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Article

Flood Risk Management in Remote and Impoverished Areas—A Case Study of Onaville, Haiti

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Abstract: In this study, geographic information system (GIS)-based hydrologic and hydraulic modeling was used to perform a flood risk assessment for Onaville, which is a fairly new, rapidly growing informal settlement that is exposed to dangerous flash-flood events. Since records of historic floods did not exist for the study area, design storms with a variety of significant average return intervals (ARIs) were derived from intensity-duration-frequency (IDF) curves and transformed into design floods via rainfall-runoff modeling in hydrologic engineering center's hydrologic modeling system (HEC-HMS). The hydraulic modeling software hydrologic engineering center's river analysis system (HEC-RAS) was used to perform one-dimensional, unsteady-flow simulations of the design floods in the Ravine Lan Couline, which is the major drainage channel of the area. Topographic data comprised a 12 m spatial resolution TanDEM-X digital elevation model (DEM) and a 30 cm spatial resolution DEM created with mapping drones. The flow simulations revealed that large areas of the settlement are currently exposed to flood hazard. The results of the hydrologic and hydraulic modeling were incorporated into a flood hazard map which formed the basis for flood risk management. We present a grassroots approach for preventive flood risk management on a community level, which comprises the elaboration of a neighborhood contingency plan and a flood risk awareness campaign together with representatives of the local community of Onaville.

Keywords: DEM; TanDEM-X; HEC-HMS; HEC-RAS; mapping drone; hydrologic and hydraulic modeling; flood risk analysis; flood risk management; flash-flood

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1. Introduction

According to the World Disaster Report [1], seismic events killed the greatest number of people of all natural hazards in recent years, averaging 50,184 people per year from 2000 to 2008, whereas flood events affected the largest number of people, averaging 99 million people per year between 2000 and 2008. Haiti, currently rated as the poorest country in the Western hemisphere, is vulnerable to both of these natural hazards. In January 2010, a 7.0 magnitude earthquake struck Port-au-Prince, the capital of Haiti. It caused more than 300,000 deaths and left more than 1.5 million people homeless [2]. Only two years later, Hurricane Isaac crossed the southern peninsula of Haiti bringing flooding and storms to areas affected by the earthquake of 2010. As many as 5000 people were evacuated due to the flooding and 180 earthquake refugee camps were affected [3]. Due to the lack of disaster preparedness, the 2010 earthquake also led to an extensive resettlement process in which an estimated 500,000 people spontaneously left the capital and sought refuge in other provinces [4]. This process led to the formation of numerous informal settlements in previously uninhabited areas.

The area of Canaan north east of Port-au-Prince is a good example for this resettlement process. In order to address overcrowded refugee camps in acute risk of flooding in the capital, internally displaced people (IDP) camps were constructed in the previously uninhabited area of Canaan (Figure 1). Since then, Canaan has grown in an uncontrolled way and meanwhile, transformed into an increasingly urban settlement with likely more than 100,000 residents [5].

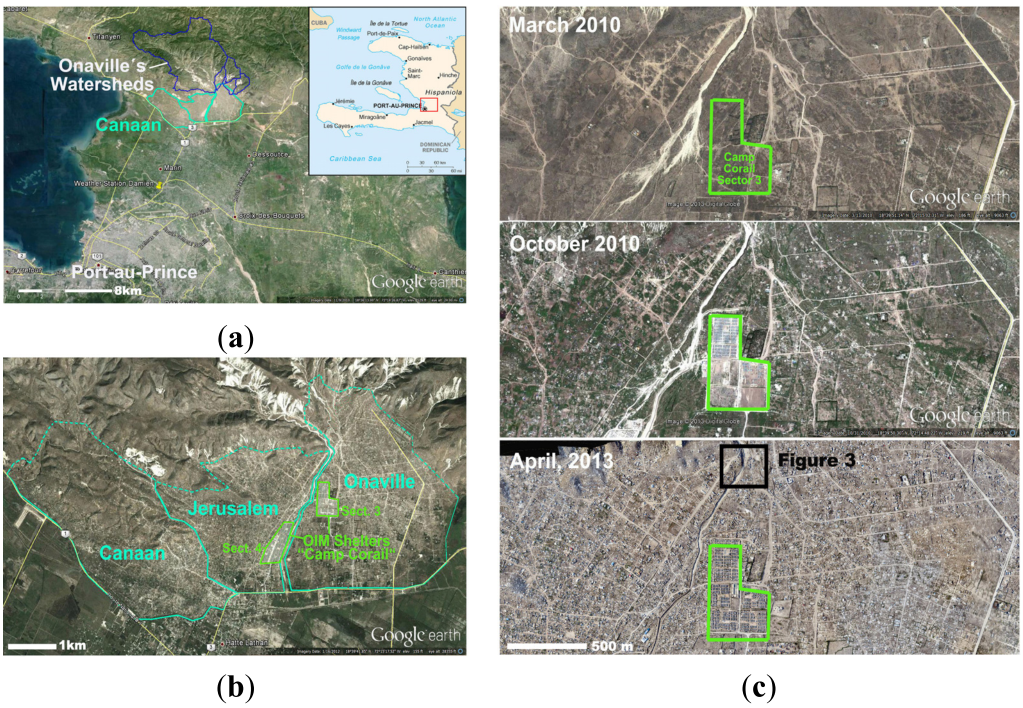


Figure 1. (**a**) Location of Canaan in Haiti; (**b**) Location of Camp Corail and Onaville in Canaan; (**c**) settlement process of Onaville between 2010 and 2013 [6].

The overall aim of this study was to perform a state-of-the-art flood risk analysis for Onaville by addressing the difficult socio-economic situation and the lack of readily available data through a variety of innovative approaches. The study was conducted in the frame of the Technical University of Munich (TUM) research project Urban Strategies for Onaville (TUM-USO) [7], in which researchers from different backgrounds as well as the non-governmental Organization (NGO) TECHO, currently active in Haiti, collaborate with local stakeholders in planning and implementing strategies for sustainable development of the settlement.

Previous studies indicate that parts of Onaville are currently at high risk of being affected by flooding [8,9]. The state-of-the-art to handle such natural hazards is to establish a defined procedure for handling risks like Flood Risk Management (Figure 2), which is the process of managing an existing flood risk situation which, beside the assessment and mitigation of flood risk, includes a continuous and holistic societal analysis [10]. The technical part for a functioning flood risk management and for preparing a decision basis is risk assessment, which comprises understanding, evaluating and interpreting the perceptions of risk and societal tolerances of risk [11]. Risk assessment for floods is based on hazard maps, which are part of the risk analysis process, a methodology to objectively determine risk by analyzing and combining probabilities and consequences [10].

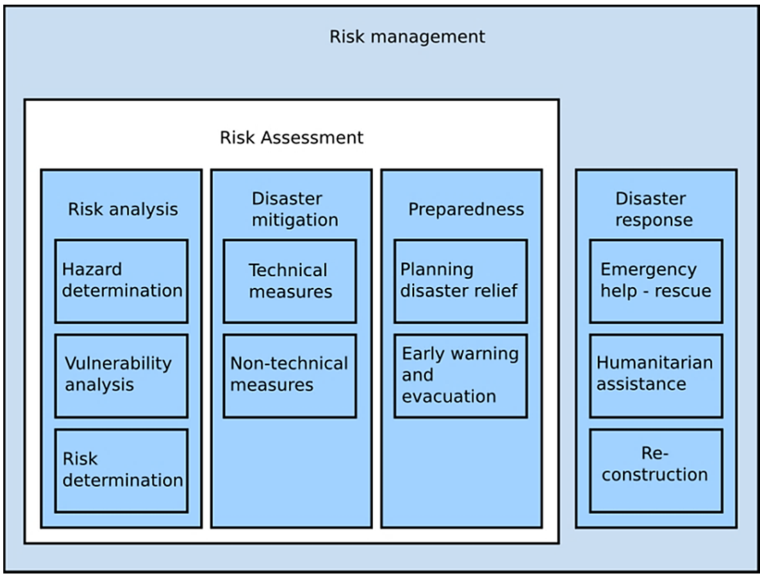


Figure 2. Elements of operational (flood) risk management, adapted from Plate [11].

In the case of remote and impoverished settlements, one of the main challenges is commonly the acquisition of sufficient regional, hydraulic, hydrological and meteorological data for the risk assessment. Additionally, it is crucial to assess the socio-economic situation of the study area in detail (Vulnerability analysis-risk determination) and to establish information channels to the residents of the settlement in order to communicate the risk situation and to improve disaster preparedness. Therefore, this study is focused on the materials and methods that are necessary to establish a functioning risk assessment for informal settlements located in remote, impoverished and data sparse areas like Onaville.

Based on the available data, a suitable modeling approach had to be found, which would allow performing the risk analysis while simultaneously serving as a flood risk management and planning tool. Since no records about the runoff characteristics of the rivers and watersheds that affect the Onaville settlement exist, rainfall-runoff modeling was used in combination with subsequent hydraulic modeling to estimate the flood hazard of Onaville and to create a flood hazard map as a basis for flood risk management. In such a coupled modeling approach, the annual exceedance probability (AEP) related to the magnitude of flood events is determined based on the AEP of the design storms used as the input to the rainfall-runoff model. The design storms were generated based on existing IDF curves, which are derived from several decades of rainfall measurements and thus represent the local long-term rainfall characteristics.

Based on the encountered flood hazard situation, a grassroots approach for improving risk awareness and disaster preparedness in the complex socio-economic setting of Onaville is presented that is expected to be applicable to other informal settlements with similar risk situations. The main challenge for implementing a functioning risk management for the study area was the poor socio-economic state of the unplanned settlement, its political status and the uncertainties related to future urban development.

2. Study Area and Data

2.1. Onaville and Canaan

Onaville is located about 15 km north-east of the Haitian capital and covers an area of approximately 7 km^2. Together with simultaneously developing informal settlements, it forms the rapidly urbanizing area commonly known as Canaan, situated in the transitional area between the Chaine-de-Matthieux mountain chain in the north and the Cul-de-Sac plain in the south (Figure 1).

Canaan is the result of a large resettlement process that was triggered by an expropriation decree that the Haitian government issued for this area in response to the 2010 earthquake. The decree was declared on 22 March 2010 along with the opening of the IDP camps Corail-Cesseless, which the international community had set up in the area. As interviews with local plot holders by the TUM research group revealed, these actions were widely understood as a land offer to the people. The location of Sector 3 and 4 of these IDP camps is outlined in Figure 1. Since the government and the so-called international community did not provide any further assistance to the area, Canaan has grown in a rapid and uncontrolled way ever since (see sequence of images in Figure 1). Public services such as water supply, sanitation and electricity are absent in most areas.

The area is currently expected to host 64,378 people (11,477 in Onaville; 31,156 in Canaan; 21,745 in Jerusalem) [5]. In comparison to that, Haitian government officials estimate about 300,000 people in the area [12]. The relative closeness of the area to the capital as well as the possibility of obtaining a piece of land informally can be seen as main drivers of this exceptional rise of a new city. A comprehensive overview of the geographic and socio-economic characteristics of Onaville and Canaan is given by Hannemann *et al.* [13].

All drainage courses (in Haiti commonly called “ravines”) in the area are ephemeral, meaning that they are usually dry all year, except after strong rain events. The alluvial cone on which Onaville is situated is the result of accumulated sediment that the ravines deposit in this transitional zone. Due to the steep hills and the availability of debris as a result of erosive processes in the watersheds, mountain torrents often collect and carry significant amounts of sediment during intensive rainfalls. After passing a transit section, the streams enter the deposit region where sedimentation increases drastically due to the reduction in slope and the resulting decrease in flow velocity. The watersheds of Ravine Lan Couline in Onaville (also known as Ravine Madan-El) show many of these characteristics with high levels of erosion as well as numerous debris bodies next to the river channels resulting from landslides. Due to the abundance of debris in the watersheds, flood runoffs in Onaville can thus be expected to have high solid concentrations and bed load transport.

