World Applied Sciences Journal 4 (6): 869-885, 2008
ISSN 1818-4952

Analysis of Watershed Vulnerability to Flooding in Haiti

Scot E. Smith and Daniel Hersey

Professor, Geomatics, University of Florida, Gainesville, FL 32611
GIS Analyst, St Johns County, St Augustine, FL

Abstract: A GIS-based analysis of watersheds in Haiti was performed with the objective of identifying the most vulnerable watersheds to flooding. We ranked a set of indices (soil erosion potential, potential of soil for agricultural use, population vulnerability, road infrastructure vulnerability, shopping market infrastructure vulnerability, irrigation infrastructure vulnerability and total infrastructure vulnerability) with respect to risk of flooding. This analysis produced a versatile and standardized approach to assessing watersheds with several advantages over more conventional approaches, notably:

- Decision-making tool which is based on quantitative data
- Rapid assessment based on GIS data
- Defensible rationale to develop strategies and orient aid agency activities in three major sectors:
    - Odisaster preparedness and risk management
    - Onatural resource management
    - Oinfrastructural investment
- Effective framework to organize and integrate spatial data for planning, evaluative and monitoring purposes
- Reference database for current and future analytical purposes

INTRODUCTION

The island of Haiti has always been flood-prone due to its location in the Caribbean and rugged terrain. Tropical storms and hurricanes are an all-too-frequent occurrence [1]. The tropical island is in the path of seasonal weather disturbances and is frequently hit with heavy precipitation and high velocity winds. It has been particularly hard hit in the 2008 hurricane season.

In September 2004, wide swaths of the northern part of Haiti, beginning with the Central Plateau to Cap Haitien and East to Port au Paix were inundated with water from Hurricane Jeannie as shown in Fig. 2. Haiti had suffered in the past from tropical storms and hurricanes, but this was one of the worst is memory. Several thousand people died either directly or indirectly from the flooding, millions of dollars of damage to infrastructure was incurred and tons of soil was eroded from the hill sides to the sea.

One reason for the susceptibility to and severe damage from flooding is the degree of deforestation in the country. Deforestation has always been a problem for Haiti, but it accelerated during the period of French colonization. At this time large swaths of forest, especially hardwood, were clear cut and never re-planted. Today, most of Haiti's formerly forested land is bare of trees [2 and 3].

In Haiti, trees are used as fuel for cooking and other activities involving fire. Even industries not normally attributed to fuel wood consumers, such as dry cleaning, are responsible for a high demand for fire wood. Land owners, tenants and thieves routinely cut and sell firewood for these purposes [4].

Figure 3 is a recent satellite image of Haiti and the Dominican Republic. The international border is marked in yellow, but it is hardly necessary to demark the two countries. Haiti is largely devoid of vegetation compared to the Dominican Republic which still is dominated with forests.

The international community took notice of the severity of the loss of forest and it's relation to flooding after the 2004 flood. The World Bank and the Inter-American Development Bank developed a set of "priority" watersheds in Haiti which were selected based on their importance as areas vulnerable to flooding and the loss of human life and property in addition to areas with significant opportunities for economic development [5]. All the "priority" watersheds are ridge-to-reef systems and include all of the major coastal urban populations of

Corresponding Author: Scot E. Smith, Professor, Geomatics, University of Florida, Gainesville, FL 32611

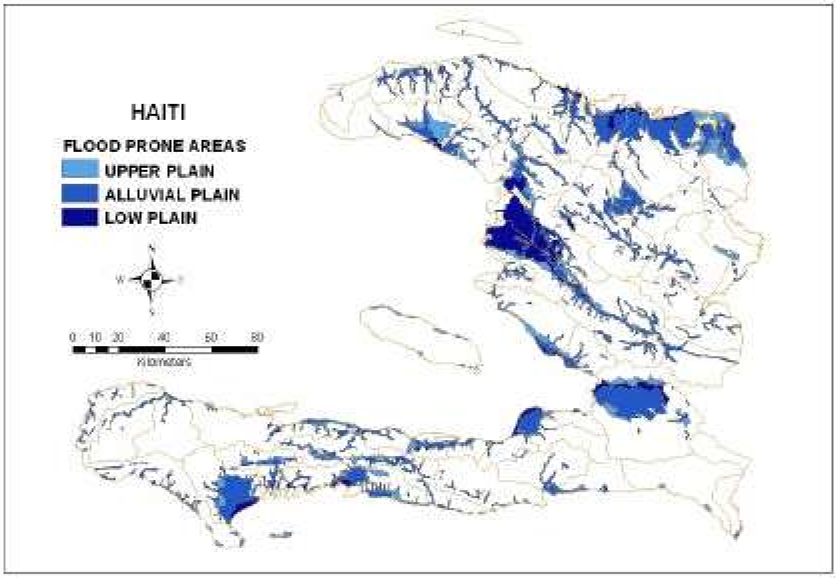

Fig. 1: Flood Prone Areas in Haiti
Adapted after Guilland (2005)

Before Hurricane Jeanie (12 May 2004) After Hurricane Jeannie (26 September 2004)

Fig. 2: Hurricane Jeanne's damage to Haiti is evident in this pair of ASTER satellite images of Gonaives. A gray "stream" coming down from the middle center of the left image is the gravel deposits left from flood waters that covered part of Gonaives.
Source of image: NASA/GSFC/METI/ERSDAC/JAROS and U.S./Japan ASTER Science Team

