FLOOD LOSS ESTIMATE MODEL: RECASTING FLOOD DISASTER ASSESSMENT AND MITIGATION FOR HAITI, THE CASE OF GONAIVES

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This study aims at developing a model to estimate flood damage cost caused in Gonaives, Haiti by Hurricane Jeanne in 2004. In order to reach this goal, the influence of income, inundation duration and inundation depth, slope, population density and distance to major roads on the loss costs was investigated. Surveyed data were analyzed using Excel and ArcGIS 10 software. The ordinary least square and the geographically weighted regression analyses were used to predict flood damage costs. Then, the estimates were delineated using voronoi geostatistical map tool.

As a result, the factors account for the costs as high as 83%. The flood damage cost in a household varies between 24,315 through 37,693 Haitian Gourdes (approximately 607.875 through 942.325 U.S. Dollars). Severe damages were spotted in the urban area and in the rural section of Bassin whereas very low and low losses are essentially found in Labranle. The urban area was more severely affected by comparison with the rural area. Damages in the urban area are estimated at 41,206,869.57USD against 698,222,174.10 17,455,554.35USD in the rural area. In the urban part, damages were more severe in Raboteau-Jubilée and in Downtown but Bigot-Parc Vincent had the highest overall damage cost estimated at 9,729,368.95 USD. The lowest cost 7,602,040.42USD was recorded in Raboteau. Approximately, 39.38% of the rural area underwent very low to moderate damages. Bassin was the most severely struck by the 2004 floods, but Bayonnais turned out to have the highest loss cost: 4,988,487.66 USD. Bassin along with Labranle had the least damage cost, 2,956,131.11 and 2,268,321.41 USD respectively.

Based on the findings, we recommended the implementation and diversification of income-generating activities, the maintenance and improvement of drains, sewers and gullies cleaning and the establishment of conservation practices upstream of the watersheds. In addition, the model should be applied and validated using actual official records as reference data. Finally, the use of a calculation-based approach is suggested to determine flood damage costs in order to reduce subjectivity during surveys.

DEDICATIONS

This work is dedicated to the people of Haiti who struggle everyday against socio-economic, political, and environmental problems. I am grateful to God as he guides me through every step that I take. To my relatives, my friends and my family, I offer this work. May it contribute to make them feel happier.

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ABREVIATIONS AND ACRONYMS

B.S.	: Bachelor of Science
CDMP	: Caribbean Disaster Mitigation Project
CIMH	: Caribbean Institute for Meteorology and Hydrology
FAO	: Food and Agriculture Organization
FEMA	: Federal Emergency Management Agency
GIS	: Geographic Information System
GWR	: Geographically Weighted Regression
H T G	: Haitian Gourdes
IDW	: Inverse Distance Weighted
IHSI	: Institut Haïtien de Statistiques et d'Informatiques (Haitian Statistics and Informatics Institute)
LfUG	: Landesamt für Umwelt und Geologie
NDVI	: Normalized Difference Vegetation Index
OAS	: Organization of American States
OLS	: Ordinary Least Square
OXFAM	: Oxford Committee for Famine Relief
UK	: United Kingdom
UNISDR	: United Nations International Strategy for Disaster Risk
U.S.	: United States
USAID	: United States Agency for International Development
USDE	: Unit of Sustainable Development
UTSIG	: Unité de Télédétection et de Systèmes d'Information Géographique (Remote Sensing and GIS unit).
VIF	: Variance Inflation Factor
WFP	: World Food Program (PAM)

CHAPTER 1

INTRODUCTION

1.1 Background

Direct damages associated with Hurricane Katrina hitting New Orleans in 2005 was estimated at ninety billion dollars. Sixteen billion of this total cost was caused by flooding to residential property (Jonkman, 2008). Prior to the passage of Katrina, Hurricane Jeanne floods killed more than 2800 people as recently as 2004 in Gonaives, Haiti (Colindres, 2009). In fact, it makes no doubt that flooding is an expensive and deadly global issue that needs to be accounted for in risk management.

Due to Haiti's geographical location and topographical characteristics, flooding from hurricanes and storms is quite frequent. From 1968 to 2001, the island has been affected by 30 hurricanes and 90 floods due to heavy precipitation. The disasters are not totally of natural origin. In fact, they are aggravated by anthropogenic activities. With oil too expensive for the bulk of the population, charcoal from burnt trees has provided at least 85% of energy in Haiti for decades. As a result, many citizens have relentlessly hunted and chopped down huge amount of forest. In addition to deforestation and disasters, hoed crops are being practiced for more than 20 to 30% in areas that are not fit for that type of agriculture. Not to mention that 2.5 million cubic meters of stones are extracted from the ground annually for construction, leaving denuded mountain slopes that rainwater washes down unimpeded. Twenty-five out of thirty watersheds in the country are degraded. That situation has a huge impact on agriculture, and commerce and has severely affected the communities and the poor, in particular. Catastrophic floods are considered a barrier to sustainable development especially because the less developed a country is, the more prone it is to economic damages and loss of life. Haiti is identified as a country where there is a strong link between the level of development and the impact of natural hazards. Effective flood risk management plans consisting of forecasting and warning systems and plans for evacuation and relief and post-flood recovery can substantially reduce losses.

The present study focuses on the area of Gonaives, which has been greatly damaged by the 2004 and 2008 flood events. The goal of the study is to quantify the flood damages to the city and the surrounding areas. This will help in planning and designing flood protection measures, managing emergency in real-time and recovering from flood. Countries such as Germany, Australia, United Kingdom, United States and others have conducted similar studies. Software tools such as ArcGIS 10 and Microsoft Excel were used. This study also provides some guidelines for flood risk mapping in developing countries.

1.2 Justification

Previous efforts to assess disaster risk in Haiti have not been extensive. According to Felhome (2007), there have been three major efforts in hazard mapping in Haiti: an island wide seismic map done by OAS/USDE/CDMP, an island wide atlas of probable storms effects prepared by OAS/USDE/CDMP/CIMH, and a national multihazard map produced by OXFAM. Some vulnerability assessment projects have been undertaken, and few mapping efforts have been made. This includes, for instance, UTSIG (2004), FewsNet (2005) and USAID (2007). The scale at which information is gathered is important to decision makers. Broad scale studies often result in generalization of the spatial dimensions of risk and vulnerability, with minimization of their complexity and variability.

To date, few studies have quantified flood risk at a useful scale in Haiti. Recent floods in the city of Gonaives and other parts of the country such as Mapou and Fond Verrettes have increased community, governmental and international awareness of the need to do more research at a local level. The development of a flood loss estimation model will serve several major applications. Examples include but are not limited to: planning and designing flood protection measures, managing emergency in real-time and recovering from floods.

1.3 Problem Statement

Certain regions of Haiti are under a permanent threat of flooding. Gonaives, Fonds Verrettes, Port-au-Prince and Léogane are among the areas that have particularly been hit several times, particularly 2004 and 2008 by massive floods. The location of the Island on the hurricane path in the Atlantic Ocean, the artificial degradation of watersheds in the upper land combined with urban sprawling and land use in the bottom land amplify the vulnerability of the weakened population to respond to the impact of a flood hazard, not to mention steep slopes in the upper and heavy rain falls that characterize the tropical climate of Haiti. The purpose of this study is to develop a model to estimate residential damages resulted from the floods caused by Hurricane Jeanne in 2004. Also, flood damage maps are created showing the distribution of damages for residential areas in the Quinte River watershed.

1.4 Research Questions

The study aims at answering two specific questions:

1. What are the damages in a residential household with an inundation depth ranging from 10 to 200 centimeters?

2. What are the flood losses for a farm household surrounding the city of Gonaives?

1.5 Definition of Terms

Disaster

According to UNISDR 2004:3, disaster can be defined as: "a serious disruption of the functioning of a community or a society causing widespread human, material, economic or environmental losses which exceed the ability of the affected community or society to cope using its own resources."

Vulnerability

"The conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards". Not to mention that "these hazards might originate from the natural environment, such as droughts, floods or sinkholes or may be anthropogenic in nature, for example nuclear meltdowns, pollution or terrorism" (Riet, 2009).

Capacity

Capacity is defined as "A combination of all strengths and resources available within a community, society or organization that can reduce the level of risk or the effects of a disaster" (Riet 2009).

Disaster Risk

"The probability of harmful consequences, or expected losses (death, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between natural or human-induced hazards and vulnerable conditions", (UNISDR, 2004:3).

Disaster Risk Reduction

The conceptual framework of elements considered with the possibilities to minimize vulnerabilities disaster risks throughout a society, to avoid (prevention) or to limit mitigation and preparedness) the adverse impacts of hazards, within the broad context of sustainable development.

Risk and Flood Mitigation

According to the Federal Emergency Management Agency (FEMA), mitigation is the "effort to reduce loss of life and property by lessening the impact of disasters." The agency continues to explain that "this is achieved through risk analysis, which results in information that provides a foundation for mitigation activities that reduce risk, and flood insurance that protects financial investment."

Tangible Damages

Damages caused by any natural disasters are broadly classified into two categories; they are tangible damage and intangible damage. Tangible damages are those which can be evaluated quantitatively in economic terms such as, damage to lifelines, buildings, etc.

Intangible Damages

Intangible damages are ones that are difficult to express in economic value, for example anxiety, mental tremor to victims, inconvenience and disruption of social activities, etc. In case of flood damage, both tangible and intangible damages can be of two types, direct and indirect damages.

Direct and Indirect Damages

Direct damages are caused by physical contact of floodwater. Indirect flood damages are those caused through interruption and disruption of economic and social activities as a consequence of direct flood damages. Direct and indirect damages can be subdivided into primary and secondary categories. Commonly, primary and secondary direct as well as primary indirect damages are evaluated in monetary currencies using both survey procedures which consist in interviewing affected populations and stages-damaged functions where parameters like inundation and duration are taken into account. Those functions are normally from analysis of past flood data or description of flood damage ratio at a given depth and duration.

CHAPTER 2

LITERATURE REVIEW

The literature for the study is organized into four sections which are damages in Gonaives, flood hazard assessment, flood modeling and flood loss estimate components. In the first section, information about flood damages in Gonaives is reported whereas the process of flood assessment is detailed in the second section. Section three emphasizes the main focus of the study which is flood damage modeling as well as its different steps. Finally, the components of the current flood estimation model are presented in the fourth section.

2.1 Damages in Gonaives

In September 2004, the Caribbean region as well as the east cost of the United States was struck by Hurricane Jeanne. Few losses of life were recorded in the Dominican Republic, in Puerto Rico and in Barbados. Essentially, Haiti was the most damaged country by far with important damages and considerable losses of life. According to the Global Security website, as many as 34 people died for all the counties mentioned combined excluding Haiti (2004). Oppositely, approximately 300,000 people were affected by flooding and heavy rains. In fact, it was officially estimated and reported that the country lost over 3006 souls of which 2826 died in Gonaives. Other sources provided slightly different numbers for Gonaives where most damages were recorded. The casualties in Gonaives amounted to 2800 (Colindres, 2007). The same website reported that 80% the people living in Gonaives was affected. Furthermore, 35,000 houses were affected of which nearly 5000 were destroyed or damaged. According to the same source, almost all 397 elementary and secondary schools were damaged and closed. The main public hospital serving the area was damaged and became definitively non-operational. In parallel, about 70 percent of the region's agricultural areas were damaged.

According to a report of the Haitian Institute of Informatics and Statistics (IHSI, 2009), the urban population of Gonaives was particularly affected. The *Centreville*, literally "Downtown," and Kasoley were the most affected among the five zones that make up the urban area. Their population plummeted by 31% from 2003 to 2009. On the contrary, the population of the Biénac-Gathereau area increased by 26%. At the same time, the number of the urban households decreased by 46% against 8.7% in the rural area. That decrease is higher for the Downtown and Kasoley areas with 55.8% and 60.6% respectively.

The Institute categorized the damages to houses on a severity scale of four: very severe, severe, minor and none. In the urban area, the Raboteau-Jubilée has the highest percentage (3.3%) in the very severe class whereas Biénac-Gathereau and Kasoley have the lowest (2.1% and 1.1% respectively). For the severe category, Bigot-Parc Vincent has the highest percentage (10.7%) whereas Kasoley and Biénac-Gathereau have the lowest (5.3% and 5.7%) respectively. Biénac-Gathereau was the least damaged among the urban areas since it has the lowest percentage (3.7%) for the minor damage category and the highest (16.0%) for the none damage category. Also, it was noticed that 58% of houses in Biénac-Gathereau and 26.4% of those in Raboteau underwent no damage.

The rural area was less affected by comparison with the urban area. In fact, 43% of the houses underwent no damage against 30% in the urban area (IHSI, 2009). Among the five rural subdivisions, Pont Tamarin was the most damaged with the highest percentages for both the very severe and the severe categories, 3.5% and 8.7% respectively. Labranle had the lowest percentages for the same categories, 1.4% and 2.4% respectively. The pictures in Figure 1 testify of the damages that Gonaives underwent due to the passage of Hurricane Jeanne in September 2004. The two pictures at the top were taken for the rural area. They show the immersion of the National Route 1, leading to the city, and an airstrip terminal. The pictures at the bottom show damages in the urban area. The ground level was washed and people moved to the tops of houses to live. Figure 2 presents two pictures of the Downtown of Gonaives city taken before and after the September 2004 floods. The pictures show that the roads and the surrounding infrastructures were severely damaged.

Figure 1. *Flooding in Gonaives Following the Passage of Hurricane Jeanne in 2004 (Globalsecrity.org , 9/21/2004).* These pictures were taken on Tuesday September 21st, two days after the rain had started, Saturday night and Sunday. The first picture shows the road that leads to town at the top and a terminal at the lower part covered by water. The third and fourth pictures are town pictures. The latter shows that people moved to the tops of houses to live.

Figure 2. Flooding in Gonaives Haiti before and after Hurricane Jeanne 2004 (*NASA Earth Observatory, posted on 03/25/2011:4:30pm*)

2.2 Flood Hazard Assessment

Inform contingency planning, reduce vulnerability and identify high risk area are three reasons to make a risk assessment (Riet, 2009). Flood damage assessment deals with measuring quantitative, economic, and qualitative damages. In general, five conditions are required in a flood damage assessment methodology. First, an accurate and efficient prediction of flood inundation is performed. This defines the spatial scope of flood damage. This engineering factor unrelated to the economic factor is required to guarantee results' reliability. Second, an accuracy and precision assessment in surveys of land use and assets in the damaged area is performed. This represents the severity of potential damages in the target area and defines whether the assessed damages can describe the characteristics of the area. Third, reasonable information on the susceptibility of assets (or depth–percent damage relationships) is analyzed. This defines the percent of total value of assets damaged for a range of flood inundations with respect to structures, personal properties, and other items. This element is crucial in relating condition 2 with condition 1. Finally, generality and convenience of analysis are considered. As flood damage assessment is utilized in the economic analysis of various flood damage reduction projects, the methodology used must be universal and convenient to use.

