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Observational Time Series for Lakes Azuei and Enriquillo: Surface Area, Volume, and Elevation

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Report

Presentation of Observational Time Series for Lake Azuei and Lake Enriquillo: Surface Area, Volume, Elevation

by

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Abstract

In this report, we present historical time series of surface area, volume, and elevation for lakes Azuei (Haiti) and Enriquillo (Dominican Republic). The intention is to present a history of the lakes' levels for both bodies of water as derived from Landsat imagery that is augmented by reports and narratives that reach further back in time. We also summarize lake level time series data collected and developed through various other efforts and compare these data sets to our time series. The time series contains 45 years' worth of data ranging from 1972 to 2017 which we developed from Landsat imagery and the volume and elevations are constructed from combining surface area data with Digital Bathymetry Models for each of the lakes. The time series suggest that Lake Enriquillo has experienced three episodes of expansion in 1979-1981, 1998-2000, and 2003-2013 with 70%, 36%, and 2.4 times rate of changes in its volume respectively. Lake Azuei's growth occurred in 1981-1984 (1.4%), 1992-1996 (6%), and 2003-3013 (30%). We use the reports and narratives to both establish some evidence of past shrinking and expanding events (that is prior to 1972) and, for overlapping time periods, some degree of validation for remote sensing based data points.

1. Introduction

Studying and analyzing the behavior of Lake Azuei and Lake Enriquillo from a water budget standpoint of view requires the knowledge of the lakes' water volumes. Since this is not directly measurable, one needs another means to track volume. We do this by coupling lake surface area assessments using Remote Sensing, RS, imagery to bathymetry representations. This is possible because the lakes do not have vertical walls but sloping topography along the shorelines, very gentle in the W-E directions and a little steeper in the N-S near shore areas. Hence, a measurable change in surface area (SA) can be used to directly compute a change in volume, i.e. Vol = *fct*(SA), as is Surface Elevation, i.e. SurfElev = *fct*(SA). Having elevation and surface area data also helps to quantify the extent of the lakes' rise and flooded area as the lake area polygons can be overlaid with topographical information to delineate flooded areas.

Our intention for this report is to make public what these time series look like and also outline the differences of the surface area extent reported from various sources. The surface area time series were derived using processed Landsat images covering the lakes' area and extractions of water body outline (the same procedure introduced by (Moknatian et al., 2017)). Moknatian *et al.* also presents how the rating curves (hypsometric curves), relating the area, volume and elevation values, were derived combining the bathymetry of the lakes with an existing high resolution (30m) DEM and creating a "bath-tub" model for each of the lakes. Having surface area values from the Landsat images serving as input information, the volume and elevation data can then be easily obtained from rating curves.

In order to complete the time series presented by Moknatian *et al.*, which presents surface area and elevation for 1984 to 2014*, w*e added the points for the years of 1972-1984 & 2014-2017 (estimated from Landsat-1, 2, & 3 MSS and Landsat-8 OLI). We also constructed the volume time series of the lakes for 1972 to 2017.

2. Lakes' Observational Time Series Development

The lakes' time series was developed for the 1972 – 2017 time range, i.e. about 45 years of coverage. Note that the distribution of the observations is dependent on the availability of the satellite image used to extract SA. Prior to 1984 there were 46 available images from

Landsat-1, 2, & 3 MSS while Landsat-8 OLI produced imagery twice a month starting in 2013, i.e. a much denser data supply. Out of the 46 prior-to-1984 pool of images we were able to retrieve seven data points for Lake Azuei and ten data points for Lake Enriquillo. For the period after 2014, a total of six images were processed and added to the time series. The images processed have the Projected Coordinate System of UTM_zone_19N. The lakes surface area time series are shown in Figure 1 and Figure 2.

