ENVIRONMENTAL VULNERABILITY OF THE TROU DU NORD BASIN:
A PRIORITY SUB-WATERSHED ANALYSIS

VULNÉRABILITÉ ENVIRONNEMENTALE DU BASSIN DE TROU DU NORD:
ANALYSE DES SOUS-BASSINS HYDROGRAPHIQUES PRIORITAIRES

VULNERABILIDAD AMBIENTAL DE LA CUENCA DEL TROU DU NORD:
ANÁLISIS DE SUB-CUENCAS PRIORITARIAS

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ABSTRACT

The Trou Du Nord watershed has been ranked among the less vulnerable watersheds in Haiti by USAID according to five vulnerability indexes: Soil Erosion Potential, Population Vulnerability, Markets Vulnerability, Road Vulnerability and Irrigation Vulnerability. A similar ranking approach is downscaled here to characterize and rank sub-basins within the Trou Du Nord watershed, a basin where intensive industrial development is taking place at the Caracol Industrial Park (CIP) of northern Haiti. Our final objective is to establish a coherent reconnaissance-level approach for classifying sub-basin conditions, using a comprehensive set of indicators as proxies to the underlying ecological, hydrological, and geomorphic functions and processes that affect sub-watershed conditions. In other words, to establish how vulnerable those sub-watersheds are to threats, especially to flooding. Prioritizing watersheds is based on ranking each of the sub-watersheds by their level of vulnerability and identifying which one has the most environmental concerns. We have identified population conglomerates, soil erosion, soil potential, and infrastructure replacement value as the key factors of vulnerability within the Trou Du Nord sub-watersheds and ranked them accordingly. Re-scaling a national level approach to a regional framework will account for regional risk factors linked to the CIP's final objectives.
Key Words: Environmental vulnerability, priority watershed, Haiti, Caracol Industrial Park

RÉSUMÉ

Le bassin hydrographique de Trou Du Nord a été classé parmi les bassins hydrographiques les moins vulnérables en Haïti par l'USAID selon cinq indices de vulnérabilité: Potentiel d'érosion des sols, vulnérabilité de la population, vulnérabilité des marchés, vulnérabilité du système de circulation routière et vulnérabilité de l'irrigation. Une approche de classement semblable **à** une **échelle** inférieure est ici utilisée pour caractériser et classer les sous-bassins dans le bassin hydrographique du Trou Du Nord, un bassin au nord d'Haïti où le développement industriel intensif a lieu au Parc Industriel Caracol (PIC). Notre objectif final est d'établir une approche cohérente de niveau de reconnaissance pour classer les conditions du sous-bassin, en utilisant un ensemble complet d'indicateurs servant de repères aux fonctions et processus écologiques, hydrologiques et géomorphologiques sous-jacents qui affectent les conditions des sous-bassins hydrographiques. En d'autres termes, l'objectif est d'établir la vulnérabilité de ces sous-bassins versants à des menaces, en particulier aux inondations. La hiérarchisation des bassins hydrographiques se fonde sur le classement de chacun des sous-bassins hydrographiques par leur degré de vulnérabilité et par l'identification de ceux qui ont les vulnérabilités environnementales les plus importantes. Nous avons identifié les conglomérats de population, l'érosion des sols, le potentiel du sol et la valeur de remplacement de l'infrastructure comme facteurs clés de vulnérabilité dans les sous-bassins hydrographiques de Trou Du Nord et en conséquence les avons classés sur la base des facteurs indiqués. La redéfinition d'une approche nationale au cadre régional tiendra compte des facteurs de risque régionaux liés aux objectifs définitifs du PIC.
Mots clés: Vulnérabilité environnementale, bassin hydrographique prioritaire, Haïti, Parc Industriel du Caracol

RESUMEN

La cuenca del Trou Du Nord ha sido clasificada entre las cuencas hidrográficas menos vulnerables de Haití por la USAID de acuerdo con cinco índices de vulnerabilidad: Potencial de Erosión del Suelo, Vulnerabilidad de la Población, Vulnerabilidad de los Mercados, Vulnerabilidad del Sistema Vial y Vulnerabilidad de Riego. En el presente análisis de la cuenca del Trou Du Nord, una cuenca en la que se está desarrollando un intenso desarrollo industrial en el Parque Industrial Caracol (CIP) del norte de Haití, se ha utilizado una metodología de clasificación similar pero a escala reducida para caracterizar y clasificar las subcuencas. Nuestro objetivo final es establecer un enfoque coherente de nivel de reconocimiento para clasificar las condiciones de las subcuencas, utilizando un abarcador conjunto de indicadores representativos de las funciones y procesos ecológicos, hidrológicos y geomórficos subyacentes que afectan las condiciones de las subcuencas.

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En otras palabras, para establecer cuán vulnerables son esas subcuencas a diferentes amenazas, especialmente a las inundaciones. La priorización de las cuencas hidrográficas se basa en clasificar cada una de las subcuencas por su nivel de vulnerabilidad e identificar cuales tiene las mayor vulnerabilidad ambiental. En este trabajo hemos identificado a los conglomerados poblacionales, la erosión del suelo, el potencial del suelo y el valor de reemplazo de la infraestructura como los factores clave de vulnerabilidad dentro de las subcuencas del Trou Du Nord y en consecuencia clasificamos a éstas en base a los factores indicados. La reestructuración de un enfoque a nivel nacional a un marco regional toma en cuenta los factores de riesgo regionales relacionados con los objetivos finales del PIC.

Palabras clave: Vulnerabilidad ambiental, cuenca hidrográfica prioritaria, Haití, Parque Industrial Caracol

INTRODUCTION

Haiti is highly exposed to the advent of severe natural disasters given its geologic and geographic setting. On the other hand, Haiti's vulnerability is exacerbated given its economic and socio-political conditions which aggravate the impacts of natural phenomena. Geologically, the country is located on the tectonically active boundary region separating the Caribbean plate and the North America plate (Bird 2003), where two important east-west trending fault systems dominating Haiti's tectonics are responsible for 19 large earthquakes (Magnitude>6.5) occurring the last 100 years. Those systems are, the Enriquillo-Plaintain Garden fault system to the south, and the Septentrional fault system in northern Haiti.
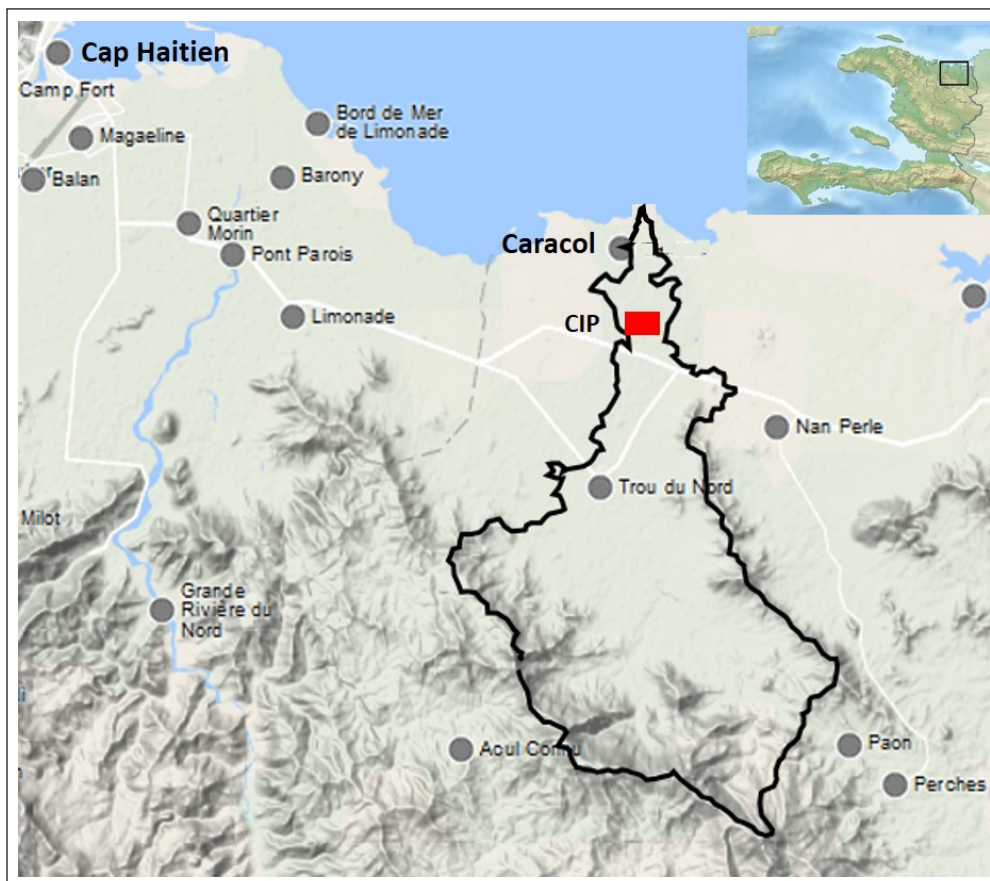
Likewise, Haiti is situated along the pathway of tropical storms that originate in the eastern Atlantic and sweep the Caribbean islands every year during the hurricane season. Environmental degradation brought about by deforestation combined with periodic downpours from storms have resulted in mayor flooding and advanced soil erosion in many regions. Haiti's disastrous floods of 2004 in Gonaïves, those of 2014 in Cap-Haitien, and the magnitude 7 Port-au-Prince earthquake of January 12, 2010 serve as good examples of major threats not only to densely populated districts like Port-au-Prince and other major coastal cities, but to rural areas alike.

