The City College of New York

Department of Earth System Science and Environmental Engineering

Reforestation in the Rouyonne Watershed for Léogâne Arrondissement, Haiti

Louiza Molohides,
Mateusz Kowalski
Nitika Pandey
Jillian Panagakos
Valentina Rappa

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We are very grateful for all of your help and guidance.

Executive Summary

Soil instability in Haiti, caused by centuries of deforestation and extreme weather events, decreases the capacity of watershed retention. As a result, when Haiti experiences severe weather events, devastating floods are triggered and local communities are left incapacitated. These problems are particularly salient in our region of focus, the coastal commune in Ouest Province, Léogâne Arrondissement which includes the Léogâne community. Léogâne Arrondissement is often subjected to high intensity and high frequency flooding events and has been of particular interest to local organizations, such as the Comprehensive Development Program (CODEP), for rebuilding and fostering economic growth due to impacts of the 2010 earthquake and other natural disasters that the region has suffered.

While researching past and current mitigation efforts in our watersheds of interest, we observed significant data gaps that we believe need to be addressed with future work in Haiti. The first of these obstacles is that there has been disagreement about the true percentage of Haiti's national forest cover. While non-government organizations (NGOs) often claim that 2% of Haiti is forested, academic sources often claim that number is closer to 30%. Although determining this value is not critical to developing a mitigation plan for our region of interest, it is important that we understand the severity of this problem on a national scale so that we can adequately project the likelihood of our devised solution being scaled up to the country level. Furthermore, the mitigation strategies in this region currently do not assess the quantitative impact of reforestation efforts. Although this area is successfully being forested, local organizations do not have the means to quantify the outcomes of their work or assess how their efforts have impacted regional hydrology. Especially since a large aspect of these programs is based in social empowerment, it is vital that local communities witness the success of current efforts in order for these initiatives to gain greater support. Finally, the Rouyonne watershed has been focused on much less than Cormier and Beloc. One would think this is because Rouyonne does not have destructive flooding events. Contrarily, publications have shown that Rouyonne experiences high magnitude and frequency flooding (Brown). Most of these flaws have not been addressed because the organizations working in this region do not have the means to address them. This is where our senior design team aims to supplement current efforts.

The goal of our project is to help mitigate the data gaps previously stated and to supplement the work that is already being done in Léogâne. The first step was to create a visualization and quantification of Haiti's national forest cover so that we can contribute to understanding Haitian deforestation. The overarching goal was to create a forward modeling characterization for different reforestation approaches that will result in different levels of resilience against flooding

during long-term, regular weather events and short term extreme weather events. Furthermore, we aimed to bring a greater focus to the Rouyonne watershed through our alternative plans.

The technical approach included: determining the extent of forest cover in Haiti, characterizing landcover in Léogâne, creating a soil shapefile from soil experimentation, creating a mitigation design and finally modeling alternatives with GSSHA for severe weather events and SWAT for long-term regular weather events. The results from the first round of the modeling processes in SWAT and GSSHA were assessed to identify areas that are currently susceptible to flooding events. Based on the initial round of modeling for the no-change alternative, the Rouyonne watershed yields the highest peak flow and volume. Thus the reforested area for the alternatives was chosen to be located in the Rouyonne watershed. It was a primary focus for this project that the proposed reforestation plan and models reflect reforesting an amount of land that would be realistically feasible for a reforestation program in the Léogâne region and thus the alternatives established were justified due to their financial feasibility. However, since this method yielded insignificant impact on Rouyonne's hydrology, a second approach was developed which involved reforesting all of the available land in the watershed.

The results from this project include the following: model results, a cost-benefit analysis, and a land cover file for Léogâne. The original alternatives show small and insignificant changes to the watershed overall. Thus, based on the results from GSSHA, reforesting small amounts of land at one time yields less than 1% change in peak flow and discharge. When looking into the last alternative where all barren land in the watershed is reforested, more impactful results were shown from both the GSSHA and SWAT hydrologic models. While the results from the cost benefit analysis from reforesting all the barren land show significant benefits, this alternative is not socio-economically sustainable. On the other hand, the lower range, upper range and combined range alternatives that are financially feasible do not produce significant hydrologic results. It was also determined that the CODEP method, which does not account for labor costs as part of the implementation costs, is a better method of financing a reforestation project as it decreased costs in addition to increasing community involvement. Finally, it was determined that the national forest cover in Haiti is around 36%.

Further recommended steps would be to continue modeling the watershed for different amounts of area in order to determine minimum and maximum thresholds for yielding significant changes in the hydrologic parameters. The minimum threshold would be used to determine how much area would need to be reforested before the watershed is impacted. The maximum would be used to determine at what amount of area the impact on the watershed no longer changes significantly. Further hydrologic modeling should also be conducted to validate the results from the models in this study and to assess the sensitivity of the models to different parameters such as soil type, slope, and land cover type. These recommendations will be advantageous as the next steps for this project in order to obtain a better understanding of the impact of reforestation in Rouyonne.

Introduction

Haiti has a long history of deforestation due to centuries of agriculture exploitation, starting from the French colonization in the 17th century. The French used intensive monocropping of export commodities such as cotton, tobacco and coffee. They also harvested timber throughout the country for export markets in Europe. With a growing population, an increased demand for wood-based fuel stressed the environment as trees were cut down without being replanted. After Haiti became independent in 1804, Haitians obtained access to the country's land and deforestation continued. Haitians grew export commodities on their farms, which were part of the expanding economy. As of 1923, over 60% of the land was forested (Zimmermann, 1986, p. 58). However, as of 2011, the percentage of forested land in Haiti was approximated to be 32.3% (Churches et al., 2014). Although significantly deforested, this estimate has been challenged by claims as low as 2% forested land made by non-governmental organizations (NGO) such as the Eden Reforestation Project which is located in central Haiti and claims on their website that 2% of Haiti's original forest currently remains. However, the source does not provide a definition for 'original forest' and therefore this claim can be easily misconstrued (EdenReforestationProjects).

Problem Statement

Soil instability in Haiti, which is a result of centuries of deforestation and extreme events (such as the 2010 earthquake), has decreased retention of the country's watersheds. As a result, when Haiti experiences severe weather events, devastating floods are triggered and local communities are left incapacitated. These problems are particularly poignant in our region of focus, the coastal commune in Ouest Province, Léogâne Arrondissement which includes the Léogâne community (World Atlas). Léogâne Arrondissement is commonly subjected to high intensity and high frequency flooding events and has been of particular interest to local organizations, such as the Comprehensive Development Program (CODEP), for rebuilding and fostering economic growth due to impacts of the 2010 earthquake and other natural disasters.

The three watersheds of our focus are the Rouyonne, Beloc, and Cormier at 63.8, 30, and 31 square kilometers respectively. The absence of vegetation in the upgradient regions of these watersheds has left the region vulnerable to the effects of tropical storms and hurricanes, such as in the case of Hurricane Matthew in 2016**.** These increasingly frequent storms trigger severe flash floods that originate in eroded watersheds, wash down into local communities, and often result in loss of human life and severe damage to infrastructure. As can be seen in Figure 1 below, Léogâne is located in the downstream, flat plain region and is in close proximity to the watersheds listed above. This area is where many settlements are located and where flooding typically occurs. The removal of vegetative cover has also negatively impacted freshwater ecosystems in Haïti by decreasing their capacities for sustained production. Additionally, massive influx of river sedimentation from deforested mountainous regions results in heavy habitat degradation in the areas near river channels.

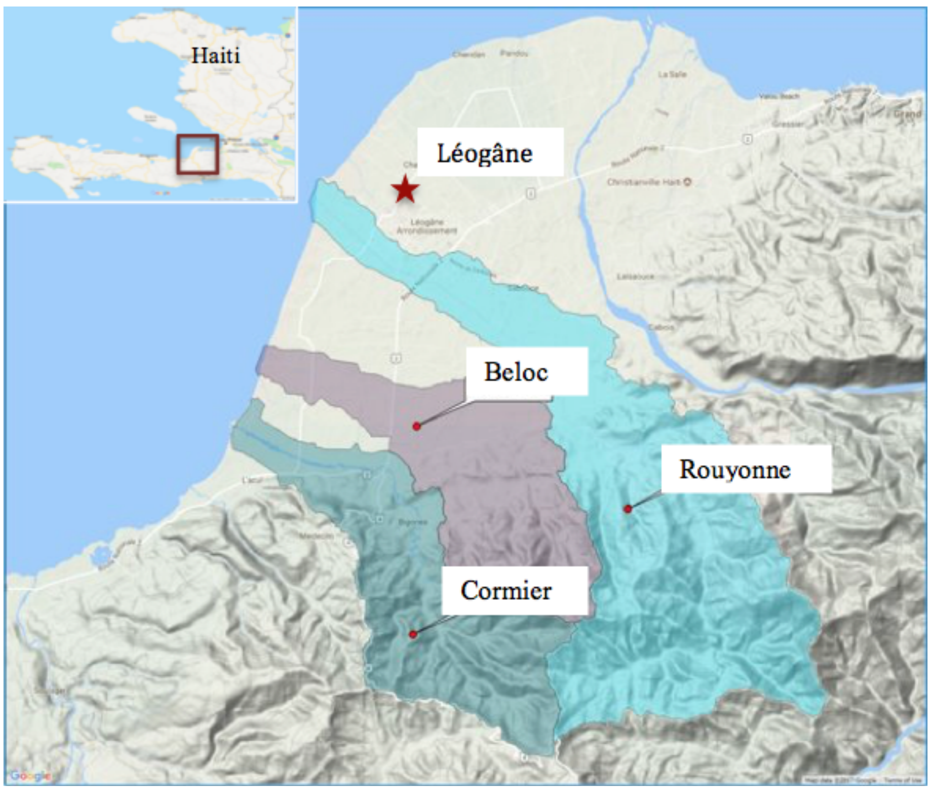

Figure 1: ***Project Study Site***. Map showing our project study site located on the Tiburon Peninsula in Haiti. This area includes three watersheds: Beloc, Cormier, and Rouyonne.

Socio-Economic Factors of Influence

Especially over the last ten years, Haiti has experienced a number of devastating natural disasters, including a 7.0 magnitude earthquake in January 2010 with an epicenter near Léogâne. The effects of this earthquake left millions displaced, tens of thousands of which were still living out of temporary shelters as of 2016. As a result, when Category 4 Hurricane Matthew hit last year, it left thousands stranded, as the effects of the storm were exacerbated.

Extreme events have led to decreased soil stability and watershed capacity, imposing high intensity and high frequency flooding events when severe rainfall causes watersheds to overflow into local towns, such as Léogâne. Flooding leads these communities to continuously have to modify and rebuild their lives, as it displaces people from their homes and destroys farmland by washing away critical topsoil.

Lack of watershed capacity is a result of not only extreme events, but also of the centuries of deforestation that have accompanied the country's economic development and population growth. Despite the fact that it has been proven harmful to local communities, deforestation is a necessity for many in Haiti: wood is burned for charcoal, there is a rapidly growing population which requires adequate space, and the country's economy has historically been based in commercial farming, which in and of itself requires land for agriculture. Overall, there is a demand for this resource, although there is no sufficient replacement or proper forest management techniques implemented. This largely stems from a lack of fundamental understanding about the benefits of forest preservation. As of 2015, 71% of Haitians older than 25 had attended secondary school ("Haiti Statistics"). This lack of access to basic education often results in not foreseeing the importance of maintaining the country's forests when there are more immediate needs: fuel, food, and adequate space for the growing population.

If a reforestation project is to be implemented along critical watersheds, local communities will benefit from flooding mitigation as it will lead to fewer instances of displacement as a result of river overflow and diminished need for rebuilding and repairing homes and infrastructure after severe rain. Furthermore, there are a number of benefits that they will be facing from specifically a reforestation project. For example, national Non-Government Organizations (NGOs) have used reforestation strategies to help communities achieve self-sufficiency, and to not be reliant on obtaining necessary goods from others. They have taught locals to farm for themselves and to manage their property, as well as have led education efforts for training in basic numeric and literacy skills (Winings). As a result, there can be a greater understanding of the need for reforestation and the benefits that can result from it.

Furthermore, reforestation poses a financial value in the stimulation of the local economy. When locals can independently grow food for consumption and for sale, they maintain ownership of their goods and resources, and they can increase household income by selling their surplus. Proper forest management techniques implemented in addition to reforestation efforts can allow for the allocation of specific regions of forest to be used for cutting down trees to produce charcoal as an energy resource (Patosaari). As this is currently the most accessible and affordable fuel type to many, it can allow for the stabilization and growth of the charcoal industry while maintaining the benefits of having forested land. In addition to generating opportunities for financial independence within the communities, these efforts have led to developed business models for local NGOs. In this way, there is a current market for reforestation efforts in-country. Although these NGOs have historically been American-based, they have developed models for shifting the responsibility and prosperity to local communities, thus bringing greater financial and social independence back to Haitians (Winings).

Reforestation for Flood Mitigation

There are a number of flood mitigation strategies that engineers and policy makers have collaborated on in order to mitigate the problems discussed above. Some of these solutions include the implementation of dams, reservoirs, and levees, which can prevent river overflow. Flood control dams enclose flood water and implements a controlled release intoto a river below the dam or stores the diverted water for other uses such as irrigation for farming ("Benefits of Dams"). On the other hand, a levee is an artificial wall that blocks water and is used to increase land availability or divert water flow from large bodies of water, primarily rivers, so that the fertile soil can be used for agricultural purposes (National Geographic). A third method is riverbank reconstruction, which utilizes engineering controls such as mesh and geotextiles in order to protect and rebuild the soil, contain the flow, and decrease the likelihood of flooding events. A final method is reforestation. Over time, reforestation increases soil stability and absorbs the impact of flooding events. Despite these numerous effective measures, we have decided to focus our project's mitigation strategy around reforestation, a decision which will be explained further in our feasibility argument.

The main strategies for implementing reforestation projects include forest management techniques, economic incentive, and educational and community empowerment initiatives. Forest management techniques allow for design possibilities, as this implementation would allow one to allocate specific regions of the watersheds to specific types of vegetation. Thus, designers may balance a community's need for fuel and food with adequate flooding mitigation. By actively involving communities in reforestation programs, residents may embody the spirit of the program by investing time, and energy into making a project their own, as it provides them with a sense of pride. By educating the locals about reforestation and how this investment would ultimately pay off, reforestation programs spread this knowledge base to more people, increasing the involvement in this effort. The economic incentive for such includes selling the fruit from the trees planted and using it as food supply to the communities. With time, other communities would join to reap the benefits. Economic incentive and education are proven methods of fostering a sense of ownership within local communities and a sense of investment in reforestation co-benefits such as increased biodiversity, carbon storage, higher water quality, and economic independence.

While reviewing several reforestation case studies, a thorough analysis was also conducted on global reforestation manuals from Lebanon, Brazil, Oregon and the Caribbean, as case studies in each of these regions had easily accessible documentation. These reforestation manuals explained the process of site assessment, selection, planning, preparation, and reforestation implementation aspects for each project, as these details are highly site-specific. These manuals provided clear guidance and best practices in reforestation that were taken into account in the *Creating a Mitigation Design* section of this report. Each manual followed the same process but had focused on site-specific problems that were tackled. The Lebanon reforestation manual focused on promoting biodiversity and thus supported the use of quality, native seedlings (Lebanon Reforestation Initiative). In the Brazil reforestation manual, ecological benefits were ranked as a priority and thus it encouraged reforestation in specific locations that would provide the most ecological benefits (Botero, Marianna). In the Oregon manual, the focus was on state regulations and thus it followed state requirements that needed to be met (Rose, Robin). On the other hand, the Caribbean manual focused on the integration of fruit tree species as their produce would be used for economic profit (Ruiz, B.I.). While all of these manuals focused on site-specific problems at the region of focus, the plan was the same: a structured procedure and a thorough analysis of their site was accounted for before the reforestation process began.

Global Reforestation Mitigation Case Studies

When developing our proposal for reforestation mitigation, we assessed similar projects in other countries that had objectives of assuaging flooding problems.

Manila, Philippines

Much has been written about the severe deforestation which has taken place in the Philippines, particularly since World War II, due to widespread logging. Large areas of forest were felled under timber license agreements in earlier years as a result of “kaingin” farming, which deals with shifting areas for cultivation on a yearly basis, and illegal logging. A variety of government programs have been implemented for forest conservation in the Philippines. Reforestation programs have been introduced in the Philippines since the early 1970’s under an Administrative Order in 1971 and have since been implemented for over 30 years. As a result, leaders of these efforts have identified weaknesses in their performance and have modified their designs. With these modified designs, forest cover has increased from 25.9% in 1961 to 41.7% in 2014; while reforestation efforts are continuing, these modified designs were considered successful for increasing community involvement and self-sufficiency instead of remaining dependent on foreign funds (World Bank). However, this did not lead to increased resilience against natural disasters, as over 1.6 million people were affected by landslides and floods between 2000 and 2010 (Pamintuan). Throughout the years, these pertinent organizations have learned and reformed methods for better success. Some lessons learned include:

1) Not using contract reforestation, which includes a private sector, since these areas are difficult to maintain.

2) Involving the community in order to decrease illegal logging and increase education.

3) Increasing emphasis on tree growing by individual smallholders, and introduction of wider stakeholder involvement and resource management objectives.

Today, the Philippines is continuing this initiative of reforesting because the country’s forests are still in danger of illegal logging, as the destruction rate is higher than the forestry recovery rate. Local organizations now focus their efforts on planting native species, particularly in the upland and mangroves (Kennedy).

Seoul, South Korea

Government-led reforestation programs in South Korea have succeeded in producing a substantial increase in forest cover over the past 55 years. In 1955, forest cover in South Korea encompassed 35% of national land area, and by the early 1970s significant increases in both forest cover and growing stock had occurred due to reforestation programs (Bae). In the late 1960s South Korean government launched strong reforestation policies, declared illegal logging a serious crime, and mobilized the police agency to enforce these policies. The comprehensive reforestation plans, which started in 1973, provided economic incentives to the general public by establishing clear quantifiable goals and also promoted inter-agency cooperation to replace firewood with fossil fuels (Bae). The increase demand for coal reduced the demand for firewood and increased forest recovery efforts. While Korea was supported by the implementation and enforcement of government policies, Korea also had a long history of a strong communitarian culture, where mountainous forests were viewed as common-pool resources as well as sacred places. This ideology coupled with government led reforestation programs encouraged public participation and increased forested land to 63% by 2005 (Rivera). The case of South Korea shows that forest transition can be cultivated in a relatively short period of time by a central authority, even with imperfect governance and low economic development.

Reforestation Mitigation in Haiti

There are currently 3 major reforestation NGOs in Haiti: Eden, Love a Child, and the Comprehensive Development Program, or CODEP. Eden has had a focus on two major projects: one in the north coast of Cap Haitian and another in central haiti by Providence University of Haiti. Originally, they had intended to reforest central Haiti with agro-community forests, or a land management method where trees, shrubs, and grass are grown among or around crops, that would facilitate food security in poverty stricken areas. In their efforts, they have learned that mangrove forests help to stabilize shorelines, improve water quality, and provide a natural habitat for fish and other coastal sea life (Eden). As a result, for the past 3 years they have been reforesting mangroves near the coast of Cap Haitien in order to restore and maintain ocean health.

Love a Child, an orphanage in Fond Parisien, central Haiti, began their own reforestation program 8 years ago on site. By providing agricultural training centers, educating locals, and allocating resources for plant nurseries, more opportunities are available for the locals to work and care for their environment. The organization's primary focus has been on renewing hillsides by planting Vetiver grass for soil support and stabilization, that lessens the impact of severe weather events in regions that are downslope of the reforestation efforts. Their second goal is to plant fruit trees, such as Moringa and Neem, to increase food security since these species grow and produce fruit quickly (Love a Child).

Finally, CODEP, has been planting and foresting in Ouest Province Léogâne for over 25 years. The initiative began by collaborating with subcommunities of 3-4 families called Lakous. The organization's progress expanded when more Lakous witnessed the success of the initial efforts and requested to join the program. This resulted in 40 Lakous participating in CODEP I, or the first phase of their program. CODEP's initial trials and errors paved the way for the proper techniques and success that the other programs have experienced. For example, in their first few years of operation, they monocropped nonindigenous plants, specifically Eucalyptus trees, on bare hills. Although these plants grow quickly, they also require copious amount of water and impede other plants from growing, thus designating Eucalyptus trees ineffective for both flooding mitigation and food security. After 4 years of the plant growth, they realized their mistakes and pulled all the eucalyptus trees out to start fresh with agroforestry (Haiti Reforestation Partnership). Once they had optimized the combination of Vetiver grass, shrubs and fruit trees, they shared the information with other reforestation organizations such as Eden and Love a Child.

While researching past and current mitigation efforts in our watersheds of interest, we observed significant data gaps that we believe need to be addressed with future work in Haiti. The first of these obstacles is that there has been disagreement about the true percentage of Haiti's national forest cover. While some sources claim that 2% of Haiti is forested, others claim that number is closer to 30%. Although determining this value is not critical to developing a mitigation plan for our region of interest, it is important that we understand the severity of this problem on a national scale so that we can adequately project the likelihood of our devised solution being scaled up to the country level. Furthermore, the mitigation strategies in this region currently do not assess the quantitative impact of reforestation efforts. Although this area is successfully being forested, local organizations do not have means to quantify the outcomes of their work or assess how their efforts have impacted regional hydrology. Especially because a large aspect of these programs is based in social empowerment, it is vital that local communities witness the success of current efforts in order for these initiatives to gain greater support. Finally, the Rouyonne watershed has been focused on much less than Cormier and Beloc. One would think this is because Rouyonne does not have destructive flooding events. Contrarily, publications have shown that Rouyonne experiences high magnitude and frequency flooding(Brown). Most of these flaws have not been addressed because the organizations working in this region do not have the means to address them. This is where our senior design team aims to supplement current efforts.