The Ravine Lan Couline marks the border between Onaville and Jerusalem (see Figure 1) and poses the largest flood related risk to the surrounding settlements. Figure 3 gives an impression of the characteristics of the study area, the size of the watercourse (2) and the dense settlement on its overbank areas (1). The location of the section of the river channel that is shown on the second image is referenced in Figure 1.

(**a**)

(**b**)

Figure 3. Ravine Lan Couline flow channel from far (**a**) and close (**b**).

Shortly after the construction of Camp Corail, an artificial flow channel was constructed to guide flood runoffs in the Ravine Lan Couline safely through the lower part of the settlement, where flows originally used to spread out over the alluvial cone. Figure 4 shows a comparison of the area’s topography before and after the construction of the channel based on hillshades derived from a light detection and ranging (LIDAR) DEM (2010) and a Drone DEM (2013). The severe changes in the flow path and channel geometry of the ravine that came along with the construction of the artificial channel can be seen clearly.

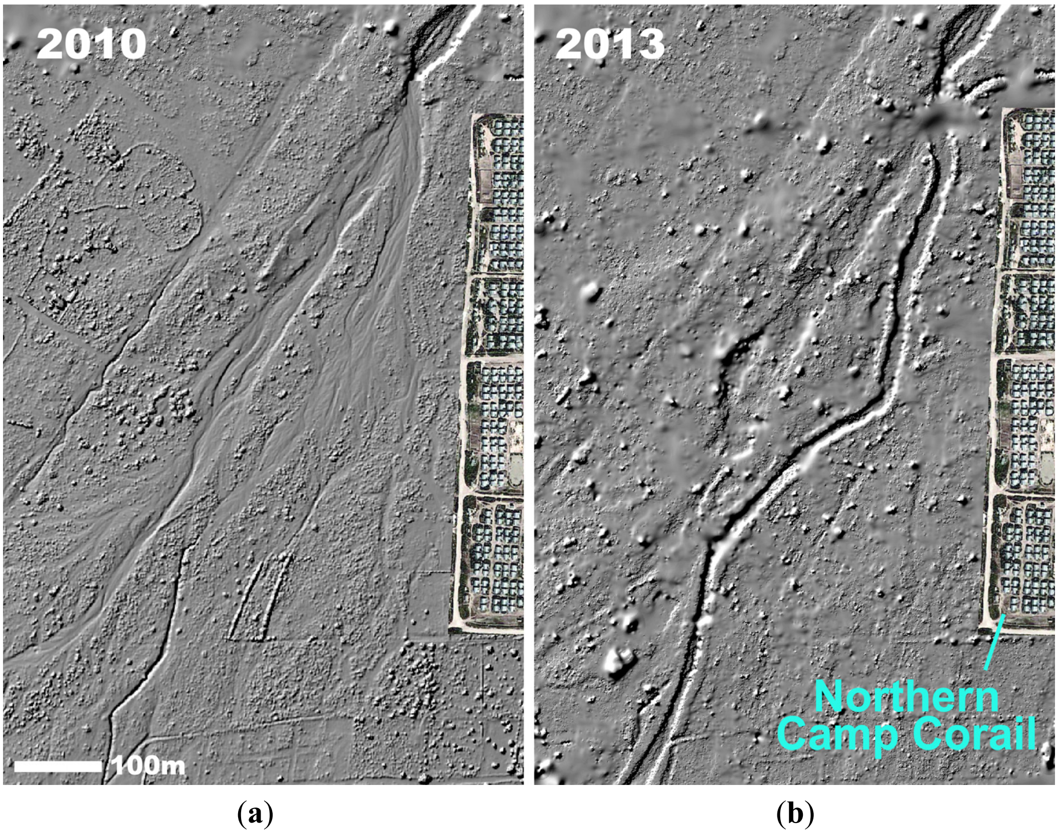


Figure 4. Comparison of the Ravine Lan Couline in the area of northern Camp Corail (Sector 3) before and after channel constructions based on the LIDAR DEM (**a**) and the Drone DEM (**b**).

2.2. Digital Elevation Models

Accurate terrain data in form of Digital Elevation Models is crucial input for both hydrological and hydraulic modeling. The topographic datasets that are available for the study area are a 12 m spatial resolution DEM provided by the TanDEM-X mission from the German Aerospace Center (DLR) (TanDEM-X DEM), a LIDAR DEM with 1 m spatial resolution initiated by the World Bank (LIDAR DEM) [14] and a mapping drone DEM with 30 cm resolution provided by Drone Adventures (Drone DEM). A comparison of the three available DEMs based on hillshades is given in Figure 5.

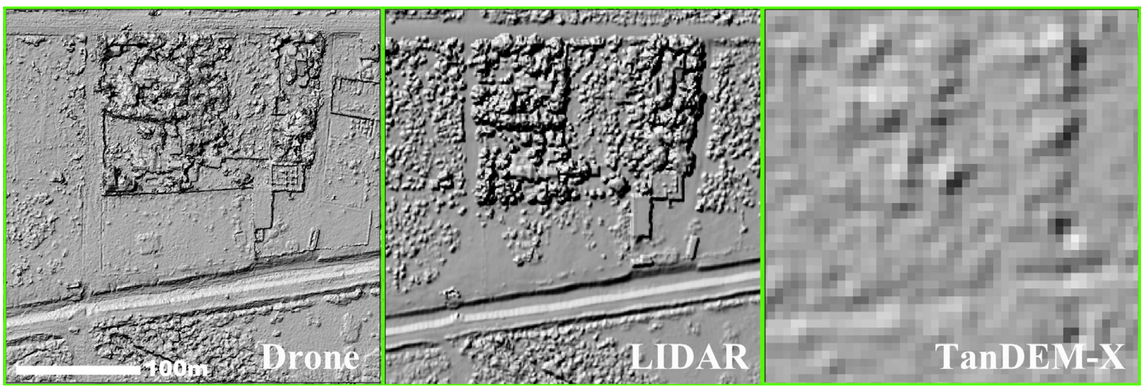


Figure 5. Comparison of available DEMs based on hillshades from an area south of Onaville, including Route Corail in the upper part and Boukanbrou Canal in the lower part.

The TanDEM-X DEM is an intermediate DEM provided by the DLR's TanDEM-X satellite mission. It is derived from the first coverage of Haiti taken on 26 June 2011. Compared to the final TanDEM-X DEM product, the intermediate DEM can be expected to have a lower vertical accuracy as well as phase unwrapping errors in mountainous regions [15]. Nevertheless, a rough analysis of the DEM together with the DLR's TanDEM-X ground segment showed that the DEM was suitable for the intended application [16].

The LIDAR DEM was initiated by the World Bank in response to the earthquake of 2010 in order to provide high resolution imagery and elevation data for the coordination of the disaster management. The Drone DEM provided for this study was created in 2013 by Drone Adventures, the Humanitarian OpenStreetMap Team (HOT) and the International Organization for Migration (IOM), using state-of-the-art fixed-wing mapping drones from the Swiss company senseFly. The DEM used in this study was provided by Drone Adventures and has a spatial resolution of 30 cm.

The steep and mountainous watersheds, which are imposing flood hazards for Onaville, are covered only by the TanDEM-X DEM, which was thus used to derive the hydrological structure of the catchments and to parameterize the rainfall-runoff model (Figure 6). The accuracy and resolution of this DEM was sufficient to derive the location of the flow channels and the boundaries of the sub-catchments in detail. For the hydraulic modeling of floods in the largest and most dangerous watercourse affecting Onaville, the Ravine Lan Couline (also known as Ravine Madan-Èl), the high-resolution Drone DEM was used in partial addition with the TanDEM-X DEM. This was done because of the limited extent of the Drone DEM in the upper part of the watercourse (see Figure 6). Nevertheless, the data availability for hydraulic modeling can be seen as sufficient since most parts of the flow channel, where overbank flow is to be expected within the settlement are covered by the high resolution DEM, which allowed the extraction of highly accurate channel cross sections. The methodology for the development of the hydraulic model structure based on these two DEMs is explained in detail in the hydraulic model application section.

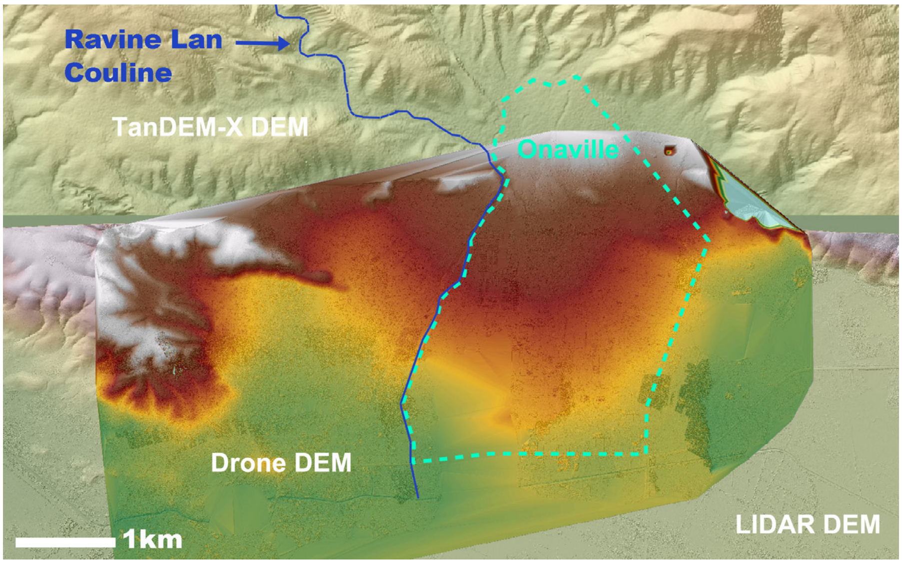
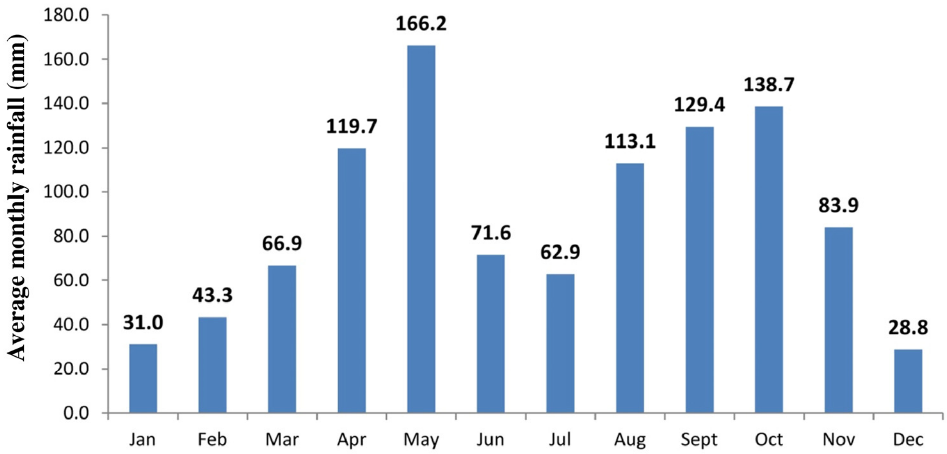


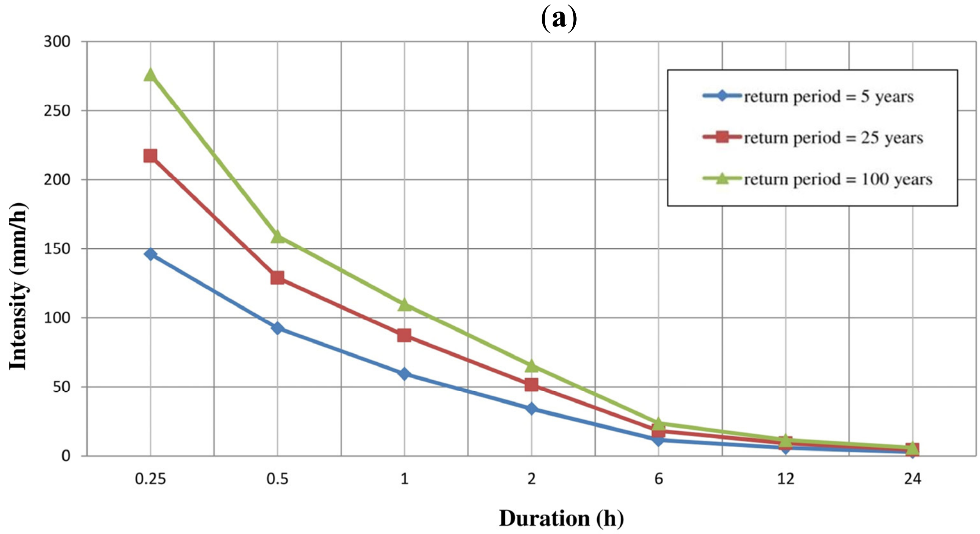
Figure 6. Spatial extent of the three DEMs used in this study.