When large hurricanes or earthquakes impact countries like Haiti, with a long history of strong political strife, consequences amplify substantially, and the country is captured in a vicious circle hampering development. The combination of all these factors is perhaps reflected by Haiti's Human Development Index value of 0.483 in 2014 (UN 2015). Such a low value places the country in the low human development category (number 163 out of 188 countries). Attempting to break the vicious circle and to foster sustainable development, a national strategic analysis by the Inter-American Development Bank identified six priority sectors with potential to transform Haiti's economy and society: education, private sector development, energy, water and sanitation, and agriculture and transport. An USAID report concluded that for Haiti to seek sustainable development it must focus on developing non-agricultural economic initiatives in secondary urban centers throughout the country, while supplying well-trained employees to private businesses which would, in turn, drive the regional economies (IADB, 2010; IMF, 2014; USAID, 2015).

In order to materialize a way out of the circle, the Government of Haiti, in collaboration with the U.S. State Department, the Inter-American Development Bank, and NGOs are embarked in the development of the Caracol Industrial Park (CIP) in the Trou Du Nord watershed of northern Haiti (Figure 1). The CIP is a 246 hectare, mixed-use light manufacturing facility located in the commune of Caracol, within the Trou Du Nord basin of northern Haiti. Given the magnitude of the watershed transformation expected from the Industrial Park creation of over 60,000 jobs, it is important to evaluate the current status of the watershed and assess the risk posed on its natural and human resources to support a management plan to avoid future environmental and socio-economic collapse. In this context the CIP must be seen as a component of an intervention plan in the framework of the overall Trou Du Nord watershed, not as an isolated industrial park and its associated urban center.

The present study is aimed to advance a step further in watershed prioritization by characterizing, comparing and quantitatively ranking the sub-watersheds making the Trou Du Nord basin. As such, we will identify those portions of the Trou Du Nord basin deemed most critical. This study represents a downscaling of a previous nationwide study (Smucker et al., 2007; Smith and Hersey, 2008) to define priority watersheds in terms of their vulnerability to loss of human life, productive infrastructure, soil potential, or erosion risk. In summary, this approach is focused on one of the watershed priorities of the Ministry of Environment of Haiti, namely, the vulnerability of local populations and productive assets (threats to human life, infrastructure, and natural resources) to natural and/or human induced conditions.

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Figure 1. Location of the Trou Du Nord basin and the Caracol Industrial Park (CIP; red rectangle) in northeast Haiti (Base map by MapCarta)

METHODS

In order to develop a coherent reconnaissance-level approach for classifying sub-basin conditions, we needed a comprehensive set of indicators as proxies to the underlying ecological, hydrological, and geomorphic functions and processes that affect the watershed, and are targeted to aquatic and terrestrial processes and conditions, and interaction with human population. Hence, our first task was to gather the required indicator data to develop relevant information layers to prioritize watersheds based upon a ranking of environmental and economic concerns. The factors we have considered relevant for prioritizing sub-watersheds of the Trou Du Nord Basin include land morphology, vegetative cover, soil erodibility, land use, hydrology, flooding, population and infrastructure

Information sources

Most geographically explicit data for this project was compiled as GIS layers and thematic maps prepared using available thematic data/charts produced by the Centre National de l'Information Géo-Spatiale (CNIGS–GEO-Space Information National Center). Likewise, geospatial data repository, www.haitidata. org, was utilized in this study to retrieve many of the data layers published by various governmental agencies within Haiti. This website hosts vector

and raster based data both from the government and independent researchers. However, many of the layers are provided with very little metadata on who created the maps, and how and why they were created. Because of this, it is often difficult to interpret the maps and to provide any assurance of the data quality.

Additional information for thematic maps was gathered from diverse sources in this project. These thematic maps include current land cover/land use, drainage, soils, and population among others. An extensive review of geospatial data availability for Haiti was published by the USDA (Quinones et al, 2006) and serves as a useful guide to finding imagery and other products from which geospatial data can be derived, however, it is not as useful as a source of much vector based data. Some of the described data hosting sources are no longer available, making retrieval of data impossible.

While the geospatial data available for Haiti may appear as quite substantial, many data gaps still exist. The main critiques are the lack of high-resolution detailed land cover and land use data, incomplete records and incomplete metadata. This point is critical because many types of natural resource assessments depend on high quality land cover and land use data. Additional information gaps also exist for high detail census population information, data on land ownership and stewardship, historical

records of the extent of natural disasters like floods, fires, landslides, and climate data. Natural resource assessments in Haiti would also benefit from improved maps of geology/geomorphology and especially of soils. The current state of the existing maps and the deficient metadata makes them less useful for ecosystem evaluations.

Preparation of Base Map

The assessment of vulnerability of a watershed begins with the delineation of smaller geographic units, the sub-watersheds. We have delineated sub-watersheds for the Trou Du Nord basin from Digital Elevation Models (DEM). Initially, the 30-m ASTER Global DEM (GDEM) was obtained from USGS Global explorer. The GDEM provides 30-meter resolution data between 83°N and 83°S which can be downloaded from http://gdem.ersdac.jspacesystems. or.jp/. The data is in GeoTIFF format which includes latitude and longitude coordinates and the WGS84/EGM96 reference system. GDEM Version 2 was released in October 2011 which included an updated algorithm used in data processing. The creation of this high resolution DEM was intended for disaster monitoring, hydrology, energy and environmental monitoring. Validation studies have been conducted by numerous groups worldwide, and in the United States, both the USGS and NASA have conducted their own validation studies (Gesch, ,et al. 2011, and Carabajal, , 2011).

