IDENTITY, MORPHOMETRY AND HISTORICAL CHANGE OF THE LAGUNA ENCANTADA IN GUELATAO DE JUÁREZ, OAXACA, MEXICO

RICARDO CLARK-TAPIA, MARIO FUENTE CARRASCO, VIVIANA RODRÍGUEZ-RIVERA, CRYSTIAN SADIEL VENEGAS-BARRERA, JORGE E. CAMPOS, MARÍA DELFINA LUNA-KRAULETZ, ANGELA VELASCO-GARCÍA, FANNY GARVEY, RAÚL JOSÉ SILVA GANDARILLAS and CECILIA ALFONSO-CORRADO

SUMMARY

Socially and culturally, the Laguna Encantada *('Enchanted Lagoon') in Guelatao de Juárez, Oaxaca state, is one of the most important bodies of water in Mexico. In this study morphometrical findings and an historical analysis of morphological changes over the past 400 years is presented. The objective was to provide data about the changes of the* Laguna Encantada *that will contribute to understand interactive processes between nature and society. The study was performed from a landscape perspective, integrating batimetrical parameters, superficial and subsurface morphometrical dimensions, and historical modification processes were also analyzed utilizing satellite photography and repeat landscape images. The results indicate that the system called the* Laguna Encantada *is a circular lake with a convex tray of 7.20m maximum depth, an area of 11,610m^2, and a maximum length of 131m. Between 1960 and 2010, there was an increase in those dimensions. It has experienced diverse transformations in its dimensions, the most notable happening in the 20th century. Hydrologic and morphometric information, and recent transformations, along with landscape reassessment in relation to scenery and eco-tourism, are deemed necessary for the management of the system.*

KEYWORDS / Bathymetry / Culture / Human Change / Repeat Images /

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Ricardo Clark Tapia. M.Sc. and Doctor of Science, Instituto de Ecología (IE), Universidad Nacional Autónoma de México (UNAM). Professor-Researcher, Instituto de Estudios Ambientales (IEO), Universidad de la Sierra de Juárez (UNSIJ). Av. Universidad S/N, Ixtlán de Juárez, Oaxaca, 68725. México. e-mail: rclark@juppa.unsij.edu.mx

Mario Fuente Carrasco. Biologist, Universidad Autónoma Metropolitana (UAM-Xochimilco), Mexico. Doctor in Environmental Sciences, Universidad Autónoma de Tlaxcala, Mexico. Professor-Researcher. IEO-UNSIJ, Mexico. e-mail: fuente@juppa.unsij.edu.mx

Viviana Rodríguez-Rivera. Chemical Engineer and M.Sc. in Natural Resources Conservation, UNSIJ, Mexico. Professor, UNSIJ, Mexico. e-mail: v_rodriguez82@hotmail.com

Crystian Sadiel Venegas-Barrera. Biologist, M.Sc. and Doctor of Sciences, CIBNOR, Mexico. en Ciencias CIBNOR La Paz Baja California Sur, México. Professor-Researcher. Instituto Tecnológico de Ciudad Victoria, Mexico. e-mail: crystian_venegas@itvictoria.edu.mx

Jorge E. Campos. Biochemical Engineer, Instituto Tecnológico de Jiquilpan, Mexico. Doctor of Sciences, CINVESTAV, Mexico Professor, UNAM-Iztacala. e-mail: jcampos@servidor.unam.mx

María Delfina Luna-Krauletz. Biologist, Instituto Tecnológico del Valle de Oaxaca, Mexico. M.Sc. in Use and Managment of Natural Resources, Instituto Politécnico Nacional, Mexico. (CIIDIR-OAX). Línea de investigación desarrollo comunitario y manejo de fauna. Professor-Researcher. IEO-UNSIJ, Mexico. e-mail: mkrauletz@juppa.unsij.edu.mx

Angela Velasco-García. Graduate in Environmental Sciences, UNSIJ, Mexico. e-mail: angela040_@hotmail.com

Fanny Garvey. Master of Arts. University of Sussex, UK. Professor-Researcher, Nova Universitas, Mexico. e-mail: acuera@gmail.com

Raúl José Silva Gandarillas. Graduate in Law, Universidad Autónoma Benito Juárez de Oaxaca, Mexico. Coordinator, Club de Pesca Antequera de Oaxaca, Mexico. e-mail: raulsilga@hotmail.com