Fig. 3: Satellite Image of Haiti and Dominican Republic
Source: Google Earth

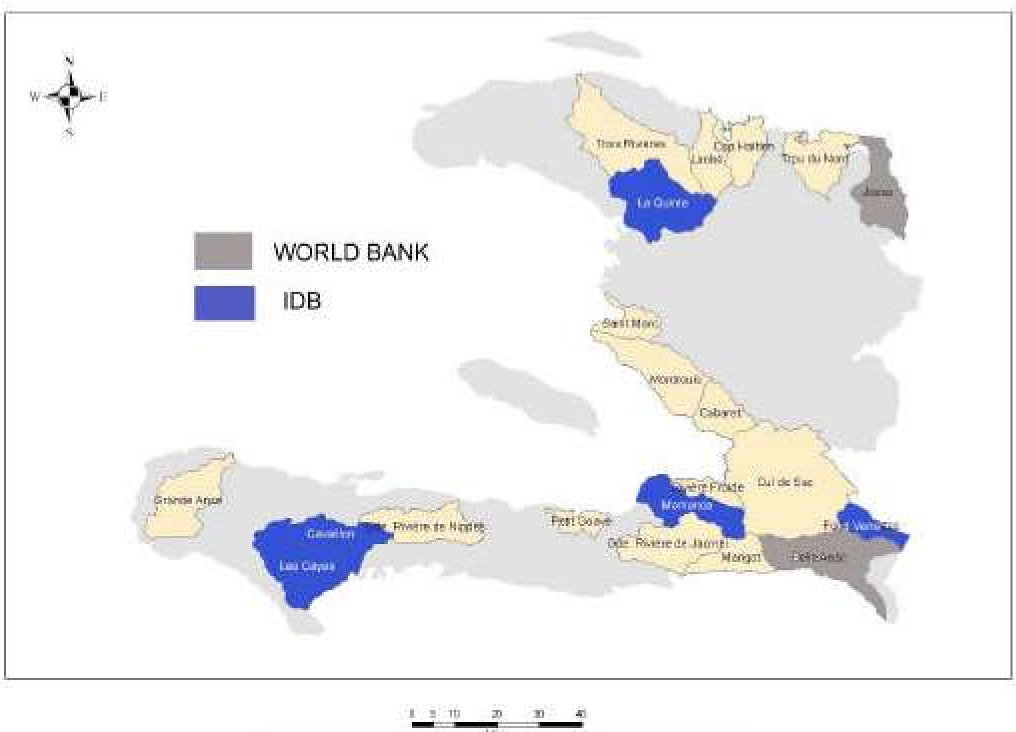

Fig. 4: High Priority Watersheds

Table 1: "High Priority" Watersheds in Haiti

Sub-Basin Code	Sub-basin Name	Basin Name	Area (km^2)
3	Trois Rivières	Versant Nord, NORD-OUEST	898
5	Bassin du Limbé	Limbé, NORD	313
6	Cap Haïtien	Cap Haïtien, NORD	325
8a	Trou du Nord	Nord-Est, NORD	428
8c	Jassa	Nord-Est, NORD	439
9	La Quinte	La Quinte, CENTRE-NORD	700
12a	Saint Marc	St. Marc/Arcahaie, CENTRE-SUD	215
12b	Montrouis	St. Marc/Arcahaie, CENTRE-SUD	604
12c	Cabaret	St. Marc/Arcahaie, CENTRE-SUD	300
13	Cul de Sac	Cul de Sac, CENTRE-SUD	1598
14	Fond Verrettes	Fond Verrettes, CENTRE-SUD	189
15a	Rivière Froide	Plaine de Léogane, CENTRE-SUD	161
15b	Momance	Plaine de Léogane, CENTRE-SUD	437
16b	Belle Anse	Sud-Est, SUD	726
16c	Marigot	Sud-Est, SUD	300
17	Gde. Rivière de Jacmel	G.de Rivière de Jacmel, SUD	561
20	Cavaillon	Versant Sud, SUD-OUEST	400
21	Les Cayes	Versant Sud, SUD-OUEST	661
24	Grande Anse	Versant Nord, SUD-OUEST	554
27	Gde. Rivière de Nippes	Versant Nord, SUD-OUEST	465
28b	Petit Goave	Versant Nord, SUD-OUEST	148

Haiti. The "priority" watersheds are shown in Fig. 4 and their basin and sub-basin names and areas are shown in Table 1.

The purpose of this study was to perform a GIS-based analysis of watersheds in Haiti with the objective of identifying the most vulnerable watersheds to flooding. We Soil erosion risk, potential of soil for agriculture, population vulnerability, road infrastructure vulnerability, market infrastructure vulnerability, irrigation infrastructure vulnerability and total infrastructure vulnerability were assessed with respect to flooding risk.

METHODS

Digital coverages were purchased from various government agencies in Haiti for the following: Watersheds, Erosion Risk (ER) as of 1998, Habitat Density (HD) as of 1998, Road Network, Irrigation Perimeter (IP), Market Locations (M), Potential Soil Quality (PS), Productive Infrastructure Vulnerability (PI), 10 meter digital terrain model and Communal Section Population Vulnerability.

We then re-projected the coverages into a common projection and datum and translated the legend from French to English.

A description of the step-by-step method and the relevant GIS map layer used to prioritize the watersheds with respect to flood potential is given below.

- Determine the boundaries and the drainage area for the "priority" watersheds by creating WS1, WS2...WSi…
- Use the *Intersect* command in ArcGIS to intersect WSi & ER = WSER. Then determine the drainage area fraction, by category, of ER index (0-5). We then multiplied the drainage area fraction by the index category to weight categories. We then summed the categories to compute a "watershed erosion risk" score. We then normalized the scores and ranked the WSERs.
- Use *the Intersect* command to intersect WSi & NFM = WSFMi . We then used *Intersect* for WSFM & HD = FMHD. We then determined the habitat density in the flood plain and multiplied HD by the flood plain area and determined the vulnerable population. We then ranked WS by the vulnerable population.
- Use the *Union command in* ArcGIS to union R & NH = ROAD NETWORK (RN). We then *Intersec*ted RN & WS = RNWS. We determined road categories and assign weights as proxies of "road replacement

value" (5 = national highway, 4 = other paved road; 3 = all-weather dirt road, 1= trail). We normalized the values by multiplying the distance per category. We summed the weighted values and computed the "road vulnerability" for each watershed by intersecting with WSFMi. We normalized scores and ranked "road vulnerability" scores.

- We used *Intersect* to intersect IP & WSFMi = FMIPi. We determined area as a fraction of total watershed area in the flood zone as an "irrigation vulnerability" score. We normalized the scores and ranked the "irrigation vulnerability" scores.
- We used *Intersect* to intersect M & WS = WSM. We determined market categories and weights per category. We multiplied weights by number of markets per category. We calculated "watershed market values" by summing the category values. We normalized values and ranked the WSMs.
- We used *Intersect* to intersect WSi & PS = WSPS. We determined the drainage area fraction by category of PS index (0-7). We multiplied the drainage area fraction by index category to weight the categories. We summed the categories to compute a "watershed soil quality" score. We normalized the scores and ranked the WSPSs.
- We summed the scores of roads, markets and irrigation for each watershed. We normalized values and ranked the watersheds by "Productive Infrastructure Vulnerability Index".
- We prepared a hydro grid from the Cul-de-Sac DEM. We computed a weighted grid and flow direction. We generated a flow accumulation grid from flow direction. We generated a link grid using stream and flow accumulation grids. W generated a catchment grid using a *create* link and flow direction grids. We generate a weighted flow accumulation grid using flow direction and weighted grids. We integrated the catchment and weighted flow accumulation grids to produce a flood risk zone map. We used *Overlay* for the Grise Rive, road network, urban zones and other layers to graphically display vulnerability of population and infrastructure to flood zone category.
- We mapped Cul-de-Sac population vulnerability at level communal section based on weighted values of habitat density x flood prone area union. We assigned a color ramp to show population vulnerability to flooding.

The following indices were then generated:

Erosion Risk Index: based on the weighted score of the erosion risk, categories from the Erosion Risk were mapped. The erosion risk categories are a function of slope, soil properties, vegetation cover and erosive climate factors. The erosion risk score for each watershed was calculated by summing the weighted risk categories, each category being weighted by multiplying its value (1-6) with its fractional area of the watershed. The watersheds were ranked according to the risk index.

Soil Potential Index: based on the weighted score of the soil potential categories from the Soil Potential map. The categories are a function of slope, Lithology, salinity and drainage factors that determine their agronomic potential. Each category was weighted by multiplying the category value by its fractional area of the watershed. The SPI of the priority and all watersheds were ranked.

Population Vulnerability Index: vulnerability of the population was defined in this assessment as the portion of the habitat density map that intersects the three categories of flood prone areas. It was based on the water surface map created from aerial photos taken in 1982 and features three categories of plains susceptible to either a storm surge, a general rise in water levels or floods: low elevation plains near the coast, elevated plains and alluvial plains. The intersection of the habitat density map with the flood prone area map allows for an estimation of the population exposed to floods and the creation of a *population vulnerability index*.

Habitat Density Index: habitat density was weighted according to its density unit multiplied by the flood plain value. The index values are normalized on a scale of 0-100 to determine a relative index. The watersheds are ranked by their index values and summarized in a table. A national map of Haiti was generated to show the spatial distribution of index values.

