table	By Dutta et al. (2003)
Replacement values	Table	Table 2

3.1 Damage calculations

The LATIS tool has been successfully implemented in Flanders, the northern region of Belgium. It identifies the areas with high susceptibility to riverine flooding and calculates the expected annual damage cost. An example of a successful deployment was the basin of the river Dender in Flanders. There, LATIS was used to determine the location of possible water storage basins, with a damage degree from low to null, which led to a significant decrease in damage from flooding as well as a minimization of the related costs.

Table 1 outlines the input data for the flood risk tool for Annotto Bay. Aside from this, the LATIS tool also requires historical flood hazard maps, land use data, and data on costs of the damage (replacement values). However, the study area shows certain limitations as data for only one flood event, the one of 2001, was available, and the level of detail of the available land use data is lower than the level of detail needed by LATIS (Glas et al. 2015). Therefore, it was not possible to implement LATIS without modifications. As a result, a new tool was developed. The methodology of this tool is shown in Fig. 2. First, a maximum damage map is created, based on the available land use data and the replacement values. Then, an estimated damage map is created by combining the maximum damage map with the flood map, using damage factors. If there are multiple flood maps with different return periods available, a risk map can be created by combining the damage maps of each return period. The vulnerability map is created in a similar manner, using population data, a mortality factor and the flood map.

The replacement values, as mentioned in Fig. 2, represent the cost to replace an element at risk when it is completely destroyed. As there was no available detailed information, these values were collected through average values of buildings, roads, and crops for the case study of Annotto Bay. A maximum damage map was created by combining the replacement values, calculated from the average costs of the assets in the town, with the available land use data. Depth damage functions were then used in combination with the created maximum damage map and the flood extent map. A depth damage function represents the percentage of damage (damage factors) to a certain element at risk as a function

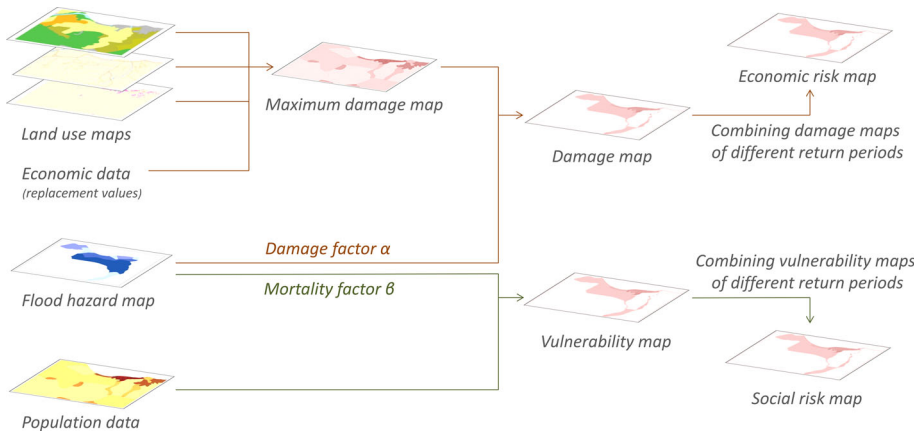


Fig. 2 Risk assessment methodology flowchart used in the study of Annotto Bay, Jamaica (based on Glas et al. 2014)

of the water depth. Depth damage functions are commonly used to estimate actual damages occurred during a flood event (Deckers et al. 2010).

Floods do not only cause material damage, but lead to casualties as well. The vulnerability map is developed through a method, similar to that employed for the damage map, which uses population data, building density and the flood map of 2001 as input data. This vulnerability methodology only calculates the possible loss of life and does not take into account the number of people affected by the flood (Glas et al. 2015). Therefore, a mortality factor, based on the water levels from the flood map, was used to determine the possibility of death in a vulnerability map.

Annotto Bay, as previously discussed, suffers from both riverine flooding and storm surges, resulting in damage from both fresh and saltwater, respectively. Figure 3 shows the extent of the 2001 flooding, as well as the flood extent for a 100-year storm surge, both of which were used in this study. Flood risk maps, however, should be created based on different return periods. As only limited data on rainfall for the past extreme events was available and a rainfall–runoff model to estimate the discharges for different probabilities of exceedances was lacking, the research was restricted to the 2001 event caused by hurricane Michelle and the 100-year storm surge map. The methodology to create the final risk map, however, was developed and is discussed here, although the map itself could not be generated due to insufficient flood data. Future research will focus on the creation of a rainfall–runoff model, making it possible to create flood hazard maps with different return periods as input for the last step in the methodology, computing the final flood risk map.

Although several cost and damage assessments have been done for the entire island, a damage assessment based on flood levels and replacement values was not yet developed. Hence, this research serves as a test case to extend this risk-based methodology to other areas of the island and helps in a better understanding of flood risk and its spatial extent, as well as the impact on infrastructures in Jamaica.

