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Climate Variability and Its Effects on the Increased Level of Lake Enriquillo in the Dominican Republic, 2000-2013

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Abstract During this century, the island of Hispaniola has been affected by climate changes that have directly impacted two major bodies of water on the island: Lake Enriquillo in the Dominican Republic and Lake Étang Saumâtre (Azuei) in Haiti. Lake Enriquillo is a hypersaline and endorheic basin (the water outlet only occurs by evaporation) so the lake level normally fluctuates between 40–50 m below sea level. During the period 2000–2013, Lake Enriquillo began to rise 17.2m.This expansion could be attributed to the effects identified by the regulating influences or Caribbean Regulators Climate Centers (CRCCs) such as the North Atlantic Oscillation, El Niño, trade winds, the Atlantic Warm Pool, as well as the Azores anticyclone. Lake Enriquillo has undergone an unprecedented increase in water level over the last decade, resulting in the inundation of thousands of acres of farms and more than a dozen villages, causing social, environmental and economic impacts. The Surface Cover Water (SCW) of Lake Enriquillo reached minimum values in 2004 (170 km^2), and then shifted to a rapid expansion to its current levels (> 350 km^2 as of late 2013). Lake Azuei has grown at a similar rate [1]. The present research provides a climatological analysis (temperature, precipitation, evaporation, and potential evapotranspiration, among others), with the aim of seeking a possible explanation for the rising level of Lake Enriquillo.

Keywords: *Lake Enriquillo, extreme phenomena Endorheic Lake, Caribbean regulators climate centers, climate change*

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1. Introduction

This article investigates climate variability (temperature, precipitation, evaporation, potential evapotranspiration, *etc.*) as a possible determining factor in explaining the recent rise in the water levels of Lake Enriquillo. Lake levels and surface cover expansion are analyzed, from the year 2000 to the present, with reference to climatic information recorded since 1967. A limited number of articles provide scientific information on the climatology of the Lake Enriquillo region. This lake, located in the southwestern region of the Dominican Republic, is the largest in the Caribbean. It had a surface area of 265 km^2, but in the last decade its size has increased dramatically to approximately 350 km^2 [1].

Lake Enriquillo encloses three islands that are also below sea level (BLS). Isla Cabritos is the most important of these, with an area of 27.6 km^2 in an elongated shape. The other two islands are Barbarita (also known locally as "Chiquita") and Islita. During long droughts, when the lake level drops, these islands, especially the last two, become peninsulas, and can be reached by walking. Isla Cabritos has the only hyperxerophytic dry forest that exists BSL in the Caribbean, or in any area in Africa or the Americas (Figure 1).

The salinity gradient of the lake increases eastward, which suggests that rainfall conditions in the past were very similar to today's and confirms that the connection to the sea occurred later, on the eastern side of Lake Enriquillo [2,3,4]. This historical review leaves a gap of information in the 15th to 18th centuries, and observations restart in the1900s, when lake levels reached 30 m BLS [3].

This suggests that, during the interval of the information gap, an accelerated process of division of the water body occurred near Jimaní and that subsequent evaporation reduced the lake to approximately 40 m BLS. The decrease in precipitation in the Lake Enriquillo Basin favored accelerated evaporation in a watershed whose water balance is in deficit throughout the year [4].

Currently, freshwater springs discharge water from the surrounding rocks into the lake at various locations around its periphery.

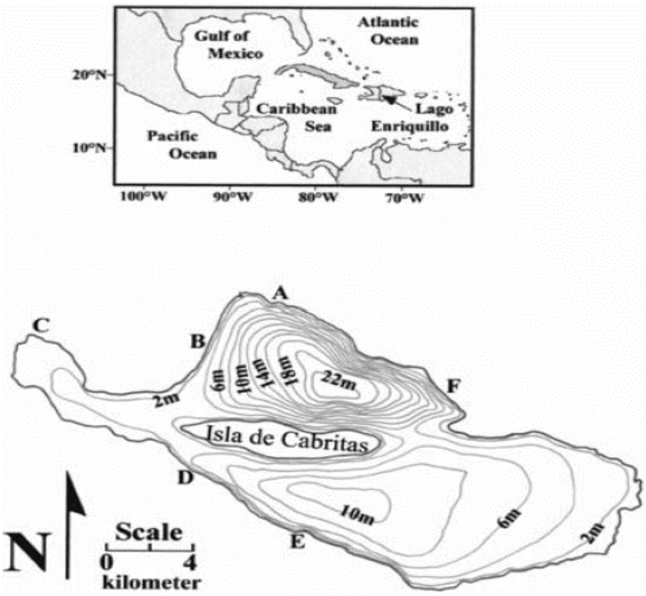

Figure 1. Map showing the location of Lake Enriquillo on the Caribbean island of Hispaniola. Bathymetric map of Lake Enriquillo showing 2-m depth contours (modified from ARAGUÁS-ARAGUÁS *et al.*, 1993). Letters along the shoreline indicate the approximate location of springs mentioned in the text: (A) La Azufrada, (B) Borbollones, (C) Boca de Cachon, (D) Caoba, (E) La Zurza, (F) El Guayabal. Source Buck et al 2005 [5]

The salinity of Lake Enriquillo varies according to the annual and seasonal cycles of aridity and humidity represented by rainstorms. In recent years, more than 100‰ salinity levels were recorded during periods of decreased surface water level, with lower salinities of 35‰ during periods of high surface level in the lake [5]. Caribbean climate depends on several factors, such as the so-called Caribbean Regulators Climate Centers (CRCCs) the North Atlantic Oscillation (NAO), El Niño Southern Oscillation (ENSO), trade winds, and Warm Water Pool North Atlantic, Multidecadal Oscillation, as well as the behavior of the Azores anticyclone. The presence of ENSO, specifically in the 3.4 phase, is associated with drought in the Central Caribbean (Cuba, Hispaniola, Puerto Rico, and Jamaica) and an increase in the intensity of hurricanes in the region [6]. The positive phase of the NAO generates a drier atmosphere in North Africa, thereby creating better atmospheric conditions for the formation of cyclonic systems, which reach the Caribbean region more frequently [7] due to the trade winds.