Productive Infrastructure Vulnerability Index: The productive infrastructure was defined as the total of roads, markets and irrigation networks. No data was available, on a national scale, for public buildings (e.g., schools, administrative, churches and shelters), utilities or other types of infrastructure considered key to the economy. The portion of the infrastructure falling within the flood prone area of the watershed was the basis of the *productive infrastructure vulnerability index.* A separate vulnerability index was determined for roads, markets and irrigation networks based on the weighted score of roads (∑ road distance x road category x flood area category), markets (∑ market number x market category x flood area category) and irrigated land (∑ irrigation category x flood area category). A map showing the selected watersheds was based on a relative scale from 0-100.

Digital Elevation Model: The digital elevation model of the Cul-de-Sac watershed was selected to create a flood zone map using the ESRI Hydro model. This watershed comprises the highly vulnerable urban population currently residing in the coastal flood plain of the Grise River. A weighted flow accumulation grid was calculated using hydrological functions based on slope and elevation. The union of this grid with the catchment grid generates a flood risk zone map. Layers are added to graphically show the population and infrastructure vulnerable to different levels of flood risk.

Communal Section Population Vulnerability: The intersection of the communal section layer with the population vulnerability layer of the Cul-de-Sac watershed creates a map showing how population vulnerability varies according to political jurisdiction.

RESULTS

Erosion Risk Index: Erosion risk index values were computed for twenty-one priority watersheds (Table 2) and all watersheds (Table 3). A map of the priority

Table 2: Ranking of Erosion Risk Ranking of High Priority Watersheds

Rank	Watershed	Index	Rank	Watershed	Index
1	Grande Anse	100	11	Montrouis	69
2	Gde. Rivière de Jacmel	84	12	Marigot	69
3	Fond Verrettes	83	13	Rivière Froide	61
4	Petit Goave	81	14	La Quinte	55
5	Limbé	78	15	Cavaillon	52
6	Momance	77	16	Cul de Sac	52
7	Belle Anse	74	17	Saint Marc	52
8	Cabaret	72	18	Les Cayes	35
9	Trois Rivières	70	19	Cap Haïtien	29
10	Gde Rivière de Nippes	70	20	Jassa	10
			21	Trou du Nord	0

Table 3: Ranking of Erosion Risk Index of all Watersheds

Rank	Watershed	Index	Rank	Watershed	Index
1	Grande Anse	100	28	Aquin/St. Louis du Sud	57
2	Voldrogue/Roseaux	94	29	La Quinte	55
3	Tiburon/Port Salut	89	30	Baie de Henne	54
4	Les Irois/Jérémie	86	31	Lociane	54
5	Rivière de Jacmel	84	32	Cavaillon	52
6	Fond Verrettes	83	33	Thomonde	52
7	Petit Goave	81	34	Cul de Sac	52
8	Limbé	78	35	Moustique	52
9	Grand Goave	78	36	Saint Marc	52
10	Fer à Cheval	77	37	Corail/Anse à Veau	51
11	Momance	77	38	Peligre Sud	50
12	Cours Moyen	76	39	Gatinette	48
13	Belle Anse	74	40	Libon	48
14	Cabaret	72	41	Colombier	46
15	Bainet	71	42	Môle Saint Nicolas	44
16	Trois Rivières	70	43	Bouyaha	42
17	Gde Rivière de Nippes	70	44	La Gonave	41
18	Montrouis	69	45	Canot	41
19	Anse à Pitre	69	46	Anse Rouge	39
20	Jean Rabel	69	47	Les Cayes	35
21	Marigot	69	48	Cap Haïtien	29
22	La Tortue	64	49	L'Estère	27
23	Port de Paix/Port Margot	63	50	Guayamouc Aval	26
24	Rivière Froide	61	51	Cours Inférieur	14
25	Côtes de Fer	60	52	Marion	11
26	Miragoane	59	53	Jassa	10
27	Gde Rivière du Nord	57	54	Trou du Nord	0

Table 4: Ranking of Soil Potential Index of Priority Watersheds

Rank	Watershed	Index	Rank	Watershed	Index
1	Trou du Nord	100	11	Marigot	27
2	Cap Haïtien	78	12	Cabaret	26
3	Jassa	66	13	Trois Rivières	26
4	Les Cayes	60	14	Belle Anse	25
5	La Quinte	40	15	Bassin du Limbé	22
6	Gde Rivière de Nippes	38	16	Momance	20
7	Cavaillon	36	17	Montrouis	20
8	Saint Marc	32	18	Rivière Froide	15
9	Cul de Sac	32	19	Gde Rivière de Jacmel	10
10	Petit Goave	29	20	Grande Anse	4
			21	Fond Verrettes	0

Table 5: Ranking of Soil Potential Index of all Watersheds

Rank	Watershed	Index	Rank	Watershed	Index
1	Trou du Nord	100	28	Cul de Sac	32
2	Cap Haïtien	78	29	Baie de Henne	32
3	Jassa	66	30	Gde Rivière du Nord	31
4	Anse Rouge	61	31	Petit Goave	29
5	Les Cayes	60	32	Marigot	27
6	Marion	58	33	Cabaret	26
7	La Gonave	56	34	Trois Rivières	26
8	Môle Saint Nicolas	55	35	Les Irois/Jérémie	25
9	La Tortue	54	36	Belle Anse	25
10	Gatinette	52	37	Libon	23
11	Colombier	50	38	Bassin du Limbé	22
12	Canot	49	39	Tiburon/Port Salut	21
13	Bouyaha	46	40	Peligre Sud	21
14	Anse à Pitre	46	41	Grand Goave	21
15	Guayamouc Aval	46	42	Momance	20
16	Aquin/St. Louis du Sud	44	43	Montrouis	20
17	Côtes de Fer	44	44	Fer à Cheval	17
18	Cours Inférieur	42	45	Thomonde	15
19	La Quinte	41	46	Rivière Froide	15
20	Miragoane	40	47	Bainet	13
21	Gde Rivière de Nippes	38	48	Port de Paix/Port Margot	12
22	Cavaillon	36	49	Gde Rivière de Jacmel	10
23	Corail/Anse à Veau	35	50	Lociane	10
24	Cours Moyen	35	51	Grande Anse	4
25	Jean Rabel	35	52	Voldrogue/Roseaux	1
26	Saint Marc	32	53	Fond Verrettes	0
27	Moustique	32	54[1]		

watersheds is shown in Fig. 5. Note that the Fond Verrettes watershed is shared with theDominican Republic. The indices for this watershed was based on only the upper part that lies entirely within Haiti and thus reflects a bias that should be interpreted with caution.

The remainder of the watersheds are “ridge to reef” systems. Their indices reflect the geomorphology of the watershed which is characterized by large alluvial plains and low mountains and so have a lower index than the watersheds with high mountains and little or no coastal plain. The watersheds of the southern peninsula are particularly vulnerable due to their high mountain ranges and the higher probability of extreme storm events. Thus, the higher index values of the southern watersheds are even more remarkable given the additional climate risks.

Soil Potential Index: The ranking of the watersheds, in terms of their soil potential index, is simply the inverse of the erosion risk index ranking (Table 4). The correlation between the two indices is highly significant, as indicated by the Spearman R statistic of-0.922. This is what would be expected given that the slope is the overriding factor and correlated with other factors considered in the agronomic potential of soil such as Lithology, Erodibility, drainage and salinity.