2.3. Climate and Meteorological Data

Haiti has a tropical marine climate with two distinct rainy seasons occurring from March to May and from August to October. Average temperatures range from 25 to 28 °C. The closest weather station to the Canaan area is located at the Haitian Ministry of Agriculture, Natural Resources and Rural Development at Damien (18°35′44.49″ N; 72°17′21.07″ W), which is about 7 km south-east of Onaville. The average rainfall at Damien is based on 68 complete years of monthly rain data from 1927 to 2002 (Figure 7a). Due to its location in the center of the North Atlantic hurricane belt, Haiti is frequently exposed to strong tropical storms and hurricanes. The northern Atlantic hurricane season expands from 1 June to 30 November, September being the most active month [17].



(**a**)



(**b**)

Figure 7. (**a**) Average monthly rainfall at Damien based on 68 years of record between 1927 and 2002 and (**b**) IDF-curves for Damien station [18].

Since the goal of this study was to assess the impact of flood runoffs with specified ARIs, statistical rain data in the form of IDF curves (Figure 7b) from the Damien weather station were used in the modeling process instead of specific historical storm events. These curves are provided by the Analysis of Multiple Natural hazards in Haiti (NATHAT) report [9] and were originally created in 1980 by

SCET International for a Port-au-Prince drainage project [18]. The usage of IDF curves is common practice in flood risk assessment with the curves allowing the generation of design storms with a variety of relevant ARIs. Since the weather station is not located inside the study area, the generated design storms are not fully representative of the local rainfall characteristics so that the modeling results should be interpreted as estimations of the actual hazard situation.

2.4. Land Use and Soil Data

For the preparation of the rainfall-runoff model, the hydrologic and hydro-geological characteristics of the watersheds were analyzed in detail. A land use map [19] was provided by the Haitian National Center for Geospatial Information (CNIGS), in which the majority of the analyzed watershed is described as savanna. Savannas are defined as grass-covered areas of tropical or subtropical regions, which are nearly treeless in some places, but generally have a mix of widely spaced trees and bushes [20]. They also have distinct wet and dry seasons, which is in accordance with the local climate of the Onaville area. It is important to note that the currently existing vegetation is the result of a recovering process that started after the area had almost entirely been deforested in the past. According to the Food and Agriculture Organization of the United Nations (FAO)'s Global Forests Resource Assessment [21], the overall forest cover of Haiti is less than 4% compared to 30% in the Dominican Republic.

The geologic and hydrogeological maps of Haiti [19,22] gave rough information about the homogeneous fissured Limestone subsoil but were found to be insufficient for estimating the infiltration characteristics as a basis for the soil parameterization in the hydrological model. Thus, a field analysis of the top-soil, which is described in Section 3.2, was conducted at two representative locations in the watershed.

3. Materials and Methods

3.1. Modeling Framework

Due to the limited data availability, hydrological (HEC-HMS) and hydraulic (HEC-RAS) modeling was applied in combination with a detailed analysis of the local hydro-geomorphology for the flood risk assessment (Figure 8). ArcMap was used for the management and manipulation of all spatial data. Together with the software extensions HEC-GeoHMS and HEC-GeoRAS, it was used for the preparation of the model input files and the visualization of the modeling results. These software extensions provide a powerful and interactive tool for preparing model input files and calculating the majority of model parameters from the available spatial datasets.

After this data preprocessing design, storms derived from the IDF-curves were used as model input for HEC-HMS which was set up for the watershed of the Ravine Lan Couline to generate flood hydrographs with different ARIs. These hydrographs were used as inflow boundaries for the Ravine Lan Couline HEC-RAS model at the northern edge of the settlements of Onaville to simulate the water levels with different ARIs along the river channel thereby forming the basis for a flood hazard zoning.

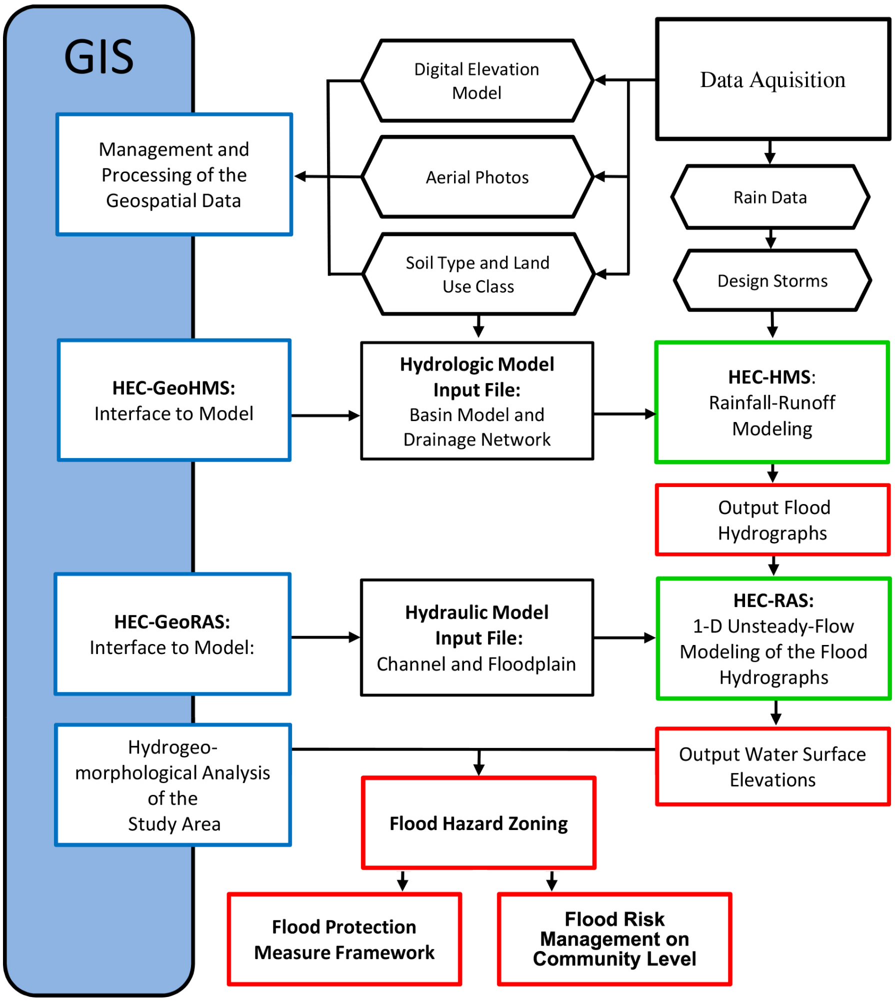


Figure 8. Flowchart of the GIS-based hydrologic and hydraulic modeling framework and flood risk assessment.

3.2. Hydrologic Modeling

The hydrologic modeling software HEC-HMS was used for modeling the rainfall-runoff process based on subsequent application of a suitable loss, transform and routing method. The analyzed rivers and watersheds are not gauged and due to their location in a remote and impoverished area, complex field surveys for a detailed estimation of hydrological parameters were not possible. Based on this background and the guidelines for model selection provided by the Hydrologic Engineering Center [23], the empirical Natural Resources Conservation Service (NRCS) Curve Number (CN) loss method, the empirical NRCS Unit Hydrograph transform method [24] and the Muskingum-Cunge routing method [25] were selected. The latter is quasi conceptual, since it is based on simplified equations of shallow water flow. Since baseflow does not occur in the analyzed watercourses, it was neglected in the modeling process.

The chosen models represent a suitable way to simulate the rainfall-runoff process in the study area, since they are designed to model single storm events rather than continuous precipitation data [23], and can be calibrated under limited availability of detailed hydrological data. Using the HEC-HMS software environment, they were applied to transform single design storm events with different AEPs into flood hydrographs, for which the AEP is then assumed to be equal to the AEP of the design storms.

3.2.1. Generation of the Basin Model

The main input data for rainfall-runoff modeling were the TanDEM-X DEM, the IDF curves from the Damien rain gauging station, a land-use map and the results of the soil analyses. The watersheds were derived by applying the HEC-GeoHMS software functionality within the ArcMap GIS environment. The first major step in creating the basin model was to delineate the stream network and watershed boundaries of the area of interest by applying a number of subsequent processing steps to the input DEM commonly referred to as terrain preprocessing. In this process, the definition of streams is based on a threshold number of cells that drain into a given cell, which was set to 20,000 cells or 0.74 km^2, respectively. This threshold was chosen because then, the resulting streams begin where the beginning of clear flow channels is observable on aerial imagery. After the completion of the terrain preprocessing, project points were placed on the drainage lines to define the outlet of the watersheds to be modeled. For the Ravine Lan Couline, the resulting watershed had a total area of 25.8 km^2 (see watershed (WS) 1 in Figure 9) and originally consisted of 17 subbasins. In order to avoid very small subbasins and to equalize the size of the remaining subbasins, basins smaller than 0.3 km^2 were merged together with the up- or downstream basin. This resulted in a total of 13 subbasins with a minimum area of 0.3 km^2. Besides the watershed of Ravine Lan Couline, rainfall-runoff modelling was performed for four more relatively small watersheds (0.8 to 1.8 km^2) that are draining through the settlement (see WS 2, 3, 4 and 5 in Figure 9).