3.1.1 Maximum damage calculations

With regard to the damage map, only tangible damages, which have a monetary value and occur within the flood zone, were taken into account. Direct damages, as well as indirect,

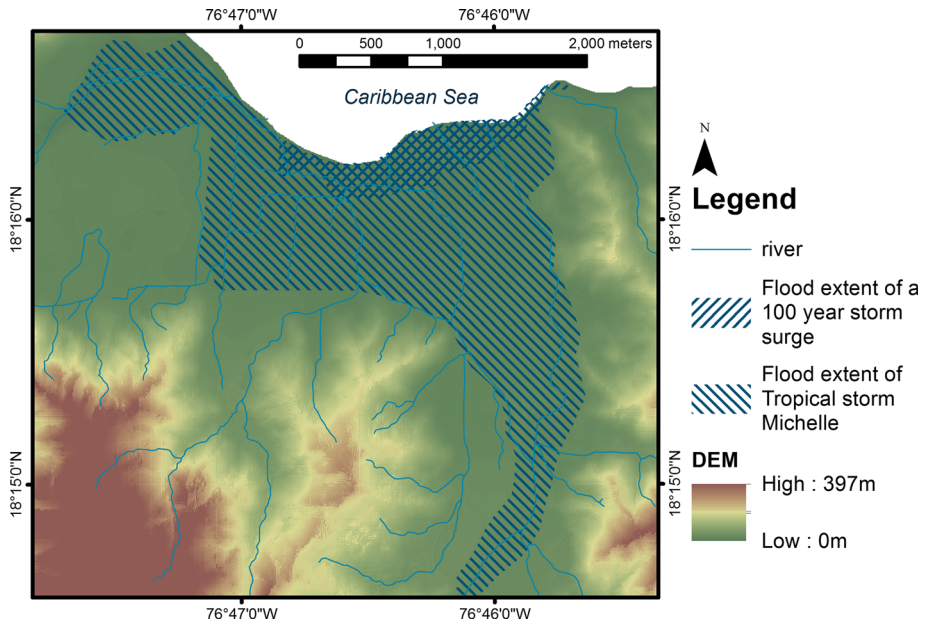


Fig. 3 Measured extent of the 2001 flood caused by tropical storm Michelle and flood extent caused by a 100 year storm surge for Annotto Bay (DEM source: NSDMD, resolution of 6,18 m)

such as production losses or clean-up costs, were determined (Deckers et al. 2010). Therefore, the first step of this research involved the calculation of the cost of the maximum damage that occurs when an element at risk is completely destroyed by a flood. This maximum damage cost was determined by linking the replacement values to the corresponding type of element at risk, for example, buildings, roads or crops.

The necessary information was derived from multiple sources, listed in Table 2. Although other land use elements, such as forests, beaches, wetlands, and water surfaces can be inundated as well, they are not considered to suffer any economic losses and are therefore left out of the calculations. Furthermore, Table 2 shows the used depth damage functions per element at risk.

The maximum damage values for fresh and saltwater for all elements at risk, except for buildings, are summarized in Table 3. The maximum damage to buildings was calculated per building separately, depending on the material used in the construction of the building and the number of floors. These characteristics were taken into account to determine average damage values for all types of buildings and to link a maximum damage to each building separately. Showing the point damages as such on a map could lead to a visual underestimation of the result. Therefore, the damage values of all buildings in one statistical sector, an area with the same characteristics as to building types, population, and building density, were averaged and multiplied with the building density of that polygon. No difference was made between residential and non-residential buildings. Strategic buildings, such as hospitals, schools, churches, and fire stations, were also taken into account in these calculations, but the damage to these buildings was calculated separately as they demand special attention since they could be used as emergency shelters after any natural disaster. Although the damage was calculated in the same manner for all buildings, a distinction was made between the buildings in the built-up area and those in the rural

Table 2 Sources of replacement values and depth damage functions per damage category

Element at risk	Source of replacement values	Source of depth damage function
Building structure	By ODPEM (2011)	By Dutta et al. (2003)
Building content	By ODPEM (2011)	By Dutta et al. (2003)
Field	By FAOSTAT (2012)	By Dutta et al. (2003)
Banana estate	By FAOSTAT (2012)	By Jonckheere (unpublished work)
Quarry	By Vanneuille et al. (2002); MTWJ (2008); sales websites	–
Other (forest, wetland, water, beach)	–	By Dutta et al. (2003) (ref. buildings)
Road	By Collier et al. (2013)	By Vanneuille et al. (2003c)
Critical building	By ODPEM (2011)	By Dutta et al. (2003) (ref. buildings)
Casualties	By ODPEM (2011); WRA (2011)	By Vanneuille et al. (2003b)

Table 3 Maximum damage values

Land use category	Maximum damage value freshwater (USD/m ²)	Maximum damage value saltwater (USD/m ²)
Field	0.5547	1.1093
Forest and field uninhabited	0.2773	0.5547
Forest and field inhabited	0.2773	0.5547
Banana plantain	0.1525	0.3049
Forest 'other' Land use	0.0000	0.0000
Wetland	0.0000	0.0000
Beach	0.0000	0.0000
Water	0.0000	0.0000
Road	36.0500	–
	Total maximum damage value freshwater (USD)	Total maximum damage value saltwater (USD)
Quarry	35,794.12	71,588.24

areas. In the former, the building damage is the only type of damage that was calculated with this methodology, while in the latter, crop damage was added to the building damage to create the total maximum damage for these areas. The maximum damage to buildings was divided into structural damage and content damage, where content damage is 50% of the structural damage (Cammerer et al. 2013; Davis and Skaggs 1992; Vanneuille et al. 2003a).

The most commonly cultivated crops in Jamaica are sugarcane, citrus, melon, bean, rice, sweet potato, and banana. Since there was no available parcel-level information for the different kinds of crops, an average crop value was generated for this study based on all possible crops. Yield (ton/ha) and annual producer prices (J\$/ton) were assembled from the Web site of Food and Agriculture Organisation of the United Nations Statistics Division (FAOSTAT) (2012). Fields where crops coexist with forest were assumed not to be completely used for agriculture. Therefore, the crop value was halved for the entire

polygon, resulting in an estimated 50–50 ratio between forest and fields for this polygon. The maximum damage value of banana plantations was calculated in the same manner as the other crops, with data derived from FAOSTAT (2012). However, since the land use data did not make a distinction between these banana plants and other crops and the plantations take up 22% of the total study area, banana plants were treated separately.

