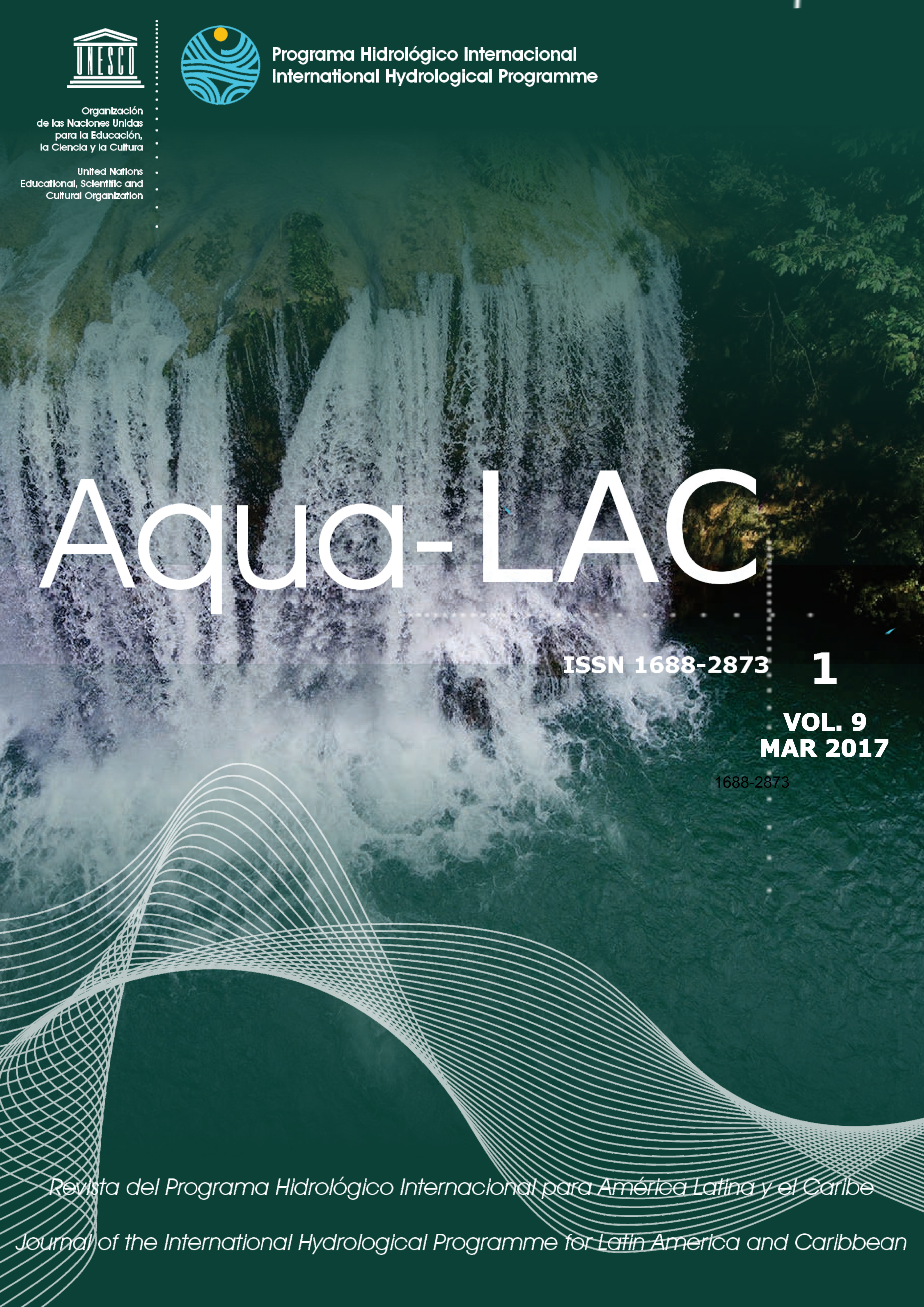

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EDITORIAL

This special issue of AQUA-LAC is a magnificent example of the solidarity expressed by the International Hydrological Program for Latin America and the Caribbean (IHP-LAC) in promoting the integrated management of the water resources of the Republic of Haiti. Indeed, in its report in 1972 on integrated technical assistance in Haiti, the OAS stated, "*The development of Haiti's natural resources is to a large extent linked to maximizing the rational utilization of its water resources. Failing these factors, the country's agricultural and industrial development, as well as the life of its inhabitants, will be confronted by severe limitations"* (OAS, 1972).

This issue has 9 articles written by authors from three countries: Haiti, the United States and Mexico. They cover very diverse fields, ranging from the reconstitution of extreme rainfall events in Haiti – currently a highly pertinent topic with climate change and extreme hydrological phenomena – to an analysis of water governance reform in Haiti, which emphasizes the numerous challenges that have to be overcome to achieve integrated and rational water management.

Furthermore, four articles refer to the water resources of the Trou du Nord watershed, which supplies the industrial zone of Caracol. They provide analytical elements on research issues that not only have to be taken further with respect to this watershed, but which can also be transposed to other watersheds in Haiti in view to carrying out comparative studies.

Regarding water intended for human consumption, the results of an evaluation of microbiological risks highlight the danger of *Crytosporidium* oocysts for the health of the population. The issue of water in emerging non-secured districts is also studied and presented in an article on water supply to Canaan.

The analysis of epidemiological transition linked to hydrometeorological disasters provides methodological tools and calls for specialists in water and health sciences to carry out multidisciplinary actions to establish, and experiment with, protocols aimed at facilitating the development of new tools for preventing and controlling certain water-borne diseases.

This special issue addresses the urgent need for the Haitian authorities to establish a national water policy. By relying on the basic principles of integrated water resource management, I strongly believe that this reform will lead the country in the short, medium and long terms to: (i) reduce the environmental risks linked to water, (ii) better satisfy the population's needs for water, and (iii) solve conflicts between the different actors in this sector.

My administration is committed to this process by proposing legislative and administrative changes, and by making new choices for investment in the water sector by waging on stronger scientific and technical cooperation between and IHP-LAC. This is the context in which I have made the management and control of surface water a major goal of my governmental program.

Jovenel Moïse
President of the Republic of Haiti

EDITORIAL

Ce numéro spécial d'AQUA-LAC est un magnifique exemple de solidarité du Programme hydrologique international pour l'Amérique latine et les Caraïbes (PHI-LAC) en faveur de la gestion intégrée des ressources en eau de la République d'Haïti. En effet, l'OEA en 1972 dans son rapport de mission d'assistance technique intégrée en Haïti a avancé que : "*Le développement des ressources naturelles d'Haïti est en grande partie lié au profit maximum d'utilisation rationnelle de ses ressources en eau. Sans ces facteurs, de fortes limitations agiront sur le développement agricole et industriel du pays et aussi sur la vie même de ses habitants*" (OEA, 1972).

Ce numéro de 9 articles, produits par des auteurs de 3 pays : Haïti, les États-Unis et le Mexique, couvre des domaines aussi divers tel que : la reconstitution des périodes de pluies extrêmes en Haïti – un sujet très pertinent aujourd'hui avec les changements climatiques et les phénomènes hydrologiques extrêmes – l'analyse de la réforme de la gouvernance de l'eau en Haïti, en soulignant les nombreux défis pour arriver à une gestion intégrée et rationnelle de cette ressource.

De plus, quatre articles se réfèrent aux ressources en eau du bassin versant de Trou du Nord, source d'approvisionnement du Parc industriel de Caracol. Ils fournissent des éléments analytiques sur des objets de recherche qui doivent non seulement être approfondis au niveau de ce bassin versant, mais également être transposés sur d'autres bassins hydrographiques d'Haïti pour des études comparatives.

En ce qui concerne l'eau destinée à la consommation humaine, les résultats d'une évaluation des risques microbiologiques mettent en évidence le danger sanitaire lié aux oocystes de *Crytosporidium* auquel la population est exposée. La problématique de l'eau dans les quartiers précaires en formation est également étudiée et présentée dans un autre article sur l'approvisionnement en eau à Canaan.

L'analyse de la transition épidémiologique en relation avec les catastrophes hydrométéorologiques fournit des outils méthodologiques qui doivent interpeller et inciter les spécialistes en sciences de l'eau et ceux de la santé publique dans une interaction multidisciplinaire à élaborer et expérimenter des protocoles devant faciliter le développement de nouveaux outils de prévention et de contrôle de certaines maladies hydriques.

Ce numéro spécial interpelle les autorités haïtiennes sur l'urgente nécessité de formuler une politique nationale de l'eau. En prenant appui sur les principes de base de la gestion intégrée des ressources en eau, je crois fermement que cette réforme conduira le pays à court, moyen et long terme vers: (i) une réduction des risques environnementaux liés à l'eau, (ii) une meilleure satisfaction des besoins en eau de la population, (iii) la résolution des conflits entre les différents intervenants dans ce secteur.

Mon administration s'est engagée dans ce processus en proposant des changements législatifs et administratifs, et de nouveaux choix d'investissement pour le secteur de l'eau en misant bien évidemment sur le renforcement de la coopération scientifique et technique entre Haïti et le PHI-LAC. C'est dans ce contexte que j'ai fait de la gestion et la maîtrise de l'eau de surface un axe majeur de mon programme de gouvernement.

Jovenel Moïse
Président de la République d'Haïti

ÉDITORIAL

Este número especial de Aqua-LAC es un magnífico ejemplo de solidaridad del Programa Hidrológico Internacional para América Latina y el Caribe enfavor de la gestión integrada de los recursos hídricos de la República de Haití. De hecho, la OEA en 1972 en su informe de misión de asistencia técnica integrada a Haití argumentó que: *"El desarrollo de los recursos naturales de Haití está en gran parte relacionado con el aprovechamiento máximo del uso racional de los recursos hídricos. Sin estos factores, limitaciones fuertes afectarán el desarrollo agrícola e industrial del país y también la propia vida de sus habitantes"(*OEA, 1972).

Este número está compuesto por 9 artículos realizados por autores de 3 países: Haití, Estados Unidos y México, y cubre áreas tan diversas como: los períodos de reconstitución de las precipitaciones extremas en Haití – un tema muy relevante hoy en día considerando los cambios climáticos y los fenómenos hidrológicos extremos que están ocurriendo –; o el análisis de la reforma de la gobernanza del Agua en Haití, destacando los numerosos desafíos para lograr una gestión integrada y racional de este recurso.

Además, cuatro artículos se refieren a los recursos de agua de la cuenca de Trou du Nord, la fuente de abastecimiento del Parque Industrial de Caracol. Éstos proporcionan elementos analíticos sobre objetos de investigaciónque deben no solo profundizarse con relación a esta cuenca, sino tambiéntransponerse a otras cuencas hidrográficas de Haití en estudios comparativos.

Con respecto a las aguas para consumo humano, los resultados de una evaluación de riesgos microbiológicos destacan el riesgo sanitario relacionado con los ooquistes de *Crytosporidium* a los que está expuesta la población. La problemática del agua en los barrios precarios en formación es igualmente estudiada y presentada en otro artículo sobre el suministro de agua en Canaan.

El análisis de la transición epidemiológica en relación con los desastres hidrometeorológicos proporciona herramientas metodológicas que deben desafiar y animar a los especialistas en temas de agua y salud pública a interactuar de forma multidisciplinaria para elaborar y experimentar protocolos de prueba quefaciliten la creaciónde nuevas herramientas para la prevención y el control de determinadas enfermedades transmitidas por el agua.

Este número especial de la Revista Aqua-LAC interpelaa las autoridades de Haití acerca de la urgente necesidad de formular una política nacional de agua. Con base en los principios de gestión integrada de los recursos hídricos, creo firmemente que dicha reforma conducirá al país en el corto, mediano y largo plazo a: (i) una reducción de los riesgos ambientales relacionados con el agua, (ii) una mejor respuesta a las necesidades de agua de la población, (iii) la resolución de conflictos entre los diferentes actores del sector.

Mi administración está comprometida con este proceso proponiendo cambios legislativos y administrativos, así como nuevas oportunidades de inversión para el sector del agua centradose evidentemente en el fortalecimiento de la cooperación científica y técnica entre Haití y el PHI-LAC. Es en este contexto que he hecho de la gestión y el control de las aguas superficiales un eje fundamental de mi programa de gobierno.

Jovenel Moïse
Presidente de la República de Haití

POLÍTICA EDITORIAL

Frecuencia de publicación

La Revista Aqua-LAC será publicada cada seis meses o dos veces al año.

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ADVANCED HYDRAULIC AND WATER QUALITY MODELING TO ASSESS FLOOD AND POLLUTION IMPACTS: A CASE STUDY OF THE CARACOL INDUSTRIAL PARK IN HAITI

MODÉLISATION AVANCÉE DE LA QUALITÉ HYDRAULIQUE ET DE L'EAU POUR ÉVALUER LES EFFETS DES INONDATIONS ET DE LA POLLUTION: UNE ÉTUDE DE CAS DE L'ESCARGOT DU PARC INDUSTRIEL EN HAÏTI

MODELACION HIDRODINAMICA Y DE CALIDAD DEL AGUA PARA EVALUAR EL IMPACTO DE INUNDACIONES Y DE CONTAMINACION. UN CASO DE ESTUDIO DEL PARQUE INDUSTRIAL CARACOL EN HAITI

Garcia, Reinaldo[1] and Miralles-Wilhelm, Fernando[2]

Abstract

In this paper, we describe the application of advanced hydraulic and water quality models to assess flood risks at the development site of Parc Industriel Caracol (PIC) in northern Haiti, and evaluate water quality scenarios of the Trou-du-Nord River downstream of the PIC to support the development of the Trou du Nord Watershed Management Plan. To achieve the study goals, we implemented the RiverFlow2D hydraulic model to perform the numerical simulations required in the PIC project. To evaluate potential flooding scenarios at the PIC, we developed design storms based on rainfall scenarios that take into account a wide variety of events that can affect the area of interest. Two types of flooding scenarios were considered: *Sunny Day* and *Rainfall*. In both cases, runs were made for 1, 2, 5, 10, 25, 50, 100 and 200 year events and results included maximum flooding depth, maximum velocities, and other parameters to assess flood impacts. The model also reports inundation times that indicate how many hours each area remains flooded to a given depth equal. Water quality model simulations were performed to evaluate the impact of the effluent discharge from the PIC wastewater treatment plant. Four simulation scenarios correspond to a range of effluent and river pollutant concentrations and different water discharges from the Trou du Nord River. Simulations confirm that the most unfavorable case is when the Trou du Nord River is dry. Even for relatively low river flows, pollutant concentrations decrease significantly due to the dilution effect of the water from the Trou du Nord River. The hydraulic and water quality models developed in this work can be used further to assess the flood risk to communities located downstream of the PIC, as well as to evaluate impacts of variations in wastewater discharges on the water quality reaching these communities.

Keywords: Hydrodynamic modeling, water quality, floods.

Résumé

Dans cet article, nous décrivons l'application de modèles hydrauliques avancés et de qualité de l'eau pour évaluer les risques d'inondation du Parc Industriel Caracol (PIC) dans le nord de Haïti, et d'évaluer des scénarios de qualité de l'eau de la rivière Trou-du-Nord rivière en aval du PIC pour soutenir le développement du plan de gestion du bassin versant Trou du Nord. Pour atteindre les objectifs de l'étude, nous avons mis en œuvre le modèle hydraulique RiverFlow2D pour effectuer les simulations numériques nécessaires au projet PIC. Pour évaluer les scénarios d'inondation potentiels au PIC, nous avons développé des tempêtes extrêmes basées sur des scénarios de précipitations qui prennent en compte une grande variété d'événements qui peuvent avoir une incidence sur la zone d'intérêt. Deux types de scénarios d'inondation ont été envisagés: « Jour ensoleillé» et « Jour pluvieux». Dans les deux cas, les essais ont été faits pour Tr=1, 2, 5, 10, 25, 50, 100 et 200 années et les résultats inclus profondeur maximale d'inondation, les vitesses maximales, et d'autres paramètres pour évaluer les impacts des inondations. Le modèle génère également les temps d'inondation. Les simulations du modèle de qualité de l'eau ont été réalisées pour évaluer l'impact de l'effluent de l'usine de traitement des eaux usées de PIC. Quatre scénarios de simulation correspondent à une gamme de concentrations de polluants des effluents et de la rivière et les différents rejets d'eau de la rivière Trou du Nord. Les simulations confirment que le cas le plus défavorable est lorsque la rivière est sèche. Même pour des débits relativement faibles de la rivière, les concentrations de polluants diminuent considérablement en raison de l'effet de dilution de l'eau de la rivière du Nord Trou. Les modèles développés dans ce travail peuvent être utilisés en outre pour évaluer les risques d'inondation pour les communautés situées en aval de la PIC, ainsi que pour évaluer les impacts des variations des rejets d'eaux usées sur la qualité de l'eau que pour atteindre ces communautés.

Mots-clés: Modélisation hydrodynamique, la qualité de l'eau, les inondations.

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Resumen

En este trabajo se describe la aplicación de modelos avanzados de hidráulica y de calidad de agua para evaluar los riesgos de inundación en el Parque Industrial Caracol (PIC) en el norte de Haití y valorar escenarios de calidad del agua del Rio Trou-du-Trou aguas abajo de la PIC. Los resultados de las simulaciones apoyarán el desarrollo del plan de Gestión de Cuenca del Rio Trou du Nord. Para lograr los objetivos del estudio, se implementó el modelo hidráulico RiverFlow2D a fin de realizar las simulaciones numéricas requeridas en el proyecto. Para evaluar los posibles escenarios de inundación en el PIC, se desarrollaron tormentas de diseño basadas en escenarios de precipitaciones que contemplan una amplia variedad de eventos que pudiesen afectar a la zona de interés. Se consideraron dos tipos de escenarios de inundación: “Día soleado” y “Dia con precipitaciones”. En ambos casos, se hicieron corridas de Tr= 1, 2, 5, 10, 25, 50, 100 y 200 años y los resultados incluyeron profundidad máxima inundaciones, velocidades máximas, y otros parámetros para evaluar los impactos de inundación. El modelo también genera los tiempos de inundación. Se realizaron simulaciones del modelo de calidad del agua para evaluar el impacto del vertido del efluente de la planta de tratamiento de aguas residuales del PIC. Los cuatro escenarios de simulación cubren un rango de concentraciones de contaminantes de efluentes y fluviales y diferentes descargas de agua del río Trou du Nord. Las simulaciones confirman que el caso más desfavorable es cuando el río está seco. Incluso para los flujos relativamente bajos, las concentraciones de contaminantes disminuyen significativamente debido al efecto de dilución del agua proveniente del río Trou fu Nord. Los modelos desarrollados en este trabajo se pueden utilizar adicionalmente para evaluar el riesgo de inundaciones para las comunidades ubicadas aguas debajo del PIC, así como para evaluar el impacto de las variaciones de descargas de aguas residuales en la calidad del agua que llega a esas comunidades.

Palabras Clave: Modelación hidrodinámica, calidad de agua, inundaciones.

1. INTRODUCTION

The vulnerability of Caribbean islands to natural and human-induced disasters and their inability to cope with the problem necessitates an understanding of the hydrological processes and responses of the watersheds to various stressors. This challenge is further complicated at a time when development pressures rise due to population growth and socioeconomic needs, while there is increased uncertainty of rainfall in a changing climate. This is particularly true for Haiti, which has the lowest GDP of the region and ranks among the first in the region in terms of environmental degradation (IADB, 2017). Therefore, sustainable planning and management are essential for sustainability of fresh water resources in the watersheds.

In this paper, we describe the application of advanced hydraulic and water quality models to assess flood risks at the development site of Parc Industriel Caracol (PIC) in northern Haiti, and evaluate water quality scenarios of the Trou-du-Nord River downstream of the PIC to support de development of the Trou du Nord Watershed Management Plan.

Previous modeling efforts in the Trou du Nord watershed have been restricted by limitations of the models used. For example, Environ, (2011) use a steady-state modeling approach to estimate runoff flow rates at the PIC; this approach fails to capture the temporal and spatial dynamics of flooding (and water quality) that occur due to rainfall variability and fine scale terrain features. Physically-based models such as the one implemented in this project can better capture the hydraulic response of an area like the PIC because they parametrize the hydrologic system’s inputs, the physical laws which govern its behavior, boundary, and initial conditions and the key relationships between storms and terrain.

This study addresses the following key questions and requirements.

- The models should be capable of addressing flooding in the PIC area under different situations including, existing conditions, future development conditions, effect of rainfall and discharge from the Trou du Nord River.
- The model should be capable of addressing future changes in the PIC development.
- Determine the evolution of the water quality in the Trou du Nord River downstream from the PIC
- Assessing flooding risk for the PIC. This involves determining flood depth, velocities and inundation times for a number of events representative of the storm occurrence frequency in the area.
- Perform discrete water quality modeling. This requires simulating effluent discharge from the PIC Water Treatment Plant into the Trou du Nord River.
- The models (both for flood estimation and for water quality) should be capable of being calibrated and validated as new data is collected.

2. METHODOLOGY

To achieve the study goals, we implemented the RiverFlow2D hydraulic model to perform the numerical simulations required in the PIC project. RiverFlow2D is a suite of two-dimensional river and estuary flexible mesh models (Garcia et al. 2006, 2009; Murillo et al. 2010) that can support flood risks and water quality assessments including hydraulic structures (www.hydronia.com). RiverFlow2D’s stable and fast numerical engine allows treating high speed flows and fast frontal waves over initially dry terrain (Mahmoudi et al. 2015). Setting up RiverFlow2D simulations with the integrated GIS user interface is fast and straightforward. The high performance GPU version is able to run up to 100 times faster than a non-parallelized single-processor model.

To solve the shallow water, sediment and pollutant transport equations, the RiverFlow2D model uses an unstructured *flexible mesh* formed by triangles of different sizes that can be adapted around the most complex geometries (Murillo et al. 2005, 2008, 2010). The mesh can be generated and refined over the areas of more interest to the project such as main river channel, buildings, etc.

RiverFlow2D can handle discharges of any number of different pollutants simultaneously accounting for advection by the river velocities, dispersion, and reaction rates if applicable (Murillo et al. 2010). This greatly simplifies the analysis of multiple pollutant discharge scenarios providing high accuracy taking advantage of the high resolution triangular element mesh.

2.1 INPUT DATA

Rainfall Scenarios and Design Storms

To evaluate potential flooding scenarios at the PIC, we developed design storms based on rainfall scenarios that take into account a wide variety of events that can affect the area of interest. We used the maximum daily rainfall storm amounts that were generated in an earlier stage of the study, and assumed typical 24-hour storm distribution applicable to southern Florida (and herein used for this region) using a SCS Type IIIG (See Figure 1) as an approximation for the rainfall intensity that can occur in Northern Haiti.

The total 24-hour rainfall accumulations for each return period used to generate the design storms for the PIC flood simulations are shown in Table 1.

Table 1. Total 24-hour rainfall for Return Periods Considered

Return Period (years)	Total 24-hour Rainfall (mm)
1	60.00
2	153.32
5	222.93
10	273.45
25	342.18
50	396.72
100	454.4
200	515.53

With these assumptions, we generated design storms consisting on hyetographs for return period events of 1, 2, 5, 10, 25, 50, 100 and 200 years.

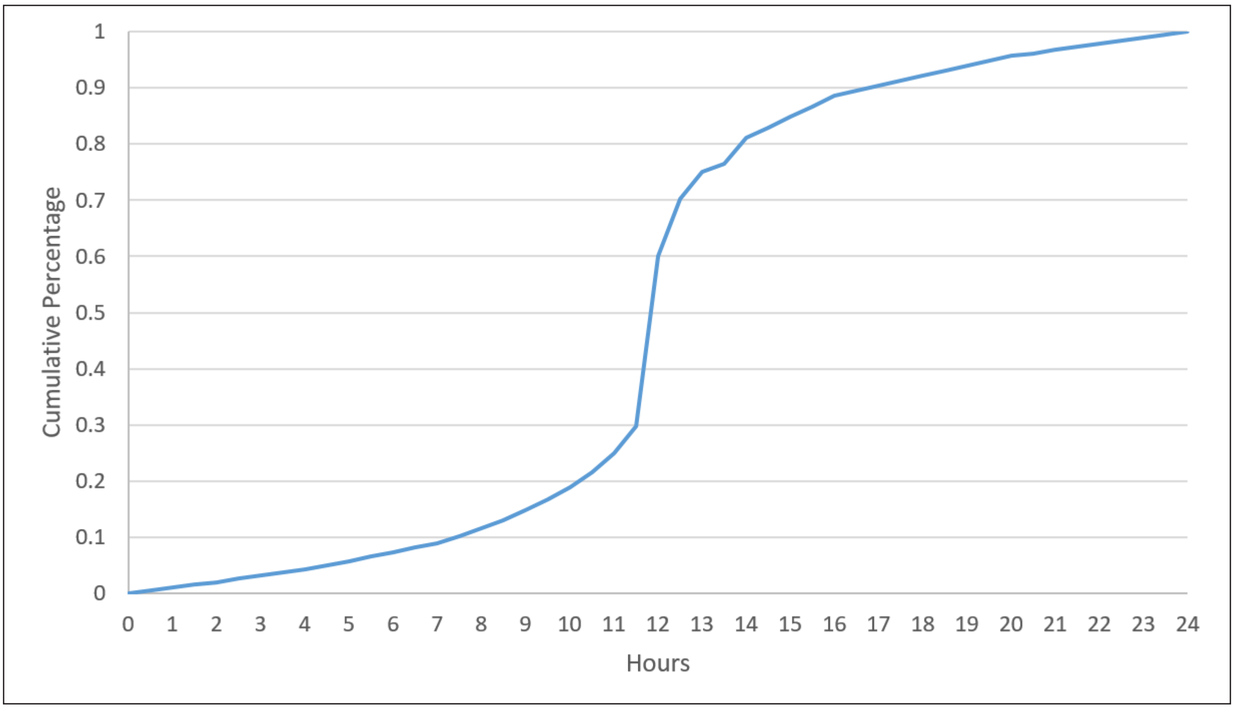

Figure 1. Twenty-four hour rainfall distribution SCS-Type IIIG

Inflow Hydrographs from the Trou-du-Nord Watershed

For the purpose of the flood simulations presented in this paper, we used the outflow hydrographs generated by the SWAT model applied to the Trou du Nord watershed that is reported in a companion paper of this same journal [Reference to companion paper]. The hyetograph for each return period described in the previous section were input in SWAT and resulted in hydrographs upstream of the PIC for each event. These hydrographs shown in Figure 2 were in turn introduced into the RiverFlow2D model as inflow conditions to perform the flooding simulations. The peak discharges for each hydrograph are presented in Table 2.

Table 2. Peak discharges for each return period considered

Tr years	Peak discharge m^3/s
1	13.00
2	47.80
5	69.30
10	82.60
25	104.54
50	122.76
100	140.05
200	160.00

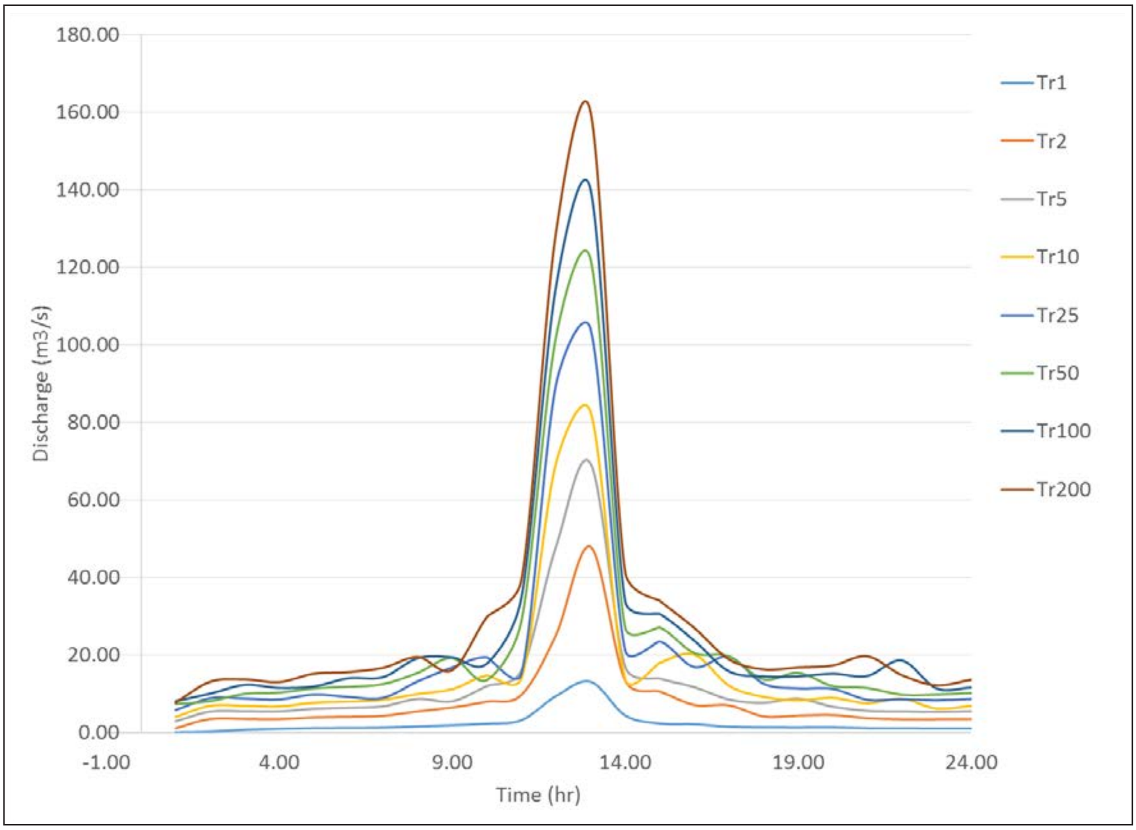

Figure 2. Inflow hydrographs. Tr is used to denote return period (in years) as in Table 1

Digital Elevation Model

A digital elevation model with a resolution of 2 meters was used to represent the terrain topography. The DEM corresponds to UTM_Zone 18 Northern Hemisphere DATUM WGS84 SPHEROID WGS84 PROJECTION Transverse_Mercator. The data was obtained as part of this investigation, and was processed to determine elevations on the centroids of each triangular cell, through sampling and Inverse-Distance-Weighting interpolation. The cross sections of the Trou du Nord river were extracted from this DEM.

Modeling Area

Figure 3 shows the extent of the modeling area that has 16.3 km^2. Several of the existing industrial buildings of the PIC can be clearly observed on the figure. The INFLOW annotation at the lower end of the area is where the inflow hydrographs from the Trou-du-Nord watershed previously described, were imposed. Downstream at the coastal line, we set open free outflow boundaries to let the water from the river enter into the Caracol Bay.

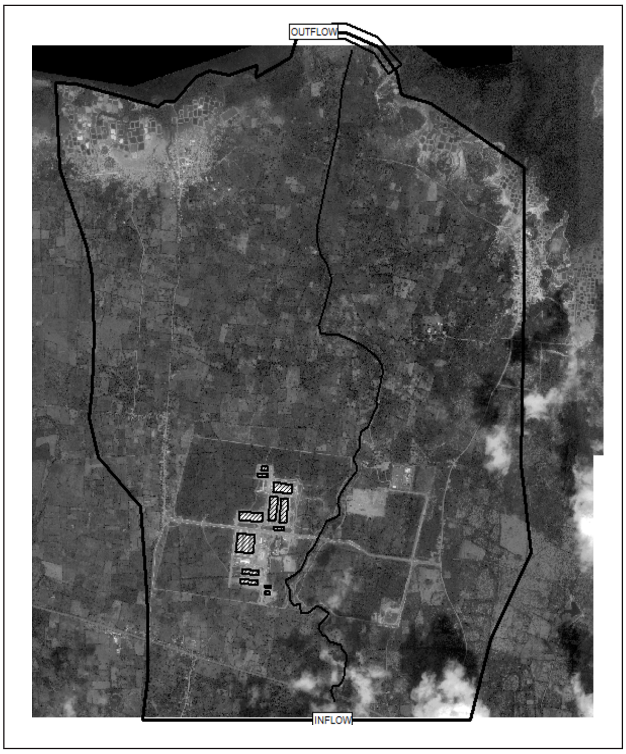

Figure 3. Extent of the Modeling Area

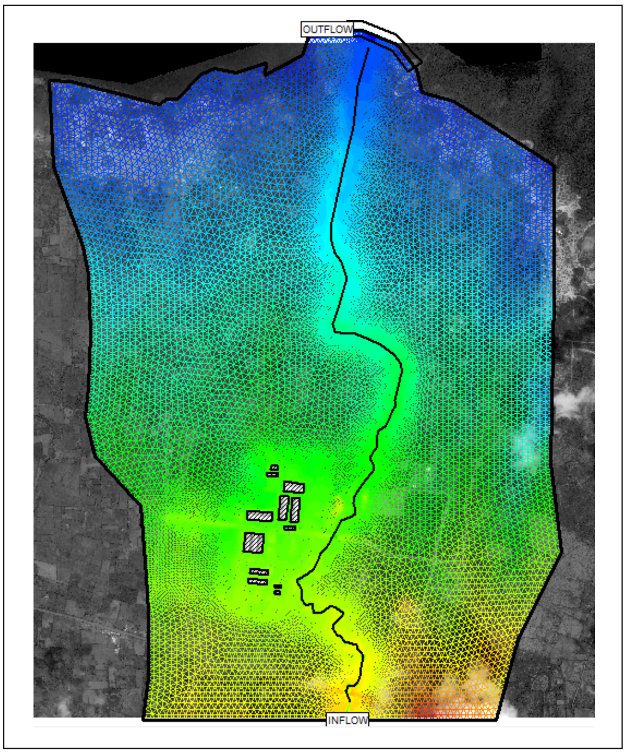

Figure 4. Triangular-element mesh used by the RiverFlow2D model. The average size of the triangular grid in the finest resolution (near the river and the PIC infrastructure) is 1.5 meters

Figure 4 shows the triangular-cell mesh used by the model to calculate velocities and depths at every cell. The mesh was refined to have a higher resolution along the main river and also on the PIC area, resulting on 133,848 cells. Triangle sizes ranged from 1.5 m to 16.5 m approximately.

Figure 5 depicts a detailed view around the PIC area. Note that the mesh has been generated around the main PIC buildings in order to represent the effect that these structures can have on the flooding.

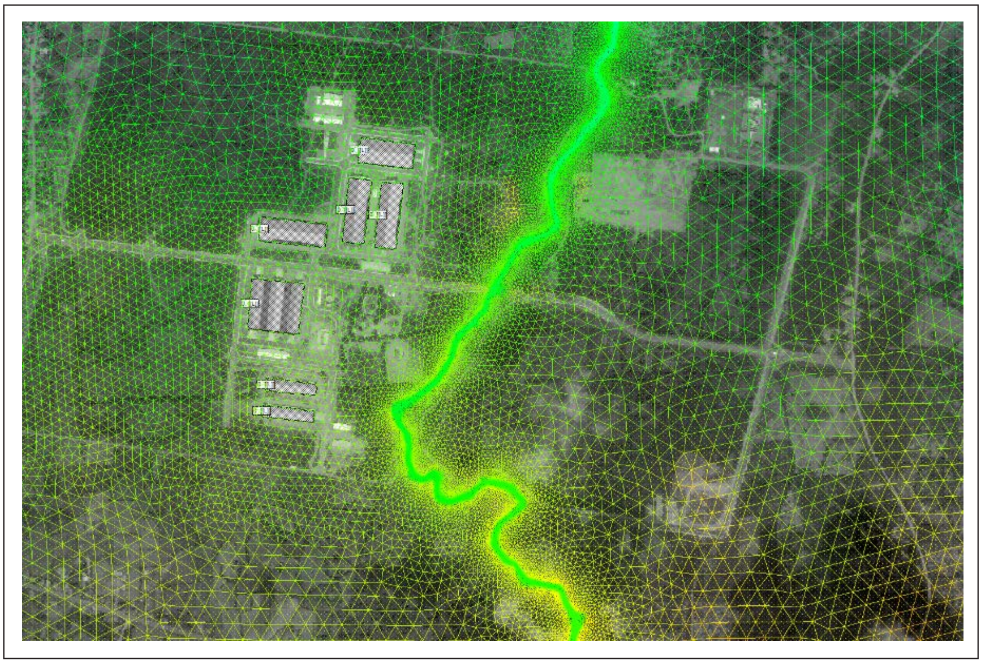

Figure 5. Detail of RiverFlow2D spatial mesh on the PIC area. The model calculates the flow velocity and depth at each triangle and throughout the simulation period of 24 hours

3. FLOODING SIMULATIONS

For the application of the RiverFlow2D model to simulate flooding at the PIC, two types of scenarios were considered: *Sunny Day* and *Rainfall* explained below. In both cases, runs were made for 1, 2, 5, 10, 25, 50, 100 and 200 year events and results included maximum flooding depth, maximum velocities, and other parameters to assess flood impacts. The model also reports inundation times that indicate how many hours each area remains flooded with a depth equal to or greater than 10 cm. Only results for the 100 year event are presented here.

3.1. Sunny-day Scenarios

In the *Sunny-day* scenarios, it is assumed that there is no rainfall and water is only coming from the Trou-du-Nord River flow. This means that only the inflow hydrographs presented previously were imposed at the southern entrance of the Trou-du-Nord River.

The following figures show plots of maximum inundation depth, maximum velocities, and inundation times for the 100-year event.

Results of the sunny-day scenario indicate that no flooding occurs in the PIC area for the 1 and 5-year events. This suggests that for peak Trou du Nord River discharges below 70 m^3/s, the river channel is able to convey the runoff coming from the upper watershed and keep an acceptable freeboard along the Industrial Park. However, for this discharge, results show that there is some flooding downstream from the wastewater treatment plant.

According to the model results, flooding starts to affect the PIC for events of return periods above 25 years. For the particular case of Tr = 25 years, flooding starts to occur just upstream of the bridge and maximum water depths reach 30 cm in a few locations. However, inundation times do not exceed 30 minutes. These results suggest that the threshold discharge to cause PIC flooding from the Trou du Nord River starts when the river discharge is about 100 m^3/s. As shown in the results for the 50, 100 and 200-year events, higher discharges lead to considerable flooding over the PIC development. For instance, the model results for the 50-year event corresponding to a peak discharge of 122 m^3/s, show that the total percentage of the PIC area affected by flood depths greater than 10 cm is about 15% with some localized spots with depths of up to 1.2 m. Inundation times for this event range from 10 to 12 hours approximately.

Maximum flooding area reach about 40% of the PIC development for the 100-year event that corresponds to 140 m^3/s peak discharge (Figure 6 to Figure 8), while the inundation can last up to 16 hours in some locations. The 200-year event with a 160 m^3/s peak Trou du Nord River discharge is the more extreme scenario considered in this study, the area flooded can reach 70% of the PIC with maximum localized depths pf 1.3m and inundation lasting up to 18 hours.

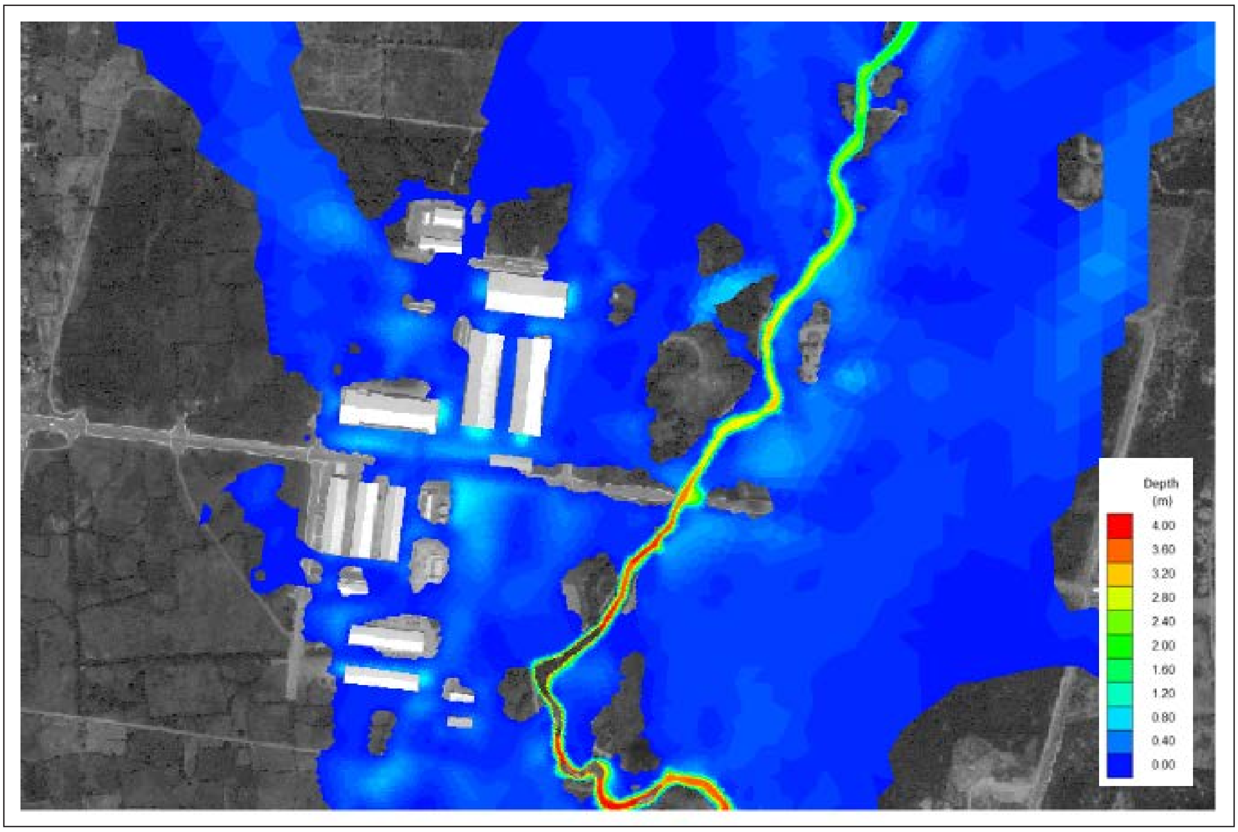

Figure 6. 100-yer event. Maximum Depths

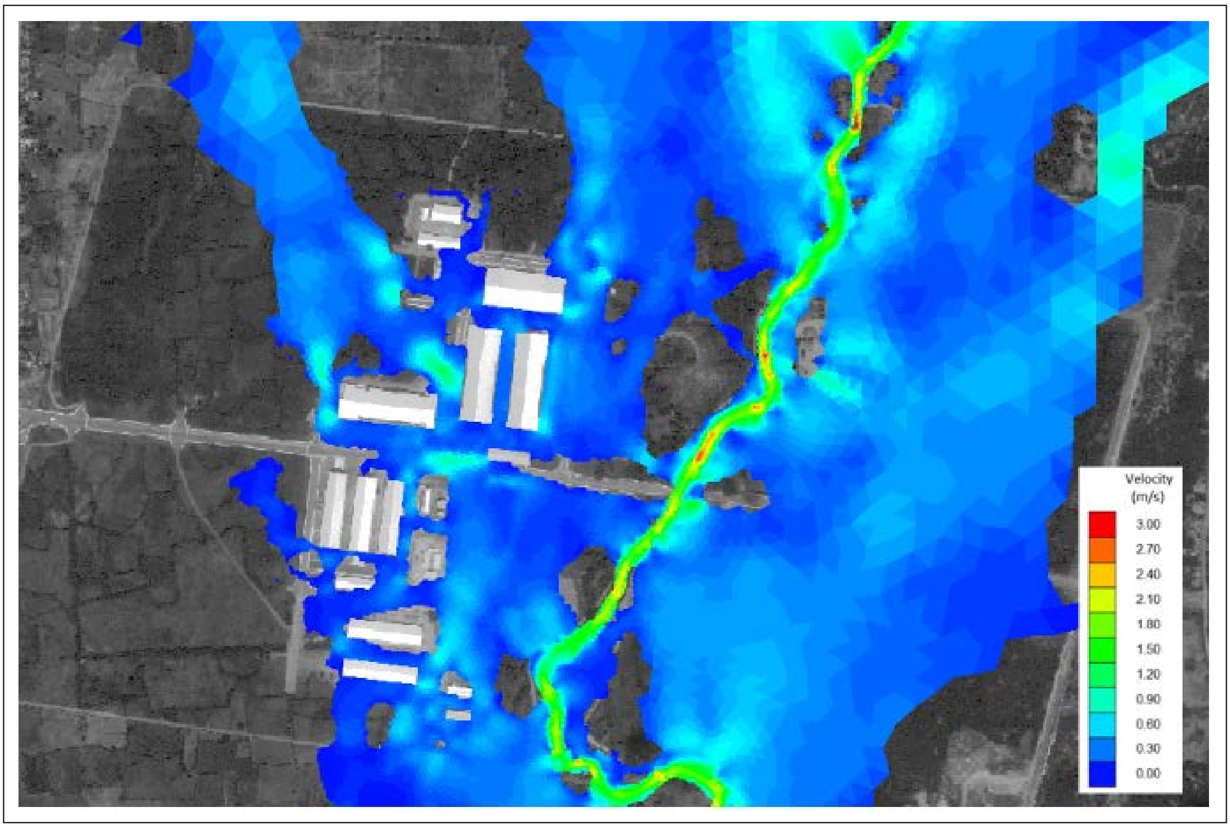

Figure 7. 100-year event. Maximum Velocity

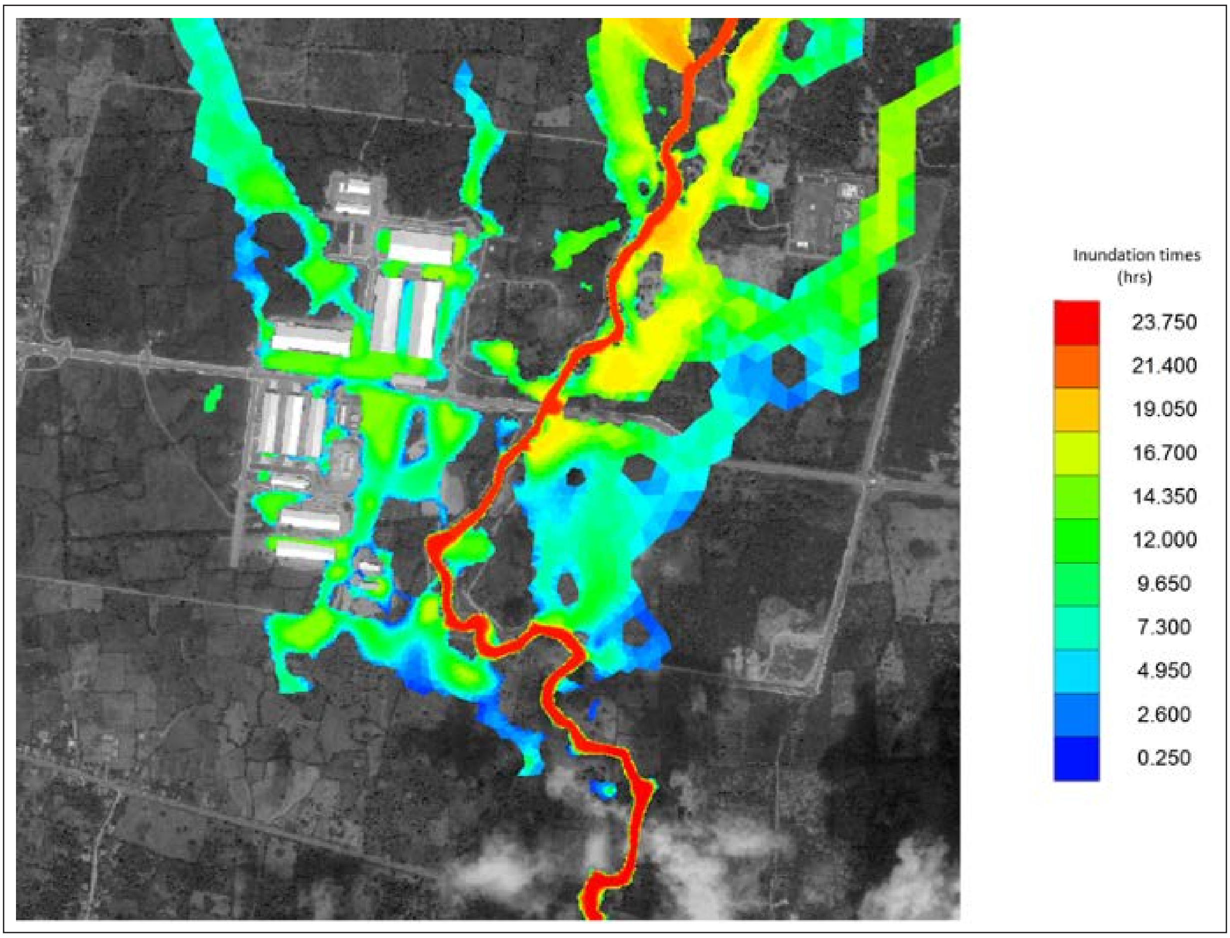

Figure 8. 100-year Event. Inundation Times

3.2. Rainy-day Scenarios

In the Rainy-day scenarios, it is assumed that in addition to the water that flows from the Trou-du-Nord watershed, the rainfall design storm is occurring all over the area of the PIC. Therefore, the inflow hydrograph, and the uniform rainfall hyetograph were considered in each run. These cases simulate the situation occurring during extreme tropical weather events, such as hurricanes or tropical storms when the river can bring high discharges and it can be simultaneously raining over the area.

The rainy-day scenarios provide a completely different flooding picture when compared with the sunny-day cases. Due to the effect of the simultaneous occurrence of rainfall and flow from the Trou du Nord River, according to the model, flooding starts to occur for the 1-year events. For this particular event, the total 24-hour rainfall is 60 mm, and the flooding area with depths above 10 cm covers about 15% or the existing PIC development and localized water depths can reach 1 m. Inundation times can be as long as 22 hours.

Model simulations for the 2-year event, with a 24-hour rainfall of 153 mm, show that 20% of the PIC area can be flooded at a given time with localized depths around 1.4 m. Inundation times can reach 23 hours.

Percentage of flooded area reaches 30% for the 5 year event that has a 24-hour rainfall of 223 mm. In this case, the maximum depths are around 2 m and the inundation times can be as large as 24 hours.

The flooding area with depths above 10 cm covers about 35% of the existing PIC development for the 10 year event with 273 mm of accumulated rainfall in 24 hours.

Simulations for the 25 year event indicate that the flooded area can reach 45% of the PIC, with depths exceeding 2.4 m for 24 hours in some.

The model results for the 50-year event corresponding to a peak discharge of 122 m^3/s show that the total percentage of the PIC area affected by flood depths greater than 10cm is about 65% with some localized spots with depths of up to 2.7 m. Inundation times for this event range from 10 to 24hours approximately.

For the 100 year event with a 140 m^3/s peak Trou du Nord River discharge the area flooded can reach 70% of the PIC with maximum localized depths of 1.3m and inundation lasting up to 24 hours.

Maximum flooding area can reach about 85% of the PIC development for the 200-year event that corresponds to 160 m^3/s peak discharge and 515 mm of accumulated rainfall in 24, while the inundation can last up to 24 hours in some locations.

4. WATER QUALITY SIMULATION RESULTS

4.1. Simulations to Determine Pollutant Dispersion Downstream of the Treatment Plant Discharge

This section presents results of the RiverFlow2D model simulations performed to evaluate the impact of the effluent discharge from the PIC wastewater treatment plant. Four simulation scenarios are presented here, corresponding to the effluent and river pollutant concentrations indicated in Table 3, and different water discharges from the Trou du Nord River shown in Table 4; the effluent discharge was assumed to be equal to 40 lps. It is important to note that the water discharge flow rates through the river considered in the water quality simulations are on the low end of the return periods analyzed for flooding (see Table 2). This implies that water quality impacts need to be analyzed at much higher frequencies of occurrence (lower return periods) than flood impacts, as high flow rates associated with higher return periods would dilute water quality impacts and render them negligible as these results show.

Table 3. Pollutant concentration data used in PIC treatment plant effluent dispersion simulations

Parameter	Outflow From Plant	Inflow From River	Units
OD	3	2.50	mg/l
BOD	30	3.40	mg/l
COD	125	3.40	mg/l
SST	50	14.50	NTU
N total	24.5	0.50	mg/l
P total	4.92	0.10	mg/l
Oil and fats	10	1.00	mg/l
Coliforms	2800	5,400.00	NMP/100 ml

Table 4. Trou du Nord River Discharges Used in the Simulations

Scenario	Trou du Nord River discharge m^3/s
1	0
2	1
3	5
4	20

Figure 9 shows the model mesh along the river and indicates the inflow from the Trou du Nord River, with the greener tones indicating higher mesh density, and the wastewater treatment plant discharge location.