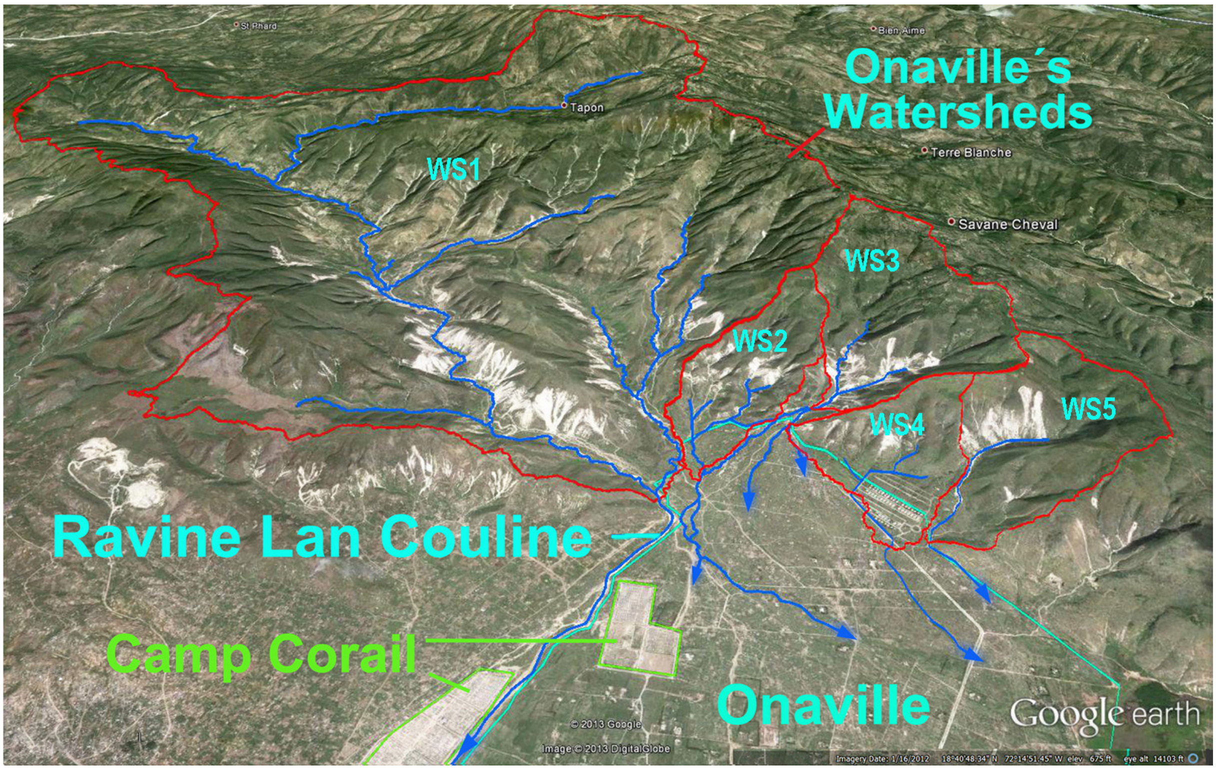


Figure 9. 3D view of the watersheds and drainage courses of Onaville including the watershed of Ravine Lan Couline [6].

3.2.2. Curve Number Loss Method

Based on the land-use classification and the semi-arid climatic characteristics of the area, the CN table for arid and semi-arid rangelands [26] was used for the determination of the CN. The cover type was defined on the basis of comparing major plants as listed in the CN table to observed vegetation cover on site. The definition of desert shrub in the CN table was found to most accurately describe the vegetation cover as observed on site (Figure 10a).

For the definition of the Hydrologic Soil Group (HSG), an on-site analysis of the top-soil was performed. Due to the uncertain security situation in the area of investigation and limited transportation possibilities, the field survey was limited to two sample points in the catchment area. These analyses were mainly based on the "estimation of the soil texture by feel" [27]. This method allows for a rough classification of the soil texture and type and is thus sufficient for the estimation of the HSG.

Excavations of the top soil layers revealed a large percentage of medium sized gravels surrounded by the actual soil at both sample points (Figure 10b). The sample included many small pebbles, but it was still plastic enough to form a ribbon with a length of almost 2 cm. Therefore, the texture of the soil was defined to be between sandy loam and loam. Since it shows a consistent soil matrix with loamy characteristics surrounding the gravel, the soil was assumed to have moderate infiltration rates. The available land use and hydro-geomorphology maps indicate that the area covered by the relevant watersheds has uniform soil and hydrologic characteristics. Because of that, the lack of more detailed soil data and the result of the soil analyses from both sample points, HSG B was assumed to be valid for all analyzed watersheds.

(**a**) (**b**)

Figure 10. Vegetation cover (**a**) and soil texture (**b**) at one sample point.

3.2.3. NRCS Unit Hydrograph Method

The NRCS Unit Hydrograph method was used to transform the excess precipitation into a flow hydrograph at the outlet of each subbasin. The main input parameter for this method is the basin lag time of each subbasin, which is defined as the time between the center of mass of excess precipitation and the peak of the hydrograph. In this method, the basin lag is approximated to be 0.6 times that of concentration. The time of concentration was determined based on the methodology described in the NRCS Technical Release 55 (TR-55) [26], which is integrated into the HEC-GeoHMS software environment. The TR-55 includes a table for the estimation of the surface roughness for sheet flow. The coefficient ranges from 0.011 for smooth surfaces, such as concrete, to 0.8 for forests with dense underbrush. Field observations revealed that the vegetation cover up to a height of 0.03 m, was best comparable to short grass prairie, as stated in the TR-55 table. Therefore, the coefficient was defined as 0.15.

Based on a table for the determination of roughness coefficients for mountain streams [25], the main flow channel was assigned a Manning coefficient of 0.045. Since channel observations further upstream into the watershed were not conducted, the value of 0.045 was assigned to all flow channels in the analyzed watershed. The resulting basin model shown in Figure 11 consists of 13 subbasins, eight junctions, seven reaches and the main outlet and includes all previously defined basin, reach and model parameters. Table 1 gives an overview of hydrological key parameters of the 13 subbasins. Subbasins W190, W250, W290 and W340 together contain the longest flow path of the watershed indicated by the grey marked columns in the table.

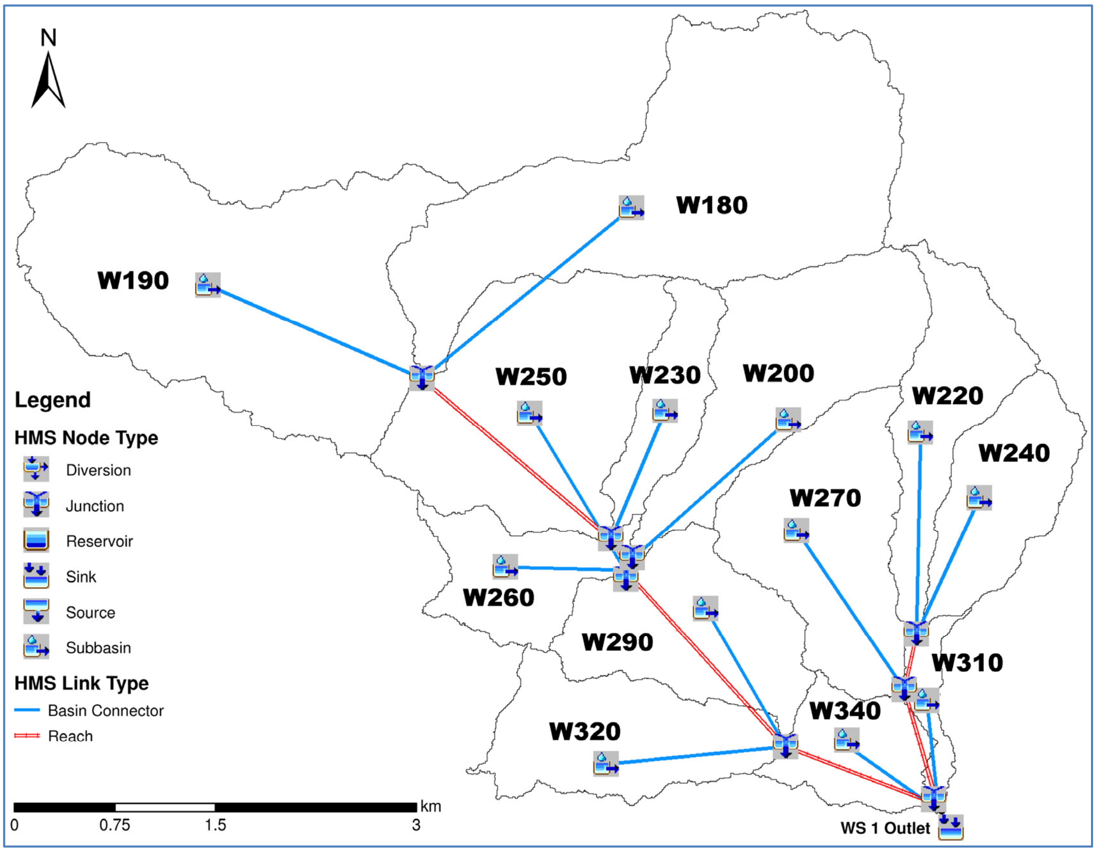


Figure 11. Model representation of the Ravine Lan Couline watershed in HEC-HMS.

The design storms for different statistical return periods were derived from the IDF curves using the frequency storm method as implemented in HEC-HMS. HEC-HMS uses the alternating block method [25] to compute design hyetographs with ARIs of five, 25 and 100 years that were used as input for rainfall-runoff modeling (Figure 12).

Table 1. Overview of subbasin features.

Subbasin	W180	W190	W200	W220	W230	W240	W250	W260	W270	W290	W310	W320	W340	Total
Area (km^2)	5.0	4.7	2.2	1.4	0.8	1.3	3.0	1.0	2.1	1.7	0.3	1.6	0.8	25.8
Average basin slope (%)	61	39	60	62	58	59	51	48	46	49	29	34	34	48
Longest flowpath (m)	6509	4975	4003	3855	2619	2746	3681	2284	3619	3365	2054	3543	2336	14357
Average slope of longest flowpath (%)	10.6	5.7	18.5	19.9	20.4	25.5	10.5	14.7	13.4	8.6	8.4	7.2	9.9	8.3
Time of concentration (min)	37	48	21	22	19	16	25	21	32	26	18	36	22	121

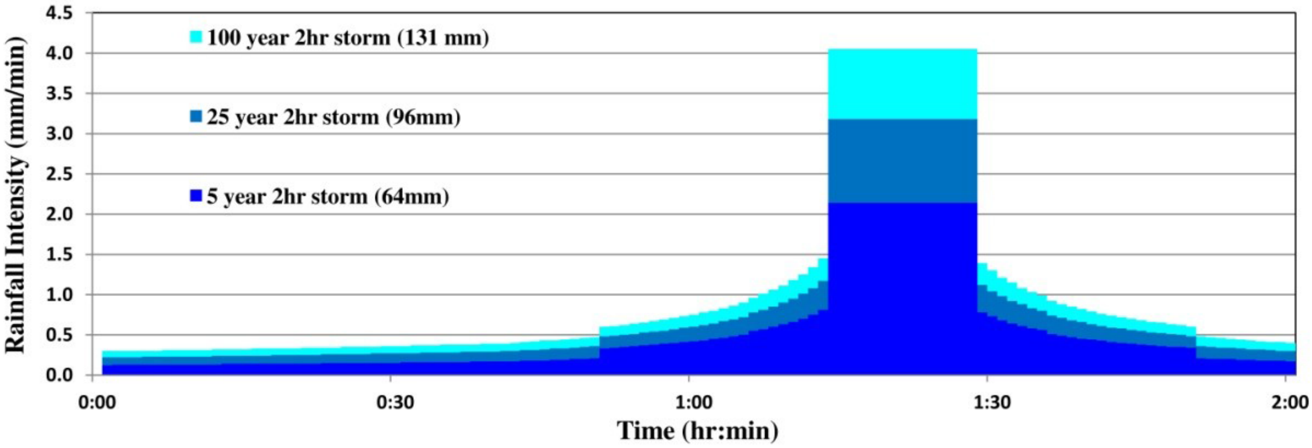


Figure 12. Design storms used as input for rainfall-runoff modeling.

3.3. Hydraulic Modeling

Hydraulic modelling was primarily used to define the locations of the Ravine Lan Couline channel in the settlement, where bank overtopping can be expected to occur first after a certain threshold flood discharge is exceeded. Due to the topography of the channel and the alluvial cone, it was assumed that the location of the cross sections where bank overtopping begins during the modeling of a flood wave, roughly defines the "bottleneck" fraction of the channel. From this point on, only the threshold discharge of the bottleneck is conveyed further downstream in the channel whereas the rest of the discharge is leaving the channel and spreads out laterally on the alluvial cone. For the analysis of the threshold flow carrying capacity, the definition of levees on both sides of the flow channel was found to be crucial for the flow simulations. As shown in Figure 13, levee points limit the flow to the main channel until the calculated water surface level in the channel exceeds the elevation of any of the two levee points on each side of the channel. Thus, the model can be expected to produce realistic flow simulations as long as the modeled discharge does not exceed the flow carrying capacity of the main channel. Nevertheless, the basic assumptions for 1d flow routing are violated as soon as the water level exceeds the levee elevation. Figure 13 shows an exemplary cross section from the Ravine Lan Couline channel along with the water surface and energy line just before and after levee overtopping occurs during an unsteady flow simulation.