Cecilia Alfonso-Corrado. Biologist, Universidad Autónoma de Aguascalientes, Mexico. Doctor of Science, IE-UNAM, Mexico. Línea de investigación Ecología, Conservación y Genética. Professor-Researcher, IEO-UNSIJ, Mexico. Address: Instituto de Estudios Ambientales, UNSIJ. Av. Universidad S/N, Ixtlán de Juárez, Oaxaca, 68725. México. e-mail: liana@juppa.unsij.edu.mx; encino1@hotmail.com

Landscape is a dynamic, multidimensional environmental entity upon which are delineated the impacts of integrated social, cultural and economic activities (Troll, 2003; Jansen and Pérez, 2008; Berroterán and González, 2010). These factors may also simultaneously constitute a planning unit (Davidson-Hunt, 2003; Berroterán and González, 2010). Bodies of water, particularly lakes and lagoons, have been used and modified in various ways by humans according to their necessity (Rico *et al*., 1995; Fisher, 2007; Alcocer and Bernal-Brooks, 2010). These activities can indicate relevant historical and economic changes to the lacustrine landscape (Nicholson, 1998; Hui *et al*., 2008; Obregón *et al*., 2011).

In the Sierra Juárez mountain range of Oaxaca, Mexico, there lies a body of water called the *Laguna Encantada* ('Enchanted Lagoon'), located in the center of the community of San Pablo Guelatao de Juárez. This body of water is a landscape element that expresses a multidimensional convergence between nature, culture, history and economy in a multidimensional manner. Culturally, it is a regional reference point for Zapotec identity, in that it expresses a diversity of mystical beliefs (Cordero, 2004; Morales, 2006). The etymology of the location's name reflects this significance (Cordero, 2004): *guiela, laguna* (lagoon) and *tao, encantada* (supernatural-enchanted). This lacustrine system is further associated with the child-shepherd who would become president of Mexico, Benito Juárez García (Morales, 2006), and also is a distinctive element in the productive and economic activities of the community (Morales, 2006).

Despite the cultural and socio-economic relevance of this system, the basic morphometric and bathymetric information that is critical for its management is lacking (Montoya-Moreno, 2005; Torres-Orozco, 2007). There is also the need for implementation of limnological and hydrological projects that can aid in preventing its deterioration (Montoya-Moreno, 2008; Roldán-Pérez and Ramírez-Restrepo, 2008; Alcocer and Bernal-Brooks, 2010). The data gathered could resolve the diverse opinions about the dimensions and depth of this body of water. For example, Cordero (2004) indicated that its diameter was 133m with an unknown depth, while Martínez-Luna (2006) and Morales (2006) estimated a diameter of ~60m and a depth of 12m. Also, people in the community suggest diameters between 100-150m and depths of 20-60m (Clark-Tapia *et al*., 2013). Furthermore, processes of historical changes at the *Laguna Encantada* are not well known, making it difficult to link societal activities to changes in dimension and depth.

Lacustrine systems are an excellent way to chronicle environmental history and also to reconstruct successive modifications that have occurred during centuries of social experience (Fisher, 2007; Hui *et al*., 2008). A complementary paired analysis of historical and modern images permits knowledge of changes that have occurred over time, and creates an historical profile of the landscape that may be used to predict future changes (Moseley, 2006; Hendrick and Copenheaver, 2009). In rural communities, where information is lacking, the use of paired images (Hendrick and Copenheaver, 2009) in conjunction with satellite images (Jakobsson *et al*., 2007; Obregón *et al*., 2011) permits the reconstruction of changes in the environment.

The aim of this work is to study the bathymetry and morphometry of the *Laguna Encantada*, along with historical changes in its dimensions, in order to understand the processes of interaction between nature and society in the Guelatao community.