The value of the gravel quarry was defined by the number of vehicles present at the site, as the gravel itself does not suffer any damage. These vehicles were subdivided into heavy duty vehicles and personal vehicles (motor cars) to differentiate the values for each. The values of the heavy duty work vehicles were collected on different sales websites for Jamaica. Values of personal vehicles were calculated by using the same method as in LATIS (Vanneuville et al. 2002) meaning that their price change was calculated in function of their age, based on the history of 31 cars in Flanders and the car park in Jamaica (Richardson 2010). The eventual average value of all the vehicles in the quarry was determined by the average value of the heavy duty work vehicles (2/3 of the total value) and the average value of the personal vehicles (1/3 of the total value). This number was then multiplied by the vehicle density to generate the maximum damage value of the quarry, expressed in USD/m².

A last type of damage is the damage to road infrastructure. Only paved roads and bridges were taken into account in the calculations. The average value of a road unit in developing countries was estimated by Collier et al. (2013) at 216.30 USD/m. With an average road width of 6 m, this value was converted into 36.05 USD/m². Maximum damage values were calculated for four categories of paved roads and bridges, by using this average value.

3.1.2 Calculating estimated damage: depth damage functions

In the second step of the LATIS methodology, the maximum damage map is combined with the flood map to create a map of the estimated flood damage, corresponding to the 2001 flooding event. Often, flooding does not cause the complete destruction of a good. Hence, the actual damage cost is lower than the maximum damage cost upon total loss. Depth damage functions represent the relationship between the water depth and the damage factor, which is a percentage of maximum damage. This type of function is also called “stage damage curve” and it is different for each land use category (Deckers et al. 2010; Vanneuville et al. 2002). Other independent variables, such as flow velocity or rise velocity, the rate at which the water level rises, are also used in the LATIS methodology, but are not available for the study area. It is crucial to use adequate depth damage functions that are representative for the economic situation in Jamaica. Therefore, the depth damage functions that are used in LATIS for Flanders are not suitable for this study area.

As presented in Table 2, five different depth damage functions from three different sources were used: structure of buildings, content of buildings, crops, banana plants, and roads. The quarry is not taken into account because it is located well beyond the flood extent. Since most houses are somewhat elevated from ground level, the methodology adopts an average doorstep level of 0.5 m that the flood water has to overcome before a building will be inundated (Deckers et al. 2010; ODPEM 2013; Vanneuville et al. 2003b). Therefore, 0.5 m is deducted from the water depths for all buildings.

Estimated damage is expressed by the following expression (Deckers et al. 2010):

$$S_w = \sum \alpha_i \times S_{i, \max} \quad (1)$$

Table 4 Flood damage factors (%) for wooden and concrete structures and their content, based on Dutta et al. (2003)

Water depth (feet)	Water depth (m)	Wooden structures	Concrete structures	Content
0	0.00	0	0	0
1	0.30	0	0	0
2	0.61	6	6	2
3	0.91	12	12	10
4	1.22	20	20	19
5	1.52	23	26	25
6	1.83	30	30	32
7	2.13	36	36	39
8	2.44	40	40	43
9	2.74	43	43	45

Table 5 Flood damage factors for crops for a 2-day flood, based on Dutta et al. (2003)

Water depth (feet)	Water depth (m)	Beans	Chinese cabbage	Dry crops	Melon
0	0.00	23	40	20	22
1	0.30	30	58	30	30
2	0.61	30	58	30	30
3	0.91	40	66	43	39
		Paddy	Vegetable with root	Sweet potato	Green leave vegetables
0	0.00	20	34	11	20
1	0.30	24	43	26	24
2	0.61	24	43	26	24
3	0.91	38	74	40	44

where S_w estimated damage in a zone, $S_{i, \max}$ maximum damage in a land use class i , α_i coefficient (damage factor) expressing the relationship between water depth and damage for land use class i .

The depth damage functions, shown in Tables 4, 5 for building structure, building content, and crops originate from a Japanese model (Dutta et al. 2003). These functions were selected on the basis of considerations, and in particular, (i) the structure of buildings in Japan is more similar to that of Jamaican buildings than Flemish, as most Japanese and Jamaican buildings are constructed with solid concrete or wooden walls and no insulating material, in contrast with Flemish buildings, which are constructed with insulating material or with two leaf masonry cavity walls, (ii) there is a distinction between wooden and concrete buildings, a distinction that has also been made in the database for buildings in Annotto Bay, (iii) there is a detailed distinction between types of crops, similar to the ones that are cultivated in Jamaica, and (iv) damage factors are expressed in percentages instead of absolute values, as it is the case for many other studies; this is essential to implement the methodology of LATIS.

Since an average maximum building damage value was calculated per statistical sector, the two depth damage functions for wooden and concrete structures cannot be used

separately; therefore, an average value of the two functions was used. The value of the estimated damage to structures and content with the respective damage factors are defined as direct damage. In addition to direct damage, indirect damage, which involves for example clean-up costs, was also calculated for buildings. This is expressed as a percentage of the direct damage (Vanneuille et al. 2002), by using following equation:

$$\text{Indirect damage (\%)} = 1 + \left(1 - \frac{2 \times \alpha_{\text{stru}} + \alpha_{\text{con}}}{3} \right) \times (15 - 1) \quad (2)$$

where α_{stru} damage factor from structure and α_{con} damage factor from content.