A negative NAO phase, by contrast, provides higher moisture conditions in North Africa and this sometimes decreases the occurrence of cyclonic systems. The combination of a positive NAO phase and ENSO generates greater hurricane activity in the Caribbean [7] The Azores High (a high-pressure region over the Azores) plays a large role in directing storms that blow off the Sahara, which eventually become hurricanes when the conditions are correct, with impacts on the Caribbean and North America. When the Azores High extends further south than normal, it directs hurricanes into the Gulf of Mexico. When the Azores High extends further north, it causes hurricanes to travel up the east coast of the United States. The impact is significant: in periods where the Azores High is positioned further south, catastrophic hurricanes make landfall [7,8,9,10].

Evidence from Dominican coral proxies, these decadal scale oscillations are interpreted to reflect regional precipitation patterns as influenced by the mid-Holocene migration of the ITCZ or precipitation and freshwater flooding patterns as driven by mid-Holocene hurricanes and tropical storms. Both hypotheses rely on a decadal to multidecadal mode of tropical Atlantic SST variability similar to that at present where SST anomalies have profound affects on global and regional atmospheric circulation that in turn affect Atlantic hurricane activity, West African (Sahel) drought and Pacific ENSO activity. Increased northern insolation during the mid-Holocene may have extended the influence of tropical SST anomalies to Hispaniola via a more northerly migration of the ITCZ on decadal to multidecadal timescales (12-20 years). [11].

The salinity of Lake Enriquillo has changed greatly since 1977, from 76.8‰ to 103.1‰ in 2002. However, since 2003, the salinity has decreased and did not exceed 31‰ until 2013. In this paper, the potential role of global climate change in the Caribbean on the water levels of Lake Enriquillo and inputs on lake salinity is addressed.

It is very interesting to analyze the region's hydrology, the flow of water to Lake Enriquillo is made through the Canal Cristobal to the Laguna Rincon (with a surface of 30 km2), furthermore the Yaque del Sur river that discharged its water in the Caribbean Sea now discharges them in the Laguna Rincon, and all this runoff water is later discharged in the Lago Enriquillo.

According to [12], the hydrology of modern Enriquillo Valley is complicated by a hypsography sink and tectonics in the Caribbean region. Because isotope ratios and salinity can vary independently, they used a multi-proxy approach by morphometry pores ostracod shell with stable isotope geochemistry allowing differentiation between salinity and temperature driven by isotopic variability. [13,14,15]. in your approach can facilitate paleohydrological reconstructions such that distinction between hyposalinity (0<34‰) and hypersalinity (>34‰) in ancient deposits.

Yaque del Sur River, presents an important erosion process which drags vast deposits of material that incite the river to lose its channel hauls immense amounts of sediment which contributes to the increase in the level of the Laguna de Cabral, and therefore the Lake Enriquillo. Another important factor to consider is the land-use/land-cover change (LUCC) [16,17,18]. which has greatly contributed to the increasing rate of runoff in the area and therefore the carry over effects of sediment.

In addition to study the impact for this region in this analysis the climatic zones of the Dominican Republic [19], who used method Thornthwait, due to the importance of evaporation in the area, which is greater than the average annual rainfall was considered, other researchers as [20] in China using FAO Penman-Monteith, in this its database is more complete.

To identify pixels in the Lake Enriquillo River Basin that contribute to runoff by land use changes [21], needed to use Landsat imagery because it had a high resolution of 30 m. The east of the lake is where the most density of farmland is found, and you can see the increase from 1984 to 2010 in these images, more so along the edges of the lake itself. Just west of the major part of the farmland is mixed marsh and shrub growth that seems to be affected by rainy season erosion. Compared with 1998 it can be observed that more rain produces more patches of bare soil that might further effect continuing downpour in later months.

In studying the lake's variability it is very important to understand the economic and social impact in the area, the leading cause of the first human displacement by climate change in the Caribbean. [22,23], have reported that more than 18,865 hectares of agricultural land and livestock around the lake were flooded, affecting 16 communities and 10 000 families and the destruction of roads hurting the business of the region. Lago Enriquillo has shown a similar behavior to Lake Lahontan Basin, Nevada (USA), which [24], have taken as an indicator of climatic and environmental change.

The population is directly affected by the flooding of Lake Enriquillo and Laguna de Cabral and it is estimated at a 27.046 citizens, equivalent to 22% of the total population of the municipalities surrounding the Lake and indirectly 80% of the total population. The most impacted municipalities have been Jimaní (5,855 people), Duvergé (11,395 people) and Cristóbal (3,865 people), and to a lesser extent Neyba (375 people), Postrer River (1015 people), Villa Jaragua (1750 people), La Descubierta (526 people) and Mella (750 people) [25].

Recently National Geographic [26]. says. "For the estimated 400,000 people living in the watershed of the two lakes, the fallout has been severe. Lake Enriquillo rose an incredible 37 feet in less than 10 years, doubling in size and swallowing at least 40,000 acres of farmland.

The purpose of this paper is to find an explanation for the increase in the level of Lake Enriquillo during the period 2000- 2013, using the existing surface climate data in the Basin of Lake Enriquillo. Most research conducted models [1,26] on these works have focused mainly on three areas, in year's geological, ecological, hydrology and social aspects.

2. Study Area

The Lake Enriquillo region contains exceptionally well-preserved relict marine and saline lake deposits of the mid-Holocene [11]. According to Winsor *et al.* [12,13], during the early Holocene, the rising waters of the Caribbean Sea flooded the Enriquillo Valley. A fringing coral reef developed and flourished along the margins of the Enriquillo Lake Seaway for several millennia, until the seaway became restricted due to a combination of slowing sea-level rise, tectonic uplift, and increased sedimentation. The Holocene coral reefs in the Enriquillo Valley provide a unique record of reef development in an environment that seems to have been exposed to high sediment input. The corals exhibit excellent preservation and offer an exceptional opportunity to examine the details of the community assemblage and sedimentary patterns of Holocene coral reefs [15,27,28,29]. The Lake Enriquillo Basin (18°31.7N, 71°42.91W) was isolated from the Caribbean Sea between 5000 and 2800 BP by tectonic uplift and fluvial damming by the Yaque Del Sur River [12,30,31]. Today, the Lake Enriquillo Basin is a closed-basin lake and home to a unique flora and fauna. Its sediments also serve as an excellent source of paleo-environmental information [32].

In the present study, precipitation, temperature, evaporation, and evapotranspiration potential were measured in four towns surrounding the Lake Enriquillo Basin (Jimaní, Duvergé, Neyba, and La Descubierta) (Table 1) and in stations located inside the lake, with the aim of providing climatic information to explain the increase of 17.2 m in the levels of Lake Enriquillo during the period 2000–2013.