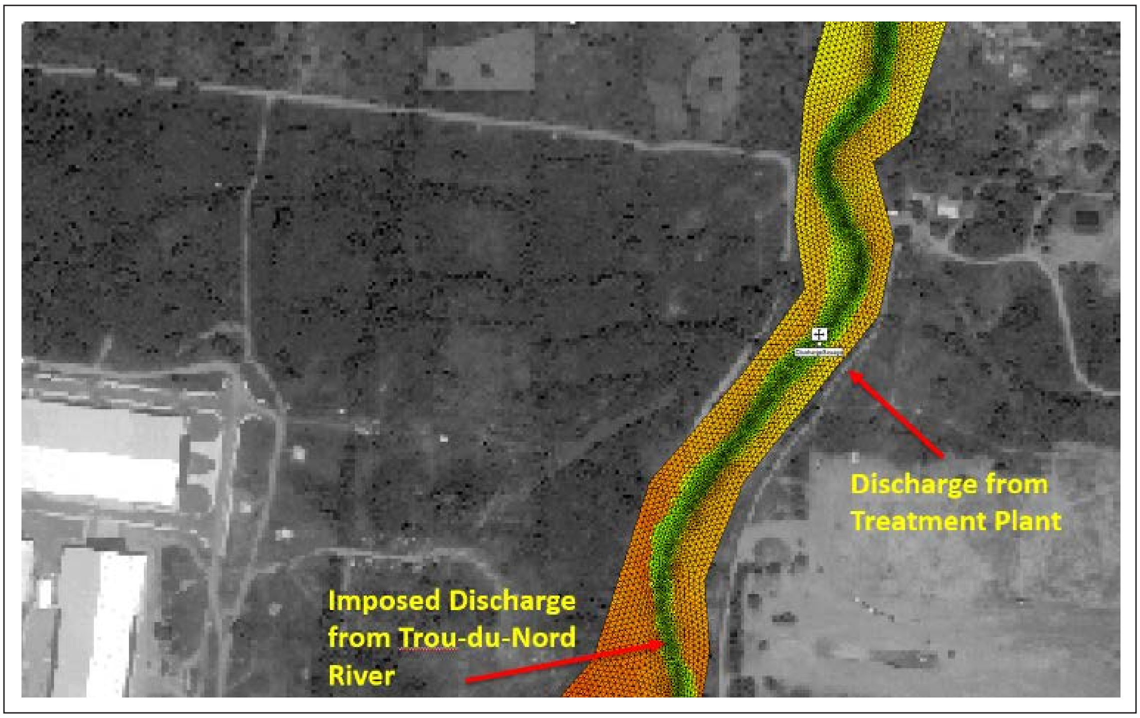

Figure 9. RiverFlow2D model on the Trou du Nord river along the PIC. The green shading indicates the highest spatial resolution numerical grid in order to capture flooding impacts at that resolution (1.5 meters)

Figure 10 to Figure 15 present the pollutant concentration maps for each scenario and concentration profiles along the river from the treatment plant location. These plots allow determining how the concentration of each pollutant varies with distance as a function of the river discharge.

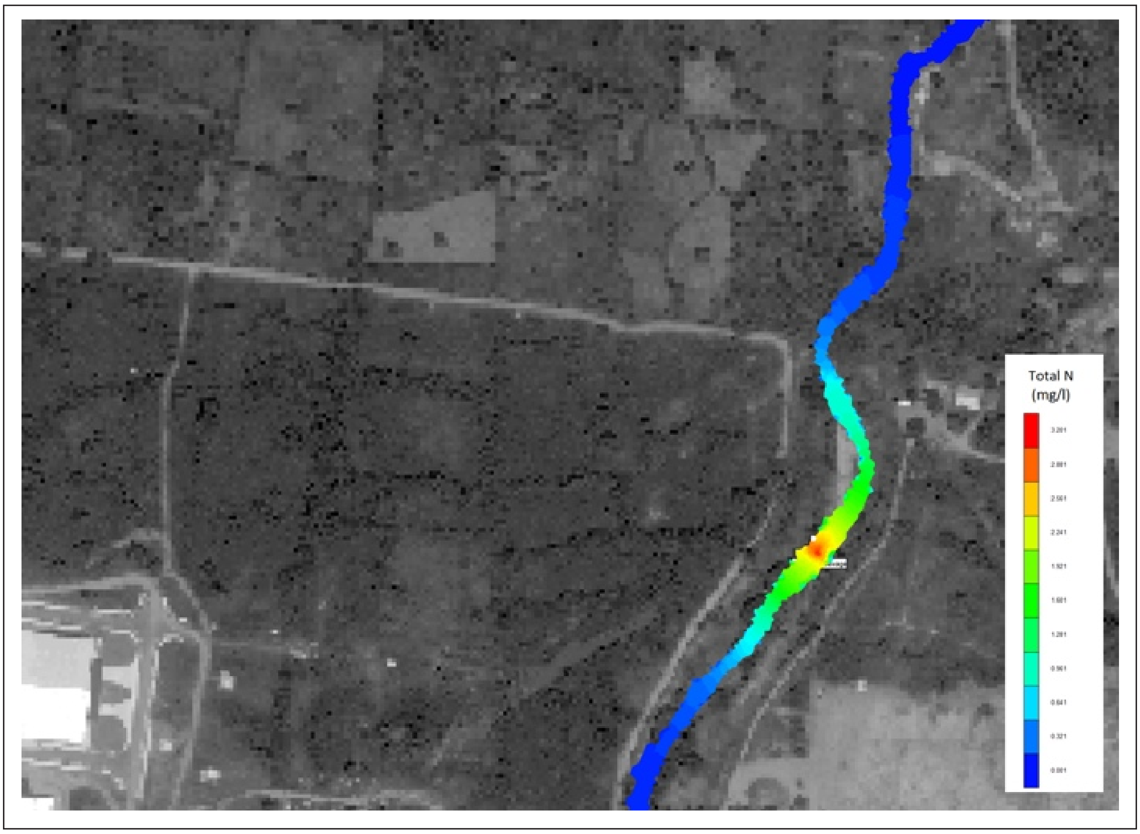

Figure 10. Total Nitrogen concentration in the Trou du Nord River when river discharge is 0 m^3/s

Figure 11. Total Nitrogen concentration in the Trou du Nord River when river discharge is 5 m^3/s

Figure 12. Total Nitrogen concentration in the Trou du Nord River when river discharge is 20 m^3/s

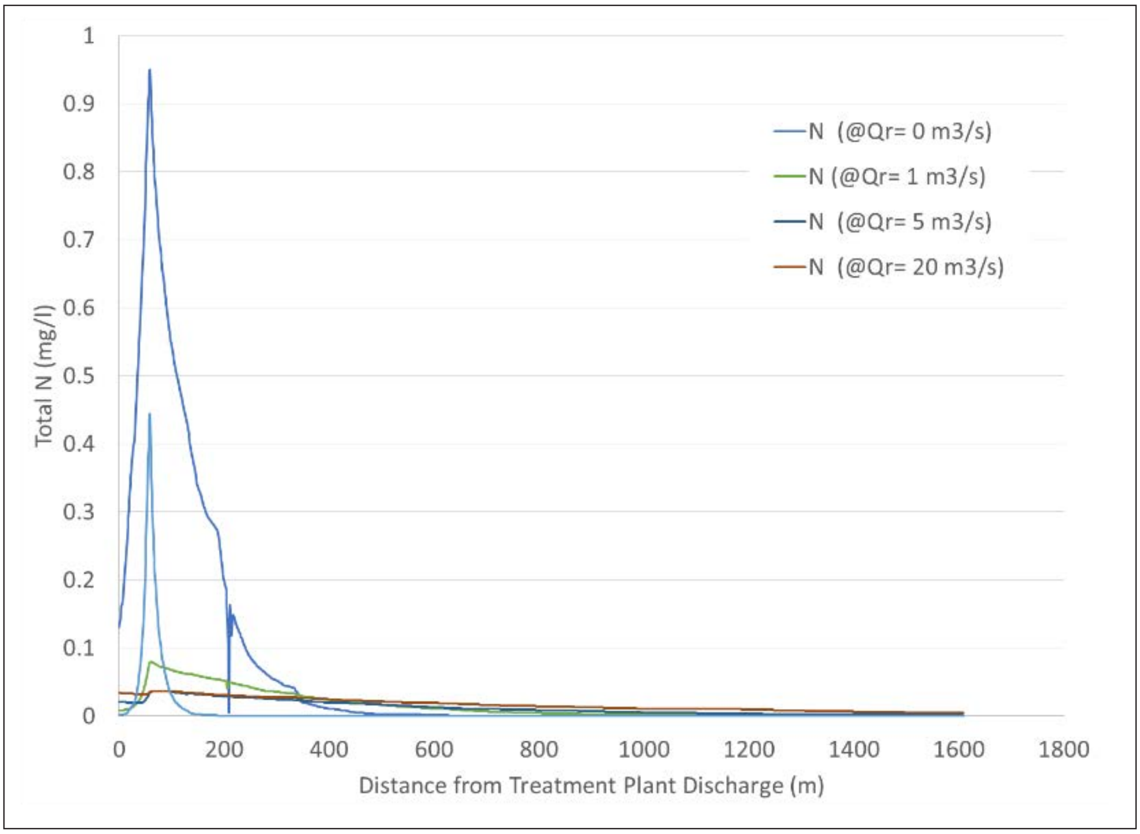

Figure 13. Total Nitrogen concentration variation with distance from the water treatment plant discharge for various Trou du Nord River Discharges

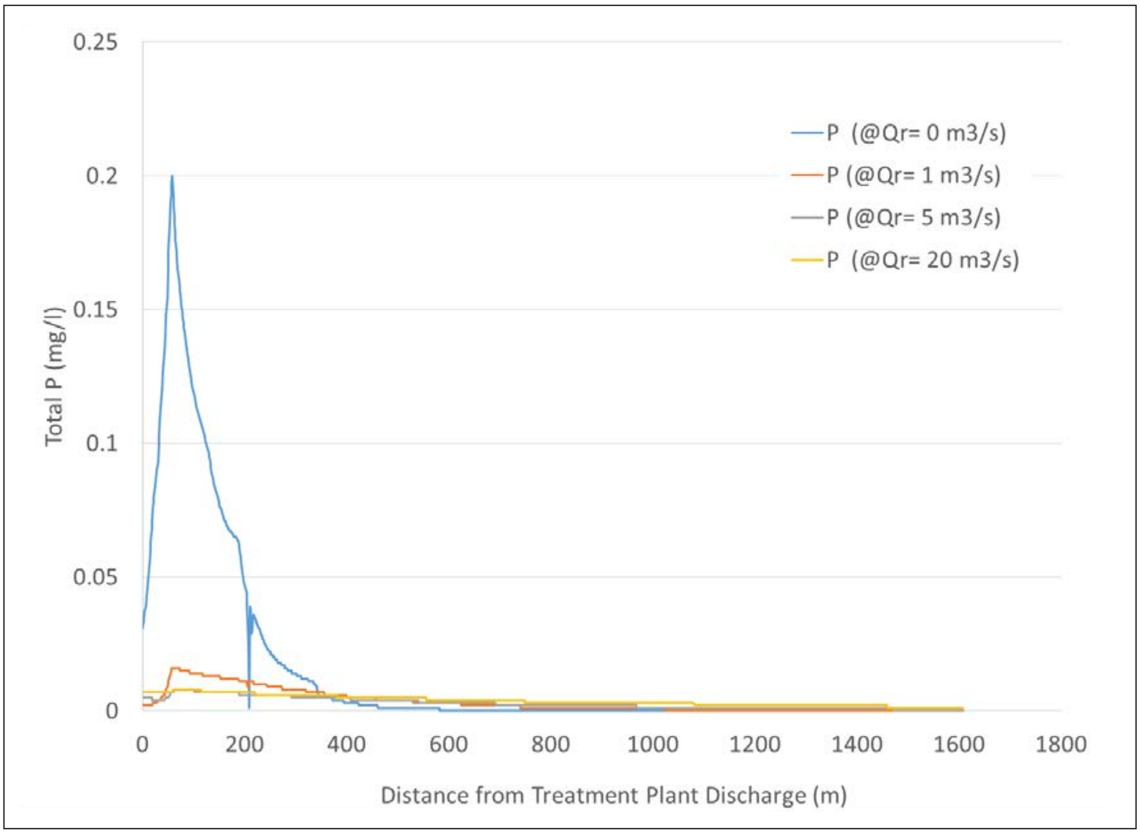

Figure 14. Total Phosphorous concentration variation with distance from the water treatment plant discharge for various Trou du Nord River Discharges

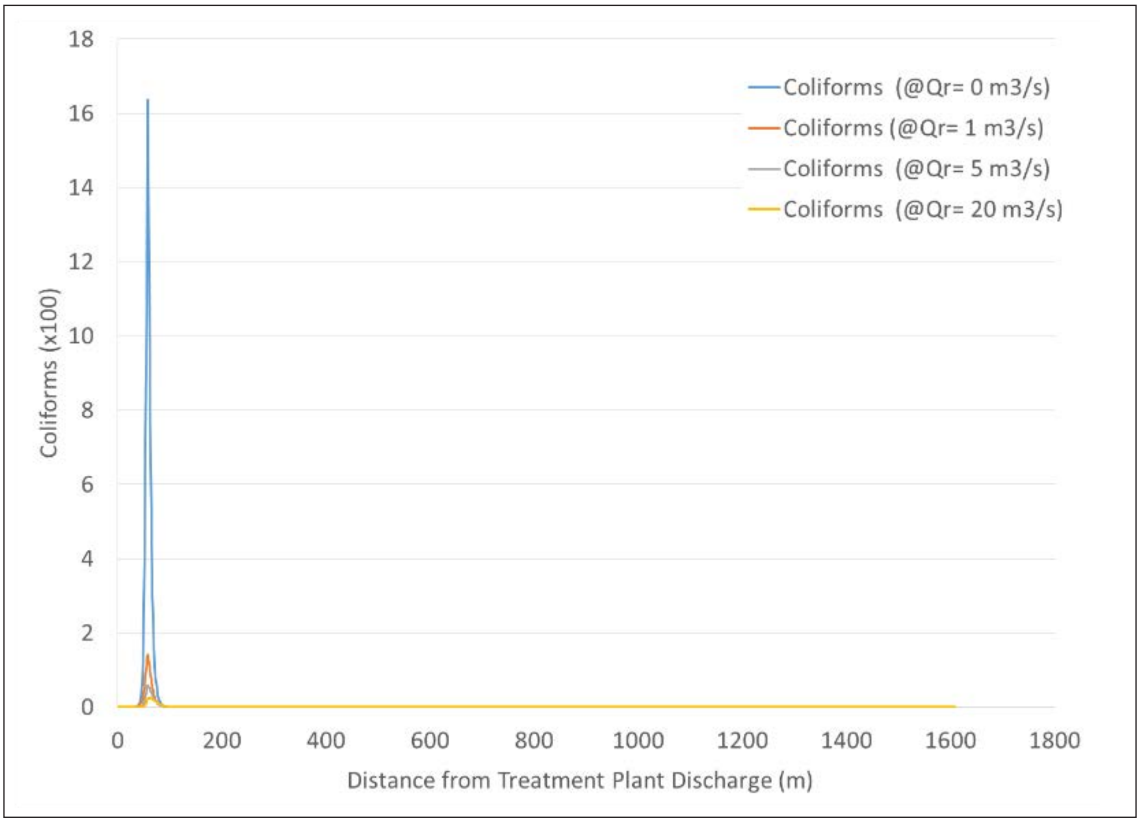

Figure 15. Coliforms variation with distance from the water treatment plant discharge for various Trou du Nord River discharges

Effluent concentration remains invariable even 100 m downstream of the discharge when the Trou du Nord River is dry. Concentration decreases significantly due to the dilution effect of the water from the Trou du Nord River. Even for a relatively small river discharge of 1 m^3/s concentrations reduce to less than 4% of the discharge intensity very quickly. For larger river discharges of the order of the 1-year event the pollutant concentrations drops to 0.16% of the effluent discharge.

Simulations show that the most unfavorable case is when the Trou du Nord River is dry. In this scenario, concentrations of the pollutant dominates the flow. However, even for relatively low river flows, the dilution effect of the water coming from upstream is enough to lower the color intensities to very low values in relation to the discharge. Thus, the areas below the point of source will view the river water to have very low concentrations.

5. CONCLUSIONS

In this paper, we describe the application of high-resolution hydraulic and water quality models to assess flood impacts at the development site of Parc Industriel Caracol (PIC) in northern Haiti, and evaluate water quality scenarios of the Trou-du-Nord River downstream of the PIC to support de development of the Trou du Nord Watershed Management Plan. The high-resolution numerical modeling is supported on a high-resolution DEM, and because of its two-dimensional (depth-averaged) formulation, allows to perform flood and water quality analysis both in the river channel and in the aerial extent of the PIC.

The key results derived from this work with respect to flood impact assessment simulations can be summarized as follows:

- Results of the sunny-day scenarios indicate that no flooding occurs in the PIC area for peak Trou du Nord River discharges under 70 m^3/s that correspond to an event with a 5-year return period. For discharges equal or lower than this, the river channel has the capacity to contain all the water volume that comes from the upper watershed, with a water surface that stays below than the maximum river bank elevation along the industrial park.
- When Trou du Nord River discharge reaches 70 m^3/s, the model results indicate that there will occur flooding further downstream from the PIC limits.
- According to the model results, flooding starts to affect the PIC for events of return periods above 25 years which correspond to a river discharge of approximately 100 m^3/s. Higher discharges lead to considerable flooding over the PIC development area,
- For a 200-year event, that is the more extreme scenario considered in this project, the area flooded can reach 70% of the PIC, with maximum localized depths of 1.3 m and inundation lasting up to 18 hours.

- When rain is considered to occur in the PIC area simultaneously with the river discharge, the scenarios simulated provide a completely different flooding picture than those of the sunny-day cases. Due to the effect of the simultaneous occurrence of rainfall and flow from the Trou du Nord River, the flooding would start to occur for 1-year events.
- Percentage of flooded area reaches 30% for the 5 year event that has a 24-hour rainfall of 223 mm. In this case, the maximum depths are around 2 m and the inundation times can be as prolonged as 24 hours.
- The maximum flooding area can reach about 85% of the PIC development for the 200-year event that corresponds to 160 m^3/s peak discharge and 515 mm of accumulated rainfall in 24 hours, while the inundation can last up to 16 hours in some locations.

The key results with respect to the water quality simulations along the Trou du Nord river are:

- Effluent concentrations remain invariable even 100 m downstream of the discharge when the Trou du Nord River is dry.
- Effluent concentrations decrease significantly due to the dilution effect of the water coming from the Trou du Nord River. Even for a relatively small river discharge of 1 m3/s the color intensity reduces to less than 4% of the discharge intensity very quickly.
- For larger river discharges of the order of the 1-year event, concentrations drop to 0.16% of the effluent discharge.
- Simulations show that the most unfavorable case is when the Trou du Nord River is dry. In this scenario, the pollutant concentration dominates the flow. However, even for relatively low river flows, the dilution effect of the water coming from upstream is enough to lower concentrations to very low values in relation to the discharge. Thus, the areas below the point of source will view the river water to have very low pollutant concentrations.

RECOMMENDATIONS

- Install at least one precipitation gauge inside the PIC area and one on the upper part of the watershed.
- Measure Trou du Nord River discharges and water elevation particularly for events that generate flowrates above 100 m3/s.
- Apply the RiverFlow2D model to evaluate the impact that the PIC could have in the flood risk downstream communities.
- Continue to calibrate the modeling with data for flooding and water quality as it becomes available through monitoring efforts at the PIC, the Trou du Nord river and surrounding areas.

ACKNOWLEDGEMENT & DISCLAIMER

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DIGITAL ATLAS – AN OPEN ACCESS SOLUTION TO SPATIAL INFORMATION ANALYSIS FOR WATER RESOURCES MANAGEMENT IN HAITI

ATLAS NUMÉRIQUE - UNE SOLUTION D'ACCÈS LIBRE À L'ANALYSE D'INFORMATION SPATIALE POUR LA GESTION DES RESSOURCES EN EAU EN HAÏTI

ATLAS DIGITAL - UNA SOLUCIÓN DE ACCESO ABIERTO PARA EL ANÁLISIS DE LA INFORMACIÓN ESPACIAL PARA LA GESTIÓN DE LOS RECURSOS HÍDRICOS EN HAITÍ

Amartya Saha[1] and Maria Concepcion Donoso[2]

Abstract

The provision of tools to support Water Resources Management is an important mechanism used by the Florida International University Global Water for Sustainability (GLOWS) Program to assist governments in developing countries in Asia, Africa and the Caribbean. Among such instruments the Digital Atlas is a simple user-friendly tool that allows the visualization and analysis of spatial data in the form of maps. A Digital Atlas was developed for Haiti, which allows the conceptualization of water availability and demand at the national and regional level as part of the water resources management process. Digital Atlases has been developed using the open source atlas publishing software GeoPublisher. The Digital Atlas can be installed on any computer from a memory drive, it is independent of operating systems and does not need an internet connection. It is designed so that no prior GIS experience is necessary for Haitian users to utilize the instrument and produce custom made user-interactive maps. A brief description of the Digital Atlas tool is presented followed by examples of the type of products that can be generated for Haiti. The open source, platform independent Digital Atlas has the potential to be widely used as a demonstrative and analytical tool for facilitating sustainable water resources management.
Key Words: Digital Atlas, water resources management, GIS, open source code, Haiti

Résumé

La fourniture d'outils pour appuyer la gestion des ressources en eau est un mécanisme important utilisé par le programme Global Water for Sustainability (GLOWS) de l'Université Internationale de Floride pour aider les gouvernements des pays en développement d'Asie, d'Afrique et des Caraïbes. Parmi ces instruments, l'Atlas Numérique est un outil simple et facile à utiliser qui permet la visualisation de données spatiales sous la forme de cartes. Un Atlas Numérique a été élaboré pour Haïti qui permet de conceptualiser la disponibilité et la demande d'eau aux niveaux national et régional dans le cadre du processus de gestion des ressources en eau. L'Atlas Numérique a été développé à l'aide du logiciel d'édition d'atlas open source GeoPublisher. L'Atlas Numérique peut être installé sur n'importe quel ordinateur à partir d'un lecteur de mémoire, est indépendant des systèmes d'opération et n'a pas besoin d'une connexion Internet. Il est conçu de telle sorte qu'aucune expérience précédente de SIG n'est nécessaire pour les haïtiens d'utiliser l'instrument et de produire des cartes interactives personnalisées. Une brève description de l'Atlas Numérique est présentée, suivie d'exemples du type de produits qui peuvent être générés pour Haïti. L'Atlas Numérique à code source libre et indépendant de la plate-forme peut être largement utilisé comme instrument de démonstration et d'analyse pour faciliter la gestion durable des ressources en eau.
Mots clés: Atlas Numérique, gestion des ressources en eau, SIG, logiciels open source, Haïti

Resumen

La provisión de herramientas para apoyar la Gestión de Recursos Hídricos es un mecanismo importante utilizado por el Programa Global Water for Sustainability (GLOWS) de la Universidad Internacional de Florida para ayudar a los gobiernos de los países en desarrollo de Asia, África y el Caribe. Entre estos instrumentos, el Atlas Digital es una herramienta fácil de usar que permite la visualización de datos espaciales en forma de mapas. Un Atlas Digital fue desarrollado para Haití, el cual permite la conceptualización de la disponibilidad y demanda de agua a nivel nacional y regional como parte del proceso de gestión de los recursos hídricos. El Atlas Digital ha sido desarrollado usando software de publicación de código abierto de GeoPublisher. El Atlas Digital se puede instalar en cualquier computadora a partir de una unidad de memoria, el mismo es independiente de los sistemas operativos y no necesita una conexión de Internet. Este está diseñado para que los usuarios haitianos no necesiten experiencia previa en SIG para utilizar el instrumento y producir mapas personalizados interactivos. Una breve descripción de la herramienta del Atlas Digital se presenta seguida de ejemplos del tipo de productos que se pueden generar para Haití. El Atlas Digital de código abierto, independiente de la plataforma computacional, tiene el potencial de ser ampliamente utilizado como una herramienta demostrativa y analítica para facilitar la gestión sostenible de los recursos hídricos.
Palabras clave: Atlas Digital, gestión de recursos hídricos, SIG, software de código abierto, Haití,

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1. INTRODUCTION

Institutional Challenges in spatial data visualization

A picture is worth a thousand words, as the old adage goes. The ability to visualize spatial data, such as rainfall distribution, groundwater availability and locations of water users in the form of maps is essential for effective water resources management. Maps enable a concurrent examination of water availability and water demand in a region, bringing to the surface patterns and links between demand and supply that are not otherwise readily evident from tabular data alone. Maps also enable effective communication between different stakeholders and sectors involved in water resources decision-making. Geographic Information Systems (GIS) advances spatial analysis to a deeper level, by allowing users to select different layers of data, zoom into a desired scale (not possible with paper maps), obtain information specific to features, and proceed with a variety of spatial analysis and modeling.

Despite the utility of maps and GIS, it is not uncommon in developing countries to have hydrological data languish in a spreadsheet format, with very little further analysis being performed with the data. This lack of analysis, interpretation and dissemination of the data to water managers presents a large opportunity loss. While many water management institutions have technical departments with some staff trained in the use of Geographic Information Systems (GIS), challenges remain in the production of and access to maps useful for different tasks. End users such as managers and decision makers must depend upon technical GIS departments to produce maps with current data. The rapid evolution of GIS application software poses another challenge for departments to stay up-to-date with technology.

In Haiti, as in other developing countries, there are several constraints hampering the widespread adoption and continued upgrading of GIS software and applications, such as:

1. ArcGIS, the industry standard in spatial analysis is expensive, even with special developing country pricing.
2. ArcGIS cannot be freely installed on any number of computers – licenses allow for a fixed number of users at a given time, or a fixed number of computers.
3. Open Source GIS software, such as Q-GIS and GRASS, while being free, has a steep learning curve. A dearth of technical trainers, poor internet connectivity and the relatively large investment of time necessary for self-learning of open source GIS pose hurdles for the majority of water resources management professionals, especially those who are mid-career.
4. Internet connectivity is very patchy and slow, which also restricts the download of large files, such as Digital Elevation Models, raster files and satellite images.

Even when a department has GIS skills, the necessity of renewing ArcGIS licenses on a yearly basis poses an additional financial burden. We have come across numerous instances in developing countries of GIS programs grinding to a halt because the software does not work unless the license is renewed. This is a very unfortunate loss of effort, because GIS depends on ground data that is expensive and time-consuming to collect over large regions.

The Digital Atlas – universally easy access to mapping tools

With these limitations and challenges in mind, a practical mapping solution for water managers is a Digital Atlas. The Digital Atlas is a very recent application that is freely installable in any computer, is self-contained in terms of maps and data and enables users to combine and classify different layers of information to create their own customized maps. In addition, the Atlas also provides an interface for analyzing thematic maps that is similar to a GIS, thus allowing the user to select features to get underlying information from databases. Digital Atlases has been developed using the open source atlas publishing software GeoPublisher (http://en.geopublishing.org/) for a variety of applications such as natural resources management in Benin and Morocco (Impetus, Germany), water resources management and vulnerability assessment in Namibia (Cuvewaters), Jordan (GLOWA, Germany) and Tanzania (GLOWS-FIU, 2014; GLOWS-FIU, 2015). These atlases are being widely used by water resource management institutions, educational institutions and NGOs in cooperation with local communities.

Figure 1 illustrates some of the varied types of thematic maps that can be created with a Digital Atlas. The upper left quadrant shows a drainage map with rivers and wetlands along with monitoring stations (not shown) that can be clicked on to get graphs for monthly and annual discharge. The upper right quadrant shows a map of average annual rainfall isohyets. The lower right map depicts the geology of the region, while the lower left part of the figure shows an administrative map with district/ward boundaries, towns and transport infrastructure. The Atlas can be structured so that each feature in a particular map can be clicked on to display additional information. For instance, one can click on a given town on a map to get its population, gender ratio, percentage of employment, public health status, etc. In our experience, the Atlas empowers water resource managers and professionals to easily make their own maps at a desired scale, select features and use customized color schemes and symbols, using them for presentations and reports.

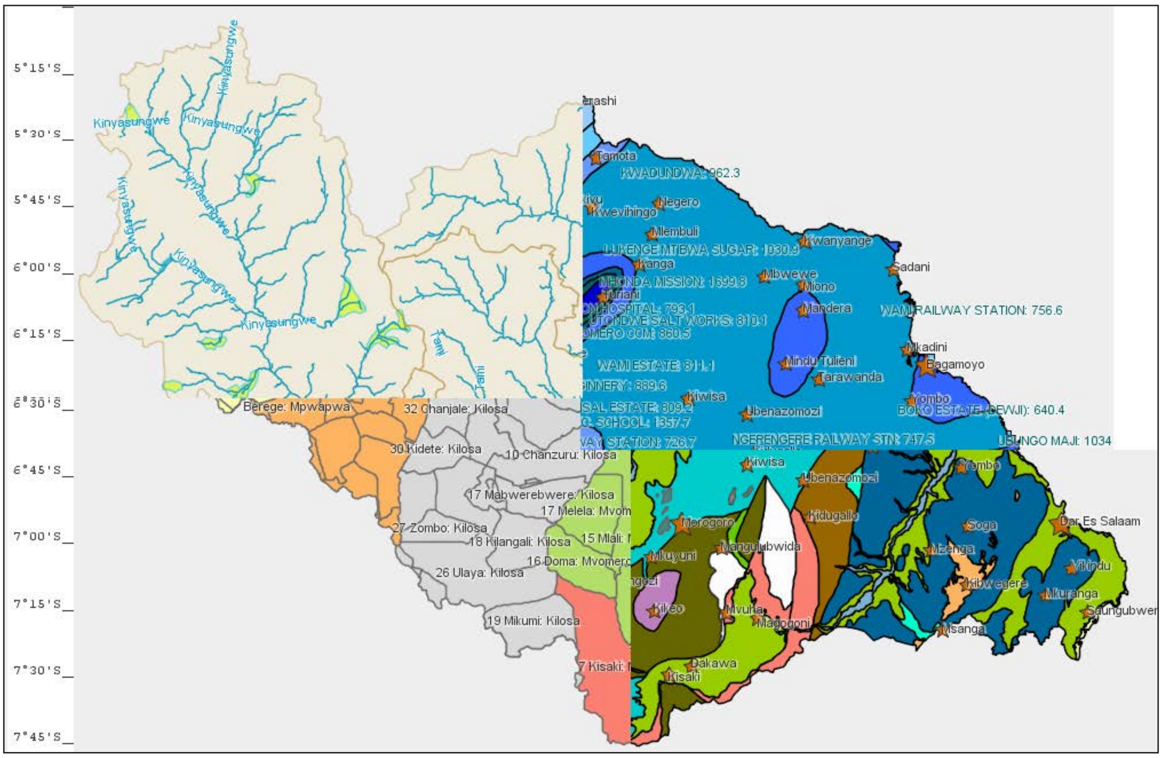

Figure 1. Examples of thematic maps that can be created in a Digital Atlas. From upper left clockwise, a map of rivers (left upper), rainfall (upper right), geology (lower right) and administrative (lower left)

Maps for this figure have been taken from the Wami Ruvu Basin, Digital Water Atlas (GLOWS 2015).

Digital Atlas Features at a glance:

- No internet connection is necessary to run the Digital Atlas.
- The Atlas can be installed on any operating system as a self- contained set of vector/raster data and Java environment files.
- This set of folders is portable and can be transferred using a CD, external memory or stored on the web.
- Information for each thematic map is displayed as a set of overlaying layers. The user can change color, symbols, size and filter data for each layer to create custom maps that can be saved as images for reports, presentations, etc.
- The user is able to zoom into a map to have greater spatial detail, access information pertinent to a particular site and combine different layers of data without the need of a GIS.
- The user can combine different layers for analysis of linkages. For example, to evaluate the relationship between evapotranspiration and land cover, or between rainfall and discharge.

The ease of use and lack of installation restrictions has led the Digital Atlas to be readily accepted by a wide range of technical and nontechnical professionals in the water resources sector in the countries for which this tool was developed. Here we briefly describe one use of the Atlas by the water resource ministry in Tanzania.

An example of a Digital Atlas in use: Wami Ruvu Basin, Tanzania

The Digital Atlas for the Wami Ruvu Basin is a geospatial information gateway on various sectors and thematic areas connected with water resources: topography, erosion vulnerability, geology, climate, ecosystem, surface and groundwater resources, monitoring wells and hydrologic data, water use permit locations, public health, administrative, demographic and infrastructure. In addition, a literature section includes a collection of relevant publications for the region of interest. The Atlas for the Wami Ruvu basin has been jointly developed by the Ministry of Water, Tanzania and GLOWS-FIU (GLOWS 2015). The Ministry of Water has since then been developing atlases for other river basins in Tanzania (e.g.. Lake Rukwa Basin Atlas).

As an example of the use of an Atlas, Figure 2 shows the locations and water yield of groundwater wells in the Wami and Ruvu river basins of Tanzania overlaid on an annual average rainfall map. This map was produced with the Tanzania Digital Atlas tool and used to examine the rising concerns about groundwater depletion, falling water tables and the sustainability of water resources in the semi-arid region of the capital city of Tanzania, Dodoma. A list of borewells, for which water permits were issued by the Ministry of Water of Tanzania, existed in spreadsheet format and was mapped to show the areas with high water extraction. This information is being used to choose locations for installing groundwater monitoring wells as well as in examining supplementary options for water supply, given that this is a rapidly urbanizing region. Seeing the clustering of borewells on a map makes it easier to communicate the groundwater depletion issue with policymakers and the general public. The same map is being used to analyze the high concentration of borewells in the major coastal city of Dar-es-Salaam, indicating the potential danger of seawater intrusion into coastal wells accompanying high groundwater extraction rates. This situation could render unusable these wells, thereby compromising a source of fresh water for this high water demand coastal area.

Other types of maps, such as those presenting overlaying rainfall distribution with topography and land cover/land use can indicate whether infiltration or runoff might be the dominant process in a catchment, and suggest the locations of discharge and water quality monitoring stations as well as strategies to store water for year-round supply. The referred products constitute a valuable tool for the development and implementation of natural resources management at the national and sub-national level.

The User Manual for the Atlas (GLOWS 2015) describes several examples of spatial analysis possible with the Digital Atlas. One example describes how to identify the vulnerability of coastal and estuarine areas to flooding from sea level rise. The approach is to reclassify the color elevation scale of the topographic map (Digital Elevation Model) contained in the Atlas to a very fine resolution scale such as 1 meter apart in the coastal areas (mean sea level, 1 m, 2m, 3m and so on). Such a rendering makes it easy to identify low-lying areas that are at the greatest risk of flooding. Areas inland from the coast that are in a river floodplain can be at a greater flooding risk than coastal areas at some vertical distance from the sea, such as on a promontory or cliff. These and other concepts are also explained in the Tanzania Water Atlas Book (GLOWS 2014).

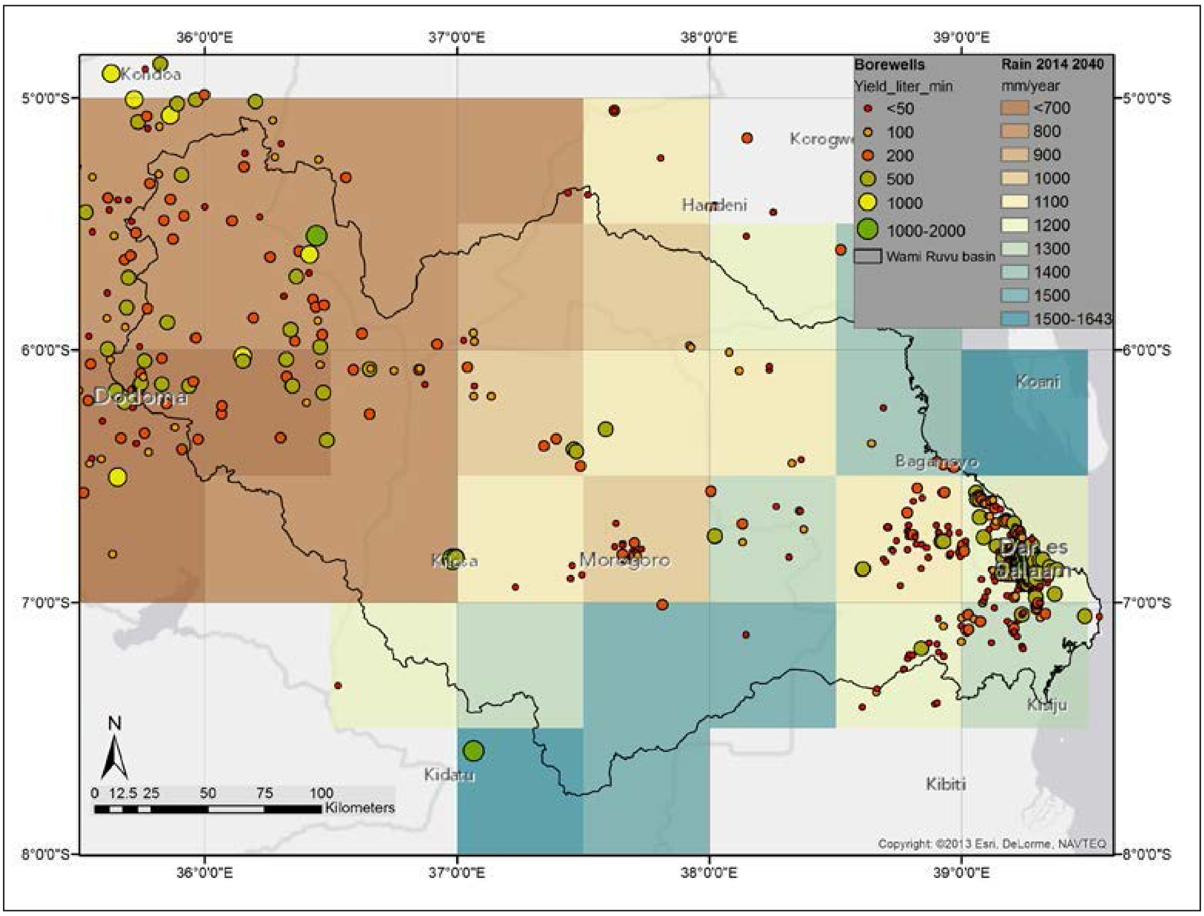

Figure 2. Borewell locations and annual rainfall in the Wami Ruvu Basin of Tanzania, showing concentrations of borewells in the semi-arid Dodoma region (left side of map) and at Dar es Salaam by the coast (right). Borewell water yield in liters/minute is shown in circles of different sizes and colors. GLOWS - FIU 2014

2. METHODS

From the field to the user's screen: The process of Atlas development

The Digital Atlas consists of a group of electronic files located in folders containing the programs, data, and the Java operating environment that is required for the Atlas to run. Once this set of folders is installed into a computer, clicking on the executable file runs the Atlas. A user cannot accidentally change the data in an Atlas. However, this security feature also means that a user cannot update an Atlas. Updating however is easily possible by atlas developers, that is, anyone who is familiar with using GeoPublisher to create an atlas. Familiarity with GeoPublisher can be obtained in a day's training.

In addition to the GeoPublisher software being freely downloadable, the atlas developer needs to either obtain GIS shapefiles from local and/or global sources, or structure shapefiles from tabular data with geographical coordinates (location information). Gathering and checking data for accuracy is typically by far the most time and effort-intensive step in map development. Spatial data (whether hydrological, ecological, climate, landscape, water use or demographic) is collected and used to create ESRI shapefiles (data geo-referenced with geographic coordinates) through GIS. The shapefiles are then imported into the Digital Atlas as layers (Figure 3). Ready-to-use shapefiles are also available from other sources, both from Haiti institutions and international data bases. Supplementary descriptive information is added for each layer, as well as for thematic maps. This information can be accessed by clicking the icon with the letter "i" on each layer as well as for the entire thematic map. The Atlas is then saved and exported as a data-driven executable (Figure 3), which can be copied onto a memory drive and loaded on to other computers, or set up as a web download.

Updates to the Atlas are thus possible by developers such as hydrologists and technicians in the various Water Resources Management Institution with knowledge of GIS and a basic understanding of GeoPublisher that can be acquired in one day short tutorial. An updated shapefile is created and imported into the Atlas using GeoPublisher, and recompiled and re-exported as an executable set of files and data (Figure 3). The development of the Atlas is complemented with hands on training to end-users within the country. For example, GLOWS has offered a series of atlas user and developer trainings in Tanzania for several years. Staff in the Ministry of Water in Tanzania who received training have gone on to create new digital atlases for several river basins in this country, evidence of the ease of creation and use of these atlases, as well as the ability to pick up these skills. Similar training exercises are being tailored for Haiti.

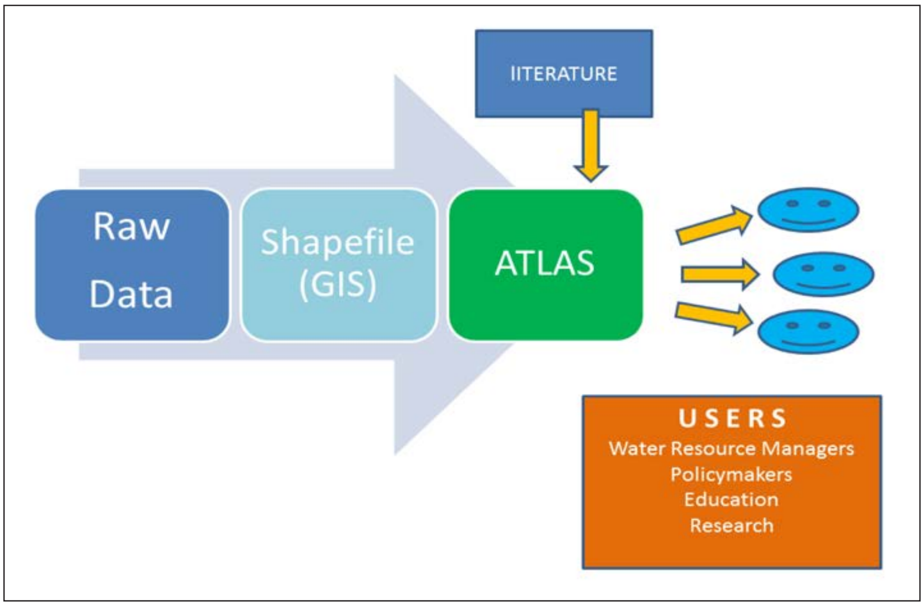

Figure 3. Steps in the development and use of a Digital Atlas

3.RESULTS AND DISCUSSION

The Water Resources Digital Atlas for Haiti

Here we briefly describe a Digital Atlas for Water Resource Management that has been developed for Haiti. Most of the data has been provided to FIU by Haitian government institutions related to water resources with additional sources such as MODIS data (NASA/University of Montana) for evapotranspiration, Climate Wizard for precipitation and temperature predictions, Google Earth Engine for forest gain/loss/cover and IUCN for biodiversity data.

Organization of the Haiti Water Atlas

Data in the first version of the Atlas has been organized into the following categories:

1. Climate – precipitation, wind/hurricanes, solar radiation and temperature.
2. Landscape – land use/land cover, soil types, geology.
3. Ecosystem – forest areas, forest cover loss/gain over the period 2000-2014.
4. Administrative – administrative units, roads, places of public interest, healthcare facilities.
5. Water Resources – river network, hydrogeology (aquifers), wetlands and surface water reservoirs.
6. Risk – hurricanes, soil erosion and landslides.

Functionality of the Haiti Water Atlas

Under each category are thematic maps, i.e. maps that display information on a certain theme, such as land use, rainfall, or water quality monitoring sites. Each thematic map is composed of a set of layers that can be turned on and off to display or hide that layer. The order of the layers can also be interchanged by dragging a layer up or down in the menu. This functionality is useful to achieve control on the order of overlaying layers. For instance, a layer of rivers can be shown over the topographical map, so that no part of the river network is hidden by elevation contours or other features on the topography layer.

The user manual for the Atlas describes the contents in detail. It includes a guide to using the features of the Atlas in order to customize the display of information by choosing symbols, colors and filters. Raster databases, such as those containing topography or evapotranspiration data, in which each cell or pixel on the map is associated to a variable numerical value, can be classified into ranges or groups as per the user's specifications. For example, the scale and range of an elevation gradient for a topography map can be set at 100 meter intervals, or 200m, or 300m, as required.

Examples of analysis enabled by the Atlas

Some examples of maps that can be created using the Digital Atlas for Haiti are shown below.

1. *Forest cover and forest cover loss:* Figure 4 depicts forest cover in Haiti in 2000 with a 4 point classification scale in quartiles represented by deepening shades of green, as can be seen on the left side map panel. Figure 5 shows subsequent forest cover loss over the period 2000-2014 as areas in red. To see forest loss in detail, the Atlas allows the user to zoom in up to a resolution of 30 m (each cell or dot in the map represents an area of30m by 30m on the ground). The data categorization used in these maps is based on the work of Hansen *et al.* (2013) who classified forest cover on Landsat 7 and Landsat 8 images from 2000 to 2012, thereby deriving changes in forest cover. Combining this map with river drainage and topography layers indicates the areas highly susceptible to soil erosion and sediment transport. Linking forest loss maps with a map of roads and human settlements can indicate the proximity of transportation infrastructure and human demand for wood, thereby identifying areas that need conservation on a priority basis.

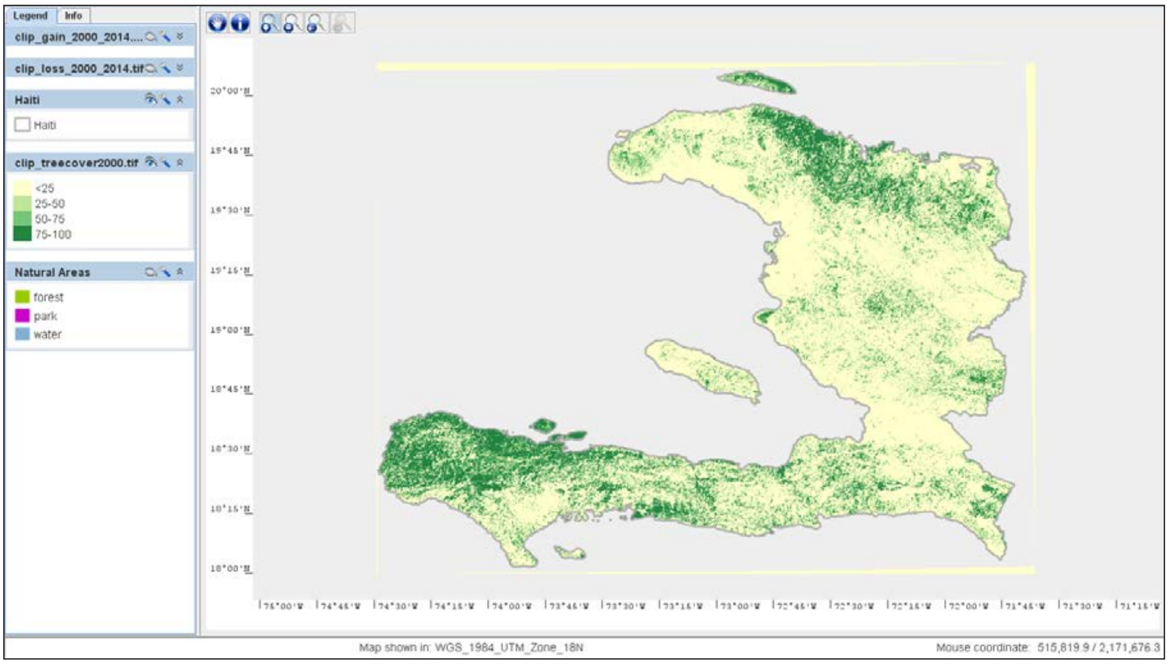

Figure 4. Percent Forest Cover in the year 2000 in Haiti in four classes – under 25%, 25-50%, 50-75% and 75-100% as depicted in legend on the left panel. Data Source: Hansen et al (2013) and Google Earth Engine. Map produced by the Geopublisher-based Digital Atlas

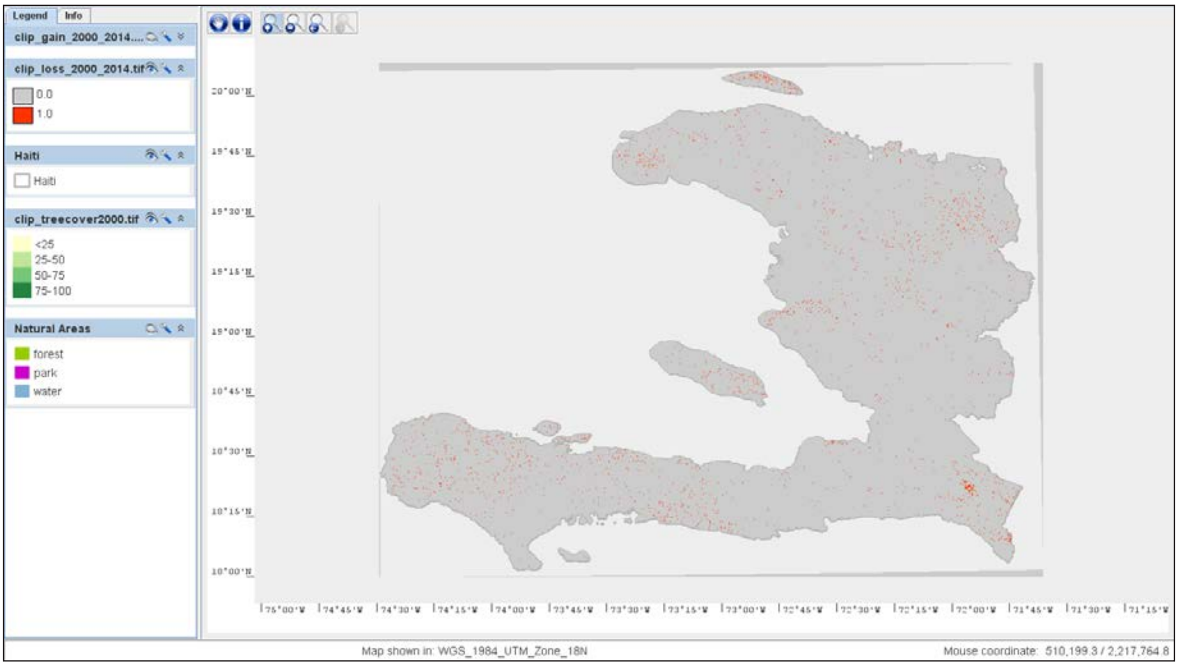

Figure 5. Forest Cover loss (2000-2014) shown in red in Haiti. Data Source: Hansen et al (2013)

2. *Hydrogeology:* Another example of a product developed using the Atlas is a hydrogeology map showing the different aquifers in Haiti. This thematic map also includes a river layer, which if turned on, would display over the hydrogeology layer, thereby displaying the geographical distribution of both groundwater and surface water in an area. Additional layers of information, such as location of towns, roads and districts, can provide a spatial reference for the above water resources. These layers can be turned on and off by clicking on the eye symbol present on the title bar of each layer (left side of maps where the legend is shown). As described earlier when presenting the example for Tanzania, spatial depiction of water resources in relation to water demand (in towns, for agriculture and industry) is necessary for understanding current water demand, forecasting future demand and identifying sustainable management strategies to meet water demand without compromising the sustainability of water sources. For instance, positioning the locations of new groundwater monitoring wells requires relating knowledge of locations of high water demand with the locations of water sources, to be able to detect conditions and trends in the water table drawdown and replenishment in real time, and thereby instill water conservation measures as required.

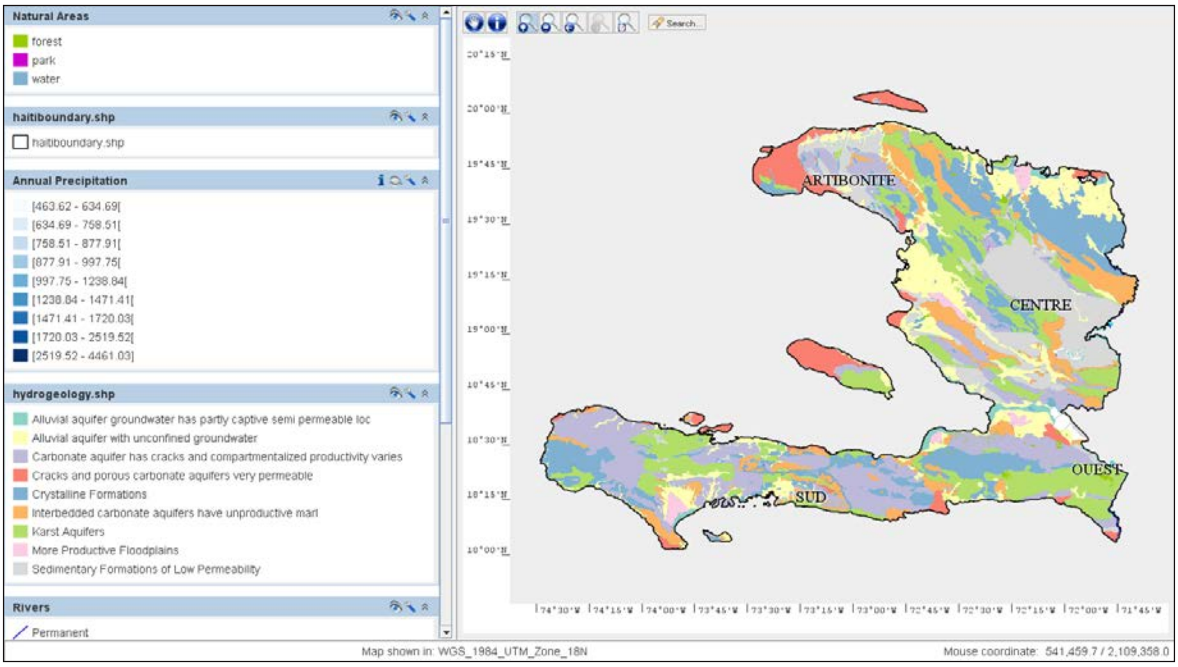

Figure 6. Hydrogeology of Haiti. Data Source: Government of Haiti

Some other examples of maps created by this Atlas are representations of erosion susceptibility zones (Figure 7), annual average rainfall at a 50 km grid (Figure 8) and a zoomed-in map of healthcare facilities along with rivers in the Port-au-Prince area (Figure 9). If river water quality data is available, this data can be combined with public health (disease outbreak and number of patients treated) maps, to indicate the linkages between water quality and public health for instance. Adding a layer of public health facilities can identify areas underserved by health facilities.