Technical Approach

I. Determining Extent of Deforestation in Haiti

Due to the extent of disagreement between academics and non-government organizations (NGOs) about the percent of forested land cover throughout Haiti, it is critical for us to have an understanding about the specific problem areas in the country (Tarter). When we develop our final product, one of the overarching goals is to identify specific areas within our region of focus that would be appropriate for the designation of reforestation efforts and which will lead to greater watershed capacity. A subset of this goal is to develop a set of criteria that, in general, dictate the best characterization of land in this region that may be appropriate for reforestation efforts. We want to create a model that can not only be used by CODEP in our region of focus, but also by NGOs throughout the country to best assess their land and validate or refute their methods of choosing land to reforest. By creating a visualization of the entire country's current forest cover, we can identify which areas are in need and can possibly be benefited by the work we are doing with this project.

In order to perform this assessment, we will be extrapolating 2016 forest cover in Haiti from a study conducted by the University of Maryland. Last year, Hansen et al. published a map that details global forest cover change from 2000 to 2016, titled "High-Resolution Global Maps of 21st Century Forest Cover Change". Their published work includes Landsat imagery and raster data in three layers: global forest cover in 2000, forest cover gain, and forest cover loss (Hansen, M.C., et al.). The Landsat ETM+ satellite is a passive sensor that detects light within the visible and near infrared wavelengths. Because it is a passive sensor, it relies of reflectance of sunlight off the Earth's surface as its light source; thus, it can only capture images during the day and produces imagery with coloring in the usual red-green-blue spectrum (Dunbar, 2015). It has a temporal resolution of 16 days and a spatial resolution of 30 meters. Below is a table that details the three layers of imagery obtained by the Landsat satellite, their range of pixel values, and the implications of these values.

Table 1. ***University of Maryland Raw Raster Files.*** A table that details the layers and pixel values of the University of Maryland 2016 study titled "High-Resolution Global Maps of 21st Century Forest Cover Change".

Layer Title	**Pixel Value Range**	**Implications**
forest_cover_2000	0 - 100	Pixel value indicates percent canopy cover of the given pixel as of the year 2000.
forest_gain	0, 1	Pixel values indicate whether forest gain occurred from 2000 - 2016.
forest_loss	0 - 16	Pixel values indicate the year which forest loss occurred from 2000 - 2016.

The pixel values of the forest_cover_2000 layer range from 0 to 100. This is an indication of percent canopy cover at time of measurement. To make this determination, it is pertinent to identify between forest and non-forest vegetation. For the purposes of this portion of the project, forest is defined as vegetation that is taller than 5 meters. This is a determination made by

Hansen et al., because it is the standard at which the canopy layer of rainforest begins. Using this classification, the researchers at the University of Maryland measured the percent of each pixel that was populated with vegetation greater than 5 m. Any pixel value greater than 50 was considered to be forested; any pixel between 10 and 50 was considered to be vegetated but not forested; any pixel less than 10 was considered to be non-vegetated, which includes other types of land use such as a permanent water body or developed land. The forest gain layer is only classified as 0 or 1: 0 meaning that no forest gain occurred for that pixel and 1 meaning that forest gain did occur. Finally, the forest loss layer values range from 0 to 16 indicating the year at which forest loss occurred (Hansen, M.C., et al.). For example, 0 means that no forest loss occurred for the given pixel while a value of 5 indicates that the pixel was deforested in 2005.

In order to utilize this study, our first step will be to download the raster data from the University of Maryland project website. To extrapolate Haiti's forest cover in 2016, we used the ArcGIS Raster Calculator in order to perform raster addition and subtraction with the forest cover in 2000 layer and the gain and loss layers. The raw raster files provided by the University of Maryland covered a larger extent than the country of Haiti so the first step was to change the extent of these files. In order to minimize the extent, a shapefile covering the extent of Haiti was produced in ArcGIS using a basemap as a geographical reference. The ArcGIS Clip tool was then used to clip the forest cover in 2000 layer, the gain layer, and the loss layer with the shapefile of the country's extent. After clipping these raw rasters, the pixel values of the gain and loss layers were altered using an If Statement in the ArcGIS Raster Calculator. Because these values are indicated under a binary classification (either forest change occurred or it didn't), we needed to change the pixel values in such a way that they can be implemented over the forest cover in the 2000 layer. Our methodology for doing this was to replace each of the gain and loss layers' non-zero pixel values with the value 51. Then, we performed raster addition between the original forest cover and forest gain layer. In this way, any pixel that changed from being non-forested to forested between 2000 and 2016 was indicated as such in the resulting raster. The same method was applied between the original forest cover and forest loss layer, except raster subtraction was performed. At this point we had a finalized raster file that is representative of the national tree cover for 2016. The pixel values in this file vary from [-51] to [+151]. Any pixel with a value greater than or equal to [+51] was considered forested and any pixel with a value less than [+51] was considered non-forested. This raster file was then converted to a vector file in order to calculate the area of each forested and non-forested polygon using the ArcGIS Geometry Toolset for vector files. Once the area was calculated for each polygon the attribute table of the shapefile was exported to an Excel Spreadsheet. The sum of the polygon areas was calculated, which represents the total area of Haiti (8.84×10^9 ft^2). Then the sum of the polygon areas with corresponding land cover values greater than 51 was calculated (2.45×10^{10} ft^2), which represents the total area of forested land. Finally, the total area of forested land was divided by the total area of Haiti and was multiplied by 100% resulting in 36% forest cover in present day Haiti. Figure 2 below is a visualization of Haiti's national forest cover.

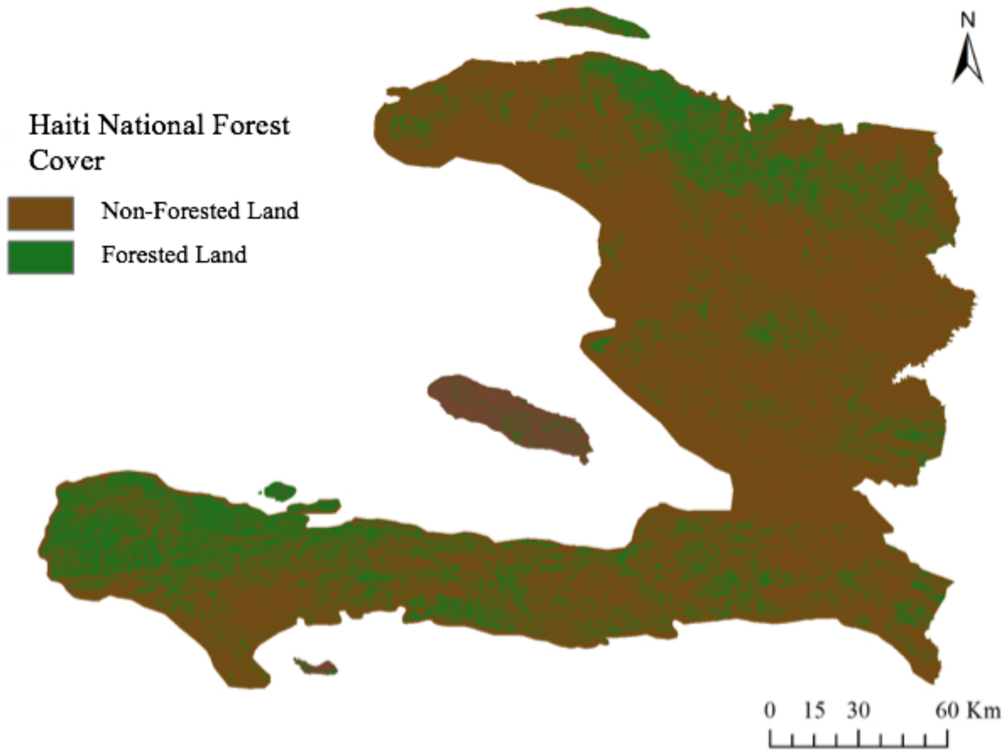

Figure 2. ***Visualization of Haiti's National Landcover.*** A map of Haiti's national land cover resulting in 36% forest for 2018. Satellite images provided by the University of Maryland were modified through raster calculations to produce this resulting map.

In this portion of the project, the main assumption made is that a single pixel is either 100% forested or 100% non-forested. We project that this will only lead to minor inaccuracies in our final outcome, as the quality of the data will allow for less margin of error. We are also relying on assumptions made by Hansen et al. at the University of Maryland, as we do not have access to their original data files and cannot alter their methodologies. The biggest assumption that we will be carrying over from their initial work is that forested land only includes vegetation within the canopy layer, or that greater than 5 m tall. However, because of the native vegetation in Haiti, there is likely to be tree cover that is less than 5 m tall, but equally likely to result in greater soil stability and fewer flooding events. This will lead to a conservative estimate of the amount of forest cover country-wide. Lastly, after consulting with Professor Kyle McDonald, the Chair of the Earth and Atmospheric Science Department at the City College of New York and an expert on microwave remote sensing of terrestrial ecosystems, we made the assumption that the change in forest cover from 2016 to present day is negligible and therefore the percent forest cover for 2016 is applicable for present day Haiti (Kyle McDonald).

II. Characterizing Land Cover in Our Watersheds of Interest

Determining the land cover type and extent in our watersheds of interest was necessary for creating reforestation alternatives because this determination was essential for modeling the current land cover state in the Léogâne region. The final product for this was a land cover characterization map that helped to determine areas throughout the study site where reforestation was necessary for improving the watersheds capacity and averting flood events. In addition, the final map was used as the "No Change" alternative when running the watershed models, which will be discussed in the *Hydrologic Modeling* section of this report.

The approach for creating a land cover classification map for the Léogâne region required the use of satellite imagery and *in situ* data to run a supervised classification. A supervised classification is a method used to identify various land cover types in a satellite image by clustering pixels in a dataset into different classes based on the input training dataset provided by the user (Harris Geospatial, 2017).

i. Creating a Training Dataset

In order to develop a supervised land cover classification, a training dataset is required to train the classification software to accurately identify land cover types from satellite imagery. An ideal training dataset should be composed of *in situ* data collected in Léogâne to provide the most accurate input for the classification software. In efforts to develop this training dataset, Valentina Rappa traveled with Dr. Michael Piasecki, an Associate Professor in the Civil Engineering Department at the City College of New York, to Léogâne, Haiti on January 6th, 2018 and returned to the United States on January 13th. Valentina visited participating CODEP Lakous as well as areas outside of the organization's influence regions.

Prior to the trip, the author of *Mountain Majesty* and former Executive Director of Haiti Fund Inc. an organization that supports CODEP, John Winings, provided the team with coordinates corresponding to the locations of existing reforestation projects as well as the organization's plant nurseries. These coordinates were mapped in Google Earth Pro for Valentina to become familiarized with the various land cover types in Léogâne and identify locations near existing CODEP territory that have different land cover types, such as rivers, agriculture, and grassland. In addition, we developed a survey which was orally administered to CODEP animators, or Haitian natives hired by CODEP to manage reforestation projects corresponding to several Lakous who are responsible for training and watching over these projects. The survey questions can be found in *Appendix A - Characterizing Land Cover in our Watersheds of Interest.* The survey includes questions pertaining to the animators' view on the severity of Léogâne's flooding events and whether they have noticed reduced flooding as a result of their reforestation efforts.

Once in Léogâne, Valentina met with an associate of Dr. Piasecki, Merlene Laguerre, who is familiar with the pricing of produce in Léogâne City Center and the mountainous regions of Léogâne. The data collected on the produce pricing was used for the project's cost benefit analysis, which is discussed in detail in the *Cost-Benefit Analysis* section of this report. During the following four days of the trip, Valentina met with CODEP animators to collect data points in various mountainous regions where CODEP has existing reforestation projects including La Freye, Gromon, Citronye, Imab, and Parezon. At each of these five locations, Valentina was led by the animator who manages the reforestation projects in that specific region and was introduced to members of the participating Lakous. When visiting Lakous in CODEP's areas of focus, Valentina analyzed the tree species as well as other land cover types, took notes on the tree species' names, and collected the corresponding coordinates of these species and other land cover types using the Garmin 87s Global Positioning System (GPS). Before leaving each region, Valentina collected one soil sample and administered survey questions to the animator who has guided her. The data collected onsite was well-documented in photos and spreadsheets, which can be found in *Appendix A - Characterizing Land Cover in our Watersheds of Interest*. On the remaining days of the trip, Valentina collected data in non-reforestation locations that are independent of CODEP. She visited one of the three watersheds of interest, Beloc, to collect data points on additional land cover types such as agriculture and built-over land with Dr. Piasecki and her translator, Jeff Vernet. On the last day of the trip, Valentina collected data in and around the Léogâne City Center, which has land cover classes dominated by built-over land and agriculture. She was also able to collect additional data points for wetland regions, beaches along the northern coastline of the Tiburon Peninsula, and the Momance River. At these locations Valentina followed a similar procedure for collecting data points within CODEP territory, but was not led by one of CODEP's animators and therefore did not administer the survey questions or collect soil samples.

When Valentina returned to New York, she compiled the ground truthing data in a spreadsheet, which can be found in *Appendix A - Characterizing Land Cover in our Watersheds of Interest* of this report, and which was used to create the training dataset. The accuracy of a supervised classification is greatly dependent on the quality and quantity of the training data points used to run the classification. Therefore, a more comprehensive and extensive training dataset is expected to yield more accurate classification results. While in Haiti, Valentina collected a total of 111 data points for eight land cover types: grass, agriculture, wetland, sand, barren land, built-over, tree cover, and river. The number of data points collected for each land cover class was not consistent and therefore some classes that are more remote had fewer data points relative to other classes. In efforts to fill in these data gaps Valentina used Google Earth Pro to identify land cover types in high resolution satellite imagery. Google Earth Pro contains numerous open source datasets ranging from orthophotos to satellite imagery, allowing it to achieve a high spatial resolution of 50 cm and 65 cm with the satellite sensors WorldView-1 and -2 and DigitalGlobe Quickbird, respectively. The high spatial resolution of this dataset allows for differentiating between vegetation classes such as trees, shrub, grassland, agriculture, and non-vegetated land as shown in Figure 3 below. Once the data collection was completed and compiled, it was then converted into a shapefile and then converted one last time to a region of interest file type (.roi) in order to be utilized as a training dataset for the supervised classification. The resulting training dataset was composed of 199 data points and consisted of the eight land cover types previously discussed in this section.

Figure 3. ***Google Earth Pro Satellite Image.*** Satellite image from Google Earth Pro showing the high spatial resolution that is necessary for characterizing vegetation.

ii. Acquiring Satellite Imagery for the Supervised Classification

The necessary datasets for this analysis include three remote sensing datasets complemented with training and validation datasets to classify land cover types in the Léogâne region and assess the accuracy of the classification results. Two remote sensing datasets were chosen to complete this analysis. The first satellite image was collected from the Landsat 8 OLI/TIRS satellite sensor, which is a passive sensor and was discussed in detail in the previous section of this report, *Determining Extent of Deforestation in Haiti*. A Landsat image from December 18th, 2017 was acquired for Léogâne (Path 9 and Row 47) from the USGS Earth Explorer website.

The second and third images, HH and HV polarized PALSAR datasets, were acquired from the Advanced Land Observing Satellite (ALOS), which is equipped with a Phased Array type L-band Synthetic Aperture Radar (PALSAR). Lastly, the mosaic PALSAR image has a temporal resolution of 46 days and a high spatial resolution of 25 meters, resulting in highly accurate pixel values (Rosenqvist et. al, 2004). This dataset is open source and can be accessed on the Japan

Aerospace Exploration Agency (JAXA) website. This active sensor is equipped with a radar instrument, which provides its own light source. The radar instrument emits a light wave and measures the signal that is reflected, refracted or scattered by the Earth's surface or the atmosphere and received by the sensor (Dunbar, 2015). This sensor was chosen because it provides high quality imagery, has an ideal spectral resolution, and a high spatial resolution. Considering the sensor is active, it is capable of penetrating through clouds and can collect data overnight. In addition, the sensor uses L-band frequency (1-2GHz), which is within the microwave range (Rosenqvist et. al, 2004). This frequency range is capable of partially penetrating vegetation making it sensitive to vegetation structure and biomass, which is necessary for differentiating vegetation species (Dabrowska-Zielinska, 2014).

The most recent available ALOS-PALSAR imagery is from 2016 which details annual global forest cover. This imagery was generated from mosaicking images collected throughout the year to detail the extent of global forest cover and the final product has greater than an 84% accuracy ("Global PALSAR-2/PALSAR/JERS-1 Mosaic and Forest/Non-Forest Map."). The specific image chosen for this was located at path W075 and row N20. The extent of the study required one tile from this mosaic for complete coverage. One of each image was obtained for both HH and HV polarimetric observation over the extent of the study site.

The three satellite images, two ALOS PALSAR images and one Landsat 8 OLI/TIRS image, were downloaded in the form of GEOTIFFs. To obtain more accurate classification results, it is common to stack HH and HV polarization imagery with one another, or to perform raster calculation, in order to minimize noise in backscattering between the two images (Deus). For the purposes of this study, three other PALSAR images were created: a file in which the values of the HV polarized image were subtracted from those of the HH (HH-HV); one in which the values of the HH image were divided by those of the HV (HH/HV); and one final image where the HH and HV files were stacked into one.

iii. Initial Methodology and Results

The supervised classification of land cover types was completed with the Environment for Visualizing Images (ENVI) software application. ENVI is an open source program used for analyzing and visualizing data and imagery (Harris Geospatial, 2017). This software is also capable of classifying imagery based on the spectral signature of different land cover types. Five satellite images (Landsat, PALSAR HH, PALSAR HV, PALSAR HH-HV, and PALSAR HH/HV) in addition to the finalized training dataset were loaded into ENVI to run a supervised classification. Before running the tool, a classification algorithm type was chosen based on the number of land cover classes in the training dataset, if the pixel values in the raster image overlap when plotted in a 3D graph, and if the shape of the pixel point clouds in the 3D graph are simple or complex (50 North, 2016). The criteria required for determining the ideal classification algorithm was based off of a decision tree diagram which can be found in *Appendix A - Characterizing Land Cover in our Watersheds of Interest*. The initial training dataset was composed of eight land cover classes: tree cover, grass, agriculture, barren, sand, water and wetland, river, and built-over. The pixel values for the Landsat image were plotted in a 3D space using the "n-D Visualizer" tool in ENVI and can be seen below in Figure 4.

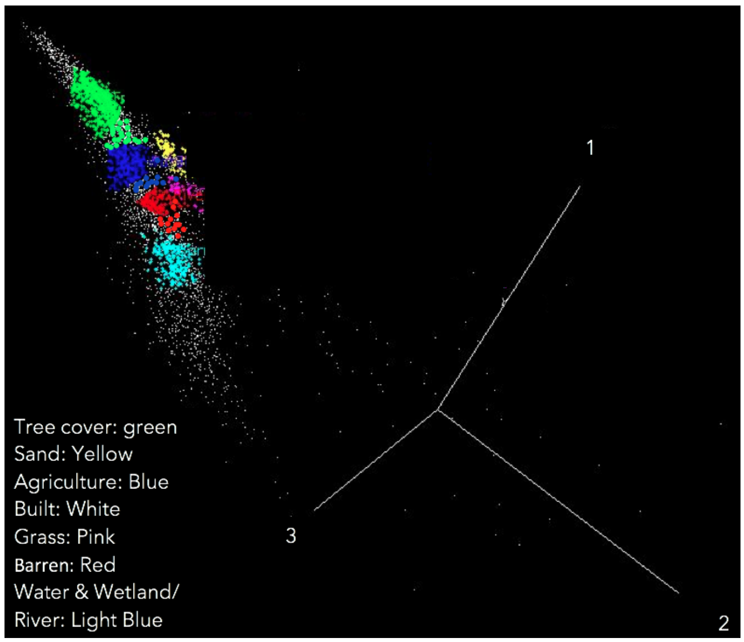

Figure 4. *Landsat n-D Visualizer Results*. 3D graph displaying the pixel values of the Landsat satellite image and the land cover classes from the training dataset. The shape and overlap of the pixel point clouds presented here determined the best-suited classification algorithm. The colored point clouds are associated with specific land cover classes and pixel values: tree cover is green, sand is yellow, agriculture is blue, built-over is white, grass is pink, barren is red, and both water & wetland and river are light blue.

By plotting the Landsat pixel values we determined that pixels corresponding to different land cover classes overlapped as seen in Figure 4 with the overlapping point clouds of different colors. We also visually identified that the point clouds have complex ameba-like shapes. With this information and having a total number of land cover classes greater than two (eight classes) we determined that the ideal classification algorithm is the Mahalanobis Distance method. These steps were repeated for the PALSAR HH, PALSAR HV, PALSAR HH-HV, and PALSAR HH/HV satellite images and resulted in a similar selection of the Mahalanobis Distance algorithm. The Mahalanobis Distance method is one of the faster algorithms to run considering it sets the covariance for all land cover classes to be equal and classifies pixels based on the training dataset class that the pixel is closest to in value (Richards, 1999). The two other possible algorithm classification types are Minimum Distance and Maximum Likelihood, which will be discussed in further detail in the following section of the *Technical Approach*, *II.iv. Output Validation and Methodology Refinement*.

After running the classification tool, the output was a shapefile with polygons colored by the corresponding land cover classes included in the training dataset. The result of the initial Landsat classification is provided below in Figure 5. The results of the HH, HV, HH-HV, and HH/HV classifications can be found in *Appendix A - Characterizing Land Cover in our Watersheds of Interest*.

