Using GIS and Remote Sensing to Analyze Lake Level Rise of Étang Saumâtre, Haiti

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Abstract
Haiti is the poorest country in the western hemisphere and is beset by catastrophic events of natural and anthropogenic origins. Therefore, Haiti is vulnerable to and ill-equipped to manage these events. Since 2004, the incidence and intensity of tropical storms over the island of Hispaniola has resulted in loss of life and been the catalyst for forced migration of the population, resulting in contamination of water and health issues, i.e. cholera. Our research uses GIS and Remote Sensing to address the potential flooding hazard to population and agriculture abutting the closed basin lake Étang Saumâtre. Our analysis of Landsat imagery from the past 30 years predicts the rate of future lake level rise and sites the lakeshore areas most at risk. This analysis indicates a 20.6% increase in lake area. Our analysis of the terrain demonstrates the vulnerability of areas to the east and the west of the lake, due to the lake’s east/west trending location in the Hispaniola Rift Valley. To the east is the border with the Dominican Republic and Lake Enriquillo; to the west is the low lying Cul de Sac plain. Areas of the Cul de Sac, which include Port au Prince, are densely populated. Large expanses of productive agricultural land are also located in the Cul de Sac. Satellite imagery and on ground research verify that homes, roads and agricultural fields have already been inundated.

Keywords
remote sensing, GIS, Landsat, global change drivers, Haiti

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1. INTRODUCTION

Ecosystems are continuously being impacted by global change drivers, which are considered by the Millennium Ecosystem Assessment as “any natural or human-induced factor that directly or indirectly causes a change in an ecosystem” (Carpenter et al. 2006). Global change drivers include anthropogenic forcings, episodic events, and/or natural variability. Anthropogenic drivers can impact ecosystems indirectly from demographic, economic, sociopolitical, cultural, religious, scientific, and technological pressures. Direct anthropogenic drivers include climate, plant nutrient use, land conversion, disease and invasive species. Natural drivers include climate variability, extreme weather events, or volcanic eruptions. For example, in aquatic ecosystems, indirect drivers from the use of fertilizers and runoff modify the nitrogen cycle and can cause eutrophication and anoxic events. Due to increased concentration of CO$_2$ in the Earth’s atmosphere, the globally averaged surface temperature is projected to increase by 1.4 to 5.8°C during the period 1990 to 2100 (Ding 2001). There is already indication that global climate change raises sea levels, increases storm intensity and frequency, and promotes heavy precipitation events and severe droughts (Knutson et al. 2010). Land-use changes such as deforestation can severely impact ecosystem function and ecosystem services and goods. Any specific ecosystem change can be the result of a combination of interactions among drivers and therefore, ecosystems are important study units for understanding the causes and impacts of global change.

Haiti, located on the Caribbean island of Hispaniola, is the poorest country in the western hemisphere and the second poorest in the world. As of a July 2013 estimate, Haiti had a population of 9,893,934 with 56% of the population under the age of 25 (The World Factbook 2014). Haiti has a myriad of anthropogenic and natural global change drivers present, resulting in drastic impacts to ecosystems and environmental degradation. Additionally, socio-economic drivers, i.e. fragmented government, unstable economy, lack of infrastructure, and a low level of education have impeded Haiti’s ability to manage its resources in a sustainable and progressive way. In the last decade, Haiti’s problems have been compounded by global driver pressures including catastrophic earthquakes, hurricanes, flooding, and landslides. For example, in 2004 severe flood waters from Hurricane Jeanne, which delivered up to 330 mm (13 inches) of rain on Haiti, resulted in 2,620 injured, 846 disappeared, 300,000 disaster victims and over 3,000 dead. (Le Comte 2005). Then in 2008, four separate hurricanes delivered heavy precipitation on the country, causing floods that affected about 800,000 people. Flood waters destroyed 70% of Haiti’s agricultural resources and damage was estimated at over 1 billion U.S. dollars (Brown 2010). Referring to damage on the island of Haiti after the 2008 hurricanes, Brown (2010) says that because of flooding from multiple storms it is difficult to determine the exact death toll from each of the storms. These tropical storms were followed by a massive earthquake in 2010 that killed an estimated 300,000 and some 1.5 million were left homeless (Cavallo et al. 2010). The impacts of these natural global drivers were a devastating setback for a country, already so poor.