Methods

Study area

The community of Guelatao de Juárez is located 60km north of the state capital of Oaxaca, Mexico, at 1600-2000masl. The region has a temperate sub-humid (Cw2big) and semi-warm humid (ACw2hig) climate, with an annual average temperature of 17.1°C and annual rainfall of 834.3mm (Morales, 2006; INEGI, 2008). The town is bordered on the north by the forest of Ixtlán de Juárez; on the south by Santa María Chicomezuchil and Yahuiche; and on the east by the town of Ixtlán de Juárez (Morales, 2006). The *Laguna Encantada* is centrally located in the town of Guelatao, between 96°29'33" and 96°29'33"N and between 17°19'05" and 17°19'05"E. The body of water is nestled between two small hills of luvisol soil and extrusive igneous rocks (andesite-intermediate volcanic breccia) and sediment (sandstone and shale) of the Lower Cretaceous and Eocene-Miocene era (INEGI, 2008).

The rugged topography, geology and climate of the region are reflected in a nascent network of intermittent surface streams and perennial rivers that surround the community. Only small and intermittent temporary streams flow into the body of water, and there are no tributaries. The lagoon's original vegetation cover was an oak-pine forest that surrounded it. This was completely replaced by cultivated fields that were abandoned between 1970 and 1980, and then replanted with induced vegetation and deciduous forest (Von Thaden-Ugalde, 2012). The body of water contains floating hydrophytic vegetation that is continuously removed as part of cleaning activities in the community. The system has an exit gate located on the south west side whose effluent flow rate is 2.16m^3 per day, coursing through farmland and later into the *Rio Grande*, a tributary of the Papaloapan watershed. One of the most recent modifications to the body of water was made in 1985: the construction of an artificial waterfall with a flow rate of 43.2m^3 per day on the east slope. This flow is not continuous, due to the conduit only being open 12-15 days per month (Clark-Tapia *et al*., 2013).

Bathymetric and morphometric analysis

In November 2012, the contour of the body of water was geographically referenced at 2m intervals with a Garmin GPS 12. Subsequently, we established seven transects (three north-south and four east-west) and two circularly located transects at 3m and 6m from the perimeter. They were recorded with a Hummingbird depth echo sounder (6-24 XHS 100SX with transducer and frequency of 200 kHz) installed in a LOWE fishing boat (model A1457). The depth recording was done at intervals of 2m, geo-referencing each point with a Garmin GPS 12. Records obtained were used to perform an interpolation of the continuous bathymetric surface, applying the spline method to the 12 nearest neighbors at a spatial resolution of 0.5m in ArcView 3.2 (ESRI, 1999). The GRID file obtained was exported to the Idrisi Selva ® program, developed by Clark University, USA (Eastman, 2012). This program was used to estimate bathymetric features (contours, slope and relief) as well as surface and subsurface morphometric dimensions, according to the method of Wetzel and Likens (2000), and Roldan-Pérez and Ramírez-Restrepo (2008). The surface dimensions analyzed were: maximum length; maximum and median width and breadth; area, perimeter, rate of coastal development and the hypsographic curve of the area, calculated with the program ArcView 3.2 (ESRI, 1999). Estimated sub-surface dimensions were: maximum and medium depth; relative depth; maximum and minimum volume, as well as the hypsographic curve and volume.

Historical morphological change

The interpretation processes of morphological changes in a body of water are difficult to assess, particularly on an ecological time scale, e.g., years to hundreds of years. Being mindful of this, we used various images and a satellite scene to analyze temporal changes in the shape and size of the Enchanted Lagoon over an approximate 50 years interval. The images that were used for digitizing the contour of the lagoon were: a) an aerial photo of 1968, scale 1:15000 (CIA Mexicana Aerofoto, Minera Natividad®), b) an orthophoto, dated 1995 (INEGI, 1:20000 scale), b) a high resolution image from Google Earth 2003 (Keyhole Inc., 1:10000 scale) and c) a scene WorldView-2 satellite image, dated 2010 (spatial resolution of 2m Digital Globe). The aerial photo, satellite scene and high-resolution image were spatially rectified (geometric correction), with the orthophoto as a reference, utilizing the ArcView 3.2 program, at a mean square (RMS) of 0.85, 0.96 and 0.73, respectively (ESRI, 1999). Regression analyses were performed in order to determine the chronological relationship between the lake's dimensional change (width and length) and its area. It was not necessary to adjust these variables as they were tested for normality prior to the analyses.