Delineation of sub-watersheds in the Trou Du Nord basin was accomplished by projecting the DEM to UTM Zone 18N (the common datum used throughout this analysis) and clipping it to the northeast region of Haiti. It was then processed through the ArcHydro 10.2 Toolset to generate the separate drainage sub-basins. The Trou Du Nord basin and its sub-watersheds were identified and extracted from the resulting vector layers. The portions of river in the Trou Du Nord that were detectable from satellite imagery were digitized and used to burn streams into the DEM. The watershed was divided into sub watersheds based on the area contributing to each of the branches of the drainage lines. Some of the tributaries have year round water flow while others may only have water flow during periods of substantial rainfall. Each sub-watershed was assigned an ID (WS1 to WS15) and the drainage areas were calculated (Figure 2 and Table 1).

Table 1: General information about the Trou Du Nord watershed

Area	118.89 km2
Length (N-S)	21.7 km
Width (E-W)	13.5 km
Perimeter Length	70.4 km
Minimum Elevation	0 m
Maximum Elevation	1.065 m
Average Elevation	160 m
Number of Sub-basins	15
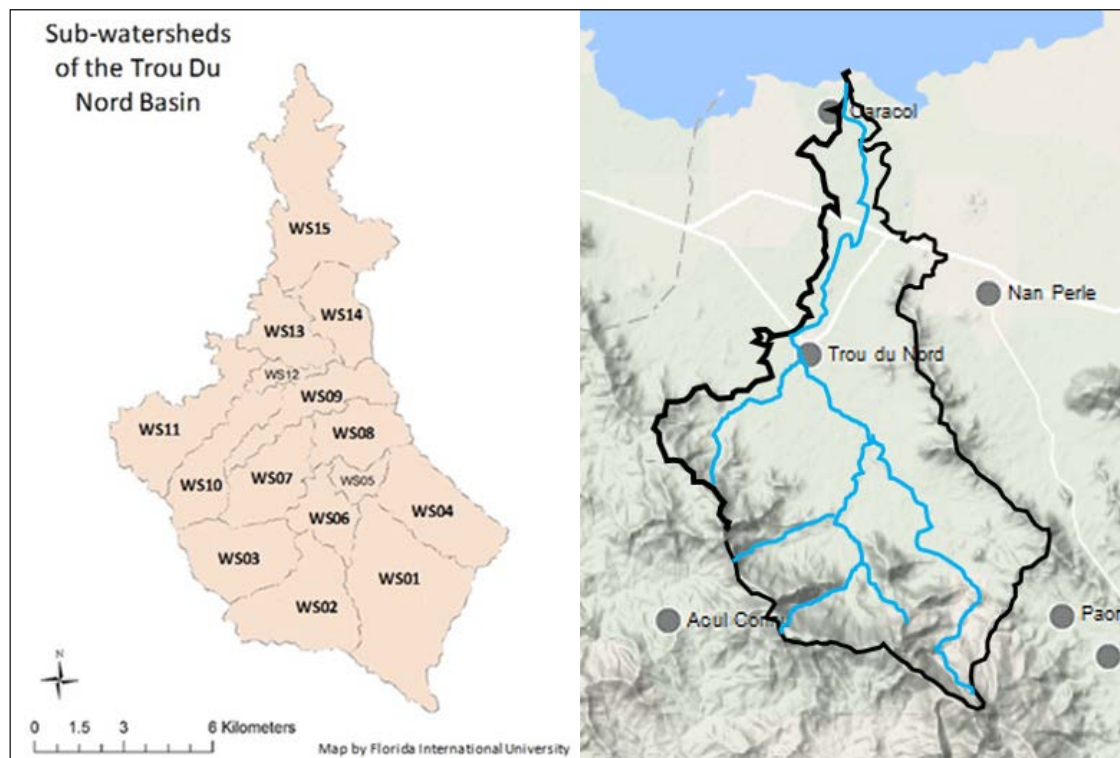
Figure 2. Sub-watersheds of the Trou Du Nord basin derived from the 30-m ASTER Global DEM (USGS), and main drainage lines of the Trou Du Nord River

Construction of thematic and risk information layers

Construction of the required thematic index information layers was either by extracting information from existing index maps (e.g. Haiti's Soil Erosion Risk Map) or constructing them from available georeferenced data (e.g. building density map). Once the information layers were constructed they were projected onto the sub-watershed map of Figure 2. Then, the *Intersect* routine of ArcGIS was used to derive the corresponding risk per sub-watershed map. The following methodology, as described by Smucker et al. (2007) and Smith and Hersey (2008) was used to accomplish the task. Thematic Index Maps (TIM) covering the Trou Du Nord was projected and intersected with the sub-watersheds layer (WSi) using the *Intersect* routine of ArcGIS. In order to spatially weight TIM index categories, the drainage area fraction of each TIM category was calculated and multiplied by the index category value. The results were summed by sub-watershed to produce an average Thematic Map Index score by sub-watershed. The scores were then normalized (0-100) to rank the individual risks of the sub-watersheds.

## METHOD IMPLEMENTATION AND RESULTS

Erosion Risk layer

Soil erosion is a primary environmental concern across most of Haiti, making it a leading watershed vulnerability factor. With over 70% of Haitians listing agriculture as their main source of income and/or subsistence, it becomes obvious that low soil erosion risk is important for maintaining the livelihood of the majority of Haitians. The source for the Erosion Risk layer is the map created by the Republic of Haiti (ROH), Ministry of Planning and External Cooperation

and IGN France International (Figure 3, Left panel). This map takes into consideration the factors that contribute to erosion, and the classification resulted from the combination of four factors: slope, soil erodibility, climate driven erosivity, and vegetative cover. Risk level calculations were accomplished by assigning weights to each factor as a function of its relative importance to soil erosion. In this case assigned values were as follows: slope=5; vegetative cover=soil erodibility=2; and erosive climate factors=1. Then the Erosion Risk was calculated for each map unit by subdividing the map units into six risk categories ranging from 0= very low risk to 6= extreme risk (Republic of Haiti 2002; Smucker et al. 2007; Smith and Hersey 2008).

This Soil Erosion Risk map was utilized in the derivation of Soil Erosion Risk Index in the Trou Du Nord basin. The following methodology, as described by Smucker et al. (2007) and Smith and Hersey (2008) was used to accomplish the task. Erosion risk (ER) covering the Trou Du Nord was projected and intersected with the sub-watersheds layer (WSi) using the *Intersect* routine of ArcGIS. In order to spatially weight ER index categories (0-6), the drainage area fraction of each ER category was calculated and multiplied by the index category value. The results were summed by sub-watershed to produce an average Erosion Risk Index (ERI) score by sub-watershed. The scores were then normalized (0-100) to rank the individual risks of the sub-watersheds.