The total estimated damage to buildings is the sum of direct damage and indirect damage.

The damage factors for crops, shown in Table 5, take into account both water depth and flood duration. In this case the flood lasted for 2 days (ODPEM 2013). Since the type of crops cultivated in Annotto Bay is unknown, an average damage factor was calculated from the crop damage values as described by Dutta et al. (2003). Indirect damage, which primarily involves production losses, was set at 10% of the direct damage (Vanneuille et al. 2002). These two values are summed up to obtain the total estimated damage for crops.

An adequate depth damage function for banana plants has not been found in the literature. Therefore, a new function, based on the characteristics of the banana plant, was drafted. These plants can only survive water saturation conditions up to 48 h because of the fragile roots (Rajamannan 2004). Consequently, the depth damage function is a linear function that reaches 100% damage after 48 h of inundation. The water depth was not taken into account as this parameter was not important. The indirect damage is 10% of the direct damage.

Most roads and bridges in Jamaica are not elevated. Consequently, they suffer considerable damage during a flood. The depth damage function for roads is the same as in LATIS because roads are constructed in the same manner in both regions and will thus suffer the same proportion of damage. The damage factor f for roads is expressed by the following function (Vanneuille et al. 2003c):

$$f = \min(0.28 \times d; 0.18 \times d + 0.1; 1) \quad (3)$$

where d represents the water depth in meters.

The total estimated damage is calculated by combining the maps representing the damage for each land use category separately. Furthermore, eight strategic buildings were taken into account in the calculations: three schools, the health center, the police station, the court, the fire station, and the hospital. To better support decision makers, the damage to these interest points was investigated. The replacement values for these strategic buildings (structure and content) were given by ODPEM (2013). By using the depth damage functions for buildings, the estimated damage to these strategic buildings was generated as point data.

3.2 Casualty calculations

The methodology used to calculate the number of people killed is very similar to the one used to calculate the damage. Small statistical sectors were drawn based on similar characteristics such as building density and land use; inhabitants were assumed to be spread homogeneously across the number of houses. In this way, the number of inhabitants

per sector was calculated on the basis of the number of houses per statistical sector (ODPEM 2011) and the number of people per household in 2001, which was an average of 3.4 for St. Mary (WRA 2011). This estimation was statistically tested and has proven to be significant with a significance level of 5%. The number of casualties is expressed by the following equation (Vrisou van Eyck et al. 1999):

$$N = fd \times A \times f_w \quad (4)$$

where A number of persons present, fd drown factor based on flood depth (%), f_w drown factor based on rise velocity (%).

Since there was no available rise velocity information for the flood event of 2001, this drown factor was set at 100%, which corresponds to a rise velocity higher than 3 m/h. This is the safest presumption, but could lead to an overestimation of the number of casualties.

The drown factor based on flood depth is expressed by the following equation:

$$fd = \exp(1.16 \times d - 7.3) \quad (5)$$

where d represents the water depth in meters (Vrisou van Eyck et al. 1999). This equation is transferred from LATIS since there are no differences in drowning characteristics between Jamaica and Flanders. People are assumed to be inside their homes during the flood. Therefore, the doorstep level of 0.5 m has to be overcome before the house is considered as inundated. (Deckers et al. 2010; ODPEM 2013; Vanneuville et al. 2003b).

3.3 Losses due to saltwater

The methods previously outlined have allowed for the calculation of the damages from freshwater only. However, Annotto Bay, like any other coastal town in Jamaica, is impacted by storm surges. Consequently, losses from saltwater need to be considered in the creation of damage maps. In most cases, damage due to saltwater will be even more extensive than damage due to freshwater. Therefore, other depth damage functions were drafted and new replacement values were determined. In these calculations, building and crop damage were taken into account, and a casualty map was drafted as well. The damage calculations were performed in the same way as for freshwater (Vanneuville et al. 2003a, d). The 100-year storm surge map, as outsourced from ODPEM, was used as input variable for the damage estimation from saltwater.

Saltwater causes corrosion to concrete structures, as well as cracks and discolorations both to wooden and concrete structures. Since there was no information on differences between the saltwater and freshwater damage values, a comparison was made by Vanneuville et al. (2003d) between damage values, originating from short- and long-duration floods (Penning-Rowell et al. 2003), which represent freshwater and saltwater, respectively. The results of this comparison proved that the depth damage function for the content of buildings is very similar both for fresh and saltwater. Depth damage functions for building structure, however, differ by up to 12 percent. Consequently, a new depth damage function for these structures was drafted. This was done by defining a ratio between the damage factors of freshwater and saltwater, as given by Penning-Rowell et al. (2003) and multiplying this ratio with the original damage factors of freshwater coming from this study (Vanneuville et al. 2003d). The saltwater damage was calculated by using this new function, the freshwater depth damage function for the building content and the saltwater flood map. Water depth values were again corrected for a doorstep level of 0.5 m and

indirect damage was recalculated. The damage to strategic buildings due to saltwater was recalculated with the new depth damage functions.

Damage to crops due to saltwater is more extensive than damage due to freshwater, because it takes time for salt to exit the soil. Salinity disturbs germination and growth processes and influences blooms, fruit development *et cetera* (Kozłowski 1997). Banana plants are also very sensitive to salinity and will suffer for many years after a flood event. Consequently, new maximum damage values were drafted for all crops, including banana plants. As flooding from saltwater will reduce harvest in the 2 corresponding years following the event, maximum damage values were doubled, as shown in Table 3 (Vanneuville et al. 2003a, d). The estimated damage was calculated by using the saltwater maximum damage values, the freshwater depth damage functions and the saltwater flood map. Indirect damage was also recalculated.