Table 1. Data from 1967 to 2013, provided by the Instituto Nacional de Recursos Hidráulicos (National Hydraulic Resources Institute of the Dominican Republic (INDRHI) and ONAMET Oficina Nacional de Meteorología (National Meteorological Office) of the Dominican Republic. (ONAMET)

Station	Latitude (N)	Longitude (W)	Altitude (m)	Precipitation (mm)	Evapot. (mm)	Temp. Max. (°C)	Temp.Min (°C)
Descubierta	18.34	71.44	9.00	548.80	1724.12	33.50	22.80
Duverge	18.22	71.31	2.00	508.00	1894.3	34.30	22.61
Jimani	18.29	71.51	10.23	713.60	1854.91	33.90	22.60
Neyba	18.28	71.25	30.90	520.20	1846.61	33.00	22.11

3. Methodology

Flows and discharges in Lake Enriquillo were documented for the period 2009–2010. A survey was conducted in the study area to identify the different points of surface water discharge into the lake. About 38 wetlands/streams and different wells around the lake were identified, but only 11 were characterized as high surface flows with significant contributions to the lake. This method yielded wading surface flows for the wetlands that discharge into the lake. Flow measurements were determined using a current meter for direct capacities. Eight trips to the identified streams were made for data collection. Information about the flows obtained previously was compared to the data obtained in these new measurements. Three measurements were taken at a frequency of 2 months, or according to the changes in the weather conditions in the area. This information is useful for making some inferences about the contributions of the flows of these wetlands and their possible influences on rising lake levels. Data on precipitation, temperatures, evaporation, and potential evapotranspiration (E_{PT}) were collected at Jimaní, Duvergé, Neyba, and La Descubierta to analyze the behavior of these weather variables.

4. Results

4.1. Precipitation

Previous papers [7,8,9] suggested that the dominant control of the geographic distribution of tropical and sub-tropical moisture in the Atlantic is the relative position of the Intertropical Convergence Zone (ITCZ), which is controlled by insolation and sea surface temperature (SST). At present, the ITCZ is located farthest north in August and September and farthest south in March and April. However, the ITCZ rarely extends as far north as the Greater Antilles. Numerous studies indicate that the ITCZ may have extended significantly farther north during the mid-Holocene [33,34], but the actual northerly extent has not been fully determined. Some models suggest an increase in precipitation as far north as the Dominican Republic during the mid-Holocene summer, as the ITCZ moved north.

Endorheic lakes [35] are found at Lake Valencia, Venezuela, which show a similar evolution to that of LE, with high lake levels during the early to middle Holocene. This is thought to have arisen due to an increased intensity of the annual cycle caused by large differences in seasonal insolation driven by orbital mechanics. Two periods of lowered lake level, during which time the lake basin was closed, are recorded during the early to middle Holocene.

Since the middle of the last century, precipitation in the lake region has shown a bimodal behavior, peaking in May and October, with two dry periods that are quite extensive (December–March) and a lower rain intensity in the months of June and July, usually interrupted by the arrival of the hurricane season [36,38] (Figure 2). In addition, global climate change is expected to affect the large-scale circulations of the atmosphere and oceans (the strength and phasing of the ITCZ) and the characteristics of hurricanes.

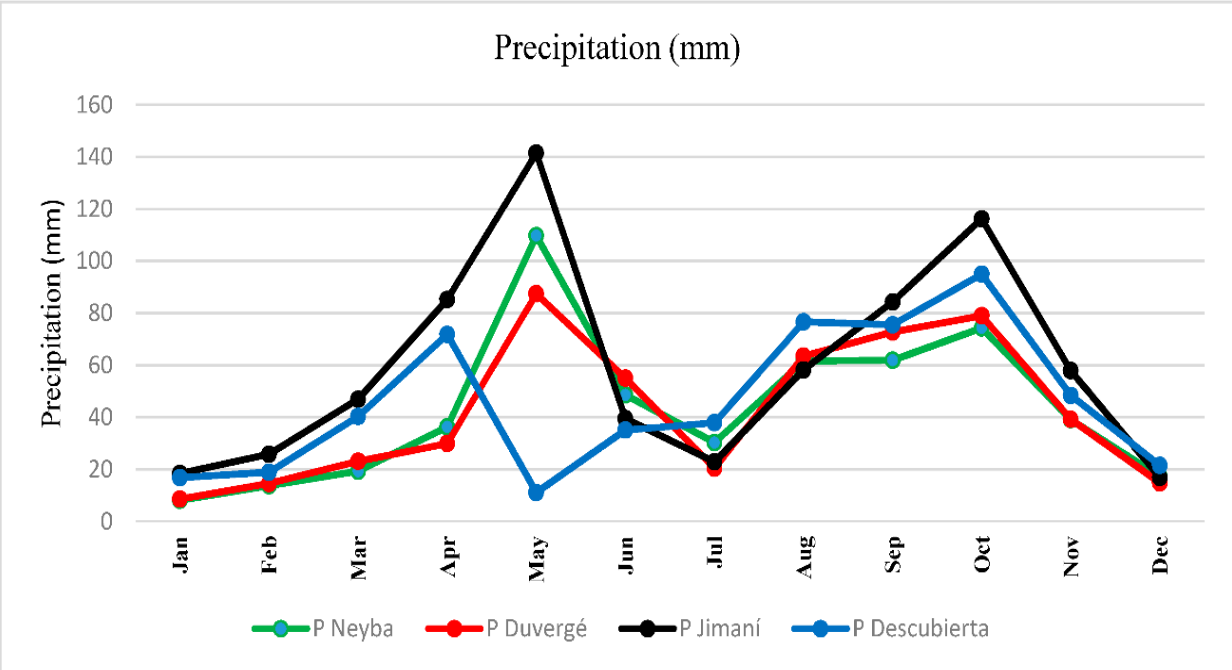

Figure 2. The behavior of the average precipitation in the period 1948–2013. Source: Data provided by National Meteorological Office (Spanish acronym ONAMET)

The annual rainfall near the Lake Enriquillo Basin (LEB) ranges from 508 mm on the SE shore to 729 mm on the NW shore [4]. In the area of the Lake Enriquillo Basin, the rainfall data were recorded from 1967–2013; the year with the highest rainfall was 1964 (Hurricane Cleo), when 1382.1 mm of rain fell and increased the level of LE to 30 m (BSL) [5]. After this event, another peak occurred in 1979 with the arrival of Hurricanes David and Frederick, which left 1221.0 mm of rain. In the 1980s and until the mid-1990s, rainfall decreased but remained above 600 mm/year. However, the last climactic event of the twentieth century, Hurricane Georges (1998), produced a rainfall of 865.4 mm in 24 h.