Gathering hydrologic data directly from rivers and streams is a valuable but time-consuming effort. If such dynamic data have been collected for many years through stream gauging, models can be used to determine the statistical frequency of given flood events, thus determining their probability. However, without a record of at least twenty years, such assessments are difficult. In many countries, stream-gauging records are insufficient or absent. As a result, flood hazard assessments based on direct measurements may not be possible because there is no basis to determine the specific flood levels and recurrence intervals for given events. Hazard assessments based on remote sensing data, damage reports, and field observations can substitute when quantitative data are scarce. They present mapped information defining flood-prone areas which will probably be inundated by a flood of a specified interval.

2.3 Flood Loss Modeling

Nowadays, flood loss modeling has gained more attention in risk analysis and risk management. It is a very challenging and complex task requiring the understanding of dynamics and the working of each and every sector concerned with flood events. Often time, researchers develop damage estimate models for specific categories such as commerce (Kreibich, 2010), agriculture (Tapia-Silva, 2011), loss of life (Jonkman, 2008) and so forth. The strategy of modeling one sector is logical given the difficulty of one single model to account for all the aspects impacted by flooding. Such a reality leads to a situation where models encountered in literature are flawed and unpractical assuming that any different aspect from that of a model is stable. In fact, literature categorizes flood damages into direct and indirect and also into tangible and intangible damages (Dutta, 2001). That classification is commonplace. However, the interpretation of what is a direct damage and what is not sometimes differs from authors (Jonkman, 2008). That classification is based on two distinctions in a sense that direct damages are located in the flooded area while indirect are outside. Also, tangible damages are those that can be priced as opposed to intangible for which there are no market prices (Table 1).

Table 1- Different Types of Flood Damages

	Tangible and priced	Intangible and unpriced
Direct	• Residences • Capital assets and inventory • Business interruption (inside the flooded area) • Vehicles • Agricultural land and cattle • Roads, utility and communication infrastructure • Evacuation and rescue operations • Reconstruction of flood defences • Clean up costs	• Fatalities • Injuries • Inconvenience and moral damages • Utilities and communication • Historical and cultural losses • Environmental losses
Indirect	• Damage for companies outside the flooded area • Adjustments in production and consumption patterns outside the flooded area • Temporary housing of evacuees	• Societal disruption • Psychological traumas • Undermined trust in public authorities

Source: (Jonkman, 2008)

2.3.1- Procedure in Flood Loss Modeling

In literature, the vast majority of flood loss estimate models have been developed for physical direct damages. Most of the time, indirect intangible damages are neglected for several reasons such as lack of consistent data. Jonkman is one of the rare researchers having attempted to develop an integrative flood loss estimate model including an indirect economic component as well as a life loss component. Generally, direct damages related to physical impacts are estimated by stage-damage functions or curves. Those functions are based on the relationship between the flood features, usually depth, and the economic damages. The first step of the process is the estimation of the structural damages to objects while the second step is the pricing of those damages. Stage-damage functions were primarily developed in the 1960's in the United States by Gilbert F. White and Robert Kates and later spread across the world. Other researchers tried, later on, to include other parameters such as flood duration and depth, contamination, and preparedness (Kreibich *et al*., 2010). In simulation, flood characteristics like depth, flow velocity, and duration can be derived from a hydrodynamic model. Those attributes coupled with land use data as well as the application of stage-damage functions help estimate direct physical damages. The next section provides more details about the process to derive flood loss estimates for direct physical damages.

2.3.1.1 Direct Physical Damage

The process of estimating physical damages includes three aspects. These are determining flood characteristics, gathering information on land use and land cover data, and on maximum damage amounts, and utilizing the so-called stage-damage functions or curves. Flooding patterns are based on the simulated model of SOBEK 1D-2D. The hydrodynamic model shows how a flow of water issued from a breach impacts land use. Mathematically, the bi-dimensional model is based on the Saint Vincent equation which requires input data on the area, location of breaches, and height and duration characterizing the hydraulic load. One must account for roughness and geometry of the surface in simulation. A lack of that may not only result in compartment of the flooded area but also in a changed flow area induced by obstacles. The overtime output of such models based on one or multiple breaches scenarios is the water depth, the velocity as well as the rise rate of the water. These output parameters can all be described on a map and consequently be linked to economic damages. In a direct physical damage assessment, five major types of assets at risk are identified. These are land use and land cover, infrastructure, households, companies, public utilities and facilities. The determination of direct physical damages is done by means of a maximum damage amount for one object. The assumption is that the value of one object is the same countrywide for that object as presented in Table 2. In such a procedure, site realities or regional specificities are not taken into account. According to Jonkman 2008, the following equation is used to estimate direct physical damages in a flooded area:

$$D = \sum_{i}^{m} \sum_{r}^{n} \alpha_i(h_r) D_{\max i,r}\, n_{i,r} \qquad \text{(Equation 1)}$$

Where $D_{max,i}$ is the maximum damage amount for an object or the land use category *i*, *i* is the damage or the land use category, *r* is the location in the flooded area, *m* is the number of damage categories, *n* is the number of locations in flooded area, *hr* is the hydraulic characteristics of the flood at a particular location, $\alpha i(hr)$ is the stage-damage function that expresses the fraction of the maximum damage for category i as a function of flood characteristics at a particular location r $(0 \leq \alpha i(hr) \leq 1)$ and $n_{i,r}$ is the number of objects of damage category *i* at location *r*.

Table 2-Direct Damage Categories, Measurement Units, Maximum Damage Costs and Data

Damage category	Damage sub-category	Measurement unit	Maximum direct damage amount (€)	Data source
Land use	Agriculture	m^2	2	CBS land use
	Greenhouses		40	CBS land use
	Urban area		49	CBS land use
	Intensive recreation		11	CBS land use
	Extensive recreation		9	CBS land use
	Airports		1230	CBS land use
Infrastructure	Motorways	M	2100	National Road Database
	Major roads		980	National Road Database
	Other roads		270	National Road Database
	Railways		25,000	Rail-NS
Households	Low-rise housing	Object	172,000	Bridgis dwelling types
	Middle-rise housing		172,000	Bridgis dwelling types
	High-rise housing		172,000	Bridgis dwelling types
	Single-family houses		241,000	Bridgis dwelling types
	Farms		402,000	Bridgis dwelling types
	Vehicles		1050	Manual input combined with bridgis persons file
Companies	Mineral extraction	Value added per working place	1,820,000	D&B employment database
	Industry		279,000	D&B employment database
	Electric companies		620,000	D&B employment database
	Construction		10,000	D&B employment database
	Trading and catering		20,000	D&B employment database
	Banking and insurance		90,000	D&B employment database
	Transport and communications		75,000	D&B employment database
Other	Pumping stations	Object	750,000	Water information system
	Water purification installations		11,000,000	Water information system

Source: (Jonkman, 2008)

Explanatory notes: CBS: statistics Netherlands; D&B: Dun and Bradstreet.

2.3.1.2 Flood Loss to Agricultural Crops Using Remote Sensing

Flood loss estimate methodology for agriculture is slightly different from that of the commercial or the residential sector. The purpose is to identify crops that are affected at the time a flood occurs and to be able to price the related damages. In this type of modeling, the crop type, inundation duration and the month of event have to be accounted for, besides the expected crop value. Tapia-Silva (2011) sets up the following equation to estimate flood losses to major crops grown in polders in Germany:

$$D = cv*df \qquad \text{(Equation 2)}$$

Where *cv* is the crop value, with crop value being the product of the yield and the price (*cv = yield*price*), *df* is a damage factor which is a function of crop type, flood duration and the month the event hits. The identification implies the understanding of the phenological phases in the life cycle of a crop.

<u>Identification of Affected Crops</u>

In the modeling process of flood damages to agricultural lands, the identification of affected crops is considered the first stage**.** That step can be performed using various methods in remote sensing such as NDVI (Normalized difference vegetation index), disaggregation of statistics and analysis of crop rotation with data mining Net Bayesian Classifier (Tapia-Silva, 2011). Using NDVI requires analysis of Landsat TM images for a period of time based on standard spectral curves. The method can be validated, and its accuracy can be derived. That may not be an ideal method since one may not spot small areas on a low resolution image. Furthermore, the method has low accuracy due to misclassification which is explained by the fact that it does not use training area.

Unlike NDVI, the disaggregation of statistical crop data method uses statistics for crops. It takes into account the probability of a crop to be cultivated in a specific type of soil. Then, the method is validated using reference data. Two main limitations of that method are the misclassification of crops and the division of parcels according to soil types. The limitations imply that other possible factors such as crop price, rotation, distance as well as parcels accessibility drive the farmers' decisions. Additionally, the Net Bayesian Classifiers method aims at inducing a network that best portrays the probability distribution over the training data. It consists in classifying a class variable given a set of attribute variables.

Hydrodynamic Model and Loss Estimation

Several specialized software interfaces are used to simulate floods. Flood characteristics such as water level, flow velocity, discharge, water depth and duration can be derived and mapped. Also, recorded water levels and flows at gauges can lead to the same modeling process, knowing the slope of the flooded area and land use information of that area. Flood duration maps are produced based on simulated water levels and digital elevation models (Tapia-Silva, 2011). Several efforts have been made mainly in rich countries to develop flood loss estimate models. Some models are presented in Table 3 and Table 4

Table 3. Summary of Existing Flood Loss Estimation Methodology

Damage categories		**Japan**	**Australia**	**United Kingdom**	**United States**
Urban	Residential	Detail	Detail	Detail	Detail
	Non-residential	Detail	Detail	Detail	Detail
Rural	Crop damage	Rough	Detail	Detail	Detail
	Farmland damage	Detail	None	Detail	Detail
	Fishery	None	Detail	Detail	None
Infrastructure	Rural	Rough	Rough	Detail	None
	Damage	Rough	Rough	Detail	None
Business losses		Rough	Detail	Detail	Detail
Environmental damages		None	None	Detail	None

Source: (Dutta, 2001)

Table 4: Comparison of Different Flood Loss Models

Authors\References	Model development	Model scale	Loss functions	Impact parameters	Resistance parameters	Differentiation of results
RAM (Australia) **(NRE, 2000)**	Empirical – synthetic	Micro	Absolute	-	Object size/value and lead time and flood experience	One figure building structure and contents
(Anuflood,2002) **(Australia)**	Empirical	Micro	Absolute	Water depth	Object size and object susceptibility	One figure:
HAZUS (FEMA, 2003; Scawthorn *et al.*)	Empirical – synthetic	Micro-Meso	Relative	Water depth	Object type	Three figures: Building, Equipment Inventory
Multicoloured manual (United Kingdom)	synthetic	Micro-Meso	Absolute	Water depth and duration	Object type and lead time	Five figures + Immobile, stock
MURL (2000) **(Germany)**	Empirical	Meso	Relative	Water depth	Business sector/ ATKIS land-use classes	Three figures
(ICPR, 200) **(Germany)**	Empirical – synthetic	Meso	Relative	Water depth	Business sector/ CORINE land use classes	Three figures
(Hydrotec, 2004) **(Germany)**	Empirical	Meso	Relative	Water depth	Business sector/ ATKIS land-use classes	One figure
(LfUG, 2005) **(Germany)**	Empirical – synthetic	Meso	Relative	Water depth and specific discharge (m^2/s)	Business sector/ ATKIS land-use classes	Three figures: Building, Equipment, Inventory

Source: (Kreibich, 2010)

Flood Loss Estimate Components

The flood loss estimation methodology consists of two components that carry out basic analytical processes. These are flood hazard and flood loss estimation analysis. The flood hazard analysis module uses characteristics, such as frequency, discharge, and ground elevation to estimate flood depth, flood elevation, and flow velocity. The flood loss estimation module calculates potential loss estimates from the results of the hazard analysis. The potential loss estimates analyzed through this process include physical damage to residential, commercial, industrial and other buildings, debris generation which includes the distinction between different types of materials, economic loss which includes lost jobs, business interruptions, and repair and reconstruction costs, and social impacts which includes estimates of shelter requirements, displaced households, and population exposed to scenario floods.

CHAPTER 3

METHODS

3.1 Study Area

3.1.1 Geography

The city of Gonaives is located at 19°27′ north and 72°41′ west in the northern part of Haiti. Gonaives stands as the third most populated cities of the country with a population of 263716. The population in its entirety has decreased by 10.7% in 2009 (i.e. 235340 inhabitants) (IHSI, 2009). That reduction is due to the exodus of people that flew, died and disappeared from five major disasters (Jeanne, Fay, Gustav, Hanna and Ike) since 2004. Haiti has a warm and humid climate with rainfalls ranging annually from 400 to 4000 millimeters. The average annual rainfall for the whole country is 1400 millimeters. The watershed of Gonaives has an average annual rainfall of 1307.96 millimeters (Prophète, 2006). Gonaives is considered a semiarid area. The aridity is due to the effect of Foehn winds that come from the northern Atlantic Ocean. The Municipality of Gonaives is administratively divided into five Sections. These are Labranle, Poteau, Bassin, Pont Tamarin and Bayonnais. The urban area is composed of five sectors: Raboteau-Jubilée, Downtown, Bigot-Parc Vincent, Kasoley and Biénac-Gathereau (IHSI, 2009). Gonaives is crossed by the National Route 1 which connects the region to Port-au-Prince, the capital located at 110 km south, and to the North part of the country. Figure 3 displays the administrative subdivisions of Gonaives.