Historical visual resources, such as landscape paintings and photographs of the water system, can provide impressions of the lake, as well as a plausible scenario of historical changes that have occurred over ~120 years. Given this, we decided to utilize photos of two paintings by José María Velasco dated 1887. Velasco was a superlative Mexican scientific researcher and landscape painter. His pictorial depictions of natural scenery were based on scientific dimension and investigation and they function very accurately as a detailed observation tool. We also used two photographs, dated 1949, that are housed in the museum of Benito Juárez in Guelatao. All of these images were analyzed using ArcView 3.2 (ESRI, 1999) in order to obtain the contour, maximum length and maximum width of the system. They were also compared with recent photos of the water system in order to verify these dimensions.

To the southeast of Guelatao is San Juan Chicomezuchil, where an early 17th century Oaxacan codex is housed. This codex is noteworthy for its depiction of the cultural and mythological importance of the lagoon, and also shows its general form 400 years ago. χ^2 tests were performed, using a significance of P=0.05, in order to evaluate changes in the size of the body of water.

Results

Bathymetric and morphometric analysis

The results of the analysis of the water body known as the *Laguna Encantada* indicate that this system is a lake, according to morphometric parameters such as depth, size and volume (Table I). The lake's maximum depth of 7.25m is due to a geological fault in a cliff with southern exposure and a steep slope of 60-83°. This cliff's counterpart has a northern exposure and is the most shallow (<1m) and lesser pronounced of the slopes, with angles of 15-35°, leading to a flat gradual relief located in the center (Figure 1). The body of water has an area of 7505m^2, with a maximum N-S oriented length of 128m and a maximum width in the middle of 79m (Table I, Figure 1). The shape of the lake can be described as ovoid, with its main axis oriented N-S (Figure 2). The value of the length width ratio (1.62) indicates that the lake shape approximates that of a circle. However, the development cost index (F=1.54) shows irregularities in its outline because lakes with values close to 1 tend to a circular form (Table I). The volume development index (D_V) is 0.92, a value less than the form unit (1), suggesting a lacustrine convex shape, as can be seen from the hypsographic analysis of the depth-area curve (Figure 3) and the isobaths on the bathymetric map (Figure 1).

TABLE I
MORPHOMETRIC CHARACTERISTICS OF THE
Laguna Encantada

Morphometric feature	Value
Maximum length (Lmax; m)	128
Maximum width (Bmax; m)	79
Lmax/Bmax	1.620
Maximum depth (Dmax; m)	-7.25
Average depth (Dm; m)	-2.2
Relative depth (Dt, %)	5.92%
Third quartile (D75)	-4.1
Dm/Dmax	0.34
Median (D50)	-1.5
First quartile (D25)	-0.63
Major axis direction	N-S
Perimeter (P; m)	386
Surface area (A; m^2)	7,505
Development index or coastal perimeter (F)	1.54
Volume development index (Dv)	1.021
Form of the lake	Ovoid
Maximum volume (Vmax; m^3)	61,270
Average volume (Vm; m^3)	18,720

The depth-volume curve shows that 93% of the volume of the lake is contained in the initial 5m of depth (Figure 4). Finally, the value obtained for the relative depth is 6.91%, indicating a high thermic stability.

Historical morphological change

The system under study has experienced historical changes in its dimensions, most particularly in the 20th century. During an interval of 50 years it has shown variations in the

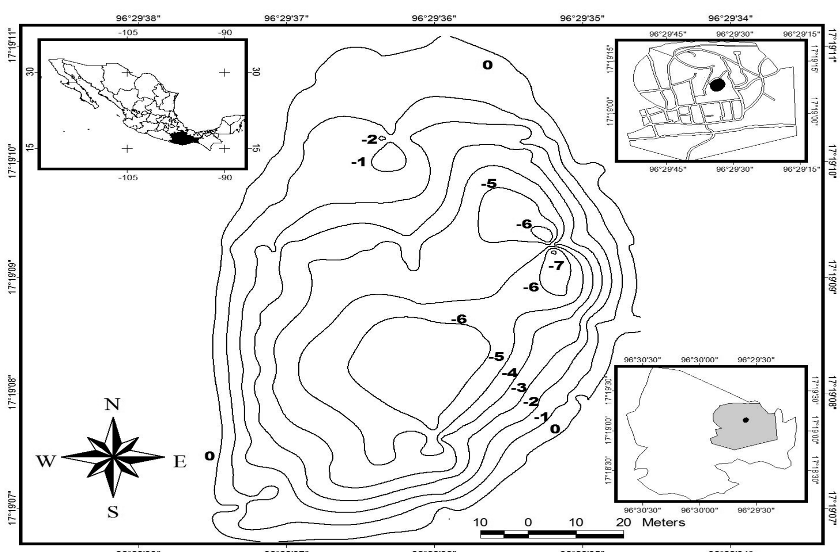

Figure 1. Bathymetric map and geographical location of the *Laguna Encantada* in the municipality of San Pablo Guelatao, Oaxaca, Mexico.