This century, several cyclonic events generated heavy rainfall in the Lake Enriquillo Basin in 2005, for instance, which was the most active year cyclonically in the Atlantic Ocean. In 2007, tropical storms Noel and Olga left a peak precipitation of 1084.2 mm, causing an increase in the lake level in the following years. The lake did not receive much rainfall in 2008 and 2009, but received 807.1 mm, 879.0 mm, and 1037.3 mm in 2010, 2011, and 2012, respectively, causing a Lake Enriquillo Basin increase that peaked at 25.3 m BSL during 2013 (Figure 5).

4.2. Temperature

The maximum temperature measured at the Jimaní Weather Station during the summer was between 30–35 °C. During the winter, the lowest temperature ranged around 21–24 °C. These temperatures promote little precipitation in the region and cause a high evaporation in the area that can reach more than 2500 mm/year (Figure 3).

4.3. Evaporation

A previous report [39] and data provided by the NASA Atmospheric Science Data Center indicate that the average monthly insolation values at the ground surface of Lake Enriquillo are 5.3 kW/m^2 Because of the high temperatures in the Lake region, evaporation was measured as a critical parameter for the period from 1967–2013. Evaporation ranged from 341.2 mm in 1998 to 2600 mm^3 in 2008 and showed its highest fluctuation in 1969 and 2008 (Figure 3, Figure 4).

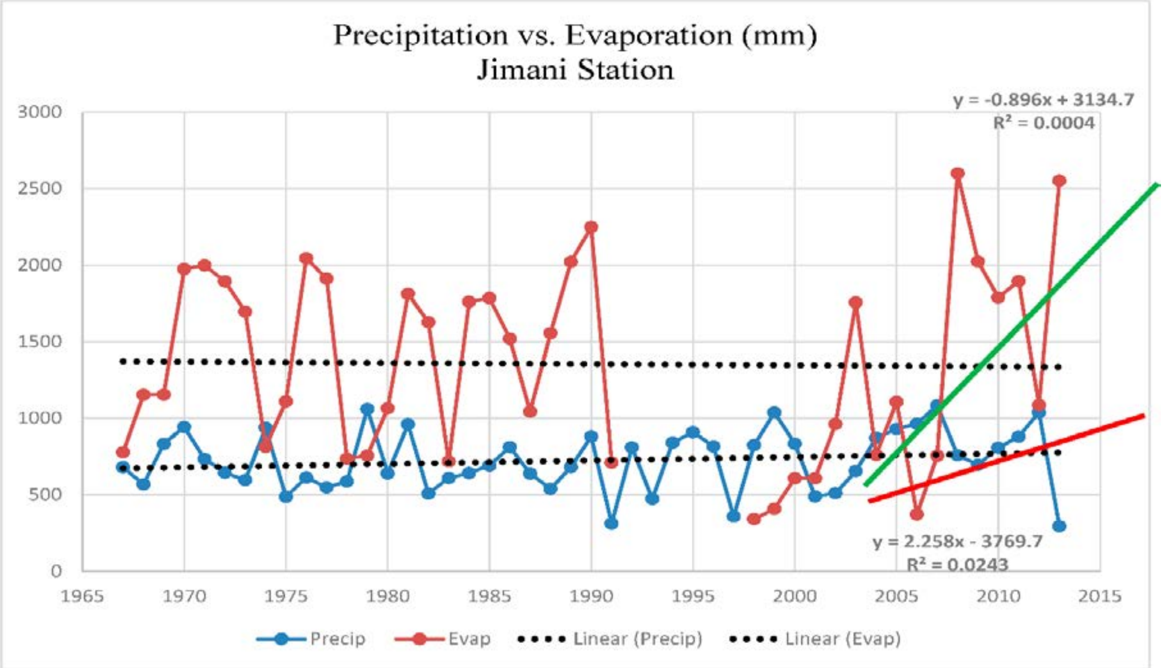

Figure 3. Precipitation *versus* evaporation time series (Jimaní station). Note that the complete series shows a slight tendency towards an increase in evaporation and a reduction in precipitation in the region. Whereas from the year 2000, this trend shows increases in both the precipitation (red line) and evaporation (green line), but the rate of increase is much greater for evaporation than for precipitation

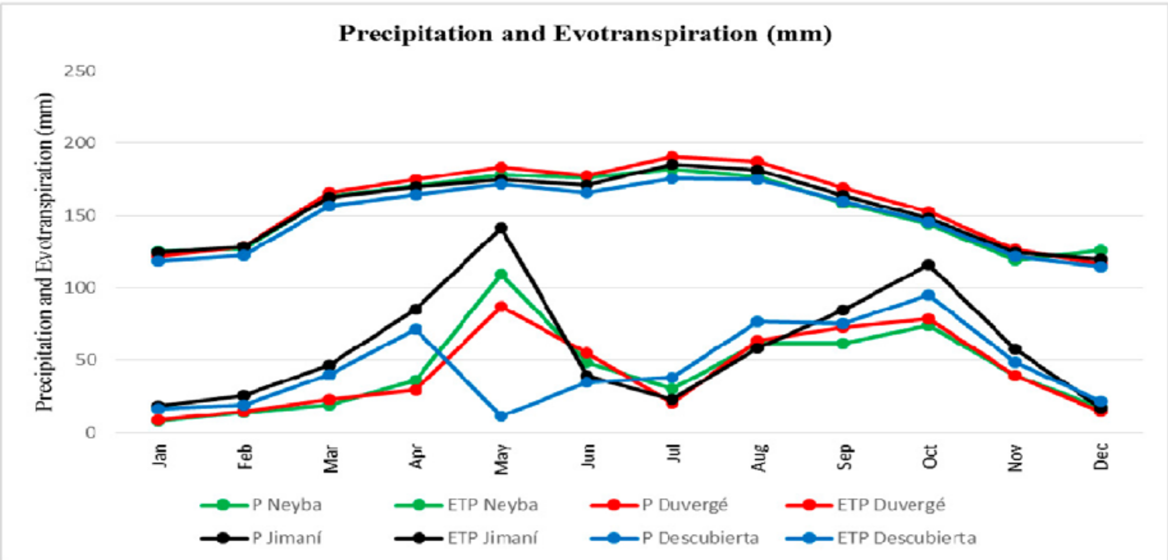

Figure 4. The precipitation *versus* evapotranspiration time series (Jimaní station). It shows a very similar behavior to the precipitation of the area

The 1980s showed the highest increase in 1989, at 2021.2 mm. In 1990 (Figure 3), the highest value of the decade was recorded, at 2248.2 mm. After that, a rapid decline was recorded and low values were reported for 1998, 1999, and 2000, with values of 341.2, 408.3, and 607.7 mm, respectively.