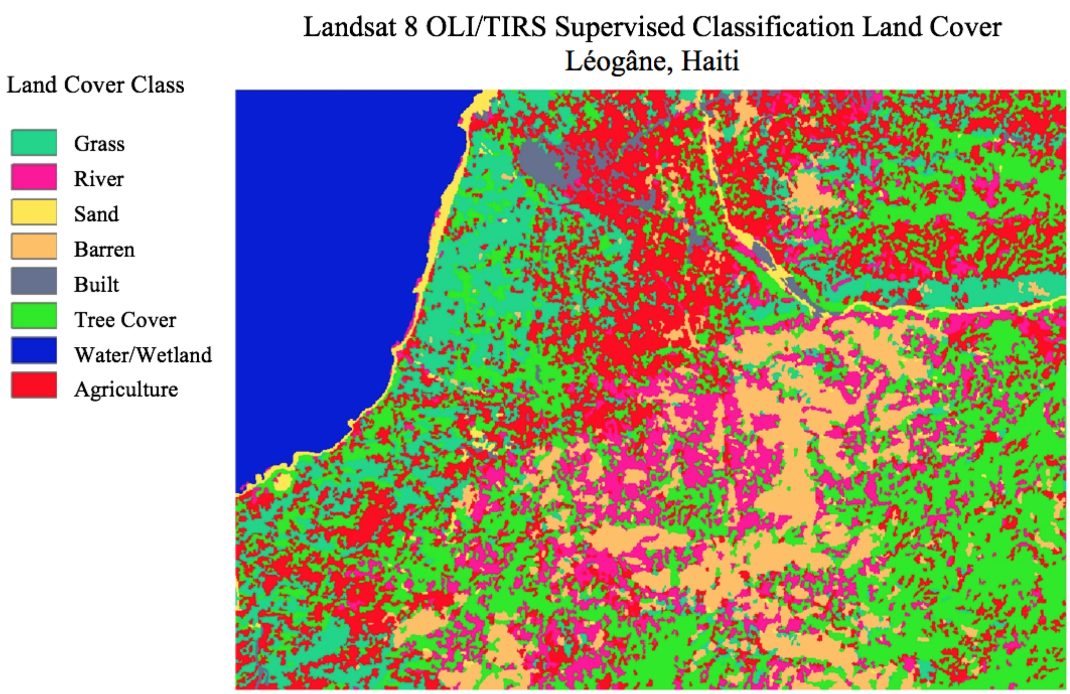

Figure 5. ***Initial Supervised Land Cover Classification with Landsat Imagery.*** Map of the supervised classification results for the region of Léogâne, Haiti using a Landsat 8 OLI/TIRS image from December 18th, 2018 and the Mahalanobis Distance classification algorithm.

The initial classification provided positive results for a majority of the land cover classes, such as water, barren, and built, but was unsuccessful at accurately classifying river. As shown in Figure 5 above, the river class (pink color on the figure) was mapped in the middle of the barren land and does not represent river/stream-like structure. In addition, the actual river is classified as sand (yellow color on the figure). These inaccuracies in the classification results may be indicative of an incomprehensive training dataset or may be a result of the chosen classification algorithm. The following section of this report will address how these classification results were validated and will discuss the solutions implemented to reduce the classification inaccuracies.

iv. Output Validation and Methodology Refinement

The results of the classification were then validated with a combination of *in situ* data points collected in Léogâne and visually assessed classifications based on Google Earth Pro satellite imagery, with a total of 30 data points per land cover class and followed the same methods that were discussed in *II.i Creating a Training Dataset*. The results from the ENVI classification outputs were compared to the known classes from the validation dataset for specific coordinate points. The number of points that were correctly classified by ENVI, as individually compared to the validation dataset, were used to calculate the percent accuracy for each class and overall for the file. This method was conducted for each of the six images that were processed in the initial classification. The initial accuracy results for each of the files can be found in Table A-1 in *Appendix A*. To obtain more accurate land cover classifications, it is common to stack Landsat and PALSAR imagery as doing so accounts for a larger number of bands in the backscattering analysis. Based on the initial validation results, it was determined that the Landsat image would be stacked with the most accurate PALSAR image, or the stacked HH and HV polarization file. The resulting file was determined to be 67.6% accurate. Based on previous studies in land cover classification, our goal was to obtain an overall percent accuracy greater than 80% and maintain that no class be less than 63% accurate (Bogner, Christina, et al.). The results from re-classifying the stacked Landsat and PALSAR image did not achieve this threshold, so the initial classification methodology was refined in the following ways:

1) The "River" class was removed because ENVI commonly mistook the silty river for "Sand" or "Barren Land". This removal was justified because this aspect of the land cover is accounted for in the SWAT and GSSHA hydrologic modeling.

2) The "Grass" and "Agriculture" classes were combined into one "Other Vegetation" class. This was decided because ENVI commonly mistook "Grass" and "Agriculture" for each other and because in creating the training dataset it was difficult to discern the difference between the two on Google Earth Pro. It was determined that the most accurate way to account for these would be to combine them into one class.

3) Different classification methods would be assessed through ENVI. The initial rounds of classification were conducted using the Mahalanobis Distance methods. It was determined that the final results from this method would be compared against those from the Minimum Distance and Maximum Likelihood methods, to assess whether the most accurate classification method was used. These are the primary three methods that ENVI uses to conduct supervised classifications and each involve the assigning of pixel classes to those of the nearest neighbor from the training dataset. They vary in their assumptions for pixel covariance (*Classification*).

The accuracy results based on the refined methodology, including the validation results from the stacked Landsat and PALSAR image, can be found in Table A-2 and Table A-3 in *Appendix A*.

v. Final Results

Based on the refined methodology discussed in the previous section, a final land cover raster file was developed using the Maximum Likelihood classification method and a updated training dataset composed of six classes.

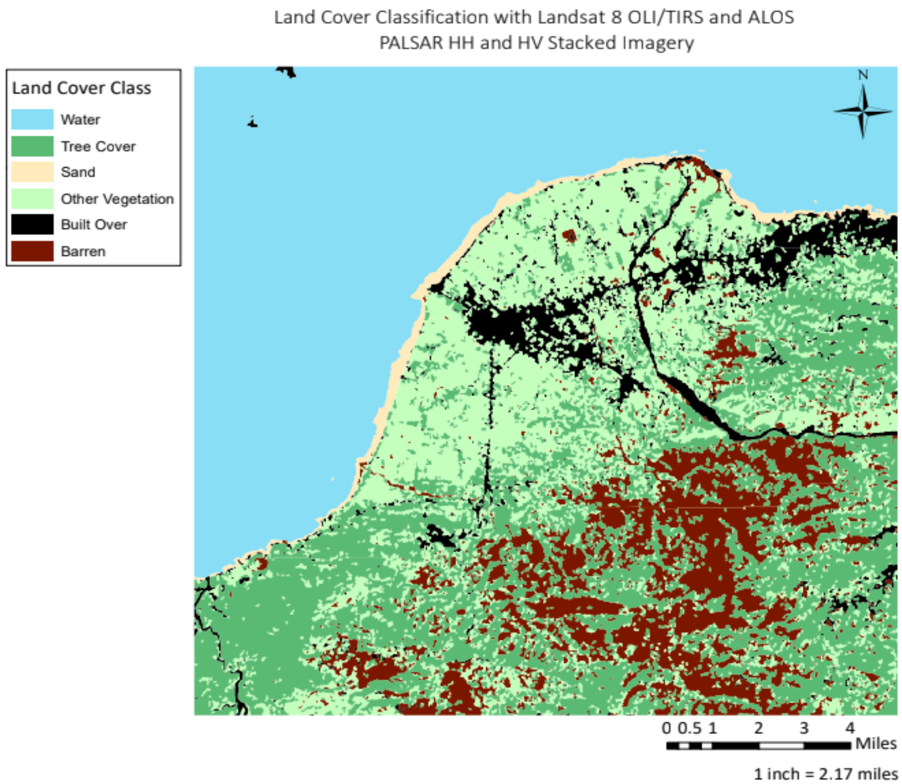

Figure 6. ***Land Cover Classification with Landsat 8 OLI/TIRS and ALOS PALSAR HH and HV Stacked Imagery.*** A visualization of the final land cover classification map of the Léogâne region.

The resulting accuracy of this classification was as follows:

Table 2. ***Land Cover Class for Final Classification.*** A table showing the classes accounted for in the final land cover classification map and resulting percent accuracy, including the total accuracy of the overall file.

CLASS	**ACCURACY (%)**
Tree Cover	86.7
Sand	70.0
Water	96.7
Barren Land	83.3
Built	90.0
Low Vegetation	63.3
TOTAL	81.7

Based on the validation methodology detailed in this report, no class resulted in less than 63.3% accuracy, and the overall accuracy is 81.7%. These results are within expected and acceptable ranges for a land cover classification (Bogner, Christina, et al.). After the creation of this file, the raster was converted to a shapefile and passed to Mateusz and Nitika for the initial rounds of modeling in GSSHA and SWAT.

Throughout this analysis we have made assumptions to make this procedure feasible. The inaccuracies within the unsupervised classification in ENVI are assumed to be minimal. In addition, Google Earth Pro is assumed to be an acceptable confirmation dataset, therefore neglecting any flaws that may result from classifying vegetation by looking at a satellite image on a computer screen. Furthermore, in the development of classes, our team confirmed with our technical mentor, Dr. Michael Piasecki, that the proper classification of the stream network in the final output is unnecessary, since this aspect of the land cover is accounted for in the SWAT and GSSHA hydrologic modeling. As a result of making these assumptions, the final vegetation classification product may have minor inaccuracies and therefore cannot be taken at face value when used as an input dataset for future modeling purposes.

III. Soil Experimentation and Shapefile Creation

In order for both GSSHA and SWAT to run, the programs require soil parameter definitions and shapefiles. Initial research was conducted to understand what soil databases currently have information available for Haiti. The most up-to date and comprehensive soil analysis and classification in Haiti is from 2006 from the World Soil Database by FAO (UNESCO). Due to the topology, as well as precipitation and soil erosion caused by major events, the period between 2006 and 2018 is difficult to account for in the soil. Thus, soil collection and testing was a pertinent portion of our understanding of the soil in our region of focus. After Professor Lampousis and Dr. Stephanie Devries, college lab technician and adjunct lecturer, provided access to the City College soil lab, the soil samples from Haiti were tested and analyzed. There were 6 soil samples in total, and each soil sample underwent textural, organic and moisture analyses.The procedure for the Soil Texture analysis can be found in the lab manual of EAS 21700 *"Lab 5: Soil Texture and Properties"* which can be found in *Appendix D - Soil Experiments and Shapefile Creation*. By first finding the percent silt, sand and clay with a hydrometer and then using the soil triangle,the soil type was determined. Next, the samples were prepared for the percent organic carbon and moisture tests, the procedure for which can be found in the lab manual of EAS 21700 "*Lab 2: Organic Matter Determination"*, also in *Appendix D - Soil Experiments and Shapefile Creation*. Since all experiments were performed 1 week after collection, the moisture test could not be properly accounted for since a moisture analysis should be performed no more than 48 hours after sample is collected. Thus, the analysis for percent moisture, although completed, was negated. As for the percent organic carbon, other than one sample that had accidentally spilled, the rest of the samples were between the 3-4% range. These measurements helped in the understanding of the type of soil located in the region. A full report on the soil analysis can be found in *Appendix D*.

The uncertainty of the soil analysis is based on the experiment uncertainty, since all parameters and tables created were based on the loamy sand soil texture. Since the measurement to obtain percent weight for sand, silt, and clay, came from reading the hydrometer, its accuracy was considered. The the hydrometer accuracy was determined through a "blank" sample. This "blank" sample was a water sample whose hydrometer reading was known and therefore could determine the percent accuracy for the hydrometer. The hydrometer uncertainty is +/- .001 g/ml^3 .

From these three analyses, the soil type was determined to be loamy sand and the percent organic content to be 3%. A soil dataset called SOTERLAC (Soil and Terrain Database for Latin America and the Caribbean) was obtained from the ISRIC World Soil Information site, exported as a shapefile and clipped to the extent of Haiti. It was then edited to make the regions in Haiti representative with the soil texture of sandy loam, based on the soil experiment. Using toggle editing and free hand editing, more nodes were added and new features were created in the layer. Six new features were added in order to make the area more specific based on the soil type - sandy loam - and to visually represent an alluvial field. For each new feature, the area, perimeter, parent material and other attributes such as taxonomy codes and landforms were determined. Area and perimeter were calculated using the measure tool from QGIS. The other attributes,(such as Soterlac, SoterlacI, NewSuid, Landform, dom_soil, parent material, numb group and cover percentage), were calculated after thorough research on the dataset methodology itself and extrapolating on current attribute values. For example, the Soterlac ID numbers are based on the amount of polygons in the data set; thus, when creating new features, the new Soterlac IDs were a continuation of the polygon IDs from before (ISRIC).Once this file was saved, it was exported as a shapefile and was projected in NAD 83 UTM zone 18N in order to match the other shapefiles used in this project.

The soil data for SWAT was divided into two groups: the shapefile and an input .csv file. The input file had columns with variable names that needed to be defined for each soil type in the entire region. Since there were 4 soil types in all of Haiti, these soil types needed to referenced with the values for each variable in this file. Once the initial Soil ID's were created in an Excel file, the soil input manual for SWAT was reviewed to become familiar with the variables and added the respective information for the remaining columns (SWAT Input Data: .sol).

Unlike SWAT, GSSHA requires various soil parameters to be defined when running each model. GSSHA has reference tables for all the parameters needed based on the soil type. For all of the criteria required,we used the values GSSHA had in the reference table. For surface roughness, GSSHA provided a range and as a conservative assumption we selected the higher value of the surface roughness. The reference tables from GSSHA did not state any ranges for initial moisture as it was dependent on the event we wished to model. Since this information was based on Sandy data, after looking over the precipitation documents and discussing with Prof. Piasecki, we decided to use .3% as the value for initial moisture. Table 3 below shows all of the soil criteria required by GSSHA, the determined value ranges for each criterium, and the chosen values for this study.

Table 3. ***GSSHA Required Parameters.*** Table indicates parameters GSSHA required for soil, the range for each parameters and the chosen value for parameter.

Soil Criteria	RANGE
Surface Roughness	(.025-.040)
hydraulic conductivity (cm/hr)	1.09
capillary head (cm)	11.01
porosity(m3/m3)	0.412
pore distribution index (cm/cm)	0.378
residual saturation (m3/m3)	0.041
field capacity(m3/m3)	0.207
wilting point (m3/m3)	0.095
initial moisture	dependent on Sandy data- .3%

IV. Creating a Mitigation Design

The overall goal of this project is to model areas for reforestation in the Léogâne region. Before the modeling phase, criteria were developed for identifying areas in particular need of reforestation efforts. According to Dr. Michael Piasecki, these criteria are dependent on the degree of slope, elevation, and soil type. For example, areas of high elevation and slopes greater than zero were considered to be focus regions because reforestation in mountainous areas is expected to result in increased watershed capacity, which will reduce future flooding events in the plains. Furthermore, Mr. John Winings provided us with elevation range limitations to which our design should be confined. According to John, no land above 914 m (3000 ft) should be considered because the delicate fruit trees planted cannot survive at such heights; land below 305 m (1000 ft) should not be considered because sediment in the alluvial plain makes the soil inadequate for reforestation efforts. In addition, the land cover raster file produced for the watersheds of interest provided a basis for additional criteria, as only land that was identified as barren was considered for reforestation efforts.

Some initial research was conducted to understand best practices for reforestation with the use of various reforestation manuals from Lebanon, Brazil, and Oregon along with current reforestation practices from the Caribbean. Through these manuals, it was realized that while reforestation is site specific, there are primary and secondary criteria that are met with each manual. The primary criteria include: soil depth, vegetation status, rockiness/ distribution of rocks, altitude, slope, aspect and soil type. The secondary criteria include: land use, security concerns, community engagement and accessibility. For the use of this project, we removed the idea of secondary criteria as they were socioeconomically driven and would assume that there would be no difficulty with land use, security concerns, community engagement and accessibility of the land.

After further research in the primary criteria, we narrowed down the criteria we would focus on based on accessibility to data for the creation of the alternatives. The criteria were narrowed down to include: vegetation status, altitude, slope, and soil.

The results from the first round of the modeling processes in SWAT and GSSHA were assessed to identify areas that are currently susceptible to flooding events. Based on the initial round of modeling for the no-change alternative, the Rouyonne watershed yields the highest peak flow and volume. Thus the based on the criteria specified previously, and the fact that Rouyonne has the greatest peak flow, the reforested area for the alternatives were chosen to be located in the Rouyonne watershed.

Throughout the course of this project, two approaches were taken to model the effects of reforestation on the Rouyonne watershed. The first approach involved only reforesting an amount of land which would theoretically be feasible for a reforestation organization in this focus area and was modeled based off of CODEP's financial records. The second approach was conceived to

Approach #1 - Financial Feasibility

The final criteria that was established for the alternatives development was financial feasibility. It was a primary focus for this project that the proposed reforestation plan and models reflect reforesting an amount of land that would be realistically feasible for a reforestation program in the Léogâne region. Using CODEP financial records from 2015 as a basis of comparison, provided to our team by John Winings, the total annual budget for the year was calculated and converted to USD. It was assumed that the budget for that year would carry over to present day, as we did not have access to a full year of financial records beyond that year. Because a typical construction project in the United States typically accounts for a 5-10% contingency, a conservative approach was taken for this project by assuming the upper value of that range (10%) and then doubling it (*7 Things You Need to Know About Contingency Budgets*). After a 20% contingency was taken from the annual CODEP budget, the final value was divided by the first-year implementation costs, or $0.09 per square foot of land reforested. It was decided to only account for the first-year implementation rather than the total long-term costs because CODEP relies on volunteer labor, and the 14-year costs only account for labor. A more detailed account of these values is provided in the *Cost-Benefit Analysis* section of this report. From this methodology, it was determined that it would theoretically be feasible for CODEP (or an organization with a similar budget) to reforest 315,948.35 square feet of land in a single year.

Using these results, as well as the pre-established criteria for optimum focus areas, a set of criteria was developed for the proposed reforestation alternatives. One of these alternatives is a

“No Change” option, based in no new reforestation efforts implemented after 2018. This alternative was based in modeling the final land cover produced as a result of our land cover classification (*Characterizing Land Cover in Our Watersheds of Interest)*. The next alternative was determined by prioritizing high elevations with greater than zero slope. Using GIS shapefiles of all elevation data clipped to the extent of barren land with slope greater than zero, the total available area at each elevation was calculated. The second alternative for this project was chosen by reforesting all area from 824 to 914 m, as this range yields close to (but not exceeding) the amount of land that would theoretically be feasible for CODEP to reforest in a single year. The third range was chosen with similar logic, using the next lowest elevation range, from 768 to 823 m. The final range was chosen in order to determine the effects of reforesting a greater amount of area on flooding mitigation, despite it theoretically being outside of CODEP’s financial feasibility. For the fourth alternative, a Combined Range was chosen of 768 to 914 m. The following table describes each of the four alternatives, the associated elevation range, and total area reforested for each.

Table 4. ***Reforestation Alternatives.*** A description of each of the alternatives used for the study, their respective elevation ranges (in meters), and amount of area that would be reforested (in square feet).

Alternative Description	**Elevation Range (m)**	**Area (sqft)**
No Change	None	None
Upper Range	824 - 914	312,217.82
Lower Range	768 - 823	313,128.89
Combined Range	768 - 914	625,346.71

Once the alternative plans were developed, new land cover files were generated using ArcGIS to reflect each of these plans. To do so, the Digital Elevation Model (DEM) was vectorized to a shapefile and the Spatial Analysis toolbox was used to calculate the slope. Next, a query was implemented to retrieve all land with a slope greater than zero, and the DEM shapefile was clipped to this extent. Next, it was clipped to the extent of all barren land, based on a selection exported from the land cover file. Finally, it was clipped to the extent of the Rouyonne watershed. The Selection feature was used again, starting with the Upper Range, to extract all barren land with greater than zero slope between the range of 824 - 914 meters. This selection was exported to a shapefile and used as a template to manually add new polygons to the land cover file with included SWAT reference codes. The new polygons, representing the new agroforested land, were matched with the Orchard (ORCD) SWAT code with a numeric reference of 61. This methodology was repeated for both the lower and combined ranges to generate three new land cover shapefiles with varying amounts of land reforested.

After alternative land cover files were generated, a second round of modeling in GSSHA and SWAT was conducted for each of the alternatives for only the Rouyonne watershed. GSSHA was used to model the effects of one extreme weather event while SWAT was used to model typical climate conditions based on previously measured hydroclimatological data.

<u>Approach #2 - Reforesting All Available Land</u>

When the results from modeling the first approach of three financially feasible design alternatives were obtained and analyzed, it was concluded that the modeling outputs of reforesting such a small amount of land would not be conducive to understanding the potential impact that a reforestation project can have on the hydrologic parameters in a watershed. A more detailed account of these results can be found in the *Technical Approach* section of this report in *V. GSSHA Hydrologic Modeling for Severe Weather Events* and *VI. SWAT Hydrologic Modeling for Long-Term, Regular Weather Events*. After analyzing these results, it was decided that a second approach would be developed in which all barren land in the Rouyonne watershed, regardless of elevation or slope, would be converted to forested land. In this scenario, a total of 288,363,502.42 square feet would be reforested. This approach was chosen to supplement the conclusions drawn from Approach #1 by modeling the potential impact of reforesting all currently available land so that the hydrologic and socio-economic effects from considerably different magnitudes of area being reforested can be compared against each other. In Table 5 below, find each of the alternatives from both Approach #1 and Approach #2, their percent area with respect to the entirety of the Rouyonne watershed, and their percent area with respect to the available barren land in the Rouyonne watershed.

Table 5. Alternatives from Approach #1 and Approach #2. The percent area with respect to the entirety of the Rouyonne watershed, and their percent area with respect to the available barren land in the Rouyonne watershed for the two Approaches.