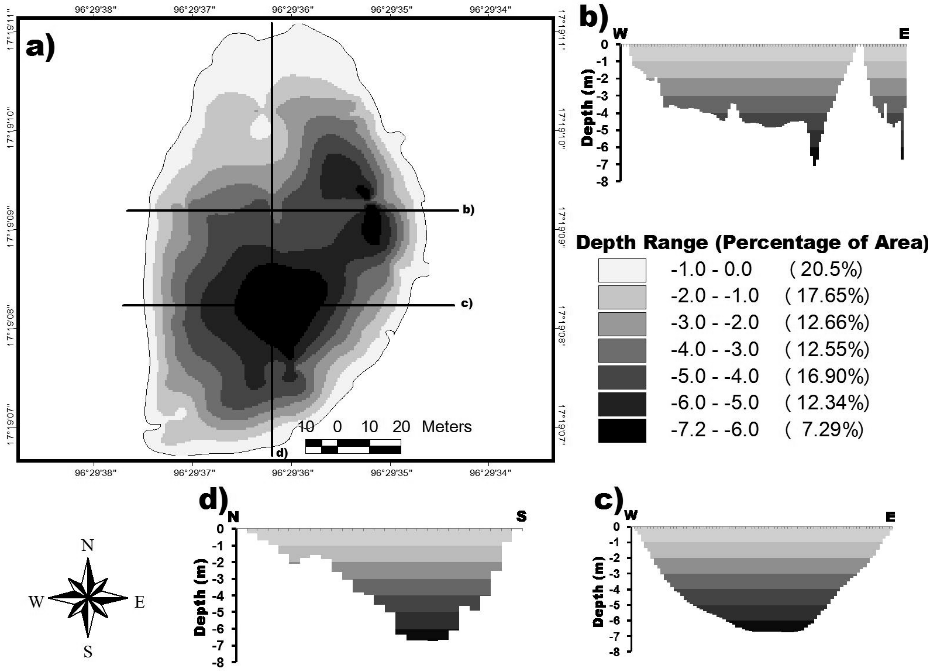

Figure 2a-d. Bathymetric map and bathymetric profiles of the *Laguna Encantada*. a) bathymetric map, b) bathymetric profile (WE) of the second fifth of the longest section, c) bathymetric profile (WE) of the third-fifth the longest section, and d) bathymetric profile (NS).

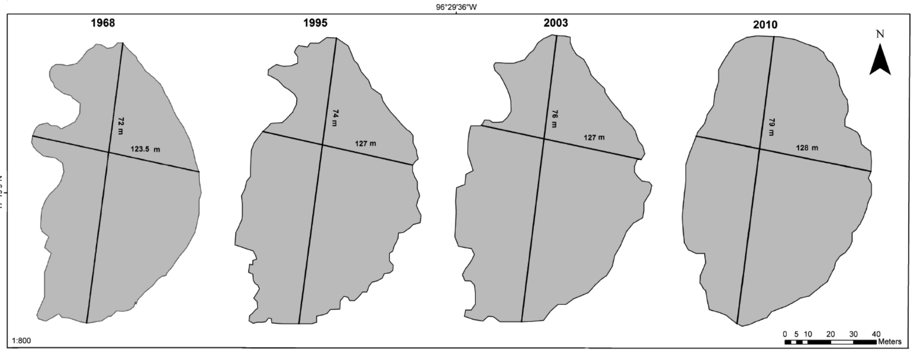

Figure 3. Process of historical change of the *Laguna Encantada* over the past 50 years.