Table 3 and Figure 4 show the sub-watershed vulnerability to erosion index and rank. The highest risk to erosion is in the southwest end of the Trou Du Nord watershed, where soils are developed on highly weathered igneous rocks displaying steep slopes. The northern section of the basin, including the flat alluvial areas of Trou Du Nord and the CIP, exhibit the lowest risk to erosion.
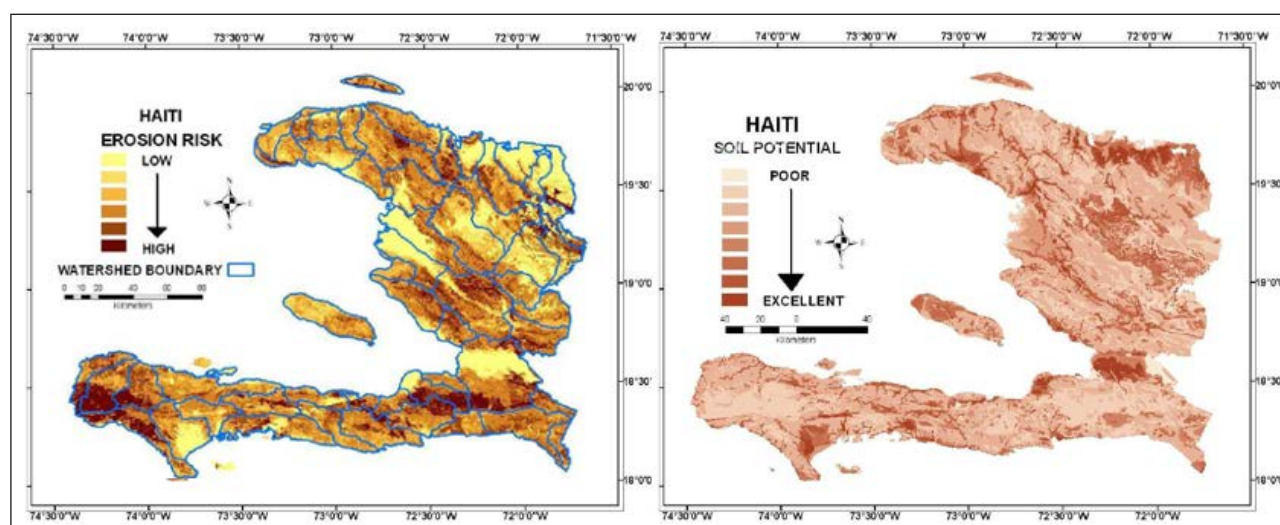

Figure 3. Left panel= Erosion Risk map (Ministry of Planning and External Cooperation of Haiti and IGN France International); Right panel= Soil Potential for agriculture map (French Bureau pour le Development de la Production Agricole,1978)

Soil Potential Index

The most important economic activity in Haiti, and especially in the Trou Du Nord so far, is agriculture. The operations in the CIP are diversifying economic activities in the watershed, but instead of displacing agriculture the CIP will contribute to further development given the fast population growth. The soil potential data was obtained from a Soil Potential map of Haiti created by the French Bureau pour le Development de la Production Agricole (1978) to show the distribution of Haiti's soils classified according to their capacity for supporting agriculture (Fig 3). The Trou Du Nord basin has been ranked as having the highest potential in Haiti (Smucker et al., 2007; Smith and Hersey, 2008). The map presents an index based upon factors important for agriculture, such as lithology, geomorphology, slope, and soil properties. The rankings divide soil quality into eight classes, following the USDA potential soils classification system and takes into account the productive potential of watersheds as well as their vulnerability.

The ability of soils to provide resources for the surrounding communities has an intrinsic value which is just as important as the risk of losing that soil to erosion. For that reason, we are incorporating measures of the soil potential for agriculture into the watershed vulnerability index ranking. The soil potential map for northeast Haiti was created in 1978 to highlight areas most favorable for supporting agriculture (BDPA, 1982). The areas with the highest potential are generally in the alluvial plains spanning areas of low slope. The mountainous areas in the south show very little potential for agriculture, as do the saline areas near the coast. Trou Du Nord and Cap-Haitien both show some of the highest potentials for agriculture in the entire country. This soil potential map was utilized in the identification of priority watersheds in the Trou Du Nord basin as follows. Soil Potential (SP) was projected and intersected with WSi to create soil potential by sub-watershed. SP categories were assigned a numerical value from 1-8 based on their potential class (Low-High). In order to spatially weight SP index categories, the drainage area fraction of each SP category was calculated and multiplied with the index category. The resulting values were summed by sub-watershed to produce an average Soil Potential for Agriculture Index (SPI) score by sub-watershed. The scores were then normalized on a 0-100 scale to rank the sub-watersheds. Figure 4 and Table 3 show the sub-watershed potential for agriculture index score and rank.
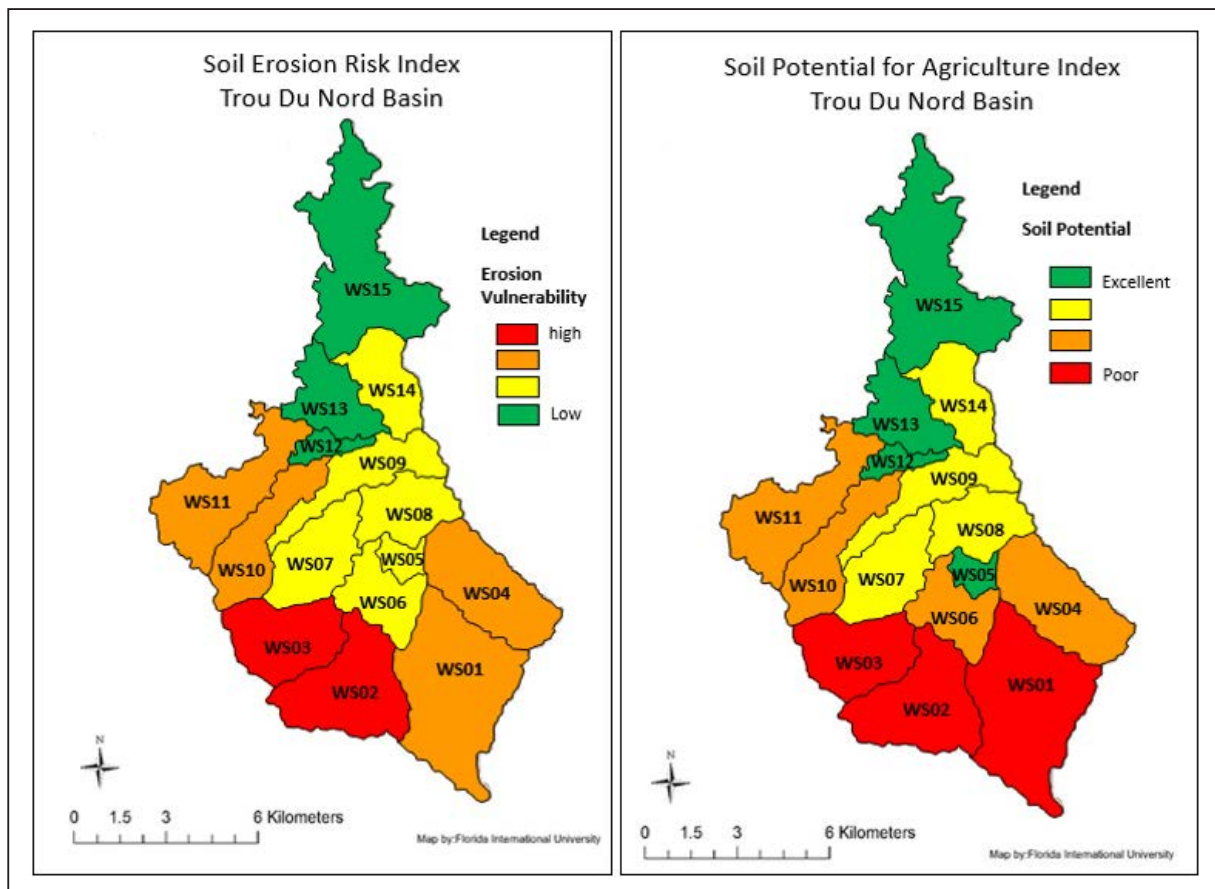
Figure 4. Map of Soil Erosion Risk Index and Soil Potential for Agriculture Index