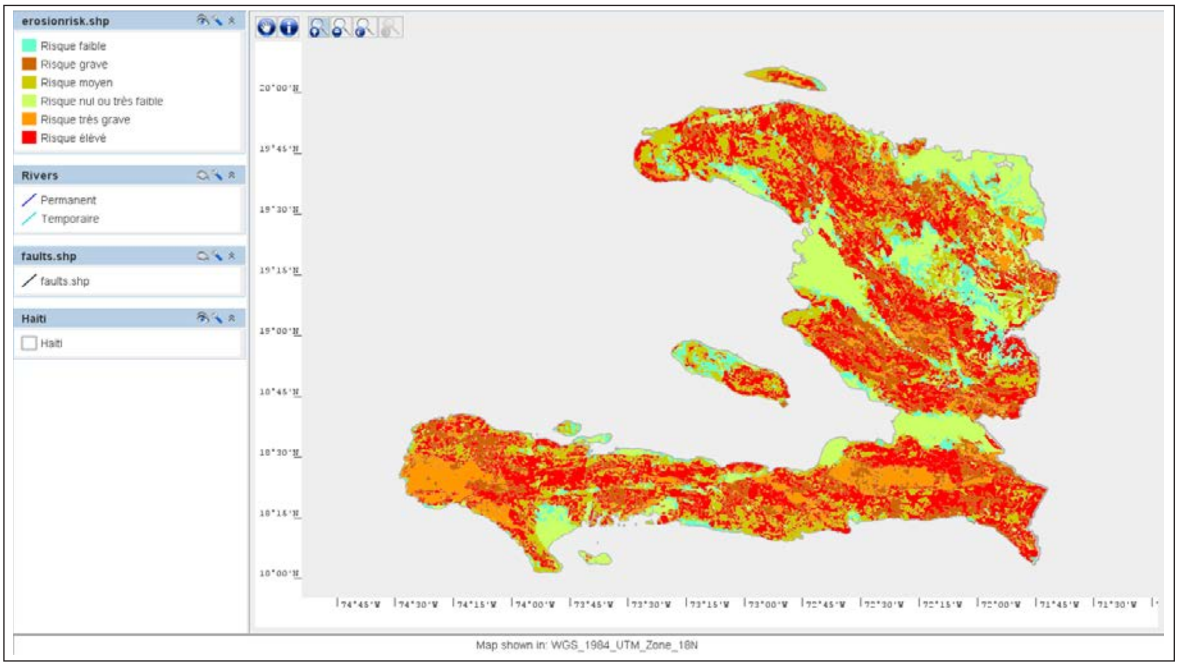

Figure 7. Erosion risk map for Haiti based on slope steepness, with red denoting areas of highest risk. Data Source: GIS analysis on ASTER-Digital Elevation Model courtesy NASA/Japan Space Research Organization

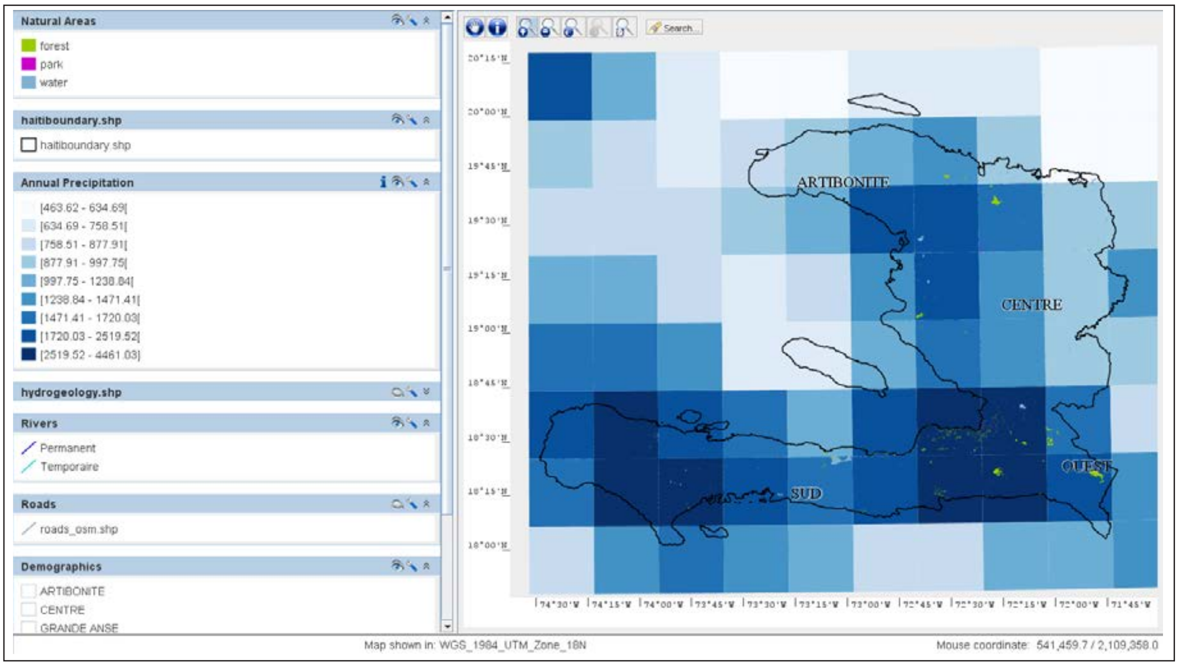

Figure 8. Average Annual rainfall for Haiti over 2000-2010. Legend on left shows rainfall scale from < 700 mm to > 4000 mm annual. Source: ClimateWizard

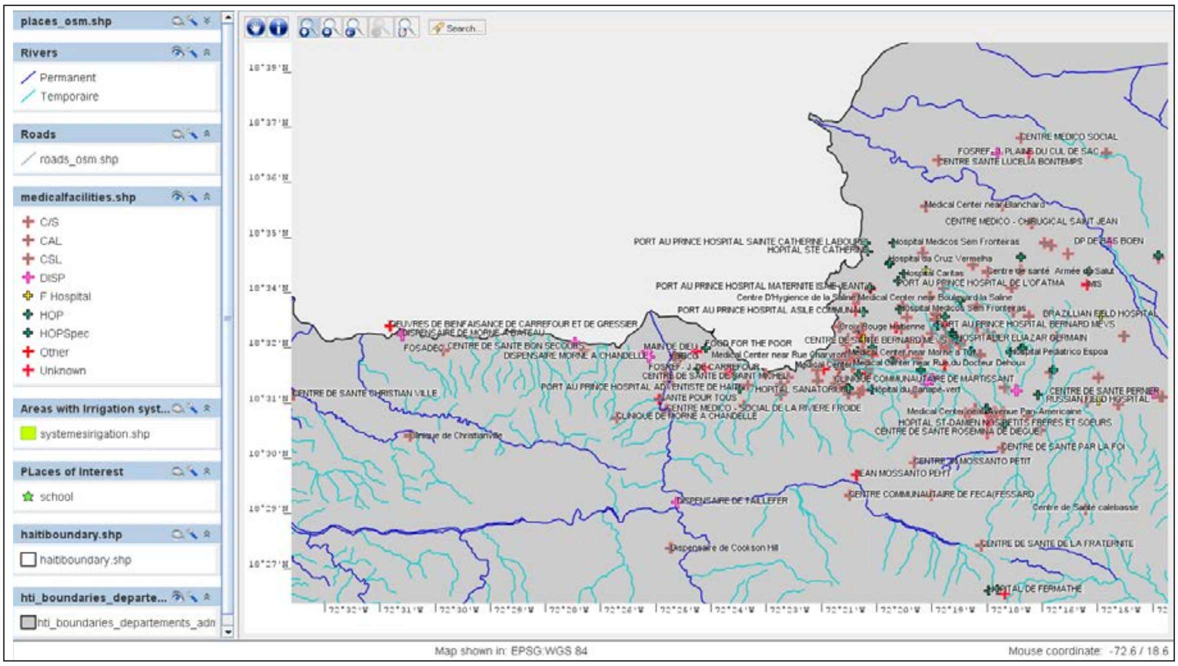

Figure 9. Close up of locations of healthcare facilities over a map of rivers for the Port au Prince area in Haiti. Data Source: Government of Haiti

The above presented maps are just a few examples of the possible products that can be generated by a user with the Haiti Water Resources Digital Atlas.

4. CONCLUSION: DIGITAL ATLAS - A UNIVERSAL TOOL:

The Digital Atlas can be freely and easily utilized by a wide spectrum of users engaged with water resources management such as water resources planners, managers, government policy/decision makers, hydrologists and scientists who can readily access and analyze the data by just referring to the developed accompanying User Manual. A key feature is that the Atlas is designed to be user-friendly; this has been proven in numerous instances in Tanzania, Rwanda and India, where the authors (FIU- GLOWS) have developed digital atlases that have been adopted by government and educational institutions. In addition, some institutions are also in the process of developing atlases for other river basins, following training in atlas development. Being user friendly, the Atlas enables water resources managers at all technical levels to analyze data and make their own maps, without having to necessarily rely upon a technical GIS department for creating maps.

The Atlas can also be utilized as a tool by educational institutions, community organizations and think-tanks to demonstrate linkages between geophysical, ecological, anthropogenic, administrative and infrastructural factors that influence the availability and management of water. The open source platform independent Atlas has the potential to be widely used as a demonstrative and analytical tool for facilitating sustainable water resources management. Water is a resource essential to every human being, and conversely is impacted by the actions of every individual. In that connection, the Atlas can easily be used in schools and colleges to demonstrate and inculcate the relationships between water, human activity, and the environment. In summary, the Atlas was developed to address the paradigm that a truly sustainable management scheme of water resources, which is harmonious with the ecosystems that maintain water availability and quality, can only be achieved when the vast majority of society is fully aware of the issues affecting water in their local region.

ACKNOWLEDGEMENTS

To Steffan Tzeggai for developing and supporting GeoPublisher, the open source atlas creation software that has enabled the technical development of numerous digital atlases in use in developing countries. The various institutions that made data sets. Funding for developing the generic Atlas tool structure was provided by USAID. Limited funding was provided by the Interamerican Development Bank at the early stage of adaptation of the Haiti Atlas.

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STRUCTURING WATER GOVERNANCE REFORM: A CASE STUDY OF THE TROU-DU-NORD WATERSHED IN NORTHERN HAITI

STRUCTURATION DE LA RÉFORME DE LA GOUVERNANCE DE L'EAU: UNE ÉTUDE DU BASSIN VERSANT DE TROU-DU-NORD DANS LE NORD D'HAÏTI

ESTRUCTURACIÓN DE LA REFORMA DE LA GOBERNANZA DEL AGUA: UN CASO DE ESTUDIO EN LA CUENCA TROU-DU-NORD EN EL NORTE DE HAITÍ

Ryan B. Stoa[1]

Abstract

Many national and subnational governments struggle to sustainably manage water resources. Accurately analyzing available water resources while distributing rights and enforcing responsibilities among water users is notoriously complex. These tasks are even more challenging when human or financial resources are scarce and regulatory capacities are low. As a result, water governance reform is often hailed as the solution to contemporary water challenges.

Unfortunately, water governance reform can be elusive, in part because water governance structures can take many different forms. This is true in the Republic of Haiti, where water challenges are numerous, and water management is often ineffective. In the Trou-du-Nord watershed in northern Haiti, in particular, institutional capacities for water management are low, and governance reforms are being considered by the watershed's stakeholders. This study provides an overview of Haiti's water governance framework, and proposes three institutional reform alternatives for management of the Trou-du-Nord watershed.

Keywords: water governance; institutional reform; Haiti.

Résumé

De nombreux gouvernements nationaux et infranationaux luttent pour gérer durablement les ressources en eau. Analyser avec précision les ressources disponibles en eau tout en distribuant des droits et en faisant respecter les responsabilités entre les usagers de l'eau est notoirement complexe. Ces tâches sont rendues encore plus difficiles lorsque les ressources humaines ou financières sont rares et les capacités de réglementation sont faibles. Par conséquent, la réforme de la gouvernance de l'eau est souvent saluée comme la solution aux problèmes d'eau contemporains.

Malheureusement, la réforme de la gouvernance de l'eau peut être difficile à realiser, en partie parce que les structures de gouvernance de l'eau peuvent prendre de nombreuses formes différentes. Cela est vrai dans la République d'Haïti, où les défis de l'eau sont nombreux, et la gestion de l'eau est souvent inefficace. Dans le bassin versant Trou-du-Nord dans le nord de Haïti, en particulier, les capacités institutionnelles pour la gestion de l'eau sont faibles, et les réformes de gouvernance sont envisagées par les parties prenantes du bassin versant. Cette étude donne un aperçu du cadre de gouvernance de l'eau en Haïti, et propose trois alternatives de réformes institutionnelles pour la gestion du bassin versant de Trou-du-Nord.

Mots-clés: gouvernance de l'eau; réforme institutionnelle; Haïti.

Resumen

Muchos gobiernos nacionales y de otro nivel (provinciales/departamentales) tienen dificultades para gestionar de forma sostenible los recursos hídricos. Analizar con precisión los recursos hídricos disponibles, al mismo tiempo que los derechos de distribución y el cumplimiento de las responsabilidades entre los usuarios del agua es una acción notoriamente compleja. Estas tareas son aún más difíciles cuando los recursos humanos o financieros son escasos y las capacidades de regulación son insuficientes. Como resultado, la reforma de la gobernanza del agua es a menudo aclamada como la solución a los problemas del agua contemporáneos.

Desafortunadamente, la reforma de la gobernanza del agua puede ser difícil de alcanzar, en parte debido a que las estructuras de gestión del agua pueden adoptar muchas formas diferentes. Esto es cierto en la República de Haití, donde los desafíos del agua son numerosos, y la gestión del agua es a menudo ineficaz. En la cuenca Trou-du-Nord, en el norte de Haití, en particular, las capacidades institucionales para la gestión del agua son escasas, y reformas en la gobernanza están siendo consideradas por las partes involucradas de la cuenca. Este caso de estudio proporciona una visión general del marco de la gobernanza del agua en Haití, y propone tres alternativas de reforma institucional para la gestión de la cuenca Trou-du-Nord.

Palabras claves: gestión y gobernanza del agua; reforma institucional; Haití

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INTRODUCTION

In October 2014, Florida International University (FIU) initiated a 27-month program to analyze water challenges in Haiti. Sponsored by the Inter-American Development Bank (IADB), the program has four primary objectives: 1) to analyze Haitian water laws and policies, and the institutions that implement them; 2) to identify gaps in hydrological data; 3) to model future risk scenarios for the Trou-du-Nord watershed; and 4) to create a water management plan for the Caracol Industrial Park and the Trou-du-Nord watershed.

A three-volume study of water governance in Haiti, completed in July 2015, represented the first of the project's objectives. It is intended to fill the gap of existing knowledge on water laws, policies, and institutions in Haiti, as well as to provide an assessment of issues, challenges, and opportunities for reform. The results of this study were presented to stakeholders in the Trou-du-Nord watershed, as well as national ministries, non-governmental organizations (NGOs), and intergovernmental organizations, in June 2015. The workshops validated preliminary results, while making clarifications and providing important insights that contributed to the final analyses presented below. Research and development efforts world-wide are not possible without meaningful stakeholder participation; this study is no exception.

The three-volume study was presented to the Inter-American Development Bank in July 2015. The IADB requested additional research that would propose an institutional structure for water management reforms in the Trou-du-Nord watershed. Accordingly, a fourth volume of the water governance study proposed three institutional reform alternatives (IRAs). This article presents the results of the fourth volume, including the proposed reform alternatives.

Each IRA includes a basic structural overview, a discussion of advantages and disadvantages, analogous applications of the structure in Haiti or around the world, and finally, a discussion of the legal challenges and reforms that would be needed to implement the IRA. While the government of Haiti has yet to endorse or formally pursue a reform alternative at the time of writing, the reform alternatives provide stakeholders with a framework from which to pursue institutional reform and water management in the Trou-du-Nord watershed.

METHODS AND BACKGROUND

Before considering water governance reform options in the Trou-du-Nord watershed, it is necessary to appreciate the water and governance context in Haiti, as well as the capacities of existing national and basin-level institutions. These conditions are investigated in depth in the three-volume study described above, but a brief overview is provided here.[2] As a starting point, Haiti has the lowest rates of access to improved water supply and sanitation facilities in the western hemisphere.[3] In 2002 Haiti was ranked last in the global Water Poverty Index,[4] and according to World Health Organization (WHO) data, it is the only country in the world whose access to sanitation facilities *decreased* from 1995-2010.[5] Those figures likely understate the situation considering the devastating impact of the 2010 earthquake near Port au Prince, Haiti's capital and largest city.

Haiti's water management landscape is dominated by small-scale agriculture, a water-intensive industry which by 2013 accounted for more than half of Haiti's labor force, eighty percent of total water withdrawals, and almost two-thirds of Haiti's land area.[6] The fragmented nature of small-scale agriculture may provide some measure of employment to Haiti's population, but presents enormous barriers to monitoring and regulation of water resources. These resources appear to be unsustainably exploited in part because very little information exists about water supplies and demands. In the Trou du Nord watershed in northern Haiti, for example, large-scale housing developments, mining operations, infrastructural improvements, and industrial manufacturing have either been planned or recently introduced despite the virtual non-existence of data on precipitation, climate, surface water flows, or groundwater that would normally precipitate such investments to ensure reliable water supplies exist for development.[7]

Today the Haitian state continues to suffer from low levels of human and financial resources, affecting regulatory development and enforcement capacities. The breakdown of effective governance creates many challenges, among them the ability to understand how a sector is organized, who has authority to manage it, and whether that authority is matched with capacity and political will. The Ministry of the Environment is statutorily responsible for most aspects of water resources management, including water quality regulation, policy-making, monitoring

2 An abridged version of the three-volume study was made available in July 2015. See Ryan Stoa, Water Governance in Haiti: An Assessment of Laws and Institutional Capacities, 29(2) Tulane Env.L.J. (2017).

3 Richard Geltin et al., *Water, Sanitation and Hygiene in Haiti: Past, Present, and Future*, 89 Am. J. Trop. Hyg. 665 (2013).

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7 Henry Briceno, *Data Gap Analysis and Review of Available Modeling Data in the Pic and its Contributing Watershed*, 59 (2015).

and evaluation, inter-ministerial coordination, conservation, and enforcement. Some of these powers were explicitly inherited from the Ministry of Agriculture in recent years.[8] Its broad and ambitious mandate is unfortunately coupled with an acute lack of capacity in both management and technical expertise.

By contrast, the Ministry of Agriculture, Natural Resources and Rural Development has extensive resources (both human and financial) at its disposal, and exerts significant control over water resources management decisions, particularly those actions affecting irrigation and land use. It retains significant and nearly exclusive authority over irrigation and agricultural water management, although it has recently attempted to broaden its powers to include watershed management in general.[9] Its watershed management policies attempt to bring local governments into its policy regime, though from a legal-regulatory perspective, the Ministry of Agriculture has little statutory support for its role in establishing water resources policy.

The Ministry of Public Works, Transportation, and Communication is responsible for water supply, sanitation, and hygiene through its *Direction Nationale de l'Eau Potable et de l'Assainissement* (DINEPA - National Directorate for Water Supply and Sanitation),[10] a poorly funded agency tasked with implementing the 2009 Framework Law on Water Supply,[11] coordinating donor assistance, regulating water service providers, and facilitating decentralization of water supply management. The Ministry of Planning and External Cooperation plays a coordinating role between the various government ministries, as well as the multitude of donors and donor-funded projects. Of particular interest is the *Comité Interministériel d'Aménagement du Territoire* (CIAT – Inter-ministerial Committee for the Management of the Territory),[12] a committee charged with coordinating actions among Ministries. The CIAT is composed of the Ministries of Agriculture, Environment, and Planning, as well as the Ministries of the Interior, Public Works, and Finance. It is chaired by the Prime Minister, and has the potential to be a strong voice in setting water policy. A Technical Execution Unit (UTE) of the Ministry of the Economy and Finance also oversees the administration of projects affecting water resources, such as the Caracol Industrial Park in the Trou-du-Nord watershed.

In principle Haiti has embraced decentralized water management policies, which promote water management and service delivery at the lowest appropriate governance level. Accordingly, the national government has promulgated several laws transferring authority over water resources (including water supply, sanitation, and hygiene, and the development of environmental action plans) to local territories (including Sections, Communes, and Departments). However, the legislation has not clearly articulated a coordinated or strategic direction for water resources management, and has not provided local institutions with the funding or human resources necessary to carry out a successful and sustainable decentralization strategy. The private sector also plays a large role in water management. Private companies offering to build manufacturing plans and provide foreign investment in Haiti have significant influence over local and national governmental affairs, and can demand water rights or shield themselves from prosecution.

Institutional capacities in the Trou du Nord watershed in northern Haiti suggest that most agencies and stakeholders have neither the human nor the financial resources in place to fulfill their mandates. Some, however, such as DINEPA's local representatives or the University of Limonade, are relatively well-staffed and exhibit the continuity of presence needed to justify targeted capacity building efforts. Others, such as the sections and communes in the region, may have low levels of capacity in water resources management but merit engagement in order to secure broad participation in water management planning efforts.

The Trou du Nord river is located in the Trou du Nord Arrondissement, a subdivision of the Northeast Department of Haiti. The Arrondissement contains four communes: Caracol, Saint Suzanne, Terrier-Rouge, and Trou-du-Nord.[13] These communes comprise the local government bloc of stakeholders most integral to a participatory water management planning strategy, as they represent the core geographic regions of the watershed, while exhibiting a level of regulatory and management activity that lower levels of government (i.e., sections within the communes) lack. For the most part the four communes do not employ any full-time staff dedicated to water resources, though some activities fall within the broad scope of water management. More important, perhaps, is the local support and buy-in that would be needed from each commune to effectively carry out a water management plan that modifies the status quo in any meaningful way.

To implement decentralized policies, national ministries created regional offices, with staff in place to represent the ministry and carry out its mandate. Local representatives of national ministries in the Trou-du-Nord watershed are therefore a potentially fruitful partner, in the sense that they can marshal

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8 Ministry of Agriculture, Natural Resources, and Rural Development: Official Site (last visited Aug. 1, 2016), http://goo.gl/kpUy8K.

9 *See* Ministry of Agriculture Watershed Management Policy (1999).

10 National Directorate for Water Supply and Sanitation: Official Site (last visited Aug. 1, 2016), http://goo.gl/VbeXaP.

11 *See* Framework Law on Water Supply (2009).

12 Committee for the Management of the Territory: Official Site (Aug. 1, 2016), http://goo.gl/QgyJsF.

13 Haiti-Reference: Districts and Cities of Haiti (last visited Aug. 1, 2016), http://goo.gl/ac7XOJ.

ministry resources toward local initiatives, while remaining knowledgeable of conditions on the ground. Unfortunately there is a stark contrast between the regional capacities of DINEPA and the Ministry of Agriculture, who are well-staffed in the region, and the Ministry of Environment, CIAT, and UTE, whose presence is marginal to non-existent.

Perhaps the most significant development for the Trou-du-Nord watershed in recent history has been the construction and operation of the Caracol Industrial Park. While the park has yet to reach full capacity, it is already making an impact in the region.[14] As a large apparel manufacturer, the Park represents both a challenge and an opportunity. A challenge because the scale of industrial and economic development projected for the Park at full capacity may have negative impacts on the watershed's resources. Water withdrawals may reduce freshwater flows in the Caracol Bay estuary, pollutant discharges may degrade water quality, and forest clearing may increase the risk of flooding. Fortunately these risks can be mitigated, in part due to the opportunity the Park represents for the watershed. With significant funding from the IADB, United States Agency for International Development (USAID), and foreign investors, the Park has the financial resources to carry out the watershed studies, monitoring programs, and mitigation projects that the aforementioned government officials cannot. The Park's dual nature as both threat and solution therefore makes it a vital stakeholder in the development of a watershed management plan.

The State University of Haiti's Limonade campus opened in 2012, with $30 million of investment contributed by the Dominican Republic.[15] It is the most modern and well-equipped university campus in northern Haiti, and sits less than ten kilometers from the Trou-du-Nord river. While the academic functions of the university remain under development, the professional staff and students represent a promising partner for water management planning in the region. While the university does not directly engage in public water resources management, it has some capacity to contribute to management planning.

Field research conducted on institutional capacities should be understood in context. Previous phases of this study provided a snapshot of existing capacities as of 2015, but capacities shift from year to year.[16] Feedback provided suggests that the existing capacities reflect long-standing limitations in water governance – the dominance of the Ministry of Agriculture vis a vis the Ministry of the Environment, for example, has been the norm even since the Environmental Management Decree transferred many powers to the Ministry of the Environment. In addition, while the institutions analyzed above were limited in their abilities to carry out sustainable water management policies, not to mention their statutory mandates, the deficit in human and financial resources is being periodically filled by the multitude of international NGOs and foreign donors in the region.[17] These organizations engage in a variety of water management activities, including drilling wells, building latrines, conducting research, providing training, and supporting government offices.[18] While influential, they were not the focus of this study in part because a robust water management plan for the Trou-du-Nord depends most crucially on leadership and engagement from domestic stakeholders.

INSTITUTIONAL REFORM ALTERNATIVES FOR WATER GOVERNANCE IN THE TROU-DU-NORD WATERSHED

The results of this study form the basis for the creation of an institutional structure that will carry out a water management plan in the Trou-du-Nord watershed. The Florida International University approach adopts a participatory approach, in which the stakeholders affected by, and affecting, water management in the region are full participants in the concept, design, planning, and implementation phases of the water management plan. A participatory approach is advantageous because stakeholders are likely to settle on a management structure that is realistic, while the participatory process increases the likelihood that stakeholders and communities feel a sense of ownership over the process and plan.

That being said, it is clear from the capacity assessments that absent intervention and external support, existing mechanisms do not exist to create an effective water management institutional structure in the Trou-du-Nord. As detailed above, communes, local ministry offices, and other stakeholders such as the Caracol Industrial Park and Limonade University have a critical role to play in the management of water resources in the watershed, but existing capacities are not sufficient to create a robust institutional management mechanism.

Accordingly, three Institutional Reform Alternatives (IRAs) are provided below. Each is designed to carry out water resources management activities in the Trou-du-Nord watershed, including hydrological

14 For contrasting views on the early returns of the Park, see Mary Anastasia O'Grady, *Hillary's Half-Baked Haiti Project*, The Wall Street Journal (Jan 11, 2015), http://goo.gl/rGTYEo; and Henri-Claude Muller-Poitevien, *A WSJ's Columnist Disregarded About Haiti. . . The Facts*, The World Post (Mar. 14 2015), http://goo.gl/BhW9Dq.

15 Haiti Officially Opens Roi Henri Christophe Campus in Limonade, Caribbean Journal (Sep. 22, 2012), http://goo.gl/0ExuIL.

16 For a snapshot of Haiti's shifting capacities across a variety of indicators, see The World Bank: Haiti – World Development Indicators and Global Economic Prospects (last visited Aug. 1, 2016), http://goo.gl/pTbG4g.

17 *See,* e.g., Madeline Kristoff & Liz Panarelli, *Haiti: A Republic of NGOs?*, 23 United Institute of Peace Brief 1 (2010); and Kathie Klarreich & Linda Polman, *The NGO Republic of Haiti*, The Nation (Oct. 21, 2012), http://goo.gl/yRPcwr.

18 The institutions canvassed reported working with the IADB, USAID, FAO, EU, Haiti Outreach, and Living Water International, among others.

modeling, stakeholder engagement, and monitoring and management of water quality. Each IRA includes a basic structural overview, a discussion of advantages and disadvantages, analogous applications of the structure in Haiti or around the world, and finally, a discussion of the legal challenges and reforms that would be needed to implement the IRA. The IRAs are intended to provide stakeholders with a framework from which to pursue institutional reform and water management in the Trou-du-Nord watershed.

A. CIAT-led Inter-Ministerial Management

As briefly described above, the *Comité Interministériel d'Aménagement du Territoire* (CIAT – Inter-ministerial Committee for the Management of the Territory)[19] is a committee charged with coordinating actions among Ministries. The CIAT is composed of the Ministries of Agriculture, Environment, and Planning, as well as the Ministries of the Interior, Public Works, and Finance. It is chaired by the Prime Minister, and has the political support necessary to be a strong voice in setting water policy and coordinating water management. In fact, one of its explicit components is watershed management,[20] and as such, the CIAT is well-placed to take up inter-ministerial leadership of water management in the Trou-du-Nord watershed.

1 The Structure

A CIAT-led inter-ministerial management structure for the Trou-du-Nord watershed would most logically mirror the institutional structure of CIAT on the national level. In other words, a ministerial committee composed of representatives from the Ministries of Planning, Interior, Public Works, Agriculture, the Environment, and Economy would be responsible for setting Trou-du-Nord water management policy, approving financial allocations, and monitoring the technical committee. Because watershed management is closely aligned with the mandates of the Ministries of Agriculture, Public Works (DINEPA), and the Environment, these ministries would likely play a larger role in the work undertaken by the inter-ministerial committee. This is especially true for DINEPA and the Ministry of Agriculture, as they maintain the largest presence in the watershed.

The technical committee would be responsible for day-to-day operations of watershed management, including monitoring of water quality, withdrawals, hydrological modeling, and balancing flow levels with the demands of the various basin stakeholders. The technical committee would be composed of, or at least work closely with, CIAT's national division for watershed management, the Cellule Bassins Versants et Gestion des Ressources en Eau, as well as the Centre National de l'Information Géo-Spatiale (CNIGS). In addition, the technical committee would be composed of representatives from existing stakeholders in the watershed, including the communes of St. Suzanne, Caracol, Trou-du-Nord, and Terrier-Rouge, as well as the Société Nationale des Parcs Industriels (SONAPI - National Society of Industrial Parks) and representatives of the Caracol Industrial Park and Limonade University.

At a minimum, the technical committee would be composed of hydrological engineers, modelers, geologists, and other experts needed to effectively manage the watershed. Given the limited size of the Trou-du-Nord watershed the technical committee may not require a daily operations staff of dozens of experts, particularly if the technical committee's work is supplemented by periodic contributions from the inter-ministerial committee and stakeholder representatives. Nonetheless, the technical committee requires qualified experts to manage the daily demands of watershed management.

2 Advantages

The CIAT-led inter-ministerial approach confers one major advantage over the two reform alternatives described below: CIAT and its participant ministries already exist and work together on a mandate to manage watershed resources. Therefore, a CIAT-led institutional structure requires little policy or legal reforms to be put into place (see below), and takes advantage of existing inter-ministerial relationships. This approach would simply apply the national CIAT model to the Trou-du-Nord watershed, allowing the institution and stakeholders to dedicate time and resources to capacity building and operational demands. A Trou-du-Nord specific structure would need to be put in place, but without needing to alter the balance of power on the national level regarding watershed management authority the CIAT-led approach is most capable of being quickly set-up and implemented. CIAT's Planning Authority for the North and North-East (AANNE) is already focused on promoting sustainable development in the Trou-du-Nord region, so focusing on the watershed in particular is a natural extension of work already being undertaken.

An additional advantage of this institutional arrangement is that it provides the legitimacy of being composed of a broad spectrum of government representatives. DINEPA and the Ministry of Agriculture already operate on a daily basis in the watershed, and are likely to participate in integrated water management activities if they (or their colleagues) are integral to the inter-ministerial or technical committees. As opposed to the two reform alternatives described below, the CIAT approach is the most democratic (in theory if not in practice) and broadly representative of disparate interests.

19 Committee for the Management of the Territory: Official Site (last visited Aug. 1, 2016), http://goo.gl/53xg6p.

20 Committee for the Management of the Territory: Watershed Management (site unavailable at time of access), http://goo.gl/KQezgv.

Finally, a CIAT-led approach utilizes the substantial institutional memory and existing partnerships that have been built between CIAT, its members, and the various stakeholders of the Trou-du-Nord watershed. Regardless of which institutional structure is pursued, each mechanism will need to work with and engage the local governments, ministry offices, and industrial park. A newly created institution will need to form these partnerships for the first time, while CIAT has invested substantial resources promoting development in the northern Haiti corridor, creating relationships with donors, local governments, and national ministries. The aforementioned CNIGS, for example, can be a key partner in the CIAT framework by providing the kind of geospatial expertise needed to project future scenarios in the watershed. Importantly, CIAT has already formed partnerships with the CNIGS and is most capable of hitting the ground running in the Trou-du-Nord.

3. Disadvantages

While CIAT and its Cellule Bassins Versants et Gestion des Ressources en Eau provide a ready-made institutional structure, that structure alone is not sufficient to create a robust watershed management institution. As of July 2015 the CIAT had little to no presence in the Trou-du-Nord watershed. That may not be surprising, since the watershed is not heavily populated or geographically extensive. Nonetheless, it does imply that the CIAT has not prioritized the Trou-du-Nord watershed at present, and may need external incentives to do so.

In addition, while the national CIAT framework provides a model for down-scaling to the Trou-du-Nord watershed, a more localized approach that mirrors CIAT's national-level management structure is as yet uncommon. It is not clear if CIAT will have the political capital necessary to ensure the requisite participation from national ministries that may not be interested in the Trou-du-Nord watershed. Even if ministries are interested, they may not have the human resources needed to adequately participate. The Ministry of the Environment, for example, has little to no presence in the watershed despite an apparent mandate to coordinate and monitor water resources management. The AANNE should alleviate these concerns to some extent as it is focused on the northern region of which the Trou-du-Nord watershed is a part, but CIAT will need to develop an even more localized approach considering the smaller scale of the watershed.

It will also be difficult for CIAT to balance the competing demands for water between ministries. The Ministry of Agriculture will be expected to push for water to be used for irrigation, while DINEPA will ask that water be used for sanitation, and the industrial park will demand water for manufacturing. CIAT's role to date typically consists of coordinating synergistic or concurrent actions between ministries; making allocation decisions that promote one water use over another may require political compromises that are easier to achieve in theory than in practice. While the broad representation achieved by having representatives from across the government spectrum confers political legitimacy on the institutional structure, it may also create a breeding ground for inter-ministerial conflicts. It is not clear how national ministries will compromise considering this broad dispersal of power dynamics.

Finally, as with other alternatives, this approach requires significant investments in human resources, technology, and infrastructure. Since CIAT is not active in the watershed specifically, it will need to acquire staff and equipment, or dedicate existing resources to the watershed. Volume II of this study revealed a lack of sustained engagement from national ministries concerning Trou-du-Nord stakeholders, partly due to a lack of resources. Despite having formed key relationships and a ready-to-go institutional arrangement, CIAT will need substantial investments in order to function as a leader in water resources management in the basin.

4. Precedent - Peligre Dam Inter-Ministerial Commission

A potential model for the inter-ministerial approach proposed by this alternative can be found in the Artibonite River Basin in Haiti. The Artibonite River watershed is the largest hydrographic watershed in Haiti, providing more hydroelectricity and irrigation water than any other water source.[21] The Peligre Dam was constructed to control flows of irrigation water to watershed farming communities, supporting Haiti's largest irrigation district. The Dam also provides Haiti's main source of renewable energy. The Peligre Dam is now capable of supporting one of the most populated regions in Haiti.

Despite this development potential, the Artibonite Valley remains underdeveloped, and in particular, the water resources of the watershed are improperly managed. Much of the land area has been exploited to produce crops even when there is little potential for agricultural productivity. This contributes to increased rates of soil erosion and siltation, reducing water quality and availability. In the dry seasons soil in the watershed is insufficiently capable of retaining moisture. While the Peligre Dam is managed by Electricity of Haiti (EDH), the institution focuses heavily on electricity generation and ignores other concerns such as irrigation, environmental flows, and flooding hazards. The irrigation district is managed by an agricultural authority as well, but it suffers from an acute lack of management capacity. The same is true of more localized water users associations.

21 Water Management Program in the Artibonite Basin, Project Concept Note, Inter-American Development Bank, (last visited Aug. 1, 2016) http://goo.gl/NzAhtE.

While the reasons for mismanagement of water resources in the Artibonite watershed are multi-faceted, one of the most significant is a lack of integrated institutional leadership. In recognition of this shortcoming, an inter-ministerial commission was created to foster communication and improve cross-sectoral water resources management. The commission was led by CIAT and supported by the IADB, and brought together various stakeholders in the watershed, including the national ministries, regional management authorities, and local water users associations. CIAT created working groups to enhance dialogue and improve synergistic management activities. An Oxfam report on the institutional commission and working groups noted that communication "increased greatly" as a result of CIAT's leadership.[22] The commission is now a key player in efforts to rehabilitate the dam, improve water resources management in the watershed, and strengthen bilateral relations with the Dominican Republic.

The Peligre Commission provides a workable model for a CIAT-led Trou-du-Nord commission for several reasons. First, CIAT has proven capable of leading an inter-ministerial effort to improve water resources management. If one of the advantages of a CIAT-led approach is that the institution already exists, then the Peligre Commission reinforces that advantage by demonstrating that a more localized, basin-level institutional arrangement has proven effective as well. In addition, many of the management challenges present in the Artibonite watershed are present in the Trou-du-Nord as well. Watershed lands are over-exploited for agricultural purposes and increase flooding risks, there is likely to be increased development and population growth, water quality is low, and existing local institutions are incapable of overcoming multi-faceted challenges. If CIAT can address these problems in the Artibonite Valley, it may be able to address them in the Trou-du-Nord as well.

On the other hand, the Artibonite watershed and Peligre Dam are undeniably vital to the development of Haiti's agricultural and energy sectors. As mentioned above, the Artibonite is the largest hydrographic watershed in the country, providing significant sources of energy and agricultural commodities. The Trou-du-Nord, while significant for the industrial development potential of the Caracol Industrial Park, is not nearly on the same level of political importance. That makes the water management challenges more reasonable to overcome, but it may also make it difficult for CIAT to mobilize participation and engagement from key ministries and government agencies.

5. Legal Reforms Required

Of the three institutional reform alternatives, the CIAT-led inter-ministerial commission requires the least amount of legal reforms. In fact, depending on the nature of the commission's structure and authority, it may not require any changes to existing laws at all. CIAT's mandate is to coordinate inter-ministerial activities, and water resources management is one of its core objectives. As the CIAT is backed by the Prime Minister, it is well-positioned to receive the political support necessary to be successful. CIAT's efforts in leading the Peligre Commission also cast doubt on the idea that significant legal reforms would be required to create a Trou-du-Nord commission.

CIAT's only statutory concern may be the 2006 Environmental Management Decree, which made explicit the Ministry of the Environment's authority over national environmental policy,[61] including the right to declare eroded land to be inappropriate for agriculture, transfer powers over forest management and water resources from the Ministry of Agriculture to the Ministry of the Environment,[62] and lead the coordination effort between ministries and local governments. The Decree doesn't provide commitments toward staffing and financing the Ministry of the Environment,[65] however, and the ministry's low levels of management capacity have created a vacuum from which many water management challenges have proliferated. While the Ministry of the Environment can and should play a large role in the Trou-du-Nord commission's leadership, the Environmental Management Decree is unlikely to pose a legal impediment to CIAT leading an inter-ministerial coordination role in the watershed.

B. Creating a Trou-du-Nord Basin Organization

A second alternative mechanism to manage water resources in the Trou-du-Nord watershed is to create a new institution in the form of a river basin organization. River basin organizations are common across Latin America and the Caribbean (see below), as they embrace decentralization and cross-sectoral water management planning. River basin organizations may have a wide variety of regulatory powers and operational functions, but at their core they share a common institutional purpose of serving the needs of basin stakeholders. A Trou-du-Nord Basin Organization would be a more ambitious undertaking than a CIAT-led body, and would require more political capital and resource support to create and maintain.

1. The Structure

A Trou-du-Nord Basin Organization could take many forms, with varying degrees of involvement from existing national ministries. In the most involved sense, the river basin organization (RBO) may look similar to a CIAT-led model in which the RBO serves a coordinating and leadership role among

22 Oxfam Quebec: Development of a Binational Technical Cooperation Structure in the Artibonite Watershed, (last visited Aug. 1, 2016), http://goo.gl/XuEihM.

ministries with independent powers and regulatory authorities. This institutional reform alternative envisions a more independent RBO mechanism, in which the RBO obtains powers over planning, data collection, modeling, pollution control, and potentially, water allocation and financing. The model is more decentralized because the institution's sole purpose is to manage water resources in the Trou-du-Nord watershed.

To be sustainably managed in perpetuity, the Trou-du-Nord RBO would require financing from the central government, stakeholders and water users, and at least initially, donor organizations. These revenue streams can be complemented with the organization's own user fees. The RBO would have management authority over the Trou-du-Nord watershed, requiring some relinquishment of authority from agencies such as the Ministry of Agriculture and DINEPA, who presently carry out regulatory and management duties in the watershed.

As with the CIAT-led approach, a Trou-du-Nord RBO would not be successful without sustained engagement from stakeholders as well as national ministries. These interests can be engaged by providing certain management powers to stakeholders where appropriate. Given limited resources, it would be strategic for the RBO to delegate sanitation control activities to DINEPA, for example, or water monitoring and research to the University of Limonade. The specifics of these roles would need to be determined through an organic RBO development process that refines duties and privileges of the various stakeholders. At its core, however, the RBO remains the decisive authority on management of the watershed.

2. Advantages

In general river basin organizations have proliferated because they create a multi-sectoral management authority dedicated to a single watershed. While national ministries each have their own mandates, some of which may conflict with respect to water use, an RBO's mandate is the sustainable management of water resources. This model embraces the principle of subsidiarity, in which water resources are managed at the lowest appropriate governance level, avoiding political dynamics brewing at the national level and incorporating local knowledge and conditions.

In the Haitian context, an RBO may be advantageous because the Trou-du-Nord lacks a meaningful management authority in the first place. A Trou-du-Nord RBO may have little to no institutional friction to deal with because it would be stepping into a leadership vacuum. The institutional capacity analysis presented in Volume II of this study suggest that there are low levels of involvement from national ministries in the watershed. This approach would not attempt to force deeper levels of involvement, but would instead create an organization dedicated to the management of water resources in the basin.

A third advantage is that an RBO provides stakeholders with a single voice with which to address water issues. While a CIAT-led approach still involves a broad spectrum of agencies with separate responsibilities, an RBO approach is more stream-lined and focused on the watershed. Considering the rapid changes to the region associated with the Caracol Industrial Park, it would be desirable to create an independent body through which water issues can be addressed and transparently resolved.

3. Disadvantages

There are significant hurdles to overcome in establishing and maintaining a Trou-du-Nord RBO. First and foremost, while the watershed may see low levels of involvement from national ministries, those ministries may nonetheless value their potential regulatory authority over the basin. Creating an RBO requires marshalling the political capital and public will necessary to create the institution, finance the institution, and work with the institution to make it successful. Given the opportunity cost of doing so, ministries may not be enthusiastic about ceding powers to a new authority. Even if an RBO is created, it will be challenging to obtain meaningful support and engagement from ministries whose powers may have been displaced in the watershed.

Second, creating an organization from scratch will require financial investments and sustained capacity building. It is unlikely that the central government or the RBO itself will be able to provide the funding needed to sustain robust management operations, meaning a third-party stakeholder such as the Caracol Industrial Park or foreign donor will be leaned on heavily for support. Creating an organization from scratch also implies a more meaningful reform effort, as described below.

Finally, while basin-level management authorities have become popular in recent years and decades, they are not without their drawbacks. Basin-level institutions are often underfunded, understaffed, and lack the political connections that central government agencies enjoy. Basin organizations are often faced with jurisdictional issues, such as management authority over an aquifer that lies outside the river basin, or conflicts with local governments, water users associations, or major private sector actors who are not beholden to the basin's authority. In the Trou-du-Nord, for example, it is not clear that a Trou-du-Nord RBO would have management authority over the Massacre Aquifer. The RBO would likely face jurisdictional challenges over water resources and land use practices from national ministries and regional governments. To overcome these challenges it would need significant political backing. Without such backing, creating an RBO risks adding yet another layer of bureaucracy and administrative boundaries.

4. Precedent – RBOs in Latin America and the Caribbean

A 2012 study by the Organisation for Economic Cooperation and Development (OECD) found that RBOs are a common feature of the Latin American and Caribbean landscape.[23] They are most common, and in general most effective, in countries with decentralized or federal governments. In Argentina, for example, the establishment of river basin committees was designed in part to facilitate development of regional governments and communities. The committees manage water quality and quantity issues, and draw their financing from both the central and local governments.[24] In Brazil, river basin committees include participation from the central government, municipalities, water users and civil society. The committees are authorized to promote dialogue, arbitrate disputes, and develop and implement water resource management plans.[25] Mexico's central water agency (Comisión Nacional del Agua - CONAGUA) has adopted a similar approach, breaking down its administrative units into thirteen river basin authorities responsible for setting regional policy, implementing water management plans, and collecting water user fees. Within the basin authorities the agency has created more localized basin councils that work with states to coordinate water management.[26]

In Argentina, Brazil, and Mexico, RBOs are relatively well-funded and legally empowered to manage critical water resources management tasks. Other countries have adopted the RBO model but have yet to develop their RBOs to full maturity. Peru has recently adopted basin-level management (with support from the World Bank and IADB), creating several river basin councils across the country. Given the nascent state of their development, RBOs are still in the process of developing financial sustainability, human resource capacity, and dispute resolution powers. Costa Rica's Law on Water Resources set up a similar institutional framework, creating RBOs for every regional hydrologic unit. And in Nicaragua, the Law on National Waters created autonomous RBOs with broad operational, technical, and legal powers.[27] These RBOs vary in terms of their mandates, legal powers, and capacities, but most share a common set of responsibilities in creating, coordinating, and/or implementing water resource management plans for their respective basins.

The Trou-du-Nord has some potential to replicate these RBO models. Haiti's 2006 Decentralization Decree called for local-level management of natural resources, so from a philosophical point of view an RBO fits with the scheme. However, while Haiti may have adopted decentralization in principle, most local governments remain far from robust. These government units lack the financial or human resource capacity to fulfill their existing mandates (see Volumes I and II of this study), so a Trou-du-Nord RBO would be unlikely to benefit from the strong federalist or decentralized foundations found in Argentina, Brazil, or Mexico that contribute to the success of their basin-level institutions. Furthermore, in many of these countries the RBO model was adopted nation-wide, with the requisite political, legal, and financial support needed to undertake such reforms. It is unclear if a Trou-du-Nord RBO could mobilize the resources necessary to be successful if it is proposed as an isolated initiative.

5. Legal Reforms Required

Many of the Latin-America and the Caribbean (LAC) countries outlined above created an RBO framework for water management through national reforms, passing laws that created the RBOs and their legal powers. Because an RBO often cuts across political boundaries and requires participation from several different ministries and sectors, no one government unit is well-positioned to quickly and easily create an RBO. This is likely the case for the Trou-du-Nord as well. Much of the watershed lies in the Northeast Department, but key stakeholders (including the University of Limonade) are located in the Northern Department. These departments lack the capacity to create an RBO on their own as well. CIAT has heavily invested in the northern corridor of Haiti, but in order to be cross-sectoral and relatively independent creation by national ministry would not be ideal.

More than likely a decree from the Haitian Parliament would be necessary to create a Trou-du-Nord RBO, especially if it is to have administrative powers to collect user fees, adjudicate disputes, and receive funding from the central government. If the RBO acts only in a coordinating capacity, a parliamentary decree may not be necessary if the relevant ministries and stakeholders agree to participate and create the RBO as a partnership initiative. However, considering the substantial investments required to create a meaningful RBO, it would be ideal if the institution were enabled to undertake more meaningful activities, such as implementing water management plans, setting policies, or controlling water withdrawals and discharges. An intermediate approach would create the RBO as a coordinating agency among stakeholders, and pursue formal institutionalization and legal powers once the framework has been established.

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23 OECD Studies on Water Governance in Latin America and the Caribbean: A Multi-Sector Approach, OECD (2012).

24 *Id.* at 86.

25 *See* National Water Agency of Brazil (ANA): Homepage (last visited Aug. 1, 2016), http://goo.gl/p50TpL.

26 *See* the Comision Nacional del Agua (CONAGUA), (last visted Aug. 1, 2016), http://goo.gl/ZoJksY.

27 *See supra* note 22 at 88-89.

C. Creating a Public-Private Management Entity

The third institutional reform alternative considered in this study is the creation of a public-private partnership (PPP) institution with management authority over the watershed. PPPs are contractual arrangements in which local governments outsource water management to a private company. The company is responsible for managing water resources sustainably, upgrading infrastructure, and providing water services to local populations. Governments retain ownership over the resource and typically compensate the private company directly for services provided. PPPs are common in areas where governments lack the capacity to manage water resources themselves, or in cases where governments lack the up-front costs to upgrade infrastructure or maintain water systems. Typically PPPs in rural areas such as the Trou-du-Nord watershed are focused on water supply (as opposed to a broader mandate to manage water resources and the various demands on them), but PPPs come in a variety of arrangements. Considering the low levels of service delivery and water management in the Trou-du-Nord watershed, a PPP to manage water resources is a viable institutional alternative.

1. The Structure

PPPs in the water sector may take several forms, authorizing the private company to take on more or less responsibility given the context. In the most involved scenarios, companies are tasked with nearly all water management duties, while the local government's role is limited to oversight and compensation. In the least involved scenarios, companies provide limited support for specific water management initiatives, such as consulting on the costs of infrastructural improvements. Given the absence of any meaningfully coordinated water management in the Trou-du-Nord, as well as the absence of a single entity to work with, a PPP for the watershed would likely call for broad delegation of powers to a private company. The company might monitor changes in water supply and quality, administer permits, collect user fees, and provide water delivery services to local communities, farms, and the industrial park.

A central tenet of this model is that the private company receives enough revenue to cover its costs. The revenue is typically provided by the government forming the PPP. In many rural and/or poor communities, however, local governments lack the capacity to finance a PPP. In these cases third-party institutions such as development banks step in to close the funding gap. Given the low levels of economic development in the Trou-du-Nord watershed, it is unlikely that the communes or departments will be able to finance a PPP. The institutional structure may therefore require financing from a foreign donor, the industrial park, or some combination of the two. The third-party would receive a significant role in oversight and strategic planning. Since the Caracol Industrial Park is itself a PPP within a special economic zone, a Trou-du-Nord watershed PPP may be pursued through an expansion of existing responsibilities of the industrial park's partners.

Some PPPs adopt a participatory approach to water management, in which local communities provide input on priority uses and the PPP builds capacity in local populations to manage water resources. This approach would be preferable in the Trou-du-Nord, as there are a variety of water users whose needs are considerable, contrasted with a lack of capacity in local institutions to address these needs. The Trou-du-Nord PPP should emphasize community engagement and capacity building as a priority management strategy.

2. Advantages

The Trou-du-Nord's local institutions are not sustainably managing water resources at present, and national ministries are struggling to balance the needs of various user groups, creating an absence of water management leadership in the basin. The two institutional reform alternatives described above implicate substantial capacity building investments in order to develop expertise. A PPP, on the other hand, would be able to step into the leadership void immediately, providing technical expertise and management capacity to address existing challenges. Many companies have experience in developing countries where conditions are similar to the Trou-du-Nord watershed, and are equipped to handle complexity.

PPPs may be mutually advantageous as well because the investment risks are shared between the local communities (or in this case, the third-party financer) and the private company. Companies typically receive remuneration upon satisfaction of certain performance objectives, or over time after committing capital infusions. The company therefore shares in the risk that a local government would otherwise absorb acting on its own. Risk-sharing may provide an added benefit in the Trou-du-Nord by projecting stability and promoting investment in the region, either in the industrial park or surrounding communities.

Of course, a central advantage of PPPs is that private companies are often able to cover the up-front costs of infrastructure installations, maintenance, and upgrades. At present the only viable sources of capital infusion in the Trou-du-Nord are not well-positioned to take on the risks or obligations of installing pipelines, levees, or water treatment facilities. A PPP arrangement, on the other hand, typically includes start-up investments from the private company. While a third-party may need to significantly finance the Trou-du-Nord PPP, leveraging private sector funding would improve the financial viability of water management in the basin.

3. Disadvantages

While there are many examples of PPPs working well in developing countries, there are documented cases in which local populations were worse off as a result of relinquishing control over their water resources. In fact, many NGOs have campaigned aggressively to limit the privatization of water service delivery in response to unsuccessful interventions from the private sector. A World Economic Forum conference dedicated to PPP in the water sector found that the most common obstacle to a successful PPP is a lack of political will or support for a public partnership with a private (and often foreign) company.[28] While there is ample political support for the public-private nature of the Caracol Industrial Park, it is unclear if a PPP for managing water resources in the Trou-du-Nord will obtain the requisite support from stakeholders. As described below, a Trou-du-Nord PPP will require legal authorizations from the central government, so the benefits of such an arrangement will need to be clearly communicated.

Second, while many private water companies are accustomed to working in under-developed watersheds, proposing a variety of service options to meet the financing capacities of local communities, it can nonetheless be difficult for communities to find a private company willing to form a partnership and absorb risks. The business case for investment may not be strong, or the government's terms for the partnership may not be acceptable. Similarly, the terms of an interested private company may not be acceptable to Trou-du-Nord stakeholders or third-party financers.

In addition, while private water companies may bring significant technical expertise to the table, a requisite of PPPs is effective oversight from government institutions. Oversight can be challenging, however, if governments lack the capacity to regularly monitor activities and interpret conditions. A participatory PPP approach advocated above may alleviate this concern, but only if the participating government representatives and stakeholders are well supported by the central government. Many of the PPP failures cited by anti-privatization advocates stem from an inability of governments to monitor conditions and step in when needed. In the Trou-du-Nord, it is not clear which agency would have oversight authority over the PPP. CIAT is likely the best positioned institution, but would need support to take on a role of this nature.