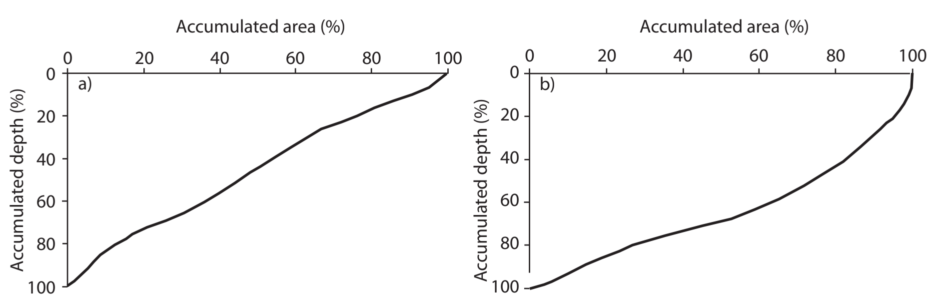

Figure 4. Hypsographic curves relative to the surface (a) and the volume (b) of the lake.

maximum length of 4.5 ±1.8m, in the maximum width of 7 ±0.57m and a mean change in the area of 294.33 ±100.32m^2 (Table II, Figure 3). Since 1968, the relationship between changes in dimensions (width and length) and lake area has been significant ($r^2 = 0.96$, $P<0.016$; Table II). Although the maximum length has varied over the past 120 years (3.66 ±2.84m on average), this measurement has been less than changes in width (5 ±3.90m on average) (Figure 5). The lateral N-S and frontal E-W sides underwent significant changes ($\chi^2= 32.23$, $P=0.05$) in maximum length and width in 1968, and then again in 2010 (Figure 5).

Discussion

Bathymetry and morphometry

Historically, the body of water in Guelatao de Juárez has been called a lagoon (Cordero, 2004; Martínez-Luna, 2006; Morales, 2006). However, the present study indicates it is a tectonic lake basin of fresh water fed by groundwater, precipitation and limited runoff of two typestypes; this is a groundwater drainage lake according to the classification of Shaw *et al*. (2004). Based on the in-depth classification of Agrawal (1999), it is a system of the third order with the same characteristics of a lacustrine system; however, by comparison it is smaller in size to other Mexican lakes (Alcocer and Bernal-Brooks, 2010). Also, it is characterized as other lakes with a well-defined vessel, stratified water volume capacity, its own sediment and macrophyte species (*e.g.* algae, emergent and submerged plants) on its coastline (Löffler, 2004; Roldán-Pérez and Ramírez-Restrepo, 2008; Lewis, 2010).

At present, there is local doubt as to whether or not the body of water in Guelatao is of natural or artificial origins (Roberto Martínez, personal communication). This study suggests that the lake's origins are natural, generated by strong tectonic activity that is characteristic of the Cuicateco lands and the mylonitic complex of Guelatao de Juárez, defined by lateral and frontal faults from the Eocene-Miocene era (Pérez-Gutierréz *et al*., 2009). Another uncertain local factor is the age of the lake; however, stratigraphic stability and volume development suggest that it is a young system (Roldán-Pérez and Ramírez-Restrepo, 2008). The present study has allowed more extensive knowledge of changes in the temporal dimensions of the lake and these may be useful in monitoring it. This lacustrine system of Guelatao is comparable in dimensions to other Mexican epicontinental bodies of water (Rodríguez, 2002; Vázquez *et al*., 2004). Nonetheless, it should be emphasized that the actual depth of 7.25m is not necessarily the original one. It has been documented that lakes are continuously impacted by large amounts of recurrent sediment

TABLE II
DIMENSIONAL CHANGE AND VOLUME OF THE
Laguna Encantada OVER THE PAST 50 YEARS

	Area (m^2)	Lmax (m)	Bmax (m)	Volume (m^3)
1968	6622	123.5	72	38810
1995	6853	127	74	40543
2003	7263	127	76	40967
2010	7505	128	78	41763

Lmax: maximum length, Bmax: maximum width.