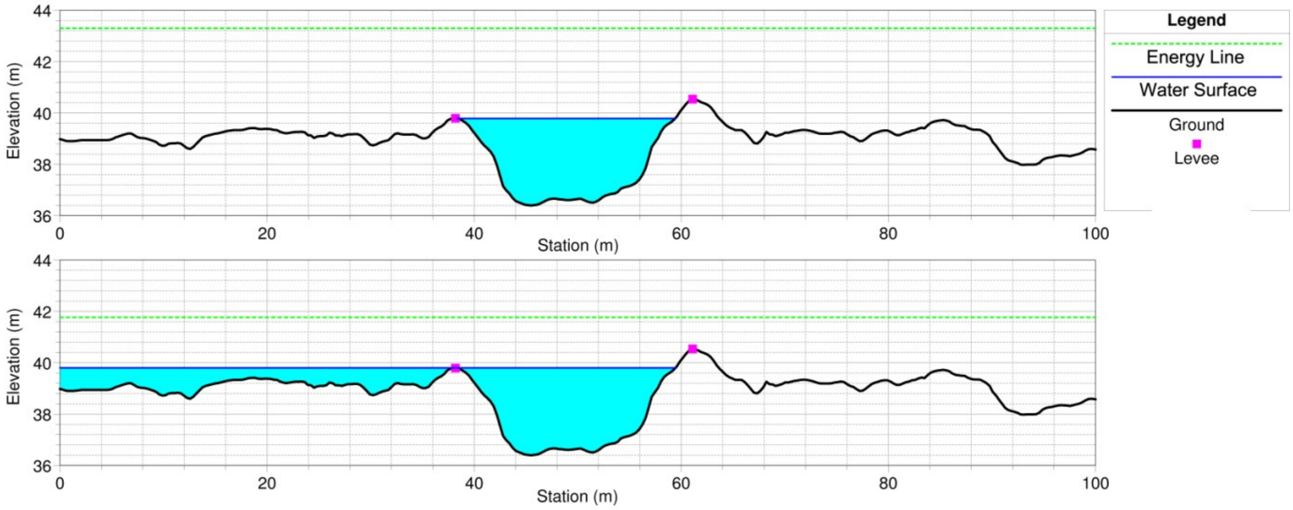


Figure 13. Water surface elevation and energy head before and after levee overtopping.

Once levee overtopping begins, the active flow area increases drastically due to the low elevation of the overbank areas behind the levees. Since the model only calculates a single horizontal water surface for each cross section, the water surface extends until the end of the cross section, where a vertical wall is assumed that defines the border of the model area. This sudden drastic increase in active flow area leads to an abrupt decrease in flow velocity observable as a drop in the elevation of the energy line (Figure 13). Furthermore, the entire flow is conveyed to the next downstream cross section which potentially could have enough flow carrying capacity to convey the entire flow in the main channel resulting in another jump in the energy line. Besides the resulting unrealistic velocity and flow pattern along the direction of flow in the ravine, another key problem is that the active flow area for overbank flow increases with increasing length of the defined cross sections. While the extent of the cross sections is predefined for larger streams with a classical channel and floodplain geometry, the definition was found to be rather arbitrary for the given situation. To address this problem, the extent of all cross sections was chosen as 100 m, which limited their extent to the main channel, its levees and a small and constant stripe of its left and right overbank areas. In the flow computations, each cross section is assumed to be representative for the reach geometry half way to the next up- and downstream cross section. The average bank full depth of the Ravine Lan Couline was estimated to be 4.5 m, which, together with an average invert slope of 0.03 (m/m), impedes that cross sections should be placed no more than 22.5 m apart from neighboring cross sections [28]. Based on these conditions, the cross section configuration shown in Figure 14 was defined for the extraction of the channel geometry for hydraulic modelling. It consisted of 374 cross sections that were placed at regularly spaced intervals along a 3150 m long section of the Ravine Lan Couline. The river stations (red numbers in Figure 14) are used to locate cross sections along the channel and are defined as the distance to the downstream end of the modeled reach in meters.

The creation of the model geometry based on two different DEMs (TanDEM-X and Drone DEM) was done in HEC-GeoRAS. The two DEMs were first referenced vertically by adding a constant value to each elevation value so that both DEMs had similar elevations in the area of the overlap. Based on a manually defined border between the two overlapping DEMs, HEC-GeoRAS automatically extracts the topography of cross sections depending on their location in respect to the border. Due to the insufficient spatial resolution of the TanDEM-X DEM, as well as the presence of inaccuracies resulting from interpolation in small areas of the Drone DEM, some of the cross sections of the geometric model had to be adjusted manually in order to accurately represent the geometry of the channel. In the same way as the parameterization of the flood routing method in the rainfall-runoff model, the main channel and overbanks were assigned a roughness coefficient of 0.045.

The flood hydrographs resulting from hydrologic modeling were used as the upstream boundary condition. In order to avoid instability issues in the flow computations, a base flow of approximately 10% of the peak flow of the flood wave was applied before and after the flood wave. Since the flood hydrograph at the downstream end of the modeled reach was unknown, the normal depth (approximated as the local channel bed slope) was used as the downstream boundary condition. This approach involves a high level of uncertainty so that the last cross section was placed far enough downstream from the area of main interest within the settlement (Figure 14).

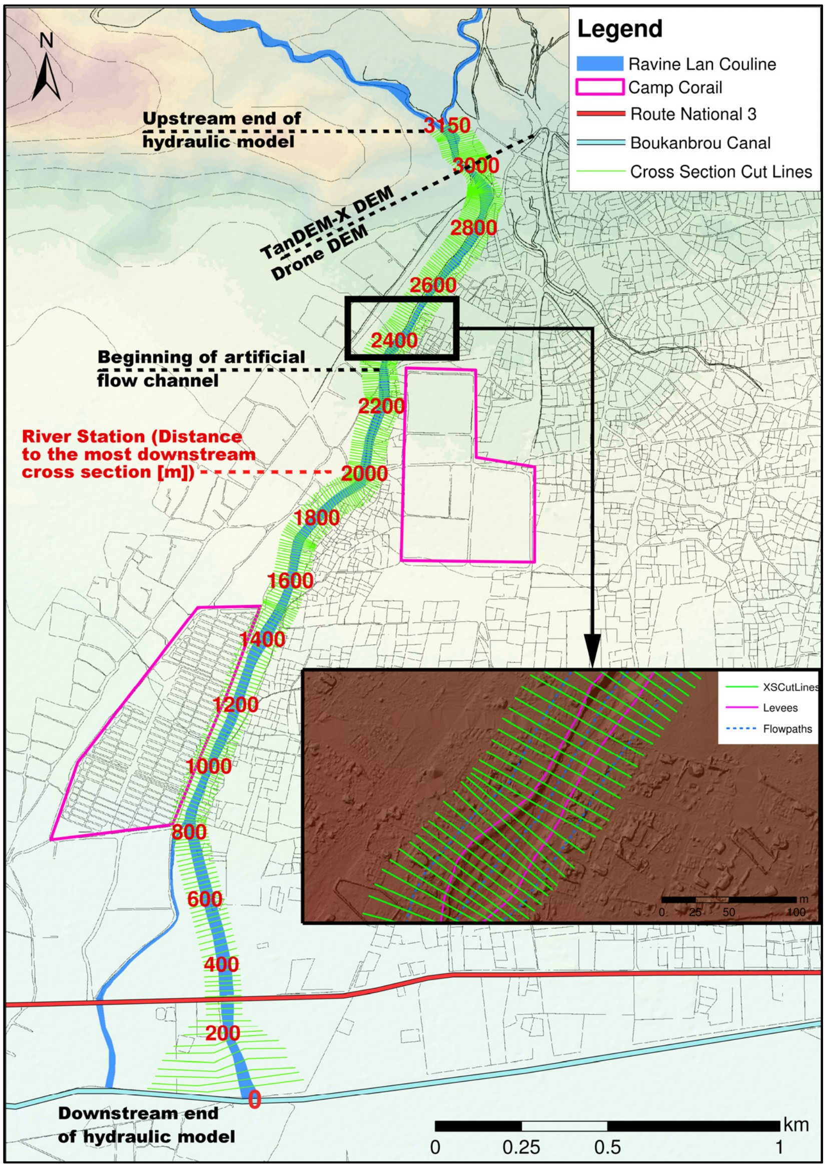


Figure 14. Geometric model configuration and development in HEC-GeoRAS.

4. Results and Discussion

4.1. Hydrologic Modeling Results

Figure 15 shows the design floods resulting from rainfall-runoff modeling of the design storms. It can be seen that a design storm with an ARI of two years only leads to a peak discharge of 2 m^3/s in the Ravine Lan Couline whereas a storm with an ARI of five years already leads to a peak discharge of 112 m^3/s. This is in accordance with the fact that no significant discharges have been seen in the ravine since the beginning of urban development in the area in 2010 (Interviews with local residents by members of TUM-USO). Even though this observation could not be verified due to the lack of historic data, it strengthens the prediction of the model that the Ravine Lan Couline watershed only produces runoff in response to larger precipitation events. Furthermore, it is seen that exceptional storms with short durations and very high intensities can be expected to produce large peak runoffs of up to more than 400 m^3/s (ARI = 100 years) and more than 300 m^3/s (ARI = 50 years). Considering the relatively small size of the analyzed watershed (25.8 km^2), discharges of more than 400 m^3/s seem very high at first. The shape of the hydrographs, however, is typical for flash flood events as the result of short and intense rainfalls in mountainous watersheds. The high rainfall intensities that the study area experiences in combination with the short time of concentration of the analyzed watershed leads to the steep and short rising limb of the flood hydrographs as well as a short overall duration of the flood.

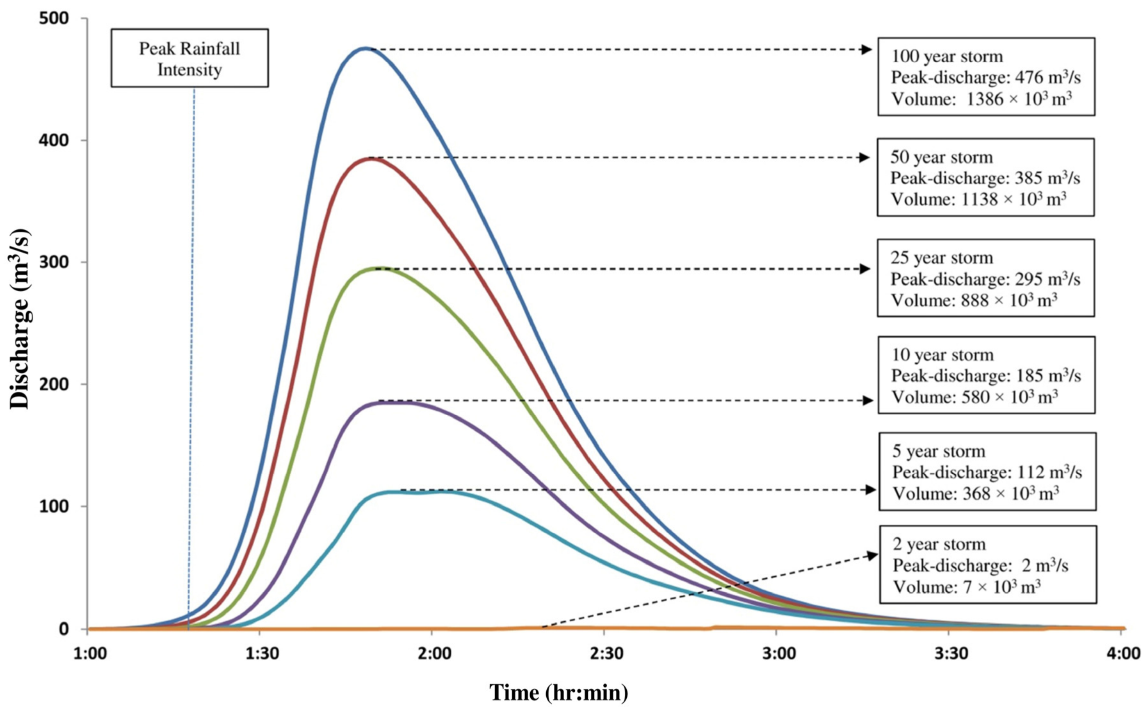


Figure 15. Flood hydrographs with ARIs of two to 100 years (Ravine Lan Couline).