The map shown in Fig. 6 illustrates the soil potential index of the priority watersheds. The top three watersheds are located in the north of the country (Trou Nord, Jassa, Cap Haïtien) and the lowest ranked watersheds occur along the southern peninsula of the Massif de la Hotter and Massif de la Selle. Table 5 summarizes the index rankings for fifty-three watersheds.

Population Vulnerability Index: The index values of the priority watersheds are ranked in Table 6. The index rankings for all watersheds are summarized in Table 7. The

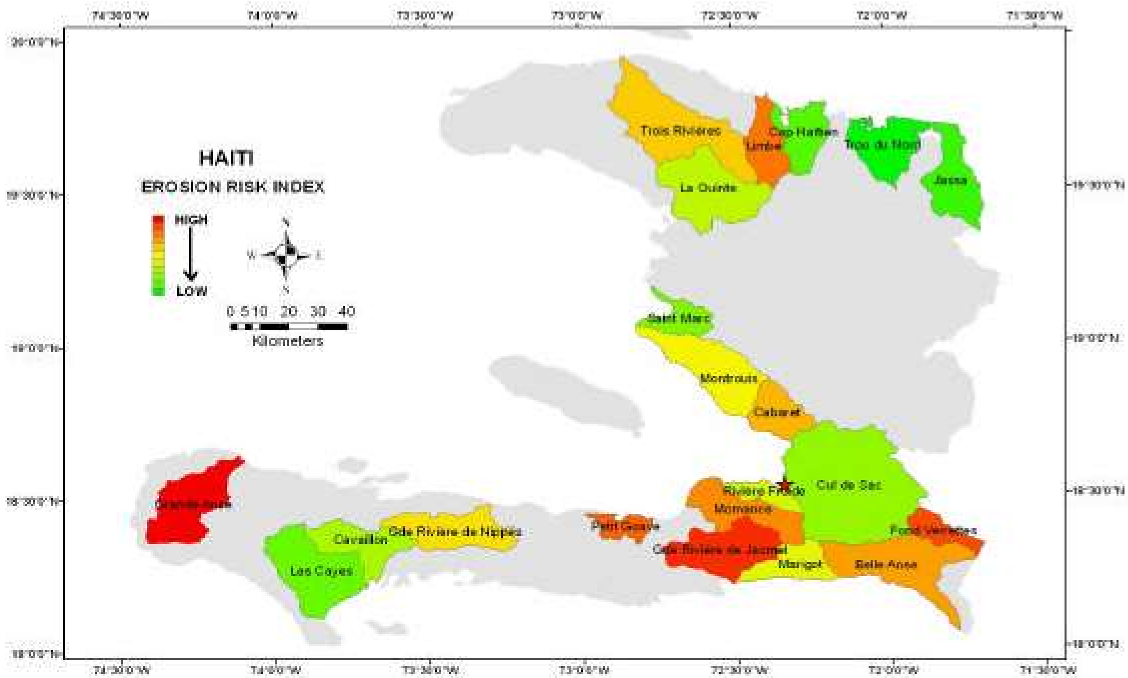

Fig. 5: Erosion risk

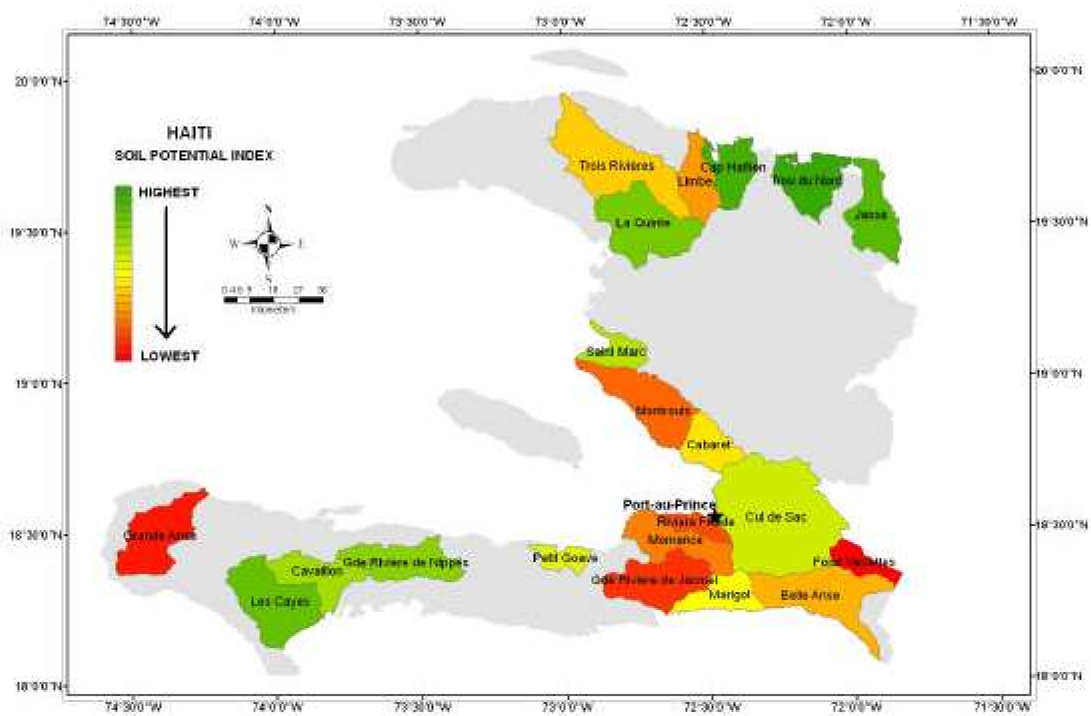

Fig. 6: Soil potential

Table 6: Ranking of Population Vulnerability Index of Priority Watersheds

Rank	Watershed	Index	Rank	Watershed	Index
1	Cul de Sac	100	11	Gde Rivière de Nippes	5
2	Les Cayes	30	12	Cavaillon	5
3	Momance	23	13	Limbé	4
4	Cap Haïtien	20	14	Rivière Froide	3
5	La Quinte	18	15	Gde Rivière de Jacmel	2
6	Montrouis	13	16	Saint Marc	2
7	Trois Rivières	9	17	Marigot	2
8	Jassa	9	18	Grande Anse	2
9	Trou du Nord	9	19	Petit Goave	1
10	Cabaret	5	20	Belle Anse	0
			21	Fond Verrettes	0

Table 7: Ranking of Population Vulnerability Index of all Watersheds

Rank	Watershed	Index	Rank	Watershed	Index
1	Cul de Sac	100	28	Tiburon-Port Salut	3
2	Cours Inférieur	38	29	Gde Rivière de Jacmel	2
3	Les Cayes	30	30	Guayamouc Aval	2
4	Momance	23	31	Miragoane	2
5	Cap Haïtien	20	32	Saint Marc	2
6	La Quinte	18	33	Colombier	2
7	Montrouis	13	34	Marigot	2
8	Aquin/St. Louis du Sud	10	35	Les Irois-Jérémie	2
9	Trois Rivières	9	36	Grande Anse	2
10	Jassa	9	37	Fer á Cheval	1
11	Trou du Nord	9	38	Petit Goave	1
12	Gde Rivière du Nord	9	39	Jean Rabel	1
13	Cours Moyen	8	40	Bainet	1
14	Port de Paix/Port Margot	7	41	Voldrogue Roseaux	1
15	Bouyaha	6	42	Peligre Sud	1
16	Cabaret	5	43	La Gonave	1
17	Gde Rivière de Nippes	5	44	Moustique	1
18	Cavaillon	5	45	Lociane	0
19	Canot	4	46	Thomonde	0
20	Limbé	4	47	Libon	0
21	Anse Rouge	3	48	Anse á Pitre	0
22	Côtes de Fer	3	49	Belle Anse	0
23	Grand Goave	3	50	Baie de Henne	0
24	Corail-Anse à Veau	3	51	Môle Saint Nicolas	0
25	Marion	3	52	La Tortue	0
26	Rivière Froide	3	53	Fond Verrettes	0
27	Gatinette	3	54[1]		

watersheds representing the largest metropolitan areas of Haiti generated the highest index values. The combination of high population densities residing in large areas of high flood potential (e.g., low coastal plains) results in the highest indices. At the other extreme, the lowest indices were characterized by relatively low population densities residing in much smaller coastal plains. This is not to say that populations with relatively low index values are not vulnerable to deadly floods (e.g., Fond Verrettes in May 2004; St. Marc in August 2003 and Rivière Froide in October 2005). However, the potential for a large-scale disaster is not as great. The index map is shown in Fig. 7.