The effects of natural global change drivers in Haiti are exacerbated by the impacts of anthropocentric global drivers. Haiti’s poor economic condition has led to drastic resource extraction and environmental degradation; political instability and corruption
have led to a reduced socio-economic condition for all but a few of its citizens. Growth in Haiti’s population has led to an increase in demand for fuel, such as wood and charcoal. Impoverished Haitians depend on the charcoal from wood as their major energy source, hence the massive deforestation. It is estimated that 85% of the Haitian population depends on biomass energy for domestic purposes with 3.3 million m$^3$ of fuel wood in Haiti per year (CFET 1997). Conversion of native forests for resource utilization has led to deforestation, soil loss, water quality degradation, and economic political instability (Stevenson 1989; and Wampler and Sisson 2011).

Land use/land cover of Haiti is constantly fluctuating, due to anthropogenic, climatic and geologic global change drivers. Monitoring change facilitates detection of problematic events that can result in loss of life, property and destruction of infrastructure. Within the Caribbean basin, land cover change in Haiti is arguably, the most notorious while also the least examined (Versluis and Rogan 2010). Haiti is particularly vulnerable to these events and ill equipped to prevent or manage them. Land use practices naturally develop over a lengthy time period under various environmental, political, and socio-economic conditions (Muttitanon and Tripathi 2005). Haiti’s increasing population is exerting pressure on the land to supply life necessities, i.e. food, water, shelter, and fuel.

Current research in Haiti led to the observance of severe and rapid lake level rise of Haiti’s largest lake, Étang Saumâtre, located in the southeast region of Haiti bordering the Dominican Republic. On subsequent visits, this change was visibly demonstrated by roofs protruding from the lake and stands of submerged trees with green canopies just visible above the water. Anecdotal evidence gathered from inhabitants around the lake attest that the lake level change has been rapid and has consumed considerable tracts of land. Historic lake level change in Haiti was documented by Hodell et.al. (1991) in his research paper *Reconstruction of Caribbean Climate Change over the past 10,500 years*. Hodell developed patterns of evaporation and precipitation based on $^{18}$O/$^{16}$O ratios in ostracod shells from Lake Miragoane, Haiti. Étang Saumâtre, Haiti’s largest lake, is a closed basin brackish lake with evaporation as the only visible output. Hydrologically, closed basin lakes are particularly susceptible to changes in land use and climate (Jones 2001) and (Battarbee 2000). Research conducted to establish a limnological profile of Étang Saumâtre showed salinity decreasing from 15 ppt; in 2007 to 8 ppt in 2011. The rapid freshening of the lake indicates a notable increase in precipitation and or underground springs over that period of time. Significant changes in lake level impact the structure of marginal habitats, can redistribute sediment, and, especially in closed lakes, significantly alter the ionic composition and salinity of the water body (Battarbee 2000).

2. STUDY REGION

Haiti occupies the western third of the Caribbean island of Hispaniola. The region is seismic and suffers frequent earthquakes, most recently on 12 January 2010. The Caribbean and North American plates are converging in an ENE-WSW direction across the east-trending Puerto Rico trench at about 20 mm yr$^{-1}$. The crustal strain caused by this oblique motion is accommodated by several active faults and folds in and around
Hispaniola (Hashimoto et al. 2011). The island geology is uplifted marine strata and consists of limestone bedrock and weathered basalt (Harp et al. 2013). Topography consists of mountainous terrain to the north and south framing the Hispaniola Rift Valley, a low-lying east/west trending depression bisecting the island. Étang Saumâtre (Figure 1) is located in the Hispaniola Rift Valley to the west of and intersecting the border with the Dominican Republic. The geographic location of the lake is bounded by these coordinates: latitude 18° 39’ 30”, 18° 28’ 40”; longitude 72°4’ 0”, 71°53’ 0”. All of the Cul-de-Sac Plain is above sea level (ASL), with the surface of Étang Saumâtre at an elevation of 14 m ASL. The lake is approximately 26 km long and 10 km wide (at widest) with an area of 140 km². The island has a tropical climate; however the rift valley has an arid climate due to the Cordillera Central rain shadow effect. The northwest-southeast trending Cordillera Central includes the highest peaks in the Caribbean, Pico Duarte and La Pelona, 3098 and 3094 m, respectively; and extends from northwest Haiti to the southeastern coast of the Dominican Republic (Kennedy et al. 2006). The physical properties are constant throughout most of the corridor (Mann 1984).