4.2. Hydraulic Modeling Results

Based on the hydrographs resulting from rainfall-runoff modeling (Figure 15), unsteady flow simulations were performed for ARIs of five, 25 and 100 years. Figure 16 illustrates the hydraulic modeling results in form of a three-dimensional view of the maximum water surface resulting from a 25 year ARI design flood, which was chosen as this is the lowest ARI where levee overtopping occurs. Additionally, the modeling results for ARIs of five, 25 and 100 years are shown in the form of cross-section views for two locations along the channel (river station 2258 and 1972). The river station is used to locate cross sections along the modeled reach and is defined as the distance to the downstream end of the modelled reach in meters. An overview of the entire reach that was modelled along with the river stations was given in Figure 14.

The artificial flow channel constructed along with Camp Corail roughly begins at river station 2350. The maximum water surface resulting from the peak discharge of the five year ARI flood runoff shows that the bottleneck fraction of the channel is roughly located between river station 1800 and 2000. In this area, levee overtopping occurs first during the rise of the flood wave. The cross section at river station 2285 (Figure 16) is representative for the beginning section of the artificial flow channel. The stability of the levees in this section is questionable, since they are entirely constructed from unconsolidated material excavated from the channel invert and clearly deviate from state-of-the-art levee design standards [29]. It is therefore expected that the levee cannot resist the 25 and 100 year ARI flood runoffs so that lateral outflow is likely to occur in this area at the right overbank in downstream direction. It is further estimated that the levees in this area are capable of resisting the five year ARI flood runoff because in this case the maximum water level is in the area of the foot of the levee (Figure 16). The cross section at river station 1972 represents the beginning of the bottleneck fraction of the channel. It can be observed that the peak discharge during the five year ARI flood almost fills up the main channel so that larger discharges are likely to cause lateral outflow in this section. The cross sections located downstream represent the channel in the area of the northern extent of southern Camp Corail. It is obvious that the flow carrying capacity of the channel is significantly larger here than at the bottleneck section, since the 25 year ARI flood peak discharge is conveyed within the main channel.

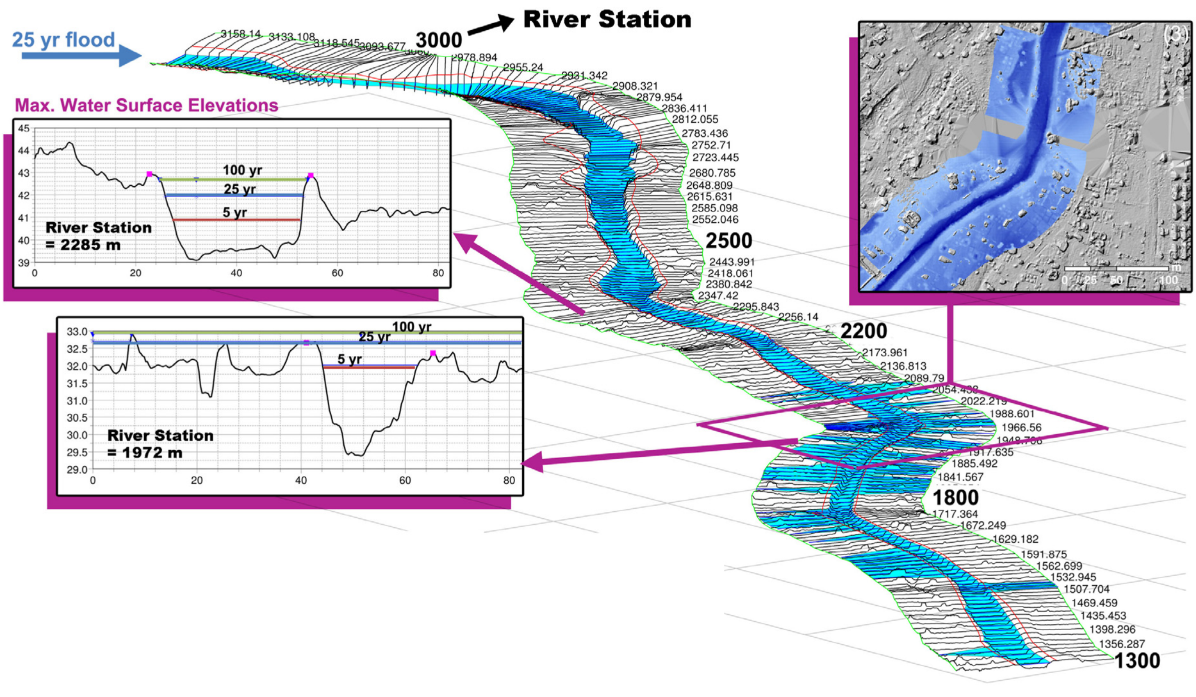


Figure 16. Maximum water surface for a 25 year ARI flood in 3D view and for a five, 25 and 100 year ARI flood for two channel cross sections (river station 2285 and 1972).

4.3. Flood Hazard Zoning

In order to provide a practical overview of the outcome of the hydrologic and hydraulic modeling as a basis for the flood risk assessment, the results were incorporated into a flood hazard zoning (Figure 17). It is important to note that a hazard zoning in comparison to a flood risk zoning does not account for the potential economic and social damages resulting from flooding. The hazard map is intended to provide an easy to understand overview of the flood hazard situation in Onaville. Following the basic structure of European flood hazard maps, the zoning outlines areas based on the ARI of flood events. The zoning can further be separated into areas potentially affected by large flood runoffs or torrential debris flows in Ravine Lan Couline and areas affected by smaller scale, torrential debris flows generated in the other four watersheds in the north of Onaville (see WS 2–5 in Figure 11). For the latter, hydraulic modeling was not performed as part of this study, since the Drone DEM did not provide sufficient coverage for the network of channels through which these smaller watersheds are draining.

To realize a more understandable zoning especially for non-professionals, the flood discharges with ARIs of five, 25 and 100 years in this study were defined as frequent, rare and exceptional hazard. In case of the Ravine Lan Couline, areas of all of these discharges were outlined. For the rest of the settlement, hazard zones were only categorized into frequent and exceptional hazards. Since hydraulic modeling was limited to locating hydraulic deficiencies of the Ravine Lan Couline channel and did not provide information about the propagation of the flood wave on the alluvial cone, a hydro-geomorphologic analysis of the area was used for the completion of the hazard zoning. Such a combined approach is common practice for the development of flood hazard maps, and was based on the following datasets:

- The digital elevation models presented in Chapter 2
- Historical aerial imagery in Google Earth
- On-site photographs

The main steps in generating the hazard zonation were as follows. Before the construction of the artificial flow channel, the propagation of floods over the alluvial cone was easily traceable on historic aerial imagery and the DEMs. The hydraulic modeling showed clearly, where overbank flow and levee breaching is to be expected first during large flood events. Floods in a five year ARI range can be conveyed safely by Ravine Lan Couline through the entire settlement. Floods in a 25 year ARI range exceed the flow carrying capacity of the artificial flow channel at the bottleneck section and are expected to lead to levee breaching right at the beginning of the artificial channel (see cross section at river station 2285 in Figure 16). Therefore, the zone of rare hazard essentially represents the propagation of floods before the construction of the artificial flow channel along two distinct and relatively wide longitudinal depressions in the alluvial cone in the area of southern Camp Corail. Since a levee breach will lead to a large increase of the flow area and a resulting decrease in flow velocity, bed load deposits are expected in the area of the breach as indicated in the map. The zone of exceptional hazard was created by gradually extending the rare zone towards more elevated areas using the DEMs.

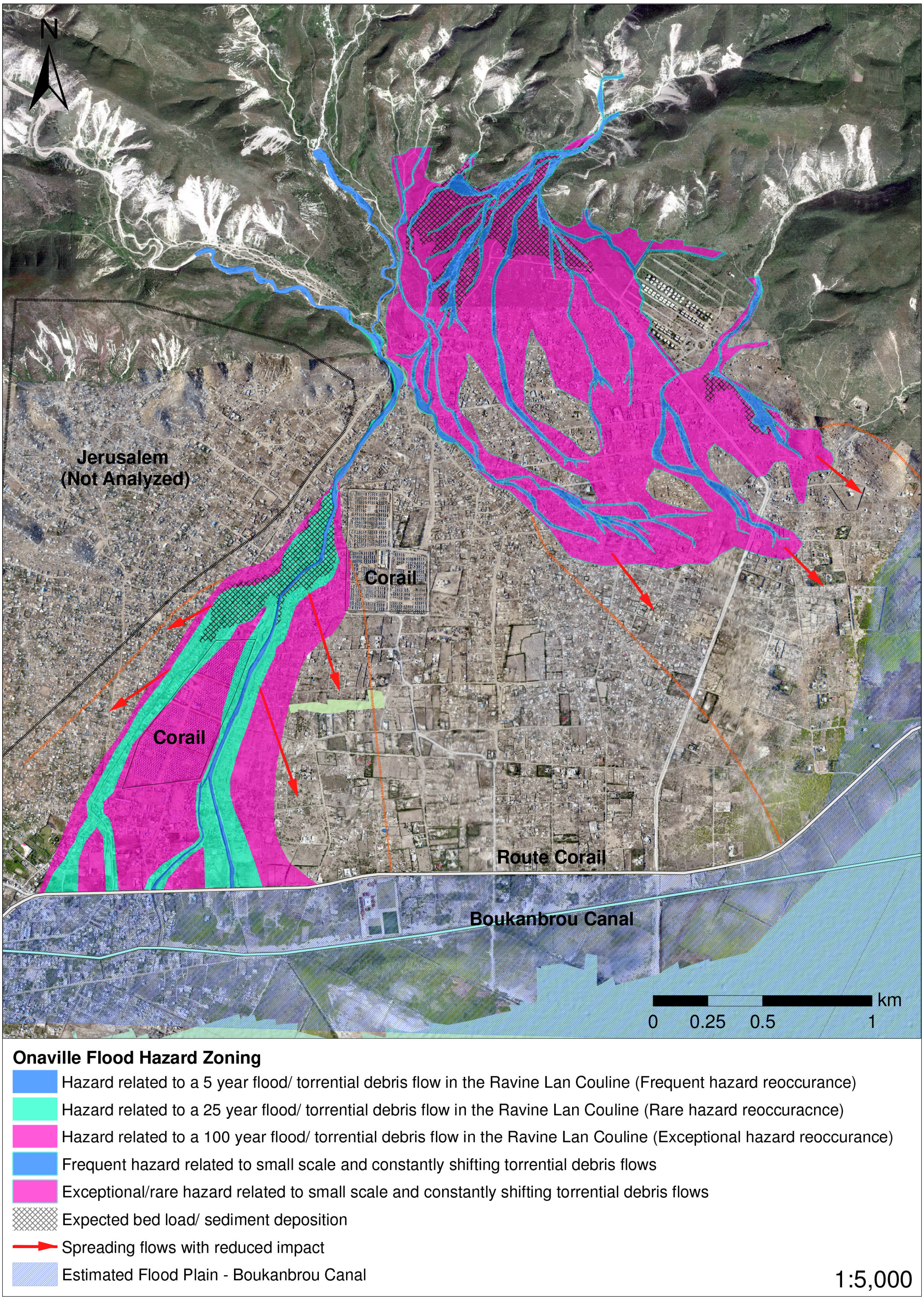


Figure 17. Flood hazard map of Onaville and the eastern part of Jerusalem (Canaan).