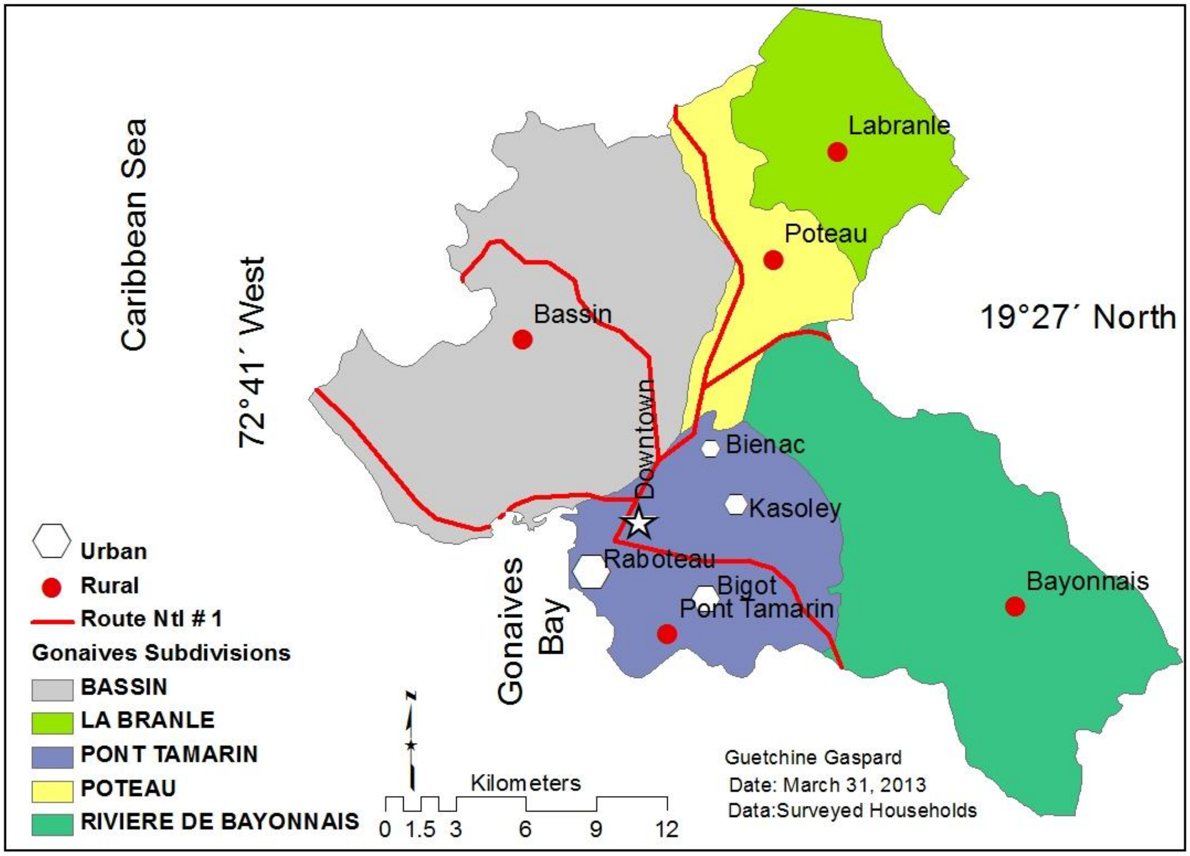

Figure 3. *Map Showing the Location the Municipality of Gonaives with the Major Divisions.*

The Quinte Watershed overhangs the highest and the most mountainous region of the Artibonite Department and covers an area of 700 km^2. The basin belongs essentially to the Municipality of Gonaives and less importantly to the surrounding municipalities such as Ennery and Marmelade. The watershed is crossed by several tributaries of the Quinte River. The most important are Branle River from north, Ennery River from northeast, Bassin River, and Bayonnais River draining the south side. The elevation of the terrain varies from sea level in the southwest to 1,000 meters (Prophète, 2006).

3.1.2.- Soil Properties

The soils are Clay-loam in the Quinte Watershed (Prophète, 2006). In certain downstream areas, the soils are suited to practice agriculture. Contrarily, other soils located in steep slopes at about 40% susceptible to erosion are convenient to practice agroforestry. Generally, the most part of the Quinte Watershed is made of mountains where farming is not practiced according to soil conservation practices and techniques.

Annually, soils are exploited in the Quinte Watershed to produce cash and subsistence crops. However, few farmers use conservation practices in order to reduce soil losses and to simultaneously reduce the degradation of the ecological systems in the watershed. The uncontrolled deforestation and the absence of soil conservation practices led to water erosion and to the desertification process. Thus, the area is considered one of the zones exposed to unprofitable production (Prophète, 2006).

The intensification of traditional agriculture in the country with the increase of needs in food often has unwanted environmental and ecological consequences such as soil erosion, salinization, and contamination of rivers with the use of chemicals. The situation is not different from that of Haiti and the Quinte Watershed. Non sustainable agricultural practices contribute to abuse the soil and to contaminate rivers and water springs. The entire tributaries of the Quinte Watershed are in a state of deterioration with a relatively low vegetation cover. The lack of plant cover exposes the arable layer of the soils to the continual washing caused by pouring rains. That entails in every shower a significant part of land into the sea.

The type of soil hydric erosion contributes to subtract tons of sediments from the watershed, to increase the gullying and the impoverishment of soils which considerably reduces the agricultural space of the region (Bernardin, 1993). The soils in the Quinte Watershed are eroded during the dry season by winds the same way they are eroded by rains during the rainy season. However, it is worth mentioning that the hydric erosion is more severe. The risks of soil erosion in the Municipality of Gonaives vary on a high to very high scale. Gullies formed on both sides of the Quinte Watershed measure about 5 to 7 meters large. The small ones measure between 0.50 and 0.70 meter deep against 1.5 to 5 meters for the biggest. A land cover land use map for the Municipality of Gonaives is presented in Figure 4. Also, an erosion map is shown in Figure 5. The geographic elements (scale bar, north arrow, legend) of the two maps (Figure 4 and Figure 5) were modified. Their titles were taken away for visualization purposes and to comply with the academic requirements.

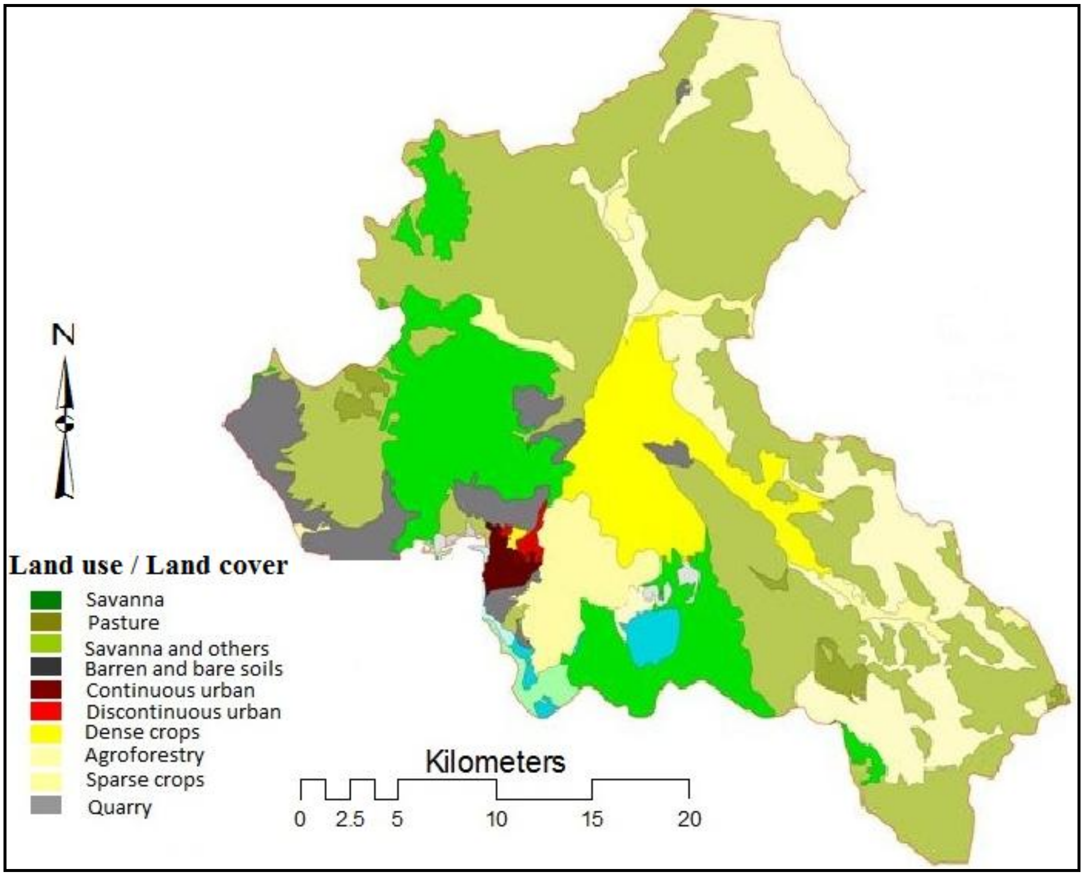

Figure 4. Land Cover and Land Use Map of Gonaives *(UTSIG/MPCE/Haïti, 1998).*

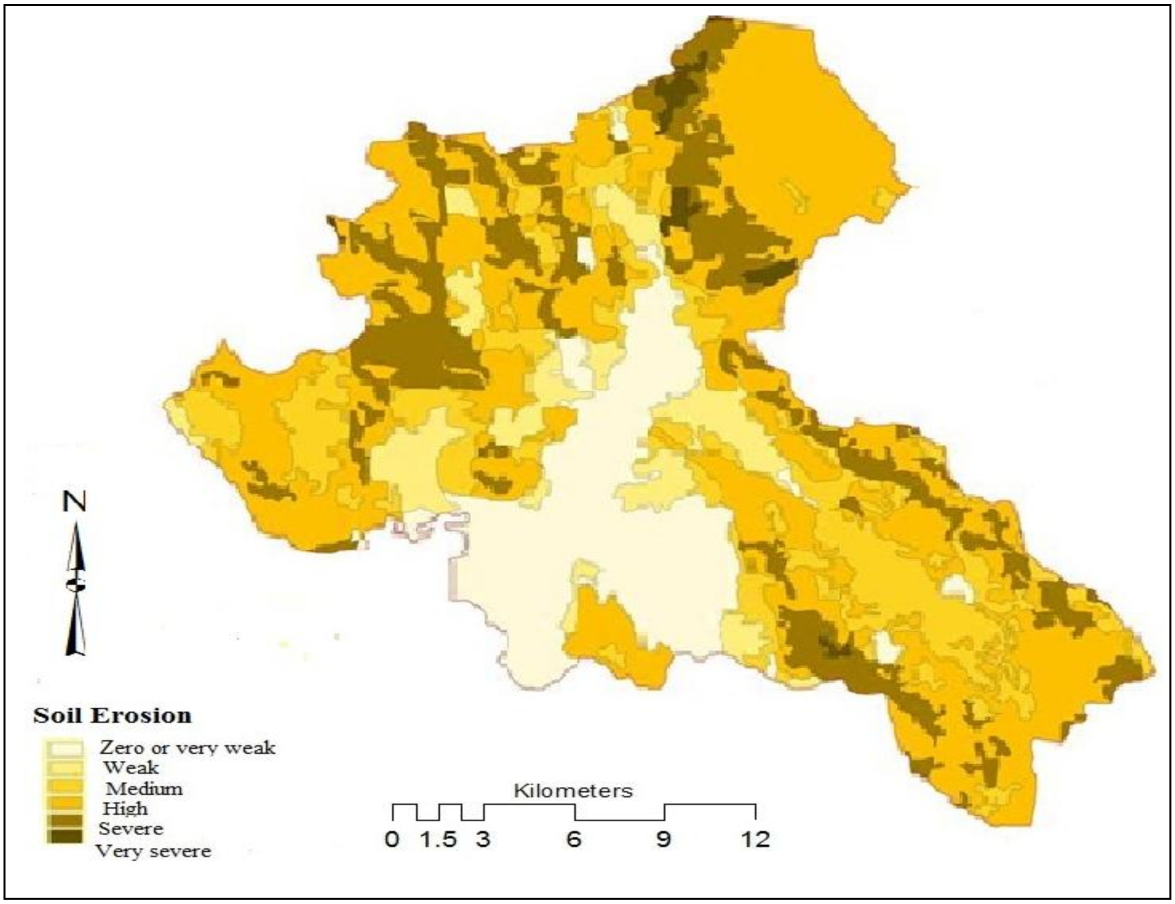

Figure 5.- Soil Erosion Risk Map for Gonaives (*UTSIG/MPCE/Haïti, 1998*)

3.1.3.- Water Resources

In Haiti, the rural population suffers from a shortage of water. Access to drinking water is very difficult. According to Magny (1991) as cited in Prophète (2006), less than 14 liters of water are available for a person on a daily basis. The water scarcity is more severe in certain rural zones of Gonaives such as Labranle which is one of the most disadvantaged Sections. The supply in drinking water of the Gonaives population relies in part on the purchase of bottled water prepared by companies located in other cities or in the neighboring Dominican Republic. Many people consume water pulled out of wells but the water is not good because of its salinity. In the Quinte Watershed springs are harnessed in certain area in order to provide the population with drinking water. On the other hand, the shortage of drinking water is a major problem in the Labranle region. It is a mountainous location where the infiltration capacity of the rain water is low and the installation of irrigation infrastructures as well as the systems of drinkable water conveyance is very expensive. The hydrographic network of Gonaives is presented in Figure 6.

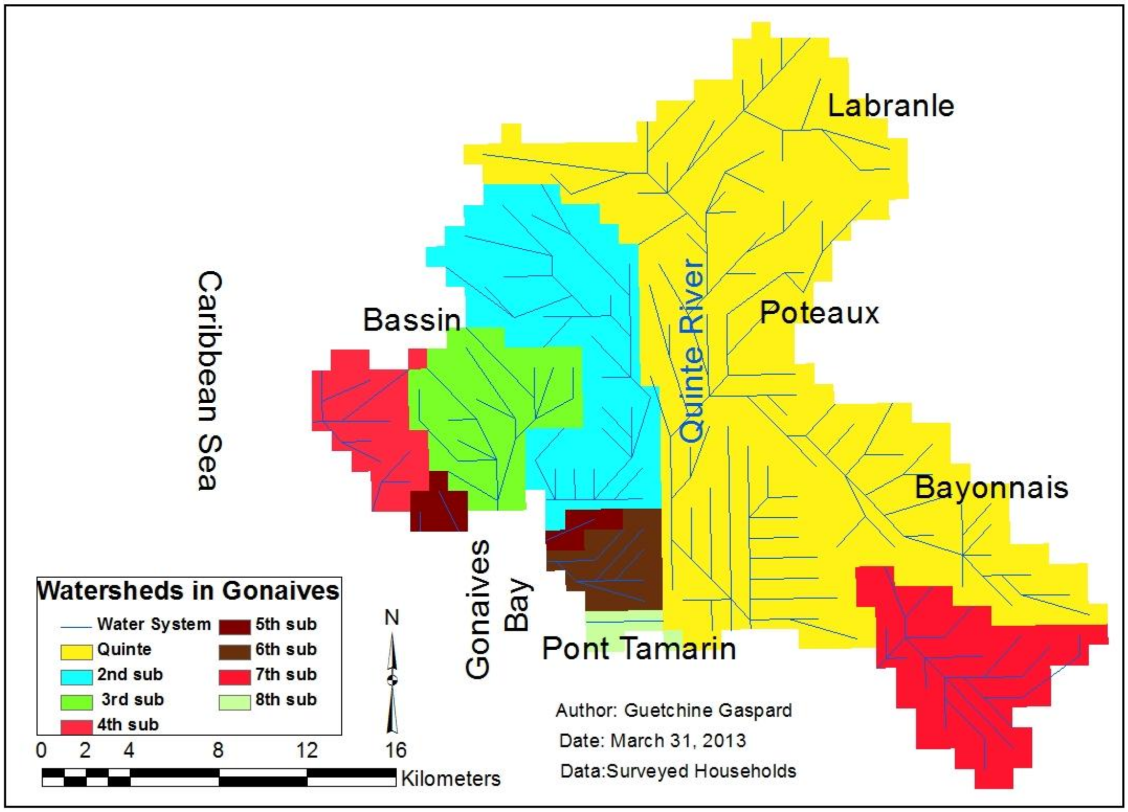

Figure 6. *Map Showing the Watersheds in Gonaives*. The Quinte River has the largest watershed. The major damages are generally caused when it is swollen during the cyclonic season from May to November.