Alternative Description	Percent of Watershed	Percent of Barren Land
Upper Range	0.05%	0.12%
Lower Range	0.05%	0.12%
Combined Range	0.09%	0.22%
All Land Reforested	41.95%	100%

This set of alternatives design assumes that the minor inaccuracies in the resulting land cover raster file from the supervised classification are negligible, the criteria assumptions are feasible, and the outputs from the watershed modeling programs, SWAT and GSSHA, are accurate. In addition, property ownership is excluded from implementation regions, which will be discussed further in the *Feasibility* section of the report. The effects of these assumptions may result in inaccuracies with the final alternative mitigation plans, including limitations of where the proposed plans can be implemented due to property ownership issues.

V. GSSHA Hydrologic Modeling for Severe Weather Events

Hydrologic models are used to predict and manage water resources by quantifying flow and quality of water, as well as generating visuals of hydrologic processes which can be useful for identifying the changes in watersheds that occur during weather events. Modeling local hydrology after extreme weather events in the Léogâne area allowed for the simulation of different scenarios and observation of the possible outcomes of reforestation efforts.

GSSHA, the Gridded Surface Subsurface Hydrologic Analysis tool, is a hydrologic model for rainfall and runoff processes. It allows users to visualize extreme weather events over short-term periods of 15 days. In the case of this project, this was done to assess the effects of storms with the same intensity as Hurricane Sandy on our area of interest. Hurricane Sandy was chosen as the model storm for this assessment because it made landfall on the coast of Haiti as a Category-1 storm in 2012 and resulted in 54 deaths and severe property destruction (The Associated Press, 2012). Because of this dramatic effect on local communities, and because we had access to the necessary hydroclimatological forcing data for this event, it was an appropriate storm to assess for increasing resiliency. Additionally, GSSHA also allows users to run models for different weather and land cover scenarios that will allow simulation of the effects of different reforestation approaches and would help to identify optimal strategies for minimizing the likelihood of flooding after extreme weather events.

GSSHA modeling was done using the WMS software developed by Aquaveo. The inputs necessary to run the model include land cover maps (which specify the physical cover of the surface of our area of interest), Digital Elevation Models (DEM) (which specify the topography), and soil data (which contains parameters of the soil such as texture, type, percent of dominant soil, and other parameters).

Table 6. ***GSSHA Input Files.*** Table showing inputs necessary to run a GSSHA model with specified file type, which will be used by the software, the original source of the file and whether the file needs to be formatted.

Inputs	File Type	Source	Format Required
Land Cover	Shapefile	Landsat 8 OLI/TIRS and ALOS PALSAR HH and HV Stacked Imagery	Yes
DEM	Gridded	Dr. Michael Piasecki	Yes
Soil Layer	Shapefile	SOTERLAC/ISRIC	No
Precipitation	Excel Table	Dr. Michael Piasecki	No

The methodology for applying short term severe weather model using GSSHA was generated after consulting with our technical mentor, Dr. Michael Piasecki. The first step in the modelling was obtaining land cover maps which were prepared by our team after conducting the supervised classification of land cover imagery. The next step was gathering the DEM data for our region of interest that was provided by Professor Piasecki. The DEM had to be formatted from a .tiff format into a gridded format. The soil data originally comes from the ISRIC (International Soil

Reference and Information Centre) and was modified to make the shapefile representative for our region of interest. Then, files were loaded into the software and the model was run for an extreme weather event based on precipitation data obtained during Hurricane Sandy. Precipitation data was gathered from the Beloc weather station and was provided to us by Dr. Michael Piasecki. After loading in the shapefiles, parameters needed to be defined in a spreadsheet pertaining to infiltration, soil, and land cover based on GSSHA references and inputted in order to begin the modeling process. The land cover parameter includes surface roughness, which is based on Manning's number. The parameters for infiltration include hydraulic conductivity, capillary head, porosity, field capacity, wilting point, residual saturation, and pore distribution. These parameters were obtained from the GSSHA Manual as they pertained to the soil texture for the watershed. The final parameter was initial moisture, which was dependent on the percentage of soil moisture from the event modeled. As stated previously in the *Soil Experimentation and Shapefile Creation* section, soil moisture was determined based on the precipitation that occured before hurricane Sandy. The simulation was repeated with different forest cover approaches to determine the optimal criteria. GSSHA models were run for a 15-day period of October 23rd to November 7th using Sandy precipitation data. The method used for short term modeling was provided via instructions from Aquaveo.

The first step in preparing for GSSHA modeling was making sure that all files are in the appropriate format. Base files include land cover layer and soil cover layer in a shapefile (.shp) format as well as DEM data in a gridded (.asc or .hdr) format. Preprocessing for GSSHA starts with computing flow direction and accumulation. The software is able to compute accumulation using a function called TOPAZ, which uses its base calculation on the DEM. Streams are calculated using the diffusive wave approach which allows GSSHA to route water through pits or depressions and regions of adverse slope. The next step in preprocessing is Watershed Delineation, which requires an outlet point from a channel and computes the extent of a watershed from the DEM. Once the preprocessing is done, GSSHA was ready to be run. First it was required to define and smooth streams. Streams are required to be defined in terms of a shape (trapezoidal), roughness (manning's number) and measurements (depth, width and side slope). Since the diffusive wave approach was used, adverse slopes in the stream have to be interpolated to smooth out the spikes in elevation along the channel route.

The next step was creating 2D Grid for the model. The selection of the grid size for a given watershed determines the total number of grid cells used to describe the watershed, which in turn sets the computational effort and memory required. Typical grid cell sizes range from 10 m to 250 m. This project utilized a 30 m x 30 m grid for the GSSHA model, which yielded the highest resolution while still maintaining a feasible processing power for the computer. The next step was setting up job controls, which requires establishing the time for the simulation as well as the time step that will be recorded. After that, defining land use and soil type was required. This is done to convey to the software which layer corresponds to which land use and soil type. Then we were able to input the necessary parameters for hydrologic computations. Next GSSHA requires a definition for precipitation over the area. This was done by importing precipitation data from a weather station in nearby region. Finally, we commanded the software to clean up our model by deleting extraneous shapefiles and clipping all files to the extent of the gridded layer of the watershed. After the GSSHA model simulation was complete, visualization of the results in the watershed could be created to show the results in an aesthetic manner which can be seen in *Appendix C - GSSHA Hydrologic Modeling.*

Uncertainties in GSSHA include: unavailable full detailed map of the soil layer in our region of interest in Haiti, unavailable exact soil parameters for the Rouyonne watershed area , no field-based measurements of the channel shape, no access to exact stream route geomorphology or exact precipitation in the Rouyonne area, and the mathematical formulas that the model bases its computations on may not be representative of the actual conditions in the watershed. When running the model, the data sets may have contained inaccuracies for the land cover and soil type inputs. Furthermore, we assumed that the magnitude of future severe weather events will mirror that of Hurricane Sandy. However, due to the effects of climate change, this may not be the case over time. Despite these uncertainties, the simulation was assumed to be representative of the area. Furthermore, because this model was not validated, it is unclear how accurate these results are with respect to actual metrics of the watershed.

Outputs from GSSHA modeling include hydrographs and summary files which include final values for our watershed. The models can be visualized and exported as video loops.

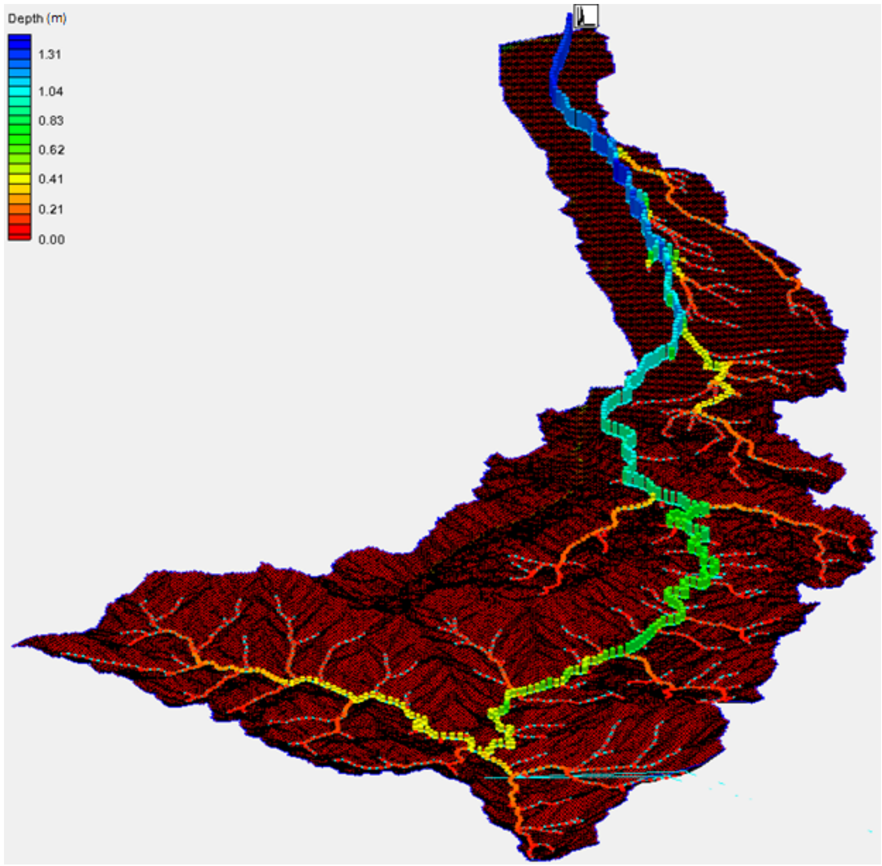

Figure 7. ***Rouyonne Channel Depths.*** Visualized model for Rouyonne watershed showing flow depth (meters) at peak flow rate.

The results for the first reforestation approach, where the different elevation ranges within financial feasibility were reforested, yielded minuscule changes in the discharge, peak flow, lateral flow into channel, and infiltration for the Rouyonne watershed with respect to the no-change alternative; while the results for the second approach, where all available barren land was reforested, yielded significant changes. This can be seen in Table 7 below. In this table, the "Lower Range", "Upper Range", and "Combined Range" all represent the first, financially feasible approach. The "All Barren Land Reforested" alternative represents the second approach.

Table 7. ***GSSHA Modeling Results.*** Results for discharge, peak flow, lateral flow and infiltration compared to the no change alternative

Alternative	Discharge	Peak Flow	Lateral Flow into Channel	Infiltration
Lower Range	-0.004%	+0.2%	-0.004%	-0.18%
Upper Range	-0.026%	-0.4%	-0.025%	-0.006%
Combined Range	-0.014%	-0.03%	-0.013%	-0.10%
All Barren Land Reforested	-6.3%	-20.4%	-6.3%	+5.1%

It was expected that discharge, peak flow, lateral flow into channel, and infiltration would all decrease as a result of implemented reforestation. Discharge and lateral flow into channels deceased for all alternatives, as was expected. However, peak flow for the lower range alternative had unexpectedly increased. This may be due to the fact that the geomorphology of the river was not taken into account when GSSHA was modeling. Infiltration for all of the alternatives in the first approach decreased, while for the second approach it increased as was expected. These results may not be reflective of the actual conditions after reforestation, due to lack of validation of the model and lack of analysis on the geomorphology of the river stream itself. Further work is necessary to validate the results from this study against a dataset of known, measured points in order to ensure that the results are representative for Rouyonne.

VI. SWAT Hydrologic Modeling For Long-Term, Regular Weather Events

SWAT (Soil Water Assessment Tool) is a modeling software that allows users to simulate the behavior of watersheds based on variable factors such as weather, soil type, land use, pollution, soil erosion, fertility and crop production ("ArcSWAT"). This tool is useful, as it is capable of quantifying the impact of regular weather events on land reforestation practices in the long-term. SWAT allows for the investigation of which reforestation method is the most optimal for long term regular weather events.

The required data for SWAT modeling includes: Digital Elevation Model (DEM) data, land cover data, soil data, and hydroclimatological forcing data. The DEM is a geospatial file composed of gridded elevation points which must be in the .tif format. The DEM file for Haiti had been reformatted from an 8m x 8m resolution to a 25m x 25m resolution because the stream network was not formed with the 8x8 resolution due to the very high resolution of this DEM.

Land cover and soil data files were uploaded in the raster format, but SWAT requires that both files have codes assigned and organized in CSV files which SWAT's reference database can refer to in order to gain access to and process the data. In order for SWAT to recognize the various soil or land use types, it must have been imported into the reference database. Land cover CSV files are required to include land use classes and their respective integer values according to the SWAT reference database. Soil data CSV files include the soil type names identified by their texture and percent compositions. The hydroclimatological data used was provided by Dr. Fekete, an Associate Professor at the Grove School of Engineering, and will be discussed later in this section. The hydroclimatological data must also be updated in the reference database and includes solar radiation, precipitation, wind speed, temperature, and relative humidity values uploaded in the form of text files. Once all data has been formatted, SWAT is equipped to run. Running SWAT models includes four major steps that must be executed consecutively. These steps are as follows:

1. **Watershed Delineation:** The first step was to delineate the watershed in to sub-basins. In this step, the DEM file was uploaded into the source database as a .tif file. Streams were then created based on the topography of the DEM file. Then, the inlet and outlet points were selected. In this situation, the outlet was located at the lowest elevation of the watershed and must flow into a body of water. The inlet can be chosen at any necessary points. In addition to inlets and outlets, the addition of point sources to each subbasin help keep them numbered and numerically represents the number of sub-basins. The sub-basins were created as a result of elevation solely.

2. **Creating HRUs:** In this step, each sub-basin was subdivided into Hydrological Response Units (HRUs). HRUs are smaller units of sub-basins, each of which is defined by particular soil type, land use, and slope range characteristics.

To create the HRUs, the raster land use and soil files are inputted to the database and their characteristics are read by SWAT and compared with the .csv lookup files. Therefore, the generation of HRUs is dependent on slope, land use, and soil type. During this process, SWAT provides multiple options for creating HRUs, two of which are the filter by area option and characterizing based on a combination of land use, soil type, and slope characteristics. For this project, the filter by area option was selected rather than setting a threshold for the land use, slope, and soil files because the latter option would likely generate an excessive number of HRUs that would result in an infeasible run-time.

In order to use the filter by area option, an area threshold was determined. The chosen area threshold was determined by clipping the land cover shapefile with the Rouyonne watershed shapefile. This clipped file was then compared to a histogram created from the land cover file to understand the distribution of the magnitude of land cover polygon areas. From this histogram, it was determined that a total of 25% of the total polygons were excluded in the Rouyonne watershed as a result of setting the threshold at 0.889 ha. It was understood that 0.889 is a small threshold which is likely to yield a large number of HRUs, but increasing the threshold further would have resulted in the loss of 50% of the land cover polygons, and setting it at a considerably small number still led to a feasible processing time.

3. **Edit Inputs and Run SWAT:** Once the HRUs were created, the input files were edited and the model was run. The first step was to input the hydroclimatological forcing data in the form of text files. There are two types of weather datasets that can be used by SWAT: generated weather data and actual weather data. For this project, actual weather data was used for five distinct categories: precipitation, temperature, solar radiation, relative humidity and wind speed. The hydroclimatological data was provided by Dr. Fekete from ISIMIP, The Inter-Sectoral Impact Model Intercomparison Project, which projects the impacts of climate change across affected sectors and spatial scales. ISMIP can be used for various forward modeling predictions as they account for climate change in a comprehensive projection. The data was extracted from Global Climate Models (GCMs) scenarios from the ISIMIP GFDL-ESM2M. NOAA's first Earth System Models (ESMs) was constructed by the Geophysical Fluid Dynamics Laboratory (GFDL). ESMs evolved from the GFDL's successful climate models and turned to new prototype models for bias-corrected climate-input data sets on a 0.5°x0.5°C global grid and at daily time steps (The Inter-Sectoral Impact Model Intercomparison Project). After inputting the data, a period of simulation can be edited to fit the timeframe of the desired data. SWAT can run for a daily or monthly time step for a chosen period.

SWAT was run for daily time steps over a 15-year period from 1/1/2018 to 1/1/2033. Daily timesteps were chosen because they allow the software to calculate the daily mean from the data, which can be helpful to visualize in comparison to the monthly mean. Once SWAT has been run successfully, SWAT outputs text files.

4. **Visualize:** After SWAT was run, the data was visualized graphically. SWAT has options of producing visual graphs for precipitation, sediment yield, and water yield along with other hydraulic variables in conjunction with csv files. It also provides summaries for daily, monthly, and annual means of variables. Some visuals that SWAT has created can be viewed in *Appendix D - SWAT Hydrologic Modeling.*

Table 8. ***SWAT Input Files***. Table showing necessary input files to run a SWAT model with specified file type, which will be provided to the software, original source of the file and whether the file needs to be formatted.

Inputs	File Type	Source	Requires Update
Land Cover	Raster	Japanese Aerospace Exploration Agency (ALOS PALSAR mosaic) USGS Earth Explorer (Landsat 8 OLI/TIRS)	- Addition of SWAT code in the Land cover Shapefile - Creating a lookup table in a csv File format.
DEM	GeoTIFF	Dr. Michael Piasecki	- Changing the resolution from 8x8 metres to 25x25 meters.
Soil Data	Raster	SOTERLAC/ISRIC	- Addition of SWAT code in the Soil Shapefile - Creating a lookup table in a csv File format. - Updating the soil reference database in a SWAT reference database system
Stream Network	Shapefile	Created from the google earth river image	No
Hydro Climate For 1999-2014	Text file Spreadsheet	Global Weather Data for SWAT	No
Hydro Climate For Forward Modelling	Spreadsheet	Dr. Fekete From ISIMIP	- Conversion of csv files in to text file format

The SWAT model was run for two different approaches:

Approach #1: The initial modelling run used the current land cover file, which accounts for no changes in reforestation. In this approach, the four step processes discussed above was implemented.

Approach #2: The second approach involved modeling the hydrologic results from reforesting all available barren land with above zero slopes in the Rouyonne watershed with. This approach was developed to understand how much of the hydrology could theoretically be changed by maximizing the amount of land reforested and to assess the socio-economic effects of doing so against those of the first approach. The same four step process was applied as discussed above. In order to generate a significant number of HRUs it was crucial to define an area threshold in which any value less than the threshold will be disregarded during the creation of the HRUs. Numerous HRUs are necessary within a sub-basin to allow the model to take into consideration land cover types that are not as prominent as others but will have an impact on the hydrologic process and therefore the model results. Thus, we updated the HRU shapefile by defining a small area threshold in order for the HRUs to diversify the representation of land cover classes.

The outputs from the SWAT modeling included .txt output files and visualizations. The visualized model results can be found below.

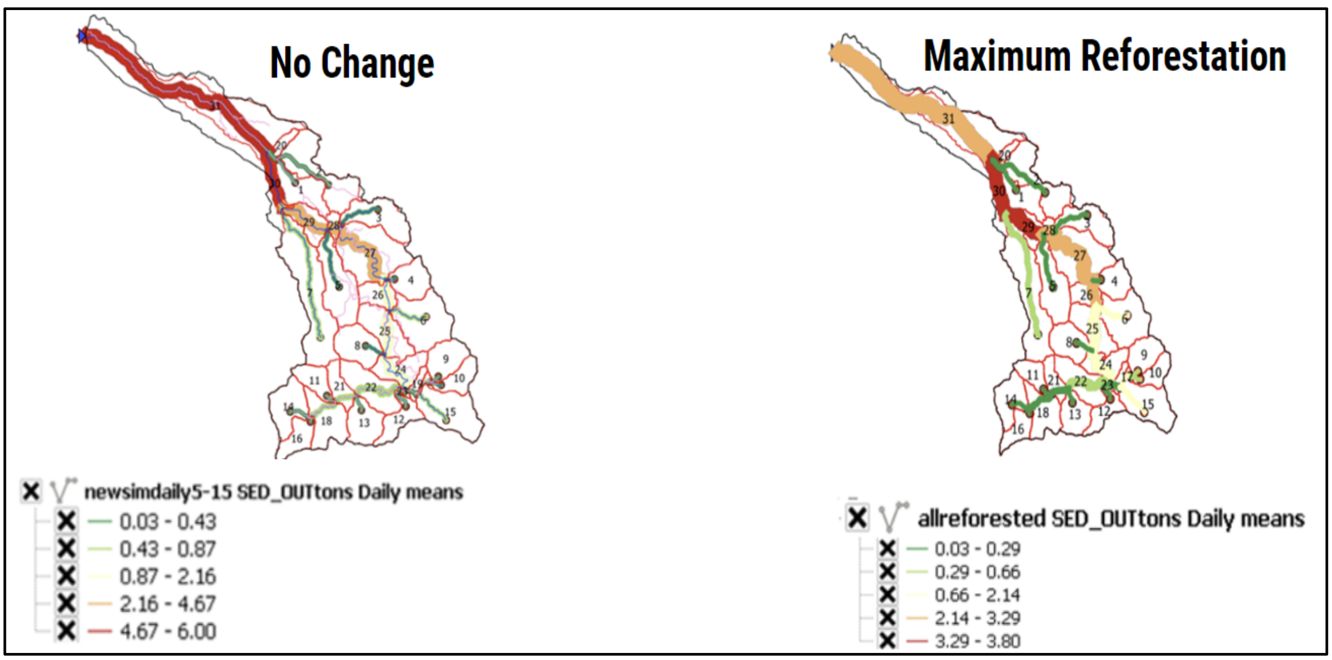

Figure 8. ***Sediment Output.*** Map showing the daily means sediments out in tons for the No change and the Maximum Reforestation approach.