Figure 1. Étang Saumâtre, Haiti study area and topographic map illustrating the Hispaniola Rift Valley and the relative location to Port au Prince, Haiti and the Dominican Republic border.
3. STATEMENT OF PROBLEM

The Caribbean island nation of Haiti is prone to floods, due to its tropical location and its mountainous terrain. Located in the path of the easterly trade winds, it is frequently beset by seasonal tropical storms and hurricanes. These storms deliver heavy precipitation accompanied by high velocity winds (Smith and Hersey 2008). Since 2004, the frequency and intensity of these storms has increased in this region. Étang Saumâtre, the largest lake in Haiti, is a closed basin brackish lake bordered by mountainous terrain to the north and south. Situated in the low-lying Hispaniola Rift Valley it is susceptible to flooding events. At the beginning of the last decade, lake level was dropping. Since 2004, the frequency and magnitude of tropical storms have caused lake level to rise back to and exceed previous levels. Specifically, 2004 and 2008 hurricane seasons significantly increased lake volume. The deforestation of the country’s forests since the French colonization to present time serves to increase the detrimental effects of rain events. At present, ill-defined and insecure property rights discourage investment in natural resource management, such as reforestation, by reducing incentives for it (Dolisca et al. 2007).

Lewis (1996) states tropical lakes are less studied than temperate lakes and, “seemed almost a mystery as recently as 30 years ago.” In most cases, the locations of tropical lakes are in areas that are difficult to access, due to topography, lack of infrastructure, insects and related disease, i.e. malaria, and/or political unrest. All aforementioned items apply to Étang Saumâtre. Since 2004, the incidence and intensity of tropical storms over the island of Hispaniola have had a devastating effect on Haiti, resulting in loss of life and catalyzing forced migration of the population. Lack of cadastral mapping and lack of land tenure law allows dispossessed populations to assume land that is not occupied (Smucker et al. 2002). These lands are marginal and have no existing infrastructure. The migrants live in tenuous shacks, with makeshift roofs (tarps), no electricity and no plumbing. The ensuing stress on natural systems has resulted in contamination of water and health issues, such as cholera. Settlement is accomplished with little thought to vulnerability of the location. Many of these areas are unoccupied, because they are at risk for flood or mudslide events. In particular, the escalation of precipitation has delivered an increased influx of water and sediment to the country’s lakes and streams, in particular Étang Saumâtre. Research undertaken to characterize the physical geography and dynamics of the watershed surrounding Étang Saumâtre, Haiti’s largest lake, has encouraged a study of Étang Saumâtre lake expansion and lake level rise.

Because many of the inhabitants surrounding the lake are displaced from ravaged areas of Haiti, they are unfamiliar with their surroundings and unaware of the present dangers. They are concerned with day-to-day survival and do not see or understand the inherent danger in the lake level rise of Étang Saumâtre. In terms of emergency response or evacuation, flooding of the lake is deteriorating existing infrastructure that abuts the lake, such as the main road from Port au Prince to the Dominican Republic. One must be able to see the big picture via remotely sensed images to grasp the severity of imminent danger to population and land-based resources. Because this population is living on the edge, they are unaware and unconcerned by their continued deforestation of the hillsides and the ensuing stress on the integrity of the slopes. Deforestation in an arid valley decreases the ability of the soil to retain water and increases the delivery of sediment to
the lake. Severe deforestation in Haiti is a long standing concern in Haiti and internationally (Versluis and Rogan 2010)

The Hispaniola Rift Valley is a northwest-southeast trending depression located in the middle of the country. Étang Saumâtre is situated in the Hispaniola Rift Valley just west of and intersecting the Dominican Republic border in the in the south east of Haiti. The Hispaniola Rift Valley is an arid region, due to the rain shadow effect of the Cordillera Central. Rain carried by easterly trade winds is directly lost to the valley. However, precipitation from these rain events is deposited to the north of the northern lake bordering mountains and to the south of the southern bordering mountains. Because the geology is predominantly limestone bedrock, the water carves its way to the lowest point – the valley – and is eventually deposited in the lake. Conversely, precipitation from low-pressure systems, i.e. tropical storms and hurricanes is directly delivered to the lake and the surrounding watershed. The counterclockwise spin of the low-pressure systems is not affected by the rain shadow affect. Due to the arid climate in the valley and the deforestation of the watershed slopes, tropical storms and hurricanes present the most danger in terms of flooding and mud/landslides to the lake and the watershed.