3.1.4.- Economy

The Haitian economy has known considerable decrease over the last few years. Political instability, weakness of the public institutions, illiteracy, lack of investment, and deterioration of the infrastructures make the economic recovery difficult. The important amounts of international assistance granted in Haiti decreased in recent years. The 822 resolution of the OAS in 2002 supported a resumption of dialogue between international financial institutions and the Haitian Government to find a mutual agreement on the preliminary technical conditions in the resumption of the activities, but the results were not satisfactory (Prophète, 2006). The living cost appreciably increased during the last five years at the rate of 15.5 % a year. Housing and food supply prices increase while people's income, in particular those living in rural areas, remains very low. The annual average income of the countrymen in Haiti is estimated at approximately 115 U.S. Dollars (Alleyn, 2006 as cited in Prophète, 2006). On the other hand, a reduction in the agricultural productivity is observed in rural areas, particularly in the production of rice. The valley of Gonaives is considered the rizicole attic of the country. The total volume of goods exported decreases considerably whereas the imported volume increases. In the Quinte Watershed, people have severe economic problems. The yield on the agricultural plots of land decreases because of the deterioration of farmlands and the rarity of irrigation water during the dry season. Table 5 and Table 6 present the cropping calendar in Gonaives. There have been no projects of rural financing over the last few years that facilitate women to undertake non agricultural activities such as the commercialization of staple commodities which would help them to hold out (Prophète, 2006).

Table 5. Cropping Calendar in the Quinte River Watershed (without irrigation)

Crops	**Sowing**	**Harvest**
Bean	April-May (1)	July
	August-September (2)	November
Corn	May	September-October
Sorgum	June	January
Peanut	May-June	November-January
Pigeon Pea (Cajanus Cajan)	May	January
Manioc	May-June	After 18 Months
Sweet Potato	May-June	November-December
Tomato	June	October-November

Source : (Prophète, 2006)

Table 6 : Cropping Calendar in the Quinte River Watershed (with irrigation)

Crops	**Sowing**	**Harvest**
Bean	November-December	February-March
Sorgum	February	May-June
Rice	May-June	October-November
Carrot, beet, tomato	September-November	January-March
Shallot	August (1)	November
	January (2)	March-April
Onion	December-January	May-June

Source : (Prophète, 2006)

In the Quinte Watershed as everywhere else in the Haitian rural environment subsistence farming is practiced. However, cash crops are produced at a small scale. Truck farming crops (hot pepper, tomato, shallot, carrot, beet among others) are mainly produced to be marketed. During the harvest period, small shopkeepers called “Madan Sara” buy agricultural commodities from the farmers and resell them in the Downtown area of Gonaives or in Port-au-Prince. Small vans provide transportation for products from the region of production to the points of sale. Generally, women take care of the sale of farm products, but it is necessary to underline that the existence of a formal and organized market to sell agroforester products is lacking.

3.1.5.- Land Tenure

In the High-Artibonite region, most of the land owners are rich. They possess large surfaces in rural areas while living in town. Generally, farmers are owners of small surfaces. They either use lands belongings to the State or to the big owners on the basis of a lease. However, in the zone of Quinte Watershed, farmers are generally owners of their plots of land. In certain cases, they occupy lands belonged to the State. In such cases they enjoy the right to exploit trees grown on the land.

3.2 Data and Methods

The flood estimation model developed in this study combines six factors to explain the variation of flood damage costs in Gonaives. These are income, inundation duration, inundation depth, slope, population density and distance to the major roads. Each of those variables was collected and processed differently. In fact, information such as receipts and expenses that allow calculating income were collected by surveying flood victims in Gonaives. Then, the values were inserted into an income field and joined to a spatial table containing the administrative subdivisions of Gonaives for further analyses. Similarly, the damage costs were collected during the same survey and spatially joined to the table. The only difference is that no calculation was made to derive the costs. The interviewee was simply asked to estimate the amount of money he or she would pay to repair the damages which will later have been used as the flooding cost for that particular household. On the other hand, depth was obtained through field measurements. This time, the interviewee was only asked to identify the spot the water reached. Once the position was identified, the height was measured and recorded into the same questionnaire of the survey. Then, the depth and duration variables were added to the common spatial table to be later analyzed with the others. As for duration, the respondent was asked to estimate the time that the water had lasted on the ground. Unlike the previous factors which were collected or derived from survey, slope was obtained from a digital elevation model of Haiti downloaded from the diva-gis.org website (2009). From the DEM, the region of Gonaives was extracted, cleaned, filled, projected and converted into slope percentages. Then, the percentages were reclassified into 30 categories and joined to the rest of the variables. The population density was determined and compiled from tabulated numbers and percentages found in a report written on Gonaives in 2009 by the Haitian Informatics and Statistics Institute. Thereafter, the data were normalized joined to the spatial table. Finally, a road layer was extracted for Gonaives from a national road network downloaded from www.diva-gis.org (2009). A 30 rings buffer of 140 meters each was run on the road layer. The buffer layer was overlaid with the point damage cost layer in order to measure the distance of each point to the road. Like the six other variables, the values were inserted under a distance field in the same spatial table. Figure 7 and Figure 8 present respectively the preparation of the variables and the flood damage cost modeling process.

After the processing and preparation of the variables, the analysis step was ready to taken. All the data were exported into Excel to undergo a preliminary analysis. A correlation matrix and scatter plots of the variables were generated. That basic analysis signaled that duration and depth factors were highly correlated. Despite the fact that redundancy was detected between duration and depth, we decided to move forward since we could not tell which one of the two was to be discarded. At that point, income, duration, depth, slope, density and distance were combined as explanatory variables against flood loss cost as the dependent variable to run the ordinary least square (OLS) regression analysis. The interpretation of the variance inflation factor (VIF) indicator generated revealed that the value of depth was significantly high; therefore it was excluded from the model. The same analysis was later conducted with the remaining variables to create the primary OLS I model. To test the trustworthiness of the model, a Moran's I test was performed to check whether there was spatial autocorrelation in the distribution of the costs' residuals. It turned out that the errors were randomly distributed. Thus, there was no need to run the geographically weighted regression (GWR) analysis since OLS I was reliable to predict flood damage costs at a global level. However, all the variables were permuted in groups of four to check which combination was spatially auto-correlated. Surprisingly, none of the combinations of four variables showed any clustering in the distribution of the residuals. The same process was done for combinations of three factors. Finally, it has been found that the residuals issued from OLS II consisted of the combination of income, slope and population density, deviated from the normal distribution at a global scale; therefore GWR proved to be necessary to check the tendency at a local scale.

Finally, it came the time to interpolate and map the flood damage costs estimated by the OLS I and GWR models. Several interpolation tools were unsuccessfully tested to see which one would best explain the point features. None of them showed enough spatial variability in the interpolation of the loss cost estimates. Among these techniques were Simple and Ordinary Kriging, Inverse Distance Weighted (IDW), Spline interpolator, Point Density and Kernel interpolator. Lastly, the Voronoi Map geostatistical interpolator was successfully used to create Thiessen polygons from the point features.

In the development of this flood loss estimate model for the residential sector, it was assumed that there was neither flood insurance, preparedness plans nor disaster experience; therefore these variables were not considered in the model. Indirect intangible damages were not accounted for in the model because of scarceness of data especially economic and life loss data. Here, the inundation depth is equal to the difference between the water level and the ground level at the entrance as defined by (Zhai, 2005) in the case of a building. Flood duration categories were surveyed in default of maps created from water level and digital elevation models. Conventionally, inundation duration and depth are two primary factors of flood modeling. In this study, income, slope, population density and distance to the major roads were added as four additional variables to build the final conceptual model.

We used a flood loss estimate model developed in Excel and ArcGIS 10 to predict potential flood damages in Gonaives associated with income, duration, depth, slope, density and distance. Each of these factors was collected from a different source or derived differently. Receipts, expenses and money transfer collected through survey enabled us to determine the income variable. The income was calculated for each household using the following formula:

$$R = \sum_{j=1}^{n} \left(PB_j - C_J \right) \qquad (Equation3)$$

Where R is income, PB is gross product of the activity j, and C the costs induced by the activity j.

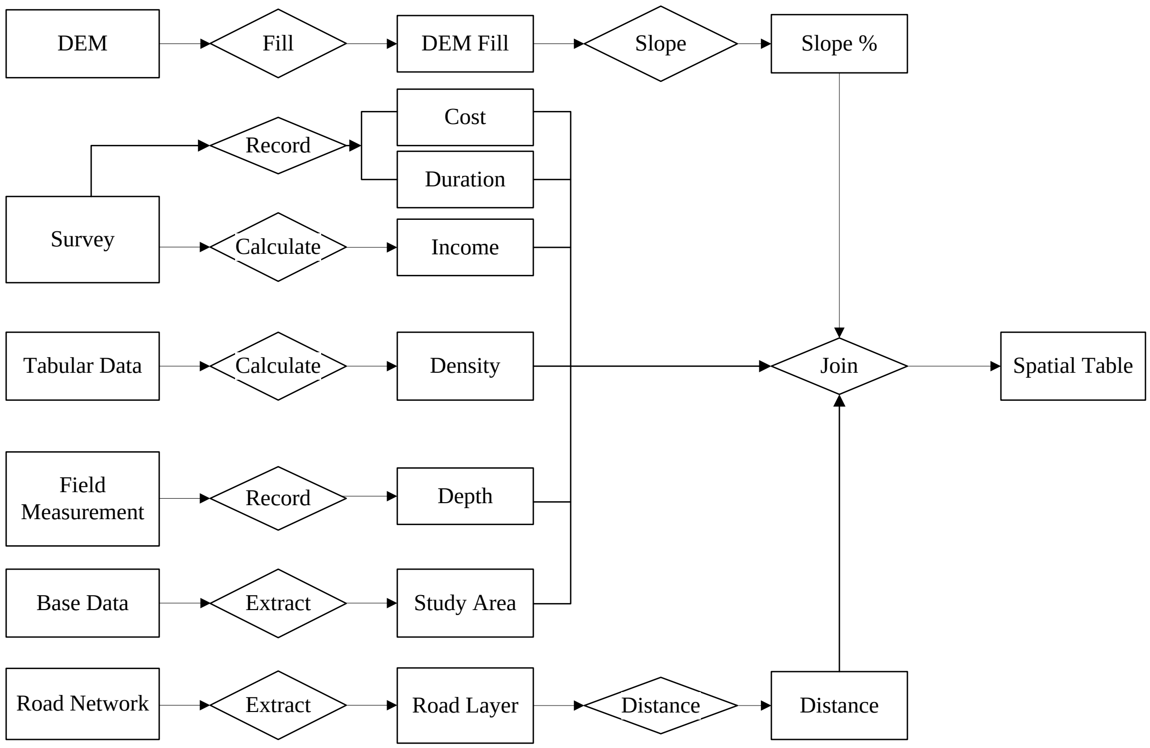

Figure 7. *Processing and Preparation of the Variables*

Table 7. Definition of Variables Used in the Regression Models.

Independent Variable	Dependent Variable	Definition
1-Income		This is the general income constituted of farming, breeding, fishing, off-farm activities, and money transfer from the diaspora.
2-Duration		This is the time that the inundation lasted. It is estimated in minutes.
3-Depth		This is the height that the water reached above the ground level. It is measured in centimeters.
4-Slope		This the slope percentages derived from the digital elevation model of Gonaives.
5-Density		This is the population density expressed in population per square kilometer of the different administrative subdivisions of Gonaives.
6-Distance		This is the distance in meters of the surveyed households to the major roads crossing Gonaives.
	Flood loss cost	The cost corresponds to the amount that an owner spent or would spend to repair the damages. It is given in local currency, the Gourdes (40 HTG = 1USD).