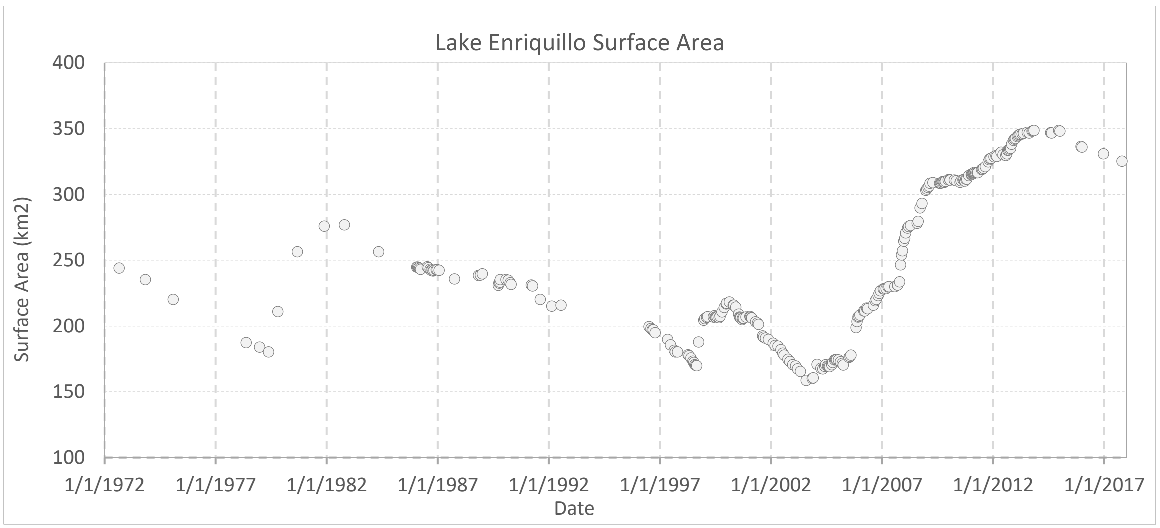

Figure 1. Lake Enriquillo observational surface area time series (1972-2017)

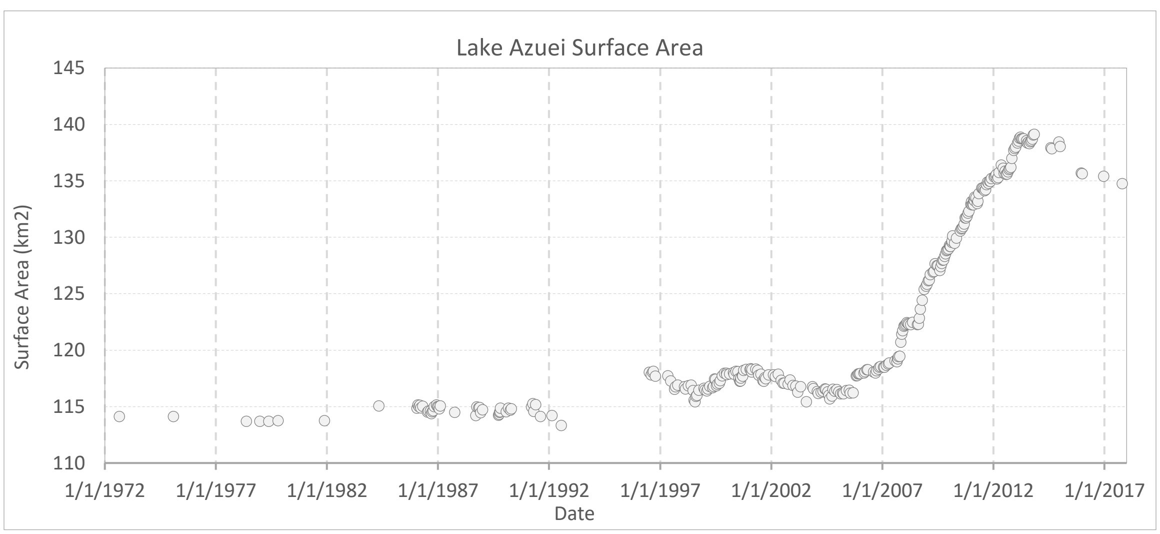

Figure 2. Lake Azuei observational surface area time series (1972-2017)

The water balance dynamics of a lake is best assessed by computing and monitoring water storage changes in addition to needing knowledge of the total volume of the lakes. Determining the total volume of a lake is only possible having a suitable digital representation of the bathymetry. In order to construct the volume time series we used a previously developed bathymetry map (Moknatian et al., 2017; Piasecki et al., 2016; Piasecki & Moknatian, 2018) for the two lakes in conjunction with the temporal and spatial variations of surface water coverage. This basically results into a rating curve from which values for Volume can be directly read off as a function of SA. Figure 3 and Figure 4 represent the volume time series of both lakes. Note that the volume errors introduced during the bathymetry creation for Lake Enriquillo and Lake Azuei were very small.