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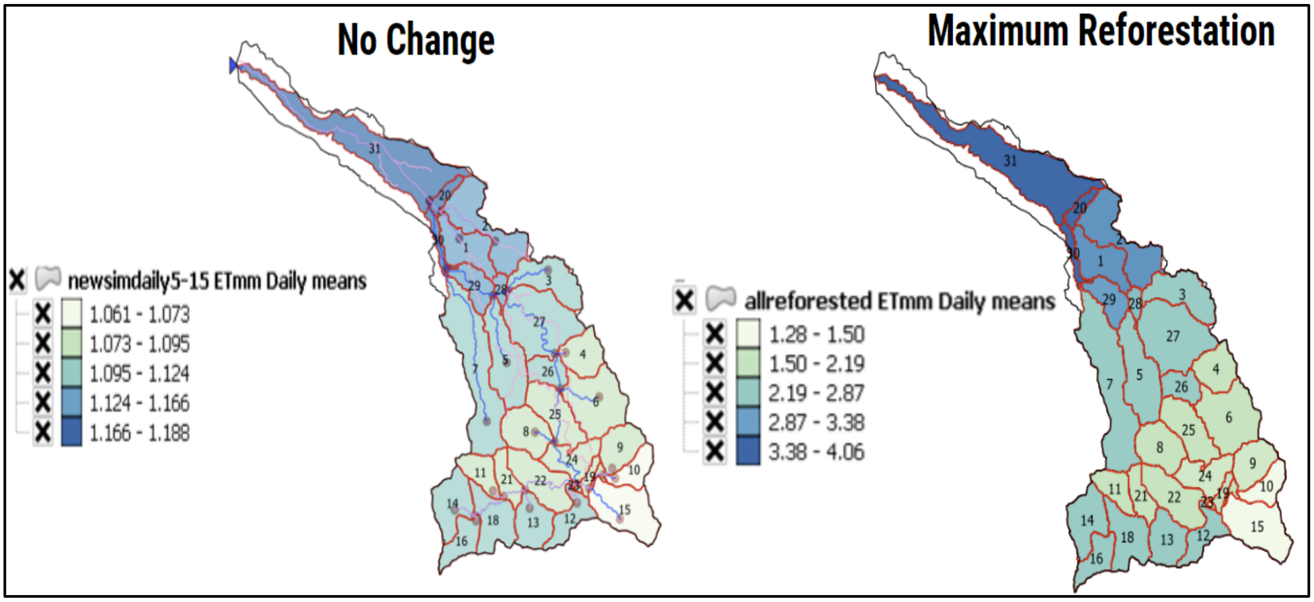

Figure 9. Evapotranspiration.Map showing the daily mean evapotranspiration (mm) the No change and the Maximum Reforestation approach.

While running SWAT, we assumed that the input data, such as the hydroclimate data, will not change dramatically over the 15-year run time. In addition, we assumed that the inaccuracies of the input datasets are negligible. However, delineating the HRUs by defining the threshold was a major challenge due to the fact that there were multiple options for determining a threshold, as stated previously. The other option would generate an excessive number of HRUs that would result in an infeasible run-time. Moreover, there is a lack of data availability, as our region is outside of United States. For example, some inaccuracy stems from the fact that soil and land cover maps were created by our team, rather than downloaded from peer-reviewed sources. The utilized land cover map, specifically, is known to have an accuracy of 81.7%. Although this is an acceptable value, it still presents a source of error. Lastly, all programs run on mathematical models which are theoretical models and always yield some errors because they are not directly measured values.

Table 9. ***SWAT Modeling Results.*** Results for the surface runoff, lateral soil flow, total water yield, evapotranspiration, and sediment yield including original output values, the difference between the two alternatives, and overall percent change. A negative percent change indicates a decrease from the no change to the all reforested option, and a positive percent change indicates and increase.

Annual Average Parameters	No Change	All Barren Reforested	Difference	Percent Change
Surface runoff (m^3/year)	9,992,791.40	7,453,782.85	2,539,008.55	-25%
Lateral Soil flow (m^3/year)	14,613,145.65	6,916,247.63	7,696,898.02	-52%
Total Water Yield (m^3/year)	43133994.85	25,329,452.46	17,804,542.39	-41%
Evapotranspiration (m^3/year)	23,740,167.20	24,124,953.80	384,786.60	+2%
Sediment yield (tons/year)	1,982.23	1,515.83	466.41	-23%

The above table shows the results for the surface runoff, lateral soil flow, total water yield, evapotranspiration, and sediment yield for the two approaches. It was expected that surface runoff, lateral soil flow, total water yield, and sediment yield would decrease between the no change and all barren land reforested options and that evapotranspiration would increase. Surface runoff decreased by 25% and lateral flow into channels decreased by 52%, as expected. Total water yield and sediment yield also decreased by 41% and 23%, respectively. Furthermore, the evapotranspiration increased by 2%. These results may not be reflective of the actual conditions after reforestation, due to lack of validation of the model. Further work is necessary to validate the results from this study against a dataset of known, measured points in order to ensure that the results are representative for the Rouyonne watershed.

Feasibility Argument

The initial goal of our project was to create a flooding mitigation plan, which considers deforestation as the primary cause of frequent and severe flooding events. This is one of the primary reasons behind why we chose reforestation as the option for mitigation, rather than other engineering solutions. By mitigating the problem of deforestation at its root, our project will have a greater impact on the consequences that this issue precipitates, such as flooding. A major cause of deforestation is illegal logging, which is often attributed to lack of education and to food poverty, or lack of available nutritious food in a community or household. Reforestation results in great possibility for community empowerment and self-sufficiency, as demonstrated by CODEP's successful initiatives, which we know is one of the most crucial aspects of this kind of work. By involving the locals in reforestation programs, the organization both assists to educate them and helps them obtain food security. This path has been proven successful with the work from CODEP. Their work for over 25 years has helped educate locals on the benefits of reforesting, preserving their current vegetation, and understanding the significant role it plays in the ecosystem and their daily lives. In this time, their reforestation program has increased public participation by twofold. According to Mr. Winings, CODEP's reforestation process educates the local community members on the importance of trees by providing them with hands-on experience to help them sustain their living through reforestation. As a result, some people grow fruit trees, such as mangoes, and sell them as a source of income. Thus, reforestation as a solution for flooding mitigation will be socially feasible because it allows for extensive community involvement, it facilitates empowerment and self-sufficiency through education, and it will support the regional economy.

We have also compared the economic aspects of implementing a dam, riverbank reconstruction and reforestation and have concluded that reforestation is the most economically feasible solution. According to Mr. Thayer Scudder, a frequent consultant on large dam projects for the last 58-years, "large dams not only aren't worth their cost, but that many currently under construction will have disastrous environmental and socio-economic consequences" (Leslie). According to Mr. Scudder, dam construction requires a large portion of financial resources from developing countries. For example his study for the Diamer-Bhasha Dam of Pakistan which cost $12.7 billion in 2008 will not be completed until 2027 and would cost $35 billion,which is more than quarter of Pakistan GDP. He recommended that, instead of building enormous dams, one should focus on other alternatives which do not require such extensive funds. Furthermore the Peligre dam which was constructed in 1956 in Haiti, near the Aribonite River, has proven to be a failure; as soil erosion resulted in severe siltation in the reservoir, reducing the dam's potential for flooding mitigation (The Editors of Encyclopaedia Britannica). Reforestation is economically feasible according to Mr. John Winings since CODEP harvests their own seeds and has minimal cost for other expenses, such as plastic bags which cost around 50 cents, fertilizers which cost around 75 dollars, tools such as shovels and picks and labor costs. Furthermore, the planting of trees does not require specialized technology, labor and knowledge-base in the way that the implementation of dams and other structures do. Thus, local communities often have the necessary resources to perform this work on their own, without hiring outside engineers. Given local resources, funding streams, and current efforts, we believe that reforestation is the most feasible option for our area of focus. This has also been proven from the cost benefit analysis, which can be found in *Cost Benefit Analysis* section of this report. This section includes implementation costs, benefits and disbenefits as they are taken into account with a monetary value. While it also discusses non quantifiable benefits, the monetary values were analyzed to determine the cost for each alternative. It was found that reforesting all of the barren land would cost around $3 billion dollars when including labor costs, and around $26 million when using volunteers. Either case proves that reforestation is a cost effective approach for flooding mitigation when compared to the costs from implementing other flooding mitigation options such as dams.

However, because our project does not account for land ownership complications, there will be difficulty implementing reforestation initiatives and thus this issue needs to be addressed by local decision-makers in order for our proposed plan to be successful. After discussing this issue with John Winings, we were informed of three major types of land ownership problems that were encountered in Haiti: familial separations, deserters, and squatters. Due to the local government rules, acquiring land is very difficult as land is distributed amongst a family equally. Therefore each member of the family must sign off on the property sale. There are also many people that own land in the area but do not currently reside there and cannot be contacted for property sales when NGO's wish to acquire land. Squatting is very common in Haiti. People will live off of land that they do not own, and assume the position of the landlord, thus making it difficult to determine the real owner of the land (Winings). These land ownership problems, although not taken into account for our proposal, decrease the feasibility of our project and would make implementation of our plan more complicated on the regional level.

Potential Impacts of Proposed Solution

Reforestation efforts will result in a number of impacts that will affect the environment as well as the livelihoods of the local population. Positive impacts of our proposed solution are expected to include an increase in soil stability in the upstream/mountainous regions from which water flow originates. It will also include reduced sedimentation in rivers and streams, as well as increased water clarity, a decrease in clogging of waterways, and fewer instances of flooding in downstream areas. Working on these impacts is one of the main focus of our mitigation efforts in the region due to the magnitude and frequency of flooding occurrence.

For unintended consequences, we have developed and assessed risk in 3 categories: low risk, where the likelihood of this event happening is unlikely; medium risk, where the event is likely to occur; and high risk, meaning that we foresee this as being an event very likely to happen. Possible unintended consequences may include increase of poachers in the reforested areas, however this is not a significant concern at the moment. As Mr. John Winings has mentioned during his visit to City College, currently there are not many cases of illegal logging happening and those that are occur mainly on the outskirts of the reforestation areas. Therefore, we have assessed this as a low risk consequence. Another unintended consequence may include invasive effect of vegetation on the ecosystem after planting trees that are not native to the region. An example of this risk is the case of the Eucalyptus tree, which was used extensively by CODEP in the past. This, too, we classify as low risk in terms of disrupting the ecosystem, as we are planning to plant only native to the area species of trees. Furthermore, CODEP and local communities have since learned the dangers of planting non-native species and are unlikely to repeat this mistake. The final unintended impact may include the disruption of charcoal market in the region. According to Mr. Winnings, locals have learned about the value of forests and currently refrain from logging. In speculation, however, this mindset might increase demand in charcoal and cause a rebound effect where people not affiliated with the local communities might start logging in the reforested areas. Although there are currently no significant problems with poachers, we have decided to classify this as a medium risk consequence due to its likelihood of happening and potential impact of this unintended consequence.

Possible co-benefits of reforestation will include greater food security and increased revenue from harvesting fruit trees. Currently, one of the fruit trees that CODEP is planting is the mango tree, from which the locals can harvest fruit when the tree is grown. The next co-benefit includes changes to the environment: reforested areas may experience lower temperatures and higher humidity, which is beneficial for plant growing and cultivation. According to Mr. Winings, this is one piece of evidence for the local communities that reforestation is in their interest, as they can physically experience these benefits. Another co-benefit of reforestation is the decrease of carbon dioxide content in the atmosphere, as a result of increased carbon sequestration due to higher forest density, which ultimately helps to combat global climate change. A final co-benefit is the avoided need for rebuilding destructed property after flood inundation.

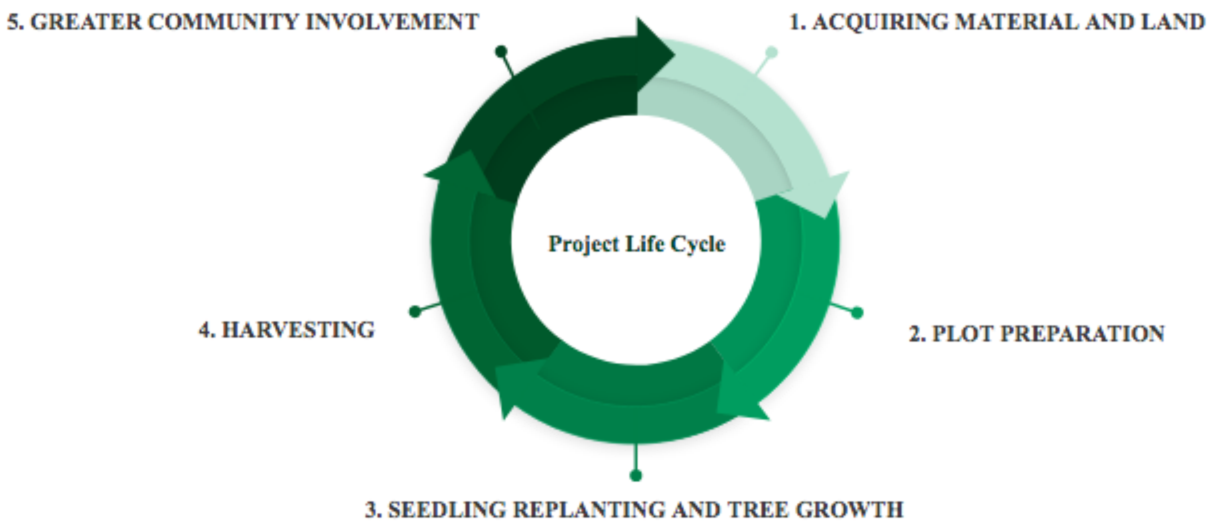

Figure 10. *Reforestation Mitigation Plan Life Cycle*. Project life cycle for the Haiti reforestation plan

The first step in the project life cycle is acquiring materials and land for reforestation. Community members acquire all necessary materials for planting seedlings and preparing reforestation plots and they also decide where reforestation efforts will be located. The second step is plot preparation, where seeds are combined with fertilizer and enhanced earth, initially planted in plastic bags, and allowed to grow. At the same time, community members are digging ditches and mixing soil with manure to increase its usability. The third step is seedling planting and tree growth, where planted seedlings grow into mature trees with supplied water from precipitation. Site management and protection against poaching need to be taken into account during this step in order to maximize the potential for project success. The fourth step is harvesting seeds for replanting and fruit for eating and selling as well as using harvested wood for furniture making and finished products. This is the step where community members are most likely to see the impacts of this project, especially in terms of economic and agricultural benefits. The final step is greater community involvement. Community members will witness the economic and social benefits of harvesting. As a result, more people will become interested in participating and learning from the educational opportunities. This cycle will then repeat itself as a new group joins the reforestation efforts.

For the risk assessment, as previously mentioned, one of the possible risks in our project is poaching or logging in reforested areas. There were instances of this happening in the reforested areas according to CODEP. Therefore we believe there is a possibility of this happening in the areas of our reforestation efforts. Another possibility is the risk of natural disasters such as strong winds, earthquakes and massive flooding (100-year event). Such events have the potential to severely impact the reforestation efforts since they can cause high losses in equipment and reforested areas. A third possible risk is theft or improper use of project materials. The equipment purchased for this project (such as shovels, picks, or vehicles) can get stolen or broken due to improper use, which can negatively impact our project's goal of reforestation.

We have decided to rank our risks in terms of the magnitude of impact. Our developed categories are: very low magnitude, where the magnitude of loss during this event is up to 20% of the overall project assets; low, being up to 40%; medium, which is up to 60%; high, up to 80%; and very high, up to 100%. Poaching and logging were assessed as low magnitude impact risks since currently there are not many cases of illegal logging happening. This is mostly found on the outskirts of the reforestation areas, therefore the magnitude of this impact should stay low. Natural disasters, such as earthquakes or hurricanes, can severely affect the the progress of the project by destroying all reforestation efforts and project equipment. Therefore, we ranked it as as a high magnitude risk. Loss of equipment due to theft or improper use could halt all operations and delay the progress of the project, therefore we ranked it as a medium magnitude risk.

We also decided to asses these risks in terms of probability. The ranking of the probabilities was developed where a likelihood of low indicates that the event is unlikely to happen, medium indicates that the event is likely, and high indicates very likely. We decided to rank all of the risks as low probability. As mentioned before, there are not many cases of illegal logging happening. Also, Extreme natural disasters don't happen that often when accounting for a 100-year storm, as was the case for this assessment. Theft and improper use were also ranked as unlikely due to community involvement and efforts put in by those people in the reforestation program which discourages this kind of behavior. Also, people who are participating in the CODEP reforestation efforts were trained to use the equipment, which decreases the risk of breaking the tools.For the risks which have been identified, the determination of the appropriate response should include: adding the risk to the project plan and scheduling for it, adding resources to the project to mitigate any potential shortage in assigned resources, and developing a course of action for avoiding the risk in the future.

Cost-Benefit Analysis

The costs for this project include both requested course project costs and calculated project implementation costs. With regards to course costs, this project did not require funding from the university because the necessary datasets and software packages were either open-source or provided to us by our technical mentor, Dr. Michael Piasecki. Although additional out-of-pocket travel expenses were necessary for the week-long data collection trip to Haiti in January 2018, we did not request reimbursement for these costs from City College.

I. *Implementation Costs*

The project implementation costs may vary depending on the organization that will be using the proposed mitigation plans. For the purpose of our project, we have developed a general implementation cost analysis that can be used as a baseline for various organizations. We have used the CODEP organization as a point of reference for a majority of these costs, considering it has been the only non-government reforestation organization in the Léogâne region for the past 25 years. However, the necessary equipment and labor prices are applicable to all organizations in this region. A major expense for reforestation programs is the planting equipment, which includes shovels and picks used for digging the ditches for the trees, buckets for carrying water from a water source (a river or stream) to a plant nursery, plastic bags for the seedlings, fertilizer, and seeds. In addition to the planting equipment, the project implementation costs include the cost of leasing land and the cost of labor. A majority of these costs were obtained from Mr. John Winings, with the exception of the cost of fertilizer, seeds, and the 5-gallon plastic buckets. CODEP is currently able to avoid the cost of seeds and fertilizer by harvesting their own seeds and using manure and enriched earth as a replacement for fertilizer. In efforts to produce a generalized cost analysis, we included these items in our analysis. The costs of these items were not provided to us by CODEP, but rather obtained from research on the pricing of planting items in the Caribbean. In addition, given the complex land tenure laws in Haiti, CODEP has been leasing land rather than buying it in efforts to avoid complications with acquiring land deeds from previous owners (Winings). Table E-1 in *Appendix E Cost Benefit Analysis* of this report includes all implementation costs that were considered for the cost analysis with the corresponding sources.

Once these costs were defined, each was calculated per a square foot of land. The square footage of land required was determined by assuming the fruit trees and forest trees will be planted every 10-16 ft^2 (Winings). Then the cost to lease land per square foot was determined. Lastly, the quantity of each item discussed in Table E-1 in *Appendix E*, with the exception of leasing land, was determined per tree planted. Of the items presented in Table E-1, all of the costs can be considered one-time costs incurred within the first year of the project, excluding the labor costs, which will continue for the entire project lifetime and will be influenced by inflation and interest. Therefore, the costs were separated into one-time, upfront costs that will be addressed within the first year and 14 year period costs that will be affected by interest and inflation. Considering a majority of the costs provided by CODEP were in Haitian Gourdes, the Purchasing Power Parity (PPP) was used to translate these costs to U.S. currency. The PPP is different from an exchange rate because it takes into account supply, demand, inflation, and interest. Haiti's PPP conversion factor was acquired for 1996 to 2017 (IndexMundi). The PPP was then extrapolated using a linear regression to 2033, considering the project period extends for 15 years (2018 - 2033). The extrapolated PPP values are presented below in Figure 11 and were used to calculate the labor costs.

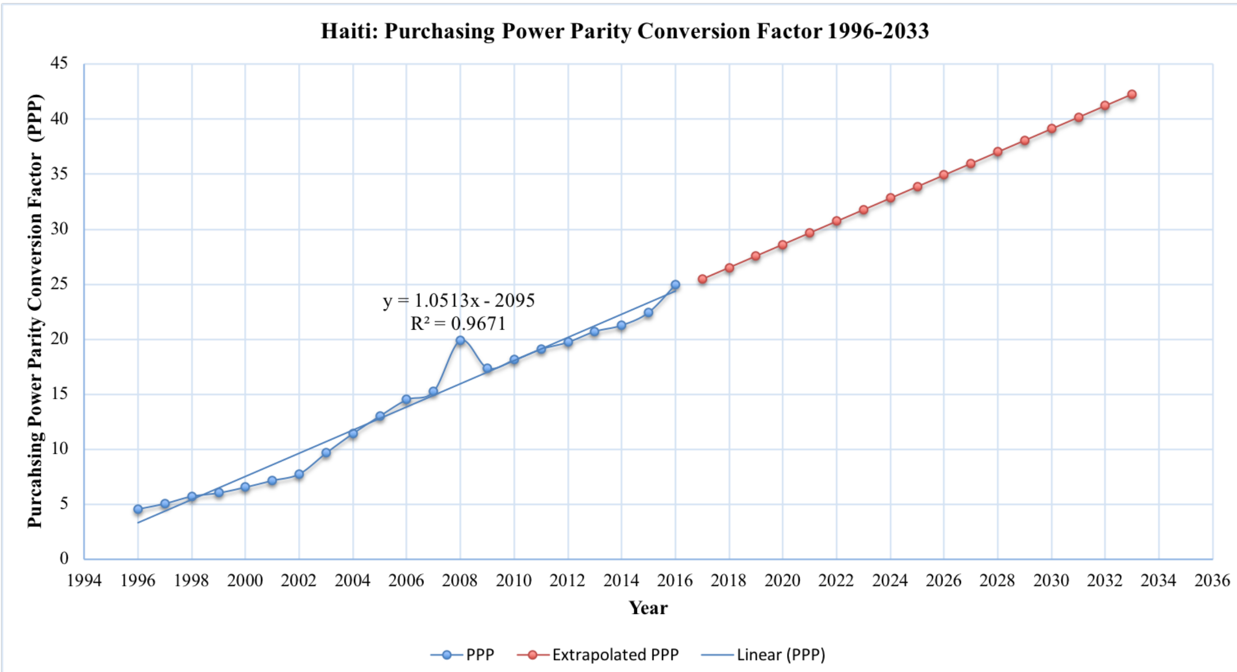

Figure 11. ***Haiti Purchasing Power Parity.*** Graph presenting Haiti's PPP Conversion Factor for 1996-2017 with the blue data line and the extrapolated PPP for 2017-2033 with the red data line (IndexMundi).