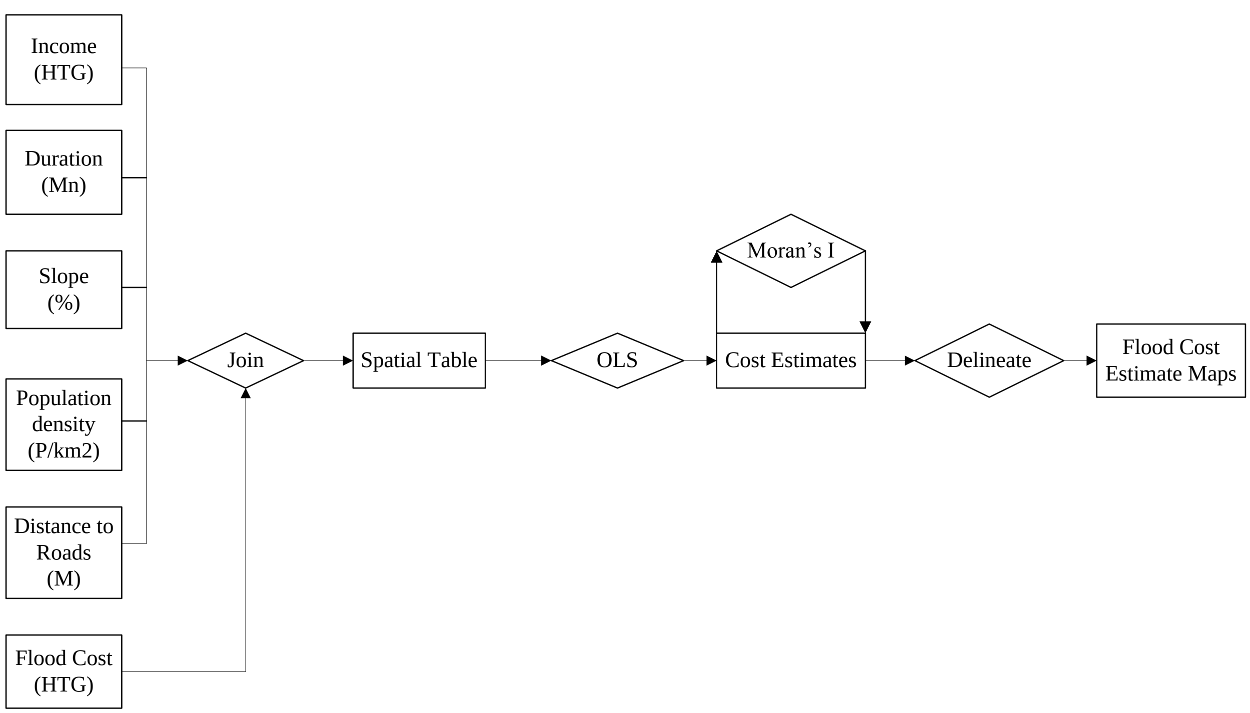

Figure 8. *Flood Damage Cost Modeling.*

3.2.1 Sampling Technique

Municipal Section is the least administrative unit in Haiti. The study area is divided into five Municipal Sections which are Bayonnais, Pont Tamarin, Bassin, Poteau and Labranle. The Quinte River crosses all the five Sections almost equitably. Also, the relief across the Sections does not vary enormously. Based on the relatively homogenous geomorphology of the study area, the systematic random sampling method was used. When determining the sample size, the confidence level, the confidence interval, and population size are the important factors. Because the population households affected by the 2004 floods is large, the population size and the confidence interval factors were not necessary in determining the sample size for the study. Consequently, no power analysis was used to select the sample size. Thirty households were chosen to constitute the sample size. Time and logistics constraints prevented us from investigating a larger sample. It is accepted that a sample size of 30 when representatively selected provides acceptable estimation of the population parameters. Six households were surveyed for each Section. Each household was picked randomly within each Section.

3.2.2 Profile of the Places

In 2003 and prior to Hurricane Jeanne, the majority of the city-dwellers lived in Downtown (24.16%) as opposed to Bigot and Parc Vincent (14.56%). During the same year, 41.6% of the new houses built in the urban area belonged to people in Bigot-Parc Vincent and Jubilée-Raboteau. Then, the Downtown was the most densely populated for the urban area with 24.2 % whereas Biénac with 19.9 % was the least populated. Also in 2003, Bayonnais lodged 28.8%, Pont Tamarin 22.6%, Bassin 24.2%, and Labranle 13.5% of the rural population. Poteau, with 402 inhabitants per km^2, was the most densely populated in 2003. Bassin and Bayonnais were the least dense with 88 inhabitants per km^2 and 180 inhabitants per km^2 respectively. Averagely, 4.7 persons lived per household. Bayonnais had most of the buildings and of the households during that period. Labranle and Bassin had the lowest proportions of buildings with 14.9% and 15% respectively. Table 8 and Table 9 provide information on the households and population age in Gonaives.

Table 8. Distribution of Buildings and Households for Gonaives in 2003

Location	2003			
	Building	**% Building**	**Households**	**% Households**
Bigot- Parc Vincent	5334	20.78	12502	24.16
Jubilée, Raboteau	5349	20.84	9222	17.82
Downtown	5112	19.92	9676	18.70
KaSoley	4844	18.87	10036	19.39
Biénac- Gathereau	5026	19.58	10313	19.93
Total Urban	**25665**	**100.00**	**51749**	**100.00**
Tamarin	6922	23.22	5250	22.2
Bayonnais	5445	18.27	6880	29.1
Poteau	4454	14.94	4577	19.3
Labranle	4472	15	3515	14.8
Bassin	8514	28.56	3453	14.6
Total Rural	**29807**	**100.00**	**23675**	**100.00**

Source : (IHSI, 2009)

Table 9. Age Distribution of the Population of Gonaives by Sex Percentage in 2009

Age Category	Percentage (%)		
	Both sexes	**Male**	**Female**
0-9	19.24	20.26	18.37
10-29	48.24	47.77	48.68
30-54	25.28	25.8	24.89
55-64	4.03	3.29	4.68
65 +	3.12	2.88	3.38

Source : (IHSI, 2009)

According to IHSI (2009), 54.67% of the population was between 15 to 44 years old, 19.24% was under 10 years old and 3.12% had already turned 65years old. According to those data, 22.36% of the population of Gonaives were at risk and exposed during disasters since children and the elderly are the most vulnerable categories.

3.2.3 Survey

At this stage, a questionnaire was prepared which allowed collecting quantitative as well as qualitative information. The quantitative data collected were: flood damage cost, inundation duration and depth, farm size whereas the qualitative data were: crop type, labor type, breeding type, income source, fixed and variable costs. The depth variable was obtained through field measurements.

3.2.4 Model

Ordinary Least Square

The multiple regression analysis was used in order to analyze the variation of income, inundation duration and depth, slope, population density and distance to the roads in regards of the flood loss costs. The primary model is given by the following mathematical expression:

$$D = \beta_0 + \beta_1 Income + \beta_2 Duration + \beta_3 Depth + \beta_4 Slope + \beta_5 Density + \beta_6 Distance + \varepsilon_i .$$

(*Equation 4)*

Where *D* is the estimated cost of the flood damages, β_0 the average cost of *D* when all the regressors (income, duration, depth, slope, density and distance) are equal to zero, β_1, β_2, β_3, β_4, β_5 and β_6 the regression coefficients. The general income is expressed in Haitian Gourdes (HTG), the inundation duration in minutes, the inundation depth in centimeters, slope in percentage, density in inhabitant per square kilometer, distance in meter and ε the error term or residuals in Gourdes.

For the OLS regression model, the five following assumptions are made and tested:

- ❖ The independent variables namely income, duration, depth, slope, density, and distance are accurately measured and each has a finite mean and variance.
- ❖ Absence of systematic bias which means that for any value of the income, duration, depth, slope, density and distance the expected value of the residuals (ε) is zero.
- ❖ Homocedasticity of the errors that is the variance of each residual is the same for all the six regression coefficients independently of income, duration, depth, slope, density and distance as regressors.
- ❖ The residual differences follow a normal distribution.
- ❖ Absence of multicollinearity among the exploratory variables.

To estimate the parameters of the model, the ordinary least square (OLS) method was used. It consists in returning the values that minimize the squared differences between the observed values of the costs (*D)* and those predicted by the model. After testing all the above assumptions, the depth variable was discarded from the primary model. The five remaining variables were kept to comply with the OLS requirements.

Geographically Weighted Regression

The geographically weighted regression (GWR) model has the ability to account for local trends, according to Fotheringham *et al.* (2002), cited in Wilke, (2010). In this study, the GWR analysis was performed for income, slope and density which showed spatial autocorrelation in the distribution of the errors. The model is given as follows:

$$D = \beta_0(u_i, v_i) + \beta_1(u_i, v_i)Income + \beta_2(u_i, v_i)Slope + \beta_3(u_i, v_i)Density + \varepsilon_i \qquad (Equation 5)$$

The dependent variable and the three independent variables remain unchanged. The coefficients are multiplied by the location variable (u_i, v_i). Furthermore, the Voronoi geostatistical method was used to delineate the statistics and the flood damage costs estimated by both OLS and GWR analyses.

3.2.4.1 Statistical Tests

Significance Test

This test enables to verify the significance of the estimate parameters as well as the overall model. The student test is performed to verify two hypotheses. The null hypothesis (H_0) which states that the five regression coefficients are equal to zero and the alternative hypothesis (H_1) stipulating that at least one of the them is different from zero that is:

H_0: $\beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = \beta_6 = 0$

H_1: $\beta_j \neq 0$ for at least one *j*, *j* = 1, 2, 3, 4, 5 and 6

Multiple Determination Coefficients

The R^2 is the proportion of the *D*'s (damage cost) total variability given by the regression. It measures the ability of the model to explain the variations in *D.* However, this test uses the ratio of the explained variance on the unexplained. It obeys the Fisher's law.

Absence of Multicollinearity Test (Klein and Tolerance)

This aims at using independent variables that maximize the correlation with the flood damage cost dependent variable while keeping the correlation among themselves at the lowest possible level. The Klein and the Tolerance indicator tests account for these assumptions. Also, the R statistics are compared among themselves.

Heterocedasticity Test (Barlett Test)

This test consists in dividing the population into samples and testing the variance of each error. This test was not necessary for this study.

Residuals Normality Test (Jacque-Bera statistics):

This test measures the effectiveness of the estimators and their maximum likelihood. It is based on the chi-square (χ^2) distribution. The null and alternative hypotheses are given as follows:

H_0: Normality of the Residuals

H_1: The residuals distribution is not normal

The test is based on a function of the shape coefficients: skewness and kurtosis. The null hypothesis is accepted if the calculated value for the function is less than the tabulated value of the χ^2 table for 95% level of confidence and 2 degrees of freedom.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Preliminary Results

4.1.2. Model Analysis

During the first steps of the modeling process a correlation matrix for all the variables was created. The values show that flood loss cost is highly correlated with inundation duration and depth (i.e. 84% and 80% respectively). It is negatively correlated with slope and distance variables. With 13%, density is the less correlated to the dependent variable. As for the variation among the independent variables themselves, the values remain relatively low (5%-42%) except for the correlation between duration and depth which is as high as 92% and that between income and depth which is 53%. That means that duration will provide the same information as depth as accurate as ninety two percent. That multicollinearity is shown in Figure 10 in which the trend between duration and depth is positive and almost linear. These statistics only signal the strength of the model as well as the presence of redundancy between duration and depth which are two important variables in flood damage estimation modeling. That was a basis for the reevaluation of the initial model to comply with the absence of multicollinearity assumption of the regression analysis. The information about correlation is summarized in Table 10 and drawn in Figure 9 and Figure 10.

Table 10. Correlation Matrix of the Variables

	Cost	Income	Duration	Depth	Slope	Density	Distance
Cost	1						
Income	0.51	1					
Duration	0.84	0.42	1				
Depth	0.80	0.53	0.92	1			
Slope	-0.36	-0.05	-0.25	-0.17	1		
Density	0.13	-0.23	0.21	0.22	0.15	1	
Distance	-0.52	-0.20	-0.34	-0.16	0.19	0.13	1

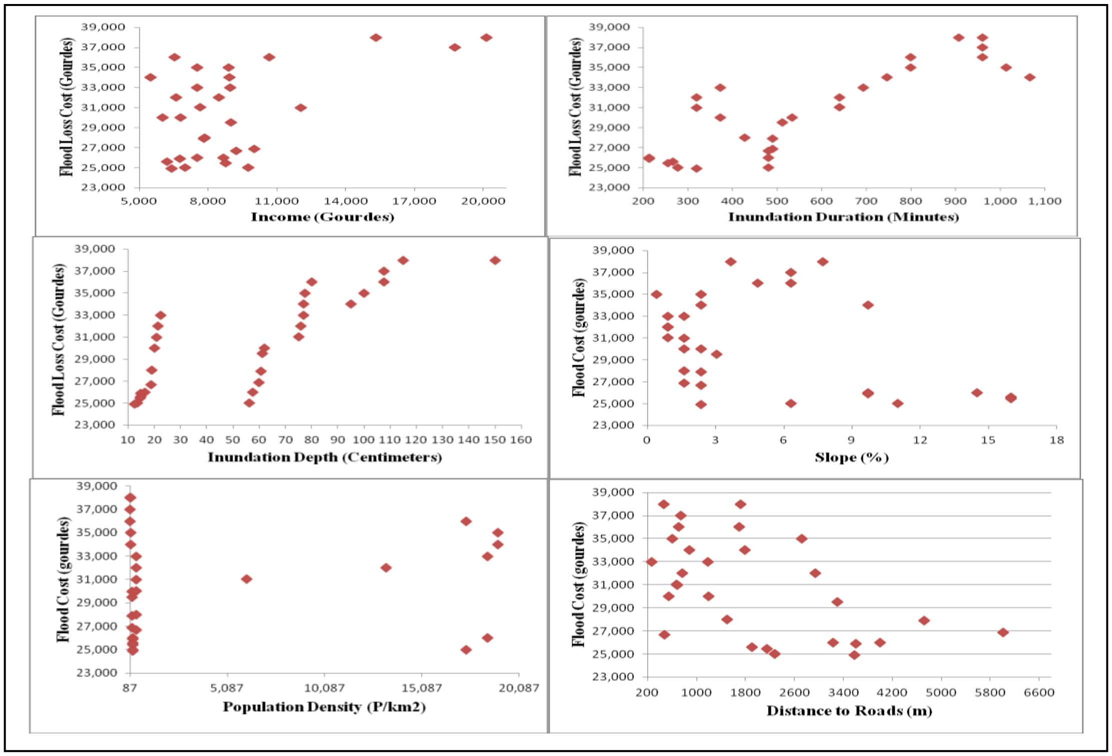

Figure 9. *The Variation of the Flood Loss Cos*t. These scatter plots show the variation of the damage cost depending on the income, inundation duration and depth, slope, density and distance variables. The graphs show that the cost varies both positively with income, duration, densityor negatively with slope and distance factors.

Figure 10. *The Variation among the Independent Variables*. The scatter plots signals the existence of collinearity between duration or depth which may flaw the model.

4.1.2 Spatial Statistics Results

Further analyses were necessary on the model in order to find out which factor is to be excluded between duration and depth to eliminate multicollinearity in the final model. As a matter of fact, the OLS analysis was run with all the six variables. Several spatial statistical results were generated. The results revealed that depth had the highest VIF (11.08) which is an indicator of redundancy. Table 11 gives the VIF values, the regression coefficients and the t-statistics for all the variables. Based on that fact, depth was discarded from the model in favor of duration. At that point, further interpretation of the other estimators was not necessary. Deeper interpretation and discussion of all the statistics are provided for the subsequent models.