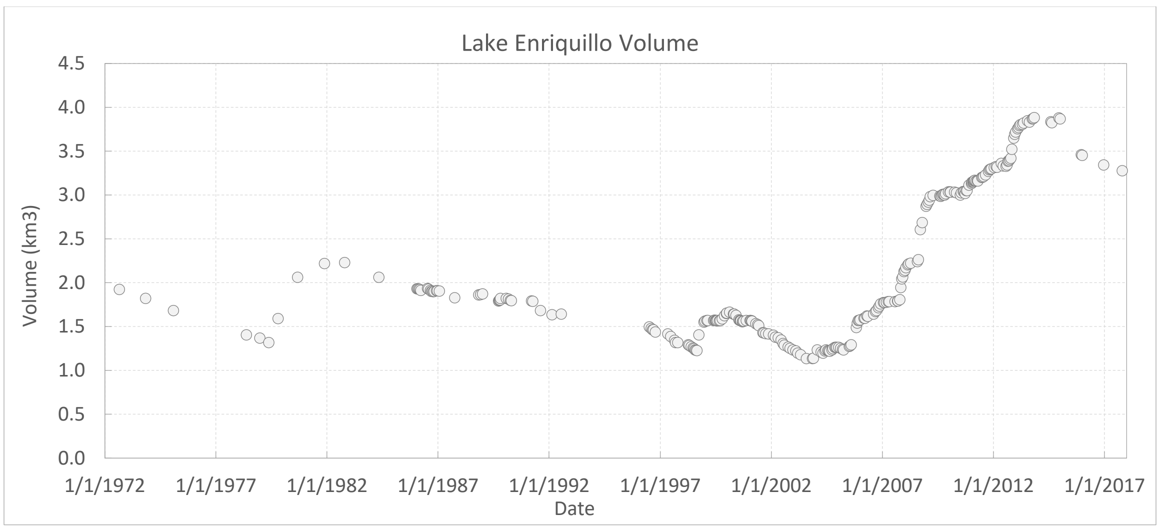

Figure 3. Lake Enriquillo observational volume time series (1972-2017)

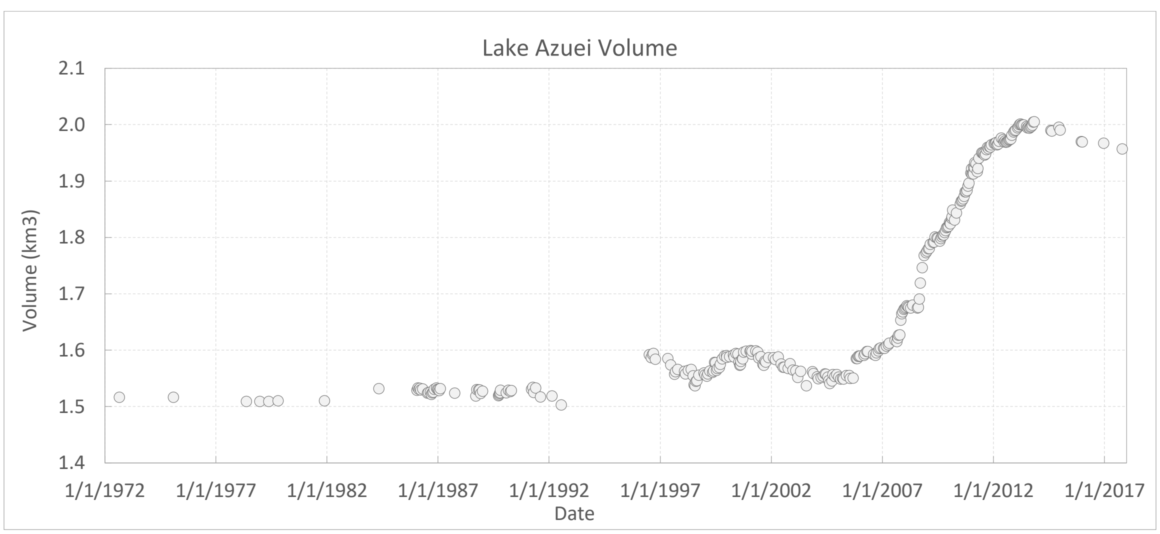

Figure 4. Lake Azuei observational volume time series (1972-2017)

Using the rating curves created for Lake Azuei and Lake Enriquillo, we derived the elevation time series based on the temporal variation of surface area (Figure 5 and Figure 6). The elevation values were derived using the seamless topography map of the study area which was created using the generated bathymetry of the lakes in conjunction with Shuttle Radar Topography Mission, SRTM, derived Digital Elevation Model ,DEM, data, as previously described. Since the SRTM/DEM itself has an absolute vertical accuracy of 7 to 9 meter for North America which contains Hispaniola (Rodriguez et al., 2005), we decided to envelop our time series with an average band of ±4 meters to reflect this uncertainty.