Table 3. Trou Du Nord Priority Sub-watershed ranking and indexing

| Sub-watershed	Area	Soil erosion		Soil Potencial		Road Replacement		Building Density				Population						
		Rank	Index	Rank	Index	Rank	Index	Buildings	build/km²	Rank	Index	Habitants	Rank	Index	%Area	Area sq km	Rank	Index
WS1	16.0	4	72	13	16	7	8	420	26	8	3	2436	5	12	10	1.6	11	9
WS2	9.9	1	100	15	0	14	3	120	12	15	0	719	11	2	1	0.1	15	0
WS3	7.9	2	98	14	7	15	0	123	16	14	1	713	12	2	1	0.1	14	0
WS4	9.4	3	74	12	37	11	5	180	19	10	2	1044	7	4	40	3.8	5	23
WS5	1.5	10	33	4	84	13	3	64	43	4	7	371	15	0	100	1.5	12	8
WS6	5.2	8	42	9	53	9	6	174	33	5	5	1009	9	4	50	2.6	7	20
WS7	6.7	12	40	8	58	10	5	127	19	11	2	737	10	2	50	3.4	8	18
WS8	5.6	9	39	6	68	6	9	88	16	13	1	510	14	1	65	3.7	4	25
WS9	6.3	11	32	5	72	7	9	195	31	6	4	1131	6	4	70	4.4	6	22
WS10	6.8	6	69	11	41	12	3	174	25	9	3	1009	8	4	35	2.4	13	4
WS11	10.1	5	69	10	46	2	54	3037	302	2	69	17615	1	100	40	4.0	10	9
WS12	1.6	13	3	2	98	4	16	695	432	1	100	4031	3	21	100	1.6	1	100
WS13	5.2	14	1	1	100	3	48	1430	273	3	62	8294	2	46	100	5.2	3	53
WS14	5.2	7	45	7	61	5	15	89	17	12	1	516	13	1	40	2.1	9	18
WS15	15.0	15	0	3	91	1	100	421	28	7	4	2442	4	12	99	14.9	2	58

Flood Risk map

Most of the middle and lower Trou Du Nord watershed is on alluvial, flat lands, amenable of flooding, especially during major storms occurring every year affecting riverine and coastal floodplain communities. The upper portions of the basin are characterized by their high relief and soils exposed to the impact of tropical storms. Deforestation contributes to make the upper basin prone to develop landslides. Even without a direct hit by hurricanes, significant volumes of rain cause rivers to overflow and flooding as well as landslides pose a real threat to vulnerable communities as those of the Trou Du Nord. Besides the physical impact of flooding and landslides on infrastructure, flooding creates breeding grounds for insect vectors, with potential to cause malaria, dengue and zika. Furthermore, flooding waters usually contain pathogens from human feces, where systems for the disposal of human waste are restricted to open pit, latrines, and field defecation.

Like in previous Index maps, flood data from Gilland's Flood Prone Areas map (Fig 5; Left panel) was projected and intersected with WSi to create flood potential (FP) by sub-watershed. FP categories were assigned a numerical value from 1-3 based on their potential class (Low-High). In order to spatially weight FP index categories, the drainage area fraction of each FP category was calculated and multiplied with the index category. The resulting values were summed by sub-watershed to produce an average flood potential index score by sub-watershed. The scores were then normalized on a 0-100 scale to rank the sub-watersheds.

The map in Figure 5 (right panel) and Table 3 show the projection of the flooding categories of landforms that are likely to flood in the Trou Du Nord according to Gilland's Flood Prone Areas map (2005). Flood prone areas are confined to the low elevations near the coast, and the upstream extension of the alluvial plains. This map was used to derive a Flood Vulnerability Index map to classify and rank the sub-watersheds in order to estimate population and infrastructure exposure to floods.
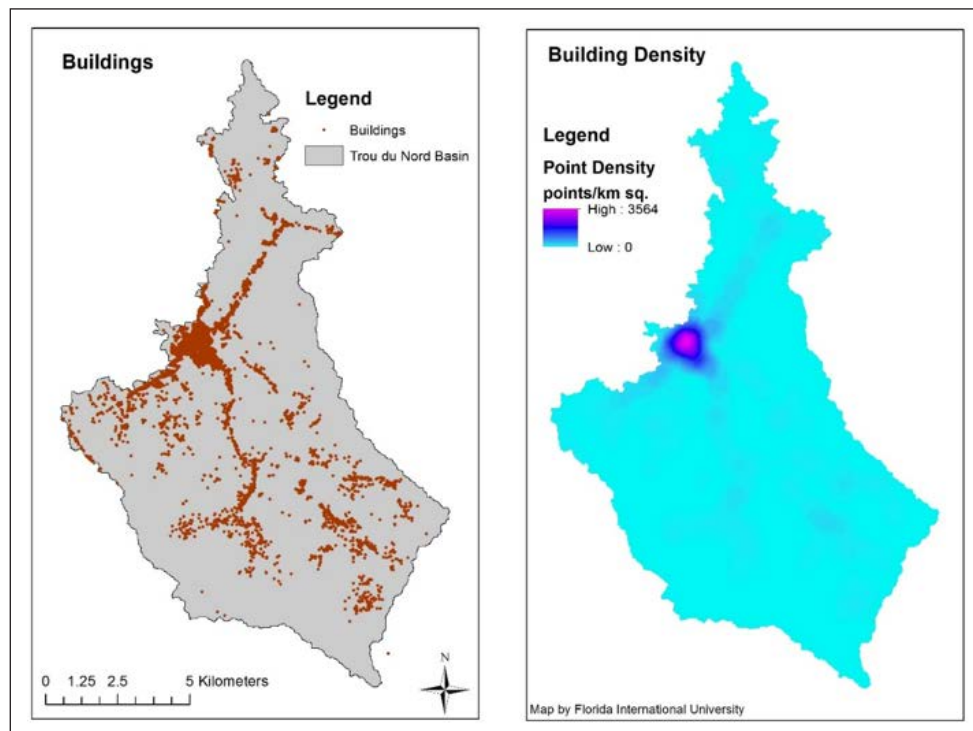
Building and Building Density layer