In 2008, a steep increase in evaporation produced the highest record over the past 50 years, with a value of 2600 mm. Generally the evaporation values exceeded the precipitation values.

4.4. Lake Level Changes

Average lake levels have been measured from 1961 until 2013 (Figure 3 and Figure 4). The levels have risen during the last 10 years in almost all areas measured around the Lake Enriquillo Basin. This includes the eastern part of Angostura, according to the information collected locally. Furthermore, levels have also risen in the area of a captive aquifer between Tamayo and Galván (> 2 m variations).

Some interpretations of the effects of the rains in 2005 were made by taking into account the events related to storms. Analysis of the average values of piezometric levels during hurricane seasons from 2007 to 2008 indicated that those levels have increased in the range of 15 m (maximum) in Puerto Escondido, 11.0 m in Neyba, and 0.45 m in Jimaní for the years 2008–2009. The discharge of groundwater during a typical wet year is about 7×10^8 m^3/year and during a typical dry year is 2×10^8 m^3/year. During the last 2 years, the measured discharge has been higher than the average discharge during typical wet seasons.

The total discharge of the River Yaque del Sur [36,37,41] and the freshwater springs at Las Marias, La Furnia, Las Barias, Boca de Cachón, and La Zurzas, and from Canal Cristobal, Rio Guayabal, Rio Amada, and Laguna Limon and Canal Cristobal was measured as 5.41 m^3/s. This represents a significant contribution to the lake.

The surface area of Lake Azuei fluctuated between 113 and 118 km^2 from 1985 to 2002 [20].

The surface area of Lake Enriquillo fluctuated between 195 and 332 km^2 from 1982 to 2010 (Figure 5 and Figure 6). After 2003, both lakes experienced a trend toward a surface area increase. The surface area of Lake Azuei has increased by about 15% compared to its 1985 levels, and that of Lake Enriquillo has increased by 40% compared to its 2003 levels [37]. As shown in Figure 5, the increase from 2003 to 2007 was a significant 19.48 km^2, with a slight decrease occurring in 2003, followed by an increase in the following years. The lake reached its highest surface area, measured at 52.53 km^2, in 2013.

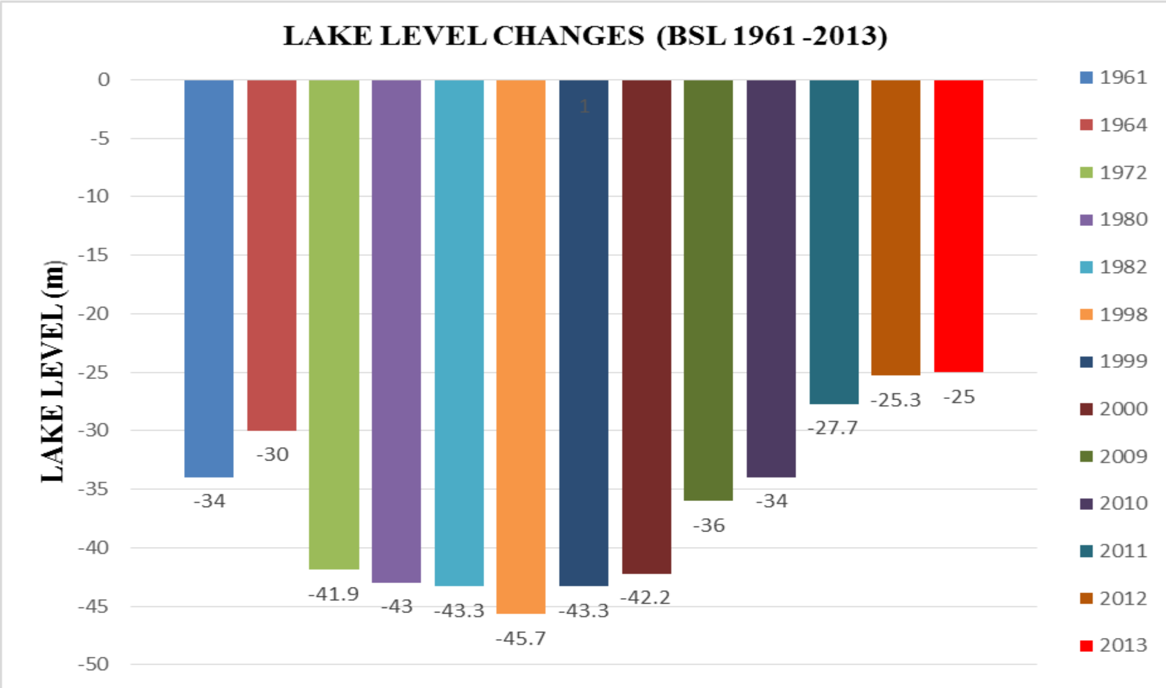

Figure 5. The variation in water levels in Lake Enriquillo from 1961–2013. Sources: Díaz del Holmo 2001 [2], Centro de Investigación en Biología Marina- Universidad Autónoma de Santo Domingo (CIBIMA–UASD) 1978, PNUD 2009, Hernández1985 [40], Proyecto MESCyT 2009-2013

4.5. Surface Cover Water (SCW)

Digital elevation models have recently been combined with single beam data to determine the lake's bathymetry, drainage, and surrounding geomorphology [21,38,41,42]. We used NOAA and local weather station data to assess the potential role that weather and climate patterns have on lake levels. Although yearly weather conditions affect these levels, the analysis of regional seismic data indicates that tectonics may also be involved in the longer-term (century-scale) lake levels. The lake's areal extent and lake level elevation depend on water supply, and also on the lake's bathymetry and regional topography, which does the Enriquillo-Plantain Garden Fault, a strike-slip fault system that extends throughout the lake, define.