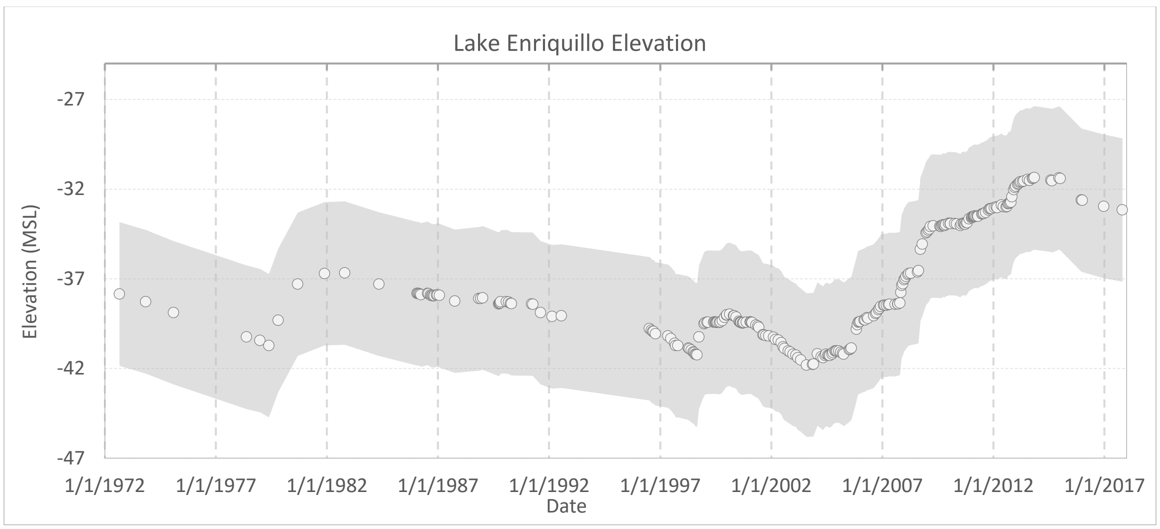

Figure 5. Lake Enriquillo observational elevation time series [shaded region is DEM error of ±4m]

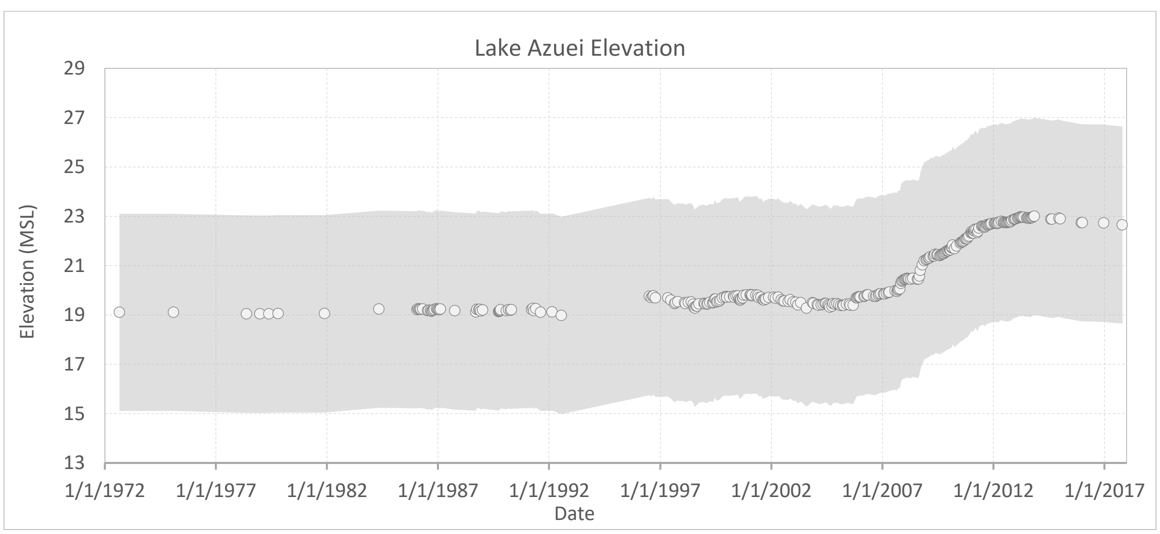

Figure 6. Lake Azuei observational elevation time series [shaded region is DEM error of ±4m]

The time series show that Lake Enriquillo's first recession phase occurred between 1972 and July 1979 when the lake trend shifted from decrease to increase for almost three years running until mid-1982. During the recession between 1972 and 1979, the lake lost 64km^2 of its area, which is equal to losing 0.61km^3 of water and dropping around 2.88 meter. Between 1979 to October 1982, the lake rose around 4m to the elevation of -36.7 MSL, and expanding its SA and volume to 276.8km^2 and 2.23 km^3, respectively.

A second shrinkage occurred between 1982 and 1998 when the lake reduced to 170.01 km^2 (Surface Area) and 1.23 km^3 (Volume) followed by another expansion to 218.61 km^2 (SA) and 1.66 km^3 (VOL) by late 2000, rising 2.3 meters. The third recession of the lake occurred between 2000 and 2003 when the lake area and volume reduced to 157.95 km^2 (SA) and 1.13 km^3 (VOL). Expanding again over the next ten years by November 2013 the lake experienced its biggest extent of record, i.e., 348.78 km^2, with an equivalent volume of 3.88 km^3. The lake rose around 10.4m from 2003 to 2013. The last image we analyzed was for 10/24/2017 showing that the lake had arrested its expansion and actually receded somewhat to 325.30 km^2 and 3.27 km^3, dropping around 1.8 meters in comparison to October 2013.

