Department of Earth Systems Science and Environmental Engineering, Senior Design 2012-2013

PRELIMINARY REPORT:

Water Balance Analysis: Lake Enriquillo Sensor Network Expansion & Analysis of Lake Bathymetric

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I. Abstract

1.1 Abstract

Over the last two decades The Hispaniola's Island has been affected by climate changes that have directly impacted the two major water bodies in the island: Lake Enriquillo in The Dominican Republic and Lake Saumatre (Azuei) in Haiti. A dramatically growth have been noticed in these lakes, Records from Satellite analyzed images show that lake Enriquillo underwent a period of shrinking prior to 2004 when the lake reached its lower surfaces area of approximately 1.71.76 Km2 since then its Area has been expanding up to 347.26Km^2 in March, 2013. Figure 1 below shows the lake expansion from the moment it started to growth until last the satellite image was analyzed in March 2013.

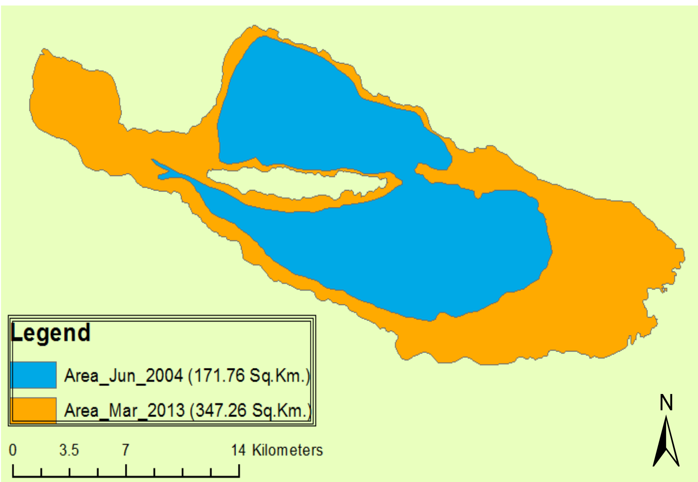


Figure 1. Lake Enriquillo Surface water Area

This rapid augmentation in surface area has affected hundreds of adjacent residents in villages bordering the lake, resulting in relocation of families, In addition big areas of agricultural land has been lost to this flooding events which, might result in permanently damages soil due to the lake's salinity levels if the water retrocede like in previous decades. Although this phenomenon of water fluctuation in the lakes area have been known to happen in previous years, its speedy growth process is what it catch everyone's attention.

Many theories have been proposed as why the lakes have been expanding, and even though lake Enriquillo has been spreading more than the lake Saumatre (Azuei) in Haiti, they both possess an almost steady rate of growth with lake Enriquillo been the one with the biggest rate of both. Due to the lack of meteorological data from the surrounding areas of Lake Saumatre, we are only considering Lake Enriquillo Water balance analysis. Some of the hypothesis that tries to explain the lakes growth includes:

a) Regional Climate Changes
b) Land use Changes due to deforestation and population growth
c) Hydrologic theories suggest Groundwater inputs due to recent tectonic movement in the region

In order to account for the water budget in the lake, we conducted a comprehensive water balance analysis that is composed of three types of data collection: direct measurements from sensors deployed on the watershed as well as depth sounder to construct a bathymetric map of the lake historical levels, Historical data retrieved from local and international agencies, and Satellite data analysis. This analysis will consider Hydro-climate changes throughout the years by studying parameters of Rainfall, Runoff, Land-use, Evaporation, Lake Surface water area, and Volume changes.

1.2 Acknowledgement

This Report is a preliminary result of a cooperative effort of many institutions that participated in the course of this investigation, which included: The City College of New York, The Instituto Tecnologico De Santo Domingo (INTEC), The National Meteorological Agency (ONAMET), and The National Institute of Water Resources (INDHRI). We would like to thanks to the people that make this report possible with their efforts and impetus. We thank our mentors Dr. Jorge Gonzalez, Dr. Fred Moshary, Dr. Michael Piasecki and Dr. Daniel Comarazamy for their advice and push toward a quality report, we also want to thanks all of the INTECT team; Candido Quintana, Yolanda Leon, and Ambar Mesa for their time and contributions. In addition, we would like to thanks all of the ONAMET's team Claudio Martinez, Juan Salado, and Robert for the companion and valuable information and data provided for the completion of this report.

II. Introduction

2.1 Introduction

The Dominican Republic Enjoy a Tropical climate during the entire year. The area of the Enriquillo basin is located in a rainfall depression of the island of Hispaniola, annual precipitation averages for the last decade on the Jimani Station (station with the most complete set of historical meteorological data recorded that is within the watershed) are 866.39 mm/year, this is an 18.68% increase in comparison to the previous decade where the precipitation average was recorded at 730mm per year. Figure 2 below shows rainfall augmentation during the last two decades.

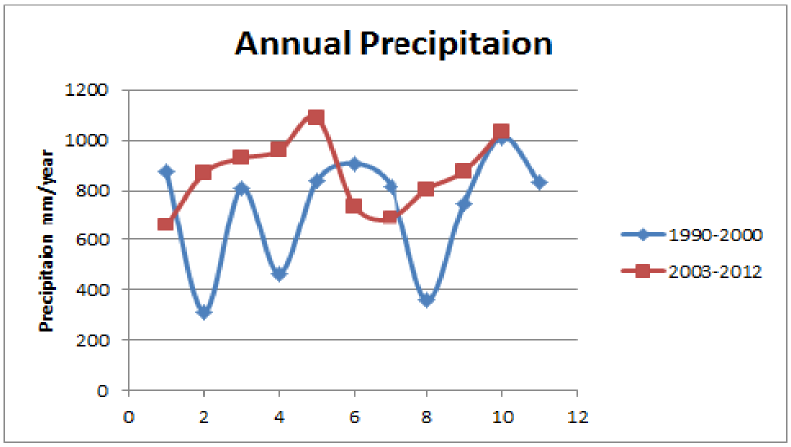


Figure 2. Shows an 18.68% increase in Precipitation in two different decades (90's and 00's)

Waters levels at Lake Enriquillo have increased and the surface area has moved and expanded in all directions especially to the East, invading lands that for many years were being used for cattle ranching and agriculture. This slow progressive flooding process could be the result of precipitation increase, possible groundwater intrusion, climates change in the region (evaporation, wind speed, etc.), and Land use changes.

This report means to quantify the water production in the area of the Enriquillo basin. In order to achieve our goals, we performed a simple water balance analysis of the areas of interest. A water balance analysis of a water body is the net calculation of water input and output into that water body thru the different medium and over a specific interval of time. This analysis will be performed over the watersheds of Lake Enriquillo.

2.2 Problem Statement

This rapid expansion in surface area has affected hundreds of adjacent residents in villages bordering the lake, resulting in relocation of families, In addition big areas of agricultural land has been lost to this flooding events which, might end result in permanently damages soil due to the lake's salinity levels if the water retrocede like in previous decades also, frequently floods of the main road connecting the two countries has add an adverse factor to the economical already declining trends. Although this phenomenon of water fluctuation in the lakes area have been known to happen in previous years, its rapid growth process is what it catch everyone's attention. According to Cocco Quezada in his report from 2009 "El Ciclo Hydrologico del Lago Enriquillo", "the most important historical flood took place in the year 1900 when the surface of the lake level reached 34.00 meters below mean sea level. Opposite to this flood an event occurred in 1979, of course before hurricane David, where there was a level of -55.49 meters below mean sea level and according to urban tells, kids could go walking to the Cabritos Island (this was verified by analyzing satellites images from 2004)." This thrilling information defines a fluctuation of 11.70 meters, something that has already been reached in the current flood when a level of 33.6 meters below mean sea level has been reported.

Pictures showing areas being affected by the lakes flooding process: Left, depot located at the border trade zone between Haiti and the Dominican Republic (Dec 2012 field Campaign). Right, House flooded by expansion of Lake Enriquillo (Mar 2013 field Campaign)

2.3 Objective

The objective was to conduct a comprehensive water balance analysis that was composed of three types of data collection: direct measurements from sensors deployed on the watershed as well as depth sounder to construct a bathymetric map of the lake historical levels, Historical data retrieved from local and international agencies, and Satellite data analysis. This analysis will consider Hydro-climate changes throughout the years by studying parameters of Rainfall, Runoff, Land-use, Evaporation, Lake Surface water area, and Volume changes.

2.4 Background

Lake Enriquillo is located in the Southwestern region of the Dominican Republic. It is the largest lake in the country and in the Caribbean with an average area of 265 km2; its watershed encompasses about3500 km2. The southwest region is a semi-arid tropical zone with mostly dry vegetation. The lake is bounded by two mountain ranges, Sierra de Neyba to the north and Sierra de Bahoruco to the south, with elevations of about 2200 m and 1600 m above sea level, respectively. See figure below.

Figure 3. Shows lake bounded by two majors sierras, Sierra de Neyba to the north of the lake and Sierra de Bahoruco to the South. Images from the 2011 senior design team.

Lake Enriquillo is a closed lake with no surface outflow. This characteristic of closed basins makes them particularly sensitive to climatic changes (Kalff, 2002). The fluctuations in the lakes' levels should reflect fluctuations in climatic variables such as temperature and rainfall. In addition, as mentioned before, it is a hypersaline lake of marine origin. A unique aspect of the lake is that it lies about 45 m below sea level, making it the lowest point in the Caribbean (Buck et al., 2005). Its salinity also varies 2 to 3 times that of nearby ocean water (before this study was conducted).

III. Project Management

3.1 Organization

Due to unforeseen events, the original team that was studying all of the different aspects of this project was defused and reduced to only two members. This reduction in manpower, directly affected the scope of work and focus of this report. Several aspects as far as Social-Economic impact, Expansion of the existing sensor network initially created by the 2012 Field Campaign led by CCNY/INTEC team and further expanded on the 2013 field campaign also led by CCNY/INTEC team, project budget, cloud frequency over the sierras, and other minor task, needed in order to create a compact report are missing, therefore they will be only mentioned superficially and not deep analysis will be discuss throughout the course of this report.

The re-assignation of tasks in order to prepare this report was divided as follow:

- **Joseph Cleto**
  - Project Methods and Procedures
  - Lake Surface Area demarcation (GIS application)
  - Lake Enriquillo Bathymetric map (Using field measured data)
  - Volume change Calculation (using field measured data and GIS application)
  - Data Collection (remote sensing, historical records, and field collected)
  - Precipitation Analysis
  - Sensor network description

- **Mandy Luo**
  - Water balance (formulation of equations)
  - Estimated Evaporation (using Penman equation)
  - Watershed demarcation (GIS application)
  - Land classification (GIS application)
  - Water surface Runoff
  - Water quality data interpretation

3.2 Project Timeline

The developments of events that corresponded to each team member are presented in the graph below. However, some of the tasks that will be described in the following timeline for the project were not covered exclusively for the creators of this report. In fact, they were part of a joint effort from part of the different institutions that are involved in this investigation.