The calculation of the implementation cost analysis was separated into two equations: the first equation addresses the costs that will incur within the first year of the project and the second equation addresses the costs that will extend for the entire project period. The first year costs and 14-year costs are presented in Equations E-1 and E-2 which can be found in *Appendix E.1 Implementation Costs.*

The denominator of 14-year cost equation (Eq E-1) accounts for the change in the PPP conversion factor for each year of the project and was taken from the linear regression equation presented in Figure 11. The costs presented in Table E-1 and the Haitian PPP conversion factor were used in Equations E-1 and E-2 and results in nine cents ($0.09) per square foot of land reforested and ten dollars ($10.00) per square foot of land reforested, respectively. The total project implementation costs for the 15-year project period, assuming the project begins in 2018 and ends in 2033, resulted in ten dollars and nine cents ($10.09).

The main assumption made during the cost analysis is that the plant nurseries will be placed within one mile of the nearest water source to avoid transportation costs for the workers transporting water to and from the facilities. In addition, the PPP conversion factor will vary only on a yearly basis, rather than a weekly or monthly basis. The effects of these assumptions will result in discrepancies in the final cost benefit analysis.

II. Benefits

The benefits from our proposed project can be categorized as financial, social, and environmental and include both quantifiable and non-quantifiable benefits.

Interest and Inflation

Unlike the implementation costs described in the previous section, many of the project benefits were provided in US Dollars, rather than Haitian Gourdes. Thus, it was necessary to determine the proper interest and inflation rates as the PPP assessment could not apply. To find the proper interest rate to apply, a list of monthly interest rate values from 2017 was determined from the United States Department of Treasury. The interest rate used for this project was found by taking the average of these values and assuming that this rate will apply throughout the project period. The same methodology was used to find inflation rate using data from the United States Bureau of Labor and Statistics. The combined interest and inflation rate was found using *Equation E-3* in *Appendix E.2 Interest and Inflation*. The following table shows the final interest, inflation, and combined rates used for this study:

Table 10. *Interest and Inflation*. The interest, inflation, and combined interest-inflation rates that were used for this study.

Interest	1.20%
Inflation	1.85%
Combined Interest-Inflation	1.03

Sequestered Carbon

The first projected benefit is the reduction of atmospheric carbon dioxide as a result of increased CO2 sequestration by a greater number of trees planted. To quantify this, an economic incentive called carbon credits was used. Carbon credits, also known as emission reduction units (ERUs) are an example of cap and trade economics developed by the United Nations in 2009, which represent a tradeable permit or certification that is equivalent to one metric ton of carbon dioxide emissions. Should an organization not use all of its allotted credits, they can be exchanged for a monetary value (UN News Center, 2009). By associating the amount of carbon dioxide stored with the value of that carbon dioxide, we quantified the financial benefits for sequestering CO2 per square foot of land reforested.

The first step of calculating this was to determine the amount of CO_2 stored over the 15 year project period with respect to the total area reforested for each alternative mitigation plan. To do so, a study was used that details the amount of carbon that can be stored in a tropical agroforest per hectare, per year. This study shows that in its first year, a tropical agroforest can store between 1.5 and 3 Mg of carbon, and that this number is expected to triple over 20 years. Based on a conservative estimate, it was assumed that one hectare of agroforest replanted in this project would yield 1.5 Mg of carbon storage in the first year, and that this value would increase linearly until year 20 (Atangana, Alain, et al.). Then, utilizing the ratio of carbon to CO_2, the grams of carbon stored was converted to tons of carbon dioxide.

To find the associated value of CO_2 sequestration for each year, a study was utilized by the EPA called "The Social Cost of Carbon" which accounts for the social, environmental, and economic effects of CO_2 emissions such as human health impacts, changes in energy costs, and changes in agricultural productivity ("The Social Cost of Carbon"). The values were provided with respect to one ton of CO_2 emissions in 5 year increments. For the purposes of this study, it was assumed that the value of emissions is equal to the value of CO_2 sequestered, and that the values increase linearly between five year increments which were interpolated for individual years. After applying the appropriate combined interest and inflation equation, the total value of carbon dioxide sequestered per area of land reforested was calculated for the project duration in dollars per square foot. All equations used for these calculations can be found in *Appendix E.3 Benefits: Sequestered Carbon*.

<u>Preventative Loss of Possessions</u>

Initially, potential avoided costs from rebuilding destructed property after severe weather would be taken into account as a benefit, but, after further research and discussion with Dr. Piasecki, this was not taken into account. Reconstruction cost are not necessary because a majority of the homes in Léogâne are made of cement and do not become severely damaged after flooding events. Rather the loss of possessions is a more detrimental result of flooding events.

After consulting with Dr. Piasecki, we set the maximum value of household possessions to be \$1,500. Based on research for loss of value of possessions, we realized that loss of value is directly correlated to the amount of inches flooded. FEMA (the Federal Emergency Management Agency) has equations set for multi-story houses with values of possessions and inches flooded. By first plotting the inches flooded to the current maximum possessions values from FEMA's "Estimated Flood Loss Possessions" with large multi-story houses (FEMA has its maximum value of possessions for a large multi-story house to be \$100,000), we can obtain an equation for the possessions to \$100,000. We chose large multi-story houses as discussions with our mentor lead us to the understanding that properties in Haiti are around 5,000 sqft, which FEMA classifies as a large multi-story house. We then modified the equation from FEMA to have the maximum possession value to be $1,500 by back calculating the value of possessions for each inch flooded. This equation, Equation E-7 can be seen in *Appendix E-3: Benefits from Preventative Measures.* The equation takes into account the amount of inches flooded which can range from 1 to 48 inches for the first year of a flooding. We then added interest and inflation, which was determined in the previous section, to the values of possessions in order to expand the values to a 15-year period (from 2018-2030), again taking into account the inches of flooding from 1-48 inches as seen in Figure 12.

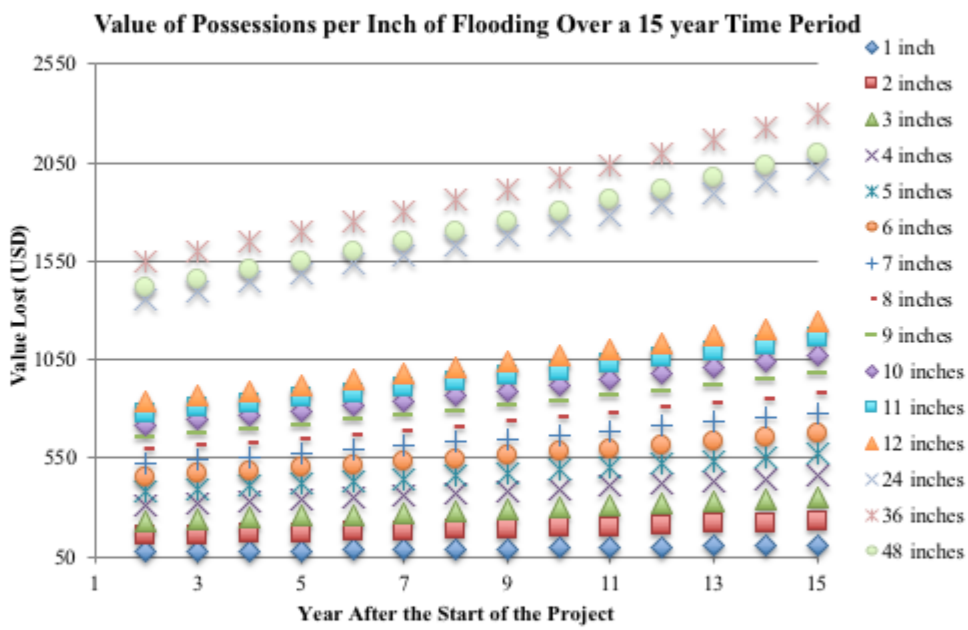

Figure 12. ***Value of Household Possession in Haiti.*** The change of value of possessions throughout a range of inches flooded over a 15 year period including interest and inflation.

This chart can then be used as a proxy to find how much money (in value of possessions) would be saved once implementing reforestation tactics to decrease flooding. Using the GSSHA WMS Modeling, we were able to find the volume of the flow runoff and the area of the watershed, thus determining the amount flooded by dividing the volume by the area. For the No Change alternative the amount flooded was 2.095 in. When plugging in 2.095 in to the Equation E-7 and take into account interest and inflation, we obtain a preventative loss of possessions to be $248.75. Thus for the No-Change alternative this was $248.75 that would be considered a cost. After running the alternatives, we found that Alternative 1, Alternative 2 and Alternative 3 yielded 2.095 in., 2.094 in., and 2.095 in. flooded respectively and thus have costs of $248.74, $248.62, and $248.74 for loss of possessions respectively. In all scenarios, this would be considered a cost.

Water Contamination Prevention

Water contamination is a major challenge during flooding events. This is often a result of unprotected wells on properties. An unprotected well can cause massive contamination to the drinking water for the entirety of the population in our region of focus. Thus the cost of remediation has been taken into account for the cost benefit analysis. Well caps were used as a proxy for the remediation costs. Well caps are made from blocks of cement and are placed on top of a well during heavy rain events in order to mitigate the consequences of water contamination from flooding. After discussing with Dr. Piasecki we concluded that 20% of the wells in Léogâne do not have well caps and therefore we plan to mitigate this issue by determining the cost of implementing well caps for this remaining 20%. Dr. Piasecki informed the team that circular wells are typically found on properties in Léogâne. The well diameters are measured from the outside and range from 12 inches to 24 inches. The 6 in. x 6 in. cement blocked used to build the well caps are sold for $1 in Haiti. Using the cost of the cement blocks the remediation costs were determined by first calculating the area of the well caps using the minimum and maximum diameter measurements. Equation E-3 in *Appendix E-3: Benefits from Preventative Measures* resulted in a cost of $4 and $13 for wells with 12 in. and 24 in. diameters, respectively.

After finding the costs for the well caps, we determined how many needed to be installed. For this process, Google EarthPro was used to determine the total area for the region of Léogâne and the amount of city "blocks" in the city region. Using one block as a reference, the amount of properties in one block were considered, assuming each property has a well. By knowing the number of properties on one block, we calculated 20% of the properties in the entire region of Léogâne to determine the number of wells without well caps. These calculations can be found in Appendix E-3. The average costs for the two well cap diameter options was used to finalize the costs of implementing. This resulted in a cost of $117,595.80 in order to mitigate water contamination. Due to the risk that flooding has in water contamination, this cost was considered a mandatory disbenefit and was implemented for all alternatives.

Produce Profit from Reforested Trees

A major project benefit is the produce grown on the fruit trees that will be planted on the reforested land. The fruit can either be consumed or sold for a profit, which indicates both social and financial value, as there is a monetary benefit that can be made from selling the produce. When calculating the produce profit from the trees planted, a select group of produce trees were chosen based on the eight most common trees planted by CODEP's reforestation projects: papaya, mango, orange, grapefruit, lime, lemon, cherry, and avocado. Additional factors were considered when developing the produce profit equation, the first of which was the variation in the cost of produce and the percentage of produce sold in Léogâne City Center compared to the mountainous regions of Léogâne (75% and 25%, respectively). Considering the mountainous region is remote and disconnected from a majority of people who live near the city, the prices are often reduced by significant factor. The costs and percentages of the produce in both regions were obtained from Mr. John Winings. In addition, the yield of produce per tree per harvesting season and the PPP factor were taken into account after researching produce yields for the Caribbean climate. Considering the produce profit will extend for the entire project period, a summation profit equation was developed to determine the total monetary benefits from produce. This is a general equation that can be applied to each type of produce tree discussed above. The starting year for the summation equation varies depending on the produce tree, since each type of tree requires a given period to bear fruit. The profit summation equation and a table including the data used to calculate the total produce profit can be found in the *Appendix E.3 Benefits: Profit from Produce* of this report.

The main assumptions made during the produce profit calculation are regarding the loss of produce yield and the ratio of fruit tree types planted in the forested land. When determining the yield per tree per year, a 5% loss of produce from rotting and insect infestation was assumed. In addition, it was assumed that the total number of each produce tree planted in the reforested land will be equivalent for individual alternatives.

<u>Non-Quantifiable Benefits</u>

Lastly, we project that a reforestation initiative will result in an increased level of community involvement and educational opportunities in the regions that adopt reforestation initiatives. This may be determined by comparing the amount of land that is reforested in each alternative plan and assuming that the more land that is included in a project, the most community involvement is taking place. As an alternative option, community involvement may be assessed qualitatively.

III. Results

The following table was generated based on the methods described in this section. The cost benefit analysis was calculated by subtracting the disbenefits from the sum of the benefits and dividing the difference by the total implementation costs.

Table 11. ***Cost Benefit Analysis Results.*** The implementation, benefits, disbenefits and cost benefit ratios for the alternatives for a 15 year period.

Alternative	Area (sqft)	Implementation Costs	Carbon Benefits	Flooding disbenefits	Produce Benefits	Cost Benefit Ratio
No Change	0.00	$0.00	$0.00	$117,844.54	$0.00	N/A
Low Range	307,368.46	$3,101,347.77	$27,663.16	$117,844.54	$17,079,335.85	5.49
Upper Range	313,256.73	$3,160,760.41	$28,193.11	$117,844.42	$17,406,525.38	5.49
Combined Range	620,625.19	$6,262,108.18	$55,856.27	$117.844.54	$34,485,861.22	5.50
Reforest All Barren Land	288,363,502.42	$2,909,587,739.42	$25,952,715.22	$117,829.30	$256,347,964,522.51	88.11

Project Management Budget Review

In order to complete our design project within the allotted time, we have established a management structure, consisting of our roles and responsibilities to keep the team organized and efficient.

Each member of the group has designated responsibilities for which they were held accountable. However, it was expected that the remaining team members would have sufficient time during this process to complete their work and help others members as necessary. Jillian created the initial methodology that Valentina and Louiza used for determining and find the percent forest cover for Haiti’s vegetation on the whole- country scale. Jillian and Valentina also worked together using remote sensing imagery and analysis techniques in high resolution for our watersheds of interest. Valentina was responsible for developing the regional land cover classification methodology and producing the initial files. Jillian then validated these files, refined the methodology, and produced the final land cover file. Louiza was responsible for updating the soil cover to be representative of 2017 using soil samples. With Jillian's methodology of generating the criteria for watershed modeling for the alternatives, Louiza implemented this methodology. Valentina, Jillian, and Louiza also conducted the cost/benefit analysis. Mateusz focused on modeling extreme rainfall events using GSSHA. Nitika modeled long-term, regular rainfall events with SWAT. Nitika, Matteusz and Louiza analyzed the modelling outputs and Louiza compared the results from GSSHA and SWAT in order to finalize the cost-benefit analysis and choose the recommended alternative.

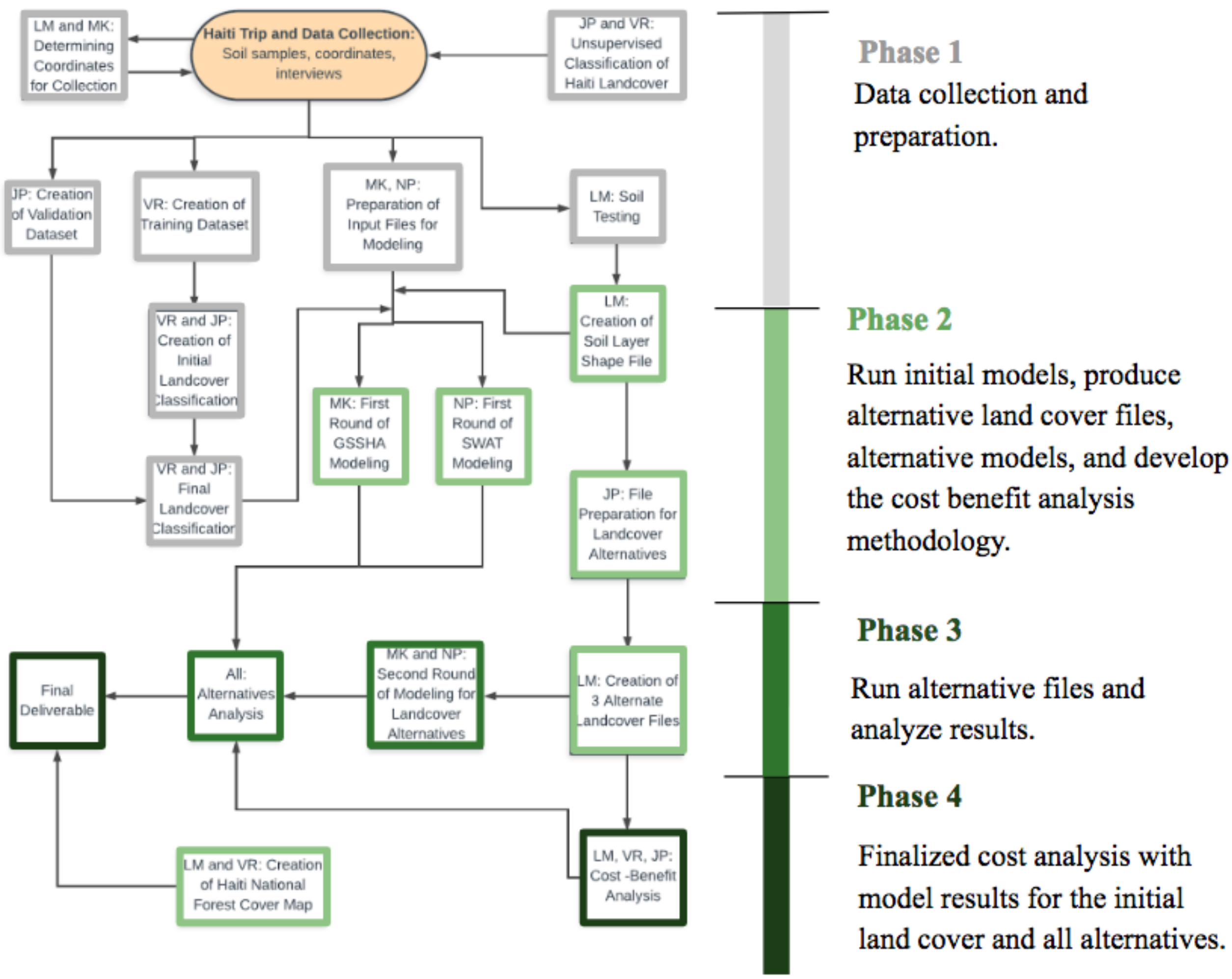

Figure 13. ***Team Management Workflow.*** Figure presenting the four necessary phases for producing the final deliverables for this project, the required steps for each phase, and the individual/ individuals who completed each step. The team members' names have been reduced to initials for simplicity: Louiza Molohides (LM), Mateusz Kowolski (MK), Nitika Pandey (NP), Jillian Panagakos (JP), and Valentina Rappa (VR).

With regards to course costs, this project did not require funding from the university because the necessary datasets and software packages are either open-source or provided to us by our technical mentor, Dr. Michael Piasecki. Although additional out-of-pocket travel expenses were necessary for the week long data collection trip to Haiti in January 2018, we did not requested these funds from City College.

After our panel presentation on Friday, May 18th, 2018, our panelists gave useful suggestions that we would like to thoroughly research and account for in our project. This largely involved an indication of what future hydrologic modeling can be conducted to supplement the work that was done in this project. A more detailed account of recommendations for future work can be found in the *Conclusion* section of this report under *I. Project Outcomes and Recommendations*. Furthermore, an external stakeholder presentation was conducted on May 19th, 2018, for John Winings. A detailed account of Mr. Wining's comments can also be found in *Conclusion* section of this report under *II. External Deliverables*.

The overarching goal of this proposed project is to supplement the work that is currently being done in the Léogâne region of Haiti with quantification of impact and forward modeling. Beyond our region of focus, it is important to us that we identify areas of the country nationally that are lacking in sufficient forest cover and to generate a final mitigation plan that can be scaled-up to the national level. We believe that this set of objectives will be the most efficient way to use engineering design to in order to mitigate flooding inundation of local communities while also boosting regional economies and promote community self-sufficiency on a long-term scale.

Conclusion

I. Project Outcomes and Recommendations

The results from this project include the following: model results, a cost-benefit analysis, and a land cover file for Léogâne. Based on the short-term modeling outputs from GSSHA, the peak flow, discharge, lateral flow, and infiltration were analyzed for each alternative discussed in *Section IV. Creating a Mitigation Design*. For the upper elevation, lower elevation and the combined range elevation, as seen in Table 6 in the *Technical Approach* section of this report under *V. GSSHA Hydrologic Modeling for Severe Weather Events*, the discharge and lateral flow decreased compared to the No Change results. Nevertheless, the alternatives show small and insignificant changes to the watershed as a whole. Thus based on the results from GSSHA, reforesting small areas of land will yield less than 1% change in peak flow and discharge. When analyzing the final alternative, reforesting all available barren land in the Rouyonne watershed, positive results were shown on the impacts of the hydrologic model.