Finally, if the Trou-du-Nord PPP is subsidized by a foreign donor or other third-party, it may be difficult to establish a path towards financial sustainability and self-sufficiency. PPPs require long-term commitments to enable costly investments to make financial returns. Development banks and organizations such as the IADB and USAID have shown a long-term commitment to the Trou-du-Nord region by supporting the Caracol Industrial Park's development, but that may not translate into sustained interest in a PPP for water management. Regardless, the PPP will need to establish a path towards self-sufficiency in order to attract investors and promote development.

4. Precedent – Water-Sector PPPs in Port-au-Prince and Saint-Marc

Haiti already has two water service delivery PPPs underway. In Port-au-Prince, a consortium of investors led by Suez Lyonnaise des Eaux has provided more than $10 million USD to the Port-au-Prince regional water utility, and provides a number of technical and operational assistance measures.[29] In Saint-Marc a full-fledged PPP was created to take over water service and management. The investor contributed $5 million USD and obtained a 15-year contract to manage the water sector.[30]

These pioneering developments notwithstanding, both initiatives have faced significant challenges that call into question the viability of PPP in the Haitian water sector. In Port-au-Prince, the consortium has been successful in translating technical assistance into improved water service delivery, but the partnership has not led to transformative change that would make the regional water utility self-sustaining. In Saint-Marc the track record is more grim, as the operator is reportedly unable to charge cost recovery tariffs and unable to break even financially.[31]

These precedents convey mixed messages for the prospects of a Trou-du-Nord PPP. On the one hand, it is promising that PPPs have already been established in the water sector in Haiti. As mentioned above, water-sector PPPs often face public and political opposition. It would be challenging if the Trou-du-Nord PPP was burdened with being the first PPP in the sector, and fortunately that is not the case. The Port-au-Prince and Saint-Marc PPPs also demonstrate interest in the Haitian water sector from foreign investors. Already there have been substantial investments and risk absorption from credible private companies.

On the other hand, these precedents have shown mixed results. It is not clear if potential investors in a Trou-du-Nord would be encouraged or discouraged

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28 World Economic Forum: *Development-Driven Public-Private Partnerships in Water, Emerging Priorities from Roundtable Discussions*, Financing for Development Initiative, 3 (last visited Aug. 1 2016), http://goo.gl/2NvSll.

29 *See* Public-Private Infrastructure Advisory Facility: Caribbean Infrastructure PPP Roadmap, 37 (last visited Aug. 1, 2016), https://goo.gl/W85sK5.

30 *Id*.

31 *Id*. at 22.

by the experiences in Port-au-Prince and Saint-Marc. Even if those experiences had been successful, a Trou-du-Nord PPP would be significantly different in nature. Not only is the Trou-du-Nord watershed much less populated (therefore reducing potential cost recovery and economies of scale), a Trou-du-Nord PPP would be broader in scope that water supply delivery, requiring the operator to balance human, agricultural, ecological, and industrial water needs.

5. LEGAL REFORMS REQUIRED

As a civil law country, Haiti could establish a PPP for the Trou-du-Nord watershed through a specific decree or concession law. In addition, in 2012 the Ministry of Finance established a PPP unit in order to set policy, promote investment, and generally facilitate the responsible use of PPPs in Haiti. To date, however, it lacks a guiding policy, legal framework, or funding base,[32] so its purpose and role in creating a Trou-du-Nord PPP for watershed management is relatively ambiguous. In 2010, the Central Bank of Haiti, who had management authority over the state-owned telecoms company, entered into a PPP to provide upgrades to Haiti's telecommunications infrastructure. In order to do so the Bank received assistance from the International Finance Corporation to structure the bidding process, and was represented by Haiti's Council for the Modernization of State-Owned Enterprises.[33]

However, a Trou-du-Nord PPP likely would require some degree of legal or political authorizations, because unlike the Central Bank's existing jurisdiction over the telecoms company, no single entity has a consolidated authority over management of the Trou-du-Nord's water resources. While the Ministry of the Environment has jurisdiction over water management generally, the Ministry of Agriculture has jurisdiction over "irrigation waters," and DINEPA is authorized to control water service delivery facilities. Some consolidation of these authorities would likely be required in order to allow the state (most likely the Ministry of Finance's PPP unit) to negotiate a PPP.

In addition, some administrative reorganization may be necessary in order to create a government unit with oversight capacity and authority. CIAT's role as a coordinating body, as well as its heavy involvement in development of the northern corridor and the industrial park, may suggest that it is well-positioned to serve this function. If that is the case, some capacity building and technical support may be needed to supplement its existing oversight capabilities.

32 *Id.* at 12.

33 *See* International Finance Corporation - Public-Private Partnership Stories: Haiti Teleco, (last visited Aug. 1, 2016), http://goo.gl/dxkzbH.

CONCLUSIONS

In this study, three institutional reform alternatives have been presented to consider the costs and benefits of pursuing water governance reform in the Trou-du-Nord watershed. Common among all three alternatives is the need to consistently engage stakeholders, provide ample financial and human resources to build capacity, and provide a clear delineation of institutional roles and responsibilities.

That being said, the three alternatives offer significantly divergent approaches to water management in the Trou-du-Nord basin. A CIAT-led approach would be the quickest to initiate, harnessing existing relationships while limiting its function to inter-ministerial coordination activities. A Trou-du-Nord RBO would consolidate responsibilities into one basin-level institution, though with a broad variance in capabilities that would be determined by the political and financial support provided. Finally, a Trou-du-Nord PPP offers risk-spreading and cost-sharing, though it may be challenging to find a partner and arrangement that satisfies all stakeholders.

While there are many governance structures available to reformers – including models that were not discussed in depth in this article – it will be important to weigh the costs and benefits of each governance structure, while keeping in mind the water governance context of the region. Regardless of the reform alternative or institutional arrangement pursued, many challenges face stakeholders in the Trou-du-Nord watershed. How these challenges are addressed will be heavily influenced by the institution that is formed to address them.

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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

Henry O. Briceño and Meghan Gonzalez[1]

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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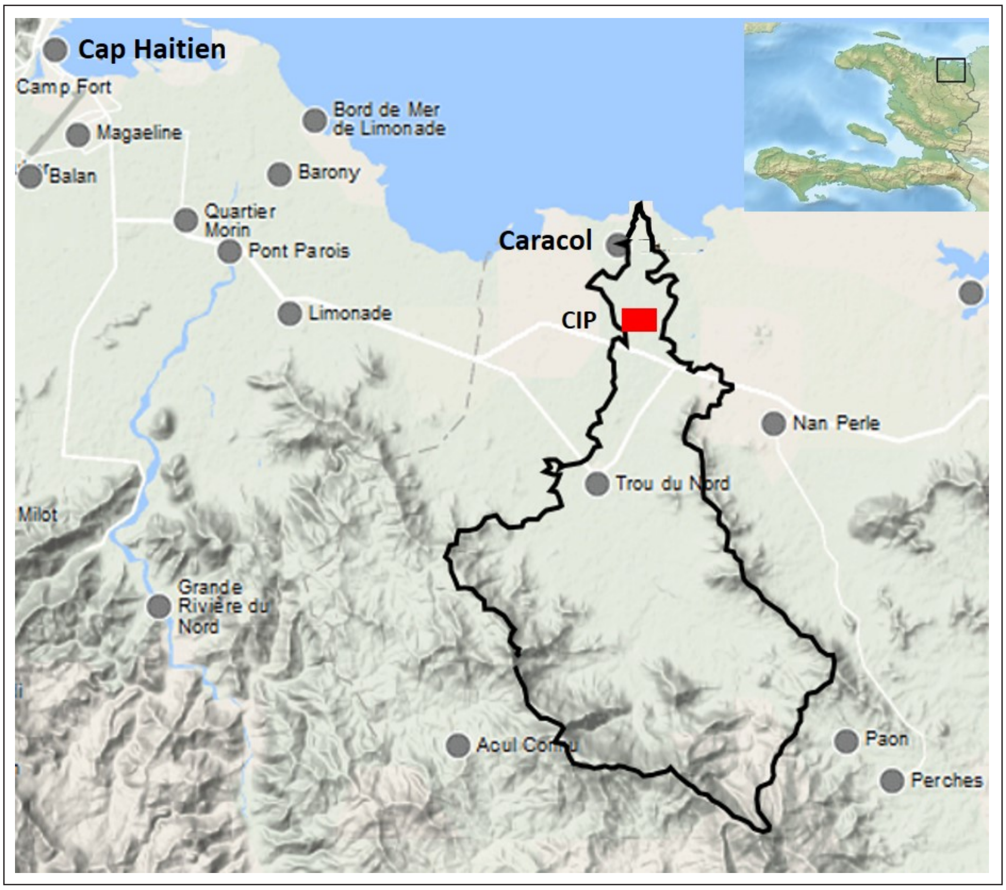

Figure 1. Location of the Trou Du Nord basin and the Caracol Industrial Park (CIP; red rectangle) in northeast Haiti (Base map by MapCarta)

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

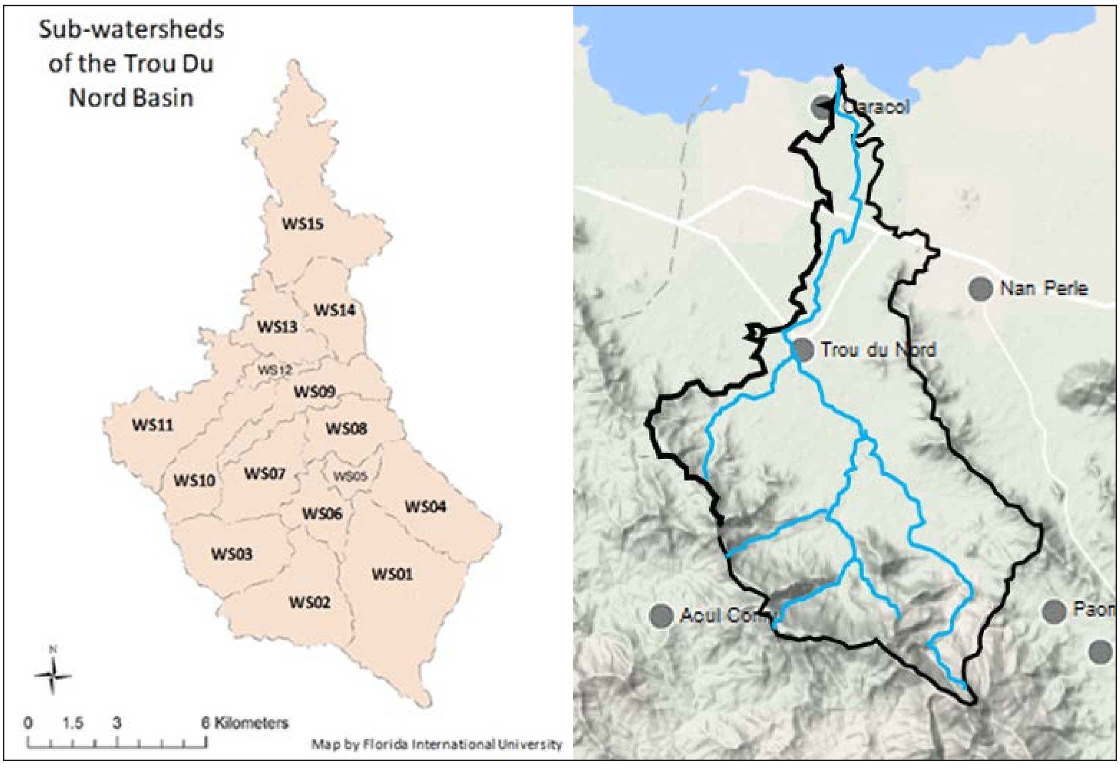

Figure 2. Sub-watersheds of the Trou Du Nord basin derived from the 30-m ASTER Global DEM (USGS), and main drainage lines of the Trou Du Nord River

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.

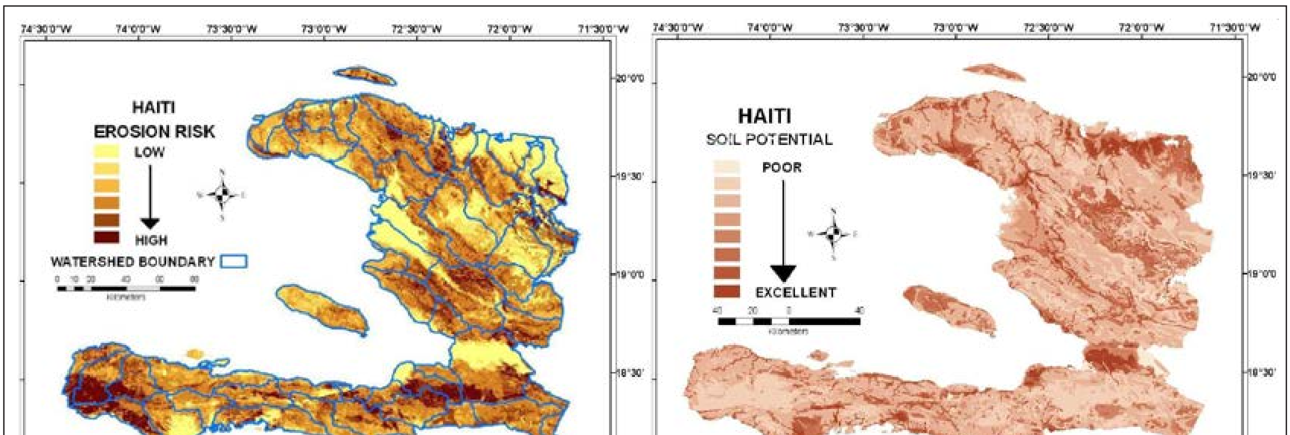

Figure 3. Left panel= Erosion Risk map (Ministry of Planning and External Cooperation of Haiti and IGN France International); Right panel= Soil Potential for agriculture map (French Bureau pour le Development de la Production Agricole,1978)

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.

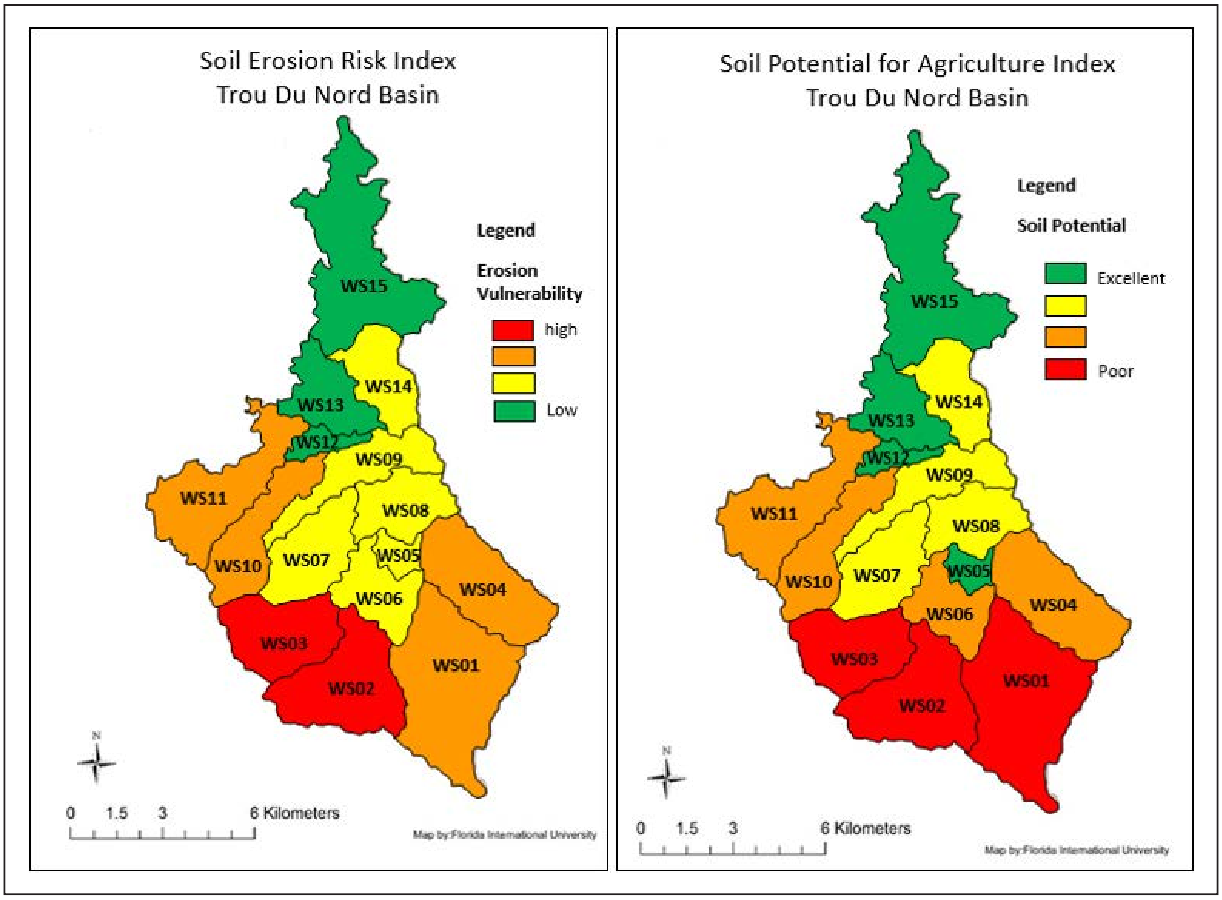

Figure 4. Map of Soil Erosion Risk Index and Soil Potential for Agriculture Index

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/km^2	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.

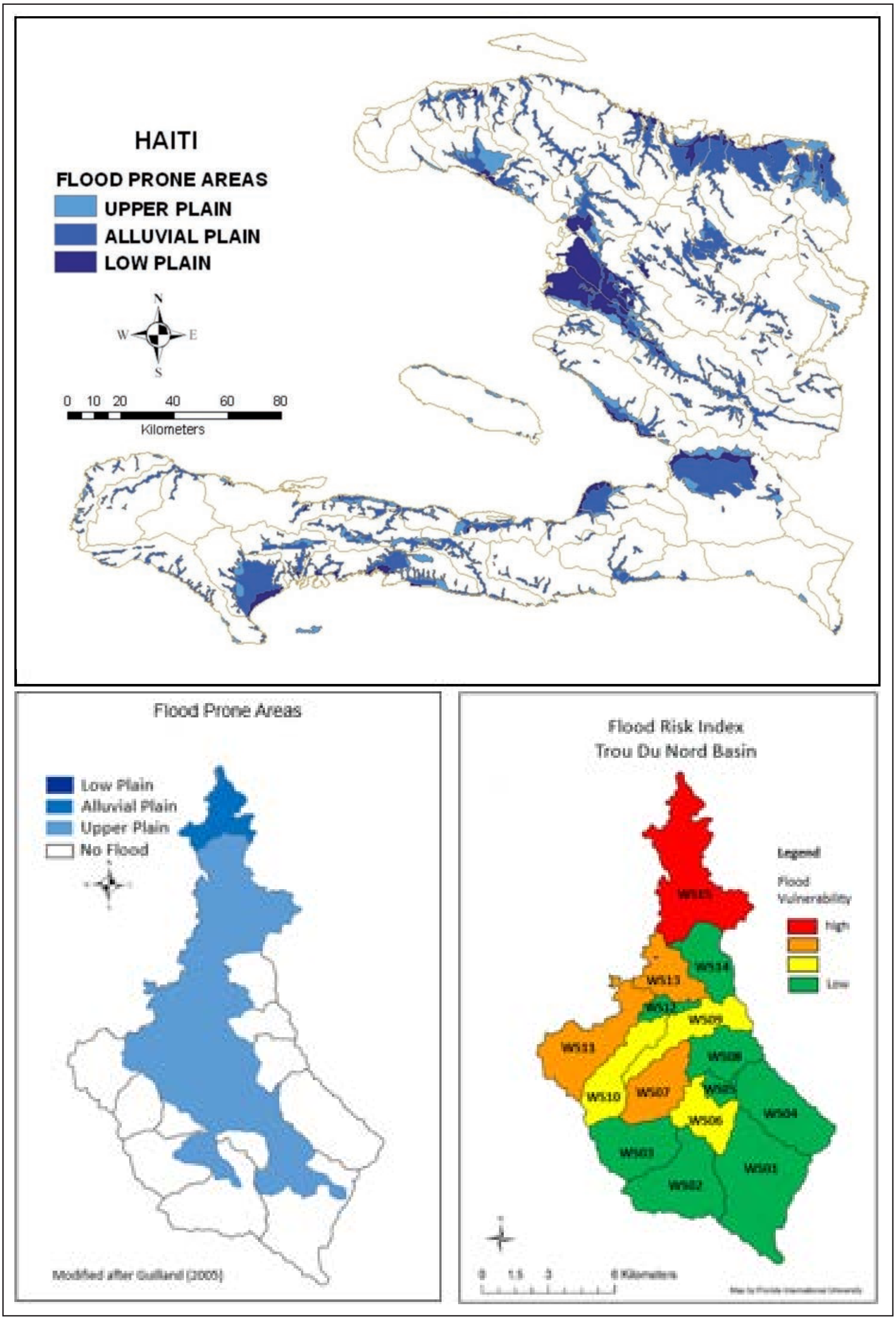

Figure 5. Flood Prone Areas Map of Haiti (upper; Guillande, 2005), Trou Du Nord Basin (left) and Flood Risk Index by sub-watershed (right)

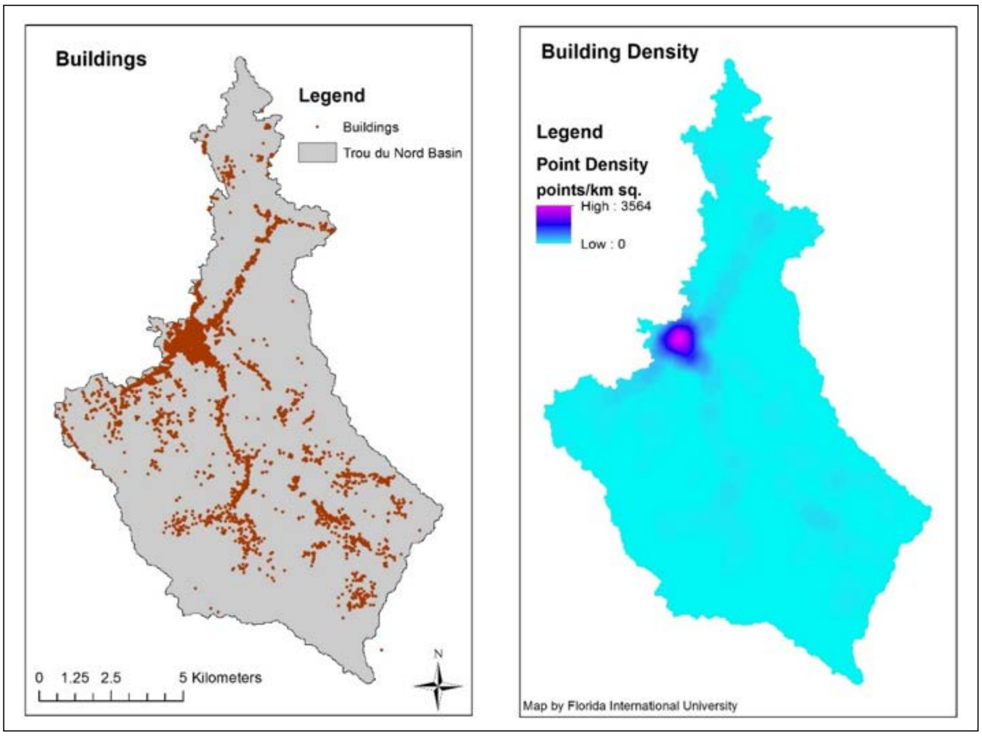

Figure 6. Building map of the Trou Du Nord watershed as a “building point” (left) and Building Density (right) information layers

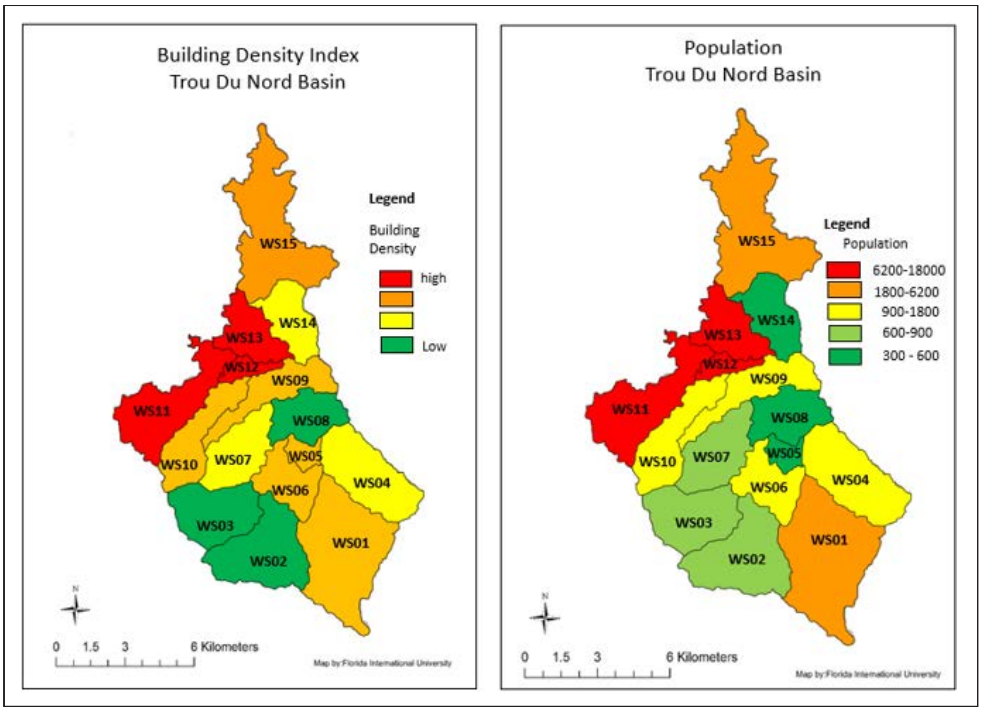

Figure 7. Building Density Index Population map of Northeast Haiti

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.

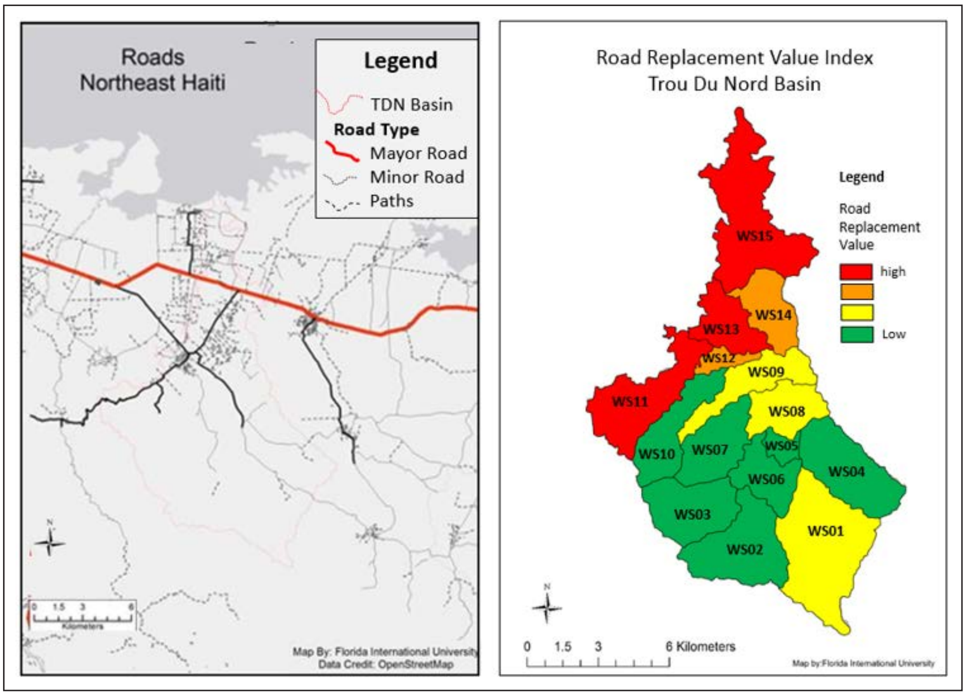

Figure 8. Road map of northeast Haiti (modified from openstreetmap.org) and Road Replacement Value Index

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.

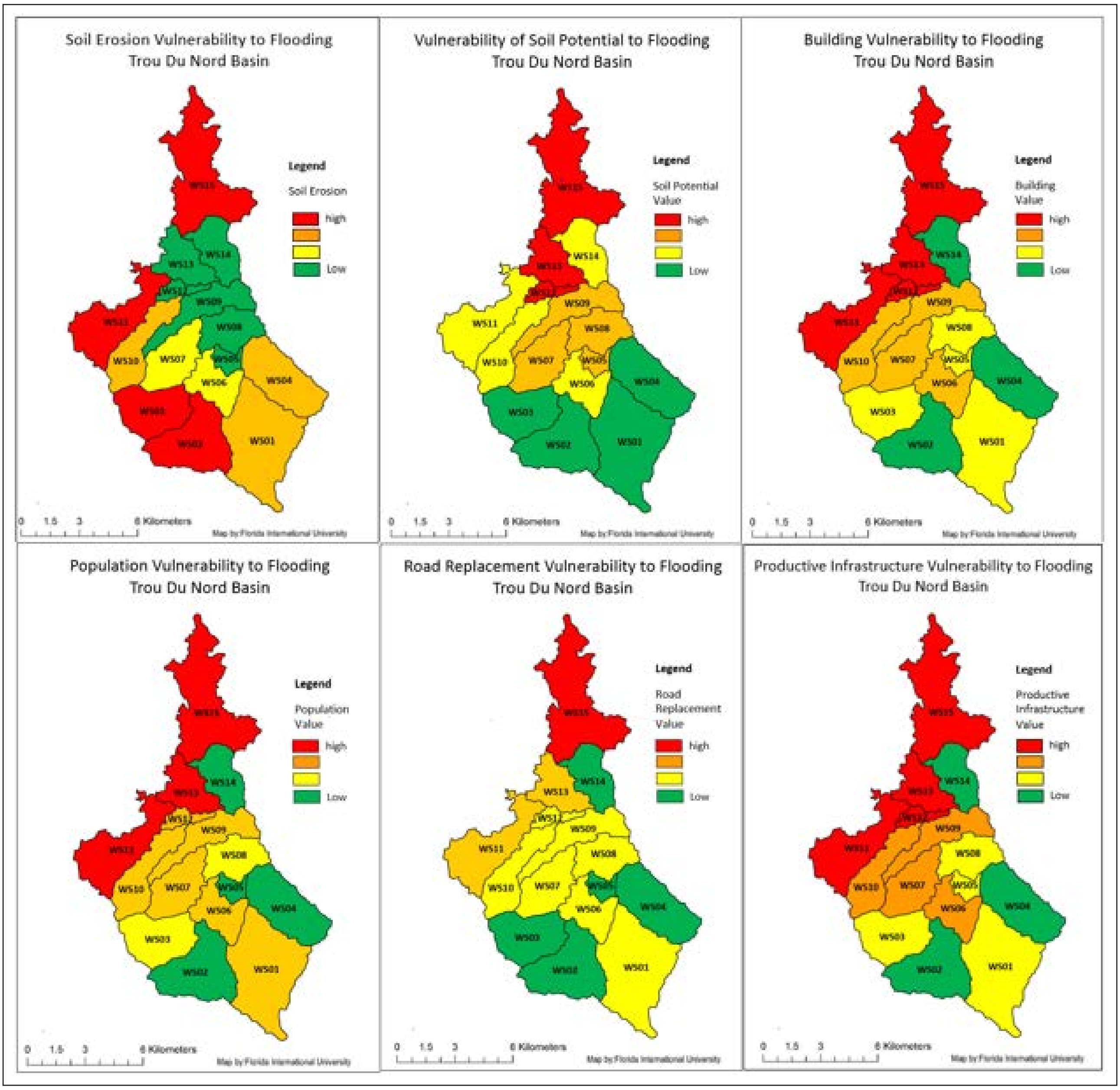

Figure 9. Priority Sub-watersheds of the Trou Du

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

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MICROBIOLOGICAL CONTAMINATION OF GROUNDWATER BY CRYPTOSPORIDIUM OOCYSTS IN HAITI. HEALTH RISK ASSESSMENT FOR POPULATION

CONTAMINATION MICROBIOLOGIQUE DES EAUX SOUTERRAINES PAR LES OOCYSTES DE CRYPTOSPORIDIUM EN HAÏTI. EVALUATION DES RISQUES POUR LA SANTÉ DE LA POPULATION

CONTAMINACIÓN MICROBIOLÓGICA DE LAS AGUAS SUBTERRÁNEAS POR LOS OOCITOS DE CRYPTOSPORIDIUM EN HAITÍ. EVALUACIÓN DE LOS RIESGOS PARA LA SALUD DE LA POBLACIÓN.

Ketty Balthazard-Accou[1],2*, Evens Emmanuel[1], Momar Diouf[3], Patrice Agnamey[4,5]

Abstract

Contamination of natural aquatic ecosystems by Cryptosporidium is a major environmental and human health issue. In Haiti, environmental *Cryptosporidium* oocysts pollution has been well documented by previous studies conducted in several cities of the country. In groundwater from Les Cayes of Haiti, significant concentrations from 1 to 989 oocysts in 100 liters of filtered water were calculated. Results of these studies revealed high level of *Cryptosporidium* oocysts pollution in surface water and groundwater. Therefore, regarding cryptosporidiosis, contaminated water resources constitute a real sanitary risk mainly for children and immunocompromised individuals. So, it is necessary to assess the biological risk for populations served by those polluted water resources. The aim of this study is to present: (i) the steps of a procedure intended to evaluate risks to human health linked to the consumption of water from groundwater; and (ii) the results of its application on groundwater from Les Cayes, city located in southwestern Haiti. The procedure is based on a scenario that describes the existence of an uncontrolled landfill leachate which are neither collected nor treated. The refuse has a close contact with the soil making easy the transfer of various pollutants from the surface to groundwater. Moreover, latrines and septic tanks are often discharged into the unsaturated zone of the geological matrix are also retained. Risk estimation was calculated for two groups in the exposed population: immunocompetent and immunocompromised individuals. As expected, the study revealed a high risk for individuals in the immunocompromised group.
Key words: Groundwater, microbiological contamination, health, biological hazards, risk assessment, Cryptosporidium sp.

Resumé

La contamination des écosystèmes aquatiques naturels par *Cryptospridium parvum* constitue une véritable préoccupation de santé humaine et environnementale principalement dans les pays en développement. En Haïti, des oocytes de cryptosporidies ont été retrouvés dans plusieurs villes du pays dans les eaux de surface et dans les eaux destinées à la consommation humaine. Dans les eaux souterraines Les Cayes d'Haïti, des concentrations significatives de 1 à 989 oocystes dans 100 litres d'eau filtrée ont été déterminées. Les résultats de ces études ont révélé un niveau élevé de pollution par des oocystes de *Cryptosporidium* dans les eaux de surface et des eaux souterraines. Par conséquent, les ressources en eau contaminés par des oocystes constituent un véritable risque sanitaire principalement pour les enfants et les personnes immunodéprimées. Ainsi, il apparaît nécessaire d'évaluer le risque biologique pour les populations desservies par ces ressources en eau polluées. Le but de cette étude est de présenter: (i) les étapes d'une procédure destinée à évaluer les risques pour la santé humaine liés à la consommation d'eau provenant des eaux souterraines; et (ii) les résultats de l'application de cette procédure sur les eaux souterraines Les Cayes, ville située dans le sud-ouest Haïti. La procédure est basée sur un scénario qui décrit l'existence d'une décharge sauvage où les lixiviats ne sont ni collectés, ni traités. Les déchets sont directement en contact avec le sol et suivent les mécanismes de transfert vers la nappe. En outre, les latrines et fosses septiques, rejetant leurs effluents dans la zone non saturée de la matrice géologique, sont également retenues. L'estimation du risque a été calculée pour deux groupes dans la population exposée: immunodéprimé et immunocompétent. Il apparaît comme attendu un risque élevé pour les immunodéprimés.
Mots clés: Eaux souterraines, contamination microbiologique, santé, risques biologiques, évaluation des *risques, Cryptosporidium spp.*

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Resumen

La contaminación de los ecosistemas acuáticos naturales por *Cryptospridium parvum* constituye una verdadera preocupación de salud humana e ambiental principalmente en los países en desarrollo. En Haití, los oocitos de cryptosporidios se han encontrado en muchas ciudades del país en las aguas de superficie y las aguas destinadas al consumo humano. En las aguas subterráneas en Les Cayes de Haití, concentraciones significativas de 1 a 989 oocitos en 100 litros de agua filtrada han sido determinadas. Los resultados de estos estudios han revelado un nivel elevado de polución por oocitos de *Cryptosporidium* en las aguas de superficie y aguas subterráneas. Por ende, los recursos en agua contaminados por oocitos constituyen un verdadero riesgo sanitario para los niños y las personas inmunodeprimidas. Así, se hace necesario evaluar el riesgo biológico para las poblaciones que se abastecen de estos recursos en agua contaminados. El objetivo de este estudio es presentar: (i) las etapas de un procedimiento destinado a evaluar los riesgos para la salud humana ligados al consumo de agua proveniente de las aguas subterráneas; et (ii) los resultados de la aplicación de este procedimiento en las aguas subterráneas en Les Cayes, ciudad situada en el suroeste de Haití. El procedimiento está basado en un escenario que describe la existencia de una descarga violenta en donde los lixiviados no son ni recolectados ni tratados. Las basuras están directamente en contacto con el suelo y siguen los mecanismos de transferencia hacia la capa de agua subterránea. Además, las letrinas y fosas sépticas, rechazando sus efluentes en la zona no saturada de la matriz geológica, están igualmente retenidas. La estimación del riesgo ha sido calculada para dos grupos en la población expuesta: inmunodeprimida y immunocompetente. Este aparece como un riesgo elevado para los inmunodeprimidos.

Palabras claves: Aguas subterráneas, contaminación microbiológica, salud, riesgos biológicos, evaluación de los riesgos, Cryptosporidium spp.

1. INTRODUCTION

Contamination of water resources by *Cryptosporidium* oocysts is a serious public health issue (Suzuki and Takida, 2015). Indeed, *Cryptosporidium,* an extremely virulent microorganism, is persistent in the environment and resistance to chemical disinfection has made this protozoan parasite one of the critical pathogens for the drinking water industry (WHO, 2009). Some species infect humans (Liu, 2012) and animals (Hong et al., 2014). They cause cryptosporidiosis disease and mild to severe diarrhea, dehydration, stomach cramps, and/or a slight fever from waterborne species (Agulló-Barceló et al., 2012). The disease is transmitted in feces by humans and other animals as an oocyst, which has a hard, environmentally resistant shell for protection (Messner et Berger, 2016). Because of it occurrence in groundwater, public water supplies (Balthazard-Accou et al. 2010), and surface water (Rose et al. 1991; Lechevallier et al. 1991a), many cryptosporidial enteritis outbreaks have been reported (MacKenzie et al. 1994; Smith and Rose 1998; Widerström et al 2014). Pathogen infection risk targets are central to some drinking (or other) water exposure evaluations (Sinclair et al., 2015; O'Toole et al., 2015). Both humans and animals may be exposed to *Cryptosporidium* through consumption of contaminated water and food as well as by direct contact with contaminated soils and infected hosts (Fayer, 2004).

The presence of oocysts in natural aquatic environment and drinking water brings a biological hazard, which is linked to the existence of the dangerous aspects of this particle (Rivière, 1998); and may generate biological risks of *Cryptosporidium* for human health. Otherwise, biological, environmental, climatic and community habits are involved in the potential risk factors for waterborne transmission of cryptosporidiosis (Rose et al. 2002). The deficit of policy in urban planning can be also taken as a risk factor for diseases related to *Cryptosporidium*. Indeed, land use activities contributing feces for example show that waters receiving cattle and sewage discharges have 10-100-fold greater concentrations of oocysts (Bagley et al., 1998). In this case, transportation through soil has usually been considered an insignificant pathway because soil is generally assumed to be an effective filter inhibiting the transport of different pathogens (Petersen et al. 2012). For colloid-sized *Cryptosporidium* oocysts the fate and transport processes depend much on the soil physical and chemical properties (Peng et al. 2011).

In Haiti, the presence of *Cryptosporidium* oocysts in soils (Bathazard-Accou et al. 2014), in surface and groundwater (Balthazard-Accou et al. 2009, Brasseur et al. 2011), and its transport from soils to groundwater have been studied (Balthazard-Accou, 2011). Several factors could be responsible for groundwater exposure to *Cryptosporidium* oocysts especially the discharge of urban effluents into rivers without any prior treatment and the existence of latrines and septic tanks equipped with infiltration wells in a high-risk flood area (Balthazard-Accou et al., 2014).

Furthermore, *Cryptosporidium* is responsible for 17% of cases of acute diarrhea observed in infants under the age of 2 (Pape et al., 1987). In Port-au-Prince districts, where water contains *Cryptosporidium* oocysts, the estimated risk of infection is between $1x10^2$ and $5x10^2$ for the immunocompetent population; for the immunodepressed population, this value varies from $1x10^2$ to $97x10^2$, depending on the oocyst load in the consumed water (Bras et al., 2007). However, this microbiological risk estimated for *Cryptosporidium* only focused on a few aquatic ecosystems in Port-au-Prince. The aim of this study is to present: (i) the steps of a procedure intended to evaluate risks to human health linked to the consumption of water from groundwater; and (ii) the results of its application on groundwater from Les Cayes.

2. METHODOLOGY

2.1 General approach of health risks evaluation

The National Research Council (1983) defines the assessment of risks as the activity that evaluates the toxic properties of a chemical product and the conditions of human exposure to this product, in order to observe the reality of human exposure and characterize the nature of the effects that may result. The general approach of health risk assessment is based on four steps: identifying the hazard, studying the dose-response relationship, estimating exposure and characterizing the risk (NRC, 1983).

In the field of chemical risks, methodological guides refer to the available tools, whether it is models or databases of toxicological and physico-chemical data. On the contrary, the biological risk has many characteristics that prevent a simple transposition of the methodology from the chemical to the biological field area. The difference in methodology between the estimate of a chemical risk and that of a microbiological risk lies in the identification of dose-response functions and particularly in the choice of the model of dose-response relationship (Gofti, 1999). Human, animal, and environmental reservoirs are notoriously difficult to control and quantify (Zmirou-Navier et al., 2006).

2.2. Presentation of study site

Les Cayes is a city located in Haiti's Southern region. Its population is currently 137,952 habitants (IHSI, 2009). The city is located at 18º34'00'' Northern Latitude and 72º21'00" West Longitude on the Caribbean coast, on a coastal plain with high rainfall (over 2,000 mm/yr), The average temperature varies from 24°C to 28°C. There are two rainy seasons: from April to May and August to October.

There are several types of groundwater, among them: unconfined alluvial aquifers, karst aquifers, giving rise to a variety of resurgences and flows (PNUD, 1991a). The groundwater resources are used for drinking water. From an ecological point of view, they represent a considerable amount of reserve water and play a major role in the feeding of many lakes and rivers. The mode of supply is from groundwater extraction with the installation of wells and boreholes, and spring catchments. Distribution is via private networks and connections, and public standpipes. According to Balthazard-Accou (2011), the municipal water system is supplied by two wells with a flow rate of 66 L/s and an average production of about 10,134 m^3/day.

In addition, due to the topography of this coastal city, the existing latrines are easily in contact with groundwater; especially during the rainy season, facilitating the movement of microorganisms. Moreover, the city is very sensitive to flooding. A brief description of the urban environment of the city is presented in the scenario (Figure 1) developed for the implementation of this biological risk assessment.

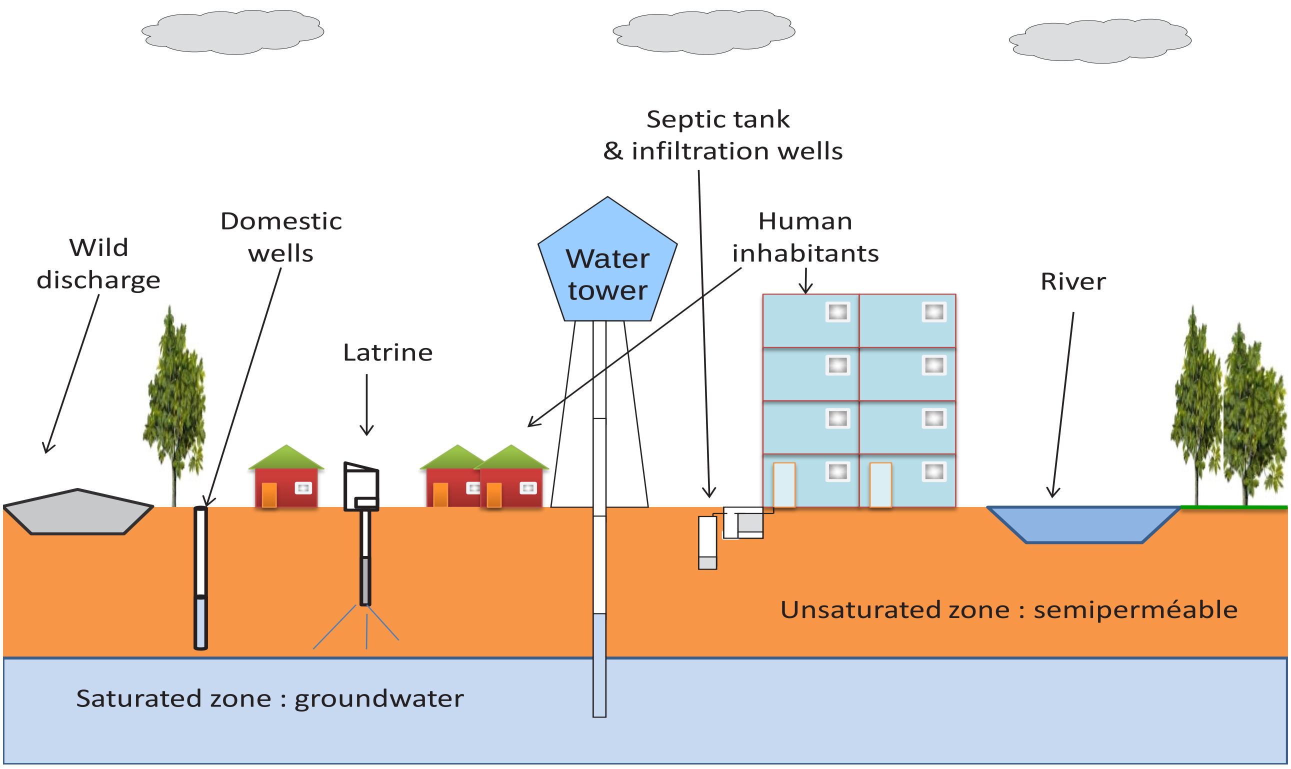

Figure 1. Graphic representation of the scenario studied

The scenario highlights the existence of a dumpsite where leachates are not collected or treated. They are in direct contact with the soil and they follow the transfer mechanisms toward the groundwater. Latrines and septic tanks, discharging into the unsaturated geological matrix area, are also noted. Other utilities such as boreholes and wells feeding a family or group of families with water, an urban water supply and an individual sanitation network are also presented in this scenario (Figure 1).

The scenario reproduces the supply mode of drinking water and wastewater management in Les Cayes. Percolation of leachates from uncontrolled discharge, the hydraulic operation of the effluents generated by latrines and septic tanks, contamination of surface water and the interactions between these aquatic ecosystems and groundwater reflect the existence of a risk to human health that may result from the ingestion of water from the aquifer or surface water. The very use of the aquifer for water supply, taken in the particular context of the scenario observed, can be an important source of distribution of infectious waterborne diseases in the study area.

In order to avoid initially conducting a major campaign of sampling in different emission sources of oocysts toward the groundwater, we have introduced in the analysis plan an initial step consisting in working only on water from the groundwater and that is used by people. This phase aims at detecting *Cryptosporidium* oocysts during the two rainy seasons of the year and comparing the different results obtained in water from the groundwater for pathogen selected within the number zero to 100 liters of water.

For any number of oocysts less than 1 per 100 liters of water intended for human consumption, the flowchart showcases the absence of *Cryptosporidium*, which in turn justifies the absence of contamination, thus there is no hazard (risk) for the population. However, this type of procedure recommends the implementation of a microbiological surveillance program consisting of periodic characterization of *Cryptosporidium* oocysts in the water from the groundwater. In contrast, for any number of oocysts greater than or equal to 1 per 100 liters of water intended for human consumption, the approach recommends the next steps of the evaluation of biological risks to consumer health (Figure 2).

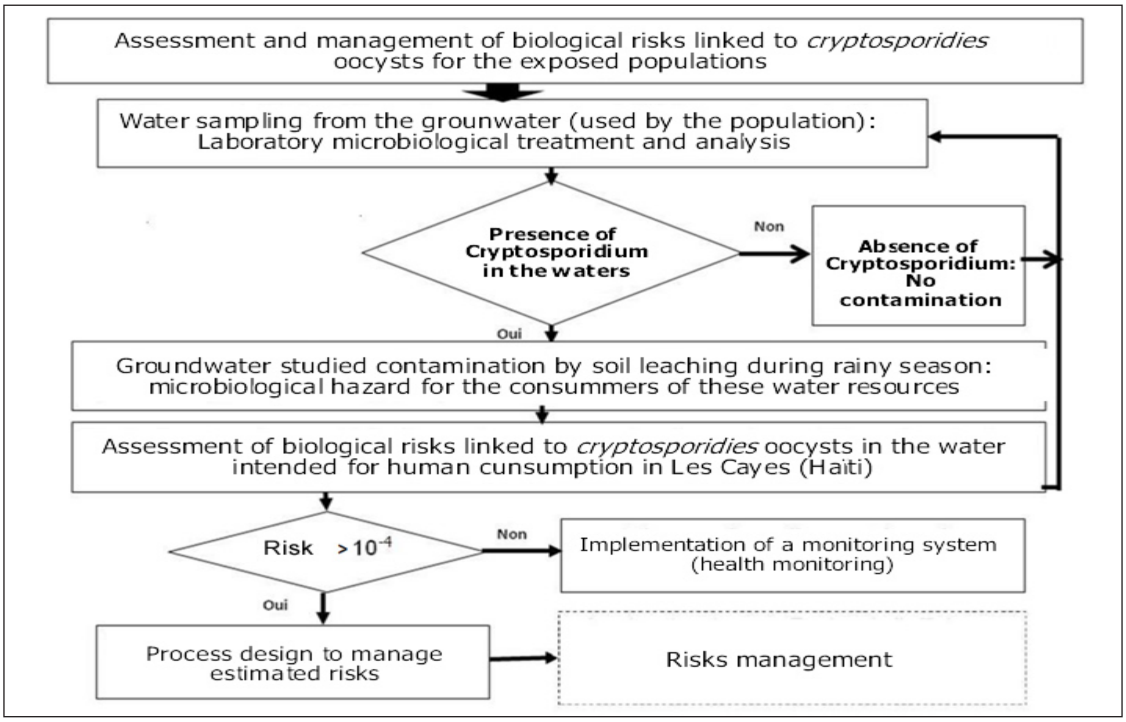

Figure 2. Flowchart developed for the implementation of the biological risk assessment due to the presence of *Cryptosporidium* oocysts

2.3. Identification of danger

For the microbiological risk assessment of *Cryptosporidium* in drinking water, an approach based on the analysis of the numerous factors responsible for potential exposure of Les Cayes groundwater to biological contaminants has been developed. Among these factors : i) cattles wandering freely in the city leading to a permanent and significant spread of their feces laden with bacteria, viruses and other parasites into the groundwater; ii) discharge of urban effluents into rivers without any prior treatment; iii) the existence of latrines and septic tanks equipped with infiltration wells in a high-risk flood area; iv) the disposal of sludge from latrines and septic tanks on the floor of an alluvial formation; v) the existence of illegal landfills in an alluvial formation with unprotected geotextile, with no leachate collection,etc. In this study, *Cryptosporidium* has been identified as the single agent potentially most dangerous for people consuming water from the groundwater of Les Cayes. Indeed, previous studies show the presence of *Cryptosporidium* in these water resources (Balthazard-Accou et al. 2009).

2.3.1. Cryptosporidium

It is an indicator or marker of faecal pollution in water. Infectious diseases are mainly transmitted by human and animal excreta, particularly faeces. Contamination can occur via diseased persons and carriers of germs in the community, who contaminate the water supply with pathogenic microorganisms. The consumption of this water can lead to infection and represents a biological hazard to the exposed population exposed. The presence of oocysts in water is an important risk factor for human health, especially for the most vulnerable groups (Craun et al. 2005; Coupe et al. 2006; Raccurt, 2006).

2.4. Exposure assessment

In the particular context of Haitian cities, where weak urban services contribute significantly to the pollution of groundwater, it seems that health risk assessment (biological and / or chemical) studies, must borrow from the conventional ecological risk assessment the use of the concept of the “conceptual model”. This model could better help appreciate the dual role played by groundwater, namely: (i) the target surface pollution, and (ii) the source of tap water for human consumption. Figure 3 illustrates the conceptual model.