4.6. Water Flow into Lake Enriquillo

A hydrological water balance model was created as a tool to aid in understanding the phenomenon of rising water levels of Lake Enriquillo. A similar pattern was shown in [41]. A model for the change in water volume stored in the lake is as follows:

Change in water volume stored in the

lake = inflow – outflow

For Lake Enriquillo, inflow components include:

(1) Precipitation (rainfall)

(2) Surface water (small rivers and streams that discharge into the lake)

(3) Groundwater

For Lake Enriquillo, outflow component includes:

1. Evaporation: Lake Enriquillo is an *endorheic* lake (the only water output is though evaporation).

Of the components listed above, only data for precipitation and evaporation is available for the period 1967–2009. The data set is also incomplete since only years when both values for precipitation and evaporation were available were used to assess the water budget.

The findings convey that lake water level was 43.23 m BSL during the period 1967–2000 and the net flow was 708.9 mm. This would imply a decrease in water levels and lake surface area. For the period from 2001–2009, rainfall and evaporation data are available for the years 2005, 2006, 2008, and 2009. During these years, precipitation values of 24 mm should have produced an increase in the water level and surface area of the lake. However, these precipitation values are too small to explain the observed increase in the lake level (about 8.2 m) between 2000 and 2010. Thus, the analyzed precipitation *vs.* evaporation values cannot explain the significant increase in the water level of Lake Enriquillo in the decade spanning 2000–2010.

5. Discussion

The values for precipitation (P) and potential evapotranspiration (E_{PT}) of the Hergreves-Samani [43] model show high values of P throughout the year (see Figure 5). With that trend, the lake should be losing water;

instead, the lake is rising. This suggests that the lake is receiving large amounts of water that have not yet been possible to measure and quantify. The sources of water measured at the Rio Yaque del Sur and the water measured at the various tributaries, when combined with measured precipitation, do not explain the observed increase in lake level. Some studies [44,46] have attempted to establish a correlation between the Natural Oscillation Lago (ONLE, Spanish acronym) and NAO and the oscillation of the Equatorial Pacific Ocean temperatures (ENSO-El Niño). These studies have concluded that the climatic phenomenon influencing the lake level was a NAO positive phase producing extreme events that tend to increase lake levels.

A previous study [6,7,47,48] showed that decreases in the ENSO warm phase in Atlantic hurricanes are the result of anomalously strong upper level westerly winds, which hinder tropical cyclone development over the Caribbean and Eastern Atlantic Basin. In addition, an increase in low-level anticyclonic vorticity is found in the warm phase of ENSO [47]. These conditions produce an anomalous upper-level ridge-trough pattern in the subtropics, with an amplified ridge over the subtropical Pacific in the area north of the enhanced convection and a downstream trough over the Caribbean Sea and the western tropical Atlantic. Over the central and eastern Pacific, the enhanced subtropical ridge is associated with weaker upper-level winds and reduced vertical wind shear, which favor more hurricane activity [48].

In 2010, a significant increase occurred in the lake level due to the impact of Hurricane Thomas in the southern region of the country. Precipitation associated with this phenomenon increased lake levels that year to about 43.92 km^2 of surface cover water (SCW), which represents an approximately 40% increase. Importantly, after the rainfall associated with this hurricane, a marked drought prevailed throughout the region; nevertheless, the lake levels remained constant throughout this period. The surface area of the water in the Lake Enriquillo Basin was 43.8 km^2 in 2010 and approximately 50 km^2 from 2011 to 2013 (Figure 6).

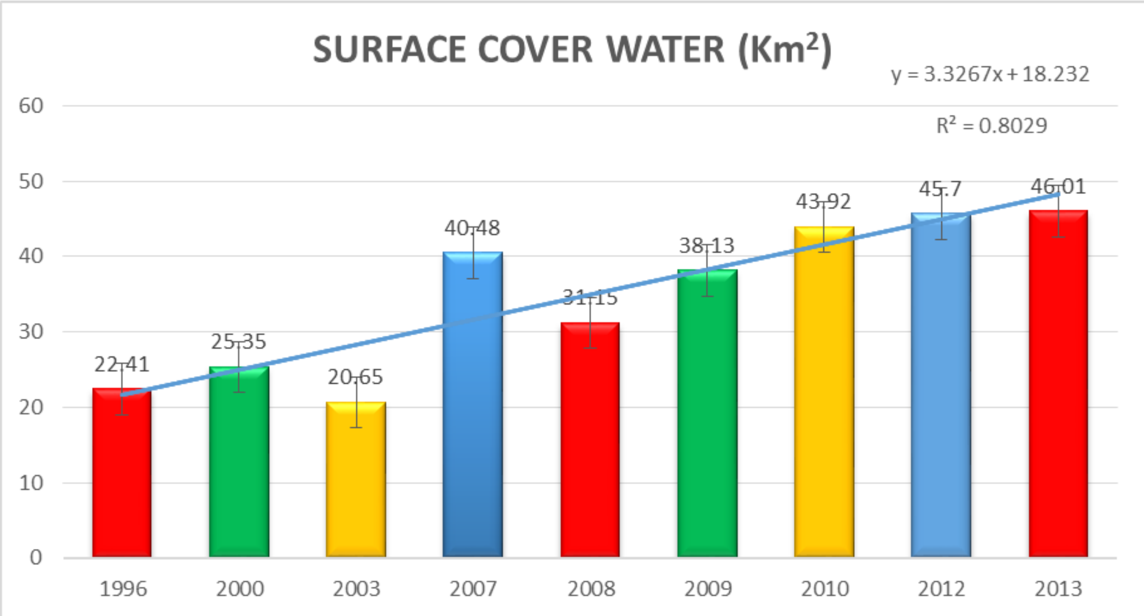

Figure 6. The area (km^2) covered by Lake Enriquillo from 1996–2012. Sources: Díaz del Holmo 2001[2], Centro de Investigación en Biología Marina-Universidad Autónoma de Santo Domingo (CIBIMA–UASD) 1978, PNUD 2009, Hernández1985 [40], Proyecto MESCyT 2009–2013

6. Analysis

Since 1967, the behavior of precipitation values in the weather station at Jimaní (which has the best set of data in the area) has been analyzed. The data available consist of a 46-year series, where episodes of high precipitation have influenced the increases in lake level. For example, the lake surface area increased by 20.54 km^2 in 2000. In 2007, the surface area increased by 15.13 km^2. In 2008, the surface area increased by 31.58 km^2 and budgeting increased by 21.4%. In 2009–2010, the increase in the lake surface area was 43.92 km^2 (30% relative to the year 2000).