The changes of Lake Azuei were less pronounced when compared to Lake Enriquillo even though both lakes experienced the same congruent recession/growth patterns. In August 1972, Lake Azuei had a surface area of 114.1 km^2 and a volume of 1.52 km^3 with an elevation of 19.1 MSL. The lake size stayed unchanged until November 1981. The next record, which is for May 1984, showed that the lake had grown by around 1.3 km^2 (SA), 0.02 km^3 (VOL) and risen 19 cm over the course of 3 yrs. The lake remained unchanged for around 8 years before it reached its first low point in 1992. There is a gap between data points for year 1992 to 1996 during which Lake Azuei grew by around 6%, i.e. gaining 0.09 km^3, expanding 4.71 km^2 and rising 79 cm. After a period of moderate growth and recession, the lake reached its second low point in August 2003 when its size was 115.42 km^2 and 1.54 km^3 with an elevation of 19.3 MSL. As Lake Enriquillo, Lake Azuei grew substantially over the next ten years to reach its maximum extent of 138.30 km^2 and 2.01 km^3 (volume) by October 2013, rising 3.7 meters between 2003 and 2013. Since then it largely retained its levels even though the last analyzed image suggests that the lake has shrunk to 134.75 km^2 and 1.96 km^3 (2017), equivalent to a drop of 31 cm. Note that the volumetric changes are quite different; from 2003 to 2013 Lake Enriquillo grew 2.4 fold while Lake Azuei only added 30%. Despite the proximity of the lakes, it is these differences that prompted additional research questions aimed at explaining this very different behavior.

3. The comparison of the time series with previous efforts

The comparison between the published time series of the lakes are presented in Moknatian et al. (2017) in detail in which the authors show how they generated a new SA time series which features the densest and most consistent data assembly with a much higher level of accuracy in comparison to previous work.

In Figure 7 and Figure 8, we added the data points we obtained for 1972-1984 and 2014-2017 along with the time series introduced by Moknatian et al. (2017) and the references which have data for the period before 1984. These references include the Coastal Urban Environmental Research Group (CUERG) at the City College of New York which publishes lake data on their Webpage called "The Hispaniola Lakes Project" (http://cuerg.ccny.cuny.edu/hispaniola/), Luna & Poteau (2011), and Schubert 2003 (Luna & Poteau, 2011; Schubert, 2003). The comparison of these references shows that all sources, except Luna and Poteau; their data starts in October 1979, captured the expansion of the lake in the late 70s. Note though, that the values they produced do not match the time series we constructed.

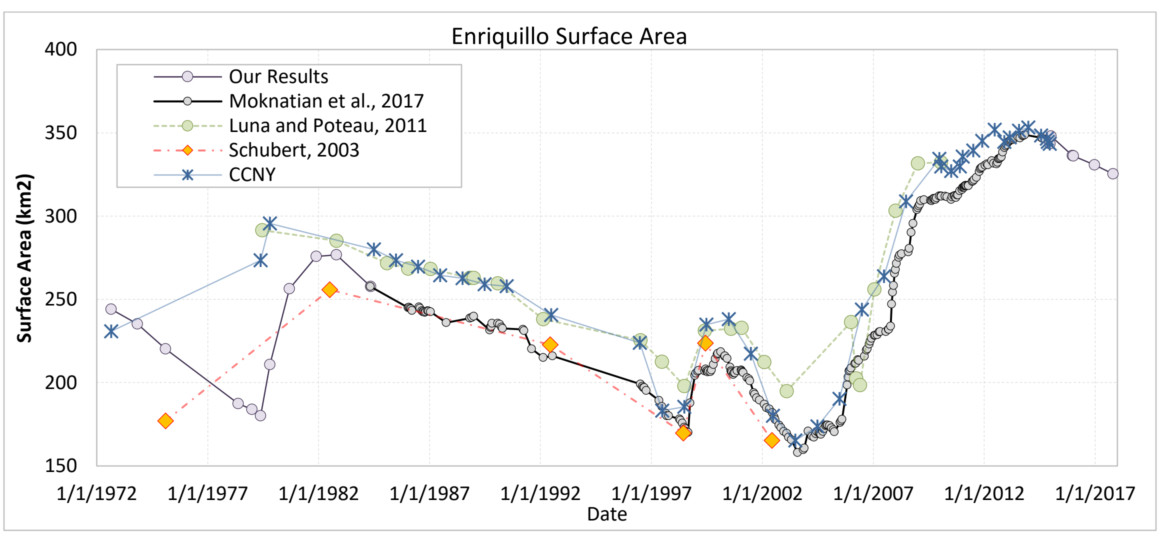

Figure 7. Lake Enriquillo surface area time series comparison (1972-2017)