Storm surges will cause casualties too. These were calculated in the same manner as for freshwater, i.e., only with the saltwater flood map as input.

3.4 Risk calculations

For the case study of Annotto Bay, a damage map was created based on a flood map of 2001 and not on a flood hazard map with a certain return period. Therefore, a flood risk map could not be created in this study. In the future, however, a rainfall–runoff model will be created for the study area and flood hazard maps with return periods will be created. For each flood hazard map with a specific return period, a damage map will be created using the same methodology, visualized in Fig. 2. All damage maps will then be combined in order to generate one flood risk map, showing the risk of damage per year. The risk can be calculated by using the following equation (Deckers et al. 2010):

$$R = \sum_{i=1}^n \frac{1}{i} (D_i - D_{i-1}) \quad (6)$$

where R risk, D damages related to a flood with a return period of i years, n highest return period.

Since the creation and validation of flood hazard maps with return periods is time consuming, only a few will be created. Therefore, in practice, the flood damage between two return periods will be linearly interpolated in order to simplify the equation (Vanneuville et al. 2003b). This simplification will be done based on the choice of return periods after the creation of the rainfall–runoff model.

4 Results

4.1 Maximum damage map

The maximum damage map, as illustrated in Fig. 4, shows the maximum damage values for all elements at risk, based on their replacement values. The map shows a division between the maximum damage values in the built-up area and those of the maximum damage in rural areas, due to the big difference in total damage cost. Damage values for beaches and water surfaces are presumed to be zero. Although forests and wetlands are also presumed to have no damage, the relative values in these areas will not always be zero due to the presence of infrastructures.

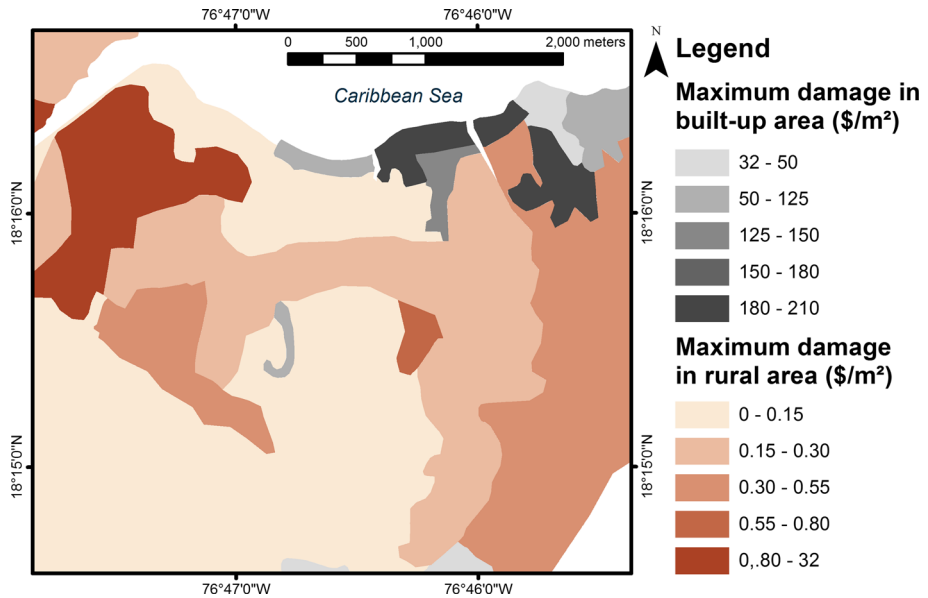


Fig. 4 Maximum damage map for Annotto Bay, Jamaica

Table 6 Overview of the maximum damage values for Annotto Bay

	Urban area	Rural area	Total
Total maximum damage (USD)	161,953,000	4,198,000	166,151,000
Total area (m ²)	1,249,000	13,480,000	14 729,000
Average maximum damage (USD/m ²)	125.59	2.91	11.28
Maximum damage (USD/m ²)	209.58	31.80	209.58

In Table 6, an overview of the calculated maximum damage values is given. Although the urban area is only a small part of the total area in this case study, the value of the elements located there, calculated per square meter, is on average 42 times higher than the maximum damage per square meter in the rural area. Floods with the same height will thus have a much larger effect on the damage cost in the built-up area than on the cost in rural regions. The total maximum damage value is calculated at USD 166 million, which would therefore be the cost to replace all elements in the study area after complete destruction.

4.2 Estimated damage maps

The results are presented in two maps that show the estimated flood damage due to freshwater and saltwater, as displayed in Fig. 5. In Table 7, the total damage cost and damaged area for fresh and saltwater are shown, as well as the average damage and maximum damage. For freshwater, the damages to all elements at risk were added up to one damage value per polygon. In the calculations of damage due to saltwater, roads were not considered. In both maps, damage in the built-up areas is considerably higher than that