Interviews with residents of northern Onaville revealed that the additional four smaller watersheds frequently produce smaller scale flash flood events carrying large amounts of solids. All four watersheds drain through a clearly visible network of relatively small drainage channels that are carved into the alluvial cone, thereby allowing a good estimation of the propagation of flood discharges through the settlement (Figure 17). The frequently affected zone was defined based on the currently visible drainage channel network. The rare zone was defined by using the DEM and by considering that the existing drainage channel network is likely to change over time with new channels emerging potentially in areas with similar but not higher elevation than the current channel network. Due to a reduction of the channel slopes along the various flow channels, these concentrated flows eventually spread out on the alluvial cone so that their impact is expected to decrease drastically from this point on. Therefore, areas that are expected to experience spreading flows are outlined separately in the map.

Overall, the flood hazard map shows that large areas in Onaville are exposed to flood hazards. The artificial part of the Ravine Lan Couline channel was found to provide protection only to flood events in the frequent hazard range. Flood events of rare and exceptional hazard range exceed the capacity of the channel and are thus expected to cause severe flooding in the outlined urbanizing areas.

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4.4. Preventive Flood Risk Management on Community Level

In Onaville, ongoing land ownership issues, uncontrolled and rapid urbanization and the lack of functioning political administration of the settlement lead to difficult and complex circumstances for implementing any kind of management. Especially, due to unresolved land tenure and ownership issues, currently no major interventions are executed by the Haitian government, so that the neighborhoods mostly rely on work executed by NGOs and self-organized initiatives.

Through preceding projects within the framework of TUM-USO research group, a relatively strong connection and communication channel has been established to residents of Onaville. The NGO TECHO has been active in Canaan since the early days of the settlement in 2010 and provides a major link to the population of Onaville. TECHO assists the community by providing temporary housing and basic infrastructure as well as social guidance and skills training imparted in weekly meetings and frequent workshops. During field research, these networks and communication channels were used to raise awareness of the encountered hazard situation among affected residents and community leaders. A small focus group on environmental hazards was established, consisting of four TECHO volunteers and a few active and influential members of the local community of Onaville. This group was familiarized in detail with the methodology and outcomes of the flood risk analysis serving as a continuing link between the research group and an ongoing flood risk management on site.

In April 2014, the planning phase for a campaign aiming at community-wide increase of awareness started with a kickoff-event in Onaville, including a thematic workshop on flood hazards (Figure 18). Together with TECHO volunteers, local leaders and a group of representatives from Camp Corail a basic emergency management plan was elaborated.

Figure 18. In a flood risk workshop, the hazard situation was presented and discussed with a group of community leaders from Onaville and nearby Camp Corail.

The core of the Neighborhood Contingency Plan is a network consisting of six local risk management representatives identified and elected during that same workshop. In order to take over emergency information coordination, each leader will be a contact person for residents, coordinating danger alarms within their specific neighborhood. Further, they will communicate with the Contingency Plan leader network, which would be in charge of coordination with local and national authorities and administration. Identified communication methods vary from (mass) text messages, "*tele-dyol*" (word of mouth) and megaphone announcements to local radio station broadcasts carried out at the same time in order to reach the maximum of people as fast as possible. When looking for potential emergency shelters, appropriate buildings and structures were discussed, as well as their fundamental requirements such as good construction quality, location in "safe" zones, good accessibility, proper size and use.

During a joint site-visit, workshop participants were able to experience and reflect on previously discussed construction issues in risk prone areas. Upcoming activities proved that the workshop has contributed to increased collaboration among leaders from Onaville and Corail camps. The spreading of information in both sectors of Camp Corail has been facilitated, since representatives and the director were involved in the collective coordination and planning by the leader network.

Additionally, a first phase of an awareness-raising campaign in risk zones was carried out on three weekends in June 2014 with about 10 volunteers, consisting of community leaders and TECHO volunteers, distributing about 200 flood risk awareness flyers to households in hazard-exposed areas of the ravines and steep slopes of Ti Sous and Fon Dyab (eastern and upper Onaville). These flyers (Figure 19) were based on both the outcomes of this study and the flood risk workshop. They were designed to communicate the current risk situation considering local circumstances in a way that is easy to understand. In personal talks, risk exposure and prevention measures such as the Neighborhood Contingency Plan and personal emergency kits were explained to the residents. Telephone numbers of local risk management representatives were handed out to allow fast communication in case of hazard observation or warning of tropical storms and heavy rains. During this awareness-raising campaign it turned out that most families living in hazard zones are well conscious about their exposure to flood and landslides, but simply have no choice, as they cannot afford living in safer zones due to the high parcel and rental prices. This fact as well as the related real estate speculations are major drivers for the invasion of risk zones by underprivileged families in Onaville.

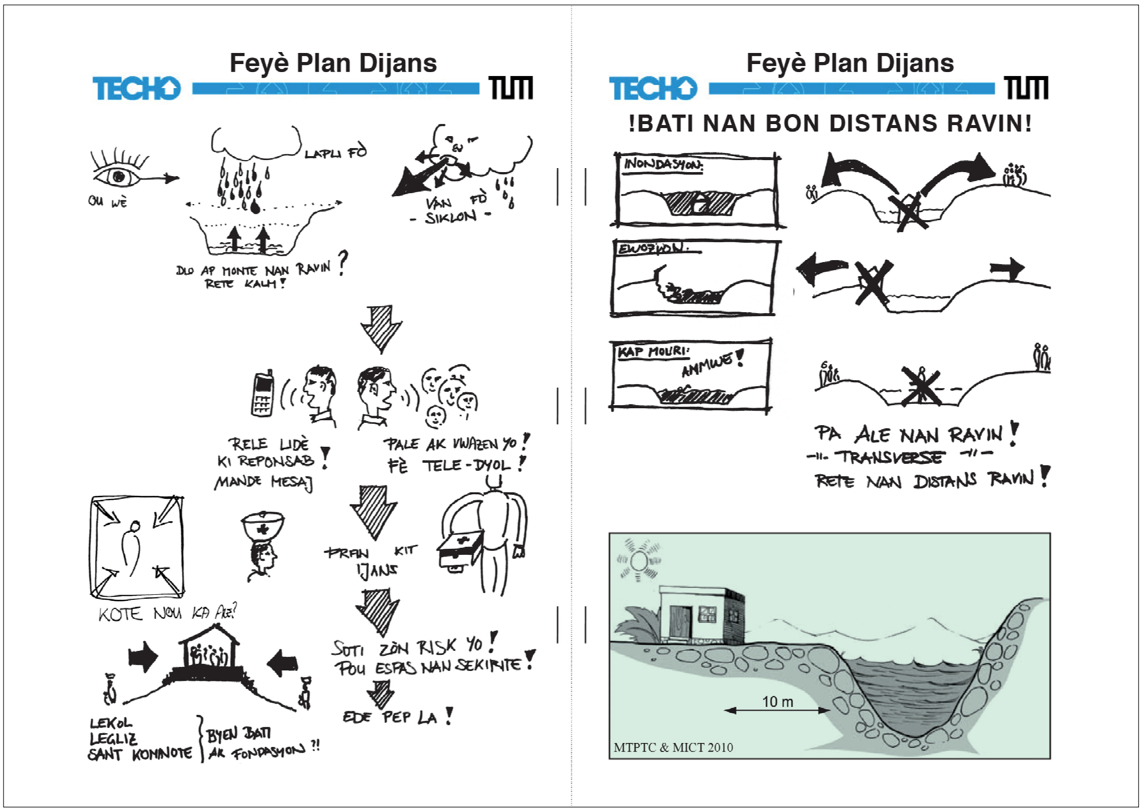

Figure 19. Excerpt from the flood risk awareness information flyers.

Beside the community-based work, the results of the flood hazard analysis were presented to key actors within the Haitian government (Unit for Housing Construction and Public Buildings (UCLBP), National Center for Geospatial Information (CNIGS), Inter-ministerial Territorial Planning and Development Committee (CIAT), Department of Civil Protection (DPC), Ministry of Environment (MDE)) same as to international aid and development agencies (Oxfam, ONU-Habitat, CordAid, American Red Cross). The flood hazard map (Figure 17) was shared with CNIGS to realize future integration into the national geo-information platform for housing and city quarters (SILQ).

In combination with the participatory field work (Contingency Plan), this research was presented by members of the focus group on environmental hazards at the exhibition of the international experts' and practitioners' forum Understanding Risk in Haiti: Innovate to Prevent in Port-au-Prince, 2014. Independent meetings of the Contingency Plan leader network were held together with (inter-)national disaster experts as well as with local and national authorities in order to evaluate potential support. Both showed interest in the grassroots initiative since its volunteer methodology of disaster prevention is considered to have potential for upscaling on the regional or national level.

4.5. Discussion

Considering the insufficient database, the predominantly empirical rainfall-runoff models can be seen as highly suitable for the generation of the design flood hydrographs. Although mainly physically-based water balance models like WaSiM or MIKE SHE are state-of-the-art in simulating the rainfall-runoff process, the suitability of such models for the given situation is limited due to the lack of data. To realize an accurate parameterization of such models regional distributed land use and soil data in high resolution are necessary as well as measured rainfall and runoff data for model calibration. Furthermore, the additional features of such physically based models (e.g., simulation of infiltration rates, evapotranspiration or interception) were not needed in this study and their validation would not have been feasible because of the limited data. In order to increase the reliability of the modeling results, measured precipitation and runoff in at least hourly resolution would have been necessary. For this study, information about the runoff behavior of the analyzed watercourses was based on the statements of the inhabitants only, so that a validation of the modeling results with measured data was not possible. Therefore, the modeling results should be interpreted as an approximation of the flood events that may occur in this region.

In contrast to this, the acquired data can be considered as suitable for generating the river channel through the settlements in HEC-RAS in a widely realistic way. Only in the northern part of the modeled reach, the TanDEM-X DEM had to be adjusted manually, because of the lower resolution of this DEM compared to the Drone DEM. Since the model is able to simulate the relevant water levels and locate the overflowing sections of the Ravine Lan Couline, it is definitely suitable to accurately estimate the flood hazard situation in the study region.

Despite the good suitability of the topographic data, the applied one-dimensional routing model shows obvious deficits regarding the simulation of lateral outflow of water from the main channel and the flow on the overbank areas, because the model is limited to simulating flow perpendicular to each channel cross section. For accurate modeling of lateral overbank flow, a two-dimensional modeling approach (e.g., HYDRO_AS-2D, MIKE-FLOOD) would be preferable. However, the development and manual correction of the model geometry based on a combination of the Drone DEM and the TanDEM-X DEM, would have been difficult for the 2D modeling approach. The Drone DEM has a number of small areas with poor representation of the terrain, which was easily adjustable for the cross sections in the 1D flow model. These difficulties would have made the development of a 2D flow model complex so that it would have exceeded the scope of this analysis.

Hydrologic and hydraulic modeling revealed that large areas of the settlement are currently exposed to a high level of flood related hazard. The artificial channel was found to mark the beginning of the high-risk zones. Before the artificial channel, the Ravine Lan Couline channel has enough capacity to convey a 100 year ARI flood runoff safely. Lateral outflow of flood runoff in the area of the market place of Onaville (see location of Figure 3 as referenced in Figure 1) as predicted by previous studies, is unlikely. The constructed channel, however, only provides protection against flood events in the frequent hazard range. Hydraulic modeling showed that flood events in the rare and exceptional hazard range are likely to have a devastating impact on the settlement in this area. Large amounts of flood runoff leaving the main channel as a result of levee overtopping and breaching have to be expected along with high flow velocities and bed load depositions in the settlement. In general, Sector 4 of Camp Corail is likely to be more vulnerable to flooding than Sector 3. Besides flood runoffs in the Ravine Lan Couline, runoffs generated in the other four examined watersheds also pose flood hazards to certain areas of the settlement. These smaller scale flow events have an unpredictable nature regarding their flow path through the settlement along with high destructive potential as a result of the high solid loads.