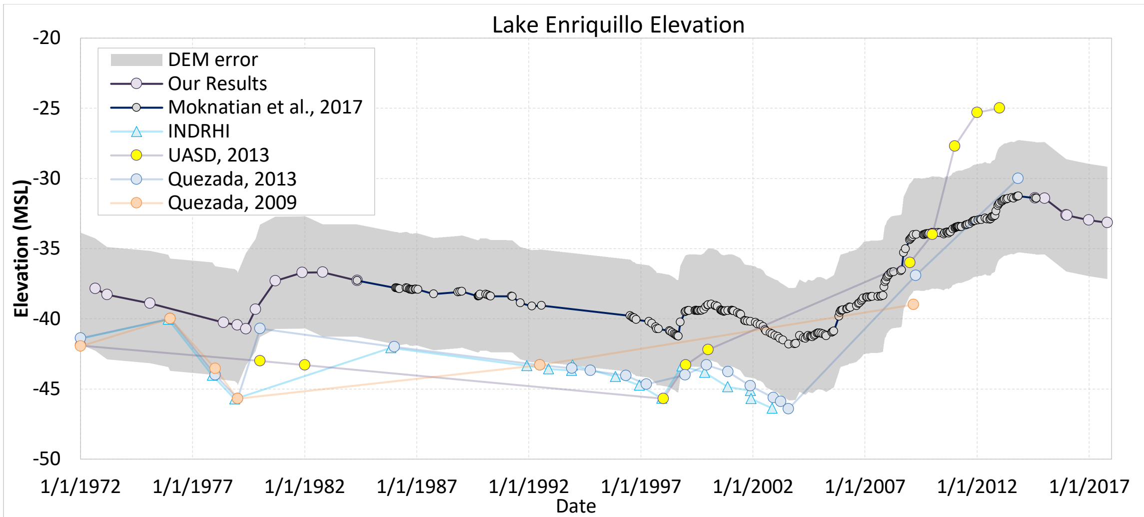

Figure 8. Lake Enriquillo elevation time series comparison (1972-2017)

The references provided elevation values are The Instituto Nacional de Recursos Hidráulicos (INDRHI) (Buck & Brenner, 2005), Universidad Autónoma de Santo Domingo (UASD) (Programa de Naciones Unidas para el Desarrollo (PNUD)., 2013), and Quezada (2009, 2013) , which reported the elevation values from different sources. Between all the values reported for the lake's level, only two sets of values were measured by same sources. The water level of the year 1951 (-44.3 MSL) and 1959 (-40.10 MSL) were collected by the Military Cartographic Institute in Santa Domingo. The levels of -41.10 MSL (area of 280km^2) and -45.70 MSL (area of 180km^2) associated to the years of 1969 and 1979 (before storm David) were both recorded by the Canadian Oil Company (Quezada, 2009, 2013). Our results proved the drop of 3 meters from August 1972 to June 1979 and total rise of about 4 meters until October 1982 for Lake Enriquillo which is close to the rise of 5 meters stated by (Schubert, 2003). It has to be mentioned that, none of the references stated how their reported elevation values were extracted.

4. Historical Reports of the Lakes

In this section, we summarize all historical information mentioned in the literature with regard to the lakes' size changes. Most of the documents we were able to obtain refer to Lake Enriquillo which is symptomatic for most available references on the lakes, i.e. Lake Azuei has a much smaller body of associated literature.

According to Schubert 2003 & 2012, Lake Enriquillo was separated from the sea about 2500 years ago because of sediment deposits originating from the Yaque del Sur River. Since then the lake rose due to the delivery of the fresh water to the lake, causing it to grow above the sea level (Schubert, 2003, 2012). Approximately 500 years ago when Columbus and the first Spanish historians set foot on the Hispaniola Island, they mentioned a very large lake named Hagueibon by the Tainos (primate residents of the Hispaniola Island) and an island called Guarizacca in the middle of the lake (Schubert, 2003, 2012). At that time, it is not clear if they were describing the Lake Enriquillo and its Cabritos Island inside of it or a lake formation that included both Lake Azuei and Lake Enriquillo. However, based on today's available elevation data from the Hispaniola SRTM/DEM, connection and merging of both lakes would appear to be impossible since the highest point between the two lakes is 34 meter above the mean sea level (MSL) and the lakes would overflow at the opposing ends of either side of their watersheds before reaching 34 MSL. The overflow water level is 13m (MSL) for Lake Enriquillo and 28m MSL for Lake Azuei (Moknatian et al., 2017). The highest elevation on Cabritos is at the sea level (zero MSL), which suggests that for the Cabritos island to be visible Lake Enriquillo must have had an elevation below sea level, from which it is clear that the two lakes were separated.