The building layer is derived in part from the GOH Road Map and the OpenStreetmap.com buildings layer. It was reviewed by FIU in November 2014 and it seems to reflect buildings with acceptable reliability. Initially, the building polygons were converted to points. The converted "points layer" was overlaid on high-resolution satellite imagery (LANDSAT) and additional unrepresented buildings within the watershed were identified and added to the points layer (Fig 6; left panel). Also, from this combined layer, the building density layer was derived using ArcGIS point density tool (Fig 6; right panel). This tool calculates a magnitude-per-unit area from point features that fall within a neighborhood around each cell. The point density layer so obtained is a raster where each cell represents the number of buildings within the selected cell. The OpenStreet maps building layer is available for all of Haiti, while the updated building point layer created by FIU is only available for the Trou Du Nord watershed.
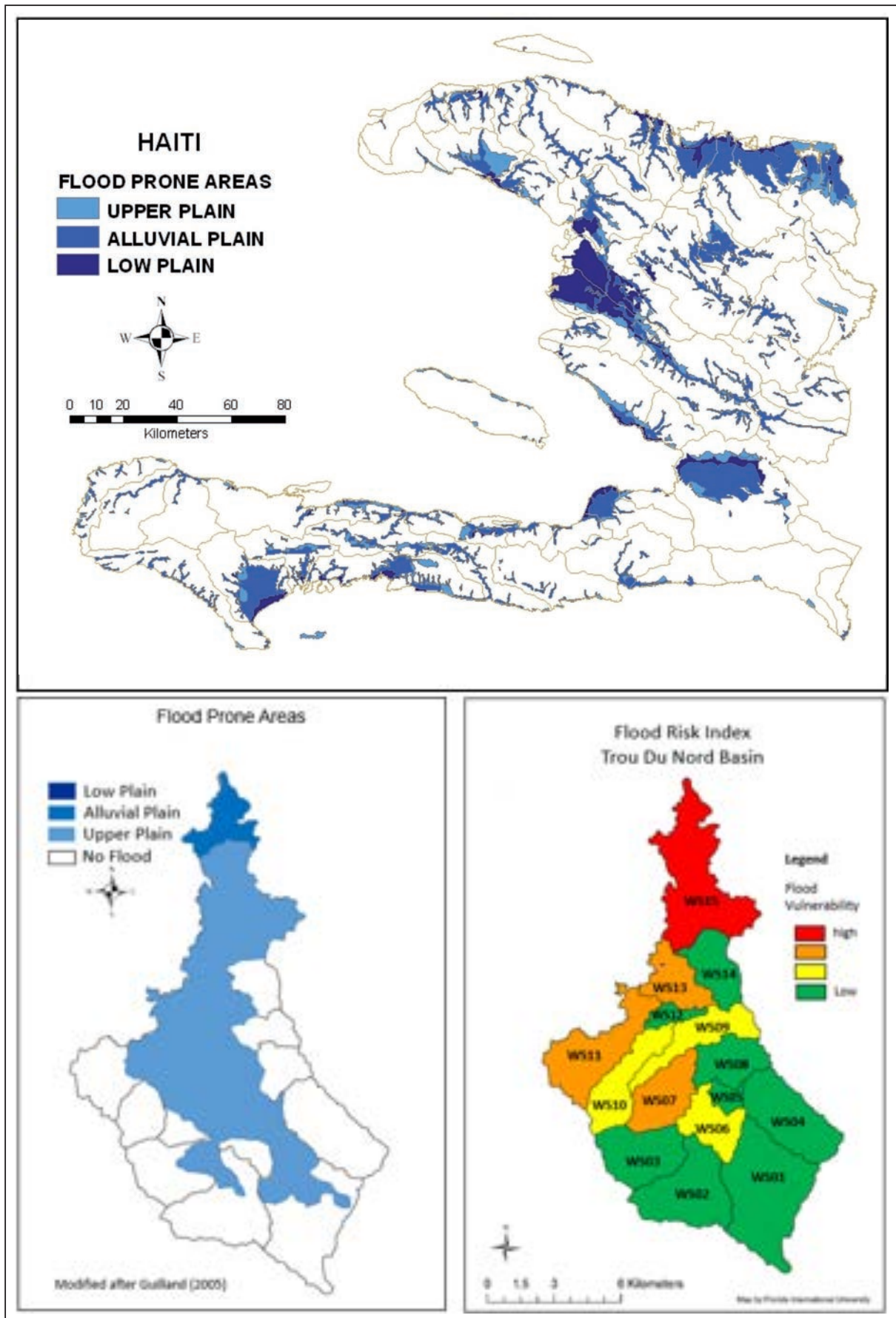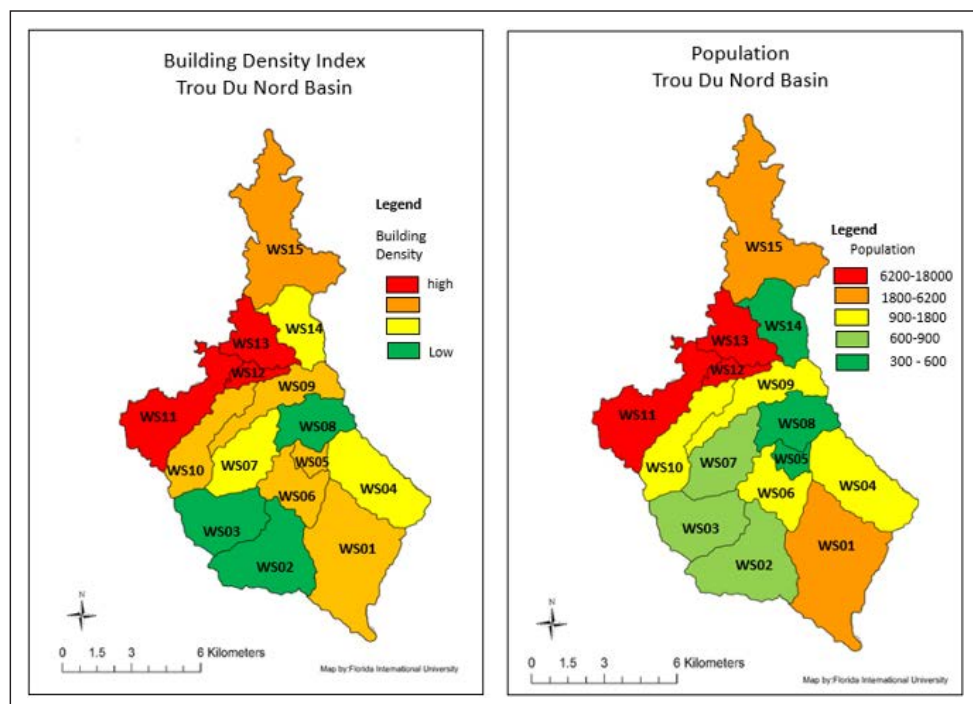
Figure 5. Flood Prone Areas Map of Haiti (upper; Guillande, 2005),
Trou Du Nord Basin (left) and Flood Risk Index by sub-watershed (right)

Figure 6. Building map of the Trou Du Nord watershed as a "building point" (left)
and Building Density (right) information layers

Figure 7. Building Density Index Population map of Northeast Haiti

The Building Density map of Figure 6, was the primary source of information to calculate building density for each sub-watershed. As done before for other indexes, Building Density (BD) was projected and intersected with the sub-watersheds layer (WSi) to determine and rank BD by sub-watershed. Table 3 provides the density (buildings per sq. km) and the sub-watershed rank. Figure 7 (left panel) shows the resulting sub-watershed Building Density Index. The largest building density is towards the west portion of the basin, where the largest urban developments and the largest population of the watershed are settled around the City of Trou Du Nord. Also, as shown in Fig 6, a significant proportion of buildings is preferentially located along roads on the large floodplain. This is a typical pattern of urbanism in agricultural areas, not only in Haiti, but in the whole Caribbean and South American countries.

Population layer

Obtaining accurate estimates of population amount and distribution is essential for policy making and planning but it is often difficult to obtain. Initially, we used census information available at the 3rd administrative level degree of detail ("sections communales"), for northeast Haiti as of 2010. The source of information was MINUSTAH (http://www.un.org/en/peacekeeping/missions/minustah/). Unfortunately, the metadata is deficient, lacks description of methodology used to capture data, and the resulting map is of low spatial resolution. Estimates of the distribution of human population is crucial, especially for operational applications, including emergency response, resource allocation projections and food security analysis, to mention a few.

Census data is often incomplete or unreliable - particularly in remote areas of less-developed countries. Remote sensing methods, on the other hand, are excellent alternatives to estimate the population of urban and rural areas when survey data is limited (Hillson et al. 2014). Given that we have already extracted and counted the number of structures from satellite images, we decided that our evaluation of population would be based on computing the product of number of buildings times 5.8, the mean number of occupants per residence found by Russell et al. (2015). Results are shown on Figure 7.