For the long-term modeling with SWAT, the results of reforesting all available barren land compared to the No Change alternative produced a significant decrease in lateral flow and water yield as seen in Table 8 in the *Technical Approach* section of this report under *VI. SWAT Hydrologic Modeling for Long-Term, Regular Weather Events*. Our results were as anticipated: the surface flow, lateral flow, water yield, and sediment yield decreased, while the evapotranspiration increased. Reforesting a greater area will result in a decreased in a runoff because the sediment yield is directly related to surface flow, which would also decrease. Lastly, with a greater reforested area, evapotranspiration is likely to increase as well. Thus based on both GSSHA and SWAT model results, reforesting all available barren land in the Rouyonne watershed yields significant hydrologic results.

When taking into account the costs, benefits, and disbenefits, the results from reforesting all available barren land were not financially feasible for a reforestation program in our region of interest. The cost to implement this scenario would be close to $3 billion when labor is taken into account and around $26 million if relying on volunteer labor. The cost of implementing reforestation is less when compared to other flooding mitigation strategies. As stated previously, the cost for implementing a dam could range from $13- $35 billion which is significantly greater than the cost of implementing our reforestation project. While a $3 billion project may not be economically feasible for an organization from our region to implement, when compared to implementing a dam from other flooding mitigation projects, reforestation can be seen as a viable option that also has many benefits as well. While the results from the cost benefit analysis, seen in Table 11 in the *Cost-Benefit Analysis* section of this report under *III. Results*, show significant benefits from produce and carbon sequestration, this alternative is not socio-economically sustainable for an organization in this region. On the other hand, the lower range, upper range and combined range alternatives that are financially feasible do not produce significant hydrologic benefits.

It was also determined that CODEP's approach of avoiding labor costs is a successful method of decreasing implementation costs while increasing community involvement. This can be seen in Table 11 in the *Cost-Benefit Analysis* section of this report under *III. Results*, which indicates that reforesting all of the available barren land in the watershed while including labor costs would be $2,909,587,739.42. However, if labor costs were not included (per CODEP's method of engaging the local communities by relying on volunteer labor), this cost would be $25,952,715.22, or two orders of magnitude less than what the cost would be with labor included. This is a clear indication that the CODEP method for acquiring labor is the more financially feasible option for this region. It should be noted, however, that this method also increases community involvement and investment in the project's success. Based on the interviews conducted during the visit to Haiti, Valentina Rappa found that most people who participate in the reforestation efforts through CODEP do not see themselves as volunteers. Instead, they see themselves as being paid not by salary but in the stable food source that the planted trees provide over time (Rappa "CODEP Interview on Reforestation Efforts", 2018). Furthermore, they also reap the benefits of the educational initiatives led by CODEP employees to develop numeracy and literacy skills. This highlights the major benefit overall of maintaining CODEP's method of unpaid labor in exchange for the programs and agriculture provided by the organization: the people who participate in this program take ownership in what they produce while also gaining essential skills needed to obtain self-sufficiency in the region.

Lastly, based on the results of the national forest cover analysis, 36% of present day Haiti is forested. This finding is 3.7% greater than the percentage of forested land determined by academics in a study produced with land cover data from 2010-2011 as previously discussed in the *Introduction* section of this report (Churches et al., 2014). This is a significant finding firstly because it reinforces conclusions drawn by academic sources that the country is in the magnitude of ~30% forested rather than ~2% (as is often claimed by NGOs). Furthermore, the Churches study indicates national land cover as of 2011. Our study, however, is based on accounting for change between 2012 and 2016. As a result, the conclusions from this study depict a more recent land cover map and indicate that there has been an increase in forest cover over this time.

Future recommended steps would be to continue modeling the watershed for various magnitudes of reforested areas in order to determine minimum and maximum thresholds for yielding significant changes in the hydrologic parameters. The minimum threshold would be used to determine how much area will need to be reforested before one sees a notable impact. The maximum threshold would be used to determine the point at which reforesting additional area would no longer result in significant hydrologic impacts. These recommendations will be advantageous as the next steps for this project in order to obtain a better understanding of the impact of reforestation in Rouyonne.

Furthermore, it is recommended that a more detailed hydrologic modeling of the current conditions be conducted. For example, this study is limited by the lack of validation implemented for the GSSHA and SWAT models throughout all alternatives. A critical next step would involve comparing the outputs from each of these to known, measured values (e.g. stream gauge measurements). Another useful step would be to conduct a sensitivity analysis both on the HRU delineation during SWAT modeling and for defining soil during GSSHA modeling. The main parameters that were considered for the creation of HRUs in this study were land cover type, soil type, and slope. For further work, it would be important to understand how drastically each of these parameters affects the number of HRUs that are delineated by SWAT. This could be done by repeatedly undergoing the process of creating HRUs while keeping two of these parameters constant and gradually changing the third parameter in constant increments. A similar process can be done with GSSHA since there are many variables defined for the soil parameters. Knowing how sensitive the model is to changes in these parameters would be useful for understanding how best to set up the model in a way that will yield the most accurate results.

II. External Deliverables

Our approach for this design project was greatly impacted by the insight provided by John Winings and various others employed by CODEP organization. In order to receive feedback on our results, we conducted a stakeholder presentation for Mr. Winings on May 19th, 2018 via Skype call at 9am Eastern Standard Time. The stakeholder presentation, similar to the panel presentation, updated Mr. Winings on our results and recommendations for future work in reforesting the Léogâne region. A record of Mr Winings' comments can be found in *Appendix F*.

One of the main comments that Mr. Winings made was that the determination of 36% forest cover nationally is good for dispelling a myth that has been misunderstood for years. Furthermore, in developing the overall costs and benefits for water contamination and agriculture production it should be noted that banana trees are complicated to model in this region because of complications with root stability during extreme weather events and that communities in the rural areas of the region are less likely the experience water contamination because they do not use wells so often as rooftop cisterns. Mr. Winings also commented on the inability to acquire all land. As he mentioned during our meeting, this is something that eventually would need to be accounted for. Throughout this time, CODEP has developed a main strategy to overcome this obstacle that involves renting land from 'squatters' for long periods of time. This land can then be used to redevelop and plant on and the 'squatters' can obtain money needed for survival.

Finally, in line with the conclusions determined in this study with regard to CODEP's method of relying on volunteer labor, Mr. Winings said: "In Haiti, in particular, there is a strong sense of entrepreneurship. Look at local street vendors, who are ubiquitous throughout the country. The same spirit exists for the family/friends units which comprise the lakous. All CODEP has done is take this spirit of entrepreneurship (capitalism) and use it to leverage reforestation." These comments reinforced the main decision in this study to use reforestation as a mitigation strategy in order to increase community involvement and self-sufficiency based on CODEP's method of donated labor in exchange for a stable food source and lifelong literacy and numeracy skills.

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Appendix A - Characterizing Land Cover in our Watersheds of Interest

Data Collection: Questions Administered to CODEP Animators in Haiti

1. What plants does you use primarily in this area?
    a. Is this due to the soil?
    b. What plants grow in this soil?

2. In the Wet season, what are the types and names of the plants that you reforest with?
    a. Forest Trees
        i. Kalypt, Akasya,Kasyarina,Kapab, Saman, Fren, Chen, Kasya, Taveno, Kaliandra,Sed, Wakoz
    b. Fruit Trees
        i. Kokowa, Sitwon, Nwa, Papay, Dolive

3. In the dry season, what are the types and names of the plants that you reforest with?
    a. Forest Trees
        i. Kalypt, Akasya,Kasyarina,Kapab, Saman, Fren, Chen, Kasya, Taveno, Kaliandra,Sed, Wakoz
    b. Fruit Trees
        i. Kokowa, Sitwon, Nwa, Papay, Dolive
4. What is the most expensive crop sold in the wet and dry season?What is the difference in price if you sell a mango on the street vs. Kafou Difo?
    a. How much benefit do you get from a single tree in a single year?
        i. How many seeds will you receive?
    b. What other benefits do you see in a single year?
        i. Especially with eucalyptus trees being cut down

Data Collection- Google Drive Link to Data collected in Haiti

1. Google Drive Link:
    a. https://drive.google.com/drive/folders/1NI1BGLIrLjTbybi2R3FGrs-vwOjUrt5M?usp=sharing
    b. Content Description: Folder containing photos, meeting minutes, and data spreadsheets from the trip.

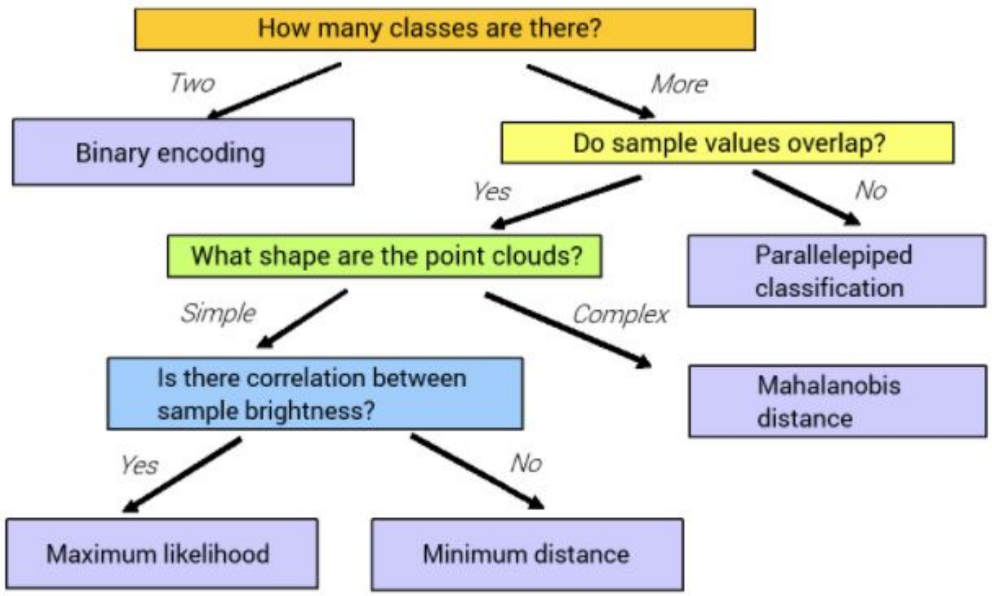

Figure A-1. Decision tree figure used to determine an accurate supervised classification algorithm using ENVI software (50 North 2017).

Table A-1. The validation results from the initial classification run for the six original images: Landsay, PALSAR-HH, PALSAR-HV, Stacked HH and HV, Merged HH-HV, Merged HH/HV. This table includes the percent accuracy for each of the original seven classes (Built, Sand, Water, Tree Cover, Barren, Agriculture, and Grass) and the overall percent accuracy for the file.

Image	Built	Sand	Water	Tree Cover	Barren	Agriculture	Grass	TOTAL
Landsat	40.0	86.7	100.0	73.3	80.0	40.0	28.6	63.8
HH	0.0	80.0	60.0	0.0	26.7	0.0	80.0	35.2
HV	0.0	86.7	73.3	20.0	0.0	0.0	86.7	38.0
Stacked	46.7	93.3	73.3	6.67	60.0	0.0	33.3	44.8
HH-HV	0.0	80.0	60.0	0.0	40.0	13.3	60.0	36.2
HH/HV	0.0	0.0	73.3	100.0	0.0	6.7	0.0	25.7

Table A-2. The validation results from the classification of the Stacked Landsat and PALSAR land cover file. This table includes the percent accuracy for each of the original seven classes (Built, Sand, Water, Tree Cover, Barren, Agriculture, and Grass) and the overall percent accuracy for the file.

Class	Percent Accuracy
Built Over	53.3
Sand	100.0
Water	100.0
Tree Cover	73.3
Barren	66.7
Agriculture	66.7
Grass	13.3
TOTAL	67.6

Table A-3. The validation results from the classification of the Stacked Landsat and PALSAR land cover file. This table includes the percent accuracy for each of the three tested classification methods (Mahalanobis Distance, Minimum Distance, and Maximum Likelihood) and the overall percent accuracy for each file. This table is also representative of the modified classification method and only six classes are accounted for (Built, Sand, Water, Tree Cover, Barren, Low Vegetation).

Image	Built	Sand	Water	Tree Cover	Barren	Low Veg	TOTAL
Mahalanobis	60.0	100.0	96.7	90.0	70.0	70.0	81.1
Maximum Likelihood	90.0	70.0	96.7	86.7	83.3	63.3	81.7
Minimum Distance	50.0	30.0	100.0	73.3	53.3	60.0	61.1

Appendix B - Soil Experiments and Shapefile Creation

1. Google Drive Link:
    a. https://drive.google.com/drive/folders/1x1Lvbw3SNwAItw2CCEhSOe83Yhoilt62?usp=sharing
    b. Content Description: The two PDF files pertaining to the lab manual of EAS 21700 *"Lab 5: Soil Texture and Properties"* and "*Lab 2: Organic Matter Determination."* It also contained the full report on the soil analysis conducted for percent moisture, percent organics and soil texture.

Appendix C - GSSHA Hydrologic Modeling

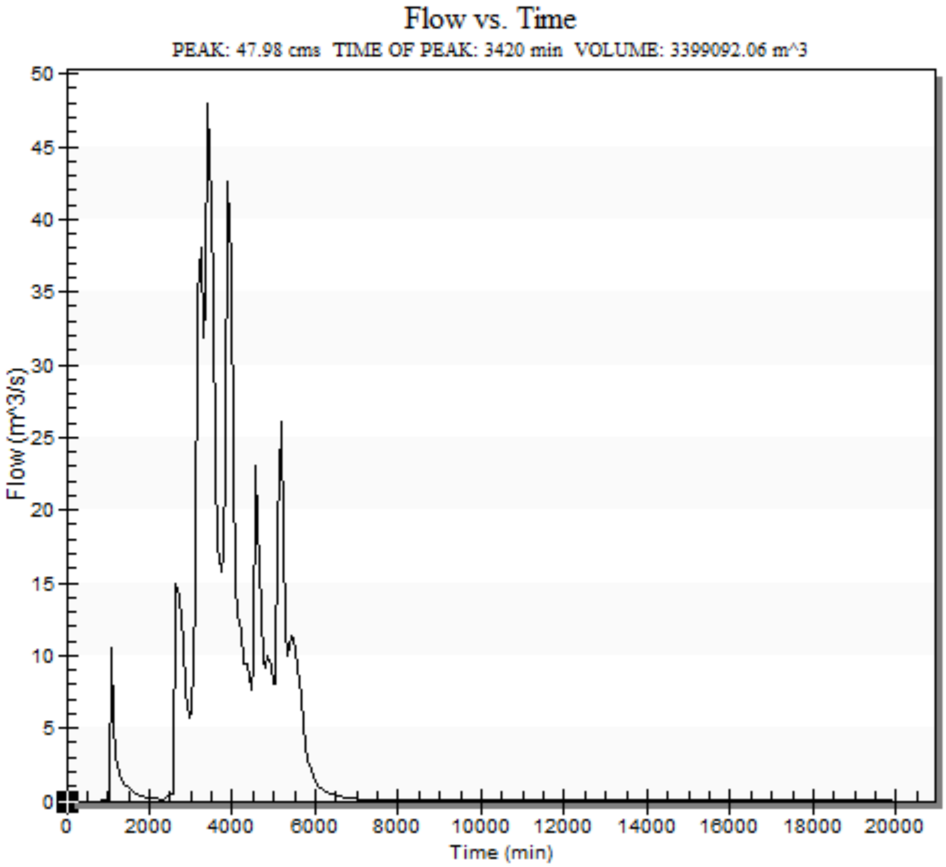

Figure C-1: Hydrograph for no change alternative from GSSHA modeling

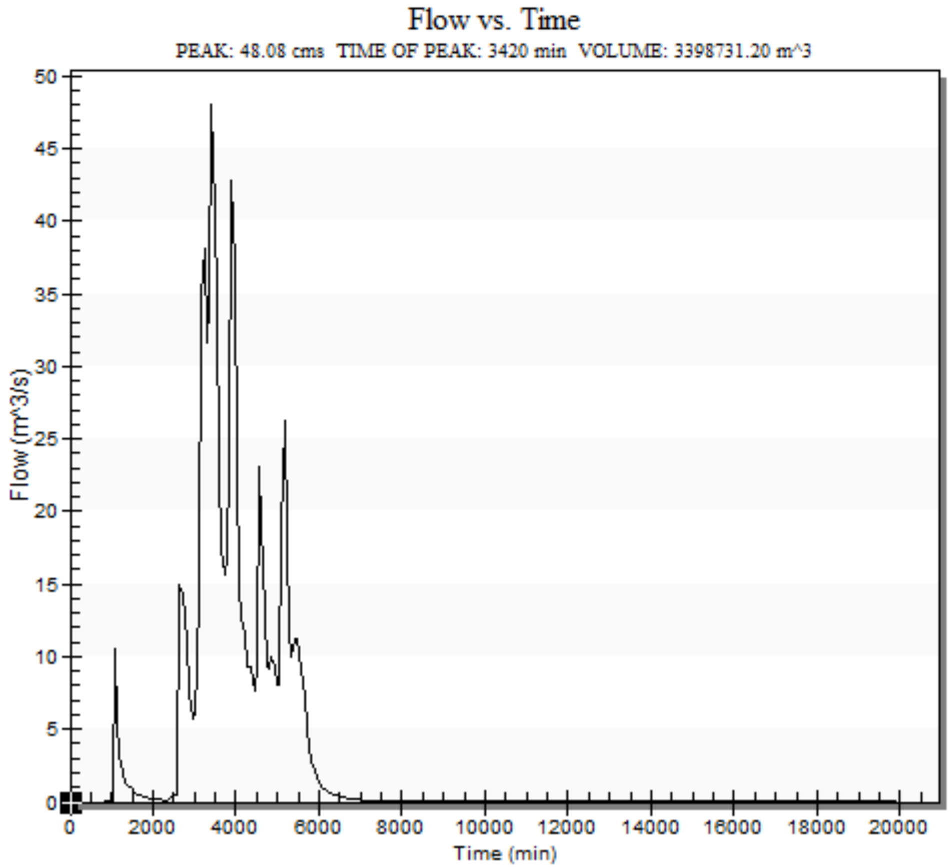

Figure C-2: Hydrograph for low band elevation alternative from GSSHA modeling

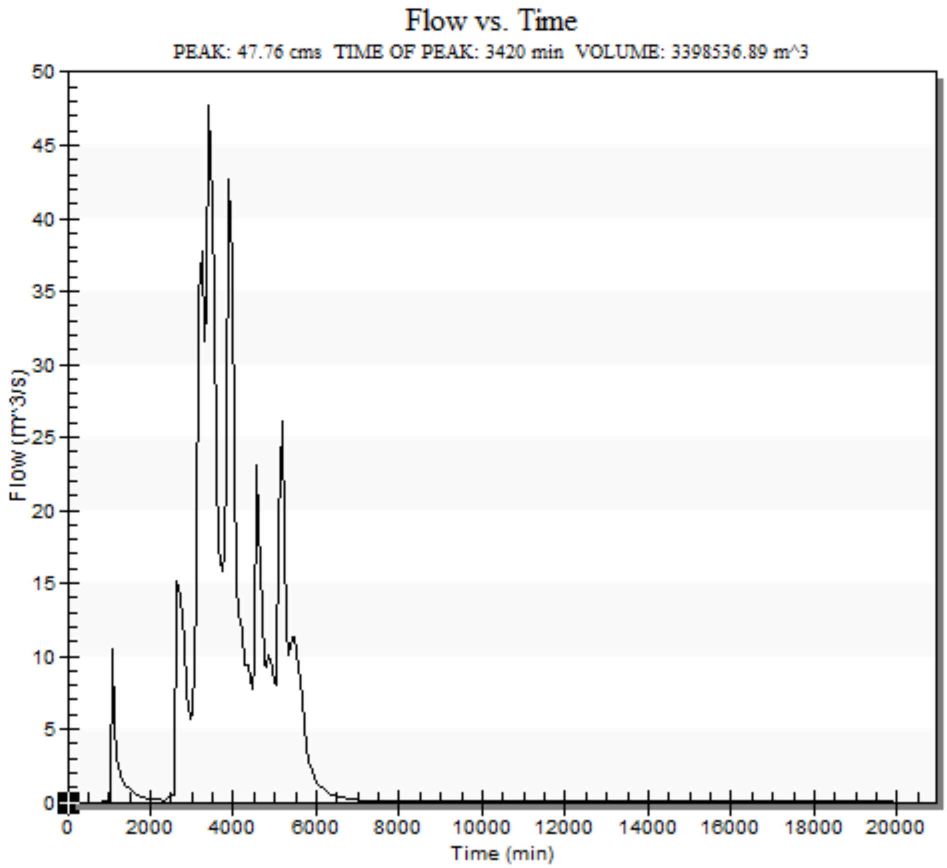

Figure C-3:Hydrograph for high band elevation alternative from GSSHA modeling

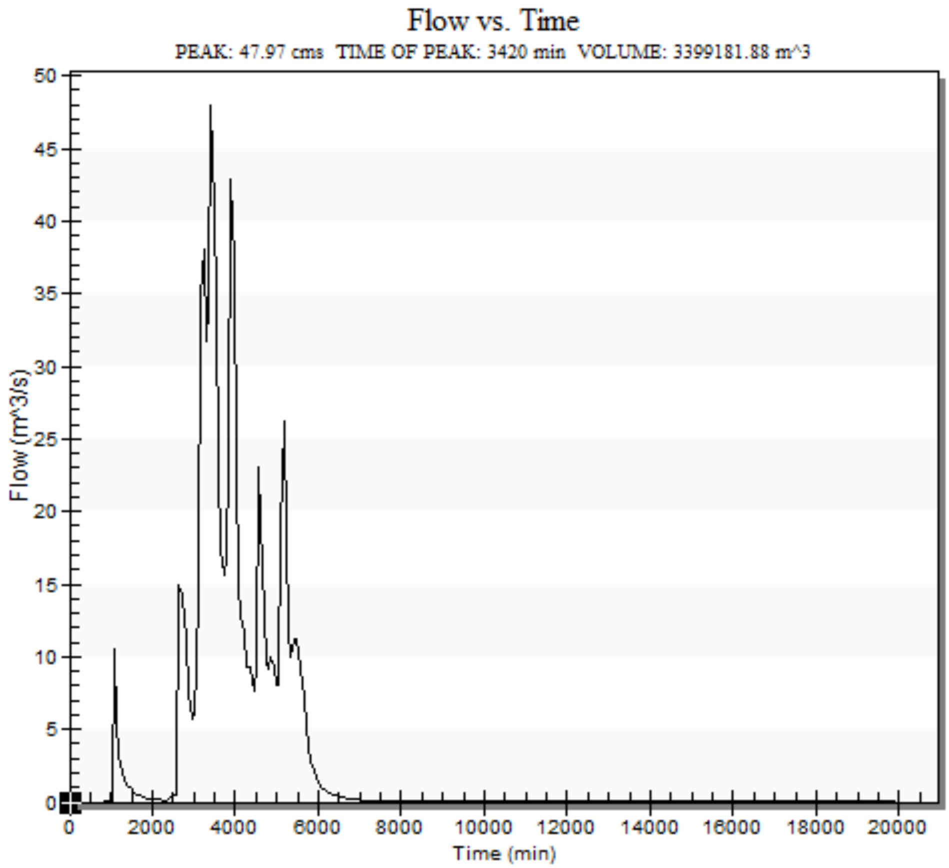

Figure C-4: Hydrograph for combined ranges of elevation alternative from GSSHA modeling