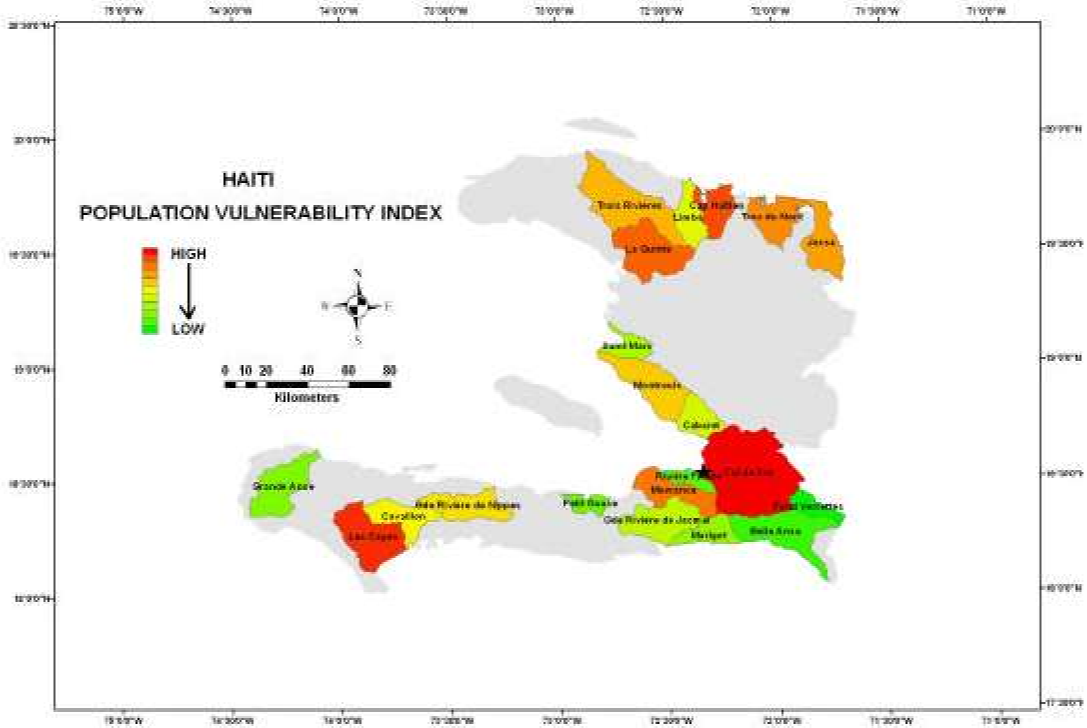

Fig. 7: Population vulnerability

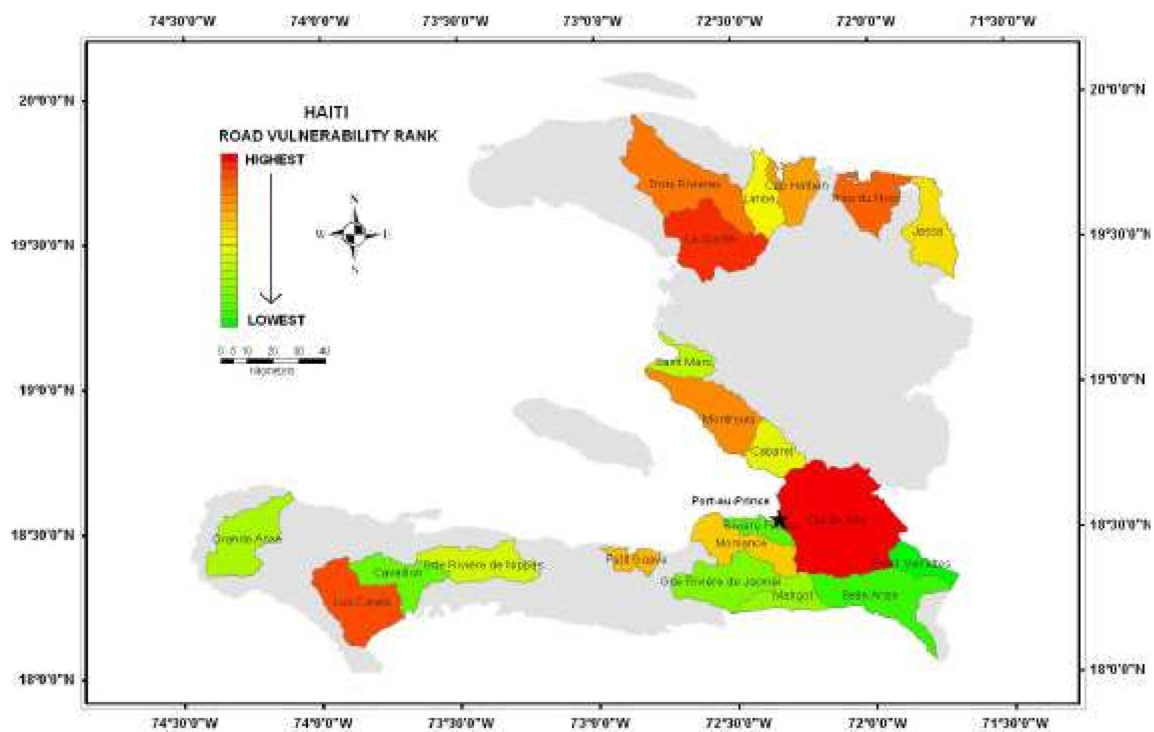

Fig. 8: Road vulnerability

Table 8: Ranking of Road Vulnerability Index of Priority Watersheds

Rank	Watershed	Index	Rank	Watershed	Index
1	Cul de Sac	100	11	Limbé	27
2	La Quinte	100	12	Cabaret	19
3	Les Cayes	90	13	Gde Rivière de Nippes	18
4	Trou du Nord	62	14	Saint Marc	17
5	Trois Rivières	55	15	Grande Anse	14
6	Montrouis	51	16	Marigot	13
7	Cap Haïtien	45	17	Gde Rivière de Jacmel	11
8	Petit Goave	29	18	Cavaillon	9
9	Momance	29	19	Rivière Froide	6
10	Jassa	27	20	Belle Anse	1
			21	Fond Verrettes	0