Road Replacement Value Index

Infrastructure development is required to achieve economic development and for eradicating poverty, not only by fostering growth, but by reducing inequality (Estache, Foster and Wodon, 2002; Estache and Wodon, 2011; UN-OHRLLS, 2014). Adequate transport infrastructure is a major contributor to economic growth and poverty reduction. The road information was downloaded from openstreetmap. org. The data appear to be a combination of government generated maps and user sourced data. Because of this, not all roads may have accurate or complete descriptions attached to them, but it seems to be the most updated roadmap of northeastern Haiti. Combining this map and the official road map (http://www.haitidata.org/map) it was possible to identify the following classes: National Highway, Service Road, other paved road, dirt road, and trails (Figure 8)

The road map was utilized to derive Road Replacement Value Index by watersheds in the Trou Du Nord basin. As before, the roads (R) layer was projected to a common datum and intersected with WSi to create RWS. Each road segment was assigned a "replacement value" based on road type on a 1-10 scale (10=National Highway, 9=Service Road, 5=other paved road, 3=dirt road, 1=trail). The length of each road was multiplied by the replacement value and the resulting weighted values were summed for each sub-watershed to produce road vulnerability. The road vulnerability scores were normalized on a 0-100 scale and ranked accordingly. Results are presented in Figure 8 (left panel) and Table 3 shows the index ranking for road replacement value. The watersheds with the highest road replacement value are those along the northwestern edge of the basin. This is because of the National Highway, Trou Du Nord, and the development of the CIP, all located on this portion of the watershed. These areas have more urban development and a higher concentration of more expensive paved roads.
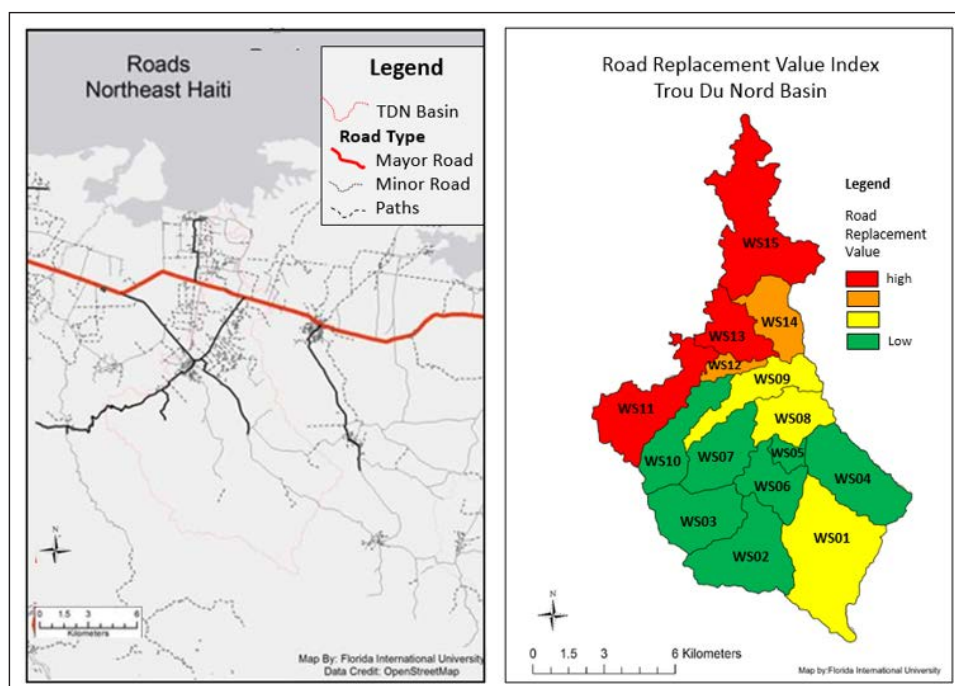

Figure 8. Road map of northeast Haiti (modified from openstreetmap.org) and Road Replacement Value Index

Definition of Priority Sub-watersheds

Smucker et al. (2007) and Smith and Hersey (2008) were the first to rank and compare Haiti's watersheds in terms of their vulnerability to loss of human life, productive infrastructure, soil potential, and erosion risk. We have followed their methodology in a downscaling exercise and have classified the Trou Du Nord sub-watersheds in the same terms. including natural conditions (e.g. geomorphology, slope, climate driven erosivity, vegetative cover, lithology and soil properties) as well as human components and their induced modifications (population, buildings, roads, etc). We have defined the priority sub-watersheds by intersecting the previously developed index layers with the Flood Risk Index (FRI) GIS layer derived from Guillande's map of Flood Prone Areas (2005). In practice we calculated the product of FRI by each individual index, and then normalized the results to a 0-100 scale, as shown in Table 4 and Figure 9.
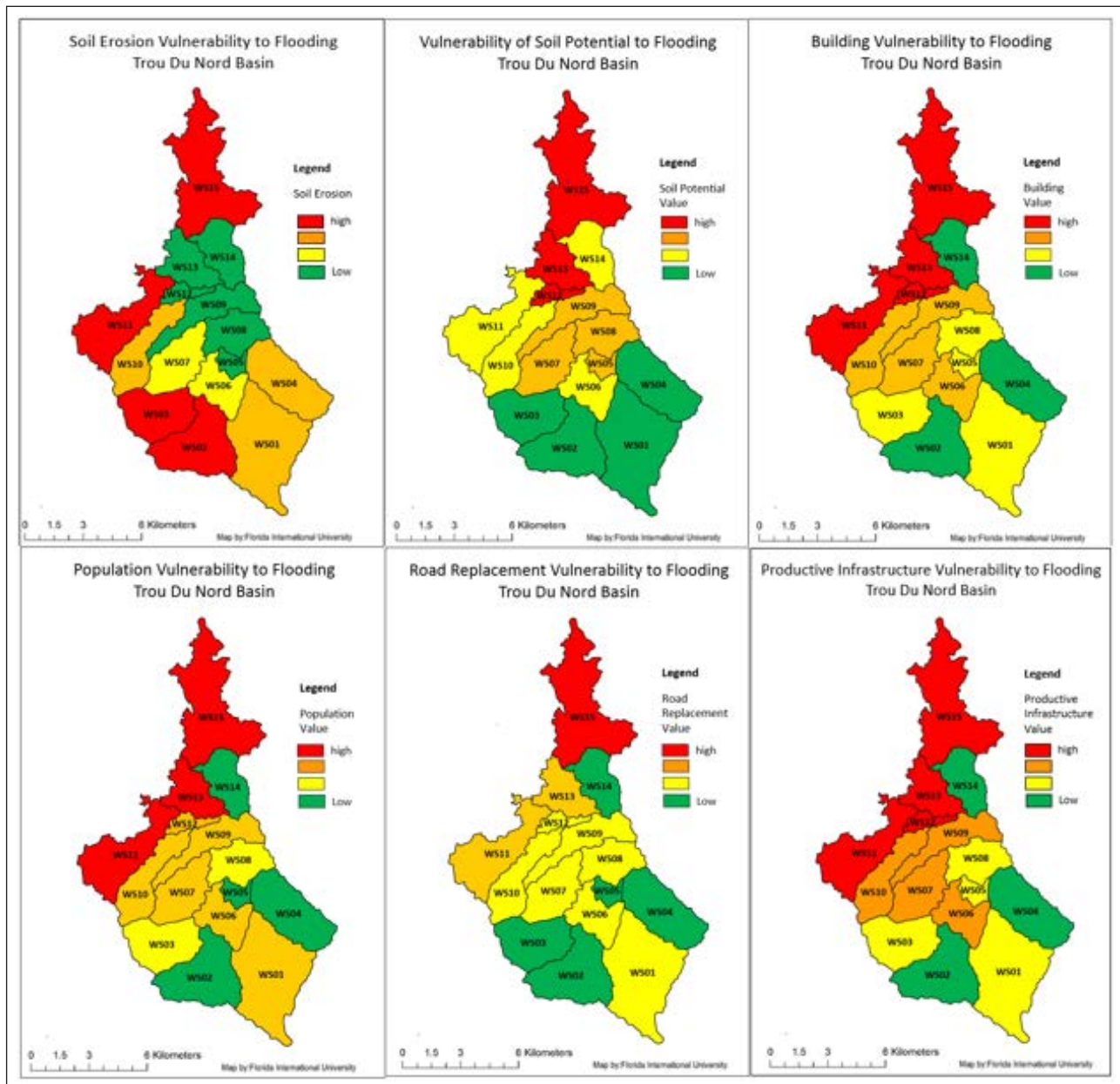
Figure 9. Priority Sub-watersheds of the Trou Du