First Term

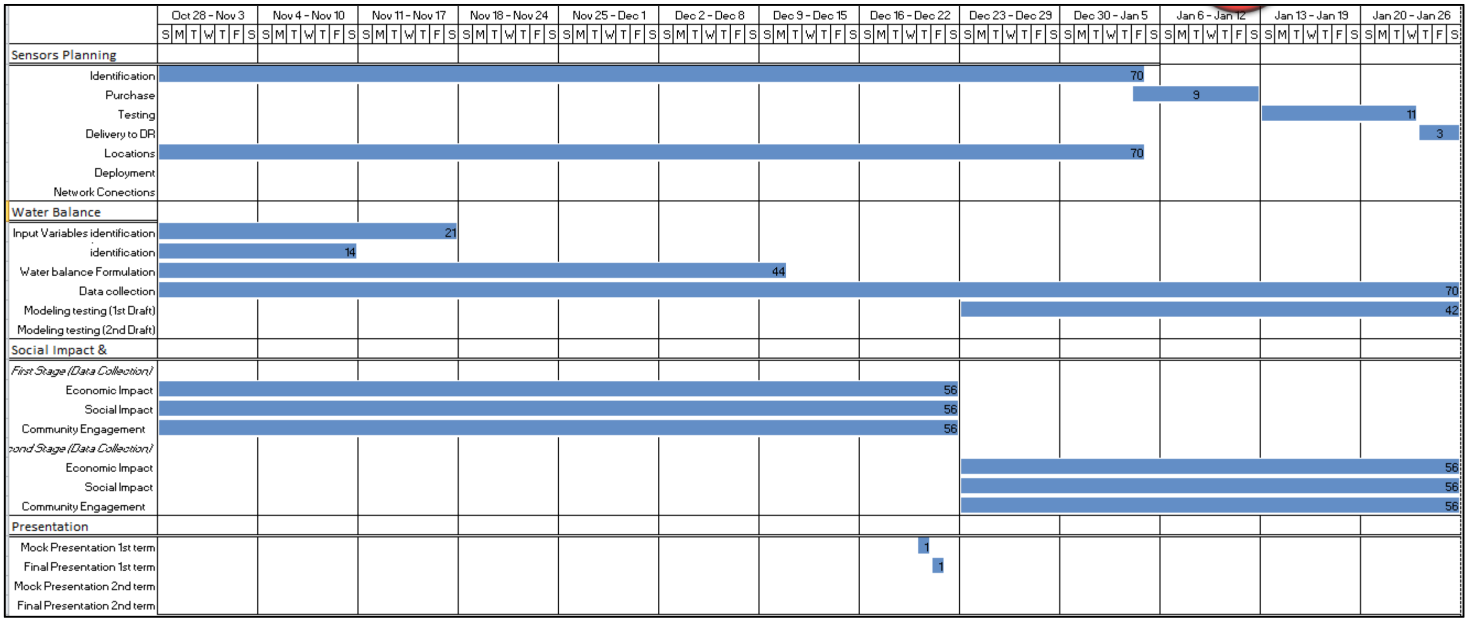


Figure 4a. Represent the timeline for the first term of the project (Oct. – 2012 to Dec. 2012)

Second Term

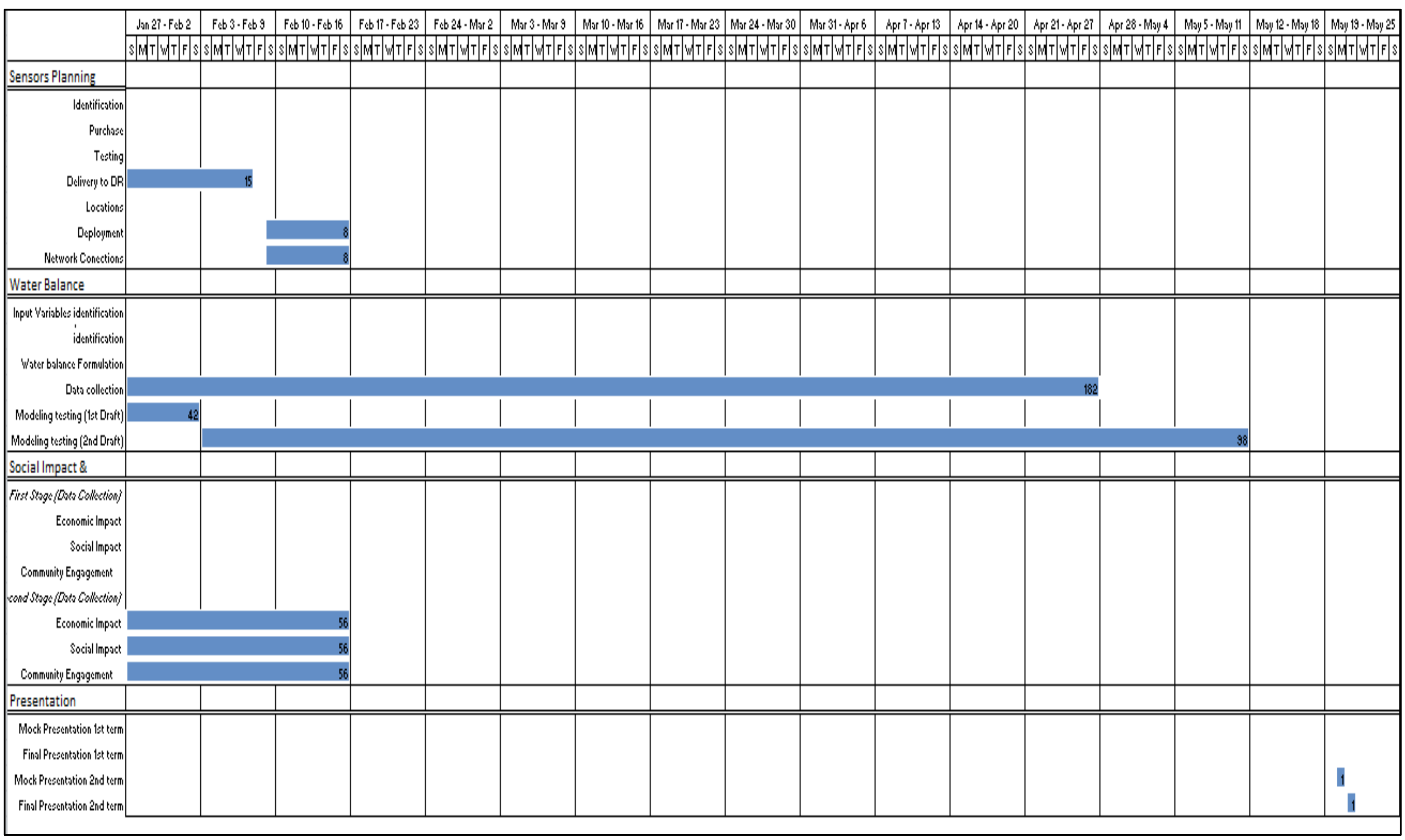


Figure 4b. Represent the timeline for the Second term of the project (Jan. 2013 to May. 2013)

3.3 Project Budget

This project has been financed by the National Scientific Association thru a Rapid Grand Awarded to Project Director Dr Jorge Gonzalez. As far as purchases orders to acquire all of the equipment and sensors to be deployed at the lakes and Sierras, the team allocated around US $35,000.00 the money was distributed as follow:

Table 1. Summary of Instrumentation expenses

Station/ location	Manufacture	Amount (US$)
Jimani (onamet office)	Campbell Scientific	$ 10,201.29
Sierra of Bohoruco Deployment and upgrade to existing sensors in Sierra of Neyba	Onset (HOBO Instruments)	$ 9,009.62
Lake sensors	INW Insrtuments	$ 4,741.00
Depth Sounder	Humminbird	$ 1,300.00
	TOTAL	**$ 25,251.91**

Noticed that in the about table, expenses of Travel, stay in the lake area, Logistics, contingencies, and shipping of equipment to the Dominican Republic are not included as they were managed by the project managements and director office.

IV. Socio-Economic Impact

4.1 General View

The area where the lake is located has been known by having the highest rate of poverty in the Dominican Republic. According to the economist and specialist in environmental economist matters in the Dominican republic Solhanlle Bonilla, in 2009 about 55% of the population living in the Independencia providence did not reach the basic level of education, and that unemployment rate reached about 26.8%, while in the Bahoruco’s providence, about 51% of the population did not reach the basic level of education, and that unemployment rate reached about 34.8%. This fact can be confirmed by data gathered by Denia Guzman in her report from May 2013 called ‘’ Socio-Economics Impact; Lake Enriquillo”.

Table 2. Communities affected by the Lake Enriquillo Growth. Denia Guzman (2013)

Provinces	Affected Communities	Population	Poverty %	Extreme Poverty %	Affected Farmer	Affected Breeders	Affected Producers	Affected Land(acres)
Before the increment of the lake area								
Bahoruco	Los Rios	5579	77.3	35.1				40,000
	Villa Jaragua	11437	82.5	44.9				
Independecia	Las Clavellinas	2032						
	Duverge	13,506	58.6	15.5	2290	450	786	40,000
	Postre Rio	3740	84.2	39.8			71	3392
	Descubierta	6939	71.1	24.6			61	4140
	Venga a Ver	2635	73.1		60		57	
	Jimani	5901	70.2	19.2	300		500	55,000
	Boca de Cach	1578	75.3		283	135		10000

In addition, Denia added that "this information was provided by *The Demographic Profile*, conducted by the National Statistical Office of The Dominican Republic (ONE), using data from the census of 2002. However the blue right side of the table information is not official is based on the work of the NGOS operating in the area of Enriquillo Lake"

During the 2013 field campaign to the lake area, a set of interviews with a predesigned schematic questionnaire were conducted in order to officially quantify the communities and individuals that have been directly or indirectly affected by this problem. Dr Mimi Sheller was leading this task. In order to prepare the survey, she created two stages that would easy the targets identifications: First stage included the identification of resident's idiosyncrasy, the collection of statistical data, and the identification of the principal Communities Stakeholder and Nonprofit Organization working in the region. The second stage's objective is to recognize the mitigation alternative that these communities already started to develop. Unfortunately, at the moment of producing this report, the results of the social-economic analysis have not been finalized yet, therefore that would be a task that need to be included later when it is fulfilled.

V. Sensors Network & Deployment

5.1 Sensor Network

In order to understand the cyclical movement of water throughout the watershed, we need to obtain valuable data that help us to fill in missing information in our water balance model. During the 2012 field campaign, a network that measures different climate parameters was put into work. The network measures Solar radiation, Temperature, Relative Humidity, soil moisture, it contains winds speed and direction devices, rain gauges, fog gauges. It is comprised of 18 nodes along sierra of Neyba, deployed at different elevations.

During the 2013 field campaign, the network was expanded to the Sierra de Bahoruco. It is comprised of a less dense node-chain of sensors, however it is more comprehensive and it is improved at every single node. This network was designed with the purpose of provide vertical climate change reference on the south sierra of Lake Enriquillo. Just like the network in the north Sierra of Neyba, the network measures solar radiation, Temperature, Relative Humidity, soil moisture, it contains winds speed and direction devices, rain gauges, and fog gauges. See bellow table 2 containing network sensors description.

Table 3. Shows the final configuration of the sensor network deployed by the CCNY 2012 senior design team. They claim that each site is listed in ascending order by altitude. Sensors are denoted by the following abbreviations: TRH= Temperature & Relative Humidity, RG= Rain Gauge, FG= Fog Gauge, WS= Wind Speed, SR=Solar Radiation, SM= Soil Moisture, EP=Evaporation Pan.