Satellite images show the evolution of the lake surface area in decades. Mapping the surface area of the lake for the year 2000 shows the SCW was 25.35 km^2. In 2007, the SCW increased to 15.13 km^2 due to the influences of storm Noel, which caused flooding in the area. The cyclone season of 2008 increased the surface area of the lake by about 31.15 km^2 ha or 21.4% relative to 2000. In 2009, the lake SCW increased to about 38.13 km^2 and in April of the same year the level of Lake Enriquillo was 36.94 m BSL, an increase of 30% relative to 2000. The surface area of Isla Cabritos decreased to 15.89 km^2 due to the increase in lake levels. In 2010, during the passage of Hurricane Thomas in the southern region of the country, the increase in lake levels was documented as 43.92 km^2.

The environmental conditions in the study area were analyzed for the years from 1967–2010 for the parameters of rainfall and evaporation. The average rainfall in the period from 2007–2010 was similar to that recorded for previous years in the region. In 1979, rainfall values were 1221.3 mm and subsequently in 2008 they dropped to 1084.2 mm. In 1979, the lake level doubled its size after Hurricanes David and Frederick. Lake SCW did not increase in 1979 because that year was preceded by several years of precipitation deficits. However, recent years (2000–2012) have shown very active hurricane seasons. Tropical Storm Odette's heavy rains left 230 mm in the region of the Lake Enriquillo Basin [49]. This storm crossed the island of Hispaniola south to north in December 2003. Since 2005, 28 tropical systems struck the region, including Tropical Storms Noel and Olga in 2007, Fay and Gustav in 2008, and Hurricane Isaac in 2012. During this period, the measured increase in lake level was 17.2 m, the highest rise since 1961 (Figure 6).

Small differences in the physicochemical parameters and their spatial and seasonal distribution were detected in Lake Enriquillo from 2009–2011. A slight increase in pH was noted (the water became slightly more alkaline) in 2010 and 2011. Salinity has been one of the most variable parameters measured during the last 30 years. The lake was hypersaline, with a salinity concentration of 70‰–101.4‰, until 2003. For the years 2009 and 2010, a slightly lower concentration than seawater was measured, ranging from 26.06‰–25.41‰. The water temperature presented small fluctuations with time, reflecting a slight decline in recent years of 1 °C in 2009 and 2 °C in 2010. The temperatures remained within the range reference set for tropical waters.

An earlier paper [1] for the period 2003–2013 documented that Lake Azuéi's area increased by 22% (from 114 to 140 km^2). Recent bathymetry measurements, combined with surface area calculations and a digital elevation model of the area, revealed a 4-fold increase in volume for Lake Enriquillo (from 1.2 to 4.7 km^3).

6.1. Summary

The figures (Figure 7-Figure 11) presented below show the changes in the level of Lake Enriquillo occurred in the period 2000 to 2012. It may be noted that for the years 2011 and 2012 increased lake level was 6.2 m in a short time. The most significant weather event occurred in 2011, that of Tropical Storm Emily, which made landfall in the south of Hispaniola Island, leaving 528 mm of rain in 24 h [35].

Figure 7. This image from the year 2000 confirms that the lake level continued to rise, as indicated by the decrease in surface area of the 3 islands within the lake. During this time, the most significant weather event in the region was Hurricane Georges in 1998, which dropped a total of 865.4 mm of rainfall in 24 h

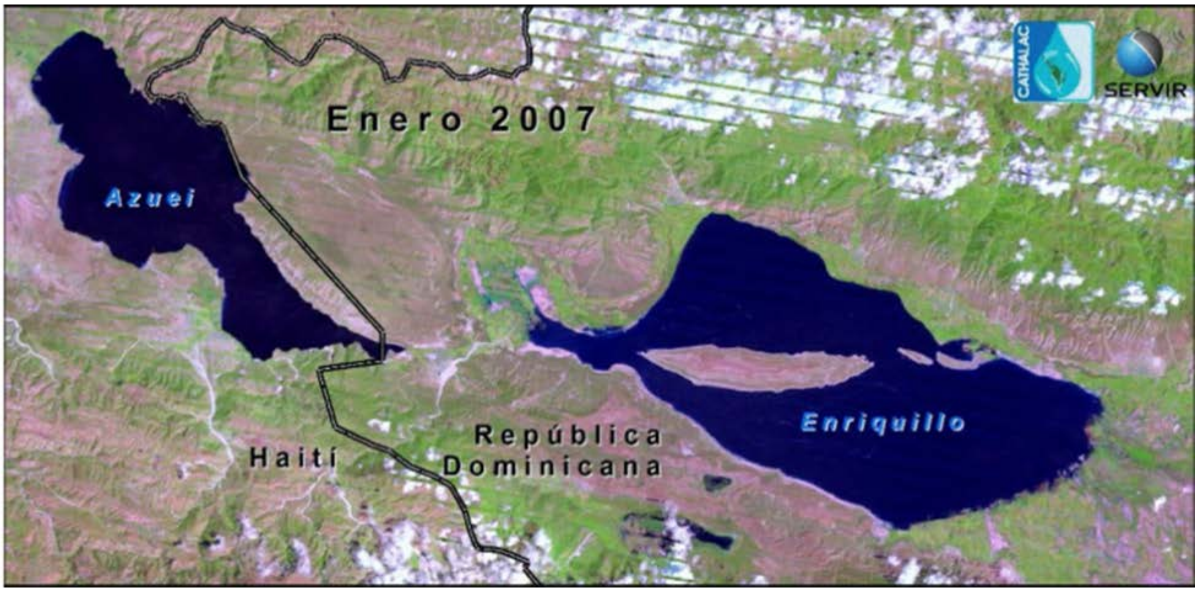

Figure 8. This image clearly shows the two lakes, but there is separation between them. The Tropical Storms Olga and Noel struck during this year and greatly affected the region, but they occurred at the end of the year and the image was obtained at the beginning of the year 2007

