Holistic Approach to Watershed Management and Freshwater Conservation and Rehabilitation: A Case Study

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ABSTRACT
Lake Tuxpan is a shallow holomictic water body with a capacity of 18.89 hm^3, a surface area of 4.1 Mm^2, and a maximum depth of 7.86 m. Physico-chemical and biological data in the lake and its main affluent, the El Tomatal River, show the inflow of 107.01 kg $year^{-1}$ of N, 24.54 kg of which come from point sources (22.93%) and 82.41 kg from non-point sources (77.07%). The river's subwatershed produces an average of 18.7 T $year^{-1}$ of sediments, equivalent to 7.45 T ha^{-1} $year^{-1}$ inflowing to the lake. A proposal is made to manage the microwatersheds that have been degraded the most by agricultural activities.

INTRODUCTION

The holistic approach in the integrated management of the watershed involves the orderly and coherent management of everything within its territory (ecosystems and infrastructure and services created by man to meet the needs of housing, transportation, livelihood, recreation, and work), articulated by the geohydrological system delimited by the watershed divide. The goal of management is to regulate human activities, both individual and collective, that take place in a geographical space or region, state, municipality, watershed or aquifer, be they performed by corporations or by social organizations, to execute them harmoniously with the function of the ecosystem. The goals of development are definitions that guide the actions of all the actors that interact in the watershed and that give management processes their sense and rationale (Chavez 2007). The end goal of watershed management is to maintain balance in the ecosystem and an acceptable level of environmental quality though water quantity and quality in the watershed (Caire 2007).

The environment represents a special type of water user, which is why its conservation is the key to for the sustainable management of natural resources, and is the core of aquatic resources management. These are critical points for agricultural, industrial, and energy productivity and for the sustainable development of communities near rives, seeking to reduce poverty and improve health. Environmental strategies should link and balance interests between the environmentally sustainable management of aquatic resources and the generation of wealth for eliminating poverty (Poff et al. 2009). Thus, in this paper, the causes, levels, and degree of the environmental deterioration of the lake are determined, and a strategic plan is developed for the sustainable management of the El Tomatal and Lake Tuxpan subwatersheds in order to achieve the ecological rehabilitation of Lake Tuxpan.

STUDY AREAS

The Tuxpan subwatershed belongs to Hydrological Region No. 18, middle and lower Balsas watershed, located 4.5 km NE of the city of Iguala (Guerrero), between 18° 20' and 18° 22' N and 99° 28' and 99° 30' W. The area of the hydrographic basin is 70 km^2, 2.9 km^2 of which are occupied by the lake. The runoffs in the watershed, which feed the lake and internal springs, form the Tomatal River and the seasonal streams Ceja Blanca, Las Tijerillas, and El Naranjo. It has an artificial effluent called Canal de Llamada. The weather is type A(C)w1(w)i: rainy tropical, with mean temperature in the coldest month over 18 °C and mean annual temperature between 18 and 22 °C; warm in the summer; humid or subhumid with summer showers. Intermediate between hot and warm (semi-hot). Lake Tuxpan is surrounded by limestone/dolomite hills and land with slightly to moderately steep slopes. Standing out in the topography are the hills located towards the NE, N and SW with a height of 1,731 masl. The low-flow streams, together with El Tomatal River, conduct stormwater into the lake. In addition to limestone-dolomite, there is alluvium, polymictic conglometate-sandstone, and luthite-sandstone from the Lower Cretacic, Paleogene Tertiary, and Quaternary periods. A quite diverse array of soil types can be observed, with predominance of ortic and calcic Luvisol (31.24%), calcareous Regosol (19.70%), and calcic and chromic Cambisol (17.97%). These three types of soil occupy 69% of the watershed. There is also Vertisol, Kastanozem, Phaeozem, Rendzina, and Lithosol. There is predominance of lower caducifolia forest (35.85%), followed by induced grazeland (29.88%), and rainfed agriculture (19.28%), which occupy 80.94% of the area. The rest is occupied by oak tree forest, grassland, nopal (cactus leaf) plantations, palm plantations, two-season agriculture, and hydrophytes.