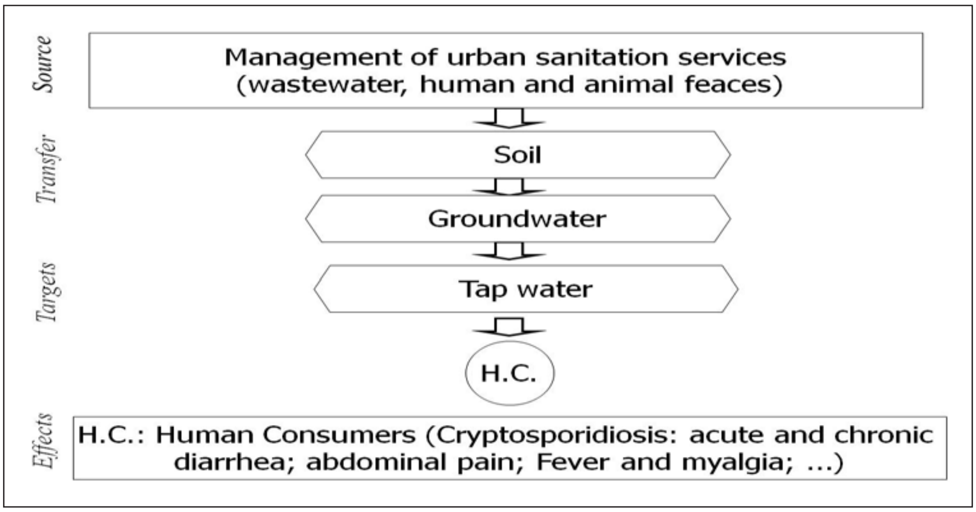

Figure 3. Conceptual model studied

In this study, the term “transfer” is represented by the groundwater. It is therefore chosen to study the impact of “pollution on the surface” on groundwater quality. Not taking into account that surface water does not mean that it is of lesser importance in the contamination of groundwater. We believe that the phenomena of microbiological contamination of groundwater through hydrological mechanisms that govern the interactions between surface water and groundwater will require further studies.

However, exposure assessment also aims to investigate the potential contamination by *Cryptosporidium* oocysts of water from groundwater beneath the site. For this purpose, data on population exposure, routes of exposure, concentrations and the frequency or distribution of *Cryptosporidium* oocysts in space and in time, the duration of exposure, the quantitative estimation of human exposure and also the transport of these oocysts to the groundwater are required (Haas et al. 1999).

3. MATERIALS AND METHODS

Collection of water samples

Between September 2007 and February 2010, a total of five sampling campaigns of water samples were performed, including three rainy seasons in 2007-2009 and two droughts in 2009-2010, specifically between the end of the long rainy season and the beginning of the long dry season. During these campaigns, 25 samples were collected on 5 sampling points (CA03, CA05, CA07, CA09, CA13) used for drinking water. Turbidity, pH, electric conductivity and temperature were performed in situ. Samples for physico-chemical analyses were placed in clean polyethylene bottles. All samples were collected by the instant manual sampling method. The pH was measured using a multimeter HACH HQ40d field case 58258-00. The turbidity of the samples was measured using a 2100P 46500-00 Hach turbidimeter. A multimeter HACH HQ40d field case

58258-00 was used to measure electric conductivity and temperature.

To minimize cross-contamination in the field, new water sampling equipments (bucket, tumbler and funnel) were used at each sample site. A sample of at least 100 L of water was collected and immediately filtered using a polyethersulphone capsule (Environchek, Pall Gelman, Saint Germain en Laye, France). Capsules were stored at 4°C until the elution step.

Purification of Cryptosporidium oocysts

Capsules were processed respectively the method of concentration and counting AFNOR NFT90-455 (AFNOR, 2001). Briefly, capsule filters were rinsed with 240 ml of a detergent elution buffer (phosphate-buffered Saline, pH 7.4 with 0.1% (v/v) Tween 80). Specimens were concentrated by centrifugation at 3500g for 30 min and at a temperature of 4°C. The final sediment was suspended in double-distilled water with a final volume of around 5 ml. Any *Cryptosporidium* oocysts present were then purified using immunomagnetic beads coated with anti-*Cryptosporidium* monoclonal antibody (Dynabeads, Dynal, Norvège) according to the manufacturer's instructions.

Detection and counting of Cryptosporidium oocysts

Twenty microliters of suspension derived from the IMS procedure were placed on a glass slide and dried at room temperature. Slides were fixed in cold acetone (20°C) for 10 min and were then incubated for 30 min at 37°C in a humid chamber with a 1:10 final dilution of a fluorescein isothiocyanate (FITC)-conjugated monoclonal antibody (MAb) directed against a *Cryptosporidium* wall antigen, which was selected because of its lack of cross-reactivity with other microorganisms (FITC-Cow MAb, Monofluokit *Cryptosporidium*, Bio-Rad, Marnes la Coquette, France). Slides were rinsed with PBS (pH 7.4) before applying coverslips. The entire smear of each slide was examined using an epifluorescent microscope (UVexcitation at 490 nm, emission 456 nm; BX41, Olympus) and oocysts were counted. A positive control slide was used to ensure IFA results. The number of oocysts was expressed per 100L of filtered water.

3.1. Risk characterization

3.1.1. Definition of populations exposed by studying the type of exposure identified

The available information on the performance of the public service of water supply does not allow us to exactly define the exposed population. For the purposes of this study, a total population served by the public water supply service and four small family and / or community systems, was estimated through the criteria defined by OPS/OMS and BID (1996) for public water supply in the urban areas of Haiti.

The computation criteria adopted for estimating individuals being served with drinking water in the urban area are (OPS/OMS and BID, 1996) : (i) the number of people served by regular private connection is: ... 14 and, (ii) the number of persons served by public fountain is ... 500. In this study, a coefficient of 14 is applied to 986 connections served by the SNEP, and another one of 500 to the 4 small community water supply systems. In general, the total population considered in this work is 15804 persons exposed (children and adults of both sexes). The main exposure path identified and studied was the consumption of drinking water.

In the general approach of health risk assessment of drinking water, total consumption of 2 liters of water per day for adults and 0.75 liter per day for children is often adopted to calculate the average daily dose (Fawell and Young, 1999). Body weight of 70 kg and 10 kg respectively were attributed to adults and children under 10 years.

In this study, the total exposed population was divided into two major types: immunocompetent and immunocompromised. Each of these types has 2 classes: children 0-14 years and adults 14 years and older. The exposed population is thus distributed as follows:

- immunocompetent children aged under 14;
- immunocompromised children aged under 14 years;
- immunocompetent adults aged 14 years and older;
- immunocompromised adults aged 14 years and older.

Information coming from: (i) the general census of the population and housing for the year 2003, produced by the Haitian Institute of Statistics and Informatics, and (ii) study on the HIV seroprevalence in Haiti for the period 2007-2012 (USAID, 2007), has been used to distribute the 4 target groups on the study site.

For each sampling point, 40% of the population served is represented by children under 14 years, and 60% of the population is aged 14 and over. A total number of 6322 children under 14 years, and 9,482 people of 14 years and over constitute the exposed population. In Table 1, the "Infected population in %", were applied to each point studied in this work. Table 2 shows the distribution numbers of immunocompetent and immunocompromised for each of the age groups considered.

Table 1. Estimate of the immunocompromised population in the Commune of Les Cayes

Site	"Less than 14" population	"14 and more" population	Total	References
Département du Sud	254,940	429,862	684,802	IHSI, 2003
HIV infected population	630	8,272	8,902	USAID, 2007
Infected population in %	0.25	1.92	1.3	
Commune of les Cayes	55,342	82,610	13,7952	IHSI, 2009
Population distribution in %	40	60	100	
Infected population in %	0.25	1.92	1.3	
HIV infected population	138	1,586	1,724	

Table 2. Estimated populations of the sites under study

Site	"Less than 14 years old" population		"14 years old and more" population	
	Immunocompromised	Immunocompetent	Immunocompromised	Immunocompetent
Ca03	1	199	6	294
Ca05	14	5,508	159	8,123
Ca07	1	199	6	294
Ca09	1	199	6	294
Ca13	1	199	6	294
Total	18	6,304	183	9,299

The infected population rate has been maintained to estimate the number of people infected with HIV in the town of Les Cayes. Certain assumptions were made: i) the weight of each of the age groups in the total population has not changed in terms of time (between 2003 and 2009) and spatial (between the various municipalities), ii) the seroprevalence is spread evenly over the entire department.

3.1.2. Biohazard

According to the "Exponential" model (Haas et al. 1999), which assumes independence of action of microorganisms during the initiation phase of an infection, each microorganism has a nonzero chance to cause the infection by itself. The amount of ingested microorganisms does not affect the probability of infection. It all depends on the relationship between the actual number of surviving organisms and the likelihood of colonization of the host. According to this model, the probability P of being infected by the ingestion of a dose of pathogenic agents is expressed mathematically by the following equation:

$$P_{inf} = 1 - \exp(-rD) \quad \text{With } D = \mu.v \qquad \text{Eq.1}$$

This exponential model provides a mathematical description of the infection probabilities distribution.

P_{inf}, represents the probability of infection of an individual exposed to a dose D of microorganisms; V, is the unique volume of fluid consumed;

μ, the number of organisms per liter in volume consumed;

r, the fraction of surviving organisms ingested to cause infection.

This model seems to best describe the dose-response relationship of C. *parvum*.

The dose-response relationship admits the hypothesis of a lack of synergy between the oocysts; this may reflect that the risk associated with the consumption of 1 oocyst all 365 days of the year is exactly equal, by using the exponential dose-response law, to the risk associated with the consumption of, on any given day, 365 oocysts (AFSSA, 2002). To assess the annual risk of infection, it suffices to estimate the number of oocysts ingested by an individual during a year. The risk of a year of exposure is estimated by the expression (Haas et al 1999.):

$$P_{ann} = 1 - \exp(-rD_{365}) \qquad \text{Eq.2}$$

D, average dose of oocysts ingested in 1 day or

$$P_{ann} = 1 - (1 - P_{inf})^{365}$$

D is the total number of oocysts ingested during the year; P_{ann}, represents the probability of infection per year.

At the risk characterization level, we have also made clear the assumptions retained at each stage of the process and we justified them. These are surrounded by uncertainties that lie at the level of the assumptions retained in terms of dispersion of the pathogenic micro-organisms and the exposure of an individual or population, non representative sampling issues, measurement error, inadequate data (use of generic data), spatial variability, temporal and interindividual.

Therefore, one must collect all the uncertainties. This allows for a confidence index in the final result. The Bootstrap method was applied. Also called Bootstrap Simulation, it involves generating repeated data using a re-sampling (Efron and Tibshirani, 1993). The methodology of estimating the uncertainty involves generating subsets of data, based on a random sampling, replacing them gradually as the data are sampled. Thanks to such re-sampling, each data can be shown in an experiment. The model can then be adjusted to each replicate data sets, thereby generating a random sample of the parameter estimates, one for each repetition. These estimates can then be used to establish a confidence interval for the dose-response relationship or to assess the uncertainty for a given dose.

4. RESULTS AND DISCUSSION

4.1. Results of physicochemical analyzes and of Cryptosporidium oocysts in groundwater

The results of the physicochemical and microbiological analyses of groundwater are summarized in Tables 3 and 4.

Table 3. Results obtained during the rainy season 2007-2009

Site	pH	Turbidity (UNT)	Conductivity (µs/cm)	T°C	Number of oocysts/100 L
Ca03	7,41 [7,36 - 7,46]	0,28 [0,27 - 0,28]	340 [315 - 365]	29,25 [28 - 30,25]	3,33 [0 - 10]
Ca05	7,50 [7,50 - 7,51]	0,37 [0,24 - 0,50]	453 [446 - 460]	28,5 [28,4 – 28,6]	6,33 [5 - 9]
Ca07	7,46 [7,42 - 7,50]	0,79 [0,49 - 1,09]	342 [321 - 362]	25,7 [25,0 – 26,3]	1,33 [2 - 2]
Ca09	7,13 [7,13 - 7,13]	0,74 [0,70 - 0,77]	453 [425 - 480]	27,9 [27,8 – 28,0]	34,33 [1 – 100]
Ca13	7,44 [7,42 - 7,45]	0,38 [0,37 - 0,39]	361 [339 - 383]	28,4 [28,0 – 28,5]	9,26 [3 - 23]

Table 4. Results obtained during the dry season 2009-2010

Site	pH	Turbidity (UNT)	Conductivity (µs/cm)	T°C	Number of oocysts/100 L
Ca03	7,58 [7,50 - 7,65]	0,93 [0,53 - 1,33]	337 [330 - 344]	25,7[25,5 - 25,9]	2 [0 - 4]
Ca05	7,45 [7,40 - 7,50]	0,23 [0,22 - 0,23]	258 [251 - 264]	26,2 [25,6 – 26,7]	121,5 [3 - 240]
Ca07	7,53 [7,48 - 7,57]	0,29 [0,20 - 0,38]	338,5 [338 - 339]	25,05[24,7 – 25,4]	506,5 [24 - 989]
Ca09	7,30 [7,29 - 7,32]	1,15 [0,59 - 1,71]	258,5 [257 - 260]	26,7 [25,6 – 27,8]	0 [0 – 0]
Ca13	7,49 [7,46 - 7,52]	0,26 [0,14 - 0,38]	314,0 [310 - 318]	25,8 [25,5 – 26,1]	18 [0 - 36]

During the rainy and dry seasons the pH values measured on the sites show an average around 7.13 to 7.65, indicating that the drilling water has a slightly basic trend. All results recorded for this parameter are included within the ranges proposed by OMS (1994) for drinking water. Similarly, the conductivity values vary from 257 to 480 $\mu S.cm^{-1}$. Some are greater than the threshold value (400 $\mu S.cm^{-1}$) for the conductivity of the water intended for human consumption (Sigg et al., 2000).

The values for turbidity are in the range of the intervals found in the literature (Lechevalier et al 1991b; Di Giorgio et al 2002; Simmons et al 2001). From one sample to another, the measured values present a variation from 0.14 to 1.71 NTU. The maximum values obtained are above the threshold value of 1 NTU imposed by international guidelines (USEPA, 1999). It seems that high levels of turbidity (more than 1 NTU) and rapid changes in this parameter (from 0.5 NTU in a few hours) are indications of a possible contamination of groundwater by these microorganisms. A similar relationship was highlighted by Laing (2002) and reminds a value of 0.3 NTU should not be exceeded; otherwise the risk associated with the presence of oocysts is more important.

The numbers of oocysts detected during the dry and rainy seasons of the years 2007-2010 for the five sites selected for drinking water from the groundwater are shown in Tables 3 and 4. The lowest concentrations were recorded during the months of August - September, which is the period of the rainy season (Table 3). Other concentrations, the highest in oocysts, were recorded during the months of December to February, which is the (Table 4). Peak oocyst concentrations were observed for both seasons. In the absence of epidemiological data on the prevalence of cryptosporidiosis in Les

Cayes during the 2 seasons, it should be interesting in the future to correlate the infections caused by *Cryptosporidium* at the city level with the seasonal concentrations of oocysts detected in drinking water. Newman (1994) reported the observation of cases of cryptosporidioses in tropical developing regions during the hot and humid season.

The information provided in Tables 3 and 4 allows to hold a number of oocysts between 0 and 989 in the samples studied. With reference to the flow chart developed for the implementation of the biological risk assessment, especially in the phase on the number of oocysts in water used for human consumption, the need to move to the estimation of biological risks to the consumer health becomes important in order to complete this study.

4.2. Characterization of Risks for human health

Table 5 shows the concentration of oocysts in the different sites and the number *of oocysts found in 1 liter of water consumed*

Table 5. Concentration of oocysts measured from the different sites and the number of oocysts per liter of water consumed

Site	Sep 2007 (P)		Aug 2008 (P)		Aug 2009 (P)		Dec 2009 (S)		Fev 2010 (S)	
	C_i	C_f	C_i	C_f	C_i	C_f	C_i	C_f	C_i	C_f
Ca03	0	0	10	0,04	0	0	4	0,016	0	0
Ca05	9	0,036	5	0,02	5	0,02	3	0,012	240	0,96
Ca07	0	0	2	0,008	2	0,008	989	3,956	24	0,096
Ca09	100	0,4	2	0,008	1	0,004	0	0	0	0
Ca13	23	0,092	3	0,012	3	0,0112	36	0,114	0	0

Ci : Concentration of oocysts (/100 L) in the different sites; P: Rainy
Cf : Concentration of oocysts found in 1 liter of water consumed; S: Dry

The method (AFNOR T90-455-NF) advocating the immunofluorescence technique was used for the identification of *Cryptosporidium*. However, it is reported in the literature that there is uncertainty in relation to the method (Drozd, 1996). In order to make the results more viable, AFSSA (2002) estimates the yield of the analysis of oocysts at 40% for distribution water. As part of this study, this yield was applied to estimate the number of oocysts in 100 liters of water, with the assumption that all are viable and potentially infectious. Table 6 shows the yields for the analysis and the number of oocysts per liter of water consumed.

For different classes of the population, the average probability for daily and annual infections was estimated from information reported in the literature on the infectious dose of cryptosporidiosis (DuPont et al., 1995; AFSSA, 2002; Pouillot et al., 2004). Eq.1 and Eq.2 equations were used to calculate the average probability for daily and annual infection.

The main results for the immunocompetent population of 14 years and over are summarized in Table 6.

Table 6. Probability of infection and number of expected diseases cases for immunocompetent and Immunocompromised Population 14 years and over

	Immunocompetent				Immunocompromised			
	Individual infection probability		Population and expected diseases cases		Individual infection probability		Population and expected diseases cases	
Site	Daily	Annual	Population	Diseases cases	Daily	Annual	Population	Diseases cases
Ca03	0,0009	0,03	294	4	0,008	0,94	6	6
Ca05	0,002	0,48	8123	1560	0,11	1	159	159
Ca07	0,006	0,9	294	106	0,19	1	6	6
Ca09	0,006	0,2	294	24	0,05	1	6	6
Ca13	0,004	0,13	294	15	0,03	1	6	6

The portion of the *immunocompetent population aged 14 years and over* consuming water from the site CA03 is exposed to a daily infection probability of 0.0009 and an annual infection probability estimated at 0.03. The site CA05 for its part has an average probability of daily infection of 0.002 while the average probability for annual infection was estimated to be 0.48. As for the CA07, with an average probability of daily infection estimated at 0.006, the average probability of infection over a year is at 0.9. However, the probability of infection for site CA09 was 0.006 and it was estimated to be at 0.2 on an annual basis. The estimate of the probability of infection related to the contamination of water intended for human consumption by *Cryptosporidium* oocysts for site CA13 showed it is approaching 0.004 and while it amounts to 0.13 on an annual basis.

In Table 6, are summarized the main results for *the immunocompromised population 14 years old and over*. For the age group referred to above, immunocompromised and consuming water from the site CA03, the daily probability was 0.008 while it was 0.94 on an annual basis. These values are respectively measured at 0.11 and 1 (that is to say 100%) for the site CA05. They are, in the same order, estimated at 0.19% and at 100% in the site CA07, at 0.05 and at 1 on the site CA09. Substantially following the trend, the probability of infection related to contamination of water intended for human consumption by *Cryptosporidium* oocysts for site CA13 were respectively 0.03 and 1.

Table 7. Probability of infection and number of expected diseases cases for immunocompetent and Immunocompromised Population under 14 years

	Immunocompetent				Immunocompromised			
	Individual infection probability		Population and expected diseases cases		Individual infection probability		Population and expected diseases cases	
Site	Daily	Annual	Population	Diseases cases	Daily	Annual	Population	Diseases cases
Ca03	0,0003	0,001	199	0	0,08	0,95	1	1
Ca05	0,0007	0,21	5508	463	0,05	1	14	14
Ca07	0,002	0,59	199	47	0,14	1	1	1
Ca09	0,002	0,08	199	6	0,02	1	1	1
Ca13	0,001	0,05	199	4	0,01	0,98	1	1

The results for the immunocompromised population of 0-14 years are much higher than those obtained for the immunocompetent population**.** To illustrate, the immunocompromised population is exposed to a daily infection of 0.01 to 0.14 and an average probability of annual infection of 0.95 to 1 from the different sites.

The results from the estimates of the probabilities of infection for the immunocompromised populations categories are comparable between the different sites and much larger than those estimated for the immunocompetent populations. The average probability of infection over a year for some sites is between 0.95 and 1, that is to say, the exposed populations had 95 to 100% of a chance of being infected. Information showed in Table on immunocompetent or immunocompromised population aged less than 14 years, that health impacts reported to the population level are important.

The results presented in the previous paragraphs provide a first quantitative data on the risk of cryptosporidiosis in the population of Les Cayes. However, certain limits must be made, both on the analytic and the methodology level. Only five sampling campaigns have been conducted. This number is low and less than the number of recommended actions in order to obtain an estimate of the distribution of contamination (AFSSA, 2002). Since, estimations of the number of expected cases were made by using a strong assumption that all detected oocysts are viable, the result can have uncertainties in the estimations of the expected cases number. These conditions could lead to an underestimation or overestimation of the risk. Only an epidemiological survey in the population could allow to validate these first results.

4.4. Risk management of contaminated water from Les Cayes groundwater

In Haiti, the groundwater is contaminated by human and animal waste, therefore processing techniques must be developed for removal of *Cryptosporidium* of, at least, 3 log (99.9%). With such treatment, a concentration of 13 oocysts/100L of water from a source of water can be reduced to 1.3×10^{-2} oocysts/100L. This ability to reduce the contamination, that is the reduction of 3 log used, will provide drinking water, with an acceptable risk of infection for the general population. A significant benefit can be expected with a reduction of 2 log. For example, let's assume that the average annual dose ingested by a population of 5,200 inhabitants is 10^2 oocysts, using the risk estimation model described above, the number of cryptosporidiosis cases/year will be equal to 1,268 patients. With the installation of a small unit of water treatment with a reduction capacity of 2 log contamination, the number of cryptosporidiosis cases / year will be reduced to 20 patients.

The estimated impacts and the risks calculated in the framework of this thesis lead not only to highlight the relevance of prevention, but also of the need for medical care, the conduct of an epidemiological study and the implementation of microbiological monitoring of water resources feeding the population. It is particularly important to take these preventive and adapted measures in order to improve the health of people in the city of Les Cayes.

5. CONCLUSION

The approach developed to investigate the microbiological contamination by *Cryptosporidium* of the groundwater in the city of Les Cayes, and the risk assessment for consumers leads to a quantitative assessment of the risks of infection. It should be improved in relation to deeper soil analyzes enabling the study of the absorption kinetics and the hydrodynamic mechanisms of transfer of *Cryptosporidium* oocysts in groundwater. Moreover, the estimation of an average and its accuracy depending on the number of observations is a well-known statistical problem. The highly asymmetric and widely dispersed distribution of the contamination of a resource involves a large number of observations which are required for a good estimate of the average. It will then be necessary to carry out the verification of these first results and to couple them by measuring other indicators of fecal pollution of waters such as fecal coliforms and enterococci, other parasites (*Giardia* and helminthes) and the enteroviruses.

In the specific case of groundwater in the city of Les Cayes, it would be interesting to study, the efficiency of adsorption in zeolites oocysts. Indeed, zeolites are excellent ion exchangers their application in the treatment process of water contaminated with oocysts can probably reach a retention level higher than 91%.

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RECONSTRUCTING EXTREME RAINFALL FIELDS IN HAITI

RECONSTRUIRE DES CHAMPS DE PLUIE EXTREME EN HAÏTI

RECONSTRUCCIÓN HISTÓRICA DE LOS CAMPOS DE LLUVIA EN HAITÍ

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Abstract

A description of the main objectives of urban drainage works in the environmental and hydraulic aspects is presented. It is mentioned the corrective actions related to the optimal operation of a rainwater management system, as well as the importance of having the intensity-duration and frequency curves for the design of works and hydraulic utilization. Employ 24-hour maximum rainfall data from 43 climatological stations, satellite images and in particular from nine stations with extensive records from 1997 to 2003, the intensity-duration and return period curves are calculated. Using the formulations proposed by Sherman and Bell, maps of intensities are created for periods of return of 10, 25 and 50 years; Taking into account durations of 10, 30, 60, 120 and 240 minutes. The results of this work present a collection of maps that allow knowing the spatial distribution of precipitation intensities throughout the country, which can be used in the design of works and in the reconstruction of the country's infrastructure.
Key words: Intensity-duration and return period curves; satellite images, precipitation intensity.

Résumé

Ce document montre une description des principaux objectifs qui ont des travaux de drainage urbain dans les aspects environnementaux et hydrauliques. Nous commentons les mesures correctives liées à l'exploitation optimale d'un système de gestion des eaux pluviales a également l'importance qu'elle représente ont des courbes intensité-durée et période de retour (IDF) pour les travaux de assainissement et des ouvrages hydrauliques. En utilisant l'information de précipitation maximale dans les 24 heures à partir de 43 stations météorologiques, Image satellite et en particulaire neuf stations météo avec des donnes depuis 1997 à 2003, les courbes d'intensité-durée et période de retour on a été calculés. En utilisant les formulations proposées par Sherman et Bell on a cartographié (cartes IDF) des camps de pluie pour des périodes de 10, 25 et 50 années et pour les durées de 10, 30, 60, 120 et 240 minutes. Les résultats de cette étude montrent une collection de cartes qui offrent un aperçu de la cartographie spatiale des intensités des précipitations en Haïti, qui peut être utilisé dans le travail d'évaluation des ouvrages hydrauliques et de reconstruction des infrastructures.
Mots clé: Courbes intensité-durée et période de retour ; Image satellite ; intensités des précipitations.

Resumen

Se presentan una descripción de los principales objetivos que tienen las obras de drenaje urbano en el aspecto ambiental e hidráulico. Se comenta sobre las acciones correctivas relacionadas con la operación óptima de un sistema de manejo de aguas pluviales, asimismo se menciona la importancia que representa contar con las curvas de intensidad-duración y periodo de retorno para el diseño de obras y de aprovechamientos hidráulicos. Empleando información de lluvia máxima en 24 horas proveniente de 43 estaciones climatológicas, imágenes de satélite y en particular de nueve estaciones con registros extensos de 1997 a 2003, se calculan las curvas de intensidad-duración y periodo de retorno. Utilizando las formulaciones propuestas por Sherman y Bell se crean mapas de intensidades para periodos de retorno de 10, 25 y 50 años; tomando en cuenta duraciones de 10, 30, 60, 120 y 240 minutos. Los resultados de este trabajo presentan una colección de mapas que permiten conocer la distribución espacial de las intensidades de precipitación a lo largo del país, los cuales pueden ser empleados en el diseño de obras y en la reconstrucción de infraestructura del país.
Palabras claves: Curvas de intensidad-duración y periodo de retorno; imágenes de satélite, intensidad de precipitación.

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INTRODUCCIÓN

One of the most important and important projects in the work of a civil engineer is undoubtedly the elaboration of a Master Plan Rector of Urban Drainage. If we understand the urban drainage as the set of works built to dislodge rainwater and industrial and domestic waste, it would be necessary, especially in these times, to add the component of respect for the environment. In photograph 1, it can be observed the negative impact created by inadequate management of rainwater in urban areas, both in the environmental and hydraulic aspects. It can be said that an urban drainage system is built to achieve three fundamental objectives: (i) to avoid to the maximum the possible damages that the pluvial and domestic waters can cause to the people and their goods; (ii) guarantee the normal development of people's daily lives and traffic of vehicles during the occurrence of rainfall; and (iii) To evacuate in an economical and ecological way the surplus waters of an urban zone. These objectives are related to specific actions that are systematically carried out for the optimal operation of an urban drainage system. These actions can be of the preventive or corrective type. *Corrective actions* in the strictest sense are considered all actions that involve the construction or modification of a hydraulic work; among the most common can be mentioned the construction of dam dissipating works of canalization/ rectification, works of regulation/temporary reservoir, settlers, culverts and conduits in general. *Preventive actions* include conservation of tributary watersheds, territorial planning, acquisition of priority areas for conservation (one of the tasks proposed by the *Action Plan for National Recovery and Development of Haiti* in 2010 in the metropolitan area of the city of Puerto Principe, Haiti), regulation and regulation in the use of land routes and of course all actions of information and education to citizens. In all these actions a fundamental concept is implicit that we must not forget those who plan, design or construct hydraulic works; and is the concept of "degree of protection". That is, to define the acceptable level of risk of occurrence of damages or discomfort resulting from the management of rainwater and domestic waters of a city. The degrees of protection will always be associated with the first two objectives mentioned above; being the protection of people and property the main. This degree of protection is translated, for example in the case of floods, in the definition of the level of maximum permitted waters, before the impact of people, goods and road infrastructure (Planos, 2013). Likewise, this maximum permissible water level or height must be related to a probability of occurrence or to a value expressed in years that is commonly known as the return period (the probability of occurrence is the inverse of the return period).This leads us to define for each of the hydraulic works, a design event associated to a critical probability of occurrence from which, the considered event would begin to cause damages. Since the return period is defined as the average time elapsed for a certain phenomenon to recur within a time series of events recorded annually (for example, annual maximum runoff in some river or annual maximum rainfall recorded within a hydrological basin).

Image 1. Environmental impact that generates in an urban area a channel of discharge of rainwater combined with black waters, Prince Port, Haiti. (Photographer: Alfonso Gutiérrez 2005)

METHODOLOGY

To characterize a rainy event it is used to detail its behavior defining what is known as: “the regime of an event”; That is, the magnitude and frequency of a hydrometeorological phenomenon (in this case precipitation).In this way the magnitude of a storm is defined by its intensity (i) and its frequency will be defined by its probability of occurrence or period of return (Tr).The mathematical construction of this relation was presented by Sherman, in 1931 and modified by Bernard, in 1932; Is an equation of the type:

$$i = \frac{k \cdot T_r^{\,m}}{d^n}$$

where:

i	is the intensity of precipitation, in mm/h
T_r	is the period of return of the event, in years
d	is the duration of the storm, in minutes
k, m, n	are coefficients that are determined by a regression analysis

It is important to note that the intensity and duration of a storm are inversely related and that “m” is a dimensionless parameter that is constant and independent of duration. The characterization of a region is given by the parameters that define this equation. The curve obtained by plotting this equation for different return periods is referred to as intensity-duration-frequency (IDF) curves. The data used to construct these IDF curves come from pluviograph records. However, in many countries of Latin-American and the Caribbean information is not always available for precipitation records to allow the development of such curves. In Mexico, as in other countries, this type of rain-gage is scarce and there are few studies that use these registers (Campos and Gómez, 1990, Campos, 2010).At present Satellite Images, there is an alternative for the estimation of these curves.

The rainfall records that are obtained from conventional stations, which have on average records from 1997 to 2003. The relationship of stations is shown in Table 1. Table 2 shows the precipitation intensities for different storm durations and various return periods; the reference values correspond to Damien station located in the urban area of Puerto Principe (Gutierrez-Lopez and Olvera, 2011). Their parameters k, m and n were obtained by means of a cross-correlation between stations, in addition to comparing the values obtained, with those presented by the Analyse Géotechnique, *Hydrologique et Hydraulique de la Clinique de Soins D’urgence à Delmas 40b, Port-Au-Prince developed for the reconstruction of houses in Haiti* (Mora et al., 2012)

A hydrological model based in satellite images calibrated their parameters k, m and n. These type of models are used for resolutions of latitudes and longitudes of approximately 0.5° as well as to parameterize physical atmospheric processes. They are able to simulate regional climate characteristics, such as orographic precipitation (Frei *et a*l., 2003), extreme events (Fowler *et al*., 2005; Frei *et al*., 2006) and regional or climatic anomalies, Such as those associated with the El Niño southeastern oscillation (Leung *et al*., 2003). However, the model’s abilities depend heavily on the presence and influence of regional phenomena such as orography and vegetation cover. Studies in the western United States, China, Europe and New Zealand, where the effects of topography on temperature and precipitation are strong, have always been reported acceptable and consistent results with values of precipitation intensities obtained from images of Satellite and regional meteorological models (Wang *et al*., 2004).

Recent research highlights the use of remote sensing systems and the access to the public of different databases for the development of early warning systems, such as; Flood risk maps in tropical areas and prone to both material and human damage and/or loss in the tropics. Bozza *et al*. (2016) use such tools for the Quinte River near Gonaïves Haiti.

Rainfall estimation using satellite imagery is mainly based on the use of data from IR spectrum images as well as on passive microwave radiation values. These techniques that interpret the IR images additionally require complementary empirical methods that infer quantitatively the rainfall, such methods start from the supposition that the clouds with deep convection can generate precipitation.

The most used Methodologies around the world are listed below:

- Arkin’s technique (Arkin, 1979)
- The GPI index of GOES precipitation (Arkin and Meisner, 1987)
- The GWT Griffith-Woodley technique (Griffith *et al*., 1978)
- The NAWT Negri-Adler-Woodley technique (Negri *et al*., 1984)
- The convective-stratiform technique (Adler and Negri, 1988)
- The PERSIANN artificial neural network technique (Hsu *et al*., 1997)

In general, it can be said that the estimation of precipitation by satellite images is based on the clear relation that keeps the temperature of the cloud formations with the place, time and intensity of the storms.In addition, there is a practically linear relationship between the brightness of the clouds and their temperature. Vicente *et al*., 1998 have proposed to estimate rainfall through IR satellite images in the band 10.7 μm (channel 4), from the GOES-8 and GOES-9 satellites, in particular for events related to the summer season and deep convection. This is a potential adjustment between instantaneous rain estimates made by surface radars and temperatures at the top of the clouds obtained by satellite, both for equal time and space (the authors worked with data from May to June 1995 for the central zone Of the Great Plains, USA). The expression is as follows:

$$I=1.1183 \times 10^{11} e^{(-0.036382\ T^{1.2})}$$

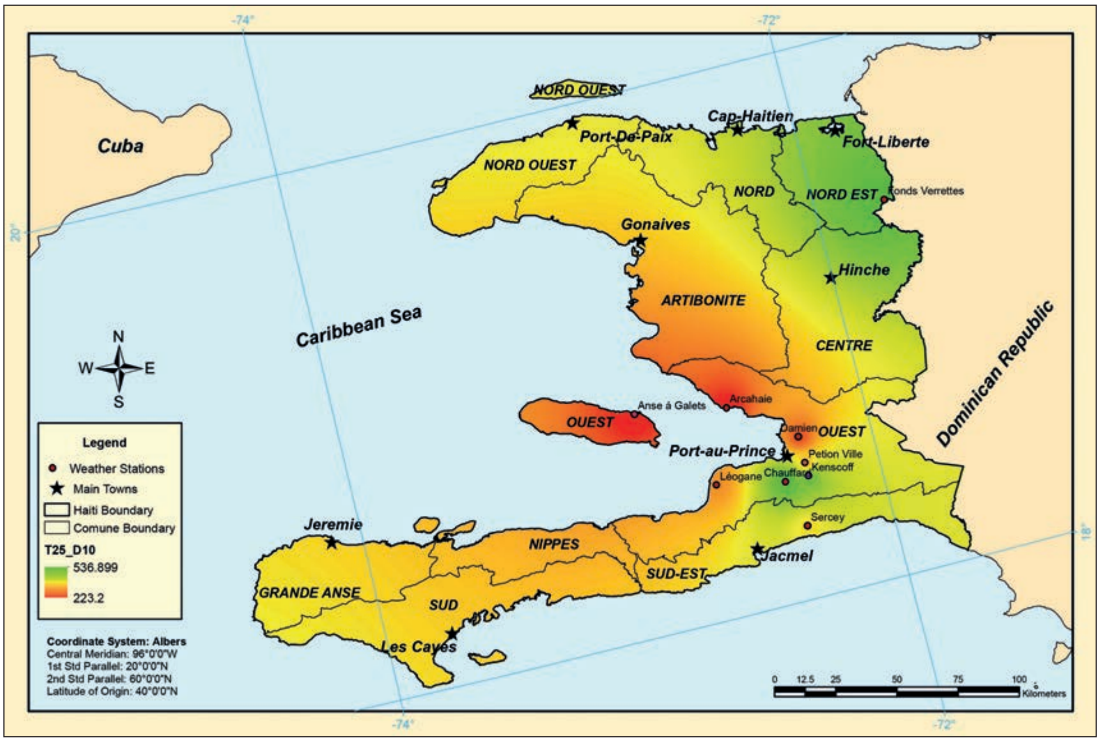
where I is the intensity of precipitation, in mm/h and T is the temperature at the top of the clouds, in °K (degrees Kelvin), for the range 195 <T < 260 °K. For a better estimation, the above equation is corrected by factors such as humidity, cloud growth and gradient temperature. The moisture correction is related to the amount of precipitable water, Pw (in inches) and relative humidity, Hr (as fraction), whose product is indicative of a dry or wet environment depending on whether the result is less or greater than one, respectively. Such correction is applied to the adjustment equation as follows (Vicente *et al.*, 1998):

a. If T > 210 °K and Pw Hr <1.0, it means that the ambient humidity is low and, in such case, the intensity R must be multiplied by the factor Pw Hr; otherwise, the calculated value is left unchanged.
b. If T <200 °K, the precipitation rate should be limited to 72 mm/h, which is the maximum intensity observed in the study area (central area of the EU), for a resolution with 4 km pixels per side. It is important to identify the maximum rainfall recorded in each of the meteorological stations in some Latin American and Caribbean countries and to be able to establish this limit.

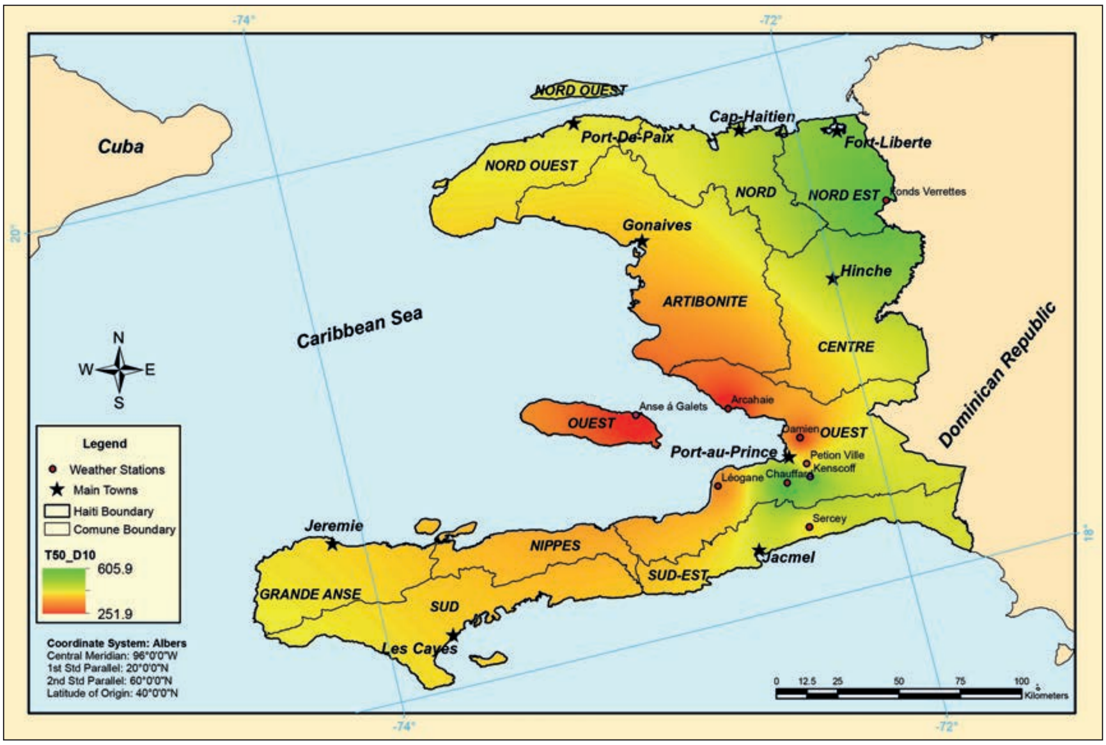
Once the parameters k, m and n of the intensity Shermann´s equation are obtained, it is possible to construct the IDF maps, as shown in figure 1. In this figure we can observe the maps for different probabilities of occurrence, and in table 2 data from 10 to 50 years of return period. Recent studies have shown that these equations must be corrected by geographic position and topographic relief for greater accuracy in the estimation of design events (Olvera, 2012). The practical way of using these IDF curves or characteristic equations of storms is associated, as already mentioned, to the degree of protection of a works or to define the acceptable level of risk of occurrence of damages that can cause an extreme hydrometeorological event on a hydraulics work.

Table 1. Rain gage stations used in the study

Number	Station	Latitude	Longitude
1	Anse á Galets	18.83	-72.87
2	Arcahaie	18.77	-72.52
3	Damien	18.60	-72.28
4	Léogane	18.50	-72.63
5	Sercey	18.27	-72.33
6	Petion Ville	18.50	-72.28
7	Chauffard	18.45	-72.37
8	Kenscoff	18.45	-72.28
9	Fondsverrettes	19.37	-71.73



(a)



(b)

Figure 1. Precipitation intensity-duration-frequency (IDF) map for 10 minutes duration of rainfall and 25 years (a); 50 years (b) return period

Table 2. Intensity-duration and return period curves for Haití (mm/h)

Station	Latitude	Longitude	Alt	T10D10	T10D30	T10D60	T10D120	T10D240	T25D10
Anse á Galets	18.83	-72.87	5	185.9	102.8	67.5	43.3	27.4	223.9
Arcahaie	18.77	-72.52	10	185.3	102.5	67.3	43.2	27.3	223.2
Damien	18.60	-72.28	18	213.5	118.1	77.5	49.7	31.4	257.2
Léogane	18.50	-72.63	18	257.4	142.4	93.5	60.0	37.9	310.1
Sercey	18.27	-72.33	430	297.1	164.3	107.9	69.2	43.7	357.9
Petion Ville	18.50	-72.28	390	276.9	153.1	100.5	64.5	40.7	333.6
Chauffard	18.45	-72.37	1300	445.7	246.5	161.8	103.9	65.6	536.9
Kenscoff	18.45	-72.28	1400	410.9	227.3	149.2	95.8	60.5	495.0
FondsVerrettes	19.37	-71.73	560	442.9	245.0	160.8	103.2	65.2	533.6

Station	T25D30	T25D60	T25D120	T25D240	T50D10	T50D30	T50D60	T50D120	T50D240
Anse á Galets	123.9	81.3	52.2	33.0	252.7	139.8	91.8	58.9	37.2
Arcahaie	123.5	81.1	52.0	32.8	251.9	139.4	91.5	58.7	37.1
Damien	142.3	93.4	59.9	37.8	290.2	160.5	105.4	67.6	42.7
Léogane	171.5	112.6	72.3	45.6	349.9	193.6	127.1	81.6	51.5
Sercey	198.0	130.0	83.4	52.7	404.0	223.5	146.7	94.2	59.4
Petion Ville	184.5	121.1	77.7	49.1	376.5	208.2	136.7	87.7	55.4
Chauffard	297.0	195.0	125.1	79.0	606.0	335.2	220.1	141.2	89.2
Kenscoff	273.8	179.8	115.4	72.8	558.7	309.0	202.9	130.2	82.2
FondsVerrettes	295.2	193.8	124.4	78.5	602.2	333.1	218.7	140.4	88.6

Alt= = altitude in meters
T= duration in minutes
D= return period in years

RESULTS AND DISCUSSION

The use of satellite images in this study was of great importance because of the scarce precipitation data available in Haiti, it was necessary to estimate some events through the technique of the hydroestimator. Once you have the values of the parameters of the Shermann equation, you can create the IDF maps. These curves or maps can be used as a reference for the design of hydraulic work. In this aspect of design it is important to mention that each country, state and also municipality has, in some cases, its own specifications regarding the regulations of design of hydraulic works, for example, for the state of Querétaro, la *Comisión Estatal de Aguas* (CEA) selects the return periods associated with different levels of risk and expected life of the works it builds. Although for practical purposes and considering that a large part of the storm drainage system of the small towns is carried out by surface, the CEA establishes as a period of return for the analysis and design of its pluvial works of water supply and conduction a Tr = 10 years and for head-works Tr = 25 to 50 years (CEA, 2011). This means that using figure 1a or the values quoted; For example, a storm drainage work associated with a storm duration of 30 minutes and a return period of 25 years should be designed (or revised) with a precipitation intensity of approximately 142.3.7 mm/h (also obtained from the Table 2). Some other important values that we must keep in mind are for example 25 to 100 years for the design of road bridges (depending on the population); From 500 to 1000 years for channeling works in rivers in large populations and from 50 to 100 years for diversion dams in large areas of agricultural irrigation. Now it is interesting now to ask what magnitudes have been presented in our state and in Puerto Principe metropolitan area in recent years. To mention some interesting data last year, several important extreme events were monitoring since 2014 for www.redciaq.uaq.mx using a *Hidroestimador* presented for analysis (figure 2). For example on August 2013, where the storm began in Dominic Republic area at 15h00 GMT, it became widespread throughout the island at 15h30 GMT, and finished at 21h20 GMT. In this event, a maximum intensity of 85 mm/h(in one hour) was estimated in the Damien and Chauffard station cover area. If we look at table 2, we can conclude that this maximum intensity event is associated with a return period of just over 20 years. Also, during that event the maximum estimated rainfall high was 121 mm in 40 minutes. In this way we can only wonder if our hydraulic works in urban areas are designed for this type of events or we must review them. Finally, it should be mentioned that in recent years precipitation intensities have increased in Haiti as a result of climate change, so for the next rainy season it is recommended to monitor the evolution of the storms.

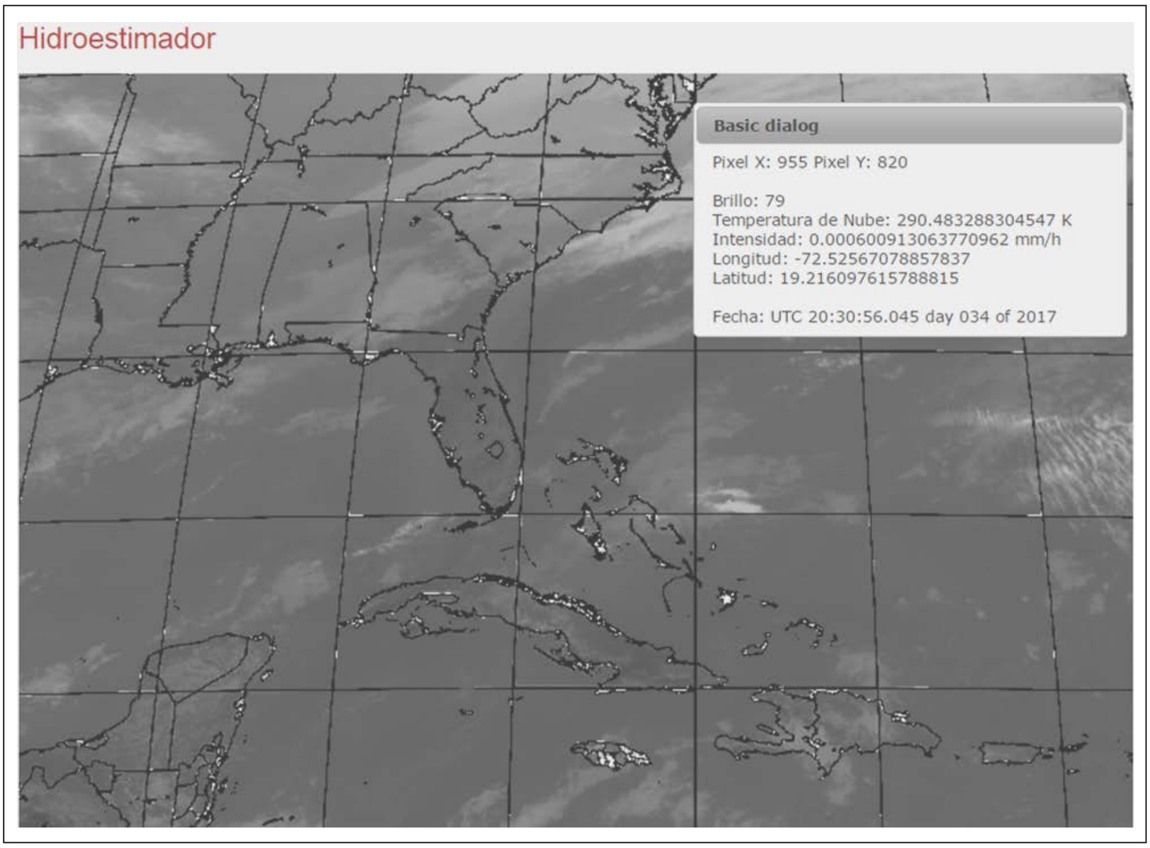


Figure 2. Screen view oh hidro-informatic tool called *Hidroestimador* in www.redciaq.uaq.mx

CONCLUSIONS

The historical reconstruction of the rainfields in Haiti was successful. The few rainfall data that were available were the basis for knowing the maximum rainfall in 24 hours, however, it was necessary to use the technique of the hydroestimator that consists of using satellite images to determine the temperature of the clouds and this way to find the intensity of precipitation. Some estimations of intensities were realized with the use of these satellite images to obtain the instantaneous intensities; from them the parameters m and n of the Shermann formula were obtained and in this way supplement the daily rainfall records to obtain as shown in Figure 1 and Table 2 different values associated to different storm durations and return periods. These maps now allow us to use them for the design of hydraulic works in Haiti. They also allow to know intensities of short duration which could not be obtained from daily records; That is to say the frequency of the satellite images that are taken every 15 minutes allows to obtain events for short duration and therefore to construct reliable IDF curves.

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WATER RESOURCES' RESPONSE TO CLIMATE CHANGE IN THE TROU DU NORD WATERSHED, HAITI

RÉPONSE DES RESSOURCES EN EAU AU CHANGEMENT CLIMATIQUE DANS LE BASSIN VERSANT DE TROU DU NORD, HAÏTI

RESPUESTA DE LOS RECURSOS HÍDRICOS AL CAMBIO CLIMÁTICO EN LA CUENCA DEL TROU DU NORD, HAITI

Shimelis Setegn[1] and Maria Concepcion Donoso[2]

Abstract

Haiti experiences pervasive land, water and environmental degradation due to local and global changes and climatic anomalies. The lack of decision support tools and limitation of data concerning weather, hydrological, topographic, soil and land use are factors that significantly hinder research and development. Appropriate decision support tools are needed for better assessment of the hydrological processes for planning governance and management of land and water resources. The tools concern various hydrological, soil erosion and hydrodynamic models as well as geographical information system (GIS). The modeling tools will finally assist to make appropriate planning and timely decision which will ultimately help to save the physical quality of the land and water resources. The objective of this study was to assess the influence of topography, soil, land use and climatic variability on the hydrological processes of the Trou du Nord watershed. The main tasks performed in this study includes development of physically based Soil and Water Assessment Tool (SWAT) model, water balance analysis of the Trou du Nord watershed, and analysis of climate change impact on the hydrology of the watershed. The output of different general circulation models (GCM) indicated that there is an increase in temperature and reduction in precipitation in the Trou du Nord watershed. The temperature is predicted to increases up to 2.7 ^{o}C for the A2 high emission scenario for the period 2071 - 2100. The precipitation also is expected to reduce up to 25% for the A2 high emission scenario for the period 2071 – 2100. The water yield of the watershed is anticipated to decrease due to increase in temperature and reduction in precipitation under many of the scenarios tested in the watershed. The study indicated that climate change would have a significant impact on the future water availability of the watershed.
Keywords: Hydrology, modeling, climate change, SWAT, Trou du Nord, Haiti

Résumé

L'Haïti est exposé a des processus de dégradation des sols, de l'eau et de l'environnement en raison de changements locaux et globaux et les anomalies climatiques. Le manque d'instruments pour la prise de décision, ainsi que la limitation des données sur le climat, l'hydrologie, la topographie, les sols et l'utilisation des terres sont des facteurs qui restreignent la recherche et le développement. Afin d'améliorer la prise en compte des processus hydrologiques dans la planification et la gestion des ressources en eau et de la terre, il est nécessaire de disposer d'instruments adéquats pour appuyer la prise des décisions. Ces instruments sont constitués de plusieurs modèles hydrologiques, hydrodynamiques et de l'érosion des sols. ainsi que des systèmes d'information géographique (SIG). Les modèles sont destinés à aider une bonne planification et décision en temps opportun pour assister à préserver la qualité physique des ressources terrestres et aquatiques. Le but de cette étude est d'évaluer l'influence de la topographie, le sol, l'utilisation des terres et de la variabilité climatique sur les processus hydrologiques qui se produisent dans le bassin de la rivière Trou du Nord. Les actions entreprises dans cette étude comprennent un modèle SWAT sur la base des conditions physiques, l'analyse de la disponibilité de l'eau du bassin du Trou du Nord et de l'analyse de l'impact des changements du climat dans le bassin. Les résultats des différents modèles de circulation générale (GCM) indiquent l'augmentation de la température atmosphérique et la diminution des précipitations dans le bassin de Trou du Nord. Il est prévu l'augmentation de la température jusqu'à 2.7^{o}C pour le scénario d'émission élevé connu comme A2 pour la période 2071 - 2100. Il est également prévu que les précipitations vont se réduire 25% pour le scénario A2 au cours de la période 2071-2100. Il est prévu que la disponibilité de l'eau dans le bassin va diminuer en raison de l'augmentation de la température et réduction des précipitations dans les conditions de la plupart des scénarios analysés dans le bassin. L'étude indique que les changements climatiques peuvent avoir un impact significatif sur la disponibilité de l'eau dans le bassin.
Mots-clés: Hydrologie, modélisation numérique, changement climatique, SWAT, Trou du Nord, Haïti.