Table 11. Statistical Results for the Initial OLS Model

	Income	Duration	Depth	Slope	Density	Distance
VIF	1.90	10.38	11.08	1.15	1.37	1.49
Coefficient	1.19	3.62	46.13	-167.14	0.06	-0.99
t-statistics	1.34	0.83	1.46	-2.03	1.02	-3.27

4.2 Model Reevaluation

The initial model was reevaluated according to the following form for not satisfying the multicollinearity assumption. The preliminary analyses showed that the depth variable was positively correlated with the duration independent variable.

$$D = \beta_0 + \beta_1 Income + \beta_2 Duration + \beta_3 Slope + \beta_4 Density + \beta_5 Dis\tan ce + \varepsilon_i \qquad \text{(Equation 6)}$$

Ordinary Least Square I (OLS I)

As presented in Table 12 below, OLS I is the primary model which is composed of all the five independent variables. It is also the final model after the depth variable was discarded. OLS II is the submodel that shows spatial autocorrelation of the damage cost residuals at a global scale; therefore the GWR was run on it. The VIF statistics is an indicator of redundancy and multicollinearity in regression modeling. A VIF greater than 7.5 indicates that there is redundancy among the independent variables. All the VIF values in OLS I are less than the critical value (0.00, 1.42, 1.69, 1.14, 1.32 and 1.19 < 7.5). They confirm that the model is free from multicollinearity. The R^2 statistics indicates that the factors account for the damage cost for 83% in OLS I. This percentage tells that OLS I performs very well. As for the t-statistics, a significant value rejects the null hypothesis (H_0) stipulating that the independent variables have no influence on the dependent variable. In OLS I, the observed t-values of 16.57, 2.33, 5.24 and -2.85 representing intercept, income, duration and distance respectively are significant since they are all greater than the critical value of 2.042 at 5% threshold and for 29 degrees of freedom. That is $t_0, t_1, t_2, t_5 > |t_{(0.05; 29)}| = 2.042$. The values indicate that these factors influence significantly the damage cost variable. On the other hand, slope and density, with the observed t-statistics values of -1.90 and 1.26 respectively, do not influence the damage cost significantly because these observed values are both less than 2.042 ($t_3, t_4 < |t_{(0.05; 29)}| = 2.042$). The Joint-F statistics measures the overall significance of the model. A significant p-value or observed F value indicates that the overall model is significant. The observed F value of 22.80 is greater than the critical value of 2.62 at 5% error and for 5 and 24 degrees of freedom. That confirms the alternative hypothesis (H_1) stipulating that at least one regression coefficient is different from zero ($22.82 > |F_{(5; 24)(0.05)}| = 2.62$). The results suggest that the model is significant. The Joint-Wald statistics measures the robustness of the significance. The observed value of 317.15 is largely greater than 11.07 chi-square critical threshold for 5 degrees of freedom and at 95% degrees of confidence ($317.5 > |\chi^2_{(0.05; 5)}| = 11.07$). That tells that the model is robustly significant. The Keonker BP statistics measures the tendency of the errors and the significance of the estimates. A significant p-value indicates that the errors are biased and recommends using robust estimates. Here, the observed value of 5.05 is less than 11.07 critical values. The null hypothesis (H_0) stipulating that the errors are unbiased is accepted for 5 degrees of freedom and at the 0.05 level ($5.05 < |\chi^2_{(0.05; 5)}| = 11.07$). The Jacque-Bera statistics measures the distribution of the errors. A significant p-value indicates that the residuals deviate from a normal distribution. The 1.86 observed value is less than the critical threshold of 5.99 ($1.86 < |\chi^2_{(0.05; 2)}| = 5.99$). That confirms the null hypothesis (H_0) stipulating that the residuals are homocedastic which means they vary according to a normal distribution. The Moran's I analysis is done to test the randomness of the residuals' distribution. A small Moran's Index and p-value indicate a tendency of dispersion. The 0.87 observed z-score value is less than the 1.96 z-score critical value at the 5% error level. The findings indicate that the residuals are randomly distributed. Figure 11 illustrates the normality in the distribution of the OLS I residuals. The map on the figure shows that the errors are homogenously distributed toward the center of Gonaives along the Quinte Watershed.

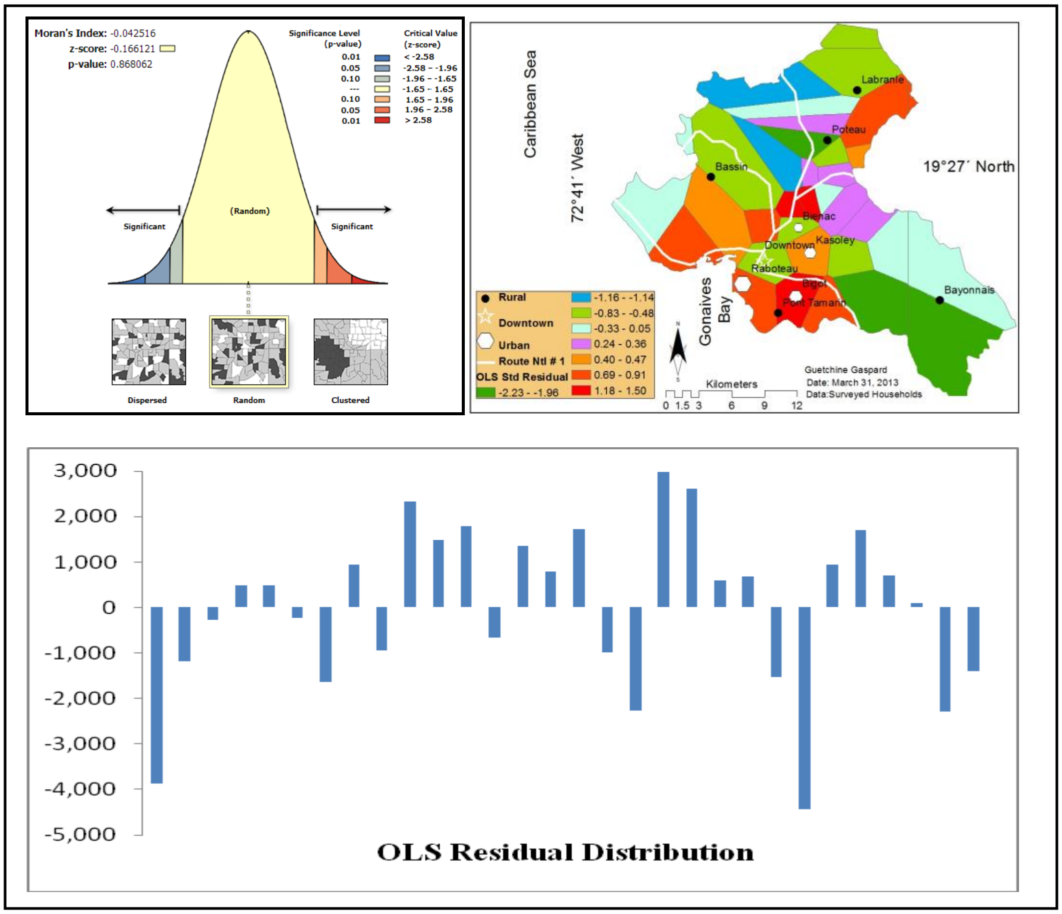

Figure 11. Moran's *I test result for the OLS I model.* The figure shows that the distribution of the residuals is random for the primary OLS model, a necessary assumption for the regression model fitness. There is neither clustering nor dispersion in the distribution of flood loss cost.

Ordinary Least Square II (OLS II)

The final OLS I model is trustworthy to predict flood damage costs in Gonaives. Indeed, it met all the requirements of the multiple regression analysis. The factors are exogenous, the model is significant, there is no collinearity and the errors are homocedastic. Thus, there was no need to run the GWR analysis since the latter is necessary only when the residuals of the OLS analysis are spatially autocorrelated. However, scientific curiosity pushed the author to discover for which combination of variables the errors of the OLS analysis would deviate from the normal distribution. As a result, income, slope and density satisfied that combination. In fact, these variables when combined perform poorly at the global level. They only account for the damage cost for 47%. This is extremely low compared to OLS I. It is logical that the VIF values did not vary much differently from those of OLS I since the variables and their values had not changed. Like the observed t-statistics in OLS I, the observed t-statistics for the three respective factors are significant for they are greater than the 2.042 critical values (3.86, |-2.64|, 2.14 >$|t_{(0.05;\,29)}|$ = 2.042). That tells that income, slope and density influence the flood loss cost dependent variable. Similarly, the observed Joint-F statistics is significant for being greater than the 2.98 critical thresholds for 3 and 26 degrees of freedom and at 0.05 level (7.65 > $|F_{(3;\,26)(0.05)}|$ = 2.98). One concludes that the model is significant. Also, the 69.56 observed Joint-Wald statistics is significant because it is greater than the 7.82 values read in the chi-square table for 3 degrees of freedom and at the 5% error level (69.56 > $|\chi^2_{(0.05;\,3)}|$ = 7.82). This translates the robustness of the OLS II's significance. Like OLS I, OLS II model went on to satisfy the regression analysis assumptions through the Keonker and Jacque-Bera statistics by accepting the null hypothesis. The tests suggest respectively that the errors are unbiased and that the residuals follow a normal distribution. Both 0.91 and 0.82 are less than the critical threshold of 7.82. So, the reliability of OLS II came down to the Moran's I test. As a matter of fact, the 6.97 observed z-score is much larger than the 1.96 z-score critical value at the 95% level of confidence. Table 12 contains the results for OLS II in numbers whereas Figure 12 shows visually that the residuals are clustered at the global scale.

Geographically Weighted Regression (GWR)

At this point, the GWR analysis was necessary to gauge the impact of income, slope and density factors on flood loss costs at a local scale since they were ineffective globally. Table 12 shows that the variables explain the damage cost as high as 74% which is enormous by comparison with the 47% of the OLS II homologous model. The local R-squares are mapped and presented in Figure 13. As for the t-statistics, though, density does not significantly influence the model with the 1.36 observed t-statistics (1.36 < $|t_{(0.05;\,29)}|$ = 2.042). Despite the fact that density does not weight much, the model's residuals are free from spatial autocorrelation. The absolute value of the observed z-score of -0.28 is less than the absolute value of -1.96 critical value (|-0.87| < |-1.96|). The null hypothesis stipulating that the errors are randomly distributed is accepted. Figure 12 shows the randomness in the distribution of the GWR's residuals. It also presents a histogram and a map of the GWR standard errors.

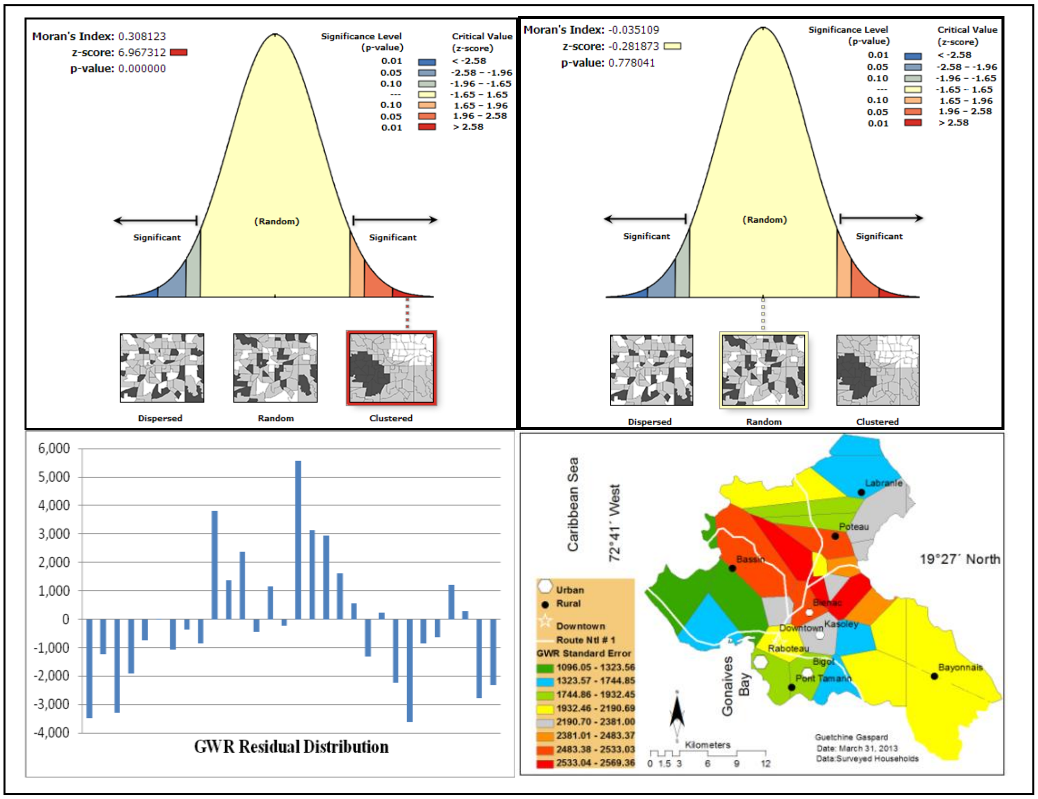

Figure 12. *Variation of income, slope and density at global and local level*. The map shows spatial autocorrelation in the residuals at global scale and none at local scale. Also, it shows that more errors occurred around Poteau.

Table 12. *Statistical and Spatial Autocorrelation Results for the OLS and GWR Models*. The table contains the results for both OLS and GWR models and their respective Moran's I test results.

Description		Regression Coefficients				
		OLS I	VIF		OLS II	GWR
Constant	β_0	24567.43	0.00	0.00	25120.39	28225.01
Independent Variables	Income	0.29	1.42	1.06	0.71	0.38
	Duration	9.47	1.69	--	--	--
	Slope	-159.66	1.14	1.02	-350.69	-301.24
	Density	0.07	1.32	1.08	0.18	0.12
	Distance	-0.79	1.19	--	--	--
Observed Statistics	R^2	0.83			0.47	0.74
	AR^2	0.79			0.41	0.60
	AICc	545.96			575.46	575.36
	t_0	16.57*			12.58*	11.72*
	t_1	2.33*			3.86*	1.64*
	t_2	5.24*			--	--
	t_3	-1.90			-2.64*	-2.26*
	t_4	1.26			2.14*	1.35
	t_5	-2.85*			--	--
	Joint-F	22.80*			7.65*	--
	Jacque-Bera	1.86			0.91	--
	Keonker BP	5.05			0.82	--
	Joint Wald	317.15*			69.56*	--
	Moran's I	-0.04			0.31*	-0.04
	p-value	-0.16			0.00*	0.78
	z-score	0.87			6.97*	-0.28
Critical Statistics	VIF	7.5				
	$\lvert t_{(0.05; 29)} \rvert$	2.045				
	$\lvert F_{(5; 24)(0.05)} \rvert$	2.62			--	--
	$\lvert F_{(3; 26)(0.05)} \rvert$	--			2.98	--
	$\lvert \chi^2_{(0.05; 5)} \rvert$	11.07			--	--
	$\lvert \chi^2_{(0.05; 2)} \rvert$	5.99			--	--
	$\lvert \chi^2_{(0.05; 3)} \rvert$	--			7.82	--
	$\lvert$z-score$_{(0.05)} \rvert$	1.96				

*: significant at the 5% threshold

The distribution of R-squares in Figure 13 for the GWR model suggests that income, slope and density correctly specify the flood damage costs in Gonaives. In fact, the variables account for the costs more in the southwest of Bassin, the south of Bayonnais and the southeast of Labranle. As for the t-statistics, the maps in Figure 14 show that the income t-statistics are significant only in the urban area and in the northwest of Bassin. It varies from 2.21 through 2.88 which are greater than the critical 2.045 t-statistics values. That means that income significantly influences the damage costs only in these locations. When it comes to the slope t-statistics, the absolute values of the observed ones are statistically significant everywhere except in Raboteau and in the west of Bassin. Finally, it is obvious that only Bayonnais has significant observed t-values for the density variable. Consequently, the coefficients of the factors are interpreted only for these places where the t-statistics are statistically significant.