Table 4. Vulnerability Index to Flooding for Sub-watersheds of the Trou Du Nord Basin

Sub-watershed	Vulnerability to Flooding					
	Soil erosion	Soil Potencial	Building	Population	Roads	Infrastructure
WS1	76	14	17	20	10	12
WS2	95	0	5	6	2	3
WS3	100	7	12	11	4	7
WS4	62	16	0	2	0	0
WS5	30	47	15	7	4	8
WS6	50	36	23	18	11	16
WS7	57	44	27	23	15	20
WS8	41	41	13	11	10	11
WS9	40	47	22	19	13	16
WS10	80	31	23	19	11	15
WS11	91	40	93	100	42	62
WS12	0	55	100	23	11	44
WS13	23	70	88	60	40	58
WS14	32	29	0	0	5	3
WS15	89	100	94	84	100	100

Nord Basin

The north and northwest sub-watersheds (SW11, SW14 and SW15) are the most vulnerable to all flooding risks, while vulnerability declines upstream, to the south. Construction in the CIP and associated urban growth will exacerbate the vulnerability of WS15, as well as urban areas around the village of Trou Du Nord (WS11 and WS13), where building density is greater and the eventual replacement of the road network would be onerous. The best agricultural soils are also those in the coastal plain and low areas along the axis of the basin in WS15, WS13 and WS12, where flooding probabilities are also higher, increasing their vulnerability. Finally, vulnerability of the productive infrastructure, obtained from the intersection of Road Replacement Value Index and Building Density Index with the flood prone area map renders estimates of Productive Infrastructure Vulnerability

CONCLUSIONS

Land use within the Trou Du Nord watershed has and continues to undergo significant change. Forest and agricultural areas are being rapidly converted to residential, commercial, and industrial uses, and forest are being decimated for charcoal production. At the same time, Haiti suffers the impact of major storm and hurricanes every four to five years, and the new Caracol Industrial Park, located in the lower Trou Du Nord basin is within the most vulnerable sub-watershed to flooding impacts under all the analyzed criteria, even when the industrial complex itself, and the new housing subdivisions were not included in the analysis. The purpose of this paper was to identify priority sub-watersheds at the basin level. In order to achieve that goal, we selected a group of indicators that are surrogate variables expressing the underlying ecological, hydrological, geomorphic and ecological functions and processes that affect watershed condition. The vulnerability indexes derived from those factors contribute to identify areas within the basin that are potentially most at risk.

We have identified the location, type and extent of potential flood damages hoping to achieve flood damage reduction and flood preparedness. This is, to foster public safety while reducing flood losses and avoiding economic havoc. We envision the future development of a management plan with the following objectives, flood damage reduction, water quality and ground water recharge protection, and enhancement of wildlife habitat, especially in the mangrove forest and coral reefs to the North. These results can be useful for prioritizing areas where integrated flood management measures may be implemented. These high priority sub-watersheds should become the preferential targets for programs and policies, if protection of the natural and built environment is the primary goal.

DISCLAIMER

REFERENCES

Bird, P., 2003, An updated digital model of plate boundaries: Geochemistry, Geophysics and Geosystems, v. 4, no. 3, pp. 1027- 80

Carabajal CC, Harding D.J., Jean-Paul B., Danielson J.J., Gesch D.B., Suchdeo V.P. 2011. Evaluation of the global multi-resolution terrain elevation data 2010 (GMTED2010) using ICESat geodetic control. In: Proceedings of SPIE-The international society for optical engineering. Nanjing

Estache A., V. Foster and Q. Wodon 2002; Accounting for Poverty in Infrastructure Reform Learning from Latin America's Experience. The World Bank Institute, Washington, DC

Estache, A. and Q. Wodon, 2011. Accounting for Poverty in Infrastructure reform: Learning from Latin America's experience. World Bank Publications. The World bank, Washington, DC

Gesch, D., M. Oimoen, Z. Zhang, J. Danielson, D. Meyer. 2011. Validation of the ASTER Global Digital Elevation Model (GDEM) Version 2 over the Conterminous United States. Report to the ASTER GDEM Version 2 Validation Team.

Guillande, Richard. 2005. Consultation pour la définition d'une méthodologie de réalisation de cartes sur les risques d'inondation en Haïti et élaboration d'un prototype. Geosciences Consultants, Paris & Projet HAI/03/002 – Appui à la mise en oeuvre du Plan National de Gestion des Risques et des Désastres, Programme des Nations Unies pour le Développement. 55 pp.

Hillson, Roger, Joel D. Alejandre, Kathryn H. Jacobsen, Rashid Ansumana, Alfred S. Bockarie, Umaru Bangura, Joseph M. Lamin, Anthony P. Malanoski, and David A. Stenger. 2014. Methods for Determining the Uncertainty of Population Estimates Derived from Satellite Imagery and Limited Survey Data: A Case Study of Bo City, Sierra Leone. PLoS One. 2014; 9(11).

IADB. 2010. Country Strategy Haiti 2011-2015. Inter-American Development Bank http://www.iadb.org/en/countries/haiti/country-strategy,1014.html

IMF. 2014. HAITI: Poverty Reduction Strategy Paper. International Monetary Fund. IMF Country Report No. 14/154.

Quinones, M., W. Gould, C.D. Rodriguez-Pedraza, 2006. Geospatial Data Availability for Haiti: an aid in the development of GIS-based natural resource assessments for conservation planning. Gen. Tech. Rep. IITF-GTR-33. San Juan, PR: U.S. Department of Agriculture, Forest Service, International Institute of Tropical Forestry. 55 p.

Russel, Kory, Sebastien Tilmans, Sasha Kramer, Rachel Sklar, Daniel Tillias, and Jennifer Davis. 2015. User perceptions of and willingness to pay for household container-based sanitation services: experience from Cap Haitien, Haiti. Environ Urban. 2015 Oct; 27(2): 525–540

Smith, Scot and Daniel Hersey. 2008. Analysis of Watershed Vulnerability to Flooding in Haiti. World Applied Sciences Journal 4 (6): 869-885. ISSN 1818-4952

Smucker, Glenn R. (Editor), Mike Bannister, Heather D'Agnes, Yves Gossin, Marc Portnoff, Joel Timyan, Scot Tobias and Ronald Toussaint, 2007. Environmental Vulnerability in Haiti. Findings & Recommendations. Report to USAID, Chemonics International Inc. and the U.S. Forest Service. Washington, D.C.

WHO. 2003. Environmental Health in Emergencies and Disasters: A Practical Guide. Wisner, B. and J. Adams (Editors). World Health Organization. Copenhagen, Denmark

World Bank.2006. "Social Resilience and State Fragility in Haiti: A Country Social Analysis." World Bank, Washington, DC.

UN. 2015. Haiti. Human Development Report 2015. http://hdr.undp.org/sites/all/themes/hdr_theme/country-notes/HTI.pdf Visited May 2016.

UN-OHRLLS. 2014. State of the Least Developed Countries 2014. United Nations Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States. New York, USA.

USAID. 2015. Haiti Reconstruction. http://pdf.usaid.gov/pdf_docs/PBAAC745.pdf GAO report # 15-517.