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Resumen

Haití experimenta procesos de degradación de la tierra, el agua y el medio ambiente debido a cambios locales y globales y a anomalías climáticas. La falta de herramientas para la toma de decisiones, así como la limitación de datos relativos al clima, la hidrología, la topografía, los suelos y el uso de la tierra son factores que obstaculizan la investigación y el desarrollo. A fin de mejorar la consideración de los procesos hidrológicos en la planificación y la gestión de los recursos hídricos y territoriales se requiere poseer herramientas adecuadas de apoyo a la toma de decisiones. Estas herramientas contemplan varios modelos hidrológicos, hidrodinámicos y de erosión del suelo, así como sistemas de información geográfica (SIG). Los modelos tienen la finalidad de asistir a la planificación apropiada y la toma oportuna de decisiones que asistan a salvaguardar la calidad física de los recures de agua y tierra. El objetivo de este estudio es el de evaluar la influencia de la topografía, el suelo, el uso de la tierra y la variabilidad climática en los procesos hidrológicos que se dan en la cuenca del rio Trou du Nord. Las acciones llevadas a cabo en este estudio incluyen de un modelo SWAT basado en las condiciones físicas, el análisis del balance hídrico de la cuenca del Trou du Nord y el análisis del impacto de los cambios del clima en la cuenca. El output de los diferentes modelos de circulación global (GCM) indica el aumento de la temperatura atmosférica y la disminución de la precipitación en la cuenca del Trou du Nord. Se predice que la temperatura aumente hasta 2.7^{o}C para el escenario de alta emisión conocido como A2 de alta emisión para el periodo 2071 - 2100. También se espera que la precipitación se reduzca hasta un 25% para el escenario A2 durante el periodo 2071 – 2100. Se anticipa que la disponibilidad de agua en la cuenca disminuya debido al incremento de la temperatura y la reducción de la precipitación bajo las condiciones de muchos de los escenarios examinados en la cuenca. El estudio indica que los cambios del clima pueden tener un impacto significativo en la disponibilidad de agua en la cuenta.

Palabras clave: Hidrología, modelación numérica, cambio del clima, SWAT, Trou du Nord, Haití

1. INTRODUCTION

Availability of freshwater resources to meet all the consumptive and non-consumptive needs is a global challenge which many nations are facing. The vulnerability of the Caribbean islands to natural and human-induced social, environmental and economic negative changes and disasters and their inability to cope with the problem necessitate the understanding of the hydrological processes and responses of the watersheds to various stressors. Haiti, in the island of Hispaniola, is the poorest country in the Caribbean, and therefore more susceptible to the impact of the drivers negatively affecting water resources. The challenge of managing water resources is further complicated at a time when demands for freshwater is increasing owing to population growth and the need for more food production in the face of uncertainty of the rainfall emanating from a changing climate. The severity of this problem is even further exacerbated in the Caribbean where freshwater resources and healthy coastal lines are the mainstay of economy for tourist attractions.

The resources of the Trou du Nord watershed are important to the economic wellbeing of its inhabitants and management of these resources determines improvement or degradation for both agricultural and urban areas. Planning and management are needed to ensure the protection of resources and prevention of further degradation and for sustainability of water resources in the watershed. Hence, there is a need for hydrological research of the Trou du Nord basin that can support improved catchment management programs. A better understanding of the processes that govern individual watershed hydrology can be used to safeguard the alarming degradation of soil and water resources in the island. The present research is an attempt to obtain a scientific understanding of the hydrological characteristics of the Trou du Nord watershed as well as defining adequate tools for long-term predictions of the basin characteristics. The main objective of this study is to develop a hydrological model and to analyze the spatiotemporal variability of hydrological processes and study the impact of climate change on water resources in the Trou du Nord watershed, Haiti.

2. METHODS

2.1 Description of trou du nord watershed

The Republic of Haiti has a total area of 27,750 km^2. The Trou du Nord River originates in the mountains near St. Suzanne within rugged terrain. It descends fast to run North over alluvial fans, meandering within coastal plains developed by thick unconsolidated sediment piles of the Massacre Aquifer. Being the largest aquifer in Northern Haiti, the latter provides fresh water to a total population close to 500,000 people. Lastly, at the end of the watershed, the river loses strength and empties in the Caracol Bay. Over its course, the widest part of the river is approximately 30 meters with maximum water depth of 1 meter. Figure 1 shows the location map of the Trou du Nord watershed which covers 118.89 km^2.

The Northern Caribbean is characterized for having spatial and temporal complexities in climate. Precipitation is projected to decrease in most of the region in all seasons by the end of this century, as can be seen from the analysis presented in the section on climate change further below in the present report. Specifically, in the Trou du Nord watershed, the climate is tropical modified by the upper watershed surrounding mountains and is subject to periodic droughts and hurricanes. The average annual temperature is 25.7 °C. Because of the actual impacts of climate variations, weather extremes have distinct effects on soil erosion, agricultural production, and water quality.

Current climate data sets are poor for the Trou du Nord watershed. Precipitation data sets derived from stations close to the watershed are not continuous, but sporadic in time. Data obtained during the first half of the last century points towards having a bimodal rainfall, with the main rainy season occurring from September to December and the second rainy period extending from April to June. The analysis of more recent data (2000-2012) for Trou du Nord watershed indicate that these two maxima have shifted to April and October respectively, but more important yet, rain volume seems to have declined. In average, about 1551 mm of precipitation falls annually. ENVIRON, 2011 indicated that the climate of the Trou du Nord floodplain is classified as a moderate arid climate, with an average mean annual precipitation of 1,280 mm. The mean annual precipitation progressively increases from east to west and follows a bimodal distribution, with a primary rainy season from September to November and a secondary, less pronounced, rainy season from April to June.

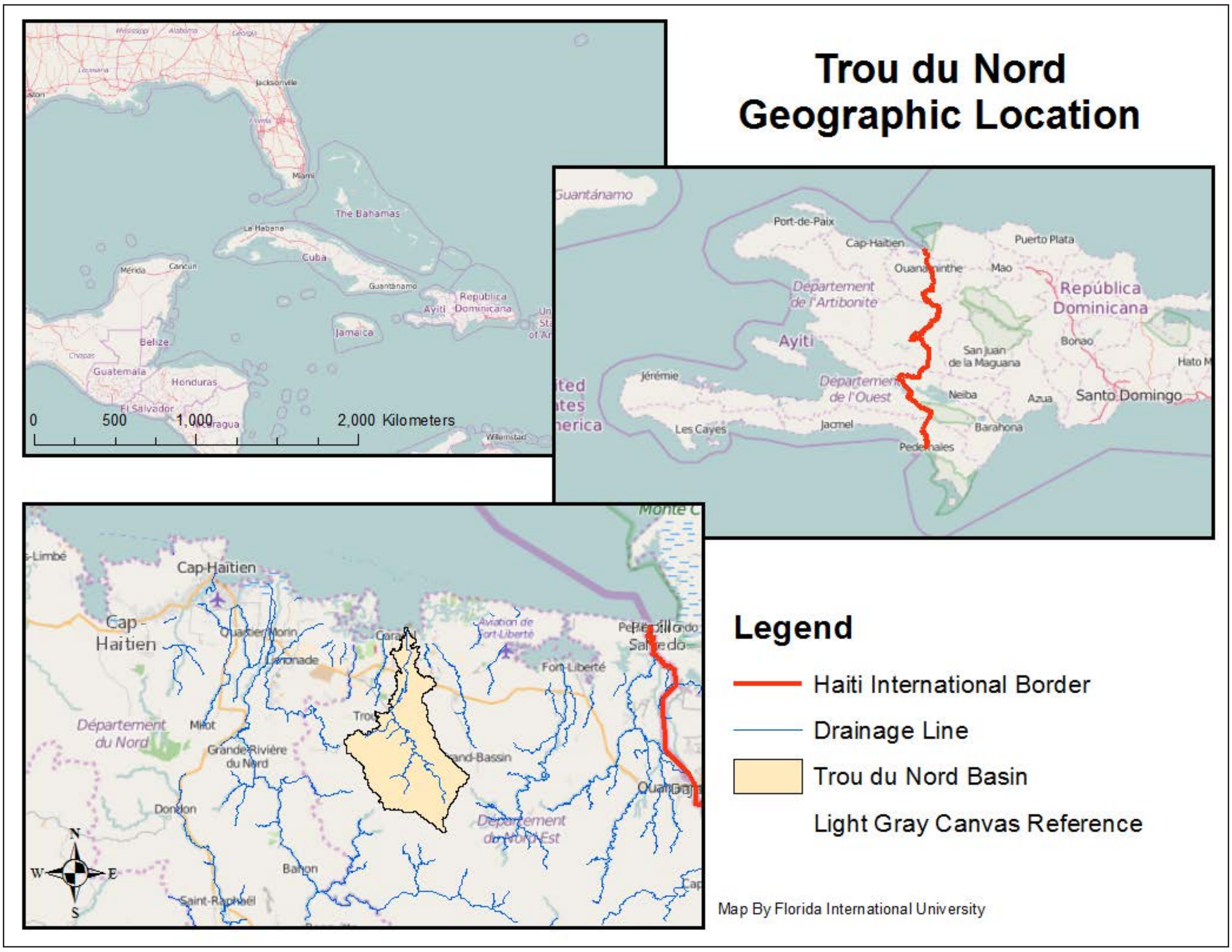

Figure 1. Location map of the Trou du Nord watershed

Daily river discharge values over the period 1923 – 1940 for the Trou du Nord River were provided by Centre National de l'Information Géo-Spatiale (CNIGS). This discharge data was measured at the Chambert Hydrological Station. The station is located just upstream from the industrial park (latitude of 19º38'44'' N and a longitude of 72º00'40'' W) in the vicinity of the bridge over the Trou du Nord in *Route Nationale 6* close to the community of Chabert. Figure 2 indicates the time series daily discharge at the Chambert Station for the given period of 1923 to 1940. The daily discharge trend corresponds to the rainfall distribution in the watershed. These daily river discharges were used to understand the seasonal and inter annual variability of the river discharge which served to evaluate the prediction performance of the SWAT model under limited data conditions. Per the ENVIRON study (2011) reports indicate that during the primary dry seasons (February 2011) and mid summer drought (July 2011) the Trou du Nord River averaged 0.45 m^3/s and 0.70 m^3/s respectively.

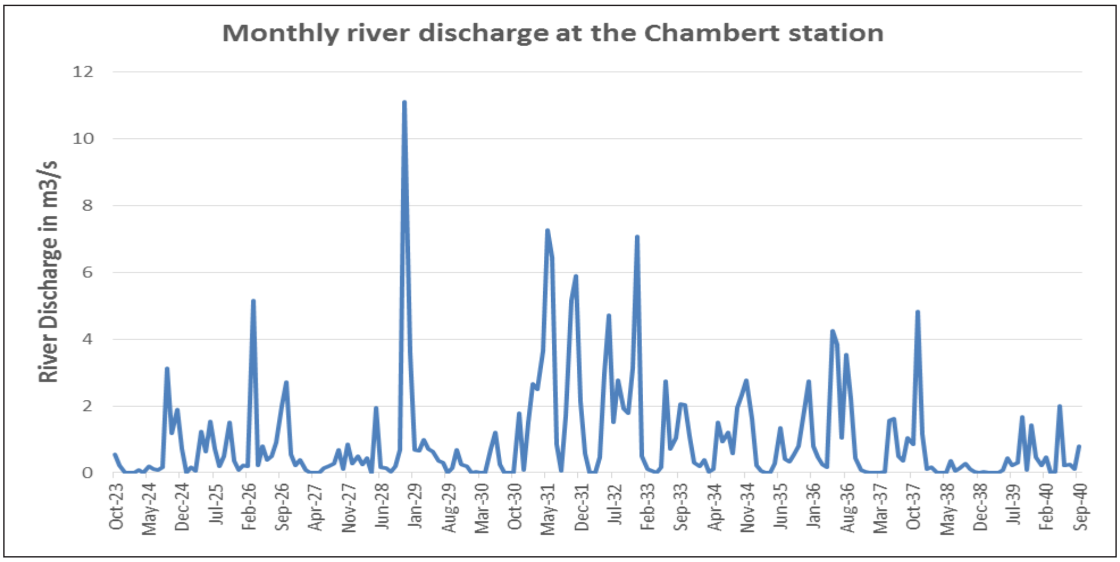

Figure 2. Discharge at the Chambert Station on the Trou du Nord watershed 1923-1940

2.2 Description of the SWAT model

Soil and Water Assessment Tool (SWAT) is a public domain model actively supported by the USDA (United States Department of Agriculture) – ARS (Agricultural Research Service) at the Grassland, Soil and Water Research Laboratory in Temple, Texas, USA. SWAT is a river basin scale, continuous time, spatially distributed model developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time (Neitsch et al. 2005). SWAT can analyze both small and large watersheds by subdividing the area into homogenous parts. As a physically-based model, SWAT uses hydrologic response units (HRUs) to describe spatial heterogeneity in terms of land cover, soil type and slope within a watershed. The SWAT system embedded within geographic information system (GIS) that can integrate various spatial environmental data including soil, land cover, climate and topographic features. Currently SWAT is imbedded in an ArcGIS interface called ArcSWAT. It is computationally efficient, uses readily available inputs and enables users to study long-term impacts. More detailed descriptions of the different model components are found in Arnold et al. 1998, Neitsch et al. 2005.

2.3. Model Setup

2.3.1. Delineation of the watershed

The model setup involved five steps: (1) data preparation; (2) sub-basin discretization: (3) HRU definition; (4) parameter sensitivity analysis; (5) calibration and uncertainty analysis. The Model setup and parameterization was done using ArcSWAT interface. The DEM (digital elevation model) was used to delineate the watershed and to analyze the drainage patterns of the land surface terrain. In this study a 30m by 30m resolution DEM was used that was downloaded from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model. A DEM mask was used that was superimposed on the DEM. The ArcSWAT interface uses only the masked area for stream delineation. A predefined digital stream network layer was imported and superimposed onto the DEM to accurately delineate the location of the streams. The watershed delineation process includes five major steps, namely, DEM setup, stream definition, outlet and inlet definition, watershed outlets selection and definition and calculation of sub-basin parameters. For the stream definition, the threshold based stream definition option was used to define the minimum size of the sub-basin. The ArcSWAT interface allows the user to fix the number of sub-basins by deciding the initial threshold area (TA). The threshold area defines the minimum drainage area required to form the origin of a stream. In this study, we have delineated 18 subbasins in the Trou du Nord watershed.

2.3.2 Delineation of hydrological response units

The land use/land cover spatial data were reclassified into SWAT land cover/plant types. A user look up table was created to identify the SWAT code for the different categories of land cover/land use on the map as per the required format. The soil map was linked with the soil database which is a soil database designed to hold data for soils not included in the U.S.

Watershed heterogeneity was accounted for by partitioning the watershed into smaller areas known as hydrologic response units (HRUs). HRUs are the basic building blocks of SWAT at which all landscape processes are computed. The unique combination of subbasin land use, soil, and slope overlay determine HRUs. Subdividing the sub watershed into areas having unique land use, soil and slope combinations makes it possible to study the differences in evapotranspiration and other hydrologic conditions for different land covers, soils and slopes. Using the ArcSWAT interface, we overlaid land use, soil, and slope layers to create a unique combination of HRUs by subbasin.

2.4. Model Input

2.4.1. Geospatial data

GIS input files needed for the SWAT model include the digital elevation model (DEM), land cover, and soil layers. A 30 m by 30 m resolution DEM was used that was downloaded from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model. The DEM was utilized by ArcSWAT to delineate basin and sub-basin boundaries, calculate sub-basin average slopes and delineate the stream network. The land use, soil and slope layers are used to create and define hydrological response units (HRUs).

2.4.2. Weather Data

The hydrological model SWAT requires daily meteorological data that could either be read from a measured data set or be generated by a weather generator model. The weather variables for driving the hydrological balance are precipitation, air temperature, solar radiation, wind speed and relative humidity. A great challenge of this modeling work has been obtaining the necessary dataset which have sufficient spatial and temporal distribution. Table 1 (a and b) indicates annual average rainfalls and temperature of Trou du Nord watershed. In this study, the weather variables used for driving the hydrological balance are daily precipitation, minimum and maximum air temperature for the period 2005 – 2014. These weather variables were collected from the nearby stations. The precipitation was registered at the Ouanaminthe and Cap-Haitien stations.

To complete the precipitation data provided by the Haitian counterparts (CINGS and the Ministry of Agriculture), we used information obtained from the NOAA-ESRL climate and weather global databank (http://www.esrl.noaa.gov/psd/data/). Rain data from the Ouanaminthe and Cap-Haitien meteorological stations was spatially interpolated onto a polygon that contains the Trou du Nord watershed. Using the concept of Thiessen polygons, the value of precipitation was derived for the four locations defined as NW, SW, NE, SE stations which correspond to the corner of the polygon that encapsulates the Trou du Nord watershed (refer to Table 1.a, Table 1.b, and Figure 3). These values were input to the SWAT model simulation runs. The input precipitation data was analyzed to check that the series used had captured the registered storms that impacted the region of Northern Haiti during the study period.

Table 1a. Total annual rainfalls (mm) in the Trou du Nord watershed

Years	Total annual rainfall in mm			
	NW Station	NE Station	SW station	SE Station
2005	1209.5	949.6	1611.6	1243.7
2006	1690.2	1310.4	2084.2	1711.8
2007	1423.9	1182.5	1706.4	1391.6
2008	1886.8	1510.1	2187.1	1839.5
2009	1816.5	1499.7	2244.4	1709.0
2010	1843.2	1849.3	1804.3	2226.3
2011	1242.5	1346.3	1099.6	1674.2
2012	1800.9	1834.8	1473.7	2126.2
2013	651.2	748.5	530.9	959.9

NE- North East, NW – North West, SW – South West, SE – South East

Table 1b. Average annual minimum (Tmin) and maximum Temperature (Tmax) in °C

Year	Average annual minimum (Tmin) and maximum Temperature (Tmax) in °C							
	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin
	Station							
	NW	NW	NE	NE	SW	SW	SE	SE
2005	28.5	24.6	30.1	24.4	32.1	20.5	32.1	20.5
2006	28.8	24.6	30.5	24.3	32.7	20.4	32.8	20.4
2007	28.8	24.8	30.5	24.6	32.4	20.7	32.5	20.7
2008	28.4	24.4	30.1	24.2	32.0	20.3	32.2	20.3
2009	28.4	24.4	30.0	24.2	32.1	20.4	32.2	20.4
2010	28.2	24.4	29.8	24.2	31.5	20.5	31.7	20.5
2011	29.7	21.6	28.0	22.3	31.9	21.7	29.9	19.1
2012	30.0	21.8	28.1	22.4	32.2	21.9	30.6	19.2
2013	30.4	22.0	28.5	22.7	32.9	22.1	30.8	19.3

2.4.3. Soil types

In this study we have used the global soil data map and soil properties developed by FAO (2000). According to FAO soil database, the watershed consists of three major soil types. The major soil physical properties used for setting up of the SWAT model for the Trou du Nord watershed are maximum rooting depth of the soil profile, number of layers in the soil, texture of soil layer, saturated hydraulic conductivity, soil water capacity of the soil layer, organic carbon content, moist bulk density, clay-sand-silt content and soil hydrological group. In order to facilitate the modeling setup we used the three major soil classifications that were obtained from the FAO global soil data.

2.4.4. Land Use/cover

Spatially distributed data of land cover, soil types and slop are required by the hydrological model to create hydrological response units (HRU's). Land use is one of the most important factors that affect runoff, evapotranspiration and surface erosion in a watershed. Land use in the Trou du Nord watershed is diverse, with a mixture of agriculture, agroforestry, small urban, industrial area and rural settlements. The land use / land cover types of the watershed is obtained from the data set provided by the Centre National de l'Information Géo-Spatiale (CNIGS). The data indicated that the majority of the watershed is used for dense crop agriculture followed by dense agroforestry and moderately dense crop.

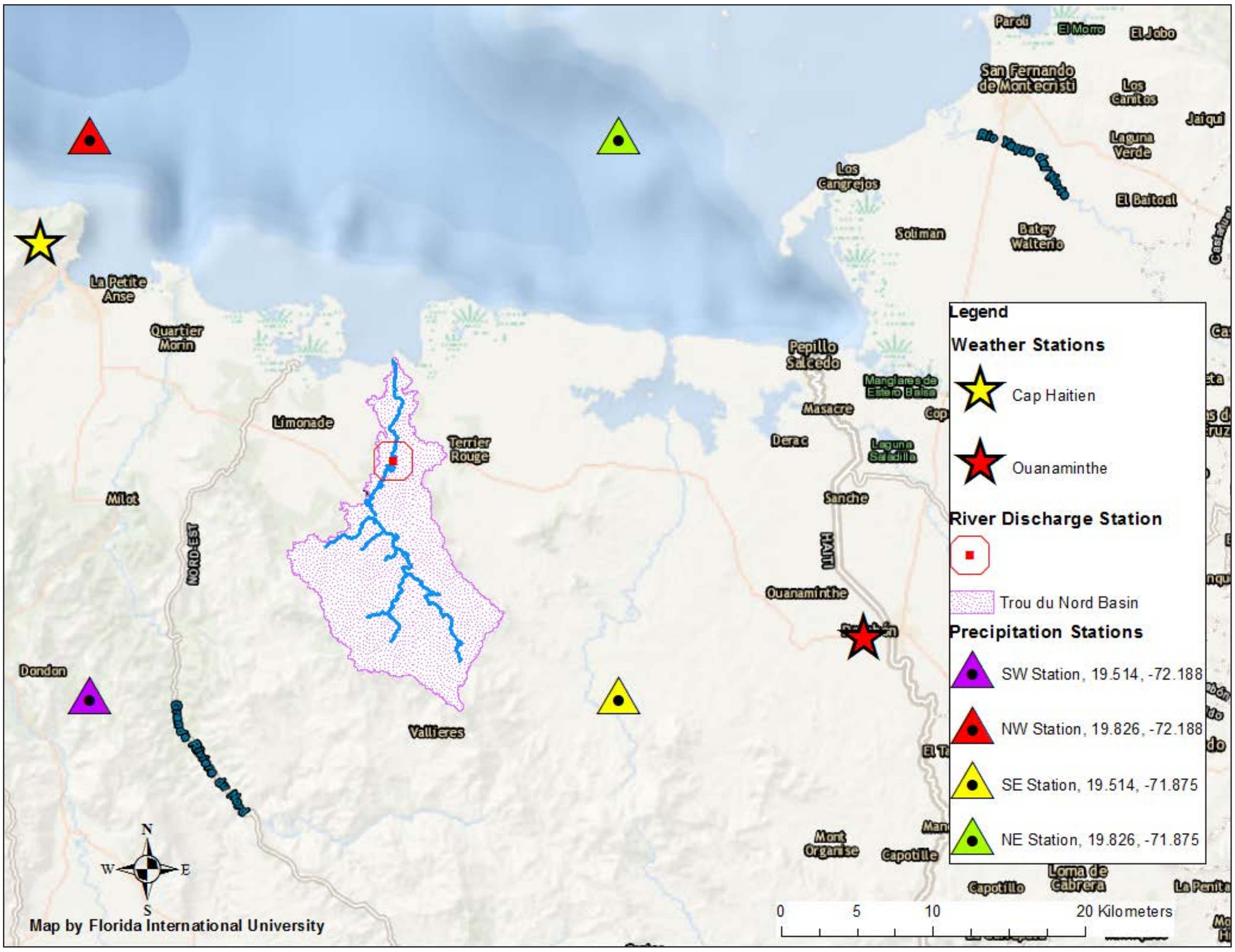

Figure 3. Location map of weather and streamflow monitoring stations

2.5. Assessment of Climate change impact

2.5.1. Global Climate Change Scenarios and Global Climate Model Data

In this study, we used outputs from GCM simulations that were run with three standard greenhouse gas emission scenarios. These standard scenarios were developed by the IPCC through the Spatial Report on Emissions Scenarios (SRES) to facilitate comparison of future climate change as simulated by different climate models. The SRES emission scenarios explore alternative global development pathways, covering a wide range of demographic, economic and technological driving forces and resulting GHG emissions. Further details can be found in IPCC (2000). The SRES emission scenarios are most useful when used in the context of current developments and policy. In this context, the SRES A1 family (representing rapid, global economic development) is often considered "business-as-usual" – when the SRES scenarios were compiled, this scenario for 21st Century development was the economic model most commonly used in academic literature (Nakicenovic and Swart, 2000). Thus, the SRES A1B marker scenario from the A1 family is generally-considered to be a mid-range emissions scenario. In this study, we used climate change scenarios based on the SRES A1B scenario to represent "business-as-usual", and the SRES B1 and A2 scenarios to represent low-end and high-end emission scenarios, respectively.

The GCM output data used for this study were obtained from the World Climate Research Programme's (WCRP's) Coupled Model Inter-comparison Project phase 3 (CMIP3) multi-model data-set. We used climate change scenarios based on the SRES A1B, B1 and A2 scenarios. These were the most important transient scenarios run during the CMIP3 project. We used two sets of GCM ensembles. The first set was used to quantify the range of the projected climate changes for Haiti. This dataset comprised the *monthly* precipitation and air temperature outputs from 21 GCMs for the A1B scenario, and from 18 models for the B1 and A2 scenarios. These were all the GCMs for which data were readily accessible for these scenarios. Data were downloaded for the periods 2011-40, 2041-70 and 2071-2100. GCM outputs for 1961-1990 from the Climate of the 20th Century Experiment were used as base-period data. Our second set of GCM ensemble data were used to generate inputs for the SWAT model for assessing the impact of climate change on stream flows, soil moisture, ground water and other hydrological parameters in the selected watersheds. This dataset comprised daily precipitation, minimum and maximum air temperature from 8 GCM models, for the same three SRES scenarios. These were the only GCMs for which daily outputs for these variables were available. Daily data were only available from CMIP3 for the time-periods 2046-2065 and 2080-2098, and for the 1961-1990 base periods, for most of the GCMs.

2.5.2. Downscaling of Global Climate Models

Assessing the impact of climate change on stream flows, soil moisture, groundwater and other hydrological parameters essentially involves taking GCM outputs of climatic variables (e.g., precipitation, temperature, humidity, mean sea level pressure etc.) at a global scale, downscaling these global-scale climatic variables to local-scale hydrologic variables, computing hydrological components, and finally assessing future water resource variability and risks of hydrologic extremes.

In this study, we use a statistical approach, following the historical-modification procedure of Harrold and Jones (2003) which produces climate time-series that have similar statistical properties to the observed calibration datasets. Daily climate projections were generated by modifying the historical datasets to represent changes in the GCM climatologies. The historical-modification approach was used because hydrological models often perform poorly when run using datasets that have distributions of daily climate data different from their training data, and statistical downscaling techniques often result in distributions that are noticeably different from observed time-series (eg with compressed variance). Our method involved, in short, calculating the difference between the daily cumulative-frequency-distributions (CFDs) of a GCM output variable for a present-day period and a future period, and then applying these differences to an observed dataset.

3. RESULTS AND DISCUSSION

3.1. Calibration of SWAT model in the Trou du Nord watershed, Haiti

The Soil and Water Assessment Tool (SWAT) model was originally developed to operate in large-scale ungauged basins with little or no calibration efforts (Arnold et al., 1998). Observed data on both spatial and temporal scales of interest are always very limited, especially in ungauged basins (Sivapalan et al., 2003). Still model performance evaluation in ungauged basins is an important research topic. One approach to addressing the use of hydrological models in ungauged basins is developing a model that uses physically based inputs both spatially and temporally along with comprehensiveness in the model's interrelationships and ability to predict ungauged basins reasonably well (Srinivasan et al., 2010). The current task is an attempt to reasonably set up the model with the available physically based spatial and time series data.

In SWAT there are 26 hydrological parameters that can be evaluated for development of the hydrological model for particular watershed. The parameter sensitivity analysis was done for the whole catchment. Sensitivity analysis is the process of determining the rate of change in model output with respect to changes in model inputs (parameters). Twenty six hydrological parameters were tested for sensitivity analysis for the simulation of the stream flow in the study area. Table 2 shows default values of major parameters in SWAT. The details of all hydrological parameters are found in the ArcSWAT interface for SWAT user's manual (Winchell et al. 2007). The most sensitive parameters that were considered for manual calibration in the Trou du Nord watershed are Curve Number II value, soil evaporation compensation factor, base flow alpha factor(days), available water capacity, hydraulic conductivity (mm/h), threshold depth of water in the shallow aquifer for 'revap' to occur (mm), (days), (mm WATER/mm soil), groundwater 'revap' coefficient, and threshold depth of water in the shallow aquifer for return flow to occur (mm).

Table 2. Default values of major hydrological parameters in SWAT

Nº	Parameter	Description	Default Value
1	CN2	Curve number	25-92
2	ESCO	Soil Evaporation compensation factor	0.85
3	OV_N	Manning's coefficient value for overland flow	0.14
4	EPCO	Plant evaporation compensation factor	1
5	EVLAI	Leaf area index at which no evaporation occurs from water surface (m^2 m^{-2})	3
6	SOL_AWC	Available soil water capacity (mm H_2O mm^{-1} soil)	0.01-0.4
7	Slope	Slope steepness (m m^{-1})	0.0-0.24
8	SOL_Kast	Soil saturated hydraulic conductivity (mm h^{-1})	0.05-400
9	GW_REVAP	Ground water re-evaporation coefficient	0.02
10	REVAPMN	Threshold depth of water in the shallow aquifer for re-evaporation to occur (mm).	1
11	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	1
12	GW_DELAY	Groundwater delay (days)	31
13	ALPHA_BF	Base flow recession constant	0.048
14	RCHRG_DP	Deep aquifer percolation fraction	0.05
15	GW_SPYLD	Specific yield of the shallow aquifer (m^3 m^{-3})	0.003
16	CH_K2	Effective hydraulic conductivity in main channel alluvium (mm h^{-1})	1
17	CH_N	Manning's coefficient for channel	0.014
18	SURLAG	Surface runoff lag coefficient (day)	4

To verify the performance of the model for the Trou du Nord watershed we have tested different scenarios by changing the watershed most sensitive hydrological parameters mentioned earlier and comparing the simulated streamflow result with existing streamflow measured during 1923 to 1940, as well as trying to correlate the result of other previous studies in the watershed. Table 3 describes the manually calibrated parameters in the Trou du Nord watershed. We also suggest that the developed model should be further verified using current measured streamflow data for a better validation.

To determine the best set of parameter values we compared the simulated streamflow/river discharge with observed/measured streamflow data measured during 1923 to 1940. Due to limitation of streamflow data that correspond with the time frame of available precipitation data, it was not possible to make auto calibration of the model and generate optimum parameter sets for the watershed. However, we worked on a detailed manual calibration technique by changing the parameters values with reasonable parameter ranges that is acceptable in the watershed. We also used hydrological parameters reported by other studies in the area, ENVIRON, 2011.

Table 3. Calibration parameters input into the Trou du Nord watershed SWAT model

Parameter	Description	Final Calibrated
CN	Curve number	Reduced by 10%
K	hydraulic conductivity (mm/h),	35
ESCO	Evaporation soil compensation factor	0.81
GW_REVAP	Groundwater "revap" coefficient	0.02
REVAPMN	Threshold depth of water in the shallow aquifer for 'revap' to occur (mm),	Reduced by 10%
GWQMIN	Threshold depth of water in the shallow aquifer for return flow to occur (mm).	Increased by 10%
SOL_AWC	Soil available water content	0.75
ALPHA_BF	base flow alpha factor(days),	0.048
SURLAG	Surface runoff lag coefficient	2

Previously, The SWAT model was tested in six different watersheds in Puerto Rico (Rio Manati river basins), Dominican Republic (Rio Haina and Yuna river basins) and Jamaica (Rio Cobre and great river basins), Setegn, et al. 2014. FIU developed a hydrological model for the Rio Yuna in the Dominican Republic. Figure 4 shows time series hygrograph showing observed and simulated flow for the Rio Yuna Watershed. The figure indicated that there is a good match between the observed and simulated streamflow/river discharge in the Rio Yuna watershed. Since Rio Yuna watershed is a good representative of Trou du Nord watershed which is located in the same island we have used the calibrated parameters in the Rio Yuna watershed to determine our parameter ranges for manual calibration of the SWAT model in the Trou du Nord watershed.

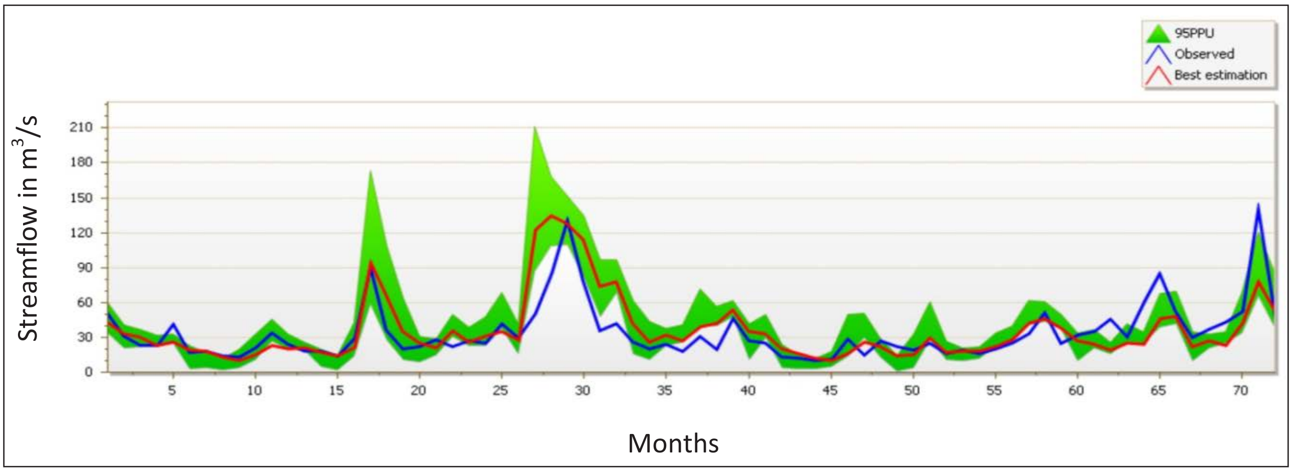

Figure 4. Time series hygrograph showing observed and simulated flow for the Rio Yuna Watershed. 95PPU is 95% prediction uncertainty

3.2. Hydrological Water Balance of Trou du Nord Basin

One of the most significant impacts to arise as a direct consequence of the land use change is the alteration to the water balance of catchments. Land use change has been responsible for modifying the hydrologic regime of catchments that were once in equilibrium. The main water balance components of the Trou du Nord basin includes: the total amount of precipitation falling on the sub-basin during the time step, actual evapotranspiration from the basin and the net amount of water that leaves the basin and contributes to streamflow in the reach (water yield). Table 4 lists the simulated annual average water balance components for the Trou du Nord watershed. The water yield includes surface runoff contribution to streamflow, lateral flow contribution to streamflow (water flowing laterally within the soil profile that enters the main channel), groundwater contribution to streamflow (water from the shallow aquifer that returns to the reach) minus the transmission losses (water lost from tributary channels in the HRU via transmission through the bed and becomes recharge for the shallow aquifer during the time step).

The monthly water balance of the Trou du Nord basin was analyzed based on the nine years (2005 - 2013) of simulation. The results indicated that above 50% of the annual precipitation is lost by evapotranspiration in the basin during the model simulation period. There is a high correlation between rainfall and surface runoff in the Trou du Nord basin. The annual water balance of the Trou du Nord watershed indicated that there is higher contribution of groundwater to the streamflow. The groundwater resources are more dominant in the watershed. Carful utilization of groundwater resources is the most necessary action to be taken to protect the groundwater availability and quality. Table 5 shows the annual monthly water balance of the Trou du Nord watershed. The results indicated that the lowest rainfall season is from January to April and the height rainfall season in the watershed is between May to November with the peak rainfall in November (205mm). The highest surface runoff, which is the actual amount of surface water flowing into the river, predicted in the months of September and November. The magnitudes of the surface runoff correspond with the highest rainfall months. The highest evapotranspiration is observed from March to May with a peak loss in May. As it is indicated in the Table 5, the watershed has the highest water yield during November to February.

Table 4. Annual average basin water balance of Trou du Nord basin. This annual average is based on nine years of simulation (2005-2013)

Water balance Component	Annual Average (mm)
Precipitation	1551.6
Surface runoff	18.45
Lateral soil	373.80
Groundwater (shallow aquifer)	263.57
Revap (shallow aquifer => soil/plants)	33.23
Deep aquifer recharge	15.48
Total aquifer recharge	309.65
Total water yield	671.14
Percolation out of soil	307.97
Actual evapotranspiration	825.4
Potential evapotranspiration	1700.8

Table 5. Annual monthly water balance of Trou du Nord basin. Monthly average based on nine years of simulation (2007 - 2013)

Months	RAIN (mm)	SURFACE RUNOFF (mm)	LATERAL FLOW (mm)	WATER YIELD (mm)	ET (mm)	PET (mm)
Jan	132.9	1.3	32.7	57.4	50.4	103.6
Feb	109.0	0.6	28.9	51.0	62.1	111.6
Mar	113.9	0.8	19.4	40.8	100.6	138.9
Apr	96.1	0.7	16.0	28.9	109.1	156.5
May	154.6	1.1	24.9	31.9	116.0	170.0
Jun	114.4	0.6	23.0	29.7	86.4	174.4
Jul	101.2	0.6	20.7	28.4	66.4	181.5
Aug	139.8	1.0	24.9	32.5	85.5	175.0
Sep	180.1	1.6	39.0	49.9	85.4	154.7
Oct	131.4	0.5	29.3	45.1	84.3	133.3
Nov	205.0	1.9	57.9	83.6	66.0	102.3
Dec	72.2	0.4	18.1	49.0	50.3	98.0

3.3. Impacts of climate change on water resources

As a consequence of its geographic location and its geological features, Haiti is exposed to many natural risks such as hurricanes, droughts, landslides, earthquakes and tsunamis; its vulnerability to the impacts of these events is exacerbated by a combination of fragile infrastructure and high levels of poverty (associated with low levels of resilience of livelihood support systems). The National Environmental Action Plan (NEAP) specifically recognizes four aspects of vulnerability to climate change: soils and desertification; the agricultural sector; coastal zones; and water resources.

3.3.1. Projected future Climate Variables

General Circulation Models (GCMs) output data used for this study were obtained from the World Climate Research Programme's (WCRP's) Coupled Model Inter-comparison Project phase 3 (CMIP3) multi-model data-set. GCMs numerically simulate changes in climate as a result of slow changes in some boundary conditions (such as the solar constant) or physical parameters (such as the greenhouse gas concentration). In this study, the outputs of fifteen Global climate change models were used to see the projected future climate variables. Namely, Canadian Center for Climate Modeling and Analysis Canada (CCCMA) (Coupled Global Climate Model (CGCM3), Centre National de Recherches Meteorologiques France (CNRM) (CNRM-CM3), Australia's Commonwealth Scientific and Industrial Research Organisation Australia (CSIRO) (CSIRO Mark 3.0), Max-Planck-Institut for Meteorology Germany (MPI-M) (ECHAM5/MPI-OM), Meteorological Institute of the University of Bonn (Germany), (MIUB) (ECHO-G), Geophysical Fluid Dynamics Laboratory USA (GFDL) (CM2.0 - AOGCM), Institut Pierre Simon Laplace France (IPSL) (IPSL-CM4) and Meteorological Research Institute Japan (MRI) (MRI-CGCM2.3.2).

The downloaded datasets were monthly precipitation, and minimum and maximum surface air temperatures. These data were used to quantify the range of the projected climate changes for Northern Haiti. The downscaled future Climate Variables is used as input to the SWAT model for assessing the impact of climate change on stream flows, soil moisture, ground water and other hydrological parameters in the Trou du Nord watershed.

3.3.2. Projected Changes in Rainfall and temperature

Assessing the impact of climate change on stream flows, soil moisture, ground water and other hydrological parameters, involves projections of climatic variables (e.g., precipitation, temperature). In this research we have assessed the output of each GCM for the three major emission scenarios (A1B, B1, and A2). Each scenario yields a different result for each future window. Figure 5 to Figure 10 show the future climate change trends in temperature and rainfall for all selected scenarios for the period 2011-2040, 2041-2070 and 2071-2100. As stated earlier, for this study we have used precipitation and air temperatures from 15 GCM models. These data were used to quantify the range of the projected climate changes for the region. Temperature changes are given in ^{o}C, and precipitation changes as a percentage change on the base-period mean. The following graphs shows in the True Du Nord watersheds for the different scenarios and models for the period 2011-2040, 2041-2070 and 2071-2100.

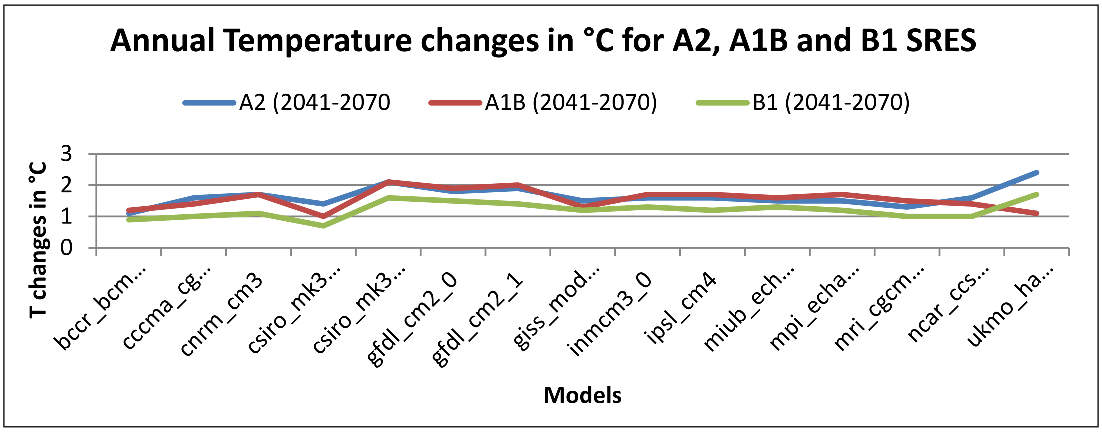

Figure 5. Projected Changes in temperature in the Trou du Nord watersheds for the A2, A1B and B1 Scenarios and for different models for the period 2011 - 2040

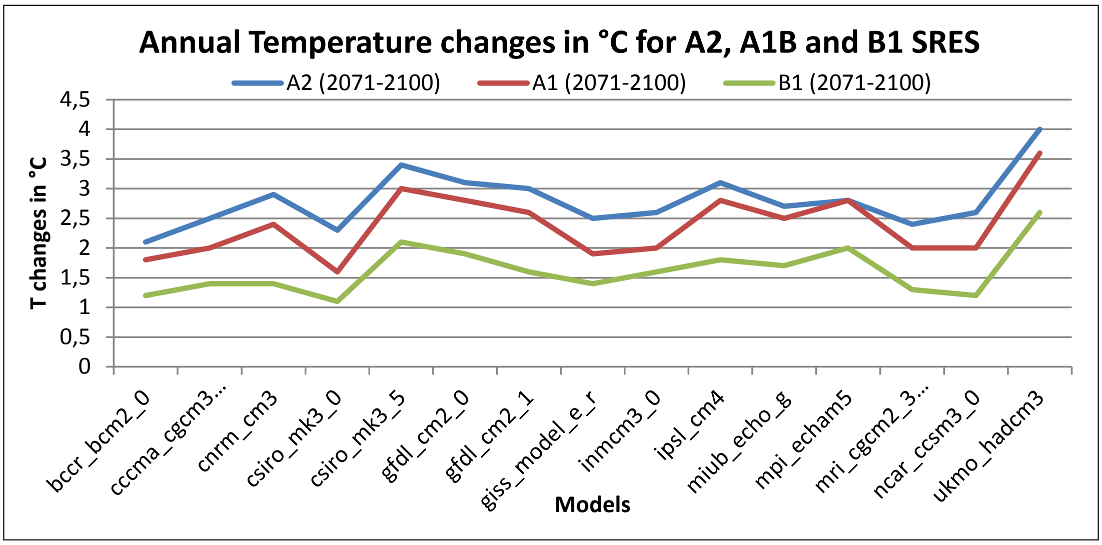

Figure 6. Projected Changes in temperature in the Trou du Nord watershed for the A2, A1B and B1 Scenarios and for different models for the period 2041-2070

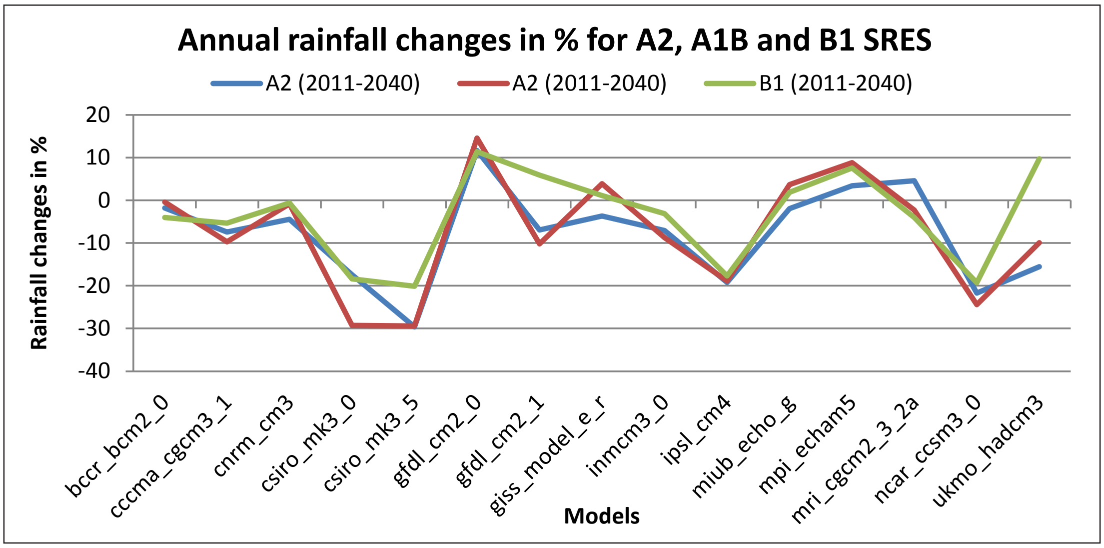

Figure 7. Projected Changes in temperature in the Trou du Nord for the A2, A1B and B1 Scenarios and for different models for the period 2071-2100

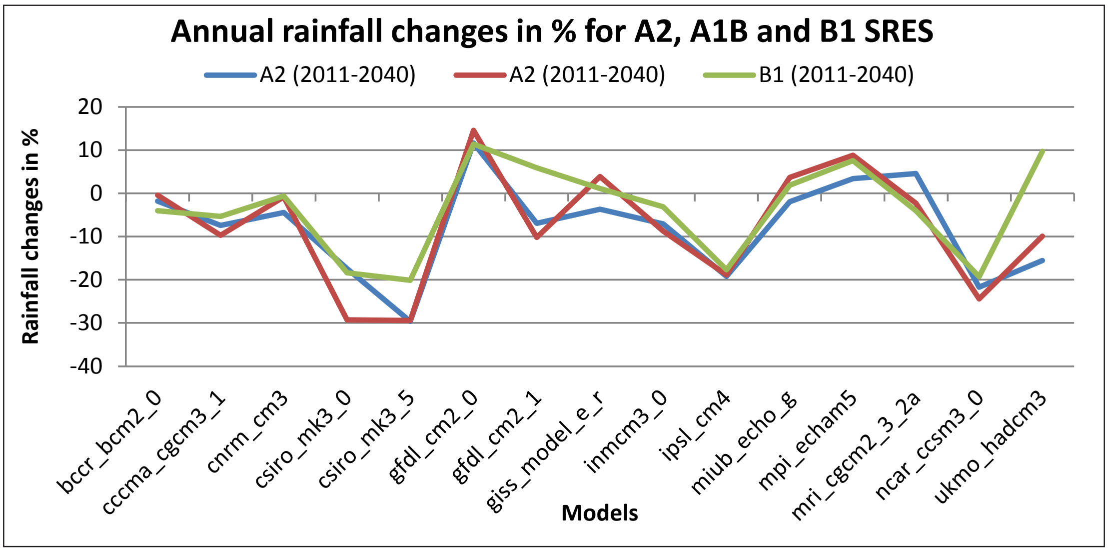

Figure 8. Projected Changes in rainfall Trends in the Trou du Nord watersheds for the A2, A1B and B1 Scenarios and for different models for the period 2011-2040

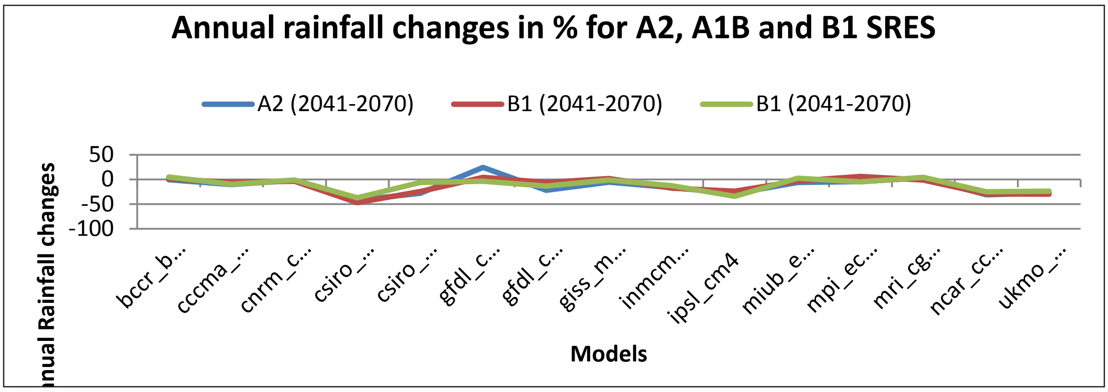

Figure 9. Projected Changes in rainfall Trends in the Trou du Nord watersheds for the A2, A1B and B1 Scenarios and for different models for the period 2041-2070

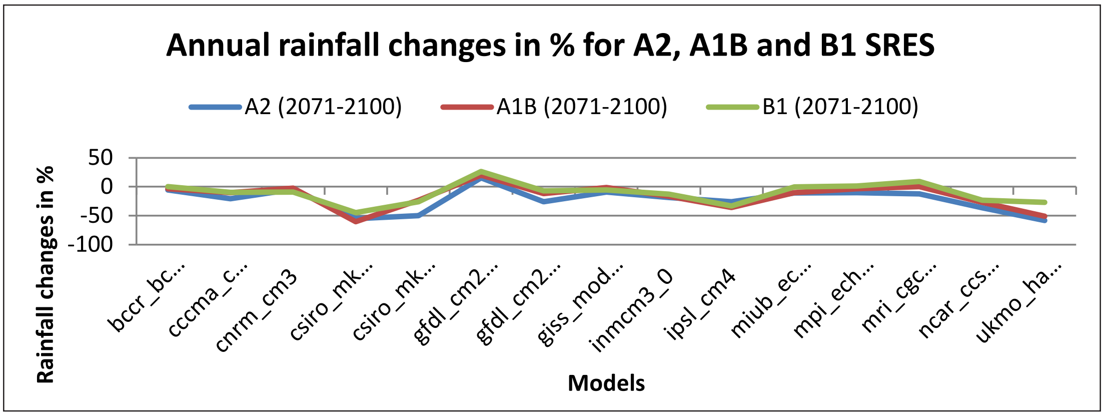

Figure 10. Projected Changes in rainfall Trends in the Trou du Nord watersheds for the A2, A1B and B1 Scenarios and for different models for the period 2071-2100

3.3.3. Changes in Annual Precipitation and Temperature in the GCM Ensembles.

Each GCM model and scenario shows a climate change value for each future time-period. Table 6 summarizes the changes in annual precipitation and temperature for SRES B1, A1B, and A2 scenarios for the periods 2011-2040, 2041-2070 and 2071-2100.

The annual precipitation changes for the SRES B1 scenario show no consensus among GCMs regarding rainfall changes for the region. However, for the SRES A1B scenario for periods 2041-70 and 2071-2100, and for all periods for the SRES A2 scenario, the ensembles showed statistically-significant declines in median precipitation using the signed rank-test.

All GCMs show temperature increases for the region, and the signed rank-test showed statistically-significant changes in median temperature for all SRES emission scenarios and all three time-periods. The temperature changes increase with time, and for any given time-period, the smallest changes are for the lowest-emission SRES B1 scenario, and the largest changes are for the highest-emission SRES A2 scenario. The modeled change in mean temperature for the 2071-2100 period ranged from 1.5°C for the lowest emission SRES B1 scenario to 2.6°C for the highest emission SRES A2 scenario.

Table 6. Ranges of modeled changes (given as 25th–75th percentiles) in annual precipitation and surface air temperature for northern Haiti for the GCM ensembles

Scenarios	Precipitation (%)			Temperature (oC)		
	2011-40	2041-70	2071-2100	2011-40	2041-70	2071-2100
SRESB1	-7% – 3%	-6% – 6%	-7% – 3%	0.6 – 1.0	0.6 – 1.0	0.7 – 0.9
SRESA1B	-8% – 0%	-8% – -1%	-12% – -5%	1 – 1.5	1.3 – 1.8	1.4 – 1.7
SRESA2	-9% – -2%	-12% – -4%	-25% – -12%	1.3 – 1.9	1.8 – 2.5	2.4 – 2.7

Temperature changes are given in °C, and precipitation changes as a percentage change on the base-period mean (e.g. a change of 100% would imply a doubling of precipitation). Changes in bold indicate were a sign-rank test found changes in the ensemble median to be statistically-significant at 0.05 confidence level

3.4. Impact of Climate Change on the Hydrology of the Trou du Nord watershed

3.4.1. Changes in Annual Streamflow/river discharge

Table 7 shows the modeled effect of climate change on annual streamflow, as output from the SWAT model, for the eight downscaled GCM models. Stream flow is one of the hydrological components which is greatly influenced by climate and land use changes. Many of the GCM models imply declines in mean annual flow, ranging from 5% to 60%. Only a few models showed increases in streamflow, with ranges from 5% to 32%. The pattern of streamflow change reflects the changes in rainfall shown in Table 1. The reduction in streamflow is due to significant reduction in rainfall, but also increases in evapotranspiration that result from temperature rises that contribute to the reduction in river discharge.