The lake was formed in a depression of the Earth's crust originated by tectonic movements or tectonic subsidence, which, together with a low porosity in the sediments, transformed it into a water deposit (cf. Wetzel, 2001). It is located at 731 masl in the town of Tuxpan, with a population of 140,363 inhabitants (INEGI 2010). The perturbances detected in Lake Tuxpan were induced by human activities in the early 40s, with the expansion of the crop zones of the region and the derivation of the natural riverbed of the El Tomatal River. This abated the depth of Lake Tuxpan at the mouth of the river due to silting, causing an ecological alteration. The input of groundwater is important and can represent half the annual inflow, but with large loads of phosphorus (P) and nitrogen (N).

According to Piperno et al. (2007), the lake had a length of 1.75 to 2.5 km, and is formed by three parallel crusts in the deepest part (5.5. and 5.8 m). They say that the diversion of the El Tomatal River to the lake, more than 50 years ago, poured a layer of four to six meters of sediments. Previously, the depth of the lake was 15 m and hosted a great variety of native fish and crustaceans. This silt caused the loss of 800 to 1,000 years of paleolimnological records. According to these authors, the lake originated in 3000 BC. Old sediments date from 2680 to 40 BC and show presence of pollen and phytoliths that reveal frequent seasonal droughts and eroded material from the lake's banks transported by rainy-season runoffs. Furthermore, they indicate the deforestation of the area due to agricultural activities. *Aulacoseira* stands out from among a wide variety of diatoms. The phytoliths found correspond to *Bursera, Cordia, Euglenia, Protium, Spondias,* and *Sapotaceae* trees, and to the *Elaeis* palm, and are explained by human influence. The steep hillsides propitiated the predominance of *Quercus podocarpus* pollen. The disappearance, in some periods, of *Thyfa* and remains of trees is due to a reduction of precipitation, runoffs and level of the lake towards 2000 BC, coinciding with the drought in Mesoamerica between 1800 and 900 BC, and with the collapse of the Mayan culture.

The vegetation that currently dominates is the lower deciduous forest by 32.1% of the area (*Bursera copallifera, B. bipinnata, Actinocheitha filipina*). Secondary vegetation (*Senna holwayana*, *Acacia macracantha* and *Piscidia carthagenensis*) accounts for 27.6%. In the high parts there is dominance of the oak forest (0.2%), with *Quercus texcocana* and *Q. magnoliifolia* standing out (Nova-Muñoz et al., 2011). The main economic activity in the municipality is tourism, with restaurant infrastructure located around the lake, without adequate water treatment systems, so that wastewater effluents go to septic tanks or directly into the lake (Figure 1).

The boat race known as "Nauticopa" and the activity of jet skiing are important events. Also contributing to the economy of the region are fishing, the mango market, livestock (bovine and caprine), rainfed agriculture (maize, sorghum and peanuts) and irrigation agriculture (vegetables, flowers, fruits).

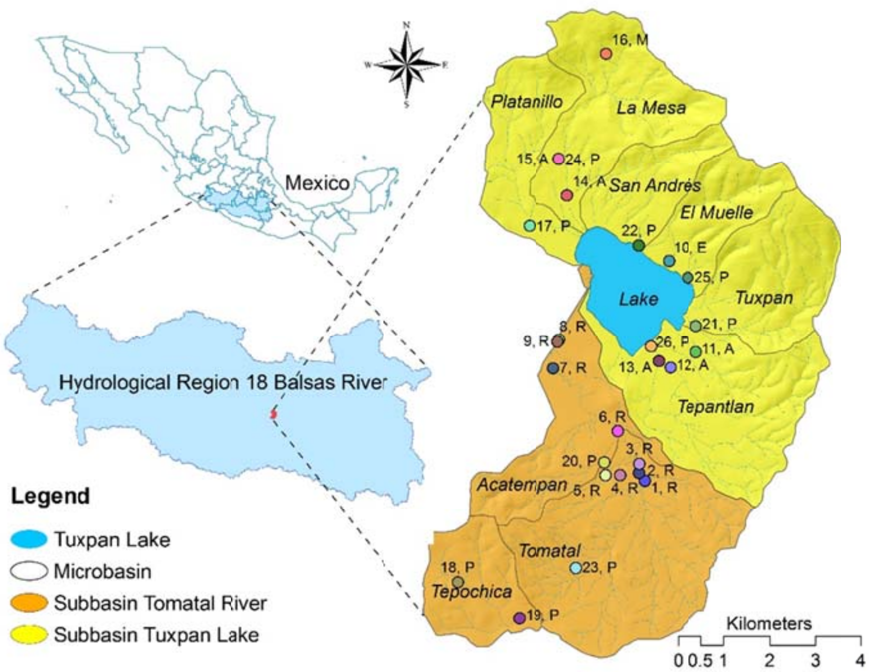

Figure 1. Location of sampling points in the wathershed.