At this time, there is a paucity of data on Haiti, one of the less studied and therefore little understood countries in the world. Original interest in Étang Saumâtre was stimulated by the desire to understand the feasibility of the lake as a fishery; to see the lake as a sustainable source of protein for a population 14 grams of protein deficient per day. This prompted the initial investigation on the limnology of the lake. The preliminary morphology indicated further study was essential to document changes in lake area and perimeter. Data production and analysis were accomplished using remote sensing and geographic information systems (GIS), described below. Landsat imagery provided an available source of information, delivering timely and complete coverage of the area of interest. Landsat imagery was used to document change in Étang Saumâtre since 1984. Remote sensing and GIS technology are invaluable in detecting and visualizing the effects of global change on regional ecosystems.

4. METHODS

There are several methods for land use/land cover change detection using time series Landsat imagery data. The type of method implemented can affect the quality and accuracy of the estimate of change. The selection of the appropriate method has a considerable significance. This research employs manual on-screen digitization to detect and quantify changes in lake level rise of Étang Saumâtre over the past 30 years from 1984 to 2014, by overlaying the digitized lake perimeters to determine area change and rate of change. On screen manual digitization data extraction (Figure 2) performed in ArcGIS 10.1 produced data for lake area (km²) and perimeter (km) (Muttitanon and Tripathi 2005).

The analysis of lake expansion of Étang Saumâtre was conducted using Landsat imagery. Preferred parameters for Landsat images were 20% cloud coverage (not available) and November every 5th year from 1984 to 2014. Landsat coverage from 1984 through 1996 is intermittent and images could not consistently be accessed for some of
the preferred dates and times. Landsat 5 and 8 Thematic Mapper (TM) data were used in this study. Near infrared wavelength was selected, because of the energy absorption characteristics of water at this wavelength (Lillesand and Kiefer 2000). For Landsat 5 spectral band 4 wavelength 0.85-0.88 was employed; for Landsat 8 spectral band 5 wavelength 0.77-0.90 was employed.

Figure 2. Digitized lakeshore Étang Saumâtre for the years 1984, 1992, 2000, 2011, and 2014.
5. RESULTS

5.1 Lake Area and Lake Perimeter

Digitization of shoreline shows ~21% increase in lake area of Étang Saumâtre over the 30 year period from 1984 to 2014 (Figure 3; Table 1). The last 14 years demonstrate an increase in lake area of ~16%. Rate of area and perimeter expansion (Figure 4; Figure 5).

Figure 3. Overlay of digitized shorelines for Étang Saumâtre from 1984-2014. Yellow = 1984; Green = 1992; Red = 2000; Blue = 2011; Purple = 2014.

Table 1. Summary of statistics for Étang Saumâtre, Haiti lake area and perimeter from 1984 to 2014.

<table>
<thead>
<tr>
<th>Year</th>
<th>Area (sq km)</th>
<th>% change</th>
<th>Cumulative % change</th>
<th>Perimeter (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1984</td>
<td>116.178</td>
<td>NA</td>
<td>NA</td>
<td>73.749</td>
</tr>
<tr>
<td>1992</td>
<td>116.581</td>
<td>0.346</td>
<td>0.346</td>
<td>73.269</td>
</tr>
<tr>
<td>2000</td>
<td>120.639</td>
<td>3.480</td>
<td>3.839</td>
<td>73.384</td>
</tr>
<tr>
<td>2011</td>
<td>136.374</td>
<td>13.043</td>
<td>17.383</td>
<td>77.819</td>
</tr>
<tr>
<td>2014</td>
<td>140.115</td>
<td>2.740</td>
<td>20.603</td>
<td>84.045</td>
</tr>
</tbody>
</table>
5.2 Locations Most at Risk for Flooding