Sensors (Sierra of Neyba)					
Latitude	**Longitude**	**Location Name**	**Transect**	**Altitude (masl)**	**Sensor Type**
18.4953	-71.7218	Isla Cabritos	1	-6	TRH
18.5619	-71.6970	La Descubierta	1	-19	TRH
18.5979	-71.7706	Los Pinos del Eden	1	544	RG, TRH
18.6169	-71.7762	P1	1	765	TRH
18.6364	-71.7685	Angel Felix	1	1139	TRH
18.6516	-71.7987	Sabana Real	1	1301	TRH
18.6580	-71.7847	Centro de Control	1	1461	TRH
18.6622	-71.7803	P2	1	1546	TRH
18.6639	-71.7622	P3	1	1720	FG, TRH
18.6812	-71.7875	Flag Point 3	1	1882	TRH
18.6813	-71.7872	Bromeliad Branch	1	1883	FG, TRH
18.6917	-71.7875	Pyramid 204	1	1960	TRH
18.6936	-71.7823	Guard Post 204	1	1874	FG, TRH, RG, WS, SR, SM(3)
18.5926	-71.6000	T1	2	576	TRH
18.5909	-71.5860	T2	2	831	TRH
18.5688	-71.5680	T3	2	1176	TRH
18.6213	-71.6059	Ecuela Higo de la Cruz	2	1339	RG, TRH
18.6477	-71.6106	El Maniel Interseccion	2	1285	TRH
Sensors (Sierra of Bahoruco)					
Latitude	**Longitude**	**Location Name**	**Transect**	**Altitude (masl)**	**Sensor Type**
18.3299	-71.7002	El Aguacate Military Post	3	1078	FG, TRH, RG, WS, SR, SM(3)
18.3127	-71.7071	Zapoten Park Ranger Station	3	1537	FG, TRH, RG
18.2899	-71.7161	Loma del Toro	3	2355	FG, TRH, RG, WS, WD, SR, SM(3)
Sensors Jimani (ONAMET)					
Latitude	**Longitude**	**Location Name**	**Transect**	**Altitude (masl)**	**Sensor Type**
18.483	-71.85	Jimani (onamet)	4	31	FG, TRH, RG, WS, WD, SR, SM(3), EP

5.2 Network Objective

Since the beginning when these networks were first created, the main objective have always been to create a wireless network of meteorological nodes that easy the collection of data and that provide us with real time data that can be used to predict extreme events in the Enriquillo Basin. However, this objective has not been accomplished yet due to many factor that include budget limitation. It is very expensive to create a network with wireless capabilities either using satellite telemetry or radio transmission. One of the major components make this task difficult is the line of sight of communication, in order for the radios to transmit data at an effective range, they need to have a clear path between them. This is very difficult to achieve due to the geographic conditions of the area, very high mountains associated with the topographic of the sierras and dense canopy complete an intimidating condition for the network to happen.

Therefore to ensure quality data, the focus of the network turned into sensors implementations that maintain stability in high humidity conditions, and log data for relatively long periods of time with minimal maintenance.

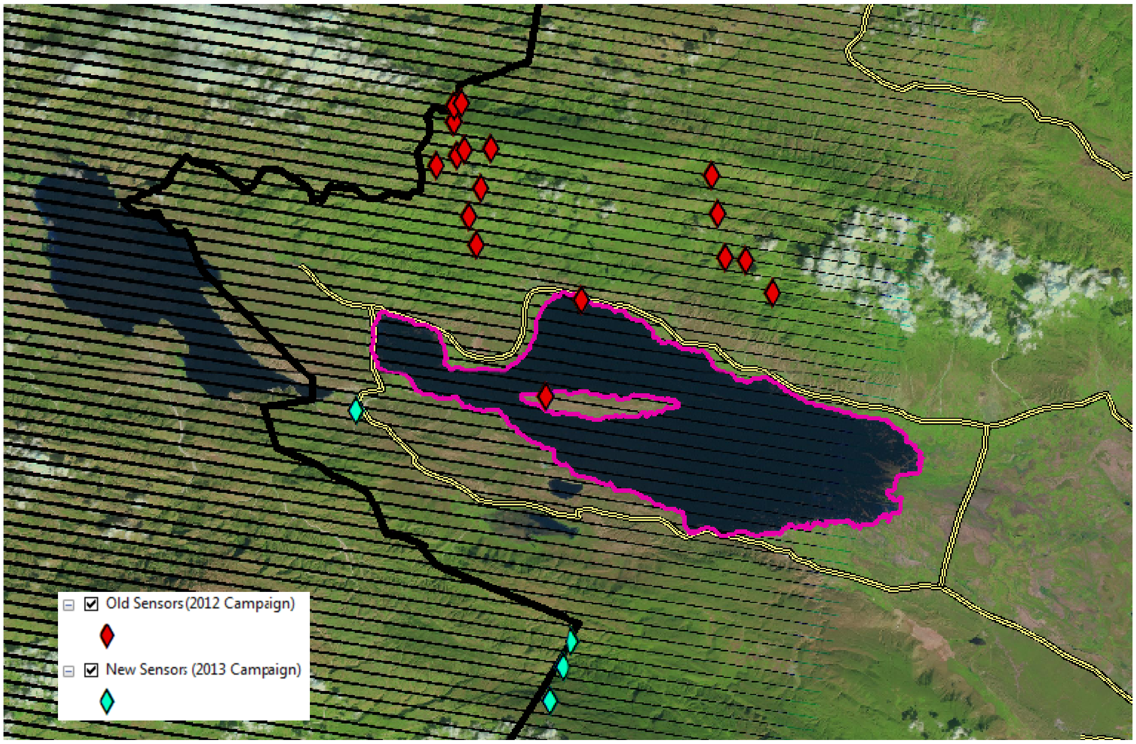


Figure 5. *Map of network created around lake enriquillo.*

5.3 Jimani Station

A full upgrade was done to the station located on Jimani. This station has been in operation for little more than 30 years, it hold the largest record of historical meteorological data of any other station within the watershed. Since its beginning, Jimani station has collected parameters of Temperatures, Relative Humidity, Dew Point, Wind Speed and Direction, Evaporation, solar radiation, and precipitation. However, due to the deteriorating of the dispositive of measurement, in last decade some of this parameter has not been measured in a continual routine. Nevertheless, most of the data used to estimate water balance in the Enriquillo basin came from this station. The team decided to implement a weather Station using Campbell Scientific Instruments so that the station will meet World Meteorological Organization standards.

Improvement to this station included the following sensors:

Table 4. Jimani Sensors description.

Item #	Model	Description	Specs
1	CR1000-ST-SW-NC	DATA LOGGER	Dimensions: (23.9 x 10.2cm x 6.1cm) Power requirement: 9.6 to 16 Vdc Temp range: -25C to 50C Weight: 2.1lb Protocols Supported: PakBus, Modbus, DNP3, FTP, HTTP, XML, POP3, SMTP, NTP, NTCIP Pulse Counter: 2 Accuracy: +/- 0.06% from 0C to 40C Max Scan Rate: 100 Hz
2	NL115-ST-SW	ETHERNET INTERFACE & COMPACT FLASH MODULE	Dimension: (10.2cm x 8.9cm x 6.4cm) Typical Access speed: 200 to 400 kbits/sec Power Requirements: 12V Cable requirements: Ethernet shielded
3	BP12	12V SEALED RECHARGEABLE BATTERY	Dimensions: (5.94" L x 3.86" W x 3.7" H) Connector Type: T2/F2 Weight: 9.2 bls Volts: 12 Capacity: 12 Ah
4	SP20	20W SOLAR PANEL	Dimensions: (50cm x 42.2cm x 5.1cm) Max peak Power: 20W Weight: 13.6 lb Current at Peak: 1.19A Voltage at Peak: 16.8V
5	ENC14/16-DC-TM	WAETHER RESISTANT (14"X16") ENCLOSURE	Dimensions: (35.6cm x 40.6cm x 14cm) Material: fiberglass-reinforced polyester Enclosure Classification: NEMA 4X
6	CS210	ENCLOSURE HUMIDITY SENSOR	Dimensions: (2.5cm x 1.3cm x 0.8cm) Accuracy at 25C: +/- 3% RH Setting time: 10 sec Weight: 0.3 oz Range: 0 to 100% non-condensing
7	05103-L40	RM YOUNG WIND MONITOR	Dimensions: (5cm dia x 55cm L x 37cm H) Accuracy: +/- 3% Operating Temp: -50C to +50C Weight: 3.2 lbs Range: 0 to 244 mph
8	TB4-L50	HYDROLOGICAL SERVICES RAIN GAUGE	Measurement Range: 0 to 700 mm hr-1 Accuracy: (+/- 2% @ <250 mm hr-1); (+/- 3% @ 250 mm hr-1) Humidity range: 0 to 100% Height: 33cm
9	HC2S3-L9	ROTRONIC HYGROCLIP2 TEMP/RH	**Temperature** Range: -50C to 100C Accuracy at 23C: +/- 0.1C Long Term Stability: <0.1C/year **Relative Humidity** Range: 0 to 100% RH Accuracy at 23C: +/- 0.8% RH Long Term stability: <1% RH/year
10	41003-5	RM YOUNG 10-PLATE GILL SOLAR RADIATION SHIELD	Dimensions: (11.9cm Dia x 203cm H) Weight: 1.3 lb Power requirements: NO
11	LI200X-L14	LI-COR PYRANOMETER	Accuracy: +/- 3% typical Dimensions: (2.38cm dia x 2.54cm H) Weight: 1.0 oz Stability: <+/- 2% change over 1 year RH: 0 to 100% Operating Temp: -40C to 65C

12	255-100	NOVALYNX ANALOG OUTPUT EVAPORATION GAUGE	Dimensions: (700mm H x 203 mm DIA) Accuracy: 0.25% Weight: 7.5 lbs Float: 4" diameter, plastic
13	255-200	NOVALYNX CLASS A EVAPORATION PAN	Material: Low carbon stainless steel type 304, gauge 18 Volume: 7.7 gallons weight: 48lbs
14	255-620	NOVALINX AUTOMATIC REFILL KIT EVAPORATION PAN	Dimensions: (20cm x 15cm x 10cm) Weight: 4lb Water Connection: Standard garden hose Operating humidity: 0 to 100% Operating Temp: 0C to 50C Housing: Aluminum and Plastic, waterproof
15	CS106	VAISALA PTB110 BAROMETER (500-1100 hPa)	Dimensions: (6.8cm x 9.7cm x 2.8cm) Accuracy: (+/-0.3 mb @ +20C); (+/-0.6 mb @ 0C to 40C); (+/-1.0 mb @ -20C to +45C); (+/-1.5 mb @ -40C to +60C) Operating Temp: (-40C to + 60C) Setting Time: 1 sec to reach full accuracy after power-up
16	CS616-L50	WATER CONTENT REFLECTOMETER (SOIL MOISTURE SENSOR)	Output: +/- 0.7 volt square wave Rod Dimensions: (300mm L x 3.2mm Dia x 32mm spacing) Probe Head Dimensions: (85mm H x 63mm W x 18mm D) Weight:9.9 oz

This station has internet connection via Ethernet cable from a local internet provider. The data gathered from these sensors will be seen thru a NOOA-CREST CENTER website once the site become available for the public. The website is based at The City College of New York and it is currently maintained by Tom Legbandt who is a senior technician at the CCNY and was who programed the sensors at Jimani prior to installation. The CR1000 Datalogger is powered by a 20W solar panel to prevent power outages that crunches the country so often.