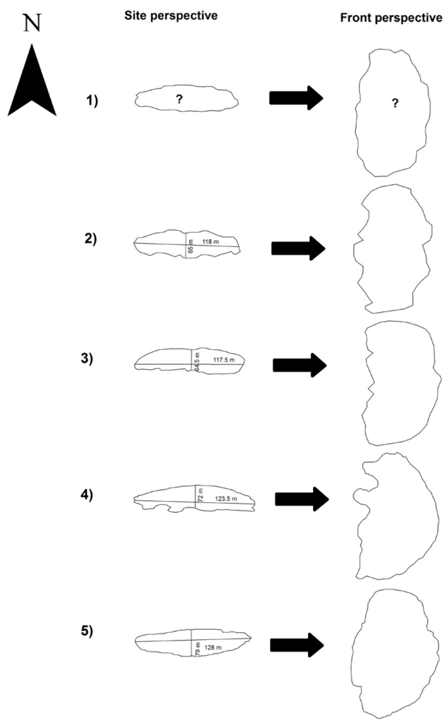

Figure 5. Process of historical change in the last 400 years of the *Laguna Encantada*, San Pablo Guelatao, Oaxaca, Mexico. 1) Chicomezuchil Codex, 17th Century; 2) paintings by José María Velasco, 1885-7; 3) photographs of the lake´s landscape, 1949; 4) aerial photo of 1968; and 5) satellite scene of the lake using WorldView-2, 2010.

contribution. For example, siltation from processes such as erosion and landslides affect their depth (Pérez-Rojas and Torres-Orozco, 1992; Roldán-Pérez and Ramírez Restrepo, 2008). In Guelatao, the lands adjacent to the lake, particularly those with NW and W orientations, have slopes >40° which have been subject to land use change in the past 80 years (Von Thaden-Ugalde, 2012), and this has been a factor in erosion and soil runoff. It is suggested here that sedimentary processes modify the configuration of the basin and lake depth, even when the ratio (Dm/Dmax) suggests a lower risk of clogging before the contribution of solids (Rico *et al*., 1995; Montoya-Moreno, 2008). In 2010, it was documented that a landslide occurred, when a small NW basin ($4m^3$) fell into the water. This has almost certainly been a regular phenomenon during the last century, as a result of changes in land use (Von Thaden-Ugalde, 2012), although it would require a sedimentation and paleo-limnological study to confirm the effect of sedimentary processes in shaping the lake.

Historical morphological change

Land use and climatic changes produce substantial decreases in lake levels (Löffler, 2004, Awange *et al*., 2008; Adrian *et al*., 2009), so it is extremely important to know a system's vulnerability to these factors. Regeneration rates of lake water consist of both surface water sources and groundwater replenishment. In this respect, lakes are similar to other continental bodies of water (e.g. Piper *et al*., 1986; Rodríguez, 2002; Vázquez *et al*., 2004). The system in Guelatao receives water from underground sources and rainfall (>800mm/year), and does not dry out, even during periods of slight or severe drought (Clark-Tapia *et al*., 2013).

The historical level of the *Laguna Encantada* is directly related to groundwater fluxes and direct precipitation and not to the inflow from rivers, as other lakes (e.g. Pipper *et al*., 1986, Ayenew, 2002, Vázquez *et al*., 2004). For 400 years, there has been no verbal or historical record of any desiccation occurring here (Clark-Tapia *et al*., 2013). Rather, historical analyses indicate an increase in both the area and volume of the lake. Community records stated there was an attempt to drain the lake in the 1970's as sanitation strategy. Three high-pressure 3.5Hp water pumps operated for four days (86h) to remove its water. However, due to natural groundwater replenishment, this project was unsuccessful (Clark-Tapia *et al*., 2013). This records also reported that in the 1980's an artificial, inlet shaped waterfall was created for aesthetic purposes. This contributes a variable volume of water to the system, on average, $61270m^3$ in the rainy season and $38763m^3$ in the dry season (Clark-Tapia *et al*., 2013).

This study also identified anthropogenic factors as one determinant of recent changes, similar to other studies (e.g. Pipper *et al*., 1986; Ayenew, 2002). In 1939 the town of Guelatao began a series of socio-political transformations as part of its township recognition process. Various government programs were implemented to give impetus to the local economy and to encourage and increase agricultural and commercial productivity (Martinez-Luna, 2006). For example, in 1955 the 'Papaloapan Commission' laid its foundations on the banks of the *Laguna Encantada*. Formerly known as the Ministry of Water Resources of Mexico, this development program later was incorporated into the Secretary of Agriculture and Hydraulic Resources (Martinez-Luna, 2006). It was during this period that the lake underwent significant modifications, including rock embankments being installed in its shores and the introduction of non-native fruit trees.