The western shoreline from the center of the lake northwest across the northwest shore has experienced the greatest lake level rise. The area on the Cul de Sac plain is primarily agricultural land with a transient and semi-permanent residential land use. Roads are unpaved, muddy ruts that are unpassable at times. This region has relatively little topographic relief; contours range from 20 meters at lake shore to 0 meters westward to the coast in Port au Prince. Continued lake level rise in this densely populated area will displace a large segment of the population. The eastern shoreline is expanding to the southeast in the rift valley, bounded by the mountains to the north. In the southeast, the lake is expanding on both sides of the major highway, Haiti 8, from Port au Prince to the
Dominican Republic; and is expanding on the south east tip into the Dominican Republic. From this section of Haiti 8, submerged dwellings and stands of trees (Figure 6) are clearly visible. The erosion of the highway (Figure 7), which is limestone, will eventually overtake the road and present a major loss of infrastructure. In addition, further expansion into the Dominican Republic will have political implications.

Figure 6. Water level changes image (houses and foundations submerged) along highway “Haiti 8”, approximately 6 km west of Dominican Republic border.

Figure 7. Erosion of highway “Haiti 8” due to lake level rise, approximately 6.5 km west of Dominican Republic border.
6. CONCLUSION

The expansion of Étang Saumâtre presents an ongoing incremental tragedy for those that live, farm, and depend on the existing roads for their livelihood. The rate and specific location of expansion of the lake are the difference between tragedy and catastrophe. The Cul de Sac region west of the lake is enduring the greatest expansion of lake water onto the land. Land use is primarily agriculture, non-government organization (NGO) settlements, and squatters. For the most part, this is a population on the margin. With no electricity, no permanent roads and no communication there is no way inform the people of impending disaster, nor is there a way to develop and implement an emergency response plan.

This research shows that continued lake level rise of Étang Saumâtre will flood the low lying surrounding countryside and place those residing there in harm’s way. Haiti is ill equipped to deal with disaster, as past events have witnessed. After the January 2010 earthquake, the government of Haiti reported and estimated 230,000 deaths (2% of the population), 300,000 injured and 383 missing. Reportedly, 700,000 people were displaced in the Port-au-Prince area, many without shelter, with more than 597,000 people who have left Port-au-Prince for rural areas (Margesson and Taft-Morales 2010). Remote sensing has provided the platform to recognize and quantify lake level rise of Étang Saumâtre. Remote sensing together with GIS enables determining locations most at risk. In future research, remote sensing will enable analysis of the watershed’s remaining forest cover and endeavor to determine the most deforested sites and their slope to identify areas most at risk for mudslide and or landslide. According to Churches et al. (2014), there is no doubt that deforestation is a serious and well-documented occurrence in Haiti. For this reason, accurate forest cover and deforestation data is needed to enable analysis and offer improved results.

As expansion of Étang Saumâtre into the Cul de Sac plain continues, it should be noted that the expansion in the rift valley is toward Port au Prince. Port au Prince is at sea level and subject to sea level rise. With only a 20-meter topographical difference from Port au Prince to Étang Saumâtre, there is no impoundment to stop or impede water flow. In the future, it appears that water will be encroaching on the Cul de Sac plain from both the west and the east. Woodring (1954) states that according to current age assignments, during the Pleistocene the present island of Hispaniola was divided into two islands by a strait along the Cul de Sac-Lago Enriquillo trough. The rate of lake level rise over the past 30 years validates this scenario is possible in the future. Lake expansion is dependent on climatic global change drivers. Episodic events, such as tropical low depressions and hurricanes will have the most impact on Étang Saumâtre.

Recent decades have seen very large increases in the economic damage and disruption caused by tropical cyclones. Historical analyses indicate that this has been caused primarily by rising coastal populations, as evidenced by the hurricanes of 2004 and 2008 in Haiti. These storms caused considerable loss of life and infrastructure in the low-lying Port au Prince area. In developing countries, the movement of the population to the coast is the result of social factors that are not easily countered. Climate change is hence one of several factors likely to affect the future evolution of damage from tropical cyclones (Knutson et al. 2010).
REFERENCES