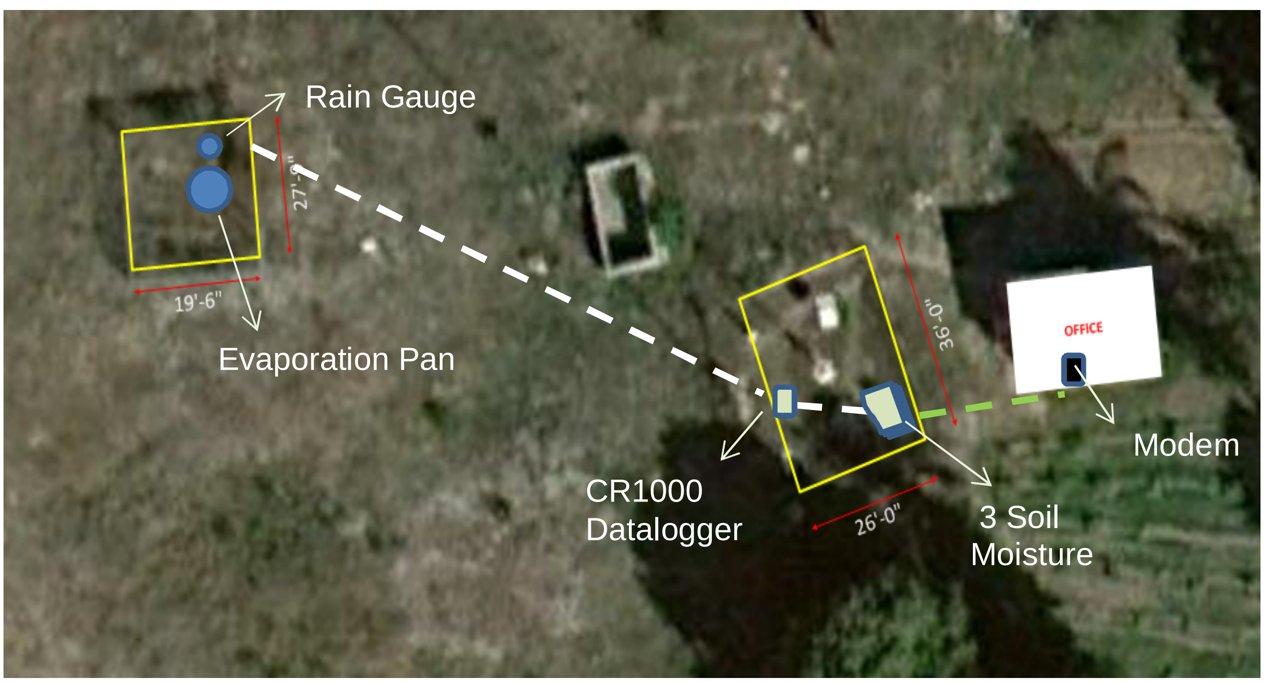


Figure 6. Jimani Station Plan View

5.4 Water level sensors

It was part of the scope of work to instrument the Lake's water in order to monitor water levels in real time; however there was a manufacture problem with the sensors at the moment of installation. Therefore these will be installed in a second trip to the lakes area this summer 2013. These sensors manufacture by INW, will be installed in both lakes, Lake Enriquillo and Lake Saumatre (Azuei). In addition to measure water levels, these sensors also measures water's Temperature and Salinity levels.

VI. Water balance

6.1 Methodology

Using available daily precipitation, temperature, pressure, relative humidity, and wind speed data, a simple Thornthwaite-Mather type water balance model was applied to the lake Enriquillo watershed to simulate water level changes. The input and output components of the lake's water balance can be estimated using the model and the sensitivity of the water level change to these components can also be analyzed.

Change in storage = watershed input + precipitation over lake – lake evaporation

$\Delta V=R+(P)*(A_{lake})-(E)*(A_{lake})$

ΔV=lake water volume change
R=runoff from watershed
P=precipitation
E=evaporation
A_{lake}=surface area of the lake

The model is based on the assumption that there is no natural inflow/outflow of the lake. Also, this water balance analysis was focus on the last decade since the year the lake started to growth. Many assumptions made during the calculation process will be explained in their respective parts.

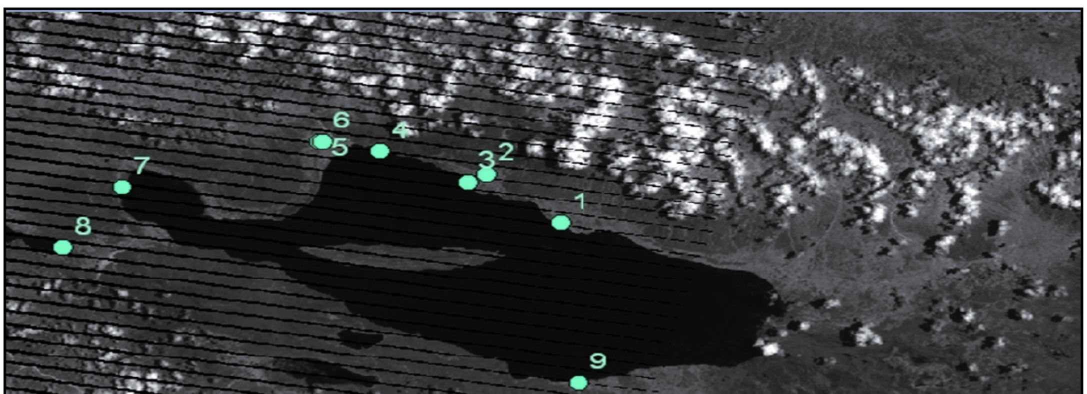
6.2 Surface Area Delineation and Calculation

In order to determine the water surfaces areas of the different years, we made use of remote sensing analysis. Remote sensing is the method used to extract information from an object without making physical contact with it. Generally remote sensing used aerial sensors technologies to collect data by mean of measurement natural radiation that is emitted or reflected by the object of interest or surrounding areas. Satellites which are object that orbits the earth are good sources of data retrieval using remote sensing technique. For the purpose of this project, LANSAT will be used as major toll of data collection to determine lake surface area. Lansat TM and and ETM are optical passive satellite that orbit the earth every 16 days, the advantage of using its historical images archive laid on the records dated from the early 1970's when Lansat was first lunched into space. Another advantage that makes lansat a good source is the fact that is images are already corrected for many of the various corrections that need to be done while processing satellites images (e.g., radiometric and geometrically corrected to a first degree and registered).

The method used to calculate the areas is described below:

- Images acquisition.
    - Images where obtained using Earth Explorer or Glovis websites from the United States Geological Survey (http://earthexplorer.usgs.gov/).
    - Download all available cloud free images. (images were downloaded from 1984 to 2013. However, this report only focused on the last decade. Remainders images will be included in the final general report).
- GIS Analysis
    - Load images into ARCmap
    - Create a polygon shape file (preferable in the same folder containing the images)
    - Assign spatial geographical coordinates to the newly created file so that it possess the same coordinates as you images.
    - Activate Editor tool bar to manually delineate the perimeter of the lake
    - Start editing your polygon and save after being complete.
- Area Calculation.
    - You can calculate the area from the table of attribute by using geometrical calculations function or
    - You can also use Phyton windows and get the area by writing a script.

This method of calculating lake area has being validated by previous research done on the lake area. In June 2010 the CCNY senior design team did a ground-truth analysis by taking measurement of coordinates of different points around the lake area and then plot them into ARCmap to verify its position with the satellite images downloaded from Lansat. Figure 8 below shows the result of their analysis.



id	x-Este	y-Norte	Cota	Observaciones
1	225679	2049007	-29	Los Rios
2	221415	2052801	17	postrer rio, rio Guayaba
3	220298	2052185	-26	Postrer Rio
4	215293	2054490	-21	Parque Isla Cabrito
5	211805	2055195	29	Rio Las Barias, La Descubierta
6	211897	2055256	35	Balneario Las Barias
7	200415	2051763	-25	Boca de Cacho
8	197012	2047124	28	Lago Sumatra
9	226763	2036790	1	Baitoa

Figure 7. Result of Ground-Truth analysis, blue points represents visited location in the area. (Image created by 2011 CCNY Senior Design Team)

A attend has been made in order to automate the process of calculating area and lake demarcation by using Mathlab software or Signature creation in ARCmap. However, both approaches present the same problem. When computing the amount of water pixels that belong to the area of interest within the satellite image, the software mixed every color band that looks like water and computes it as one single feature. While this is exactly what GIS does in order to count pixels, it is a problem for our purpose because it takes into account other water bodies' pixels that does not belong only to the area of interest (e.g. lake Azuei, Laguna del medio, Laguna Rinco, etc.) The reason for this is because they all are within the same satellite image, and even if you create a window to isolate your area of interest, in the case of shallow water where colors are less dark, the program will not considered as part of the pixel count. Therefore, the best accurate way as for now to calculate lake surface area is by manually delineate the shape of the lake using ArcMap until a way of separate pixels-count automatically from the images is found.

Table 5 below shows the different areas calculated using the method described above:

Table 5. Result of areas change thru time using ArcMap.

Year	Total Area (Sq.Km)	Area increment (%)
Dec-03	159.88	
Dec-04	171.76	7.43
Dec-05	207.26	17.13
Dec-06	227.09	8.73
Dec-07	272.72	16.73
Dec-08	309.06	11.76
Dec-09	314.05	1.59
Dec-10	318.5	1.4
Dec-11	332.14	4.11
Dec-12	344.55	3.6
Mar-13	347.31	0.79

Figure 10 below show the difference in area expansion over the last decade.

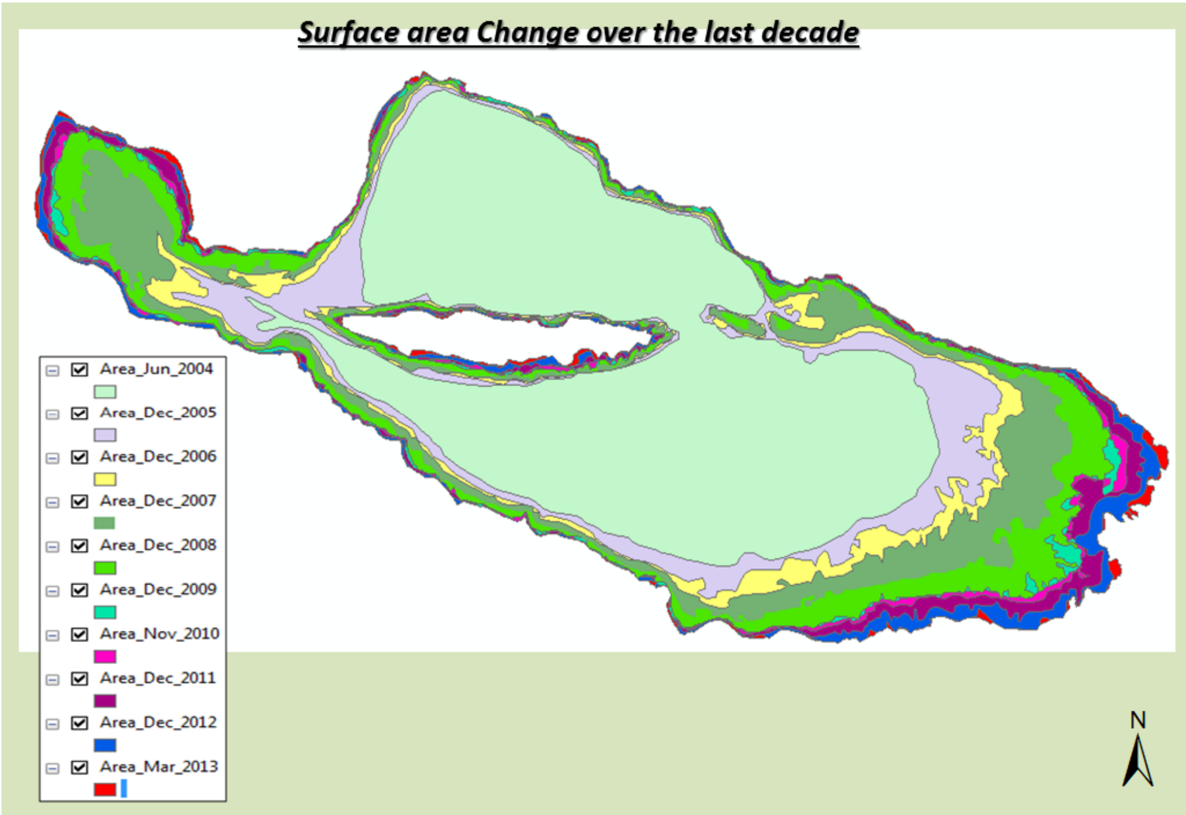


Figure 8. Surface area Change (2004-2013)