Based on a narrative originating from a man living in the town of Duverge, Lake Enriquillo extended near the north side of the town around the years of 1897 to 1903, allowing people to get to the town on a boat from Haiti (Quezada, 2009). Based on the available elevation data, the town of Duverge elevation ranges between -7m MSL to 13m MSL. Duverge, initially called "Las Damas," was populated first by Spanish people and their slaves in 1772. Based on the elevation data it can be concluded that Lake Enriquillo has never had an elevation higher than -7m MSL from 1772 on since the town of Duverge (Figure 9) had never been flooded by the lake. However, it was reported that Lake Enriquillo elevation was +0.63 meter above the sea in 1892 (Incháustegui et al., 1978; Pichardo et al., 2012; Quezada, 2009), which would appear impossible. Nevertheless, the possibility of the elevation being higher than -31.3m (MSL), which was associated with the historical maximum extent of the lake in 2013 (Moknatian et al., 2017), it cannot be ruled out entirely, thus establishing the possibility of the water level being between -7m and -31m (MSL) in earlier times.

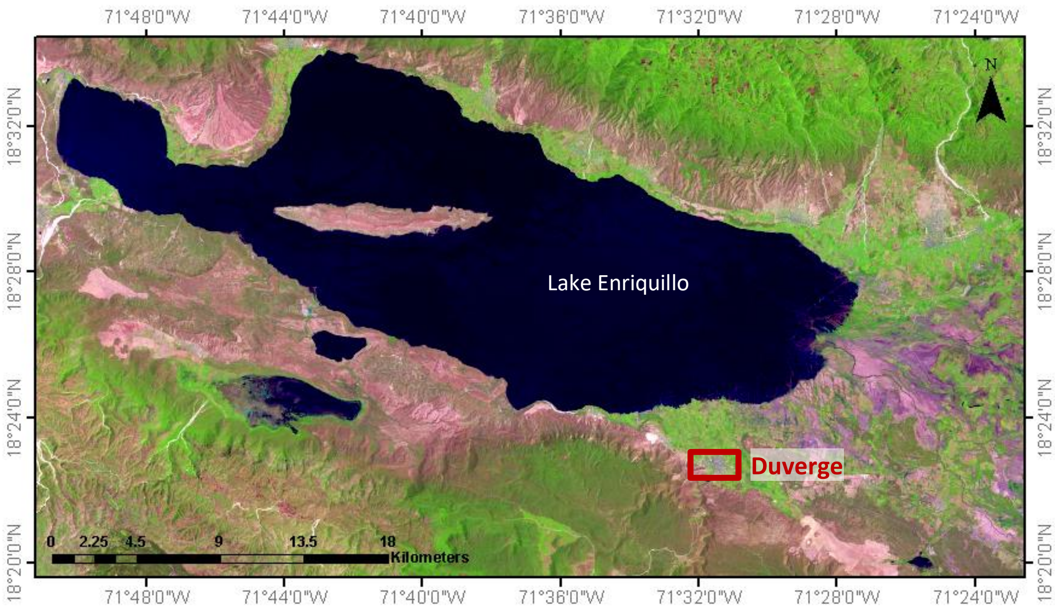

Figure 9. The town of Duverge location [Landsat Image on 8/18/2013]]

In the early 20th century, two historical floods inside Lake Enriquillo's watershed were reported for the years of 1900 and 1954 (Quezada, 2009). Moreover, based on a survey done in 2013 two people claimed to be observing a high point around the year of 1956 and 1914 for Lake Enriquillo and Lake Azuei, respectively (Sheller & León, 2016).

Nobel (1923) reports an event during which a group of men carried a boat by a truck near Lake Enriquillo and then dragged it for 2 miles on mud to the edge of the lake (Noble, 1923). His descriptions of the lake suggested that the lake might have been around three to four miles away from Duverge, which establishes the possibility of the elevation being around -38m and -39m (MSL) (The interpretation of the elevation values are based on the data presented by (Moknatian et al., 2017)). His statement regarding the Cabritos Island, "no one had been to the island for twenty years," also suggest that the lake Enriquillo water level had been below sea level as far back as 1900.

During the 1950s, several canals were opened from the Yaque del Sur River to divert water to Lake Enriquillo, which previously had experienced a significant drop, causing the lake to rise again (Schubert, 2003). One of these canals, the 17 kilometer long Cristóbal Canal, connects Lake Ricon (also called Cabral Lagoon) to Lake Enriquillo (Araguás Araguás et al., 1995; Comarazamy et al., 2014; González et al., 2010; Logan et al., 2012; Melorose et al., 2015;

Méndez-tejeda et al., 2016; Mendez-Tejeda & Delanoy, 2017; Pichardo et al., 2012; Programa de Naciones Unidas para el Desarrollo (PNUD)., 2013; Quezada, 2009; Tobergte & Curtis, 2013) and is the major water conveyor system for inter-basin water transfer to reach Lake Enriquillo. Water is directed from the Yaque del Sur River first to Lake Ricon via the Trujillo Canal and then onward to Lake Enriquillo through the Cristóbal Canal. These anthropogenic interventions occurred alongside flooding events reported in 1954 and a high lake level in 1956.