Table 9: Ranking of Road Vulnerability Index of all Watersheds

Rank	Watershed	Index	Rank	Watershed	Index
1	Cul de Sac	100	28	Corail/Anse à Veau	16
2	La Quinte	100	29	Grand Goave	15
3	Les Cayes	90	30	Fer à Cheval	15
4	Aquin/St. Louis du Sud	80	31	Grande Anse	14
5	Cours Inférieur	69	32	Marigot	13
6	Trou du Nord	62	33	Gde Rivière de Jacmel	11
7	Bouyaha	57	34	Guayamouc	11
8	Trois Rivières	55	35	Les Irois/Jérémie	11
9	Montrouis	51	36	Anse Rouge	10
10	Gde Riv. du Nord	50	37	Cavaillon	9
11	Cap Haïtien	45	38	Jean Rabel	6
12	Miragoane	36	39	Rivière Froide	6
13	Cours Moyen	31	40	Peligre Sud	4
14	Petit Goave	29	41	Anse à Pitre	4
15	Momance	29	42	Thomonde	3
16	Tiburon-Port Salut	29	43	Gatinette	2
17	Jassa	27	44	Bainet	2
18	Limbé	27	45	La Gonave	2
19	Côtes de Fer	23	46	Moustique	2
20	Port de Paix/Port Margot	23	47	Baie de Henne	2
21	Marion	23	48	Belle Anse	1
22	Cabaret	19	49	Lociane	1
23	Voldrogue Roseaux	19	50	Môle Saint Nicolas	1
24	Gde Riv. de Nippes	18	51	Libon	1
25	Colombier	18	52	La Tortue	0
26	Saint Marc	17	53	Fond Verrettes	0
27	Canot	17	54[1]		

Infrastructure Vulnerability Indices: Road Vulnerability Index: The length of roads, weighted according to estimated life cycle costs and their location within the flood prone areas, determined the road vulnerability index. The road vulnerability indices are based on relative values (scaled from 0-100). Table 8 summarizes the index values for the priority watersheds and Table 9 compares the index values for all watersheds. The index map for the priority watersheds is shown in Fig. 8.

Market Vulnerability Index: The market vulnerability index is based on the weighted value of markets (rural,

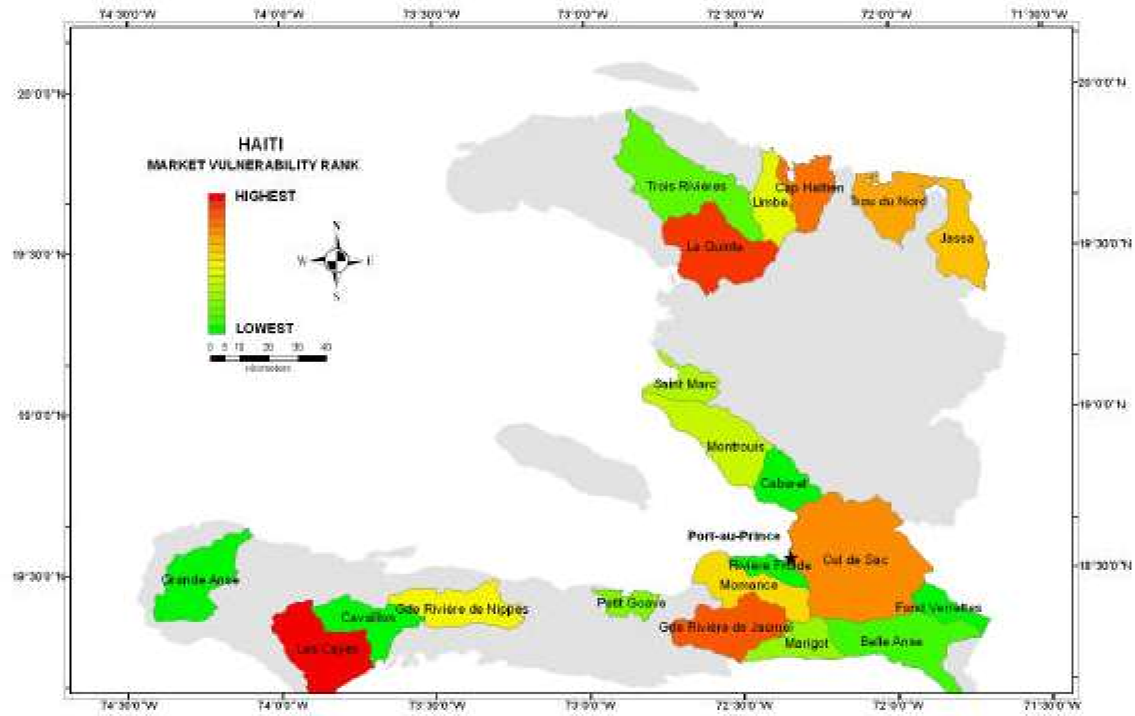

Fig. 9: Market Vulnerability Index

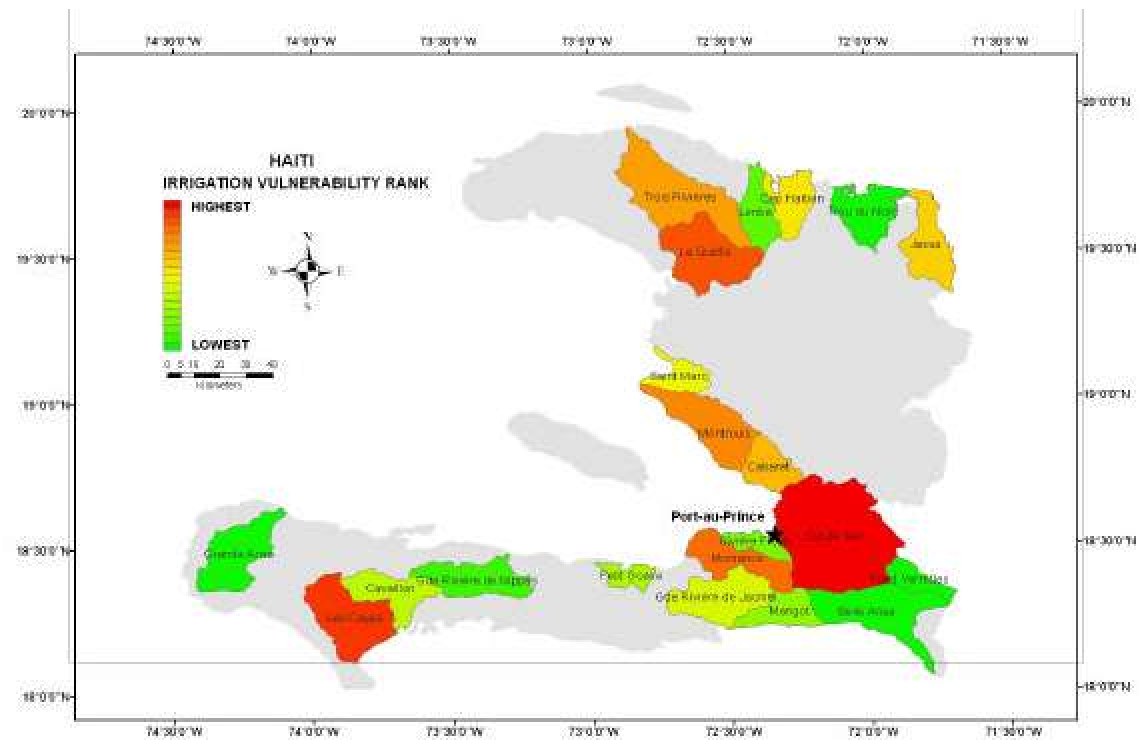

Fig. 10: Irrigation Vulnerability Index

Table 10: Ranking of Market Vulnerability Indices of Selected Watersheds

Rank	Watershed	Index	Rank	Watershed	Index
1	Les Cayes	100	9	Montrouis	17
2	La Quinte	83	10	Saint Marc	9
3	Gde Rivière de Jacmel	45	11	Marigot	6
4	Cap Haïtien	43	12	Petit Goave	4
5	Cul de Sac	34	12	Trois Rivières	4
6	Trou du Nord	26	13	Belle Anse	2
6	Jassa	26	14	Cabaret	0
7	Momance	23	14	Fond Verrettes	0
7	Gde RiviÖre de Nippes	23	14	Rivière Froide	0
8	Limbé	21	14	Cavaillon	0
			14	Grande Anse	0