3.4.2. Changes in Annual Soil Moisture, Evapotranspiration, and Surface and Ground Water

The main aim of this task is to understand how changes in climate variables could affect the different hydrological components of the basin that control the final streamflow. Impact of climate change on evapotranspiration, soil moisture, surface and ground water were also analyzed. The results from the GCM models for the 2046-2065 and 2080-2100 periods are summarized in Table 7 and 8. The results indicated that potential evapotranspiration considerably increased for many of the GCM's for the 2046-2065 period, although changes in Actual Evapotranspiration (AET) were mixed. For the period 2080-2100, Potential Evapotranspiration (PET) increases are large, exceeding 10% in the SRESA2 scenario. The increase in PET is due to increased air temperatures. The study used the Hargreaves method (Hargreaves et al. 1985) to calculate evapotranspiration, which depends on minimum and maximum temperatures.

The ranges in parentheses are ensemble minimum and maximum, intended to illustrate the spread of model projections within each ensemble, and should not be considered to be error bounds.

Table 7. Mean changes in annual stream flow, PET, AET, groundwater discharge, soil water content and surface water runoff from the SWAT model due to changes in precipitation and air temperature for the period 2046-2065

Change in…	2046 – 2065		
	SRES B1	SRES A1B	SRES A2
Streamflow (%)	-5(-42.2 – 16.4)	-8.2(-23.5 – 7.5)	-8.7(-38.2 – 15.2)
PET (%)	3.0(1.2 – 3.9)	4.3(2.4 – 5.4)	4.2(3.2 – 5.1)
AET (%)	0.3(-4.4 – 2.8)	1.0(-2.4 – 3.8)	0.7(-4.7 – 3.5)
Groundwater Discharge (%)	-14.0(-55.3 – 26.1)	-25.1(-51.4 – 1.9)	-25.4(-70.1 – 21.4)
Soil Water Content (%)	-1.6(-6.8 – 0.4)	-1.4(-2.9 – 0.6)	-1.7(-7.6 – 0.4)
Surface runoff (%)	-6.3(-56 – 28.7)	-8.6(-31.6 – 12.0)	-10.4(-38.6 – 12.9)

Table 8 shows the mean changes in annual stream flow, PET, AET, groundwater discharge, soil water content and surface water runoff from the SWAT model due to changes in precipitation and air temperature for the period 2080-2100. It was observed that soil moisture showed reduction for both periods from zero up to 14% for almost all models. Table 8 shows that both surface and ground water flows reduced in many of the SWAT model runs. The changes in modeled ground water flow are clearly influenced the changes in streamflow. The result indicated that the water yield of the watershed decreases significantly due to increase in temperature and reduction in precipitation under many of the scenarios tested in the watershed.

Table 8. Mean changes in annual stream flow, PET, AET, groundwater discharge, soil water content and surface water runoff from the SWAT model due to changes in precipitation and air temperature for the period 2080-2100

Change in…	**2080 – 2100**		
	SRES B1	**SRES A1B**	**SRES A2**
Streamflow (%)	-4.5(-52.8 – 32.4)	-21.3(-56.6 – 6.2)	-26.8(-60.0 – 9.4)
PET (%)	4.5(2.7 – 6.3)	6.8 (3.7 – 8.7)	8.4(6.4 – 10.1)
AET (%)	2(-4.8 – 6.1)	0.1(-6.5 – 4.7)	-0.1(-4.8 – 5.7)
Groundwater Discharge (%)	-10.2(-35.8 – 30.6)	-39.2(-65.8 – -9.1)	-51.6(-78.9 – -13.9)
Soil Water Content (%)	-1.7 (-9.1– 0.2)	-3.6 (-11.2 – -0.4)	-5.1(-14.0 – -0.4)
Surface runoff (%)	-3.8(-19.4 – 35.6)	-17.9(-47.2 – 9.4)	-24.6(-47.1 – 14.3)

4. CONCLUSION AND RECOMMENDATIONS

As the global community is undertaking the challenge to attain the SDG (Sustainable Development Goals), the need for a holistic integrated approach to water management is becoming ever more evident. The challenge of managing water resources is complicated at a time when demands for freshwater is increasing owing to population growth and the need for more food production in the face of uncertainty of the rainfall emanating from a changing climate (Donoso and Bosch, 2015). The severity of this problem is even further exacerbated in the Caribbean where freshwater resources and healthy coastal lines are the mainstay of economy for tourist attractions. The present research aimed to obtain a scientific understanding of the hydrological characteristics of the Trou du Nord watershed as well as defining adequate tools for long term predictions of the basin characteristics. The present study involved the application of the physically based, spatially distributed SWAT model for hydrologic budget predictions from an ungauged perspective. We proposed a framework for developing spatial input data, including hydrography, terrain, land use, soil, weather, and management practices, for SWAT in the Trou du Nord watershed.

An attempt was made to investigate the sensitivity of water resources to the changing climate in the Trou du Nord watershed. The result indicated that the water yield of the watershed decreases significantly due to increase in temperature and reduction in precipitation under many of the scenarios tested in the watershed. The hydrological water balance analysis showed that baseflow/groundwater is an important component of the total discharge within the study area that contributes more water to the streamflow than the surface runoff. More than 60 % of losses in the watershed are through evapotranspiration.

The results of the study reiterate that an important issue to consider in future predictions of hydrology, sediment yield and water quality is the uncertainties in these predictions. The main sources of these uncertainties are errors in the input variables such as rainfall and temperature and hydrological variables. Availability of measured streamflow/river discharge data is very important to efficiently calibrate and validate the model. Despite the scarcity of streamflow data that correspond with the period of available weather data in the vicinity of the watershed, we used different possible options including comparison of the trend with flow data measured during the 1923 – 2014, comparing parameters in similar watershed in the Dominican Republic and results from other previous studies, to validate the model prediction performance in the Trou du Nord watershed.

In SWAT, climate data for every subbasin is furnished by the station nearest to the centroid of the subbasin. Direct accounting of rainfall or temperature distribution error is quite difficult as information from many stations would be required. We highly recommend to establish additional hydro-meteorological stations in the watershed that monitor daily or sub daily river flow, precipitation, temperature and other necessary weather and hydrological variables in the watershed that help to improve the outputs of the modeling tools as well as making appropriate decision in the implementation of any agricultural and development activities in the watershed. We highly recommend to verify the present modeling study with future measured hydrological variables (in particular with streamflow/river discharge observations) so that the model can be further validated and used as decision support tools in the Trou du Nord Watershed as well as application of the model for other watersheds in Haiti. As it stands now, it is still the best available sufficiently robust tool capable to provide and simulate scenarios for the Trou du Nord watershed.

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THE ISSUE OF WATER IN SLUM DEVELOPMENT IN HAITI: THE CASE STUDY OF CANAAN

LA QUESTION DE L'EAU DANS LE DÉVELOPPEMENT DES BIDONVILLES EN HAÏTI: L'ÉTUDE DE CAS DU CANAAN

EL PROBLEMA DEL AGUA EN EL DESARROLLO DE LOS BARRIOS MARGINALES DE HAITÍ: UN ESTUDIO DE CASO DE CANAÁN

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Abstract

In 1992, the United Nations listed Haiti among the countries that will face water scarcity by 2025. Haitian cities, in which water demand is already high, are increasingly exposed to population growth that significantly affects water and sanitation facilities, when they exist. These settlements suffer from the negative effects of increasing water demand on a daily basis. The most critical case is that of the metropolitan area of Port-au-Prince (MAPP). The consequences of the earthquake of January 12th, 2010 included the displacement of the population, the dislocation of the general drinking water supply system, the setting up of several make shift camps in the MAPP and the creation of new slum districts, the largest of which is Canaan, where more than 200 000 inhabitants now live. In a context of low coverage of safe drinking water and basic sanitation, it seems entirely appropriate to take a fresh look at water issues in slum development. The aim of this study is to analyze the supply of, and the demand for, water at Canaan. A field survey of water suppliers and vendors and other household surveys were conducted between February and April 2016. 240 water points, totaling an available volume of 2840 m^3, were covered by the first survey. Regarding demand, a questionnaire was administered to 439 households spread over the six (6) localities composing Canaan. In 2007, only 0.23% from the population studied was living in Canaan. 31.44% of households moved into the area in 2010, just after the earthquake. The share of water in the budget of 90% of these households is higher than 5%. The selling price and frequency of supply remain the main variables responsible for spatial discrimination regarding the supply of the water market in Canaan. Future studies should use larger sample sizes to study the mechanisms capable of ensuring democratic water management in this area.
Keywords: Human settlements, water, population growth, slums, Canaan, Haiti.

Résumé

En 1992, les Nations Unies ont listé Haïti parmi les pays qui feront face en 2025 à une importante pénurie d'eau. Les villes haïtiennes, dont la demande en eau est déjà élevée, se trouvent de plus en plus exposées à une croissance démographique qui affecte considérablement les infrastructures d'eau et d'assainissement, quand elles existent. Ces établissements humains subissent au quotidien les effets négatifs de la demande croissante en eau. Le cas qui apparaît le plus critique, est celui de l'Aire métropolitaine de Port-au-Prince (AMPP). Le tremblement de terre du 12 janvier 2010 a eu, entre autres, pour conséquences un déplacement de la population, la désarticulation des réseaux et services d'eau potable et d'assainissement, la création dans l'AMPP de plusieurs camps de fortune et de nouveaux bidonvilles, dont le plus important est Canaan, dans lequel vivent aujourd'hui plus de 200 000 habitants. Dans un contexte de faible couverture en eau potable et en assainissement de base, il apparaît opportun de jeter un nouveau regard sur la problématique de l'eau dans les bidonvilles en formation. L'objectif de cette étude est d'analyser l'offre et la demande en eau au niveau de Canaan. Une enquête de terrain auprès de fournisseurs ou vendeurs d'eau et une autre auprès des ménages ont été menées entre février et avril 2016. 240 points d'eau, totalisant un volume disponible de 2840 m^3, ont été couverts par la première enquête. En ce qui concerne la demande, un questionnaire a été administré auprès de 439 ménages répartis entre les six (6) localités constituant Canaan. En 2007, seulement 0,23% de la population étudiée vivait à Canaan. 31,44% des ménages se sont installés dans la zone en 2010, juste après le séisme. Le poids de l'eau dans le budget de 90% de ces ménages est supérieur à 5%. Le prix de vente et la fréquence d'approvisionnement demeurent les principales variables établissant une discrimination spaciale au niveau de l'offre sur le marché de l'eau à Canaan. *À l'avenir, il faudra étudier*, sur un échantillon beaucoup plus important, les mécanismes permettant l'implémentationd'une gestion démocratique de l'eau dans cette zone.
Mots clés: Établissements humains, eau potable, croissance démographique, bidonvilles, Canaan, Haïti.

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Resumen

En 1992, las Naciones Unidas pusieron en una lista a Haití entre los países que harán frente en 2025 a una escasez de agua importante. Las ciudades haitianas, cuya demanda en agua es ya elevada, se encuentran cada vez más expuestas a un crecimiento demográfico que afecta considerablemente las infraestructuras de agua y de saneamiento, cuando existen. Estos establecimientos humanos sufren a diario los efectos negativos de la demanda creciente en agua. El caso que aparece el más crítico, es el del Área metropolitana de Puerto Príncipe (AMPP). El terremoto del 12 de enero de 2010 tuvo, entre otras cosas, como consecuencias un desplazamiento de la población, la desarticulación de las redes y los servicios de agua potable y de saneamiento, la creación en la AMPP de varios campos improvisados y de nuevos barrios de chabolas, de los que uno de los más importantes es Canaán, en los que viven hoy más de 200,000 habitantes. En un contexto de cobertura débil en agua potable y en saneamiento de base, resulta oportuno echar una nueva mirada sobre la problemática del agua en los barrios precarios en formación. El objetivo de este estudio es analizar la oferta y la demanda en agua al nivel de Canaán. Una encuesta de terreno cerca de proveedores o vendedores de agua y otra cerca de los hogares han sido realizadas entre febrero y abril de 2016. 240 puntos de agua, totalizando un volumen disponible de 2840 m^3, han sido cubiertos por la primera encuesta. En cuanto a la demanda, un cuestionario ha sido administrado a cerca de 439 hogares repartidos entre las seis (6) localidades que constituyen Canaán. En 2007, solamente el 0,23 % de la población estudiada vivía en Canaán. El 31.44 % de los hogares se instalaron en la zona en 2010, justo después del seísmo. El peso del agua en el presupuesto del 90 % de estos hogares es superior al 5 %.El precio de venta y la frecuencia de abastecimiento permanecen las principales variables que establecen una discriminación espacial al nivel de la oferta sobre el mercado del agua en Canaán. En el futuro, habrá que estudiar, sobre una muestra mucho más importante, los mecanismos que permitirán la implementación de una gestión democrática del agua en esta zona.

Palabras clave: Asentamientos humanos, el agua, el crecimiento de la población, barrios marginales, Canaan, Haití.

INTRODUCTION

One of the main challenges facing countries today is to find ways to ensure that people and the environment have adequate freshwater resources to maintain and support their existence (UNEP, 2010).Uncontrolled population growth is outstripping the availability of renewable water resources. This imbalanced relationship seems to be leading humanity towards an inevitable shortage of fresh water. Indeed, near the end of the 20th century, hydrologists introduced a new indicator of economic development based on the renewable water resources/population (W/P) ratio. We have now almost reached the level of water scarcity predicted in 1992 according to the annual supply of water of a region per capita. The term water stress is applicable when W/P is below 1,700 cubic meters per person per year.

The issue of sufficiency evaluated on the basis of water availability and the satisfaction of human and environmental needs, and how it lessened during the last decade of the 20th century, has led to considering water scarcity as one of the main factors holding back development in the less advanced countries (Emmanuel and Lindskog, 2002). Falkenmark and Widstrand (1992) considered that per capita water availability below 1700 m^3/year poses development problems; a supply of less than 1000 m^3/year entails a situation of relative shortage, while one less than 500 m^3/year entails absolute shortage.

The Republic of Haiti has a water/population ratio (W/P) between 1200 and 1400 m^3 per person (St-Hilaire et al, 2013). With a potential of renewable water resources estimated at between 12 and 14 billion cubic meters per year, Haiti is already facing severe water stress. The MAPP hardly manages to meet the drinking water needs of its population. BRGM-GERSAR-LGL S.A. (1989) reported an annual availability of 23.7 million m^3 of water to supply the MAPP. On the basis of the minimum quantity of water considered necessary to live a healthy life (Falkenmark and Widstrand, 1992), namely 100 liters per capita per day, i.e. 36.5 m^3 a year, available water resources (BRGM-GERSAR-LGL SA, 1989) and the estimation of the population, i.e. 2,712,958 inhabitants in 2015, (Bodson et al, 2016), the MAPP supplies only 8.74 m^3 per inhabitant, a figure that will fall to 7.61 m^3 by 2025.The phenomenon of uncontrolled urbanization that affects every urban area of Haiti, and more particularly the MAPP, is aggravating an already difficult situation, namely that of the qualitative and quantitative supply of water to the population. The increase of the latter means that the same resources must be divided between more people, thus the quantity of water per capita decreases (Hassan, 2008).

Viewed from the urban angle, Canaan is a human settlement in development and one of the immediate consequences of the earthquake of January 12th, 2010. Deprived of basic urban infrastructures such as water supply, sanitation and electricity, Canaan is a particular epidemiological environment in which there is no collective collection of solid waste, drainage or sewage, and where water consumption of uncertain quality may promote the propagation of diseases and health risk factors for the population and the environment. As a new precarious district of the MAPP resulting from actions of post-earthquake relocation of the inhabitants in camps, Canaan provides the opportunity to approach water management in slums in the context of renovation and urban integration. It also favors the development of, and experimentation with, new models of integrated water management centered on, among other things, the effective participation of the users/citizens. The aim of this study is to analyze the supply and demand for water in Canaan.

Methodology of the study

Within the framework of this study, adequate water supply and sanitation are considered as common goods and to a certain extent as environmental goods, since they are fundamental indicators of the level of implementation of public health standards.

Field of study

Canaan is situated in the north of the metropolitan region of Port-au-Prince, more specifically in the "habitation Corail-Cesseless" in the municipality of Croix-des Bouquets (Figure 1). Its approximate borders are formed by NR 1 in the south, the Titanyen mine-quarry in the west, and the districts of Jerusalem and Village-Modern in the east. Its access routes are NR 1 and 3. In 1971, the Haitian government declared it a public utility with the aim of developing an area attractive for tourism. This zone was composed of vast tracts of dry land covered only by wild vegetation (Noël, 2012). The presidential order of March 22nd, 2010, concerning the expropriation of several properties for public purposes, was the pretext for the illegal occupation of Canaan. Land held in the framework of this order will be used to reorganize the MAPP and partially to relocate the victims of January 12th, 2010 (Zidor, 2012). The geographical coordinates of Canaan are 18° 38′ 46″ N, 72° 16′ 23″ W. An estimated population of 200,000 lives on a territory covering about 50 square kilometers (UN-Habitat, 2015). Since 2010, earthquake victims that have fled the chaos in the adjacent neighborhoods of Port-au-Prince, migrants from rural zones of Haiti and people profiting from the resulting chaotic situation have invested more than US$10 million in the development of the "new city" (UN-Habitat, 2015).

Figure 1. The field study site–the orthophotoplan of Canaan

The national and communal public authorities that should have taken over failed to take on their responsibilities following the departure of the post-earthquake emergency response organizations from Canaan. This explains why the new inhabitants, in collaboration with numerous private initiatives, organized themselves according to the urgency and the means available.

The first occupant to acquire a plot of land not previously owned is responsible for staking out its boundaries. Without the involvement of public authorities, this process is potentially highly contentious and the reason why groups and networks of people quickly took control of the methods used to define and distribute plots, perform transactions (after the first settlement), stake out public spaces, and progressively organize services for the population. These different networks of people who exercise or try to exercise control over the distribution of the territory are themselves in competition and often do not have a global vision of the social and urban issues at stake in Canaan.

According to preliminary observations, the largest annual influx occurred in 2010 in the months following the earthquake. It remained considerable until 2013 and continued in 2014 and 2015, but at a slightly less sustained pace. Data for 2016 are too partial to be taken into account. This observation, it should be emphasized, refers exclusively to the survey data which concern the study area (Canaan1, 2, 3, 4, 5, Jerusalem and Bellevue; the two last localities are identified in this study as Canaan B) and must be taken into account in the context of the expansion of the territory commonly referred to as Canaan.

Field survey of suppliers and water vendors

The objectives of this field study were, firstly, to collect the geo-spatial coordinates of water points in operation and, secondly, to analyze the supply of water in the study area. The survey covered a total of 240 water points. The geographical references of these points allowed producing the map of the water supply to Canaan (Figure 2).

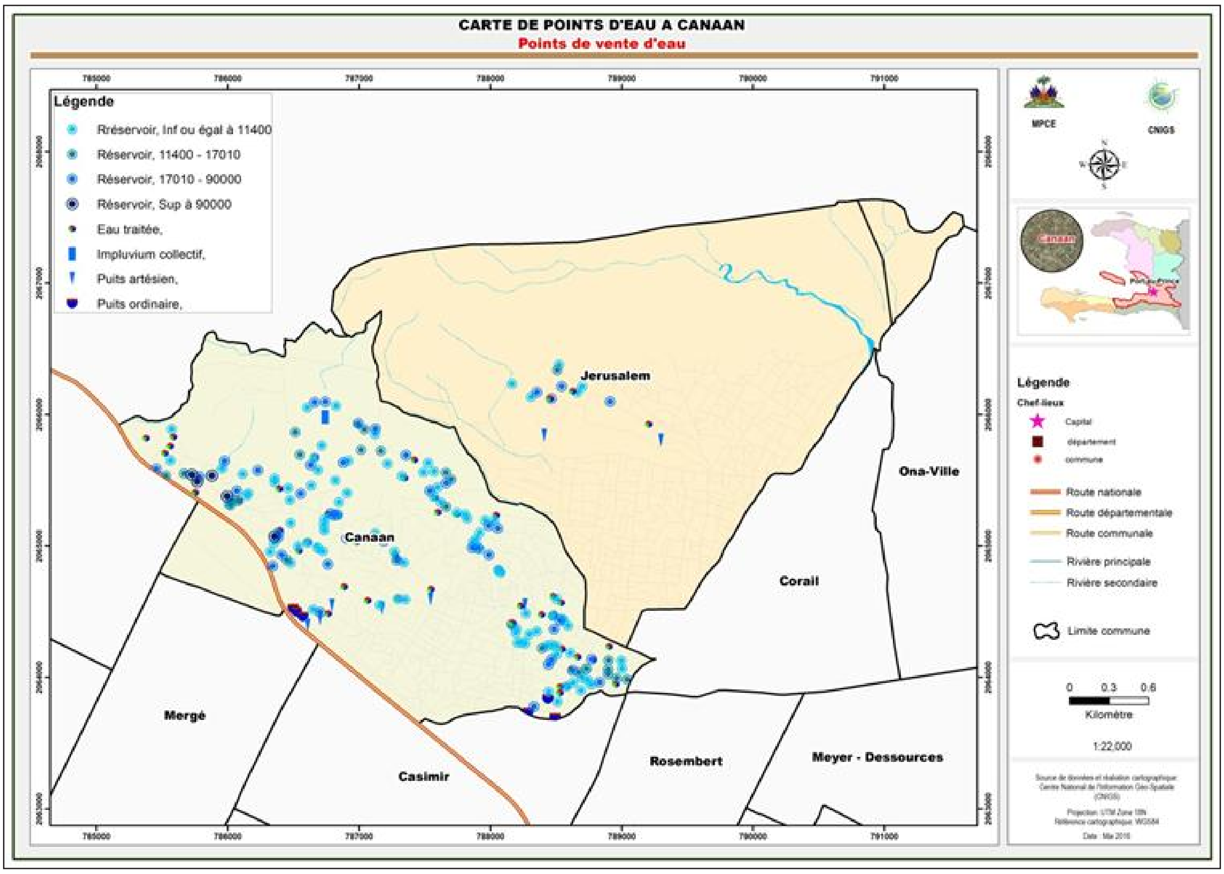

Figure 2. Map of water supply (water storage and/or distribution) in Canaan

Of the 240 water points, only 179, i.e. 74.58%, were selected for the statistical analysis of the water supply. The remaining points (61 water points or 25.42%) were not analyzed because we unable to obtain adequate information during the survey.

From a global standpoint, instead of taking the different localities into account, the subsamples used in the analysis are representative. The survey technique implemented was non-probabilistic with the itineraries method being applied within each locality and a survey step equal to 1 unit (i.e. the water point). Although the method is theoretically non-probabilistic, the representativeness of the sample made it possible to draw inferences on the basis of the results obtained. The treatments and analysis were carried out with the SPSS statistical software. Microsoft Excel was used to generate the tables and graphs.

Field survey of the population

The aim was to study the willingness and ability of this population to contribute financially and socially to the operation and maintenance of the drinking water supply system and adequate sanitation.

- **Basis of the survey -** The Haitian Institute of Statistics and Information (IHSI) has a computer file with 11,958 Sections of Enumeration (SOE) which constitutes the basis of the survey. The latest version is that of the general census of the population in 2003. This basis is old so some SOEs were updated (Gilles et al, 2015) to take into account the significant demographic changes occurring in the SOEs after the earthquake of January 12th, 2010. Within the framework of this study, the basis of the survey was not used for reasons linked to the historicity of the slums of Canaan.
- **Units of observation and analysis -** The observation unit of the survey on the willingness and capacity to pay for the drinking water supply and the quality of sanitation services was the head of household while the unit of analysis for which the data were collected was the household. However, certain conclusions concerned the head of household.
- **Sample size -** The size of the sample was determined on the basis of Simple Systematic Sampling (SSS) as the sampling technique and on global calculation based on the assumption of uniform land use in Canaan. The size of the sub-samples belonging to the blocks was determined after a visit to the area. This size was theoretically 452 households for a 95% confidence level, 5% error margin and 85% response rate. However, for reasons related to the practical implementation of this work, 439 households distributed between the six (6) localities were interviewed.
- **Sample selection -**The probability sampling method was chosen in the framework of this work, because the aim was to reach conclusions on the entire population of Canaan from the sample. Simple systematic sampling was the ideal choice in order to remain in the family of the probabilistic techniques with the best possible coverage. The sampling technique applied was a nonstandard SSS.
- **Selection of households to be surveyed –** Although the updated base of the survey containing the SOE was not chosen in the methodological framework, a series of field visits was performed before carrying out the investigation in view to first determining the number of neighborhoods composing Canaan and, second, to assess the distribution of its population from a theoretical point of view.
- **Data collection method –** The data collection method chosen was the direct interview. Interviews were conducted with the heads of households or any other person in the households able to answer the questions. In each case, a paper questionnaire was used to conduct the interview. Water scarcity is a phenomenon with qualitative and quantitative dimensions. The evaluation of the budgetary weight of water in the household finances required a quantitative approach with the questionnaire being used for data collection. However, a complementary qualitative approach was used in order understand the phenomenon and examine the behavior of the population towards the water. The questionnaire included categorized questions and subjective questions. Visual observations on the ground and interviews with certain people by opportunity, allowed obtaining information and complementary explanations for the quantified data.
- **Limits of the sampling method -** The lack of statistical information on the population of Canaan was decisive in the choice of the sampling technique used. It was not possible to stratify the sample composition. The choice of simple systematic sampling proved the most appropriate as regards the collection of units. The number of households per district was not known, and it was difficult to accurately calculate the number of steps to consider. Efforts were therefore made to achieve coverage of the area in spite of these difficulties and maintain the most scientific approach possible regarding the sample collection.
- **Process of validation, data processing, and analytical models-** The first step of supervising the questionnaires administered during the first two days of the investigation allowed correcting certain inconsistencies and avoid them afterwards. Manual recovery was undertaken thereafter, and during acquisition the statistical software used indicated certain inconsistencies by way of error messages. The validation process and the treatment were carried out on SPSS; Microsoft Excel was used to build the tables and graphs. Data analysis was both descriptive and explanatory. SPSS allowed the production of explanatory analysis tools throughout the analysis and the interpretation of the survey results. In addition to the univariate analyses, the nonparametric chi-square test was used to verify the existence of dependency relationships between two variables, and analysis of variance and the mean comparison were used to determine how a particular factor affected a response variable. A discriminating analysis was performed if data permitted when focusing on the similarity between localities, while a principal component analysis was performed on several explanatory variables.
- **The dimensions considered -** Demographic and socioeconomic characteristics were addressed in this survey as they could

influence the behavior of households in terms of water and sanitation. For water, two types were studied: (i) treated water for ingestion and water for common use. The behavior of the population was seen in terms of supply and water management at the household level. Three dimensions were chosen: rationing, treatment and water conservation. Regarding the behavior of households towards sanitation, the issue was examined in terms of solid waste management and the place of defecation usually used. Each of the dimensions considered was addressed in the collection tool by specific issues such as categorical, closed and semi-closed questions. The indicators and variables were chosen according to Haitian reality and known practices.

Results and discussion

Demographic and socioeconomic characteristics of the households

The distribution of the sample studied between the 6 localities is shown in Figure 3. 38.5% of the respondents live in Canaan 3. 60% of the heads of households are male. 71% live in a couple (married or common-law), 7% are divorced, 21% are single and 1% are widowed. 98% of the population studied lives in the household. The size of the households varies from 1 to 14 people. The sizes of the statistical series present a high concentration between 3 and 7. This edge contains 70% of households. Canaan households comprise an average of 5 people. Both the median and the mode are almost equal to the average, which is typical of normal distribution. 55% of households have between 4 and 6 people.

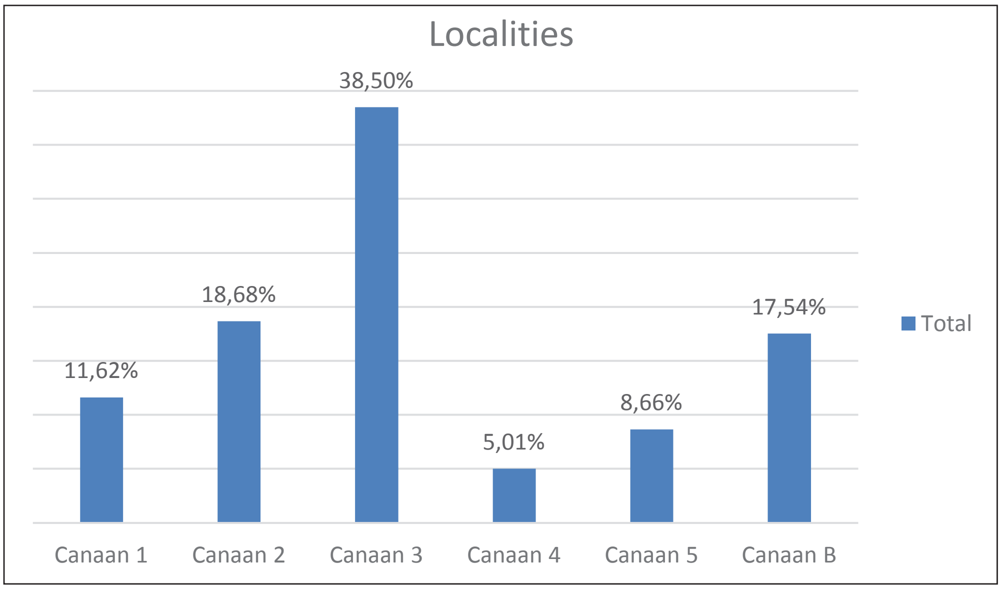

Figure 3. Distribution of the sample units between the localities

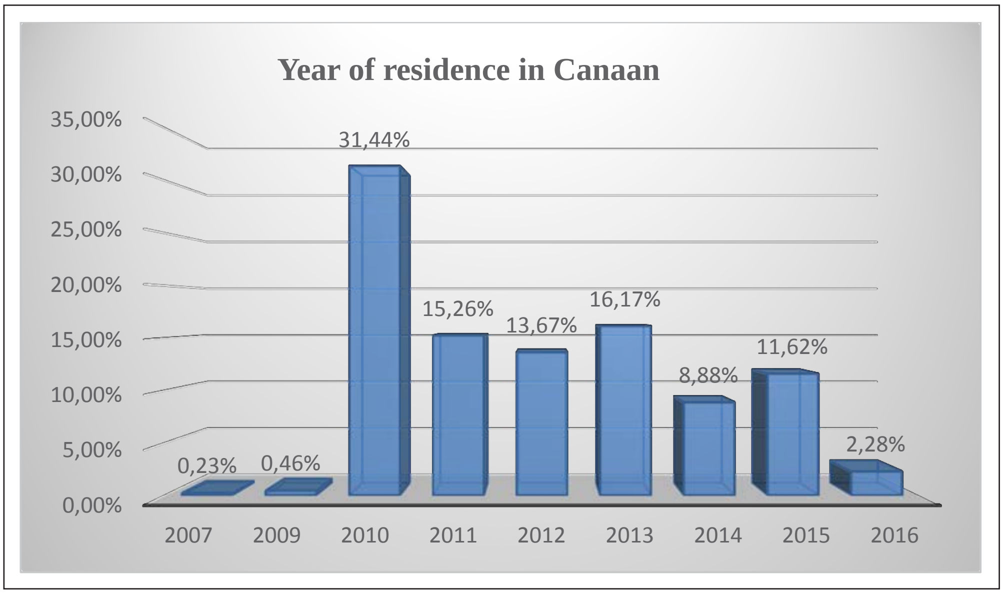

Figure 4. Statistics on the number of times that households were without water

In Canaan, 2.5% of the heads of households attended university, 31% have a high school education, and 21.41% have completed the second cycle of Haitian fundamental education. 28.47% have completed studies for the third cycle of Haitian basic education and 8.8% have never attended school.

The distribution of the households according to years of residence in Canaan is presented in Figure 4. This human settlement did not begin with the earthquake of 2010. The information obtained within the framework of the field survey highlights the existence of this settlement since 2007. Indeed, in 2007, 0.23% of the population studied was living in Canaan. In 2010, just after the earthquake, 31.44% of households moved into the area. New households settled in this area in 2016.

In 2010 and 2011, households preferred to settle in Canaan 1, 2 and 3, without excluding Canaan 4, 5 and Canaan B. After 2011, this difference in location decreased to the point that the Chi square calculated between the arrivals of households per year and their location in the 6 zones mentioned is statistically insignificant at the 0.05 threshold. Thus, the whole territory of the 6 zones progressively densified.

82% of the heads of household declared themselves to be the owners of their house. These people fled to Canaan after the earthquake and built their house there. 4.56% benefited from humanitarian aid which was used as a donation to build the house they occupy without any payment of dues. 3.64% rent their dwellings. Regarding energy, 35% of households have no power source, 27% are supplied by the public supplier, "Electricity of Haiti", 13% use solar energy, 1% is supplied by batteries and 24% by other non-defined energy sources. According to the information provided by the 439 heads of household, 73% of them reported having private latrines in their home, 13% do not have a private toilet thus they use the latrine of a neighbor, 2% use public latrines, and 4 outdoors or in the surrounding environment.

On the economic level, three classes were defined to identify the heads of household: (i) Active persons. This class includes the persons of working age who have an activity generating income. 84% of the heads of household are in this class. (ii) Active unemployed persons. This class is composed of people of working age but who have no employment and who represent 12% of the heads of household. (iii) The retired, who represent 4% of the interviewees. The salary or monthly income of the heads of family ranges from less than 1,000 to more than 10,000 gourdes. Table 1 shows the distribution of the heads of family according to their monthly income. 33.7% of household heads receive between 5,000 and 10,000 gourdes per month. 7.8% of this population have less than 1,000 gourdes per month and 28% have more than 10000 gourdes a month. 60.9% spend at least 300 gourdes per person/day on consumption. Although subject to overvaluation, the expenditure per person on daily consumption in the household ranges from 40 gourdes to 100 gourdes. These results indicate that about 42% of households have members living on less than US$1 per day for consumer spending. The statistical series of average consumer spending per day lead to the assumption that approximately 50% of the households live in a situation of extreme poverty, with an average amount per person of 62.50 gourdes to spend on daily consumption. Only 10% of these households exceed the threshold of 2 US$ a person a day.

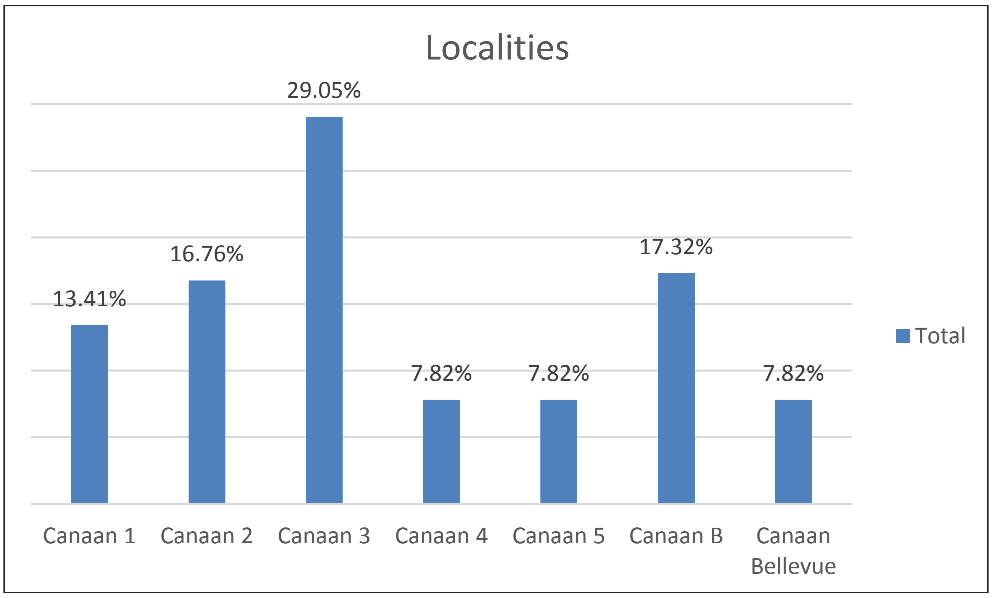

Figure 5. Distribution of water points by locality

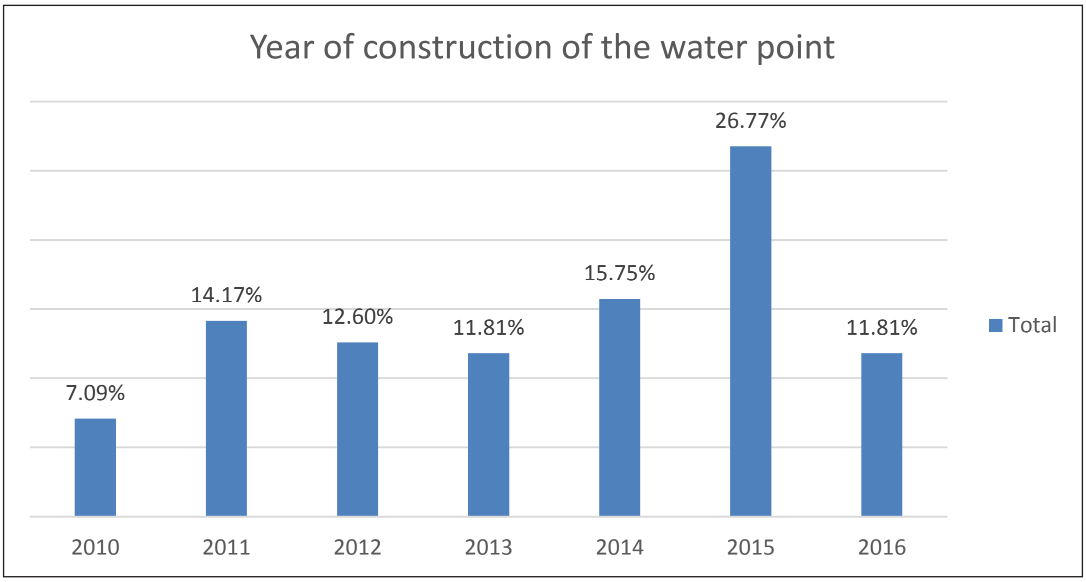

Figure 6. Distribution of water points according to their year of construction

Table 1. Distribution of heads of household by monthly income/salary

Amount in Gourdes (1 $US = 64 gourdes July 30th, 2016)	Effective	Percentage (%)
Less than 1000 gourdes	26	7.8
1000 to 2500 gourdes	50	14.9
2500 to 5000 gourdes	52	15.5
5000 to 10000 gourdes	113	33.7
More than 10000 gourdes	94	28.1
TOTAL	335	100

Analysis of water supply for human consumption in Canaan

Figure 6 provides information on the year of construction of 179 water points used for the statistical analysis. 93% of these structures were built by families, and thus become private water supply facilities. Only 7% have a collective, associative or public status. The latter have been built by NGOs or charitable institutions, or by a public institution or a group of people in the locality. Access to 95% of these water points must be paid for, whereas only 5% are free.

72% of these water points (storage tanks) are reinforced concrete structures. Wells not equipped with a pump represent 2.23% of these infrastructures; wells with hand pumps constitute 3.91% of the sample, and the collective catchment of rainwater less than 1% of the points observed. 39 water points of the179 selected provide water treated by reverse osmosis, which is theoretically intended only for drinking.

The storage tanks have a total capacity of 2,870 m^3. The minimal capacity is 1.5 m^3, and the maximum capacity is 228 m^3. The average storage capacity of these reservoirs is 17 $m^3$3. 127 of them supply untreated water and have a storage capacity ranging from 5,292 m^3 to 228 m^3. Their average capacity is 20,453 m^3. Furthermore, 40 water points of the 167 storage tanks provide water treated by reverse osmosis, which is theoretically only intended for drinking. This water is sold by volume in units of 3.78 liters or 19 liters. The storage capacity of these facilities ranges from 1.5 m^3 to 30,240 m^3. Their total capacity is 242,324 m^3. The 167 storage tanks are supplied by water tanker trucks that fill up at boreholes in the Cul-de-sac Plain. The shortest storage tank refilling (untreated water, treated water) period is 5 although refilling can take as long as 90 days. The average storage tank refilling period is at least 20 days before the next supply by water tanker truck.

Regarding the 5% threshold set, we attempted to verify for the treated water, whether the locality significantly influences the storage capacity, the duration of failure or no water supply, the frequency of supply, and the sale price by liter at the supplier. As shown in Table 2, only the frequency of supply is significantly (p=0013) lower than 0.05. Consequently, the analysis of variance concludes that the fact of being in Canaan 1, Canaan 2, Canaan 3, does not significantly influence the storage capacity, the duration of shortage, or the sale price per liter at the source of supply of the treated water. On the contrary, the locality very significantly affects the frequency of storage tank refilling. By considering the same "locality" factor and the same dependent variables, the analysis of variance for the storage tanks of untreated water showed that only the storage capacity is not significantly influenced by the locality. All other variables are affected by the locality factor (Table 3).

Table 2. Treated water storage tank with: locality as factor (ANOVA in 1 factor)

		Sum of squares	ddl	Average of squares	F	Significance
Storage capacity	Inter-cluster	119900579.600	6	19983429.933	.998	.443
	Intra-cluster	660458972.000	33	20013908.242		
	Total	780359551.600	39			
Stop of service due to breakdown or No water supply	Inter-cluster	483.250	4	120.813	2.075	.147
	Intra-cluster	698.750	12	58.229		
	Total	1182.000	16			
Frequency of supply	Inter-cluster	707.101	6	117.850	3.213	.013
	Intra-cluster	1210.274	33	36.675		
	Total	1917.375	39			
Sale price per litre	Inter-cluster	.029	6	.005	.746	.617
	Intra-cluster	.212	33	.006		
	Total	.240	39			

Table 3. Untreated water storage tank: locality as factor (ANOVA in 1 factor)

		Sum of squares	ddl	Average of squares	F	Significance
Storage capacity	Inter-cluster	8586532747.188	6	1431088791.198	1.949	.078
	Intra-cluster	88114473569.351	120	734287279.745		
	Total	96701006316.540	126			
Stop of service due to breakdown or No water supply	Inter-cluster	30277.432	5	6055.486	3.946	.005
	Intra-cluster	67526.988	44	1534.704		
	Total	97804.420	49			
Frequency of supply	Inter-cluster	2220.911	6	370.152	3.378	.004
	Intra-cluster	13040.557	119	109.585		
	Total	15261.468	125			
Sale price per litre	Inter-cluster	.060	6	.010	5.763	.000
	Intra-cluster	.207	120	.002		
	Total	.267	126			

At Canaan, the water market is segmented into two major compartments. The first includes the providers (the tanker trucks coming from the Cul-de-sac plain) and the owners of the storage facilities. The second consists of the owners of the storage tanks who reside in the area and the households of their respective localities. For each of the compartments, neither the buyers nor the sellers can significantly influence the price of the water. All they can do is to reach agreement on the indicator (the cost of water), by basing it on the price of water in the slums and the distance traveled by the tanker trucks to deliver water.

On the structural level, the market for untreated water is situated between oligopoly and perfect competition. The structure of the market for treated water is not as perfect as that for the untreated water, regardless of the compartment considered.

Water supply in Haiti is therefore a major concern for its inhabitants and for the leaders (Rosillon et al., 2016). According to PAHO/WHO (2003) the population's drinking water requirements are 20 liters per day per person to meet basic needs, if reasonable accessibility is considered on the basis of the permanent water source being located less than 200 m from the home. The establishment of the human population in Canaan requires a water supply system. In the absence of an adequate structure, some individuals have built storage tanks with a total capacity of 2,870 m^3, to provide water to the 200,000 people living there. By assuming that the volume available in the storage tanks is consumed on a daily basis, the water allocation per person per day in Canaan is 14.35 liters lower than the 20 liters per day per person calculated.

To estimate the maximum daily intake via drinking water, a normal default assumption is 2 L/day for adults and 0.75 L/day for bottle-fed infants (Fawell and Young, 1999). The 40 points offering treated water, thus drinking water, have a total capacity of 242,324 m^3. The results of the survey on the demographic characteristics of this population lead to the assumption that for a household of average size with 5 persons, 2 of its members will be older than 18. Based on the assumption that each household has two adults and three children, the daily demand for drinking water is 250,000 m^3 greater than the supply.

Analysis of water demand in Canaan

Table 4 shows the statistics for the number of times the households lack water. In Canaan, 5% of the daily budget of about 93% of households is spent on purchasing treated water for drinking, while this figure is less than 5% for households using only untreated water. The average percentage share of water in the daily consumption of the households consuming treated water is 13.5%. Without accurate information on household income, the salary of the head of household was considered to assess the percentage weight of water in the monthly income of the household. For 166 selected households, an average of 16% of the income of the head of household is spent on water. For 25% of households, the percentage weight of water in monthly income exceeds 24 %.

76.89% of people make a distinction between the water they drink and that which they use for laundry or bathing. 77% of heads of households having reached the 3rd cycle of basic education make a distinction between treated and untreated water. This percentage is 100 for those who have obtained their certificate of professional competence. A chi-square test was performed to assess the relationship existing between the level of education of the heads of household and the quality of the water used. The probability associated with the chi-square statistics (X-squared = 22.391, df = 7, p-value = 0.002175) calculated is less than 5%. Thus, these two variables are related to a risk of 5%.

The existence of a relationship between the size of the household and the quantity of drinking water purchased on average per day was studied. The resulting correlation coefficient is 0.15 (t = 3.1835, df = 437, p = 0.001559). This result proves that the relationship between these two variables is positive; on average the higher the size of the household, the greater the quantity of water purchased per day increases. This value is significant as the p-value associated with it is well below 5%.

Table 4. Statistics on the number of times that households were without water

Statistics	**Number of times when households were without water because of lack of money.**		**Number of times households were without water because they did not find it.**	
Effective	439		439	
Mean	3.21		1.42	
Median	2		0	
Mode	0		0	
Standard deviation	4.082		2.366	
Minimum	0		0	
Maximum	20		10	
Percentiles	25	0	25	0
	50	2	50	0
	75	5	75	2

The cost of water in Canaan

93% of the water supplied must be paid for. The average price per liter for drinking water is relatively the same throughout the area targeted. Its average price is 1.56 gourde with a standard deviation of 0.53. There are nevertheless differences between the sectors of the study area. The average price per liter is higher in Canaan 1, 2 and 3. It fluctuates between 1.60 and 1.63 gourdes, while it is between 1.37 and 1.45 in Canaan 4.5 and Canaan B.

The differences in average price per liter are much more noticeable with respect to water for domestic purposes other than drinking water. The overall average price per liter (0.46 gourde) is much lower than in the case of drinking water. On the other hand, average prices per liter are highly contrasted between the sectors of the study area and the statistically significant differences at 0.00 level, clearly separating Canaan1, 2,3 from Canaan 4,5 and Canaan B.

The same contrast between the two groups of sectors thus concerns both types of water. It is in all likelihood based on taking into account the different access and delivery difficulties in the two groups of sectors. Furthermore, in the opinion of those involved in the field, local solidarity was not involved in the same way in the different sectors covered by the survey.

CONCLUSION

Very few water resources are organized in Canaan. In the absence of basic social services, in particular the public supply of drinking water, the population organizes itself to bring in some water by tanker trucks to supply 167 storage reservoirs. Globally, this activity is a source of employment and income for a proportion of the population. The water service is ensured by the market and according to market logic. This market provides water supply services that are subject to competition and an oligopolistic structure. The selling price and the frequency of supply remain the main variables that establish the spatial discrimination of supply in the water market in Canaan. A larger sample will be necessary in the future to study the mechanisms capable of ensuring of the democratic management of water in this area.

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EPIDEMIOLOGICAL TRANSITION ANALYSIS IN VULNERABLE AREAS IN HAITI, IN DEFERENCE TO HYDROMETEOROLOGICAL DISASTERS

EPIDEMIOLOGIQUE DANS LES ZONES VULNÉRABLES EN HAÏTI, EN DIFFERENCE DES CATASTROPHES METEOROLOGIQUES HYDRO

ANALISIS DE LA TRANSICIÓN EPIDEMIOLÓGICA EN ZONAS VULNERABLES DE HAITÍ, ANTE DESASTRES HIDROMETEOROLÓGICOS

Gabriela Bravo-Orduña[1]**; Alfonso Gutiérrez-López**[2]

Abstract

It presents the description of the medical services and the Ministry of Health in Haiti, with different levels of organization. The epidemiological transition of the main diseases that have been presented by Departments in the last years is analyzed. In addition, the hydrometeorological information is shown in the form of intensity, duration and period of return of extreme rains, in order to characterize the pluviometric regime of the country. Using this information, a *Meteo-Epidemiological Vulnerability Index (MEVI)* is proposed. This index uses infectious-contagious disease data, the capacity and distribution of medical infrastructure, physiographic conditions of the country, and rainfall data (expressed in intensities, durations and frequency). The results show how mortality and morbidity rates are influenced mainly by communicable diseases in different risk areas. It is concluded that the territorial vulnerability exposed to hydrometeorological phenomena increases in the West and South Departments, where there is a high prevalence of diseases that exceeds the capacity of medical attention.
Keywords: Medical services**,** hydrometeorological conditions, epidemic, cholera, malaria, vulnerability by zones.

Resumen

Se presenta la descripción de los servicios médicos y del Ministerio de Salud en Haití, con sus diferentes niveles de organización. Se analiza la transición epidemiológica de las principales enfermedades que se han presentado por Departamentos en los últimos años. Adicionalmente, se muestra la información hidrometeorológica en forma de intensidad, duración y periodo de retorno de lluvias extremas, con el objeto de caracterizar el régimen pluviométrico del país. Empleando esta información se propone un Índice de Vulnerabilidad *Meteo-Epidemiológico (MEVI).* Este índice utiliza datos de enfermedades infecto-contagiosas, la capacidad y distribución de la infraestructura médica, las condiciones fisiográficas del país, y los datos del régimen de precipitaciones (expresados en intensidades, duraciones y períodos de retorno). Los resultados permiten conocer cómo influyen las tasas de mortalidad y morbilidad principalmente por enfermedades transmisibles en las diferentes zonas de riesgo. Se concluye que la vulnerabilidad territorial expuesta a fenómenos hidrometeorológicos aumenta en los Departamentos Oeste y Sur, en donde existe gran prevalencia de enfermedades que sobrepasa la capacidad de atención médica.
Palabras clave: Servicios médicos, condiciones hidrometeorológicas, epidemia, cólera, malaria, vulnerabilidad

Résumé

La description des services médicaux et le ministère de la Santé en Haïti, avec ses différents niveaux d’organisation est présentée. On analyse la transition épidémiologique des principales maladies qui ont été soumises par les ministères au cours des dernières années. Autant, les informations hydrométéorologiques sont utiliser en forme d’intensité de pluies extrêmes, aussi sa la durée et sa période de retour, afin de caractériser le régime des précipitations dans le pays. En utilisant cette information on propose un *Indicateur de Vulnérabilité Meteo-Epidémiologique (MEVI)*. Cet indice utilise les données de maladies infectieuses, de la capacité et de la distribution de l’infrastructure médicale, les conditions physiographiques du pays, et les données des précipitations (exprimée en intensités, durées et périodes de retour). Les résultats permettent de mieux comprendre comment influer sur les taux de mortalité et de morbidité due aux maladies transmissibles, principalement dans les différentes zones de risque. On conclu que la vulnérabilité territoriale exposée à des phénomènes hydrométéorologiques augmente dans les départements de l’Ouest et du Sud, où il y a une forte prévalence des maladies au-delà de la capacité des soins de santé.
Keywords: Services médicaux**,** Conditions hydrométéorologiques, épidémie, choléra, paludisme, Vulnérabilité par zones.

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INTRODUCTION

The ministry of public health and the population is the institution in charge of the health system in Haiti. The microsystems of community health units constitute the basic level of care in the country, which in turn is divided into two orders: the first order is composed of health centers, clinics and private centers where it is attended on an outpatient basis. Second order are hospitals centers of concentration where first order referrals are made; they include pediatrics, gynecology-obstetrics, surgery and internal medicine; In Haiti there is an approximate coverage for a population of 150,000 to 200,000; these hospitals are responsible for more specialized care and hospitalization service. Missing specialty services such as urology, ophthalmology, orthopedics and cancerology are made up of departmental hospitals, thus forming the last level of care (PAHO, 2004).

The Health Council is the entity in charge of the management of services of first order, the communication between this and the second order organizations is based on a medical appointment and a view of medical appointment. Approximately 35% of the care centers are made up of the public sector, private practice constitutes 32% and about 31% are made up of mixed institutions along with non-governmental and non-profit institutions. By contrast, about 80% of the population uses traditional practices, most of which live in rural areas and more than 15 km away from medical care (MPHP, 2013).

Even prior to the earthquake, Haiti had the highest indicators of maternal and child mortality, malnutrition, Tuberculosis and HIV/AIDS, with a low life expectancy and, together with the loss of much infrastructure and health services workers, The situation of the country was seriously compromised, so that diseases prevalent on the island and non-prevalent suffered a change in the course of the months prior to the earthquake and hydrometeorological events that affected vulnerable population (IFCR, 2010).