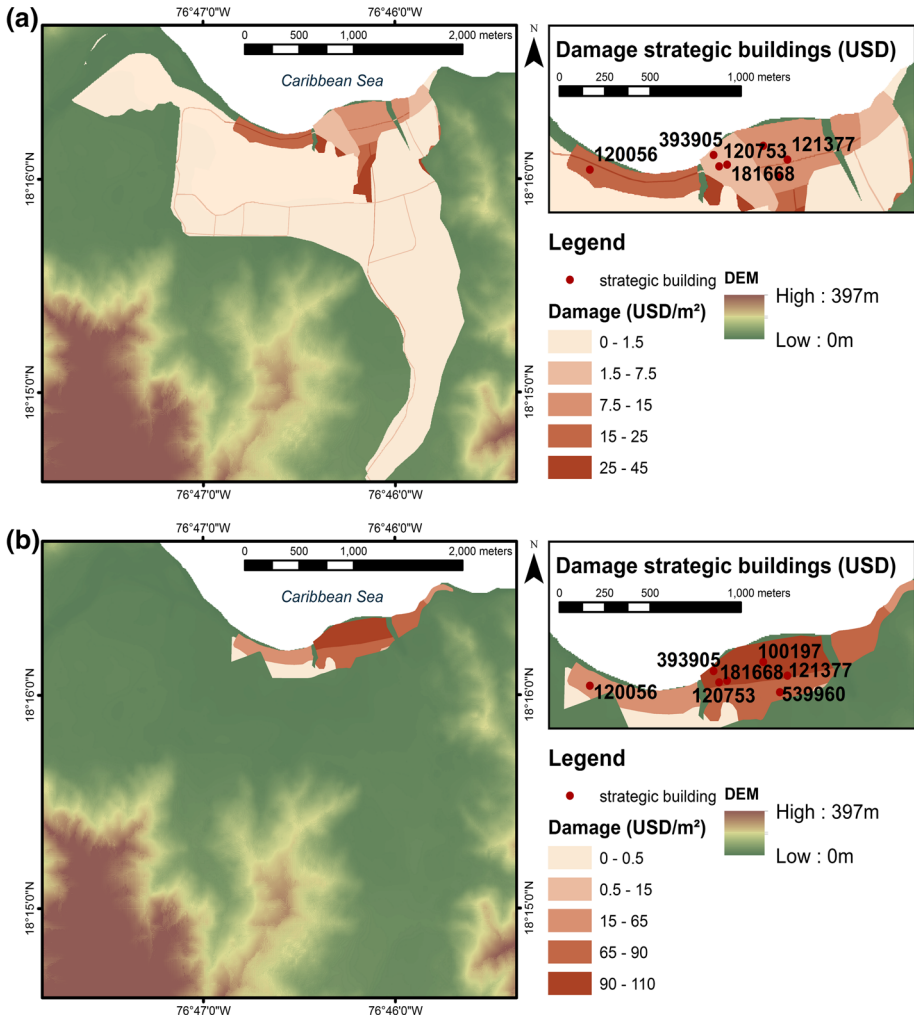


Fig. 5 Damage maps for Annotto Bay, Jamaica: fresh water (a), salt water (b) showing the total damage in $\$/m^2$ and the total damage for critical buildings in \$ (DEM source: NSDMD, resolution of 6,18 m)

Table 7 Overview of the estimated damage values for fresh and saltwater for Annotto Bay

	Freshwater	Saltwater
Total damage (USD)	7,007,000	29,766,000
Total damaged area (m ²)	3,040,000	438,000
Average damage (USD/m ²)	6.03	54.27
Maximum damage (USD/m ²)	42.01	105.12
Total damage strategic buildings (USD)	938,000	1,578,000

in the rural areas. Because of the low flow velocity of the water (<3 m/s) (ODPEM 2013), no elements at risk were completely destroyed. This is clearly visible when comparing Table 7, where the maximum damage is estimated at USD 42.01 for freshwater and USD

105.12 for saltwater, with Table 6, where the maximum damage for buildings was calculated at USD 209.58. The estimated damage for freshwater is four times lower than the value of complete destruction, while the estimated damage cost for saltwater is half of the maximum damage. The damage values caused by saltwater are considerably higher, four