6.3 Precipitation

Precipitation over the lake area has increased over the last decade from 730mms/years to 866.39mms/year during the last decade. It is very important to investigate any correlation between lake growth and precipitation since it is believed that rainfall is the major input to lake. Several assumptions were made in order to quantify the amount of rainfall over the lake area:

- Direct rainfall over the lake is the same as the amount of rainfall measured at the Jimani station.
- Since only one year of rainfall have been collected from the first sensors deployed over the north Sierra of Neyba, The same amount of rainfall calculated at the Jimani station was used to estimate runoff in the watershed. Also, you will see later on this report that there is not a strong correlation between runoff and lake volume change hence another reason to neglect the data from the sensors at the sierra.

Most of the data used for the water balance analysis come from the Jimani station, this station besides been located inside the watershed; it is just 4.6 kilometers from the Southwest area of the lake. In addition, this station holds the largest record of historical data measurements of rainfall. Nevertheless, more data was retrieved from other stations in order to create an extensive set of data that would further help to analysis the water budget from different perspectives.

6.4 Volume Estimate (Field measurements)

Water storage refers to volume of water that is contained in the water body. Both lake Saumatre (Azuei) and lake Enriquillo are Endorheic lakes, meaning that they does not allow outflow of water to others water bodies therefore their main resources of water defeat are evaporation and seepage. In order to determine the current volume of water contained in the lake, we performed a bathymetric analysis to describe a profile of the lakes depth from the surface water to the lake floors. An 898c SI HUMMINBIRD depth sounder was acquired to determine the volume of the lakes. It is uses sonar technology to locate and define structure, bottom contour and composition, as well as depth directly below the transducer.

During three consecutive days, a team lead by Dr Michael Piasecki surveyed the lake floor using the newly acquired depth sounder transducer. In order to obtain accurate measurements, a constant speed of 7.5 m/s on the boat was set. The approach to cover most of the lake which had a surface area of 347.41 Sq.Km was to make U shapes up and down within the lake area which will allow us to obtain information about the center areas of the lake as well as some readings along the shore. Figure 11 below show the path taken by the team while covering the lake surface.

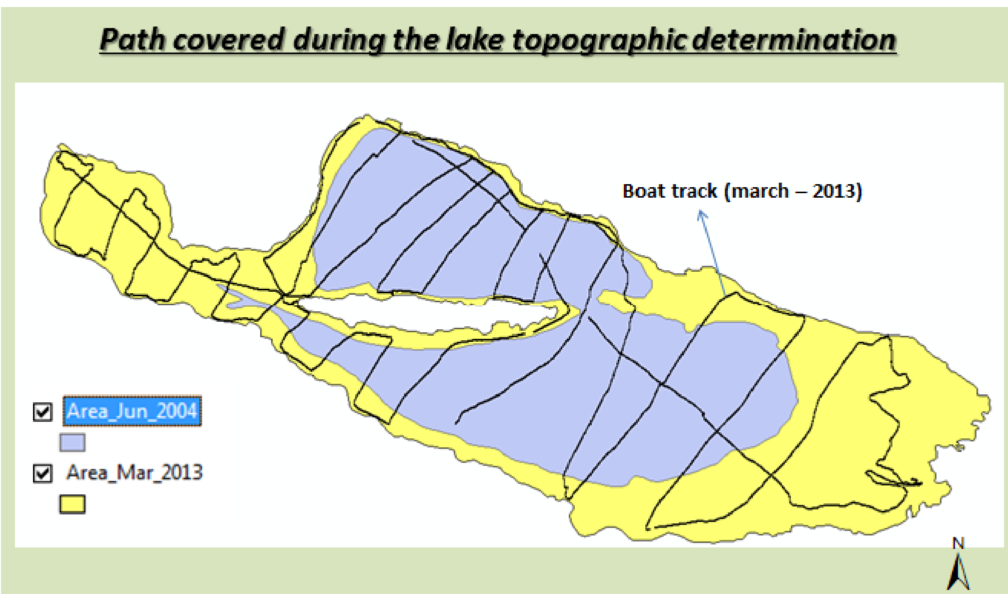


Figure 9. Boat track (2013 field campaign)

The method used to estimate volume changes during the last decade is described below:

- Field Data Points Analysis
  - Data recorded by the depth sounder was downloaded and saved as CSV file. This set of data containing XYZ information for each point, was cleaned and filtered against errors in measurement while migrating the surface area of the lake.

- Once the data was cleaned and organized, a geographical coordinate conversion was done so that the data points collected match the coordinate system of the satellite images
- Lastly, the csv file was converted into a shape point file. This last step facilitates the management and analysis of the data in ArcMap.

- Raster file Creation for bathymetric map
  - Once the data was loaded onto ArcMap, we proceeded to the creation of a raster file by mean of interpolating the data points collected.
  - Kriging function in ArcMap was used to interpolate the points of unknown areas. Kriging is a geostatistical estimator that infers the value of a random field at an unobserved location (e.g. elevation as a function of geographic coordinates) from samples.
  - After interpolating the data points, the result is a raster file that contains referenced elevation point from which a bathymetric map can be generated. Figure 12 below show the result of the kriging interpolation.

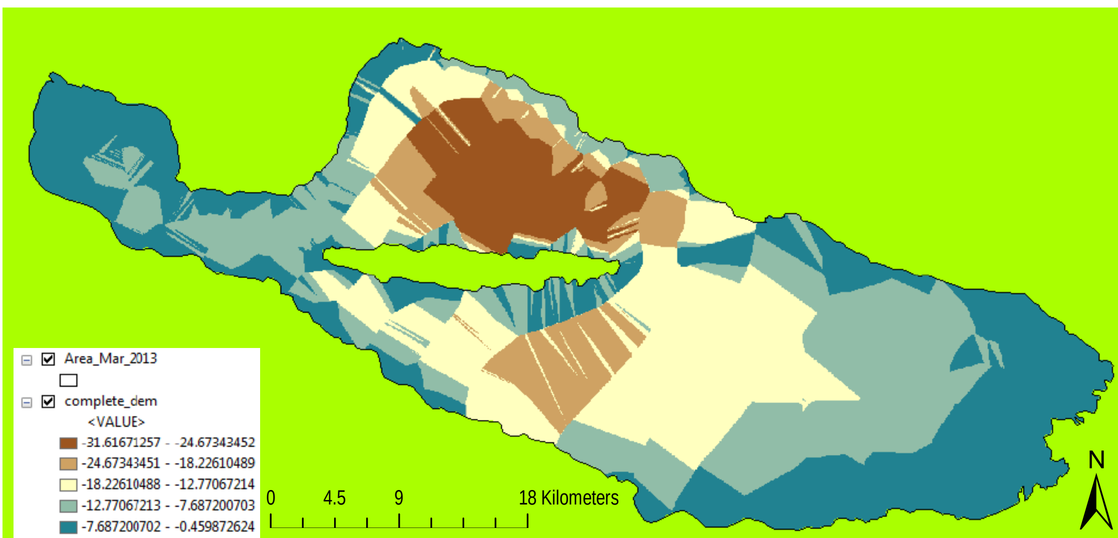


Figure 10. Raster File: result from interpolation data points

- Bathymetric Map
  - A bathymetric map generated from the DEM was obtained using Contour line function in ArcMap. However, this map needs to be improved. Its contour lines need to be smoother and make closed loops at the lake perimeter. There might be a better method of interpolating the data points that would make better bathymetric lines and improve both surface area elevation and volume estimates. At the moment of writing this preliminary report, the map was not validated yet. Therefore, we are considering this a preliminary result and not a final product and thus map should not be used to determine lake surface elevation until it is corrected and validated.
  - However, once a solution has been found to the problem of the bathymetric lines, then the approach in order to determining lake surface elevation should be the same.

- Surface elevation should be found by overlapping the delineated surface areas obtained from the satellite images over the bathymetric map. Intersection of Lake Perimeter lines and contour lines from the bathymetric should be all the same and must yield the elevation of the lake at that specific time. Figure 13 below represent the result of the bathymetric map.

Figure 11. Bathymetric Map (it is not validated yet and need to be corrected)

A three dimensional representation of the lake basin is shown in the figure below.

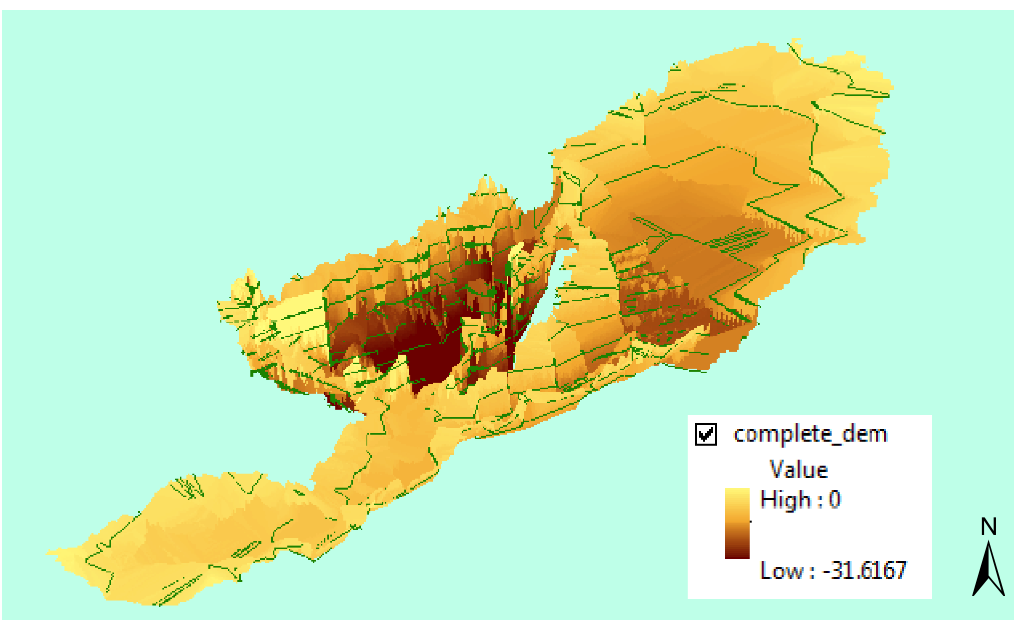


Figure 12. 3D view of the lake topographic

To be able to determine the volume of water accumulated in the lake, we made used of a DEM from NASA from 2008 provided by Mahrokh Moknatian, a Ph.D. student at The CCNY. The main idea formulated by the team was to stich the bathymetric map to the DEM and by doing so we can build a more complete DEM that would allow us to determine the lake surface elevation and volumes at difference years. In addition, we can used the DEM and Bathymetric map to predict future lake volumes if the current conditions affecting the lake do not change. Table 8 on the water balance result section, shows the different lake volumes over the last decade.