These activities created a new landscape for the region of Guelatao. After the Papaloapan Commission failed, re-evaluation of the lake's landscape took place during the 1970's and 1980's. It was during this period that the concept of the lake as part of the landscape took root, and there was a re-assessment of the aesthetic and cultural history associated with it, providing potential for its use in eco-tourism as a source of society development. However, a management plan is necessary to avoid negative impacts (Klessig, 2001; Priskin, 2008). Actually, there is very limited knowledge about ecotourism in Guelatao; accordingly, it would be important to promote safe recreation opportunities, as well as diverse and self-sufficient fisheries. These activities could well promote future lake conservation efforts.

Conclusion

Generally, the results of studying the morphometry and processes of historical change of this lake has provided data about the real dimensions of the lake system while also contributing basic knowledge for the planning of its status as an ecotourism site. Due to the potential source of economic development from such activity, this data is notably useful to the Guelatao community. Additionally, and more specifically, our findings indicate that the water system analyzed here is a natural lake. However, it is recommended to continue calling it *La Laguna Encantada* ('The Enchanted Lagoon'), due to the mythological and sacred nature given to it in oral traditions and legends from the Pre-Hispanic period until now.

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IDENTIDAD, MORFOMETRÍA Y CAMBIO HISTÓRICO DE LA *LAGUNA ENCANTADA* EN GUELATAO DE JUÁREZ, OAXACA, MÉXICO

Ricardo Clark-Tapia, Mario Fuente Carrasco, Viviana Rodríguez-Rivera, Crystian Sadiel Venegas-Barrera, Jorge E. Campos, María Delfina Luna-Krauletz, Angela Velasco-García, Fanny Garvey, Raúl José Silva Gandarillas y Cecilia Alfonso-Corrado

RESUMEN

Cultural y socialmente la Laguna Encantada *de Guelatao de Juárez, estado de Oaxaca, es uno de los cuerpos de agua más importantes de México. En este estudio se analiza la morfometría y procesos de cambio históricos de la* Laguna Encantada *durante los últimos 400 años con la finalidad de conocer procesos de interacción sociedad-naturaleza. El estudio se realizó desde una perspectiva de paisaje, e integró datos batimétricos y dimensiones morfométricas superficiales y sub-superficiales, así como procesos de modificación histórica al cuerpo de agua a partir imágenes satelitales y fotos pareadas. Los resultados obtenidos indican que la* Laguna Encantada *es un lago circular de baja profundidad (7.20m), con un área de 11,610m² y una longitud máxima de 131m. Este sistema sufrió diversas transformaciones en sus dimensiones durante el siglo XX, con un incremento en su tamaño entre los años de 1960 y 2010. La información hidrológica y morfométrica obtenida, así como las transformaciones recientes y la re-evaluación del paisaje son datos básicos que podrán ser utilizados en estudios de monitoreo relacionados con el desarrollo de proyectos de ecoturismo y ecológicos de la laguna.*

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RESUMO

Cultural e socialmente a Lagoa Encantada *de Guelatao de Juárez, estado de Oaxaca, é um dos corpos de água mais importantes do México. Neste estudo se analisa a morfometria e processos de mudanças históricas da* Lagoa Encantada *durante os últimos 400 anos com a finalidade de conhecer processos de interação sociedade-natureza. O estudo se realizou desde uma perspectiva de paisagem, e integrou dados batimétricos e dimensões morfométricas superficiais e subsuperficiais, assim como procesos de modificação histórica ao corpo de água a partir imágens satelitais e fotos pareadas. Os resultados obtidos indicam que a* Lagoa Encantada *é um lago circular de baixa profundidade (7.20m), com uma área de 11.610 m² e uma longitude máxima de 131m. Este sistema sofreu diversas transformações em suas dimensões durante o século XX, com um incremento em seu tamanho entre os anos de 1960 e 2010. A informação hidrológica e morfométrica obtida, assim como as transformações recentes e a re-avaliação da paisagem são dados básicos que poderão ser utilizados em estudos de monitoramento relacionados com o desenvolvimento de projetos de ecoturismo e ecológicos da lagoa.*