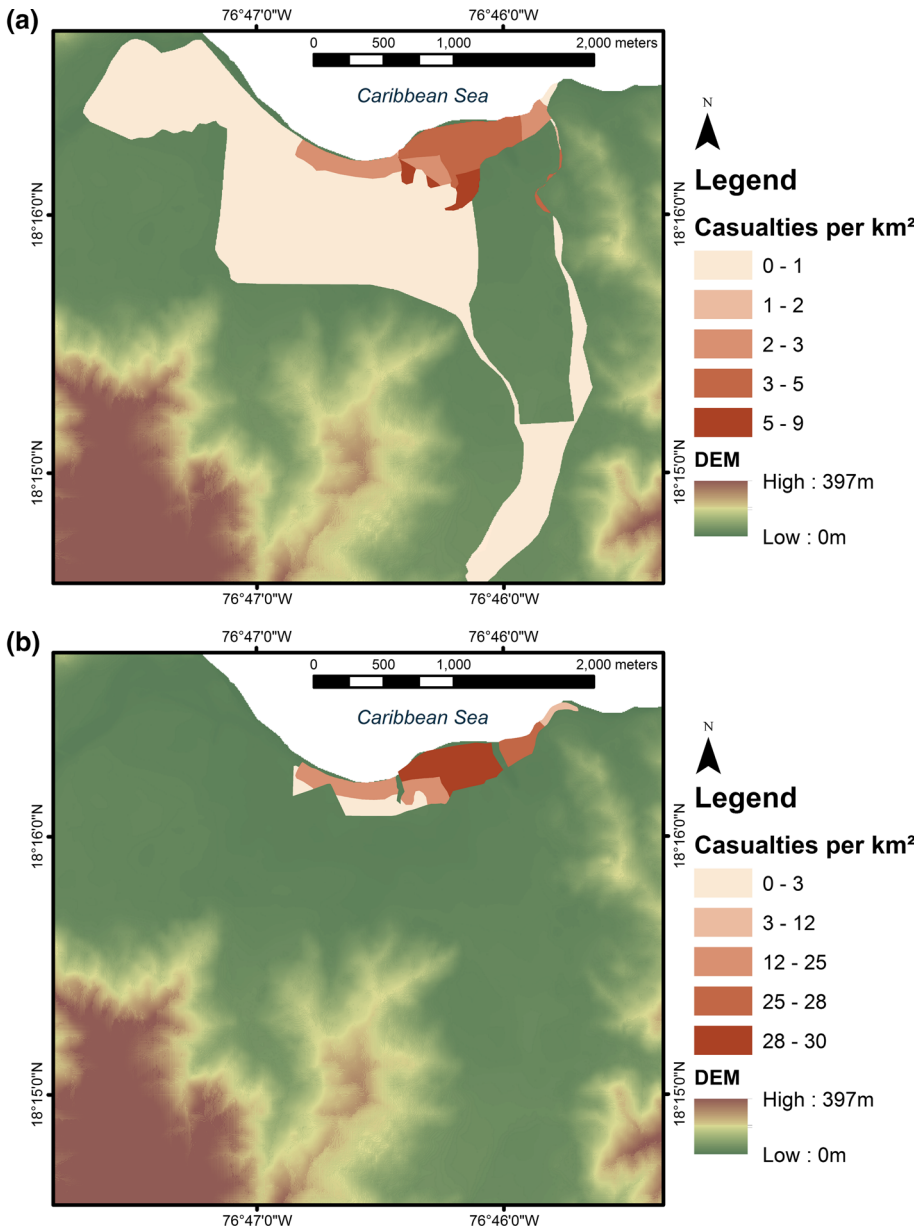


Fig. 6 Vulnerability maps for Annotto Bay, Jamaica: fresh water (a), salt water (b) (DEM source: NSDMD, resolution of 6,18 m)

times higher, than those caused by freshwater. The damage cost to strategic buildings is also clearly higher in case of saltwater flooding. The differences in damage costs can be explained by these adjustments to the saltwater damage:

- the maximum damage values for crops are doubled;
- the flood depth is twice as deep (2.3 m);
- the salt water depth damage functions for buildings consider a higher percentage of damage for a certain water depth than the fresh water depth damage functions.

4.3 Vulnerability maps

The numbers of casualties due to fresh and saltwater are presented in two maps and displayed in Fig. 6. The number is considerably higher in the built-up area, because of the higher population density in this area. In Table 8, an overview is given of the numbers estimated for fresh and saltwater. While the number of people killed during the freshwater flood is extremely low, almost zero, the total number of casualties due to saltwater is almost 100 times higher. This is explained by the deeper flood depth during a storm surge and the strong wind. Furthermore, Table 8 shows that the casualties, in the case of a storm surge, are more equally spread than in the case of a freshwater flood.

5 Discussion

Verifying and validating the results and the accuracy of the methodology is not a sinecure. There is not much information available on the exact damage costs caused by the 2001 floods. The only available source that describes the damage of the event is a report by ODPEM (2013). In this report, some general numbers for building, crop, and road damages caused by tropical storm Michelle are listed. These numbers are compared with the results of this study per damage type. Furthermore, similar calculations were made in this report for a storm surge with a return period of 100 years; these results can also be compared with this study.

Exact building damage values were not available for the historic flood. However, the ODPEM report concerning the 2001 flood states that 749 of the 1632 buildings, included in the report, were exposed to inundations at that time (ODPEM 2013). Since the borders of the study area in this study are not identical to the borders in the ODPEM report, the number of houses taken into account in this study is 1415, of which 792 were assessed as affected by the flood. This number of exposed buildings is slightly higher, due to the fact that rural buildings were also assessed in this study, as opposed to the ODPEM report

Table 8 Overview of the estimated number of casualties for fresh and saltwater for Annotto Bay

	Freshwater	Saltwater
Total number of casualties	1.74	150
Average number of casualties per km ²	0.03	21
Maximum number of casualties per km ²	0.34	30

where the buildings in rural areas were not taken into account, leading to an addition of 41 affected buildings. The number of affected buildings by a 100-year storm surge is calculated at 621 in the ODPEM report (ODPEM 2013), while in this study, 621 of the 1415 were assessed as exposed. Since none of the added rural buildings were flooded according to this study, the addition of these buildings did not impact the results.

In rural areas, there are only a few buildings per statistical sector. Since these point damages are averaged for the entire polygon, an underestimation of damage takes place near the real location of the buildings, while an overestimation of damage is made for the rest of the statistical sector, where only crops were damaged. The overall damage for the entire polygon, however, represents a good estimation.

In total, 74 ha cultivated land was inundated during tropical storm Michelle in 2001 (ODPEM 2013). The banana plantations were damaged the worst; in fact 11 ha of the total area were completely destroyed. In this study, through the methodology, a total area of banana plantations, affected by floods, was calculated to be equal to 162 ha and the area of other affected crops was equal to 86 ha. This apparent overestimation is due to the simplification of the depth damage function of banana plants and not taking into account the period of the year and the cultivation cycle. As bananas are harvested at the end of summer, after which the plants are cut at the soil line and new plants are planted again in spring, it is very likely that there were not much plants on the fields at the time of the flooding (Stover and Simmonds 1987). Furthermore, this study did not make a distinction between plants that were affected and plants that were destroyed. Wind was an additional factor that also caused a lot of damage to all crops (ODPEM 2013) and could not be taken into account in this study. Furthermore, due to the very small part of crop damage cost in the total damage value, it is impossible to assess the accuracy of the crop damage calculations in this urban study area.