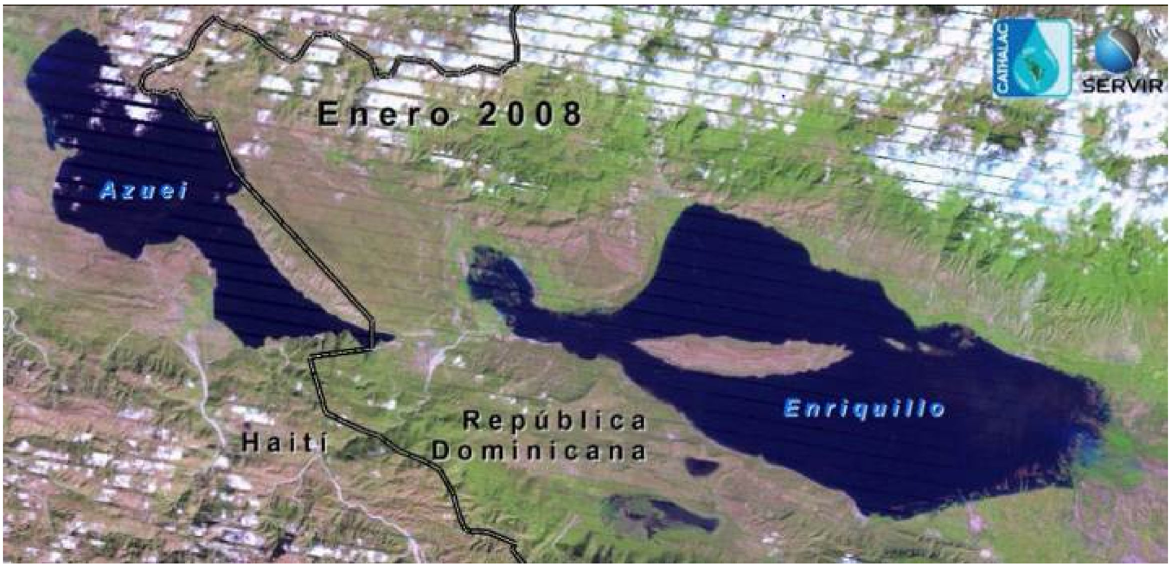

Figure 9. This image from 2008 shows a greatly reduced Isla Cabritos and the complete disappearance of Barbarita and Islita during this decade (2000–2010), reflecting the effects of Tropical Storms Olga (October 2007) and Noel (December 2007)

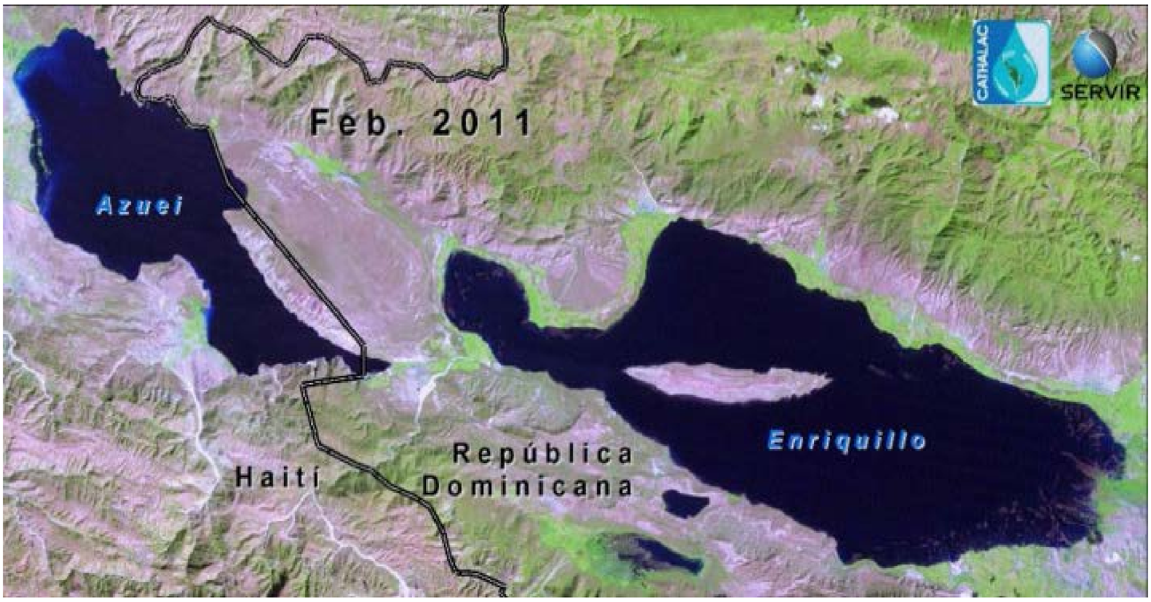

Figure 10. This image from 2011 shows the effects of the hurricane seasons of 2010 and 2011, where the lake level had an unprecedented increase of 6.2 m in a short time

Figure 11. This image reflects the effects of Tropical Storm Emily (4 August 2011), affecting the south of Hispaniola. The storm left 528 mm of rain in 24 h [35, 47,50]

7. Conclusions

The expansion and the rising waters of Lake Enriquillo is a Natural cyclic oscillation generated by hydro-meteorological events, it is related to climate variability of the Dominican Republic, Caribbean climate is governed by the CRCCs [1,46,47].

The increase level of the Lago Enriquillo is approximately 17.2 m in the period 2000-2013, generating the first refugees due to climate change in the Caribbean Region in the Dominican Republic, approximately 100,000 people. [25]

Salinity has been the most variable parameter measured in Lake Enriquillo during the last 30 years. In 2003, the lake was hypersaline, with a salinity concentration of 70–101.4‰. Since then, salinity has decreased to 22.2‰ in 2012. This indicates that the increase in lake level and surface area during this time was caused by some form of freshwater input. However, the measured input from rainfall and the measured discharge of waters from rivers and known springs cannot account for the observed increases in lake level and surface area of the lake during the last decade. Freshwater sources, different from the known ones, must be producing the significant “unaccounted for” increase in lake levels; since all the inputs along the edge of the lake basin have been identified [4,37,38]. These unknown water inputs are probably in the form of groundwater discharge from inundated areas of the basin that have not yet been identified and measured. Since a strike-slip fault system (Enriquillo-Plantain Garden Fault) trends east to west and extends throughout the middle of the lake, this possibility is not only feasible but probable.

This study lays the groundwork for future research on the dynamics of this watershed. The Lake Enriquillo Basin is a vulnerable region, so increases in extreme weather events represent a major threat to the entire region, as they threaten increases in the damage and impacts to property, land, and structures and the generation of economic losses for the regional population.

It is recommended, as an initial step, an exploration of the inundated portions of the basin, using hydrochemical parameters to identify areas where groundwater from submerged springs is being discharged. Subsequent measurements can then determine the magnitude of this discharge, thereby allowing the creation of better models with more realistic estimates of water inputs into the lake from different sources. Also recommended is continued monitoring of the various climatic and hydrochemical parameters in the area investigated in previous studies, in order to follow the evolution of the lake over time. Finally, it is suggested to conduct tests on whether the seismic activity along the Enriquillo Plantain Garden Fault Zone increases or decreases hydrological connections between the lakes.

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