VII. Water Balance Analysis

Data from the Jimani station (located in the town of Jimani in the Dominican Republic) were used for the water balance calculations of Lake Enriquillo. The reason that data from this station being used is that the station is the nearest available station that is located inside the Lake Enriquillo watershed and have data for the last 10 years. Data from stations outside the Lake Enriquillo watershed is less likely contributed to the water budget of Lake Enriquillo. Between 2004 and 2009, data other than precipitation are missing from the Jimani station. For these years temperature data from the Barahona station locate southeast of the Lake Enriquillo watershed is used because temperature at Jimani and Barahona stations is similar. Figure 15 shows an average wind speed and pressure from the Jimani station between 1979 and 2000 is used and assume to be the same for the years from 2004 to 2009.

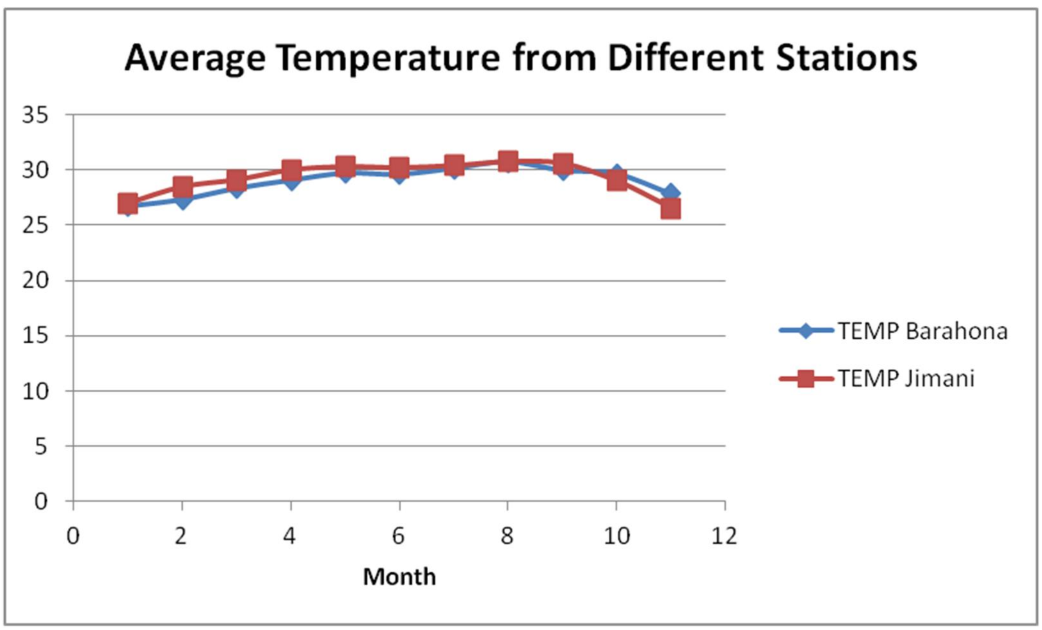


Figure 13. Comparison of Average Temperature from Different Stations 2010

7.1 Evaporation

Base on the available climate data, evaporation of the lake can be estimated using the equation suggested by Penman (1956). The Penman equation is derived from the Penman-Monteith equation by taking r_s=0 for open water.

$$ET_p = \frac{1}{\rho w \lambda}\left[\frac{\Delta(Rn-G)+\rho aCp\frac{es-ea}{ra}}{\Delta+\gamma}\right]$$

ET_p =potential evapotranspiration
$\rho_{w=}$ the density of water
λ=the latent heat of vaporization of water
Δ =the gradient of the saturated vapor pressure versus temperature curve
R_n = the net radiation
G= the soil heat flux
ρ_a =the density of moist air
c_p=the specific heat of moisture air (= 1.013 kJ/(kg°C))
e_s=the saturation vapor pressure
e_a =the ambient vapor pressure
r_a=the aerodynamic resistance to vapor and heat diffusion
γ =the psychometric constant
r_s=the bulk surface resistance (r_s=0 for estimation of potential evapotranspiration of open water, such as a lake)

7.2 Land Use and Runoff Land Classification

Runoff is the water flow that occurs when the soil is infiltrated to full capacity and excess water flows over the land down the watershed region. Runoff rate changes base on how land use changes since different runoff coefficients are being assigned to land type's base their soil moisture uptake rates and their effect on ground water infiltration. These are important data to be considered because the only know source of inflow of the lake are runoff and direct rainfall. With increasing farmland, roads, and cities, the land use change become important in determine whether this is causing an increase in runoff percentage into the lake.

Land use is determine using LANDSAT images because of its long running data imagery acquisition records and its high spatial resolution of 30 meters. After enough images that are devoid of a lot of cloud cover are acquired, the images are cut to just the region of the lake watershed since pixels outside of this region do not contribute to the flow into the lake. To do this, Digital Elevation Model or DEM is being used. Data such as maximum elevation points, river networks, drainage directions, flow accumulations, and watershed boundaries can be acquired from DEM using ArcScene. This data are used to trace and saved the watershed border of Lake Enriquillo as a polygon for use in cutting out the Landsat images using the Extraction function in ArcMap. (In ArcMap toolbox under Spatial Analyst tools, a function called Extraction allows user to input a rater file and to cut it by polygon.)

After the images have been cut to the watershed region, the images can be processed for land use classification. The image classification process involves conversion of multiband raster imagery into single-band raster with a number of categorical classes that relate to different types of land cover. In the supervised classification method, and image is classified using spectral signature (i.e. reflectance values) obtained from training samples (polygons that represent distinct sample area of the different land cover types to be classified). The training samples are collected by ground *truthing (Table 6). After distinct training samples are selected and a signature file is created and saved, the images can be classified using* *the Maximum Likelihood method. This method assigns each pixel to one of the different classes based on the means and variances of the class signatures (store in the signature file that is saved earlier). The same signature file would be used to classify all of the images so they can be used to compare land use changes over the years. The runoff values of the classes are weighted based on their percentage coverage in Lake Enriquillo basin and the total runoff can be then calculated using precipitation data from the Jimani station.*

R=C*I*A

R=runoff
C=weighted yearly runoff coefficient
I=intensity of rainfall
A=area of watershed

Table 6. Vegetation Classification Ground Truthing Points

Vegetation Type	North Coordinate	West Coordinate
Shrubs	$18^0$24’31.5” 221811	$71^0$37’59.6” 2037429
Shrubs	$18^0$23’16.3” 230684	$71^0$32’56.3’ 2034989
Urban	$18^0$22’42.2’ /E 233324	$71^0$31’25.9” /2033903
Urban	$18^0$22’38.3” E 233707	$71^0$31’12.8” N 2033777
Bare soil	$18^0$27’30.8” 202830	$71^0$48’48.9” 2043231
Bare soil	$18^0$26’31.2” 205714	$71^0$47’09.7” 2041353
Farmland	$18^0$26’01.64” 203856	$71^0$48’12.51” 2040472
Pasture	$18^0$25’31.97” E 207733	$71^0$45’60.0” 2039499
Brush	$18^0$26’16.0” 204259	$71^0$47’59.01” 2040907
Soil/rock	$18^0$26’41.25” 203688	$71^0$48’18.87” 2041693
Forest	18°35’08.73’’ N 210127	71°44’47.65’’W 2057209
Forest	18°33’56.52’’ N 205747	71°47’15.79’’W 2055055