According to the calculations, the flood of 2001 caused damage to the roads of USD 13.87 per square meter. Compared with maintenance costs (9.77 USD/m²) for roads in Latin America (World Bank 2006), this value is reasonable. Unfortunately, a closer comparison could not be made, since the real road damage, due to tropical storm Michelle, is not known.

The two damage maps are not combined because both natural hazards have different characteristics and do not always occur simultaneously. Hence, it is interesting for decision makers to study both types separately, as they require different approaches and mitigation measurements. In this study, the damage cost due to saltwater of USD 29 766 000 is four times as high as the damage cost due to freshwater of USD 7 007 000. This ratio hardly deviates from damage ratios in other studies (Penning-Rowsell et al. 2003) and can be explained mainly by the storm surge flood depth that is twice as high as the flood depth in 2001.

The coastal location of Annotto Bay and its vulnerability lead to a high flood risk. The squatted communities with informal houses raise the biggest concern, as these buildings occupy 35% of all those present in the town center (ODPEM 2013). Moreover, some are located at the watermark, as a consequence of the coastal erosion which is equal to 4 m in 7 years (ODPEM 2013). This study did not take the wave action into consideration for the 100-year storm surge, which causes some underestimation of damage in the area near the watermark. It can also be stated that the roads had a significant impact on the flood extent in 2001. The construction of the highway without drainage structures in 2000 hindered infiltration and has caused more severe floods (ODPEM 2013). Furthermore, as roads become impassable when flooded, possible evacuation is hindered (ODPEM 2013).

Casualties are expressed in human lives, not in monetary value. Hence, the result could not be added to the damage maps and a separate vulnerability map, showing the possible casualties, was generated. According to ODPEM (2013), 2740 of the 5422 inhabitants of Annotto Bay were exposed to the flood of 2001 and 2010 inhabitants would be exposed to the 100 year storm surge. In this study, this is 2693 and 2114, respectively, of the 4811 inhabitants that were taken into account. However, the vulnerability map shows only the possible casualties, which were calculated at only 1.7 people for the entire study area. This low number is still an overestimation, as in reality, no one died as a result of the event, and can be explained by the fact that people flee in case of flooding and relocate to nearby shelters to stay safe, while the methodology presumes that all inhabitants stay in their houses.

6 Conclusions

Several mitigation measures have already been taken in Annotto Bay, such as early warning systems, dikes, and drainage structures (ODPEM 2013). However, these measures would be more effective if they were based on an adequate risk assessment methodology, as presented in this study. The methodology assists decision makers in identifying the high-risk areas in need of mitigation measurements to reduce damage and decrease the flood risk of the region. Although the uncertainties in the input data and the assumptions made during the processing result in certain inadequacies in the resulting maps, the methodology has proven to give an accurate estimation of the value and location of the flood damage in the region.

However, further research can improve and expand the model. The cost of building damage in the ODPEM study, for example, is limited to the damage to strategic buildings (ODPEM 2013). In this study, this damage is complemented with the damage to all buildings, by using GPS input data, average replacement values and representative depth damage functions (Dutta et al. 2003). This has improved the accuracy of the damage estimations. The content-structure ratio, however, is an important value that is very ambiguous in the literature and should be investigated more thoroughly. The building damage calculations, as developed in this methodology, should be tested in other case study areas with more information on the damage cost of historic flood events, making a thorough validation of the model possible.

The building damage value is not the only information that needs to be further examined. The depth damage functions for buildings and crops need to be tested thoroughly for different Caribbean regions and adequate average replacement values need to be calculated. Saltwater damage to roads has to be quantified and depth damage functions of banana plants need to be drafted. Further steps in the research will include collecting more socioeconomic and land use data of categories which are not taken into account in the current model. If possible, rise velocity information could also be integrated in the existing model in order to test the last step of the methodology, the creation of the flood maps. Hydrological data in general will tremendously increase the accuracy of all steps of the risk assessment. Another option is the creation of a qualitative methodology to create a flood prediction map (Rahmati et al. 2015). This could enable the generation of a risk map without needing detailed hydrological or hydraulic data.

Future research will focus on other regions of the Caribbean. More rural areas will provide the opportunity to test the crop damage calculations while information on different

flood events will provide the option to re-evaluate the depth damage functions. The choice of study area should largely depend on the availability of historic flood data, making it possible to perform a full risk assessment and generating the final flood map. This will therefore allow for more detailed validation of the results.

This methodology provides the possibility of performing a risk assessment in data-sparse regions with a high vulnerability to flood hazards on microscale level, helping local communities in better allocation of their funds. Although this study is only a first step in creating, in the future, an accurate quantitative flood risk assessment for the entire Caribbean, the first results are promising. Informal settlements, located close to the shoreline or next to wetland, are indicated by the model to be prone to damage. This corresponds to the reality, where these buildings experience more damage of flooding and their inhabitants are more vulnerable. The results show that the cost of the damage caused by saltwater of storm surges is significantly higher than the cost of the damage caused by freshwater of river floods. This is due to wave action and water velocity and can be calculated more precisely with more data. Due to the coastal location of Annotto Bay and the presence of the Annotto River and the Pencar River, the town is highly vulnerable to flooding, and it can be concluded that this is correctly indicated in this study.

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