The regression coefficients indicate the variation of the damage costs average mean corresponding with the different weights assigned to each factor. The maps in Figure 15 demonstrate that the multivariate model's intercept is the highest in the west of Bassin and the lowest in Labranle as high as 31529.03 and 25798.43 respectively. As far as income is concerned, the coefficient values are higher (0.55) in the Northeast of Bassin down to the urban area of Bigot and lower (0.16) in the west of Bayonnais and southeast of Labranle. The income coefficient only matters in bigot since it is the only place where the corresponding t-statistics is statistically significant. When slope and density are fixed, the average flood loss costs mean varies by 0.55 for each unit of income. Like the previous factors, slope shows higher coefficient values in the west of Bassin amounted to 238.60 whereas the lowest -590.38 are recorded in the south of Bayonnais. Contrarily, the population density's coefficients are the lowest in the west of Bassin. There, they reach -0.13 which is very low by comparison with the 2.91 estimated in Bayonnais. These values mean that for each unit of density in Bayonnais, the average of the flood loss costs varies by 2.91 units if income and slope are fixed.

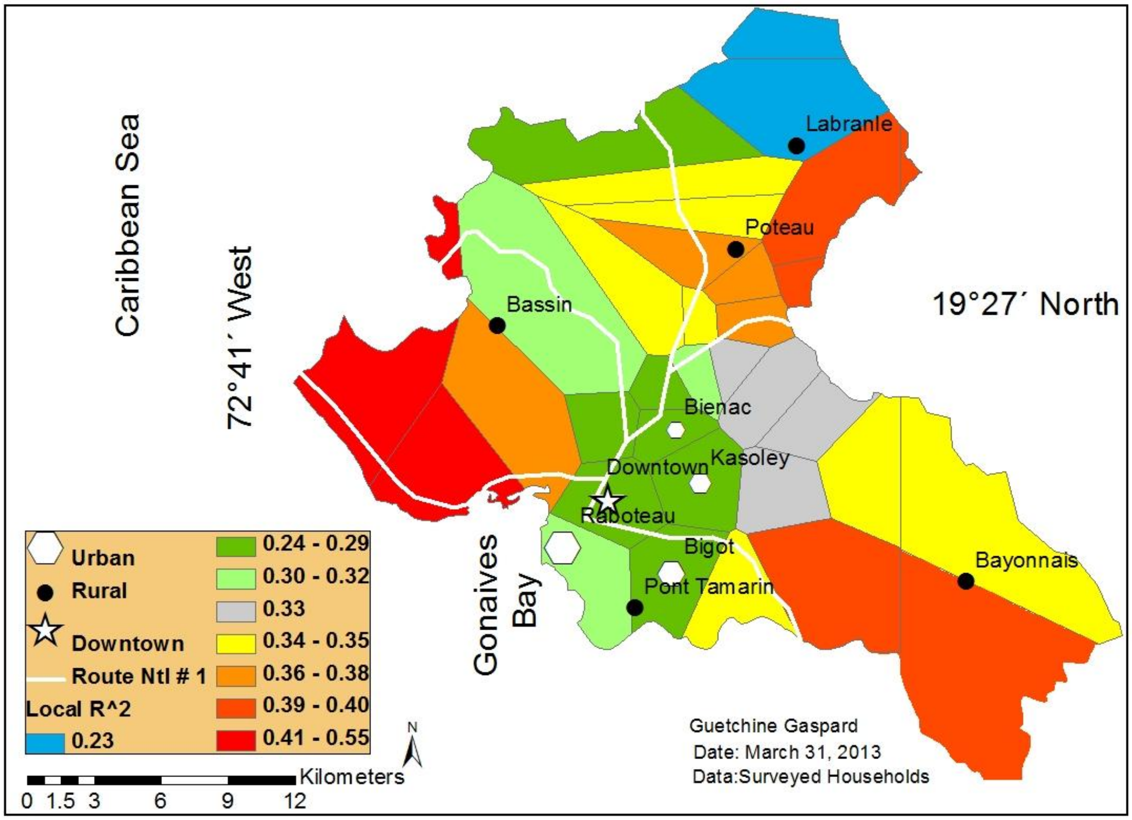

Figure 13. *This map shows the Local R^2 in the GWR model*. The results tell that the model performs much better downstream and along the coast. Income, slope and density locally account for 23% through 55%% of the flood damage costs.

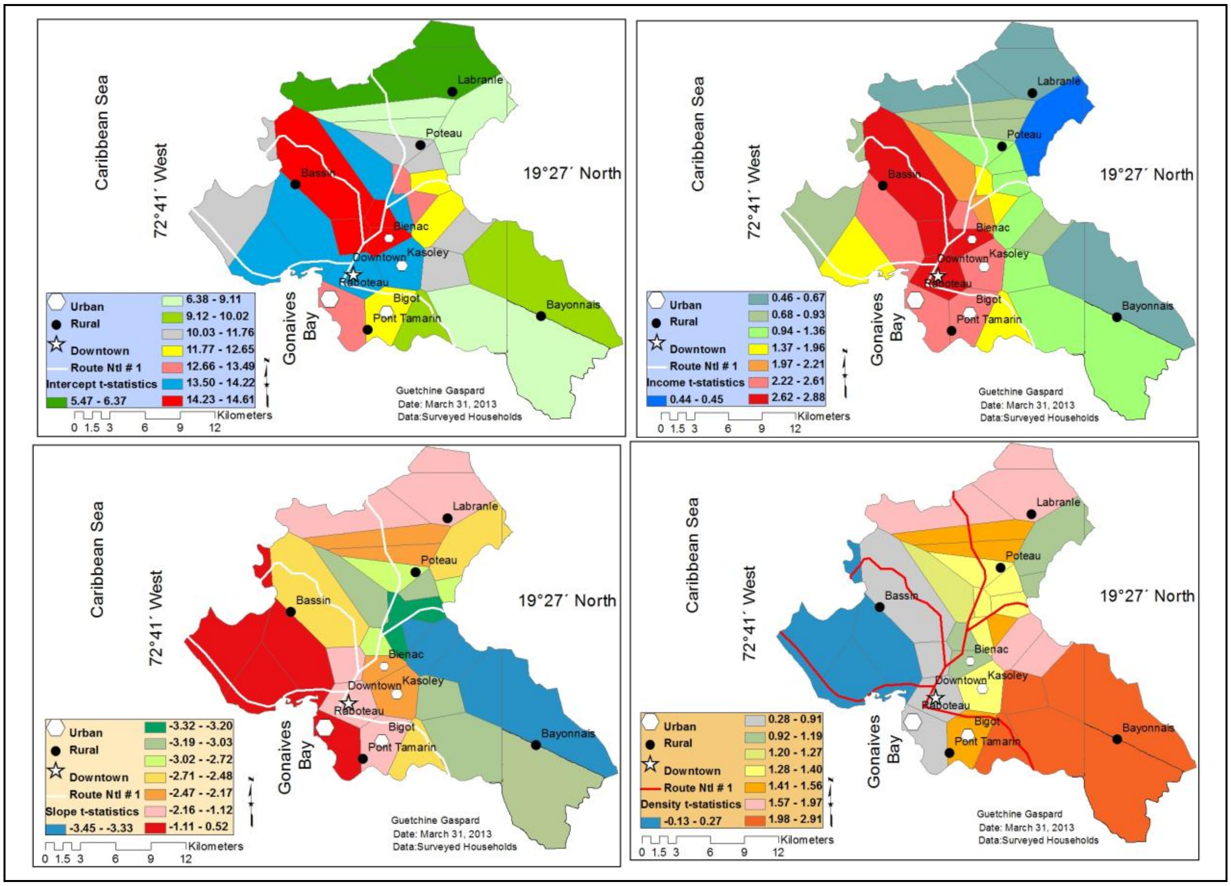

Figure 14. *t-statistics of the GWR model.* This figure contains respectively a map of the intercept t-statistics, income t-statistics, slope t-statistics and density t-statistics.

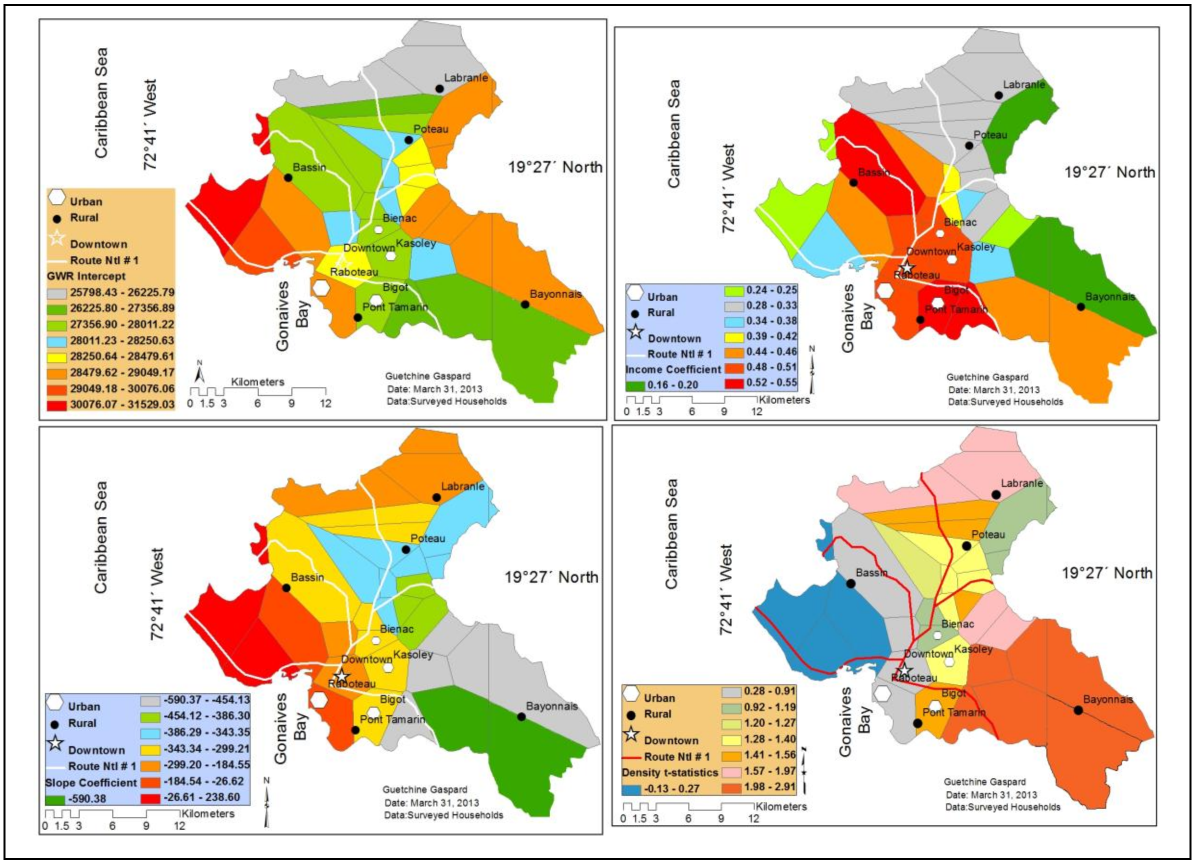

Figure 15. *The intercept, income, slope and density coefficients of the GWR model*. The map shows that the income is more important in the coastal areas of the Quinte River downstream. It is partially due to the diversification of the income with fishing as an economic added value.

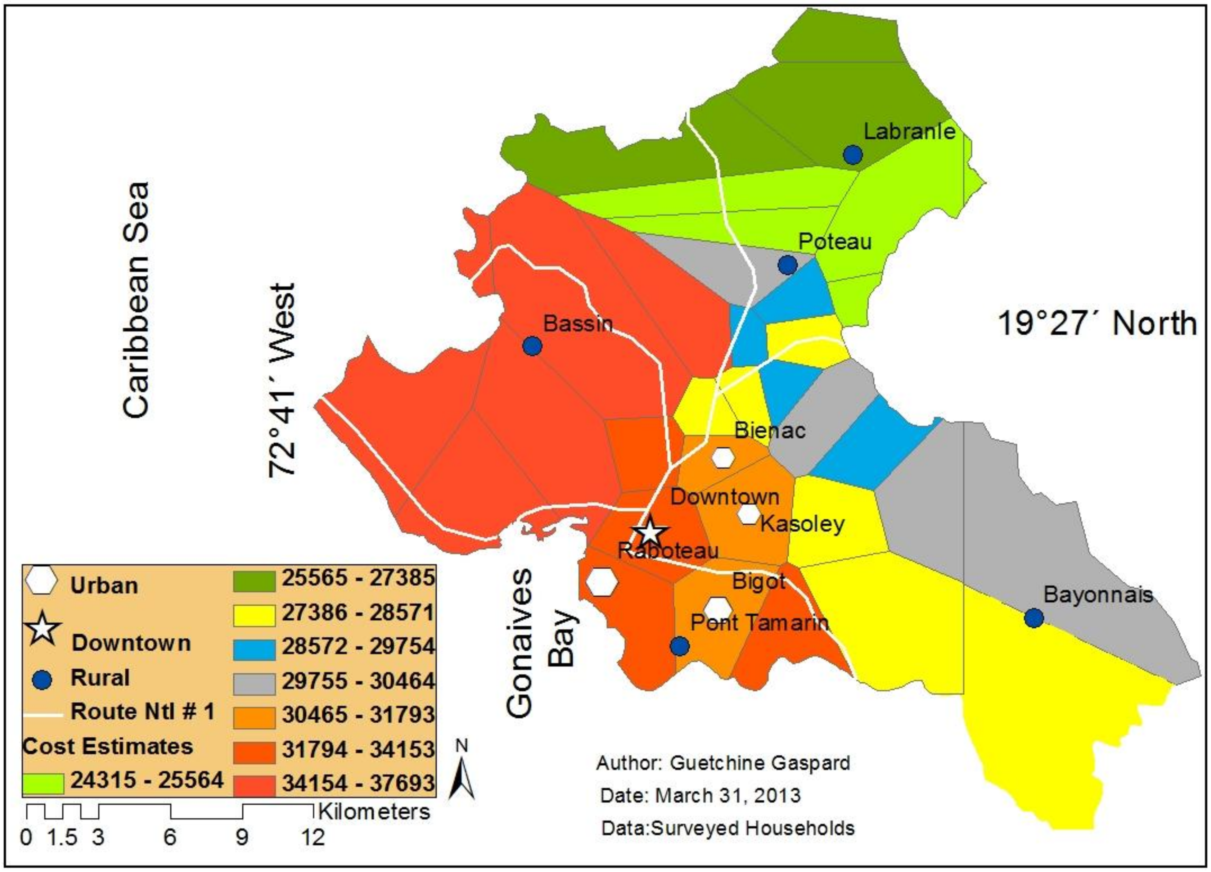

Figure 16. *Interpolation of flood cost across Gonaives*. The map shows the eight classes of flood cost using Voronoi interpolator. The method provides sufficient spatial variability to monitor the flood expenses over the Gonaives area.