VIII. Water Balance Results

8.1 Land Use and Runoff Land Classification

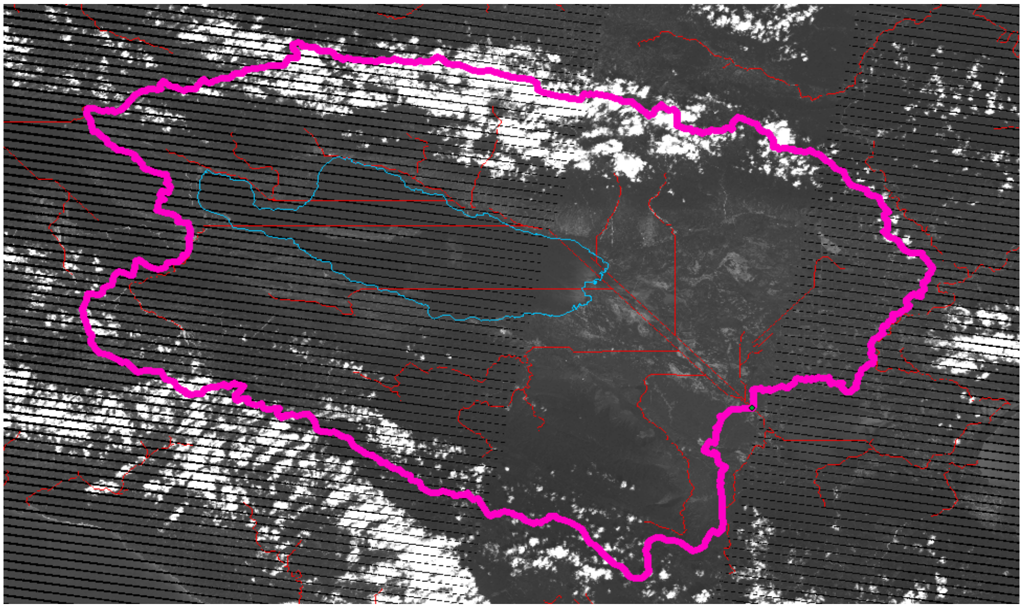


Figure14. Watershed Delineation and flow accumulations

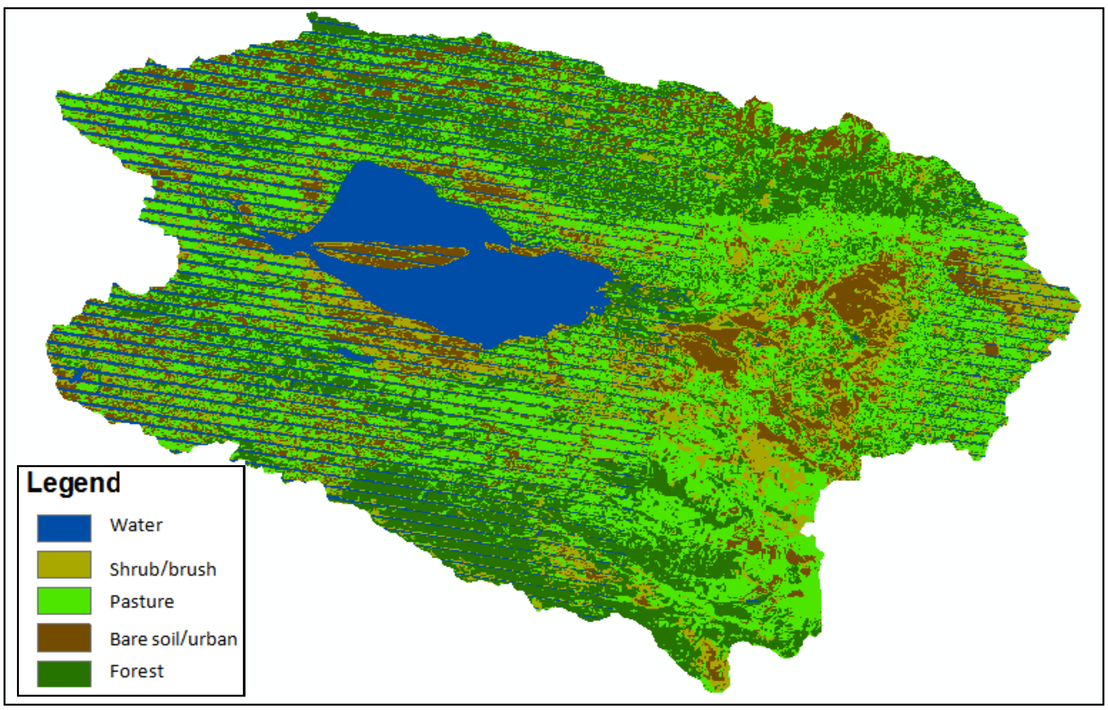


Figure 15. Land Classification 2005

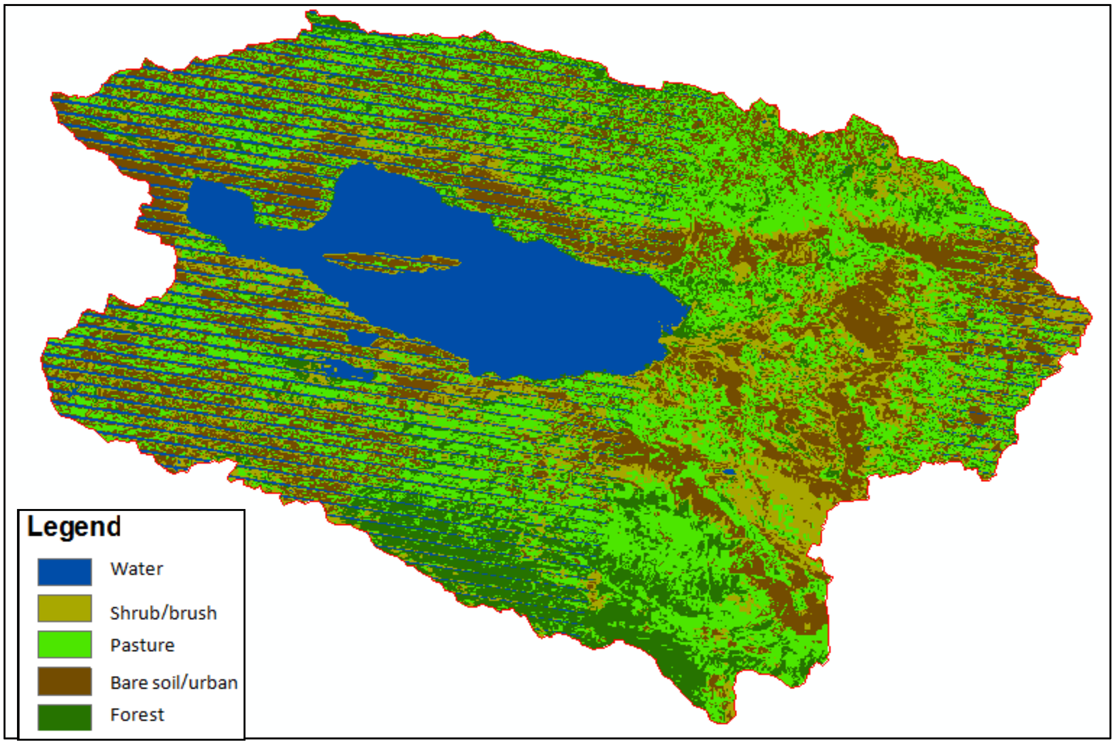


Figure16. Land Classification 2013

Table7. Weighted Runoff for observation year 2005 and 2013

2005	-	-	-	-	-
Land Type	**Pixels Count**	**Area km2**	**% Area**	**Runoff Values**	**Runoff/Area**
water	550105	495.0945	16.35802	0	0
shrubs/brush	363751	327.3759	10.81657	0.31	0.033531359
Sparse veg/pasture	1104948	994.4532	32.85694	0.25	0.08214235
bare soil/urban	497762	447.9858	14.80154	0.85	0.125813121
dense veg/forest	846340	761.706	25.16692	0.18	0.045300463
TOTAL	**3362906**	**3026.615**	**100**	**Weighted Runoff**	**0.286787293**
2013					
Land Type	**Pixels Count**	**Area km2**	**% Area**	**Runoff Values**	**Runoff/Area**
water	649341	584.4069	19.30893	0	0
shrubs/brush	475214	427.6926	14.13105	0.31	0.043806262
sparse veg/pasture	977178	879.4602	29.05755	0.25	0.072643868
bare soil/urban	834473	751.0257	24.81404	0.85	0.21091938
dense veg/forest	426700	384.03	12.68843	0.18	0.022839175
TOTAL	**3362906**	**3026.615**	**100**	**Weighted Runoff**	**0.350208686**

Table 7 shows the result of pixel count for each class, their area and their runoff values that are weighted based on their percentage coverage in Lake Enriquillo watershed. The runoff values were taken from the City College of New York (CCNY) research report that was created by the previous Environmental Engineering Senior Design Team (2010 – 2011) who take these values from the USGS website.

On the maps produced it can be seen that not only Lake Enriquillo has increased in size but also the other water bodies in the south of the watershed. (Figure 17 and Figure 18) There is more bare soil/urban area and less forest in 2013 compare to 2004. As a result, the weighted runoff value increased (Table 7). It means that with the same amount of rainfall more precipitation would flow into the lake via runoff. The produced maps have similar results as the land use maps in the Cornell University research report in which they validate the result with ground truthing points and has an overall accuracy of 77%. (Figure 19)

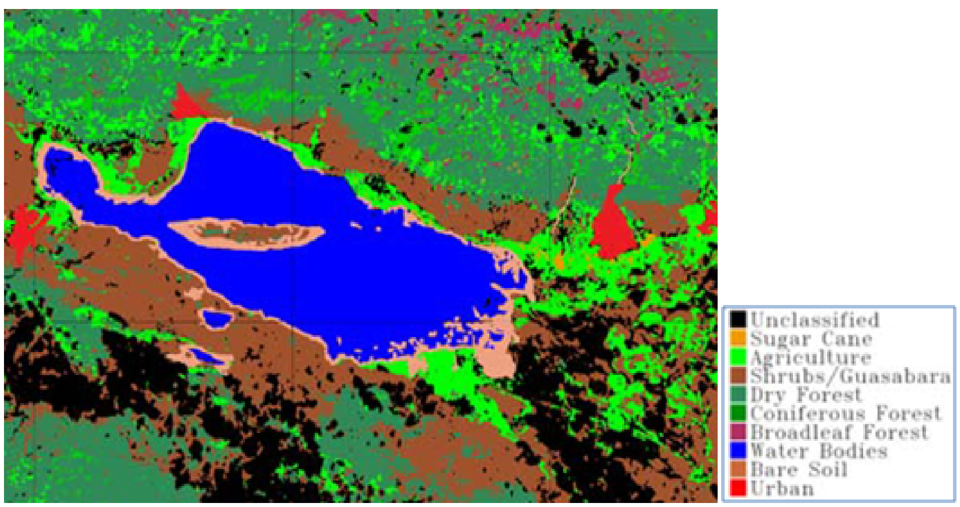


Figure 17. Land Classification results produced by Cornell Graduate students report. 2010

8.2 Analysis of Results

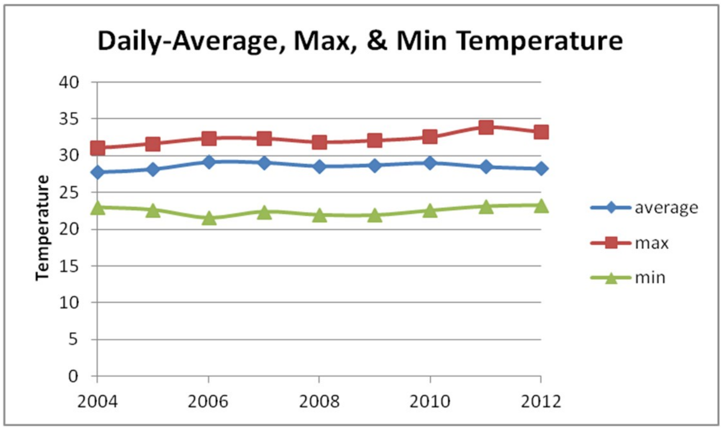


Figure 18. Daily Average, Maximum, and Minimum Temperature

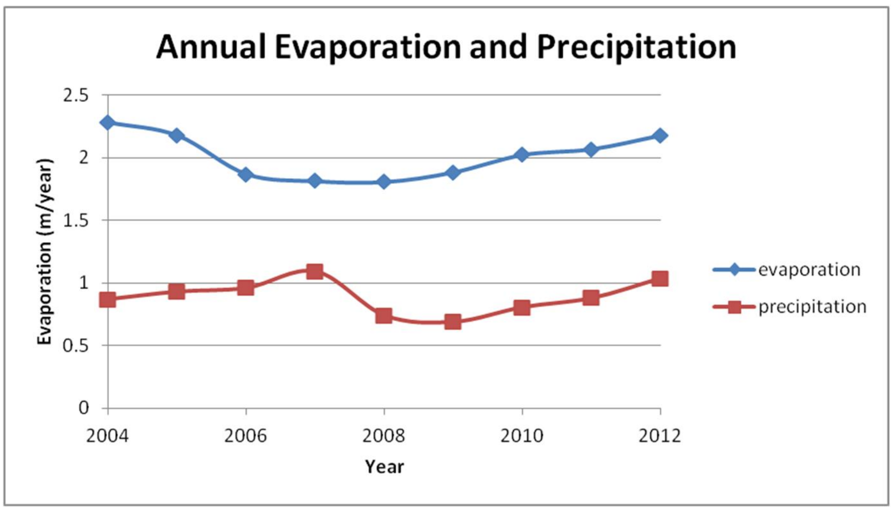


Figure 19. Annual Evaporation and Precipitation 2004-2012

Evaporation is calculated using data from Jimani and Barahona's station. When relative humidity data is not available, evaporation can be calculated using dew point temperature. Due to the lack of environmental data, the net solar radiation from April 2013 is calculated and assumes to be the same for all other years. In order to validate the results, the calculated evaporation is compared with the know evaporation from previous years. The calculated evaporations fell within the known evaporation limits with a high of 2.2 meters and a low of 1.2 meters per year. (Figure 21)