Table 11: Ranking of Market Vulnerability Indices of all Watersheds

Rank	Watershed	Index	Rank	Watershed	Index
1	Les Cayes	100	16	Jean Rabel	4
2	La Quinte	83	16	Guayamouc	4
3	Gde Rivière de Jacmel	45	16	Canot	4
4	Cap Haïtien	43	16	Lociane	4
5	Cul de Sac	34	16	Petit Goave	4
6	Cours Inférieur	30	16	Trois Rivières	4
7	Port de Paix/Port Margot	28	16	Côtes de Fer	4
8	Trou du Nord	26	16	Voldrogue Roseaux	4
8	Jassa	26	16	Grand Goave	4
8	Tiburon-Port Salut	26	16	Baie de Henne	4
9	Momance	23	17	Gatinette	2
9	Gde Rivière de Nippes	23	17	Belle Anse	2
9	Corail/Anse à Veau	23	18	Cabaret	0
10	Limbé	21	18	Anse Rouge	0
11	Marion	19	18	Môle Saint Nicolas	0
11	Cours Moyen	19	18	Thomonde	0
11	Aquin/St. Louis du Sud	19	18	Fond Verrettes	0
12	Montrouis	17	18	Rivière Froide	0
13	Peligre Sud	13	18	Cavaillon	0
13	Fer à Cheval	13	18	Grande Anse	0
13	Gde Riv. du Nord	13	18	La Tortue	0
13	Bouyaha	13	18	Moustique	0
14	Colombier	9	18	Libon	0
14	Saint Marc	9	18	Anse à Pitre	0
15	Marigot	6	18	Bainet	0
15	Miragoane	6	18	Les Irois/Jérémie	0
15	La Gonave	6	1		

regional or urban) falling within flood prone areas. The indices of the priority watersheds are shown in Table 10 and those for all watersheds are shown in Table 11. The index map for the priority watersheds is shown in Fig. 9.

Irrigation Vulnerability Index: The largest irrigation networks in Haiti are located in the alluvial plains of the Artibonite, the lower La Quinte River, the Cul-de-Sac, Leogane, Arcahaie and Cayes. Smaller networks occur throughout the country along the major rivers of the country. Several watersheds selected in this study are noted for the absence of irrigation networks, as shown in Fig. 1. However, it is likely that many local irrigation networks exist that are not shown.

The index values for the priority watersheds are shown in Table 12 and those for all watersheds are shown in Table 13. The highest index value in Table 10 is not the highest in the country. This belonged to the large irrigation network along the lower Artibonite River. However, the top five indices in Table 8a are ranked second to sixth when compared to all the watersheds in Haiti. The index map for the priority watersheds is shown in Fig. 10.

Table 12: Ranking of Irrigation Vulnerability Index of Priority Watersheds

Rank	Watershed	Index	Rank	Watershed	Index
1	Cul de Sac	71	11	Gde Rivière de Jacmel	3
2	Les Cayes	32	12	Cavaillon	3
3	La Quinte	30	13	Petit Goave	3
4	Momance	16	14	Marigot	2
5	Montrouis	16	15	Rivière Froide	1
6	Trois Rivières	9	16	Bassin du Limbé	1
7	Cabaret	8	17	Gde RiviÖre de Nippes	0
8	Jassa	7	18	Fond Verrettes	0
9	Cap Haïtien	4	18	Grande Anse	0
10	Saint Marc	3	18	Trou du Nord	0
			18	Belle Anse	0

Table 13: Ranking of Irrigation Vulnerability Index of all Watersheds

Rank	Watershed	Index	Rank	Watershed	Index
1	Cours Inférieur	100	28	Côtes de Fer	1
2	Cul de Sac	71	29	Marion	1
3	Les Cayes	32	30	Rivière Froide	1
4	La Quinte	30	31	Bassin du Limbé	1
5	Momance	16	32	Corail/Anse à Veau	1
6	Montrouis	16	33	Miragoane	1
7	Cours Moyen	13	34	Colombier	1
8	Canot	10	35	Peligre Sud	1
9	Fer à Cheval	9	36	Thomonde	1
10	Trois Rivières	9	37	Port de Paix/Port Margot	1
11	Cabaret	8	38	Aquin/St. Louis du Sud	1
12	Bouyaha	8	39	Môle Saint Nicolas	1
13	Gde Riv. du Nord	7	40	Baie de Henne	0
14	Jassa	7	41	Bainet	0
15	Lociane	4	42	Gde Rivière de Nippes	0
16	Cap Haïtien	4	43	Fond Verrettes	0
17	Saint Marc	3	43	Grande Anse	0
18	Guayamouc	3	43	Trou du Nord	0
19	Gde Rivière de Jacmel	3	43	Belle Anse	0
20	Cavaillon	3	43	Gatinette	0
21	Petit Goave	3	43	La Gonave	0
22	Tiburon-Port Salut	2	43	La Tortue	0
23	Marigot	2	43	Voldrogue/Roseaux	0
24	Anse Rouge	2	43	Libon	0
25	Moustique	2	43	Anse à Pitre	0
26	Jean Rabel	2	43	Les Irois/Jérémie	0
27	Grand Goave	2			

Infrastructure Vulnerability Index: The infrastructure vulnerability index of the priority watersheds, as reflected in the *average* vulnerability index of roads, markets and irrigation systems is shown in Table 14. The weakness of such an index is that the three categories of infrastructure are weighted equally. Thus, the watershed of the most densely populated urban area, Port-au-Prince, ranks third behind Les Cayes and La Quinte (Gonaives), primarily due to the differences in the market vulnerability index. These watersheds also rank the highest in Table 15. The index map of the priority watersheds is provided in Fig. 11.

Table 14: Ranking of Productive Infrastructure Vulnerability Index of Priority Watersheds

Rank	Watershed	Index	Rank	Watershed	Index
1	Les Cayes	73.9	11	Bassin du Limbé	16.5
2	La Quinte	70.9	12	Gde RiviÖre de Nippes	13.7
3	Cul de Sac	68.2	13	Petit Goave	12.1
4	Cap Haïtien	30.6	14	Saint Marc	9.6
5	Trou du Nord	29.3	15	Cabaret	8.8
6	Montrouis	28.0	16	Marigot	7.0
7	Momance	22.9	17	Grande Anse	4.8
8	Trois Rivières	22.8	18	Cavaillon	3.9
9	Jassa	19.9	19	Rivière Froide	2.3
10	Gde Rivière de Jacmel	19.6	20	Belle Anse	1.1
			21	Fond Verrettes	0.0