The map in Figure 16 shows that the damages were severe essentially in the urban area as a whole and in the major part of the rural area of Bassin. Also, the area of Labranle and parts of Poteau and Bassin were the least severely damaged. The flood damage costs are essentially high in the urban area of Gonaives by comparison with the rural area. In Table 14, the flood loss cost for the urban area is estimated at 1,648,274,782.74 HTG (41,206,869.57USD). The total cost in the urban area is approximately 236.06% times greater than that of the rural area. The lowest damage cost predicted at a household level for the urban area is 30465 Gourdes in Biénac-Gathereau, Kasoley and Bigot-Parc Vincent. The highest loss cost recorded at a household level is 37,693 HTG found in Raboteau-Jubilée and in Downtown. On a gravity scale varying from very low, low, moderate, high moderate, high, very high, severe and very severe, the values fluctuate from very high to severe. In the urban area of Gonaives, the damages were essentially severe in Raboteau-Jubilée and in the Downtown areas. These damages were as high as 45.95% of the urban area. Damages were very high in Bigot-Parc Vincent, Kasoley and Biénac-Gathereau areas which represented 54.05% of the urban area. These observations in the urban area are in harmony with those found by the Haitian informatics and statistics institute (IHSI) stipulating that Raboteau-Jubilée was the most severely affected and Biénac-Gathereau the least severely affected place of the urban area.

The severity of the damages in these areas is the result of several factors. First, the Downtown and the slum of Raboteau are located downstream of the Quite River where the slope is very low. The people are leaving very densely as close as possible to the National Route 1 linking Gonaives to the north of Haiti and to Port-au-Prince to practice income generating activities, buy, and enjoy the localized services offered in these places. As the population density is high the production of waste increases disproportionately to the City Hall's capacity to manage wastes. As the watersheds are degraded and the drainage maintenance is weak and not regular, these places are rapidly covered by tons of embankments and are flooded right after a moderate rain. Approximately 592,000 cubic meters of mud were to be removed after the passage of Hurricane Jeanne (Globalsecurity.org, 2004) clogging the drainage network. Rain water, unable to infiltrate the soil in the watersheds due to deforestation, becomes run-off water. The run-off water washes down the arable layer of the soil. It reaches downstream then it stagnates on the ground, being unable to be drained.

The rural area is generally less damaged than the urban area. The rural damage costs are estimated at 698,222,174.10 HTG (17,455,554.35USD). Averagely, 39.38% of the rural households underwent only low to moderate damages. Visually, that concerned Labranle, Poteau, and Bayonnais. On the other hand, most of the territory of the Bassin area was affected very severely. Likewise, Pont Tamarin was severely struck. These last places correspond to the Quinte downstream and encompass the surroundings of the city area where all the major economic activities and services are concentrated. Labranle, upper Poteau and upper Bassin suffered less for they are located upstream farther from the major National Route #1 by comparison with lower Bassin, lower Poteau, and Bayonnais. In addition to the elevation and the position to the roads, these marginalized populations less densely occupy these lands. The inhabitants practice subsistence farming and raise small animals as the main economic activities. There is a lack of diversification of income generating activities.

After weighing the flood damage costs of each places with its respective amount of households the data revealed other information. Despite the fact that the damages were more severe in the Shanty town of Raboteau and in Downtown, Bigot turned out to have the highest flood loss cost (9,729,368.95 USD). Unexpectedly, Raboteau holds the lowest cost 7,602,040.42 USD for the urban area. Similarly, Bassin along with Labranle has the lowest cost (2,956,131.11 2,268,321.41 USD respectively) in spite of the fact that Bassin was the most affected by Hurricane Jeanne. Located in the south east of Gonaives, Bayonnais is ranked first in the most damaged list with 4,988,487.66 USD followed by Pont Tamarin. These results confirmed the previous findings of IHSI that Bassin along with Labranle was the least damaged by Hurricane Jeanne. This can be explained by the fact that these areas had fewer households. Furthermore, these two zones seem to naturally offer a better refuge from flooding thanks to their altitudes. Table 14 and Table 15 present costs for all the urban and the rural places and their number of households. Table 13 provides the distribution of the damages severity for both the urban and the rural places.

Table 13. Flood Damage Cost Percentages in the Urban and Rural Areas

Rural Places	**Damage cost Gravity (%)**							
	VS	**Severe**	**VHigh**	**High**	**HM**	**Moderate**	**Low**	**VLow**
Bigot	0	0	100	0	0	0	0	0
Raboteau	0	100	0	0	0	0	0	0
Downtown	8.95	91.04	0	0	0	0	0	0
Kasoley	0	0	100	0	0	0	0	0
Biénac	0	0	100	0	0	0	0	0
Pont Tamarin	1.27	43.74	37.49	1.55	0	15.95	0	0
Bayonnais	0	0	0	44.25	6.89	48.86	0	0
Poteau	3.02	0	0	6.09	17.85	16.76	22.11	34.17
Labranle	0	0	0	0	0	0	56.89	43.11
Bassin	79.13	3.56	0	3.23	0	0.74	8.96	4.38

Explanatory notes: VL: very low, HM: high moderate, VHigh: very high, VS: very severe

Table 14. Distribution of Flood Damage Costs in the Urban Area

Urban Places	Total Households		Damage cost per category (USD)			Total cost (USD)
	Total	%	Very Severe	Severe	Very High	
Bigot	12502	24.16	0	0	9,729,368.95	9,729,368.95
Raboteau	9222	17.82	0	7,602,040.42	0	7,602,040.42
Downtown	9676	18.70	777745.57	7261614.10	0	8,039359.67
Kasoley	10036	19.39	0	0	7,810,266.1	7,810,266.1
Biénac	10313	19.93	0	0	8,025,834.42	8,025,834.42
Total	12502	24.16	777745.57	14863654.52	25565469.47	**41,206,869.57**

Table 15. Distribution of Flood Damage Costs in the Rural Area

Rural Places	Total Households		Damage Cost (USD)
	Total	%	
Pont Tamarin	5250	22.2	4,131,535.73
Bayonnais	6880	29.1	4,988,487.66
Poteau	4577	19.3	3,111,078.44
Labranle	3515	14.8	2,268,321.41
Bassin	3453	14.6	2,956,131.11
Total	**23675**	**100.00**	**17,455,554.35**

At a local level, the flood damage costs did not show significant changes in terms of the distribution tendency of the damages' severity. Bassin is still the most severely affected for the rural area. Like Bassin, Raboteau and Downtown remain the most severely damaged in the urban area for the GWR model. However, income, slope and population density variables when taken separately at a local scale show a slight diminution in the damages' gravity in the urban area of

Bigot. The flood loss cost at a household level changed from very high to high moderate in Bigot. That corresponds in value of a decrease of 31129 and 30118.5 HTG averagely. It is obvious in Figure 17 that income, slope and density factors account for the costs more significantly in Raboteau, Downtown, Kasoley and Biénac, and in the rural part of lower Bassin. These more densely populated areas are located in the plains where the slope is relatively low.

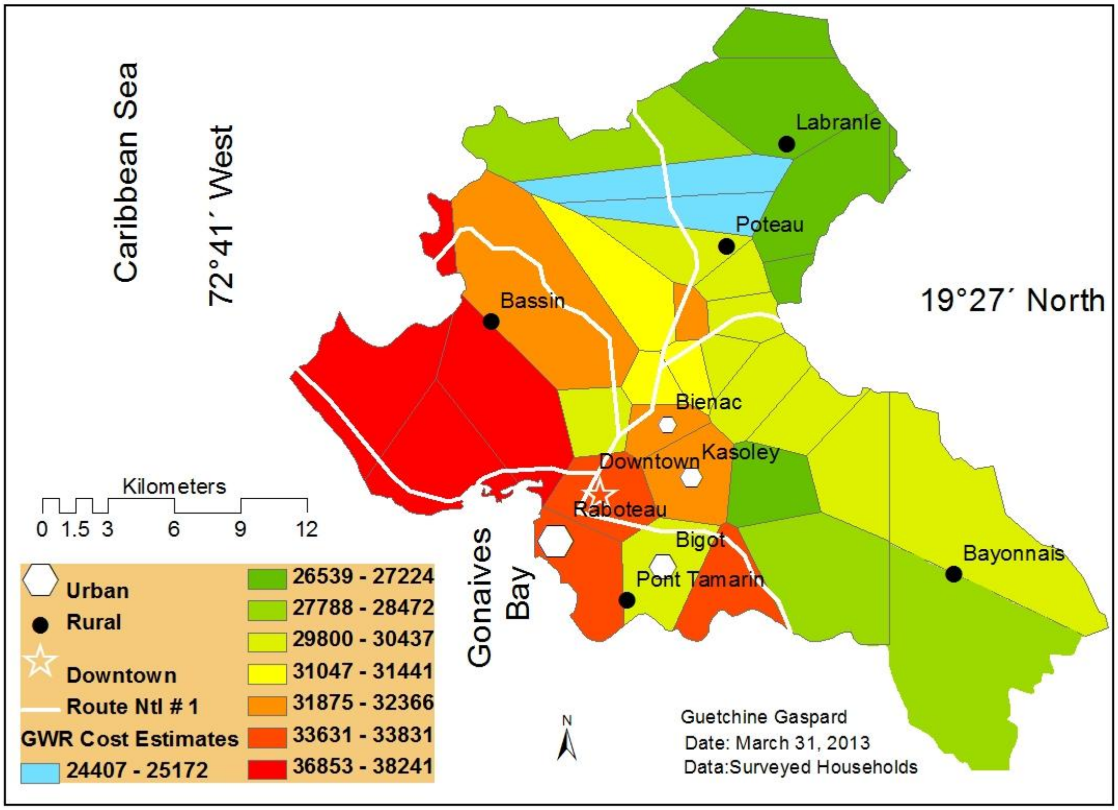

Figure 17. *Local damage Cost variation depending on income, slope and density.* This map shows the damage costs are higher in the urban area and in the rural Bassin area.

CHAPTER 5

CONCLUSION AND IMPLICATIONS

Gonaives was selected to conduct this study for its vulnerability to flooding. The vulnerability results from the combined action of the geographic location in the Atlantic Ocean, the relatively flat topography, the rising of slums, the non conservative agricultural practices, the tropical climate, and the weak capacity of the local community. The flood loss estimation model aims at serving as an emergency preparedness tool to inform contingency planning and help in flood recovery. Income, duration, slope, density and distance were analyzed as factors influencing the variation of the 2004 Hurricane Jeanne floods cost. The first objective of the study was to estimate flood damage cost at a household level for an inundation of 10 to 200 centimeters deep. After running the ordinary least square regression analysis, the following major findings were generated:

- Income, duration, slope, density and distance account for the damage costs as high as 83%. Slope and distance are negatively correlated with the flood damage costs.

- The damage cost in a household varies between 24315 through 37693 Haitian Gourdes (approximately 607.875 through 942.325 USD). Severe damages are spotted in the urban area and in the rural section of Bassin whereas very low and low losses are essentially observed in Labranle.

- The urban area was more severely affected by comparison with the rural area. Damages in the urban area are estimated at 1,648,274,782.74 HTG (41,206,869.57USD) against 698,222,174.10 HTG (17,455,554.35USD) in the rural area.

- In the urban area, damages were more severe in Raboteau-Jubilée and Downtown but Bigot-Parc Vincent had the highest overall damage cost estimated at 9,729,368.95 USD. Paradoxically, the lowest cost of 7,602,040.42USD was recorded in Raboteau.

- Approximately, 39.38% of the rural area underwent very low to moderate damages. Bassin was the most severely struck by the 2004 floods but Bayonnais turned out to have the highest loss cost (4,988,487.66 USD). Unexpectedly, Bassin along with Labranle had the least damage cost (2,956,131.11 and 2,268,321.41 USD respectively).

- Income, slope, and density show significant influence on the damage cost especially in Bigot and in Bayonnais.

It can be inferred from the results that the highest damages occurred essentially downstream in the urban area of Gonaives where people live densely around the National Route 1. These places account for most of the income generating activities and services offered in Gonaives. Based on the findings, two types of recommendations were made. The first type of recommendations is addressed to the decision-makers in Gonaives. The second type is related to the methodology and the model used.

Recommendations to Decision-Makers

- Create income generating-activities in order to improve the living conditions of the inhabitants. That will enable the population in Gonaives to take more precaution in responding to future floods.

- Maintain a regular maintenance in the existing water drainage system. The drains, sewers and gullies should be cured frequently, in particular during the rainy season. Also, new drainage networks should be established in the urban sprawl. That would reduce the duration of water during flooding.

- Improve the extant waste management in the city of Gonaives

- Stop the tree cutting and the non conservative farming practices in the watersheds overhanging Gonaives.

- Undertake new soil conservation practices to reduce the degradation of the watersheds, especially the Quinte Watershed. Agroforestry, farming on contours and terraces, banisters on the slopes, and gabions in the gullies can reduce the run-off erosivity in the upstream and mud accumulation in the Gonaives City.

Recommendations for the Model

- Apply and validate the model using official reference data. That will tell whether the model can be duplicated at a meso or large scale. Also, that will give an idea about whether or not the model can be used for other regions of Haiti or other developing countries.

- Integrate other economic, agricultural and loss of life variables. The model did not include variables that account for intangible damages nor for losses of life. The service sector of the economy, agriculture, and fishing damages should have an estimate cost as well.

- Adopt a calculation-based method to obtain information for the damage cost.

- Install meteorological stations to gauge and record water characteristics.

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