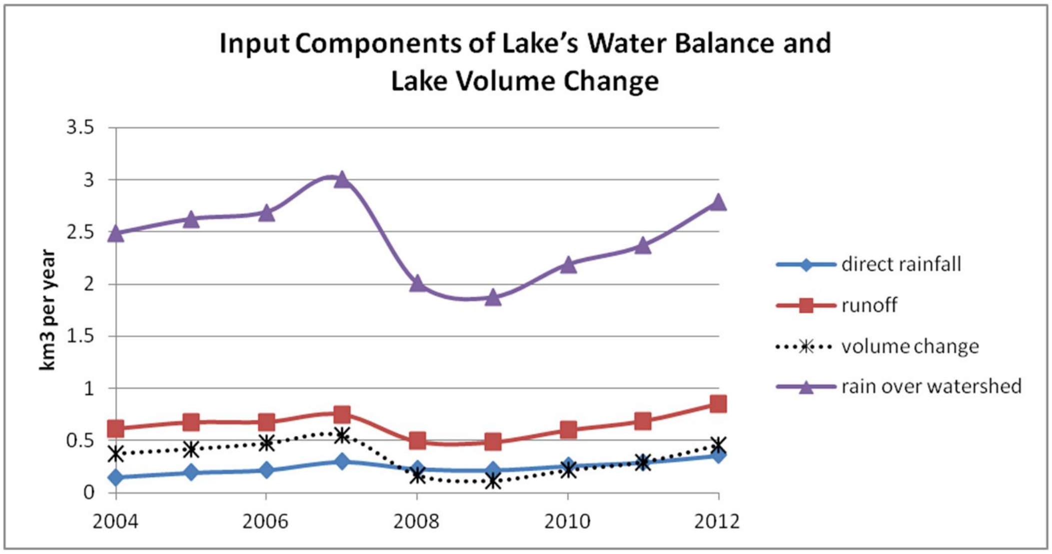


Figure 20. Input components of lake's water balance and lake volume change

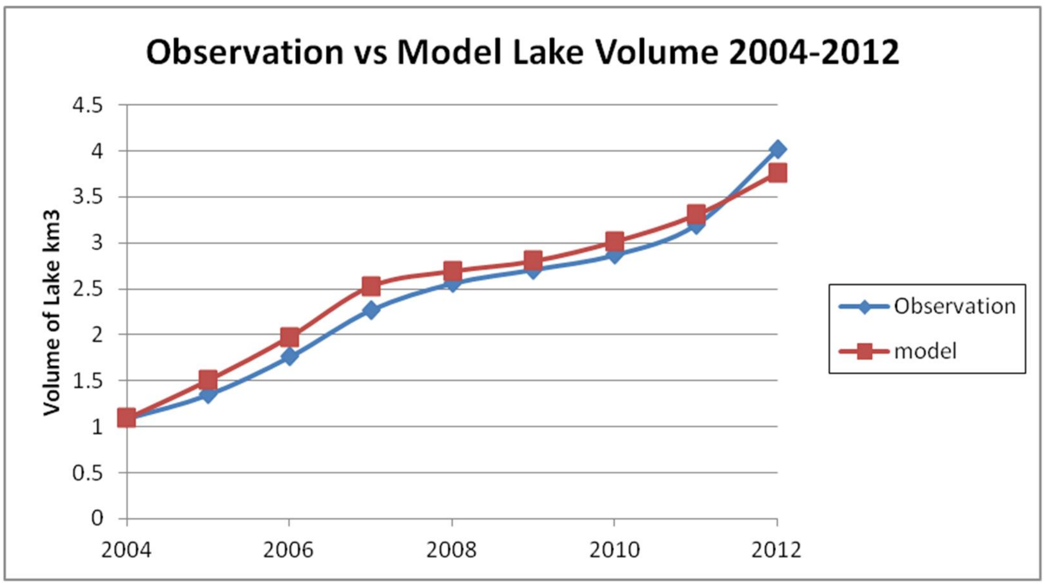


Figure 21. Observation Lake Volume and Model Predicted Lake Volume

Table 8. Observation Lake Volume vs. Model Predicted Lake Volume

	observation Lake Volume km3	Model Lake Volume km3	% error
2004	1.09	1.09	
2005	1.35	1.506703059	11.60763
2006	1.76	1.977863864	12.37863
2007	2.27	2.528598248	11.39199
2008	2.56	2.691915754	5.152959
2009	2.71	2.802489852	3.41291
2010	2.87	3.014305208	5.028056
2011	3.2	3.305353007	3.292281
2012	4.02	3.760763775	6.448662

On a yearly change the model has good prediction for lake volume. (Figure 23) The percentage error is less than 13%. (Table 8) The lake volume increase more than 200% between 2004 and 2012.

Since precipitation and evaporation are the only know input and output of the water budget of the Lake Enriquillo basin, the model is highly sensitive to precipitation and evaporation of the watershed. As show in Figure 24 and 25, both evaporation and rainfall are well correlated with the lake volume. The lake volume change is closely correlated to precipitation pattern. (Figure 24) Even though the weighted runoff values have risen, the correlation between lake volume and runoff is low. (Figure 26)

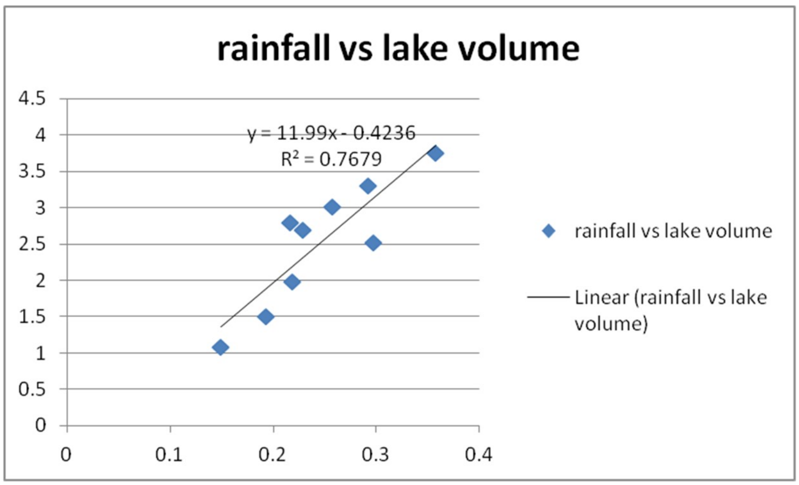


Figure 22. Correlation between Rainfall and Lake Volume

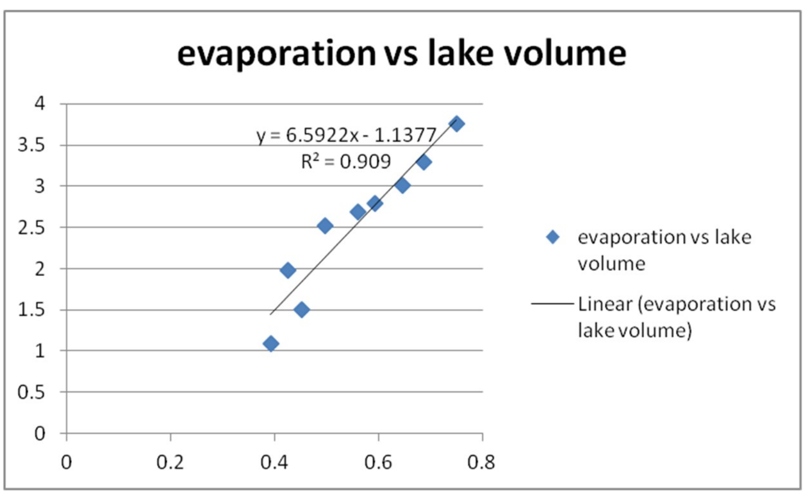


Figure 23. Correlation between Evaporation and Lake Volume

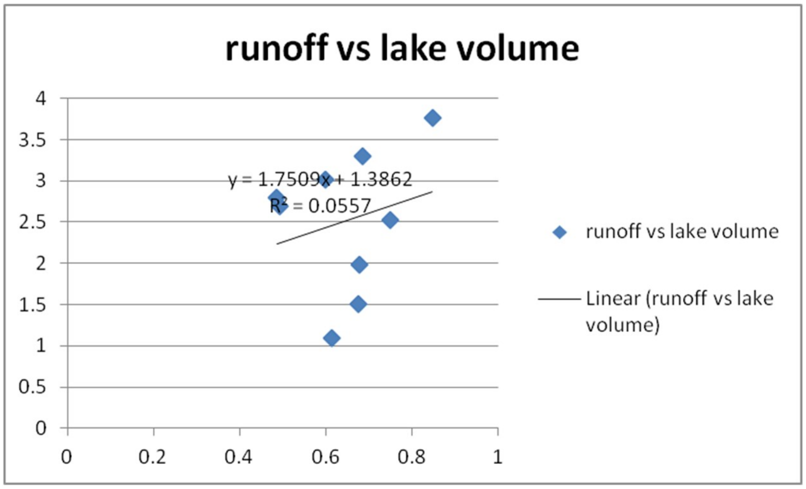


Figure24 Correlation between Runoff and Lake Volume

IX. Conclusion and Recommendation

The results obtain in this study demonstrate that the fluctuations in precipitation is account for the major change in the lake volume between 2004 and 2012. The lake is also sensitive to evaporation change in the watershed, since evaporation is the only know output of the water budget of the Lake Enriquillo. Although, the land cover change over the years 2005 and 2013, the lake volume is not highly correlated to runoff from the watershed. Land use change is not a significant factor in the lake's behavior.

If precipitation pattern remain the same as well as other climate parameters, then the lake will continue increase in size. (Figure 27 and 28) Plans such as evacuate the people that live around the area or draining the lake by means of canals should be prepared.

The limitation on the data availability and assumptions that are made on wind speed and radiation can be a significant source of error in water balance calculations. There is also uncertainty relating the land cover map and runoff since there is only one ground truthing point for some of the land type. Future research can be done with more ground truthing points and higher resolution image for the land cover map to minimize the uncertainty. The source of error in water balance calculations can be reduce with more data from the stations that we implement inside the Lake Enriquillo watershed.

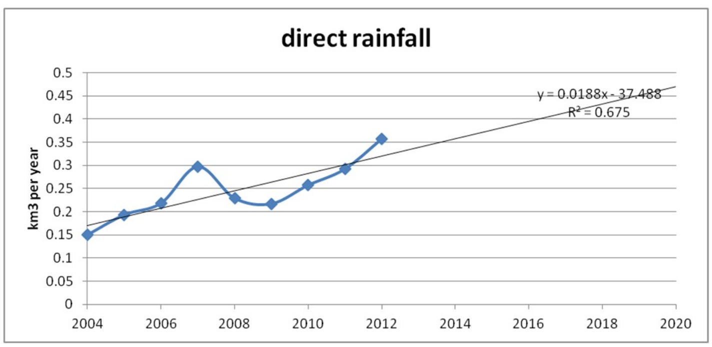


Figure 25. Linear Forecast of Direct Rainfall over the Lake

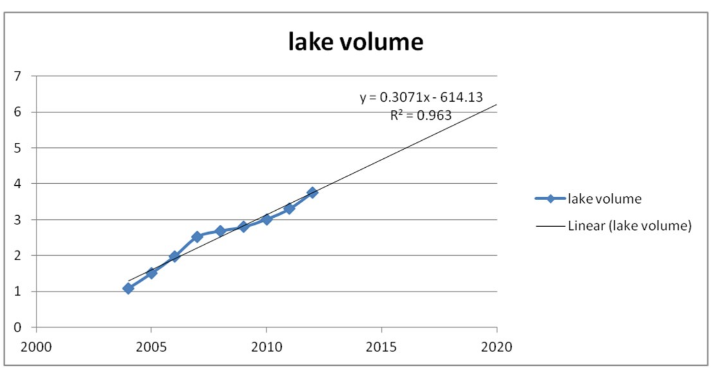


Figure 26. Linear Forecast of Lake Volume

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