Table 15: Ranking of Total Infrastructure Vulnerability Index of all Watersheds

Rank	Watershed	Index	Rank	Watershed	Index
1	Les Cayes	73.9	28	Colombier	9.0
2	La Quinte	70.9	29	Cabaret	8.8
3	Cul de Sac	68.2	30	Voldrogue Roseaux	7.6
4	Cours Inférieur	66.4	31	Grand Goave	7.0
5	Aquin/St. Louis du Sud	33.3	32	Marigot	7.0
6	Cap Haïtien	30.6	33	Guayamouc Aval	6.1
7	Trou du Nord	29.2	34	Peligre Sud	5.8
8	Montrouis	28.0	35	Grande Anse	4.8
9	Bouyaha	25.8	36	Jean Rabel	4.0
10	Gde Rivière du Nord	23.5	37	Cavaillon	3.9
11	Momance	22.9	38	Anse Rouge	3.9
12	Trois Rivières	22.8	39	Les Irois-Jérémie	3.5
13	Cours Moyen	20.9	40	Lociane	3.2
14	Jassa	19.9	41	La Gonave	2.8
15	Gde Rivière de Jacmel	19.6	42	Rivière Froide	2.3
16	Tiburon-Port Salut	18.9	43	Baie de Henne	2.1
17	Port de Paix/Port Margot	17.1	44	Gatinette	1.5
18	Limbé	16.5	45	Moustique	1.3
19	Miragoane	14.4	46	Thomonde	1.2
20	Marion	14.4	47	Anse à Pitre	1.2
21	Gde Rivière de Nippes	13.7	48	Belle Anse	1.1
22	Corail-Anse à Veau	13.6	49	Bainet	1.0
23	Fer à Cheval	12.2	50	Môle Saint Nicolas	0.0
24	Petit Goave	12.1	51	Libon	0.3
25	Canot	10.2	52	La Tortue	0.0
26	Côtes de Fer	9.6	53	Fond Verrettes	0.0
27	Saint Marc	9.6	54[1]		

River Grise 3-D Flood Zone Map: Figure 12 is a 3D map, showing the most likely high flood risk zones of the Grise River watershed. The results of the ArcGIS Hydro model clearly show the vulnerability of areas within metropolitan Port-au-Prince due to the high density of an urban population residing on a coastal flood plain. These areas include Croix des Missions, Cité Soleil and the Industrial Park.

Communal Section Vulnerability: Figure 13 shows population vulnerability within the Cul-de-Sac watershed as delimited by communal section. Vulnerability is

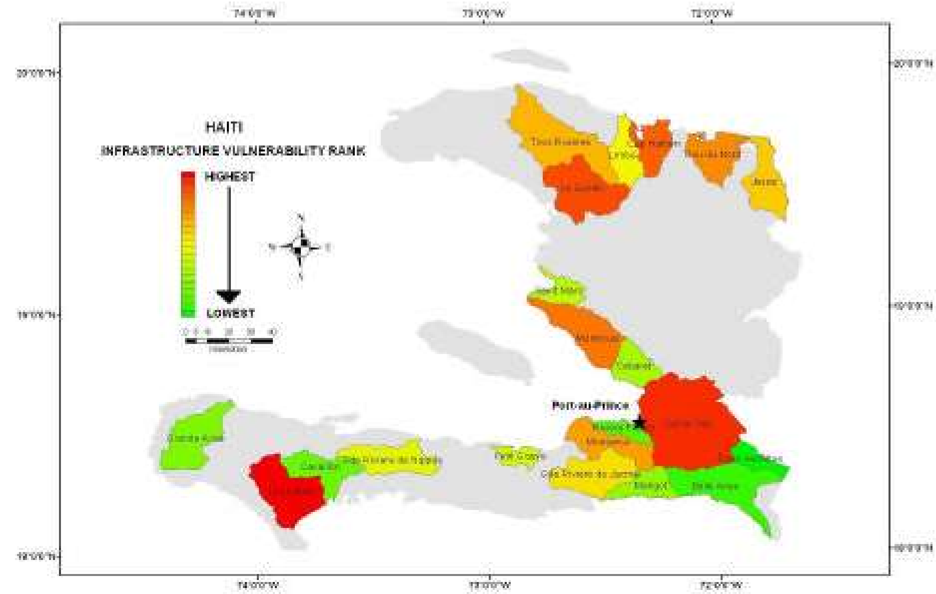

Fig. 11: Infrastructure Vulnerability Index

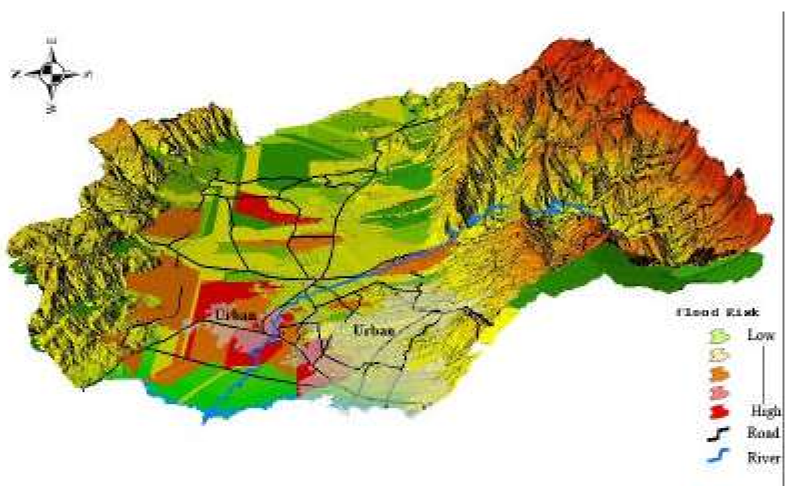

Fig. 12: Flood Risk Zones in the River Grise Catchment Area of the Cul-de-Sac Watershed

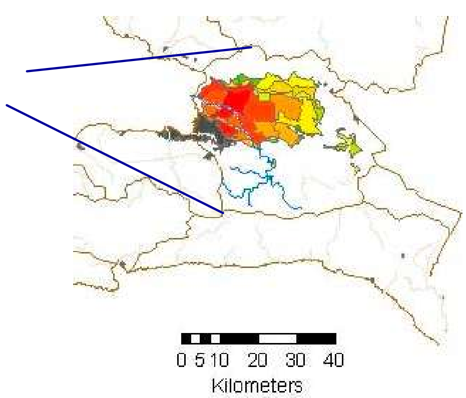

Fig. 13: Population Vulnerability of the Cul-de-Sac Watershed Showing Index Values by Communal Section Jurisdictions

concentrated among the most densely populated urban areas of the Grise River flood plain. The population residing in the upper catchment of the Grise River is not considered vulnerable due to the absence of flood prone areas.

CONCLUSIONS

When assessing an area for flood risk, many variables must to take into account. In this study we looked at population, the potential the soil was to erosion potential, the utility of soil for agriculture, transportation network, shopping market locations, irrigation infrastructure and total infrastructure. Depending on the weight applied to these variables (i.e., is it more important to protect roads from flood rather than voluble soil), decision makers can use this tool to know were to build flood control devices such as dams and levees.

Once databases such as the one developed here are built, decision makers with limited or even no experience with GIS can use them for wise resource management. In the case if Haiti, the results from this study indicates that there are areas with high population and large infrastructure investment that are more flood-prone those others. Likewise, there are areas that are not in emanate need of flood protection either because there is nothing voluble to protect or they are not prone to flooding.

ACKNOWLEDGMENTS

This project was supported by the United States Agency for International Development

Project: Environmental Vulnerability in Haiti. The work of Mr. Joel Timyan, Dr. Michael Bannister and Glenn Smucker was invaluable to this research

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