Due to a variety of uncertainties in the rainfall-runoff modelling and the incorporation of the hydraulic modelling results into the flood hazard map, the hazard zones have to be seen as a first approximation of the actual hazard situation. The ARIs of the flood events that are outlined in the hazard map have to be proven in more detail by acquiring additional data and applying state-of-the-art process based models. Developing a 2D hydraulic model is recommended since such a model could potentially lead to better estimates of the areas that will be affected by floods in the 25 and 100 year ARI range, if solid transport and deposition can be accurately accounted for.

Based on the GIS and simulation results, the methodology of bringing academic knowledge and technical aspects of flood risk assessment in the form of "applied science" back to local neighborhoods has turned out to be successful. The participants of community workshops were trained with technical, site-specific, methodological and important background knowledge as well as with the skills to come up with low-tech, low-cost solutions, which are applicable on the individual, family or neighborhood level. Yet, until this point in time, only a relatively small group of individuals has been able to benefit from that due to the fact that the undertaken activities were not up-scaled and the leader network was not reinforced.

5. Conclusions and Outlook

5.1. Key Issues and Solutions

One of the key issues related to the fulfillment of the study goals was found to be the acquisition of adequate hydrologic and topographic data. Hereby, the lack of readily available data related to the poor socio-economic state of Haiti was overcome by acquiring data generated by state-of-the-art remote sensing technologies and on-site analyses. The extensive data acquisition process lead to a database that was sufficient to set up a combined-hydrological and hydraulic-conceptual model approach. This leads to the next key issue which was found to be the limited suitability of the one-dimensional HEC-RAS model for the given situation. Even though the model was capable of evaluating the hydraulic capacity and deficiencies of the Ravine Lan Couline channel, a detailed simulation of the propagation of flows outside the main channel was not possible. In addition to that, the geometry of the hydraulic model had to be created based on two separate DEMs. Due to the insufficient spatial resolution of TanDEM-X DEM the cross sections that were derived from this DEM were manually adjusted based on the examination of the channel geometry on high-resolution aerial images.

5.2. Flood Risk Management and Future Work

Considering the available data sets and the selected modeling approach, the flood hazard zonation can be seen as a rough determination of the actual hazard situation that the settlement is facing. Since the presented zonation is at the moment by far the most accurate estimation of the flood hazard situation for the study area, it can be seen as a suitable basis for establishing a functioning flood risk management for Onaville. More complex risk assessments from governmental side are, as a result of the ongoing informal character of the settlement, rather unlikely. To realize a substantially complete operational flood risk management system, a flood protection frame work including designed technical and non-technical flood mitigation measures has to be generated in the next steps. For this, more data have to be collected concerning e.g., runoff data as well as the characteristics, the stability and erosion tendency of soils. Furthermore, the existing circumstances in this region have to be checked to ensure that only feasible measures are taken into account.

The third pillar of modern risk management strategies is prevention and preparedness, which comprises behavioral-, constructional- and risk-based prevention. The flood hazard map presented in this study provides a solid basis for preventive management, which was undertaken in the course of this study on the community as follows:

- Skills and technical training of local community leaders
- Initiation of an awareness-raising campaign and conceptualization of a local contingency plan
- Network-building among local leaders and between these leaders and external national and
- International organizations and entities
- Development of community-driven risk mitigation measures

This strategy for flood risk management on the community level is mainly based on an established focus group on environmental hazards and a network of local flood risk representatives. It is a reliable, low-cost and highly autonomous basis for risk prevention and mitigation, as it can incorporate resources and information dissemination networks of the community. It could additionally help the (local) authorities to become better prepared and react faster to unforeseeable disasters on a local scale.

Even though the flood hazard map along with the ongoing community work is a big step towards a functioning flood risk management for Onaville, this study has shown that there is an urgent need for further planning and implementation of flood protection measures and a more centralized and integrated flood risk management strategy. In this context, an Onaville-wide upscaling and reinforcement of the Neighborhood Contingency Plan activities is highly recommended, as different stakeholders have already been involved in the first pilot phase, and very positive feedback for the community-driven working methodology of the leader-led focus group has been reported by international and national entities and the community. The organizing focus group of the Neighborhood Contingency Plan should be immediately supported in its grassroots approach to bundle energies and capacities of this volunteer initiative before they are replaced by disillusion. Additionally, the campaign should be backed by technological prevention infrastructure such as the construction of simple weather stations in the hills of Onaville, and discharge gauge instruments at crucial points of the major water course Ravine Lan Couline. As for the emergency plan in general, the leader network needs to be reinforced by involving other established community leaders such as local and national experts, local teachers, pastors and so on. The network has to be supported in collecting and regularly evaluating experiences in the execution of alerts. Additionally, a site-specific assessment of available shelter structures and their surroundings ought to be required in a further step to assure the safety of the location.

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Author Contributions

Valentin Heimhuber acquired, processed and managed all spatial and hydrological data. Valentin Heimhuber and Wolfgang Rieger developed hydrologic and hydraulic modelling methodology; processed and analyzed results. Valentin Heimhuber and Johann-Christian Hannemann developed flood hazard map; implemented preventive flood risk management on community level. Valentin Heimhuber and Wolfgang Rieger wrote this paper.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. International Federation of Red Cross and Red Crescent Societies. World Disasters Report Focus on Urban Risk; Geneva, 2010. Available online: https://www.ifrc.org/en/publications-and-reports/world-disasters-report/wdr2010/ (accessed on 20 October 2013).
2. U.S. Central Intelligence Agency (CIA). The World Factbook. Available online: https://www.cia.gov/library/publications/the-world-factbook/index.html (accessed on 5 September 2013).
3. Office for the Coordination of Humanitarian Affairs (OCHA). Tropical Storm Isaac in Haiti: Damage Needs and Responses; Analysis Report. Available online: http://www.humanitarianresponse.info/en/operations/haiti/document/tropical-storm-isaac-haiti-damage-needs-and-responses (accessed on 2 September 2013).
4. Office for the Coordination of Humanitarian Affairs (OCHA). Haitiearthquake Situation Report #23. Available online: http://reliefweb.int/sites/reliefweb.int/files/resources/CEB1B7C987DB2763492576D3001ECF55-Full_Report.pdf (accessed on 25 June 2015).
5. International Organization for Migration (IOM). Displacement Tracking Matrix (DTM)-Report Version 2.0, 2013. Available online: http://iomhaitidataportal.info/dtm/downloads.aspx?file=downloads/16.DTM%20Report_Sep %2713/DTM_V2_Report_Sep_2013_English.pdf (accessed on 15 October 2013).
6. Aerial Imagery ©2013 Google, Digital Globe. Imagery obtained with Google Earth. Available online: http://www.google.com/earth/ (accessed on 6 July 2015).
7. TUM Research Platform—Urban Strategies for Onaville (Haiti). Available online: http://openarchitecturenetwork.org/projects/urban_strategies_ona (accessed on 10 May 2015).
8. Kervin, S. Drainage, Water and Sanitation Infrastructure Improvement in Impoverished Areas—A Case Study of Onaville, Haiti. Master's Thesis, Technical University Munich, München, Germany, 28 March 2013.
9. Mora, S.; Roumagnac, A.; Asté, J.-P.; Calais, E. *Analysis of Multiple Natural Hazardsin Haiti (NATHAT)*; Government of Haiti: Port-au-Prince, Haiti, 2010. Available online: https://www.iris.edu/hq/files/workshops/2010/03/docs/Report-MULTIHAZARDS-HA-English-SergioMora-Final-Red.pdf (accessed on 31 October 2013).
10. FLOODsite. *Language of Risk—Project Definitions*; Report T32-04-01, 2005. Available online: http://www.adbarno.it/rep/biblio/FLOODsite_Language_of_Risk_v4_0_P1.pdf (accessed on 11 March 2015).
11. Plate, E.J. Flood risk and flood management. *J. Hydrol.* **2002**, *267*, 2–11.
12. Lamothe, L. Press Statement about Canaan, Haitian Prime Minister, 2013. Available online: https://soundcloud.com/laurentlamothe/point-de-presse-du-premier-7 (accessed on 15 December 2013).
13. Hannemann, J.-C.; Werthmann, C.; Hauck, T. Designing for uncertainty: The case of Canaan, Haiti. In *Revising Green Infrastructure: Concepts between Nature and Design*; Czechowski, D., Hauck, T., Hausladen, G., Eds.; CRC Press: Boca Raton, FL, USA, 2014; pp. 323–351.
14. Information Products Lab for Emergency Response (IPLER). LIDAR DEM of Port-au-Prince Region, 2010. Available online: http://ipler.cis.rit.edu/projects/haiti (accessed on 10 May 2013).
15. Deutsches Amt für Luft- und Raumfahrt (DLR). TanDEM-X DEM Product Specification, 2013. Available Online: https://tandemx-science.dlr.de (accessed on 25 September 2013).

16. Rossi, C. (German Aerospace Center (DLR), Oberpfaffenhofen, Germany). TanDEM-X Ground Segment. Personal communication, 2013.
17. U.S. National Weather Service-National Hurricane Center. Tropical Cyclone Climatology. Available online: http://www.nhc.noaa.gov/climo/ (accessed on 5 November 2013).
18. *Hydrology and Hydraulic Analysis for Ravine Millet Petion-Ville, Haiti*; The United States Agency for International Development: Port-au-Prince, Haiti, 2011.
19. Haiti Landcover (Occupation du Sol), SPOT-CNIGS [04.1998]-polygon, Port-au-Prince, September 2008. Available online: http://www.haitidata.org/layers/cnigs.spatialdata:hti_biota_landcover_spot_cnigs_041998_polygon (accessed on 14 June 2015).
20. American Heritage Dictionary. *The American Heritage Science Dictionary*, 1st ed.; Houghton Mifflin Company: Boston, MA, USA, 2005.
21. Food and Agriculture Organization of the United Nations (FAO). Global Forests Resource Assessment, Progress towards Sustainable Forest Management, 2005. Available online: ftp://ftp.fao.org/docrep/fao/008/A0400E/A0400E00.pdf (accessed 22 October 2013).
22. Bureau des Mines et de l''Énergie (BME). Haiti Geology (géologie), BME-polygon, Haiti, Port-au-Prince, 2005. Available online: http://www.haitidata.org/layers/cnigs.spatialdata:hti_geology_geology_polygon_082005 (accessed on 14 June 2015).
23. *HEC-HMS Technical Reference Manual*; US Army Corps of Engineers Hydrologic Engineering Center (HEC): Davis, CA, USA, 2010.
24. Natural Resources Conservation Service (NRCS). *National Engineering Handbook*: *Part 630—Hydrology*; United States Department of Agriculture: Washington, DC, USA, 2004; Chapters 1, 4, 6.
25. Chow, V.T.; Maidment, D.R.; Mays, L.W. *Applied Hydrology*; McGraw-Hill: New York, NY, USA, 1988.
26. *Urban Hydrology for Small Watersheds*; Technical Release Number 55 (TR-55); United States Department of Agriculture: Washington, DC, USA, 1986.
27. *Soil Mechanics Level 1, Module 3*, *USDA Textural Soil Classification, Study Guide*; United States Department of Agriculture: Washington, DC, USA, 1987.
28. *HEC-RAS Hydraulic Reference Manual, Version 4.1*; US Army Corps of Engineers Hydrologic Engineering Center (HEC): Davis, CA, USA, 2010.
29. *Hochwasserschutzanlagen an Fließgewässern*; DIN 19712; Deutsches Institut für Normung e.V. (DIN): Berlin, Germany, 2013. (In German)