One of the main problems that afflict the country and involve the various strata of society is communicable diseases, notably influenced by the various natural disasters that have afflicted it in recent years. The prevalence of these diseases increased considerably after the earthquake in 2010 with the Cholera epidemic as one of its major health consequences. Due to the precarious hygienic conditions of health, climatic conditions and low resources, the predisposition to vector-borne diseases increased. In addition to these problems is the disadvantage of the country's vulnerability to extreme hydrometeorological phenomena. The territory of Haiti is especially vulnerable to hurricanes and tropical storms, as well as to geological phenomena such as earthquakes. It is for the above that this work proposes to combine the health aspects with the hydrometeorological aspects expressed in a *Meteo-Epidemiological Vulnerability Index (MEVI)*.This index uses quantitative variables formed by infectious-contagious disease data, the capacity and distribution of the medical infrastructure, the physiographic conditions of the country and the precipitation regime data (expressed in intensities, durations and return periods). The calculation of the *MEVI* is done through a Multivariate Analysis by an Empirical Orthogonal Function (EOF) in which allows hierarchizing and correlating the variables and being able to identify which areas or Departments are most affected. Similar studies with multivariate techniques have been carried out with climatological data (Rao, *et al.,* 1991; Gottschalk, *et al.,* 2015; Kima, *et al.,* 2015). However, few studies have been carried out using health variables with climatological variables.

OBJECTS AND MATERIALS

The main objective is report about the preconditions of Haiti's health services and the situation of these services after natural phenomena, such as hurricanes. Show the relationship between hydrometeorological conditions as a cause of epidemics and the response of health services according to their capacity by Departments. Use a empirical orthogonal function (EOF) analysis to reduce a data set containing a large number of variables to a data set containing many fewer variables, but that still represents a large fraction of the variability contained in the original data set (Vargas, *et al.,* 2009; Busch, *et al.,* 2012). Using this information, a Meteo-Epidemiological Vulnerability Index (MEVI) is proposed. This index uses infectious-contagious disease data, the capacity and distribution of medical infrastructure, physiographic conditions of the country, and rainfall data (expressed in intensities, durations and frequency).

DEVELOPMENT

At the beginning of the last decade, Cholera was not part of the morbidity and mortality statistics despite having a high prevalence of acute diarrheal diseases, but by 2010, as the incidence of watery bowel movements increased in some vulnerable areas and subsequent to investigations carried out by the Cuban medical brigade, it was determined that the origin of the outbreak was due to the microorganism Vibrio Cholerae O1 serotype Ogawa, causing 442 deaths in November of that year of a total of 6,742 hospitalized patients. The first case arose in the Department of Artibonite, an area with minimal earthquake damage, so it is believed that its spread to the various Departments was indirectly due to secondary conditions (IFCR, 2010). The rapid spread of the outbreak by the Departments triggered measures for their attention and containment, however unfavorable conditions such as the mass concentration of the population in some areas such as Port-au-Prince caused 143,036 cases of Cholera with a case fatality rate of 0.7 compared with The high lethality rates in the Southeast with 4.3 and Grand Anse with 4.1 and a total of 8,090 and 22,107 cases respectively (see figure 1), where it is assumed that the lack of medical centers for health care contributed as one of the main reasons of mortality.

Of vector-borne diseases, Malaria is endemic in some coastal areas, especially where the height (altitudes) less than 300 m above sea level, in other regions the outbreaks are seasonal, influenced by climatic factors, with a high prevalence after Hurricanes triggering increased activity of the mosquito transmitter, increased exposure of the population due to destruction of their homes and exposure to the environment, rainwater stalls, inefficiency of drainage systems, excreta and lack of potable water. Because it is believed that the total number of the population affected by Malaria was undervalued by the lack of notification of cases prior to the year 2010, it is not clear if it was an outbreak in the area (PAHO, 2012). According to data obtained from the National Malaria Control Program by the Ministry of Health of 2011, the highest incidence rate was reported in the Central Department with 264 cases in 2009, to 26,563 cases by 2010 (see figure 2).

Because reproduction of the Anopheles mosquito is inversely proportional to the height (altitude), coastal areas are more vulnerable to the spread of Malaria; at a height above 2,500 m above sea level the mosquito does not survive. With this we observe that much of the country is in the ideal conditions of temperature and humidity for the dissemination (see figure 3). The outbreak that originated in the Center during 2010 could have been triggered by the factors mentioned above and with the already mentioned factors triggered by the earthquake.

As mentioned above, Tuberculosis is a disease of high incidence in the country, by 2010 the prevalence was 230 cases per 100,000 inhabitants (PAHO, 2012), after this period was detected especially in the cases of displaced persons camps (see figure 4) and of 1,165/100,000 inhabitants until the year 2013, considering between these periods the affectations caused by the Hurricans Ernesto and Issac in August of 2012 and Sandy in October of the same year (Koenig *et al*., 2015).

Another hurricanes that has left considerable damage in Haiti, were Ike in 2008 (Bozza *et al*., 2016) and Tomas in 2010 (Shamir, *et al*., 2013), in those occasions was able to calculate some flow rates, and however was not associated with damage to health.

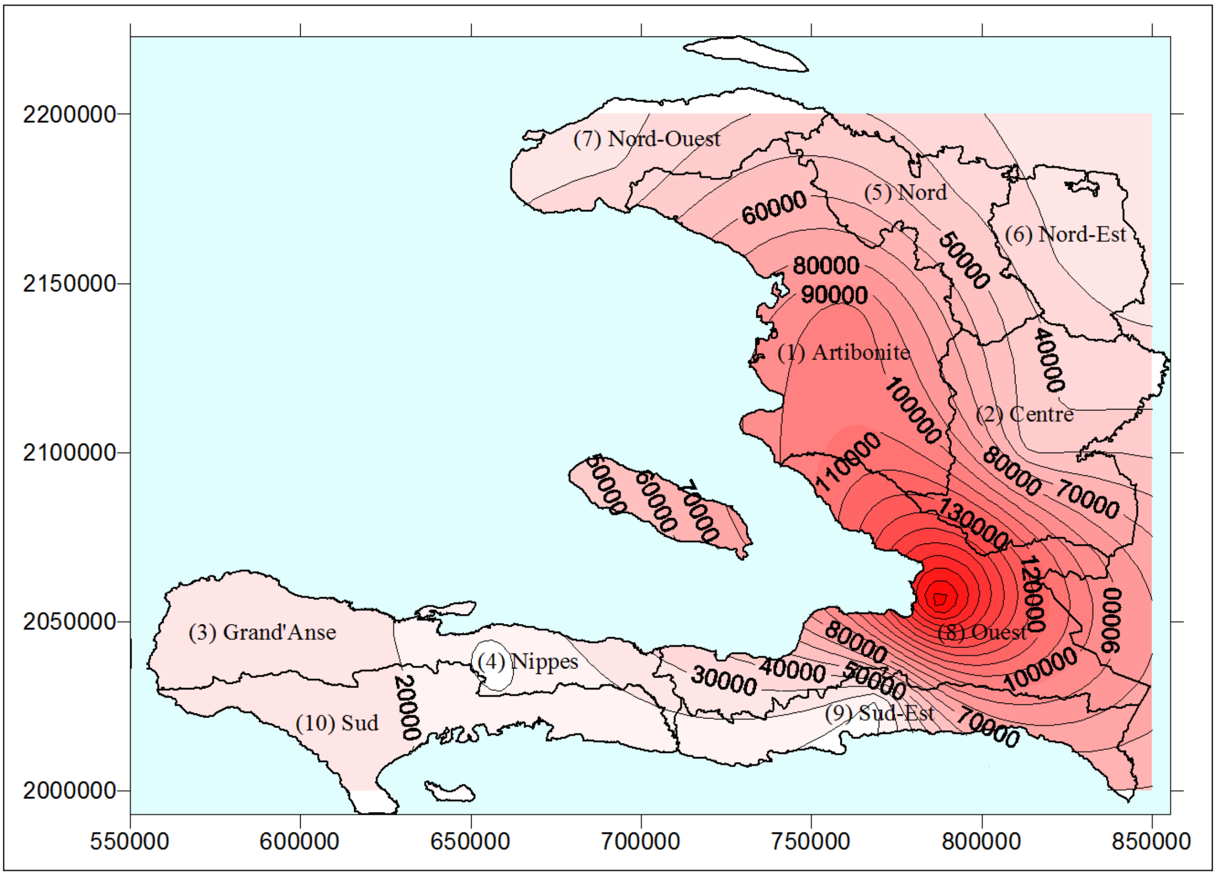

Figure 1. Number of Cholera cases presented in the period 2010-2012. Adapted from WHO, 2010

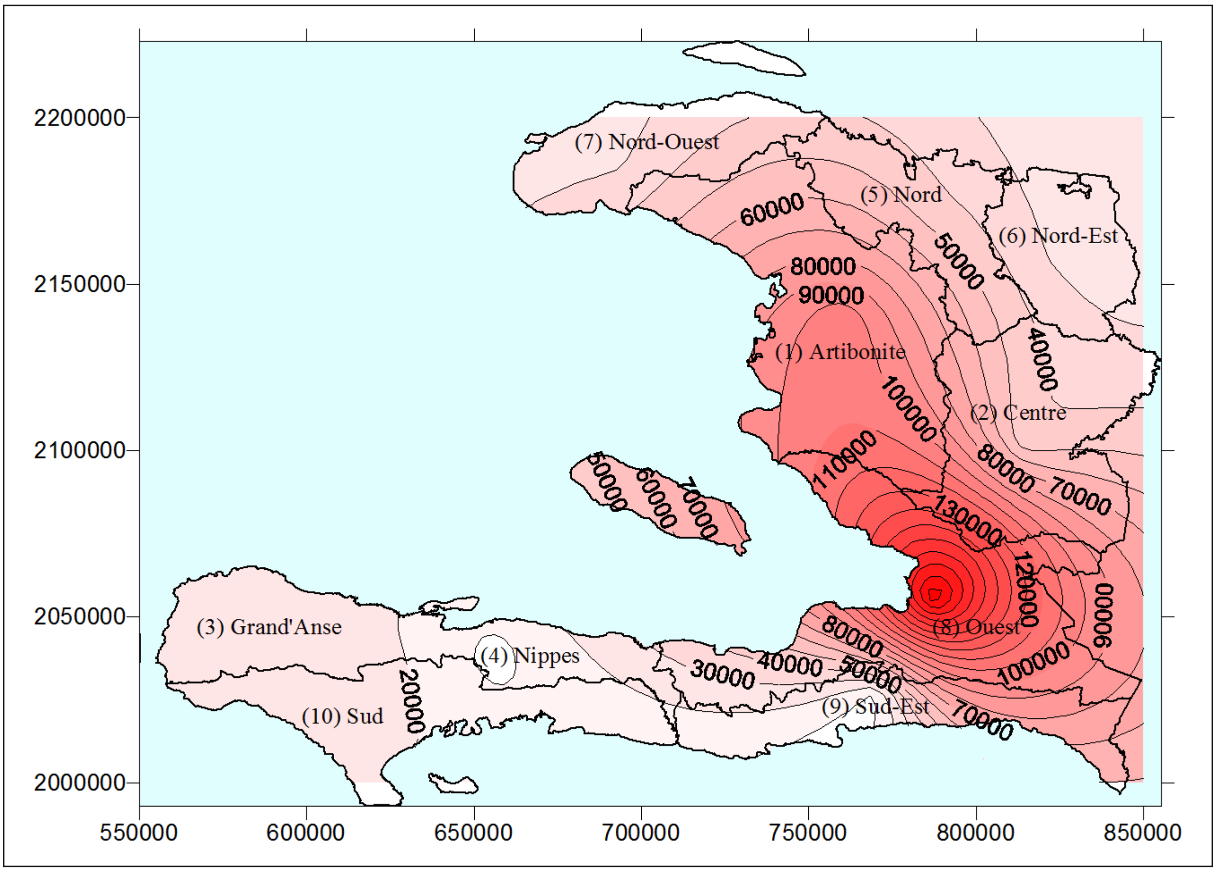

Figure 2. Number of Malaria cases presented in year 2010. Adapted from WHO, 2010

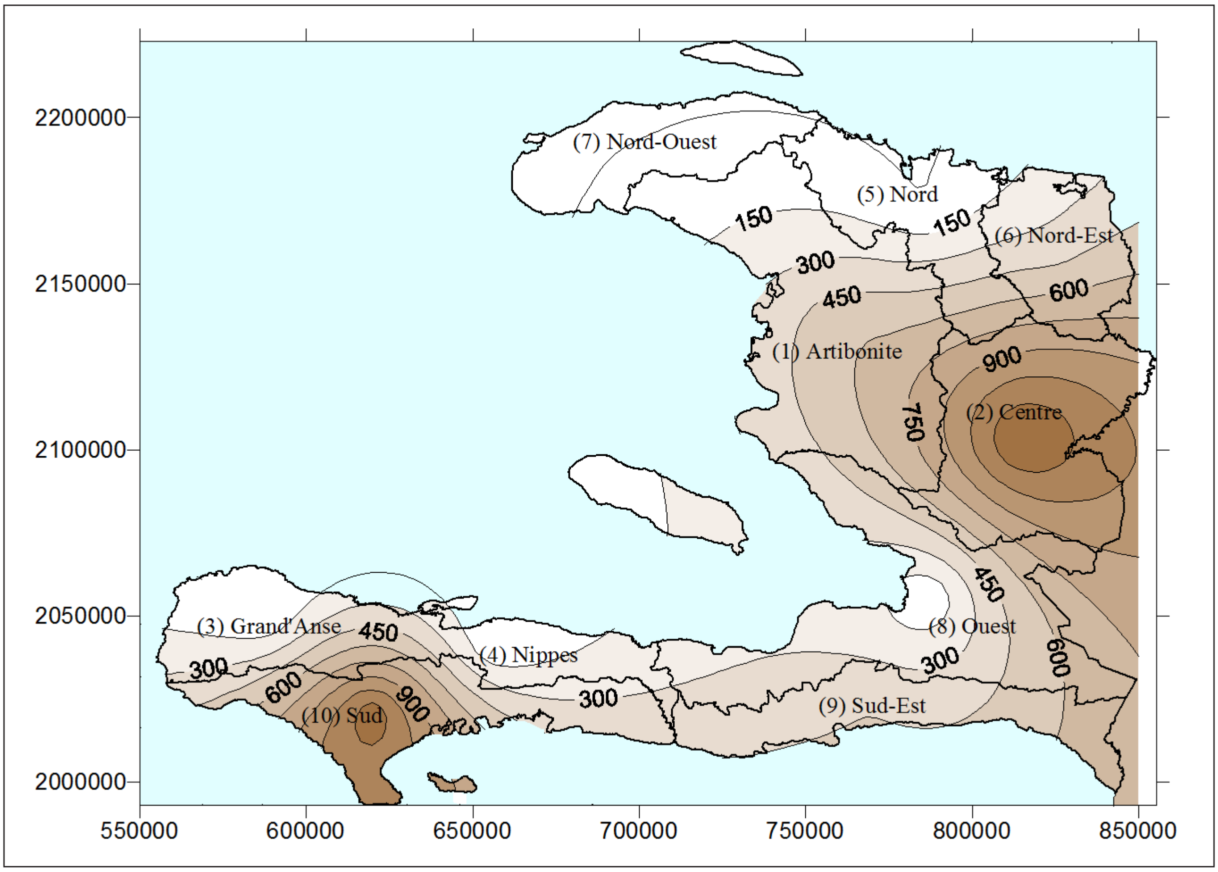

Figure 3. Topography of Haiti, altitude of zones in meters

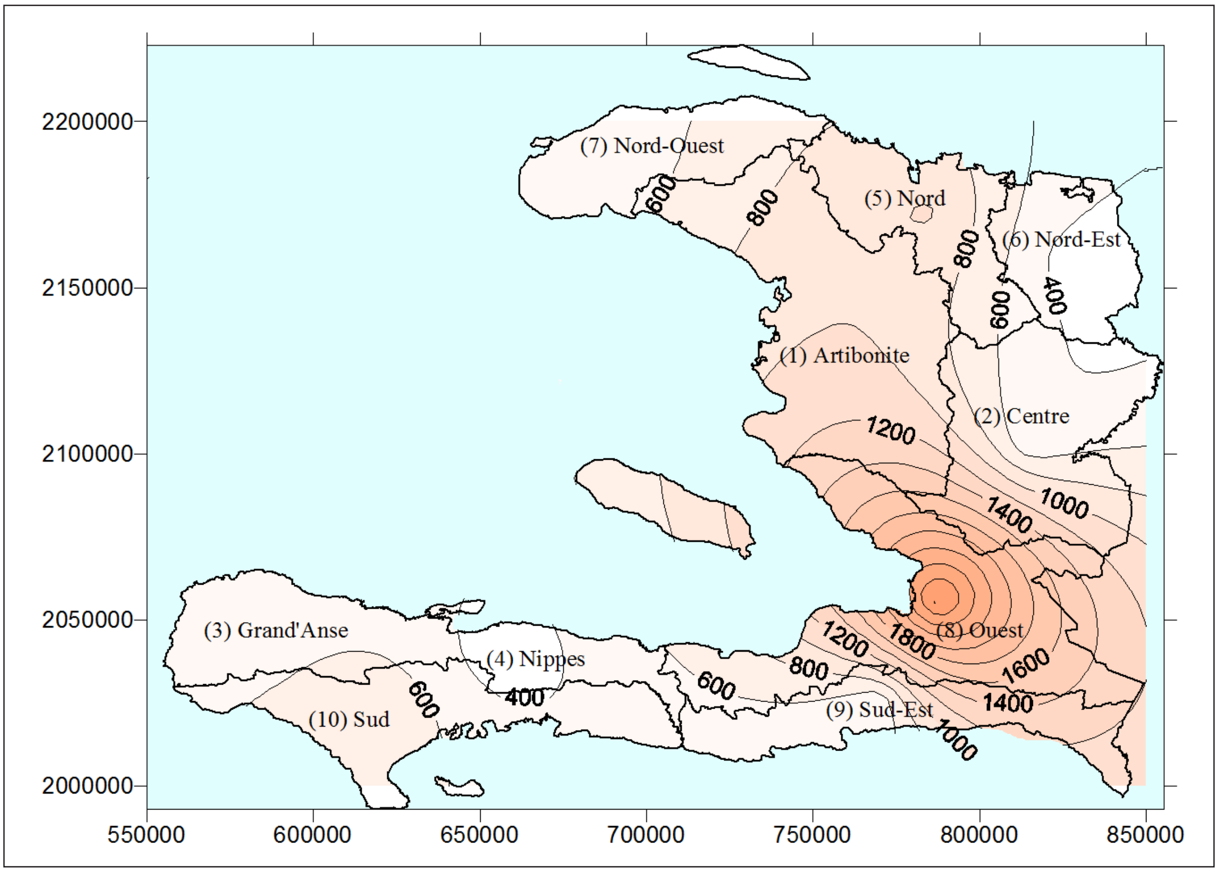

Figure 4. Number of new cases of positive bacilloscopy in 2010. Adapted from WHO, 2010

According to the Central Intelligence Agency of the United States, the proportion of beds in Haiti in 2007 was 1.3/1,000 inhabitants, ranking 137th in the world (Mexico 1.5/1,000 inhabitants) and also Haiti had 0.25 doctors per 1000 inhabitants with place 142, who establishes a minimum threshold of 2.3 physicians per 1,000 inhabitants (CIA, 2007). Considering these statistics and that 2.3 million people were left homeless with a displacement of approximately 1.4 million to makeshift camps, without the minimum optimal conditions of hygiene and sanitation, the capacity of the medical services were exceeded and with this raising the incidences of infectious-contagious diseases (IACHR, 2011).

The highest concentration of hospitals for the year 2008 lies in two main areas: Port-au-Prince and the Northern Department with coverage of 35,000 to 45,000 people and <35,000 inhabitants per hospital respectively; with less coverage in the central area of Grand Anse, the South Department and especially in the Southeast with more than 65,000 inhabitants/hospital (see figure 5). Regarding hospital coverage, it is observed that the approximate number of hospitals per zone, has a greater tendency towards the capital of the country with gradual decrease in peripheral form, and with a smaller amount in the Department of Southeast (see figure 6).

Like the distribution of hospitals, the first level centers are in greater concentration near the capital (see figure 7). The importance of these figures is that many of the specialized hospitals and health centers were seriously affected or totally destroyed by the earthquake and the subsequent Hurricanes Ernesto, Issac and Sandy in 2012, reason why many of the centers that were maintained had to be used as centers of mass attention for the victims affected in those disasters.

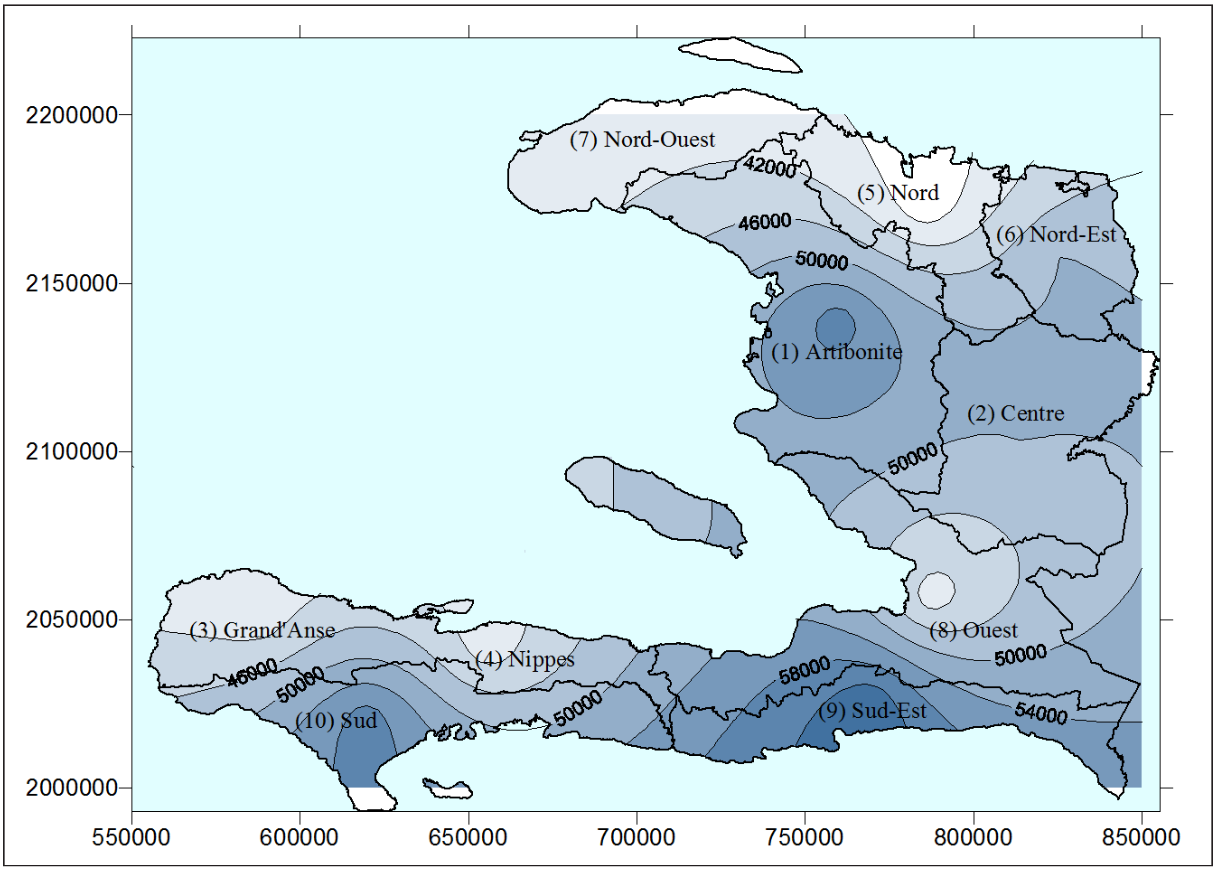

Figure 5. Number of inhabitants per Hospital, 2008. Adapted from WHO, 2010

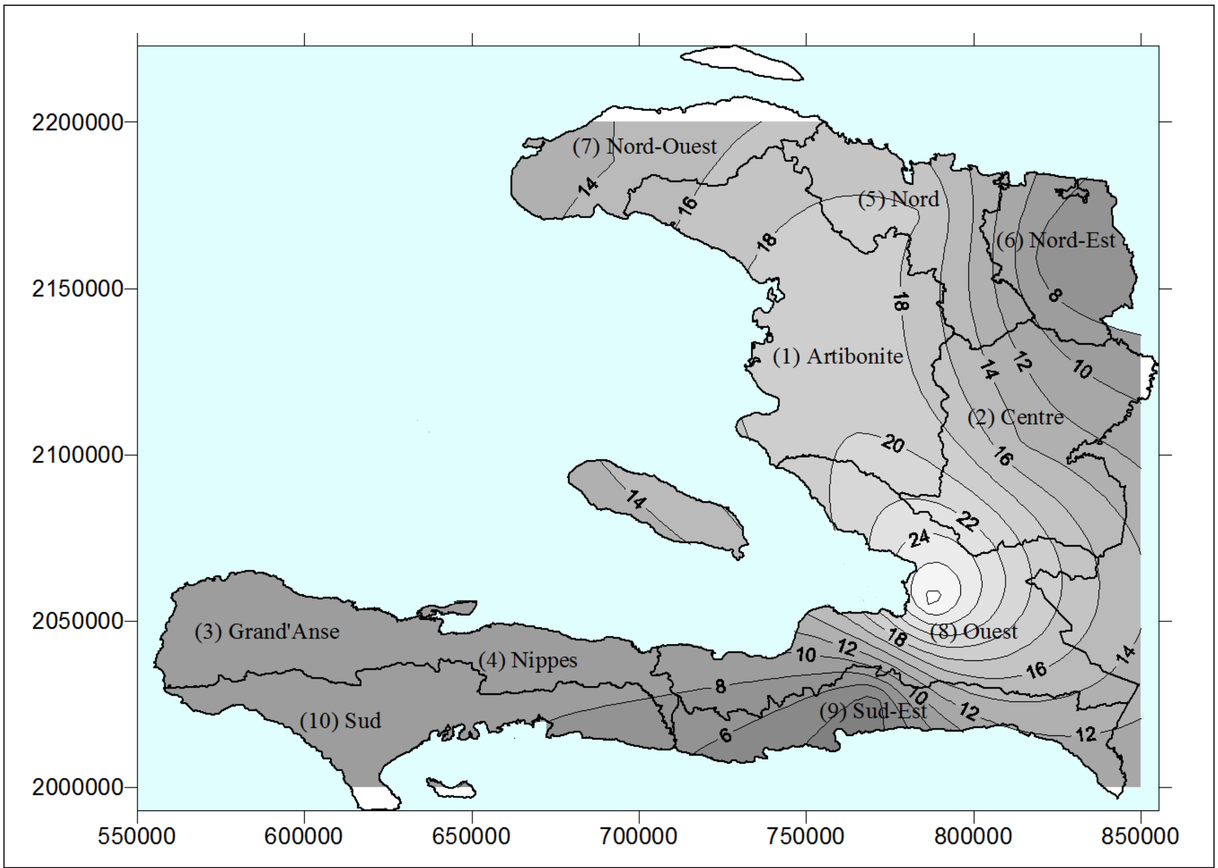

Figure 6. Number of Hospitals by zone 2010. Adapted from WHO, 2010

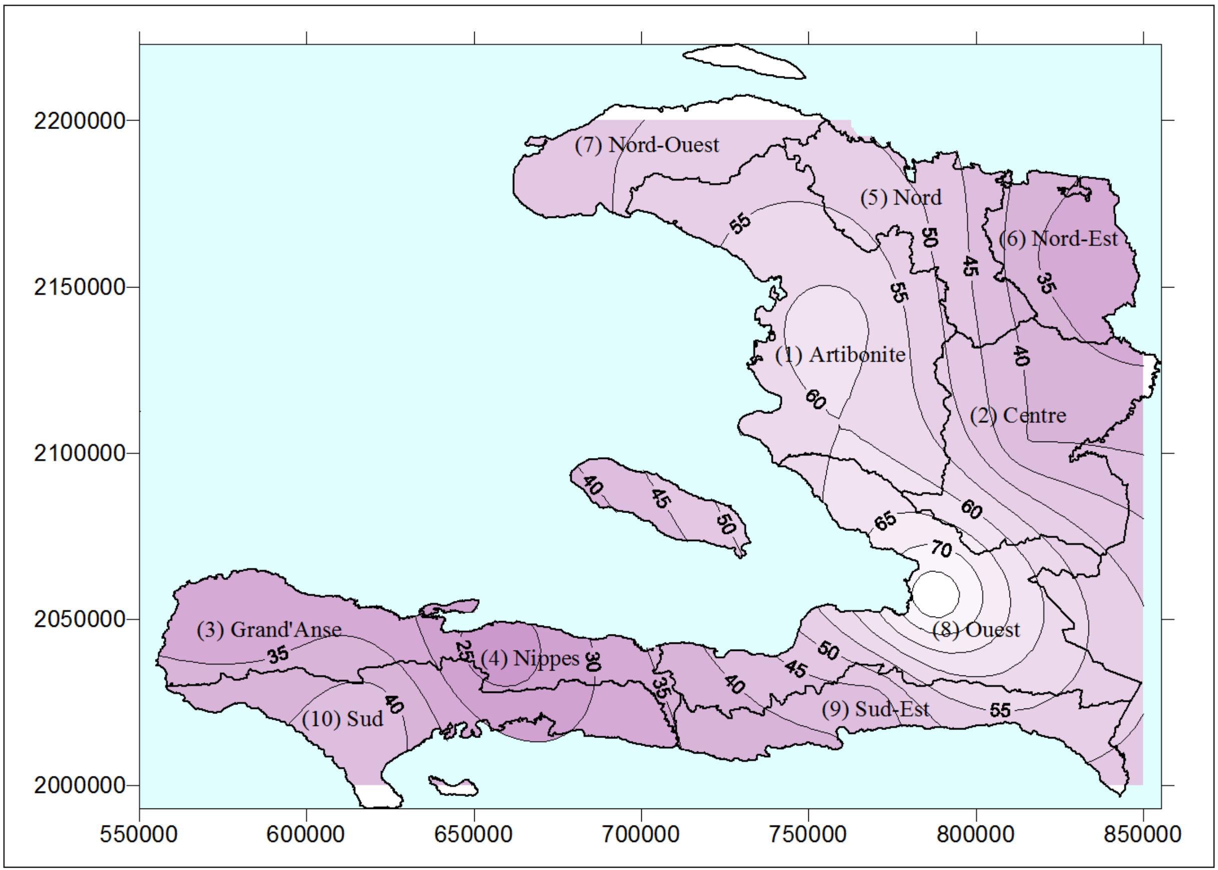

Figure 7. Number of Health Centers by area, 2010. Adapted from WHO, 2010

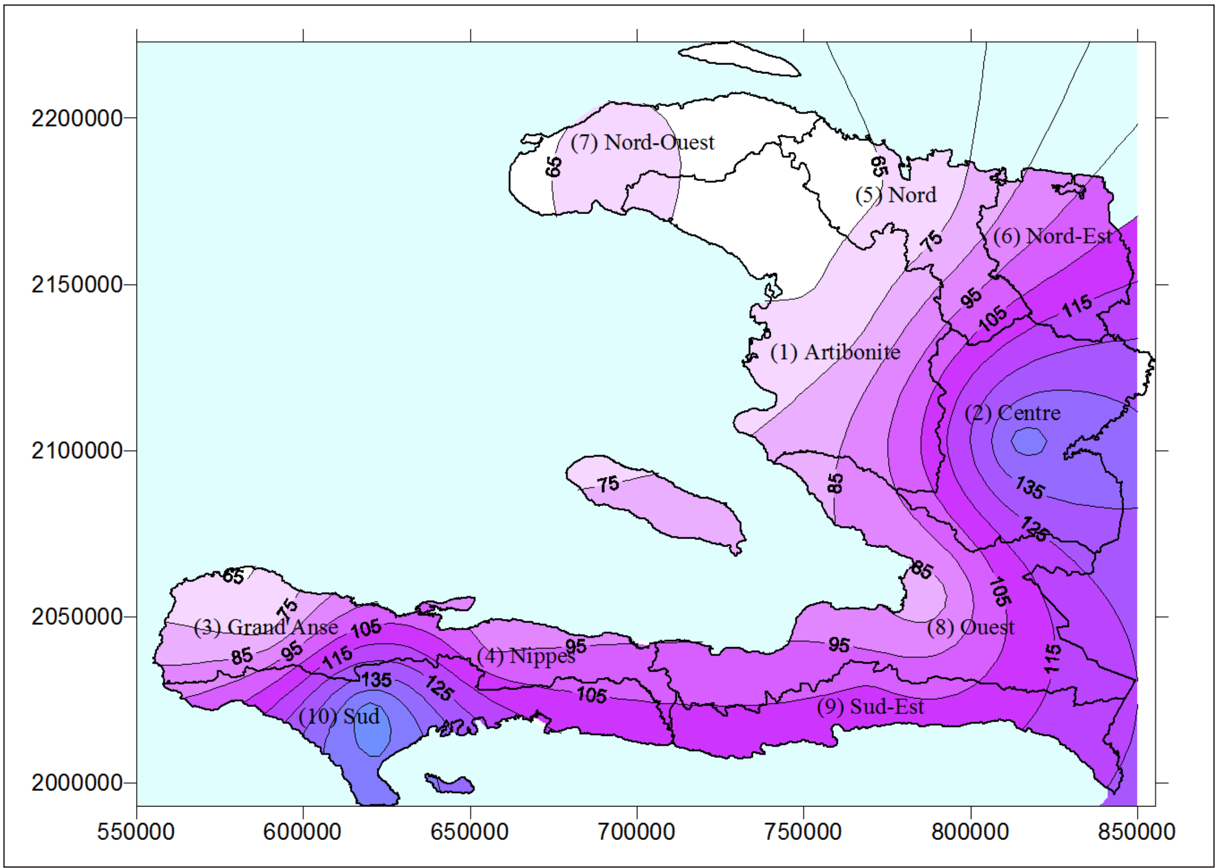

Figure 8. Intensity of rainfall 10 years return period and one hour duration storm

DEVELOPMENT

A Meteo-Epidemiological Vulnerability Index (MEVI) is the product of each one of the principal component $|\Omega_i|$ multiplied by the infectious-contagious disease data, the capacity and distribution of medical infrastructure, physiographic conditions of the country, and rainfall data (figure 8), as follow.

$$(MEVI_j) = \sum_{j}^{n} Z_j \left| \sum_{i}^{k} \Omega_{i,j} \right|$$

where

Z_j are the proposed central standardized values of the health and medical characteristics estimated by

$$Z_i = (X_i - \mu_x)/\sigma_x$$

Ω_i i-*th* principal component of each site (Department).

Table 1, shows the limits of Meteo-Epidemiological Vulnerability Index (MEVI). Table 2 shows the variables of infectious-contagious disease data, the capacity and distribution of medical infrastructure, physiographic conditions of the country and rainfall data. With these values an EOF analysis was carried out. In this analysis, it was found that the first two principal components explain the 67% of the variance of health and medical characteristics. Figure 9 shows the circle of correlation coefficients among the 8 proposed variables (table 2). EOF results show the existence of two groups of variables that define the behavior of the Haiti (figure 9). The first group is formed by the morphologic, hydrometeorological (figure 8) and infrastructure characteristics and Malaria data (Hab/Hospt; Malaria; Altitude, others and T10D60). The second group is composed by the geographic longitude, number of hospitals, Cholera, Tuberculosis, hospitals and health centers. This analysis can offer additionally a prioritization of the characteristics based on the projection of each variable over the axis of the principal components $|\Omega_i|$. This procedure corresponds to the traditional interpretation of an EOF in which it can be observed that the variable with highest importance for the first principal component $|\Omega_1|$ are hospitals and Cholera, and that of highest relevance for the second component $|\Omega_2|$ are the rainfall intensity for 10 years return period and one hour duration and altitude. Likewise, the values of the characteristics shown in table 3 are standardized.

The formed groups check the obvious hydrometeorological and heath condition of Haiti. The concentration of large masses together with the conditions of water shortage and lack of proper disposal of sewage triggers an environment of easy spread of infectious-contagious diseases. We have Cholera as the most important variable. Its means of transmission is by contact with the feces of the sick, as well as food and water contaminated by Vibrio Cholarae. Considering that the hospitals are located in zones of greater population concentration and that these were found to exceed their maximum capacity the contagion was high and with easy propagation. Something similar can be observed with Tuberculosis, which is transmitted by means of "flügge" droplets which are secretions that are sent from an infected person, especially when coughing, measuring from 1 to 5 μm and contain the bacillus responsible for the disease (Mycobacterium Tuberculosis). Taking into account its easy propagation is compressible that in areas of greater concentration and in hospitals that even having the necessary measures for their containment, it spread. In an isolated and opposite way we find Malaria, being a disease transmitted by vector through the Anopheles mosquito, the vulnerability of the affected area will depend only on the conditions that favor the reproduction of the insect. Low altitude zones, with higher rainfall frequency, poor wastewater management are the ones that will be most exposed to this disease. The only human-human transmission of Malaria is by blood transfusions or via maternal-fetal route. So concentrations of the population will not be a risk for its dissemination unless they are in areas of vulnerability. This is why the outbreak occurred in the Central Department in 2010 does not exist such a close relationship with the other variables analyzed; this justifies the opposite occurrence with the opposite variables of latitude and longitude as shown in figure 8. The distribution of hospitals is inversely proportional to greater latitude and, to a lesser extent, to the length of the capital, whereby peripheral areas have fewer hospitals, perhaps influenced by demographic and economic structures.

Table 1. Meteo-Epidemiological Vulnerability Index (MEVI) proposed limits

Minimum value	MEVI condition	Maximum value
+ 10.0	Extreme vulnerability	> + 20.0
+ 5.0	Average vulnerability	+ 9.9
0.0	Normal condition	+ 4.9
	Safety condition	- 0.1

For example, the MEVI index for the Grande Anse Department (3) is, from the figure 10, $\Omega_1 = -0.56251$

and $\Omega_2 = 1.7667$ and $\left| \sum_{i=1}^{k=2} \Omega_{i,j} \right| = 1.20419$

using the standardized variables $\sum_{j=1}^{n=7} Z_j = -3.770$

Finally

$$(\mathrm{MEVI}_j) = \sum_j^n Z_j \left| \sum_i^k \Omega_{i,j} \right| = (1.20419) * (-3.770) = -4.5397963$$

This result corresponds to a Safety condition in the Grande Anse Department (3), (see figure 11).

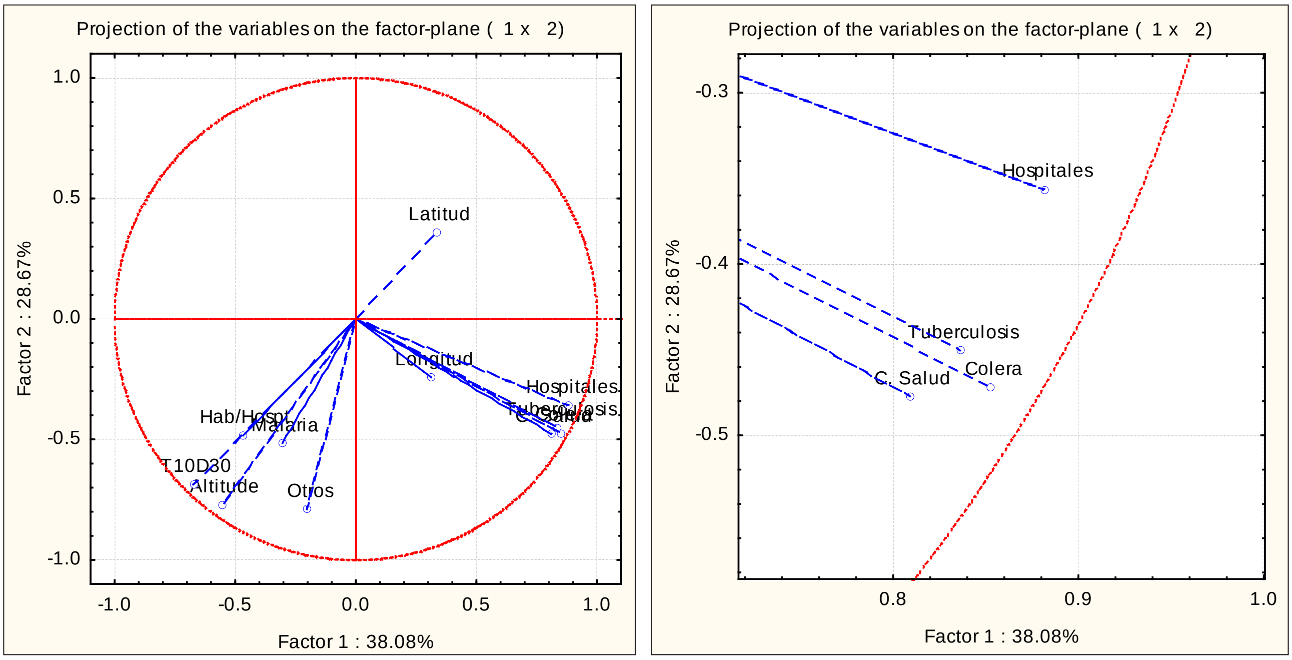

Figure 9. EOF results by variables

Table 2. Variables of Infectious-contagious disease data, the capacity and distribution of medical infrastructure, physiographic conditions of the country and rainfall data

	Department	T10D30 (mm/h)	T10D60 (mm/h)	Cholera (# cases)	Tuberculosis (# cases)	Hab/ Hospt	Malaria (# cases)	Hospitals	Health Centers	Others
1	Artibonite	102.5	67.3	107,924	1,000	60,000	3,157	20	63	4
2	Center	227.3	149.2	43,129	458	50,000	26,563	14	40	10
3	Grande Anse	102.5	67.3	22,107	488	40,000	1,808	9	32	4
4	Nippes	142.4	93.5	7,247	282	40,000	1,904	9	20	4
5	North	102.8	67.5	45,149	1,020	35,000	597	18	50	2
7	Northwest	102.8	67.5	28,168	490	40,000	1,038	14	50	3
6	Northeast	153.1	100.5	27,433	335	50,000	2,551	6	32	3
8	West	118.1	77.5	208,901	2,901	40,000	3,440	29	81	9
10	South	246.5	161.8	27,944	796	60,000	1,042	10	45	19
9	Southeast	164.3	107.9	8,090	472	65,000	7,443	3	42	1

Table 3. Standardized Variables of Infectious-contagious disease data, the capacity and distribution of medical infrastructure, physiographic conditions of the country and rainfall data

	Cholera	Tuberculosis	Hab/Hospt	Malaria	Hospitals	H. Centers	Others	*Sum Z*	*Sum EOF*	MEVI
1	0.894	0.227	1.133	-0.229	0.893	1.017	-0.350	*3.585*	*0.880*	**3.16**
2	-0.153	-0.473	0.189	2.756	0.105	-0.320	0.756	*2.860*	*4.158*	**11.89**
3	-0.493	-0.434	-0.755	-0.401	-0.552	-0.785	-0.350	*-3.770*	*1.204*	**-4.54**
4	-0.733	-0.700	-0.755	-0.389	-0.552	-1.482	-0.350	*-4.961*	*0.451*	**-2.24**
5	-0.121	0.253	-1.227	-0.556	0.631	0.262	-0.719	*-1.478*	*3.022*	**-4.47**
7	-0.395	-0.431	-0.755	-0.499	0.105	0.262	-0.535	*-2.249*	*2.455*	**-5.52**
6	-0.407	-0.632	0.189	-0.307	-0.946	-0.785	-0.535	*-3.421*	*0.174*	**-0.60**
8	2.526	2.681	-0.755	-0.193	2.075	2.063	0.571	*8.969*	*2.375*	**21.30**
10	-0.399	-0.036	1.133	-0.499	-0.420	-0.029	2.415	*2.164*	*4.787*	**10.36**
9	-0.720	-0.455	1.605	0.317	-1.340	-0.203	-0.903	*-1.699*	*1.617*	**-2.75**

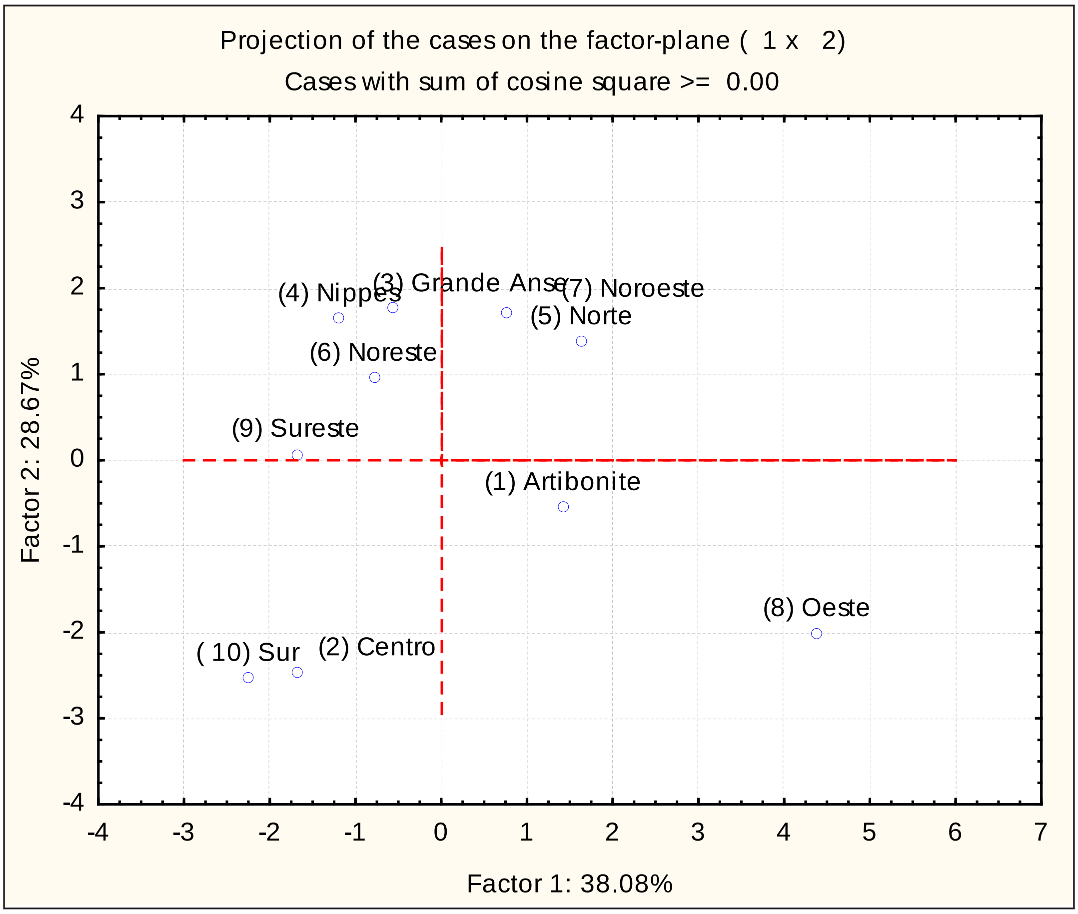

Figure 10. EOF results by Departments

The projection in the first Principal EOF Component demonstrates with greater importance Department 8 (see figure 10) influenced by the location here the capital of the country constitutes the economic, judicial and governmental center of the country and the most important port of Haiti and therefore exposed to greater concentration and influx of people who can import and export transmission diseases.

Department 10 is shown in isolation that despite not having enough hospitals for its population, there have been no threats as important as in areas more predisposed to affect public health.

A group is formed with Departments 4, 9, 6 and 3, similar to the northern zone the prevalence of diseases is moderate but with less medical coverage (see figure 10).

A group with Departments 7 and 5 with similar characteristics in their variables is formed, which favorably with their areas of moderate prevalence to the diseases mentioned above and their greater coverage of inhabitants/hospitals (see figure 10).

The Meteo-Epidemiological Vulnerability Index (MEVI) shows that the vulnerability is greater in the Western Department 8, with the maximum risk zone in the capital, starting from the peripheral zone there is a gradual decrease from 4 points to 2 (see figure 11) to the boundaries of the adjoining Departments of Southeast 9, Center 2 and Artibonite1; Leaving from there 2 to 0 and -0.5 in the north borders of Artibonite and Center, part of the Southeast 9, Grand Anse 3 and Nippes 4. In the South 10 we observe in isolation that the highest vulnerability starts from 2.5 to -0.5. The Northeast region has the lowest vulnerability zone with values of -1.5 and -2, similar to the Northern region.

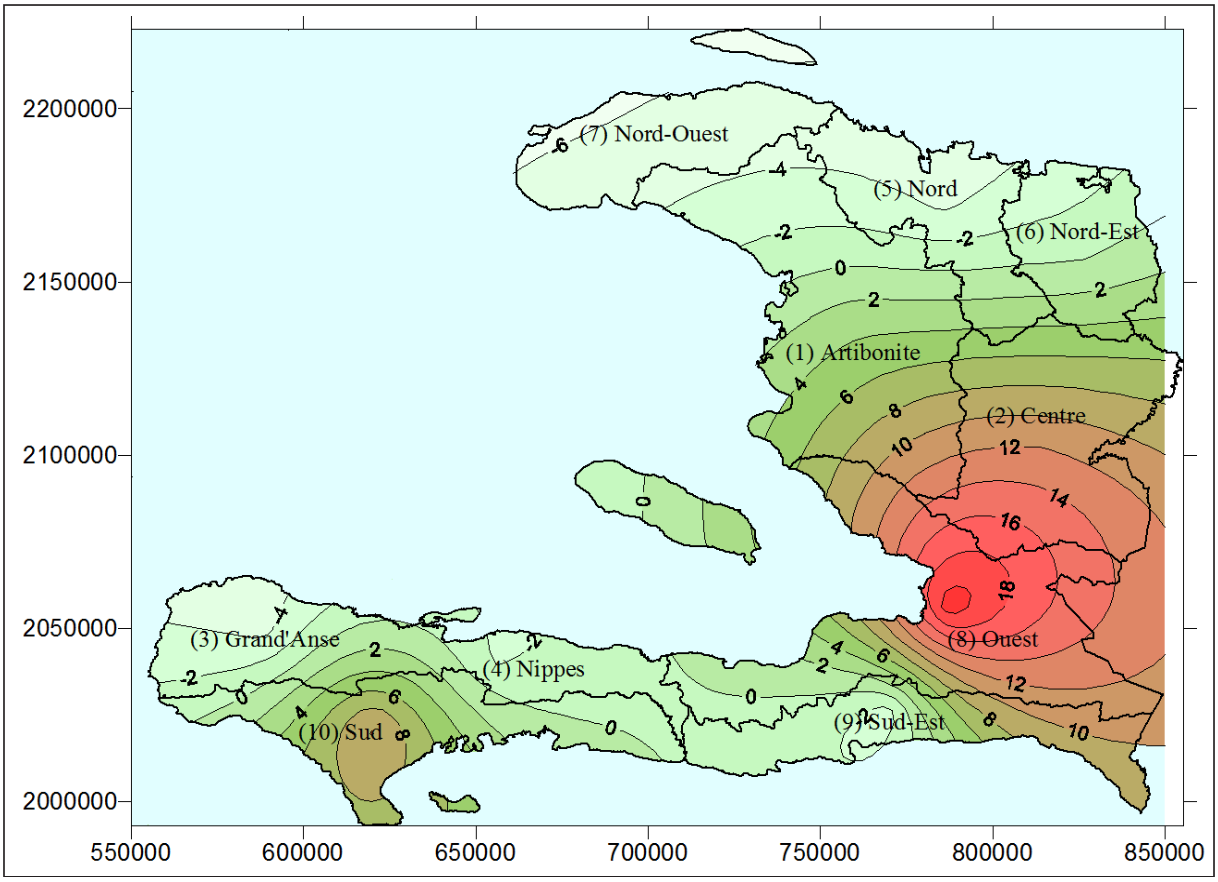

Figure 11. Meteo-Epidemiological Vulnerability Index (MEVI)

CONCLUSIONS

According to the projection of variables in the Empirical Orthogonal Function Analysis (EOF), we observed the conformation of two groups, in a group we counted on Cholera, Tuberculosis and the number of hospitals (see Figure 9). The second group relates malaria and climatological conditions, which means that the EOF analysis allowed a correct analysis of the climatic variables combined with the health variables. The concentration of large masses together with the conditions of water shortage and lack of proper disposal of sewage triggers an environment of easy spread of infectious-contagious diseases.

The topographic distribution of the diseases mentioned is variable but, with a tendency to concentrate in areas of greater population that fortunately are areas of greater number of hospitals only with the exception of cases of Malaria in the Central Department. The post-disaster internal displacement triggers a series of social phenomena that directly affect the health of the population. Lack of shelter, services, hygiene, order and security in a country where previously social situations were already seriously affected represents a public health problem and a challenge not only to national government institutions but also an international effort that despite being rough is still not enough. The vulnerability of Haiti will always represent a latent, especially with seismic and hydrometeorological events, which without any prediction of when the next disaster will occur; the work of all will be aimed at rebuilding the country with stronger foundations and awareness on preventive security. The *Meteo-Epidemiological Vulnerability Index* (*MEVI*) allowed identifying zones or Departments that are most vulnerable to health risks, combined with the hydroclimatological variables that affect the territory of Haiti. It is proposed the systematic calculation of *MEVI* to characterize the vulnerability of areas that are prone to combined phenomena where there is a strong health, epidemiological, hydrometeorological and medical infrastructure component.

It is proposed to update the data used in this study and to perform a new calculation of the *MEVI*. It is worth mentioning that *MEVI* is currently used in some mountainous areas of the Sierra Gorda mountain range of Querétaro, México, where some populations are particularly affected by the scarce infrastructure and the incidence of the changing climatic aspects detected in recent years.

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