During the late 1960s, the Yaque del Sur was diverted into the opposite direction for irrigation purposes, thus preventing water to reach Lake Enriquillo (Ducoudray, 1978). Moreover, the diversion of water of several other streams for irrigation purposes further limited the recharge rate to the lake adding to continued shrinkage (Ducoudray, 1978). During the next 10 years the lake shrunk from having an area of $280km^2$ in 1969 to an area of around $180km^2$ in 1979. After storm David (1979), the lake rose about 5 meters expanding back to its 1969 size of $280km^2$ (Incháustegui et al., 1978; Pichardo et al., 2012; Quezada, 2009; Schubert, 2003). In 1978, Incháustegui *et al.* also described Lake Enriquillo's extent during a visit in May of 1977 (Incháustegui et al., 1978) having an area of approximately between $190km^2$ and 170 km^2, which is in keeping with the 1979 size. Our results also proved the drop of 3 meters during the period of August 1972 to June 1979 and the subsequent rise of about 4 meters by October 1982 which is close to the reported rise of 5 meters stated by (Schubert, 2003) and is consistent with Incháustegui *et al.* (Incháustegui et al., 1978).

There is very little extra information in addition to the aforementioned reports that would provide further insight to Enriquillo's water levels for the years prior to 1972. Note that we also have some conflicting numbers, notably for 1965 where INDRHI reported a high level of water level at around -30 MSL which, based on our analysis, cannot be correct for that period.

While we have been able to uncover some historical trace/footage of Lake Enriquillo life cycle, we were not able to find much about Lake Azuei. The most comprehensive record is a very recent reference that describes a survey administered to locals residing near Lake Azuei who claimed that the lake level was high in the past (Sheller & León, 2016). One of the locals stated that during the years of 1914 the water level of Lake Azuei was almost as high as its level in 2013 near to their home. Two others also believed that sometime around 1915, during the

American Occupation in Haiti, big tractors were brought in to create the canals that drained Lake Azuei towards the ocean (according to a conversation we had with (Sheller & León, 2016)). Perrissol & Lescoulier in 2011 talk about two canals in Desaguas (5.7km, connecting Lake Azuei and Lake Trou Caiman) and Boucan Brou (18km, connecting Lake Trou Caiman to the sea) (Perrissol & Lescoulier, 2011). These two reports however, are not in agreement as Perrissol & Lescoulier claim that the canals were initially designed to drain Lake Trou Caiman water (which because of its shallow depth is subject to sudden changes in level during the rainy season) to Lake Azuei on the east and to the sea on the west in order to lower the risk of flood in the town of Thomazeau (Perrissol & Lescoulier, 2011). They believed the rise of Lake Azuei was due to the malfunction of the Desagua-Trou Caiman-Boucan Brou canal system, conveying water toward Lake Azuei rather than the ocean (Perrissol & Lescoulier, 2011). At the end of 2008, several attempts were made to control the flow of water to Lake Azuei, however, in 2010 the field observations showed that still significant volumes of water of Trou Caiman continued to pour into Lake Azuei (Perrissol & Lescoulier, 2011). Unfortunately, these observations did not help us to shed further light on the historical water levels of Lake Azuei except for the observation of 1914 from the (Sheller & León, 2016) survey.

5. Summary

In this report, we presented the time series of surface area, volume, and elevation for both Lake Azuei and Lake Enriquillo. Comparison of these time series with previous efforts showed that our time series present the densest and most consistent data collection for the lakes so far. Each lakes' time series is comprised of more than 250 points over the span of 45 years (1972-2017). Although the temporal intervals of the raw time series were not constant and raged between a few days up to years, we were able to retrieve sufficient information to develop monthly and yearly time series. These time series helped us to track the expansion and shrinkage phases as well as to quantify the rise and drop of the lake during each phase. During the period of 2003 to 2013 when the largest expansion of both lakes occurred, Lake Enriquillo rose around 10.4m doubling in size while Lake Azuei expanded round 30% rising around 3.7m.

We also provide a summary of historical records that have dealt with the lake expansions over the years, reaching back to the early 1900's. Many of these are anecdotal in nature and thus data does not exist in electronic form and many times just as a report of a point in time without a connection to years prior or past. Yet, this historic overview can be used to check if our time series development is congruent with what has been observed and recorded, a form of validation so to speak.

Acknowledgement

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