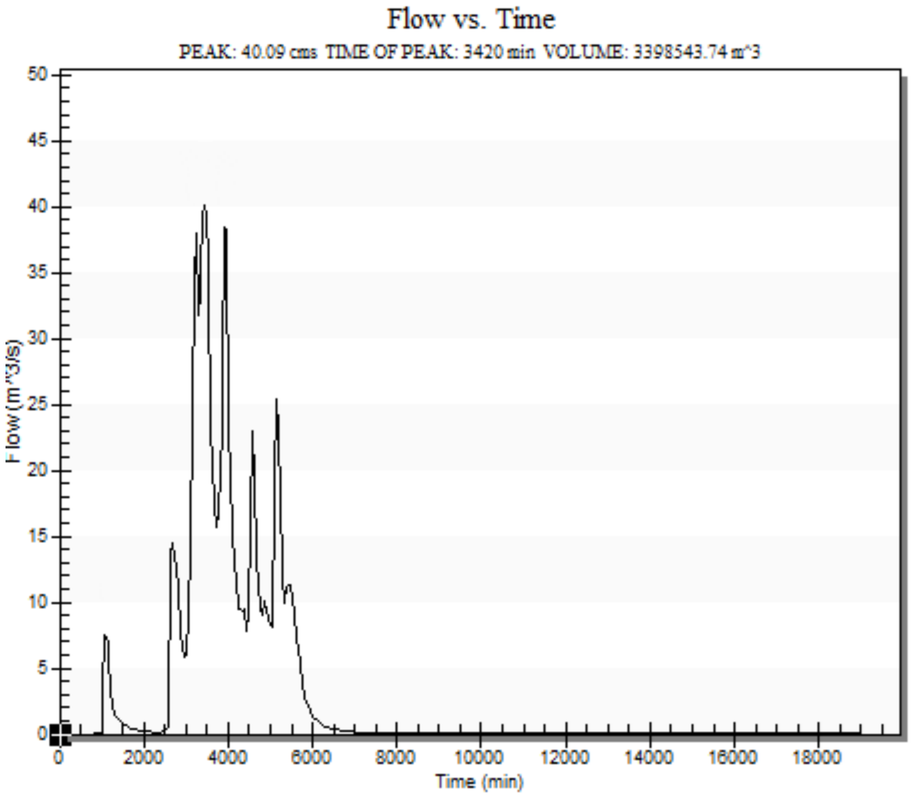

Figure C-5: Hydrograph for all barren land reforestation alternative from GSSHA modeling

Appendix D - SWAT Hydrologic Modeling

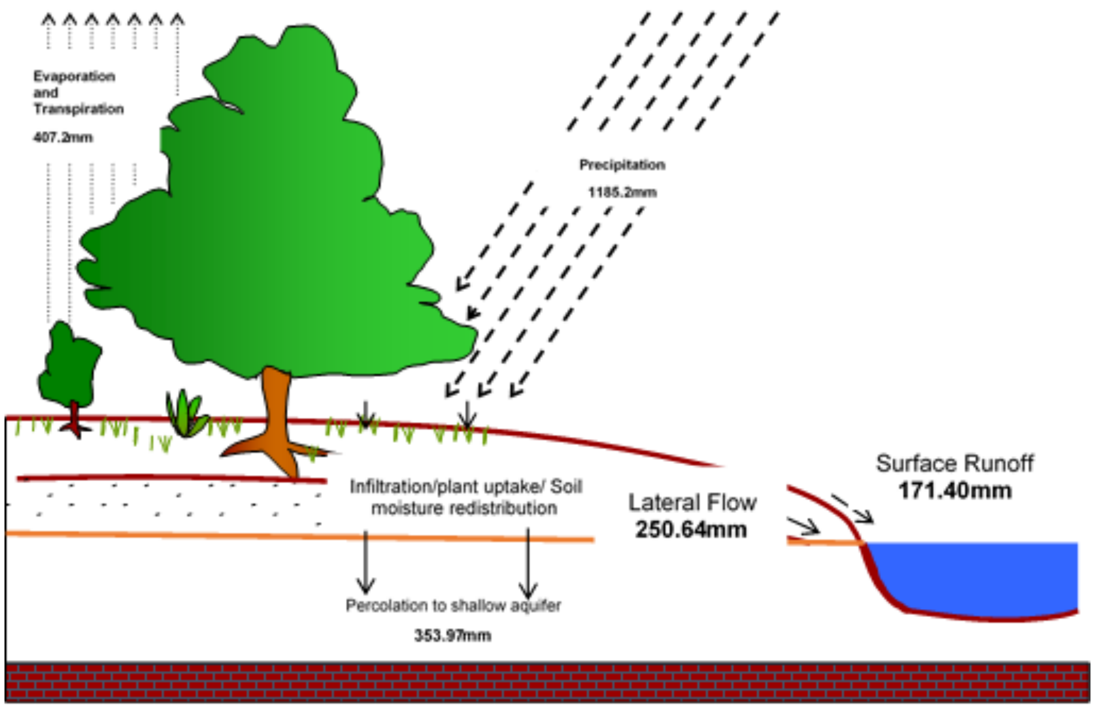

Figure D-1:. Visualization of SWAT Hydrological model for Current land cover.

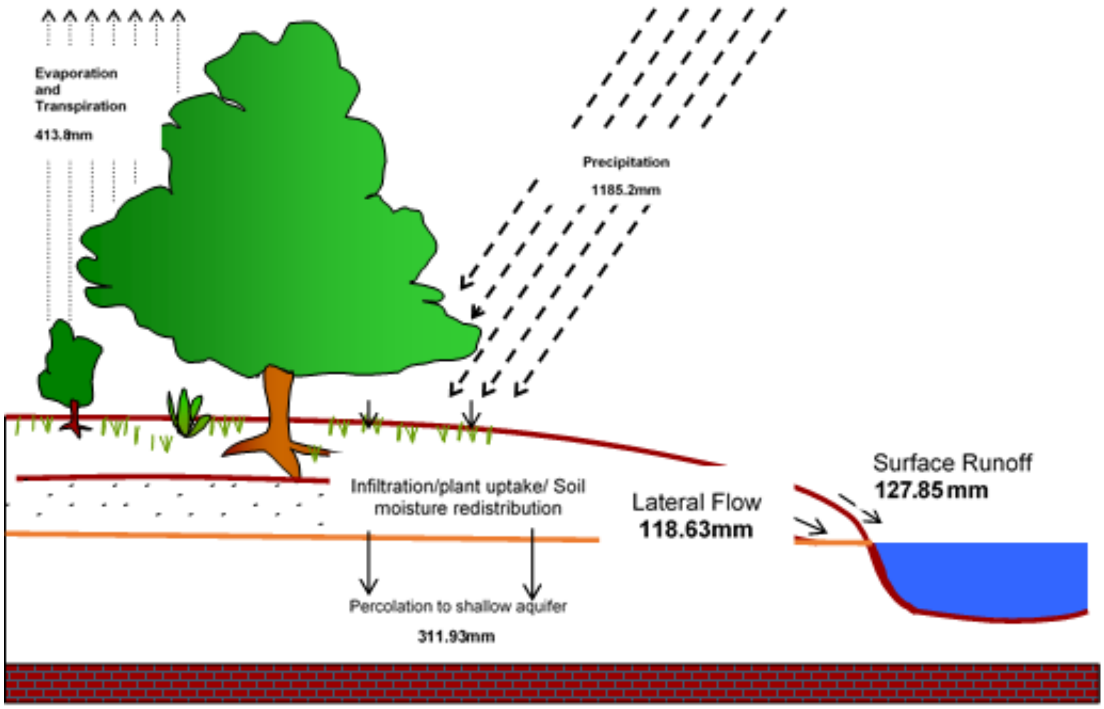

Figure D-2: Visualization of SWAT Hydrological model for reforesting all available barren land.

Appendix E - Cost Benefit Analysis

1. *Implementation Costs*

Table E-1. ***Implementation Costs.*** Table of items that were taken into consideration while developing an implementation cost equation.

Item	Cost/ Item	Source
Shovel	\$10.00 / shovel	John Winings
Pick	\$5.00 / pick	John Winings
5-Gallon Bucket	\$3.25 / bucket	The Cary Company
Planting Bags	\$0.01 / bag	John Winings
Seeds	0.004 / seed	AliExpress.com
Fertilizer	\$55.00 / 25 lb fertilizer bag	Amazon.com, Inc.
Leasing Land	\$0.005 / ft^2	John Winings
Labor	\$4.00 / 8-hr workday	John Winings

The first year costs and 14-year costs are presented below in Equations E-1 and E-2.

$$1st\ Year\ Costs = [sqft] * \left[\frac{\$\ land}{sqft} \right] + \left[\left(\frac{\#\ trees}{sqft} \right) * \left(\frac{\$\ picks + \$\ shovels + \$\ fertilizer + \$\ seeds + \$\ bags + \$\ 8\text{-}hr\ labor}{tree} \right) \right]$$

$$1st\ Year\ Costs = [sqft] * \left[\frac{\$\ 0.005}{sqft} \right] + \left[\left(\frac{1\ tree}{37.67\ sqft} \right) * \left(\frac{\$\ 0.25 + \$\ 0.50 + \$\ 2.20 + \$\ 0.01 + \$\ 0.01 + \$\ 0.40}{tree} \right) \right] = \frac{\$\ 0.09}{sqft}$$

Equation E-1

$$14\text{-}Year\ Total\ Costs = \sum_{i=2019}^{2033} \frac{\left(\frac{Haitian\ Gourdes}{8\text{-}hr\ workday\ -\ worker} \right) \left(\frac{Days}{Year} \right) \left(\frac{Workers}{sqft} \right)}{1.0513i\ -\ 2095}$$

Equation E-2

2. *Interest and Inflation Rates*

$$Combined\ Interest\ and\ Inflation\ Calculation = Value\ CO_2\ \left(\frac{\$}{hectare} \right) * (1+0.03075)^{time\ (years)}$$

Equation E-3

3. *Benefits*

<u>Sequestered Carbon</u>

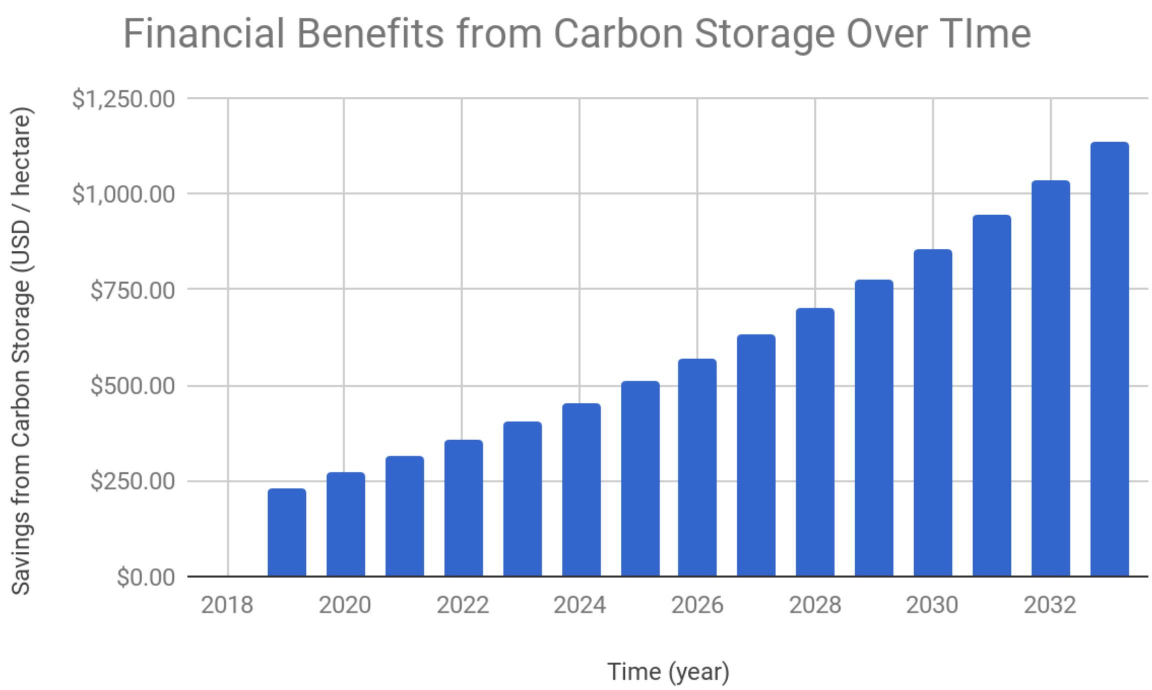

Figure E-1: Financial Benefits from Carbon Storage Over Time. A graph that shows the total financial benefits from carbon dioxide storage each year throughout the 15 year project period in US Dollars per Square Foot of land reforested.

The following equations were used in this study to quantify the financial benefits from carbon dioxide sequestration per square foot of land reforested:

$$\frac{CO_2}{year \bullet hectare}(tons) = \frac{\frac{Mg\ C}{year \bullet hectare} * \frac{1000\ kg\ C}{1\ Mg\ C} * 3.6663\ \frac{kg\ CO_2}{kg\ C}}{1000\ \frac{kg\ CO_2}{ton\ CO_2}}$$

Equation E-4

$$Value\ of\ CO_2\ (\frac{total\ \$}{area}) = \sum_{t=1}^{15} (\frac{tons\ CO_2}{year \bullet hectare}\ *\ Value\ (\frac{\$}{ton})\ *\ (1.03075)^{t\ (years)})$$

Equation E-5

$$Value\ of\ CO_2\ (\frac{total\ \$}{area}) = \$9{,}186.77\ per\ hectare = \$0.09\ per\ ft^2$$

Equation E-6

Benefits from Preventative Measures

Equation E-7 presented below is a general equation that was modified from FEMA to be applied for households with a maximum value of possessions of $1500 based on the flood height in inches.

$$Value\ of\ Possessions = [\{-1.1406 \times (inches^2)\} \times \{84.432 \times (inches)\} - 9.101]$$

Equation E-7

Equation E-8 presented below is a general equation used to determined the well cap implementation cost.

$$Well\ Cap\ Cost = \frac{area\ of\ well\ cap\ (inches^2)}{area\ of\ brick\ (inches^2)} \times Cost\ per\ brick$$

Equation E-8

Produce Profit from Reforested Trees

Equation E-9 presented below is a general equation that can be applied to each of the eight types of the produce trees: . The table below this equation, Table E-2 includes the data used to calculate the total produce profit.

$$\sum_{i=2018}^{2033} \frac{(\#\ Trees)\left[\left(\frac{Produce\ Yield}{Tree\text{-}Year} * .75 * \left(\frac{Gourdes\ in\ the\ Mountains}{Quantity\ of\ Produce\ Sold}\right)\right) + \left(\frac{Produce\ Yield}{Tree\text{-}Year} * .25 * \left(\frac{Gourdes\ in\ the\ City\ Center}{Quantity\ of\ Produce\ Sold}\right)\right)\right]}{(1.0513i\ -\ 2095)} = USD$$

EquationE-9

Table E-2. ***Produce Produce Data.*** Table including the data used to calculate the total produce profit from the goods grown on the reforested trees. The source of this data is Mr. John Winings, Merlene Laguerre, and local vendors throughout Léogâne.

Type of Tree	Yield per Tree per Year	Time to Bear Fruit	Haitian Gourdes per Quantity Commonly Sold - Mountains (75%)	Haitian Gourdes per Quantity Commonly Sold - City Center (25%)
Papaya	142	4 - 6 Years	250 Gourdes / 7 Papayas	550 Gourdes / 7 Papayas
Mango	250	2 - 3 Years	250 Gourdes / 15 Mangos	400 Gordes / 15 Mangos
Orange	200	1 Year	200 Gourdes / 4 Oranges	350 Gourdes / 4 Oranges
Grapefruit	315	4 Years	100 Gourdes / 4 Grapefruits	200 Gourdes / 4 Grapefruits
Lime	285	2 - 3 Years	1,500 Gourdes / 20 Limes	3,000 Gourdes / 20 Limes
Lemon	315	2 - 3 Years	500 Gourdes / 30 Lemons	1,000 Gourdes / 30 Lemons
Cherry	3040	4 Years	500 Gourdes / 180 Cherries	1,000 Gourdes / 180 Cherries
Avocado	280	2 Years	250 Gourdes / 6 Avocados	500 Gourdes / 6 Avocados

Appendix F - Meeting Minutes with Feedback from John Winings

*Note that all text in black represents team member notes and all text in red is John Wining's returned commentary.

May 19th 2018
Stakeholder Presentation

Attendance

- Nitika
- Valentina
- Louiza
- Jillian
- Mateusz
- John Winings

Notes:

- Technical Approach
    - Interest in land cover for all of Leogane region
    - Interest in the National forest cover. John in agreement that the forest cover would be around the 36% range due to his work and opinions of the forested land in Haiti. This has been a misunderstood issue for years; correcting the 3% myth is good.

- Project benefits
    - Profit from produce- Bananas are not included. John explains that bananas can grow very easily but can have some risks associated with planting them. Banana plants are like corn, they grow only for one season, produce one bunch per plant (tree); at the end of the season, they die. The 'plantations' thus, are plowed and new ones are planted for the next growing season. As such, again like corn, the root systems are very shallow and strong winds, rain, hurricanes will flatten a field of bananas easily; causing the farmer to lose, in most cases, his/her entire crop for the season. The price of bananas then goes up, and the economic hardships, already rather severe, are increased.
    - Water contamination- Used only for the city region. If used for the mountain region as well, should have included cisterns as source of water contamination. My point on this is that, roof water runoff feeding cisterns is likely *less* contaminated overall than for urban areas using ground or river water as sources. With cisterns, there is less likelihood of the development of cryptospiridium and legionnaire's contamination because the water does not stagnate, it is used daily. Following the earthquake, there was an NGO that repaired/replaced hundreds of wells in the plains area of Léogâne. This helped with the contamination issue, also.

- Results
    - Cost Benefit- no surprise that it would cost around 3 billion to implement a reforestation for all available barren land. When FAO (Food agriculture

Organization) came to reforest, it was very expensive for them due to the labor costs. They should have taken into account that most people in the region, 65-80% are unemployed. Thus paying people fairly for the work they do is a hard question. One of the key programs the UN uses following disasters worldwide is called Cash For Work. The theory is that, paying minimum wage to groups to work on cleanup will not only get reparations started quickly, but also will provide a much needed economic infusion directly to the people who will spend it in local markets. However, for areas within Léogâne, where the unemployment rate is so high, the Cash For Work program provides typically two weeks worth of work, and then other people are chosen to continue. So the economic impact is significantly less.

- Our conclusion with money is dead on, even though it is not what we hoped for. In addition, labor costs in most developing countries are very low and the concept of minimum wage comparatively with existing wage levels is much too expensive. It is a well-meant objective, but unworkable.
- John has found this in his work as well, that community involvement with volunteer labor will increase engagement and decrease costs. In Haiti, in particular, there is a strong sense of entrepreneurship. Look at local street vendors, who are ubiquitous throughout the country. The same spirit exists for the family/friends units which comprise the lakous. All CODEP has done is take this spirit of entrepreneurship (capitalism) and use it to leverage reforestation.

- Recommendations for future work
  - Side statement- work on ways to resolve land tenure problem
  - John's Solution- to rent property from squatters who need money for 10 years and pay them rental price upfront (rental price is significantly lower than purchasing)
    - Renting land is a good start for trees to begin growing and then continue renting the land for another 20-25 years for the trees to grow.
    - Although renting from 'squatters' sounds barbaric, it is one solution that, in the absence of any national legal system revisions, seems to work well
    - As an example, we rented about a half-acre of land for 35 years for $1,600 USD. Had we had to buy the property, it would have cost $15,000 or more. (Particularly if it had been known that 'blancs' were involved). Payment was made up front, and the squatter was able to get badly-needed money when he needed it.
    - Does this sound like crass taking advantage of a squatter? Yes, I suppose, but viewed broadly, if reforestation is to become more widespread, these kinds of solutions to the land tenure issue are valid. Plus, the land itself would increase in value much beyond its value if left barren.