METHODS

The data analyzed were obtained or determined with the following methods: Geophysical: 1) Meteorological. From the Lake Tuxpan station (12222) in the 1981-2009 period, using the Quick Extractor of Climatological Information (ERIC III, V. 2.0). 2) Topography, geology, edaphology, vegetation, and land use, by using GIS maps (INEGI 2012). 3) Erosion and sedimentation, by means of the Universal Soil Loss Equation (USLE) adapted to Mexico (Figueroa et al. 1991). 4) River flow speed, with the wading technique, with electromagnetic equipment Flo-Mate 2000. 5) Bathymetry, with the Garmin GPSMAP 400 eco-probe. 6) Bathymetric profiles, with HEC RAS software, version 4.0 (HEC 1997). Physicochemical: 1) Soil P content, at 20 cm in 20 sampling sites, with a Hanna HI 9828 equipment. 2) Non-point-source contamination was estimated by using the core watershed simulation model MapShed (GWLF-E; USA-EPA, 1999). 3) Total Suspended Solids TSS, Total Dissolved Solids TDS, Total Solids TS; Ortho-P and Total P, Organic N, N-NH_4, Total N Kjeldahl and N-NO_2 in mg/L; Fecal and total coliforms in NMP/100 mL, according to the ecological standard CE-CCA-001/89 and the Ecological Criteria of Water Quality, and other 21 physicochemical and biological parameters according to APHA 2005). 5) Temperature T (°C), electric conductivity Ω (μS/cm), TDS (mg/L), pH, salinity (mg/L), potential redux Eh (mV), dissolved oxygen (DO (mg/L) and turbidity (NTU) in the lake, by sampling in rainy and dry seasons with a YSI 6600-D multiparameter probe, in five surface points and one deep point. 6) Transparency, with Secchi Disk SD (m). 7) Cr, Pb, Cd, Zn and Cu, with flame atomic absorption (AA). As and Hg by hydride generation-AA. 8) Volatile and semi-volatile compounds, by methods 8260B and 8270B, and chromatography. 9) Organochlorinated pesticides and polychlorinated biphenyles GC, by use of the electron capture detector. 10) Organophosphate pesticides GC, by the NPD-specific detector. 11) Carbamates, by liquid chromatography (HPLC) and chemical diversion by column. 12) Water quality of river discharges, according to standard NMX-AA-003-1980. 13) Wastewater and water quality parameters, according to standard NOM-001-SEMARNAT-1996. 14) Floating matter in wastewater and treated wastewater, according to standard NMX-AA-006-SCFI-2010. 15) All with a YSI 556 MPS portable multiparameter equipment (multiprobe system). Bioecological: 1) plankton, by trawling net for 3 min., fixing with 4% formaldehyde for identification, and Lugol's iodine for counting. 2) Chlorophyll *a*, with the trichromatic method. 3) Trophic level of the water body, by applying the Trophic State Index (TSI, Carlson 1977). 4) Microcystin (MC-LR), with the ELISA test (Abraxis® kit, ADDA ELISA). Water samples were taken with a Van Dorn bottle. Toxicity, by bioessays with three indicators: the water flea *Daphnia magna* (NMX SCFI-NMX-AA-087-2010), the microalgae *Selenastrum capricornutum* (US. EPA, 1994. 600/4-90/027), and the bacteria *Vibrio fischeri* (SCFI-NMX-AA-112-1995).

RESULTS

The lake showed a volume of 18.89 hm^3, a surface area of 4.1 Mm^2, a maximum depth of 7.86 m, and a mean of 4.59 m in the altitude of 749.57 masl. It is a shallow water body (Wetzel 2001; Fig. 2), with silting at the river's mouth. The data of the 26 stations in the river, streams, discharges, storm runoffs, springs, wells, and precipitation show that the subwatershed of the river contributes the greatest amount of non-point-source nutrients, and that the subwatershed of Lake Tuxpan is the greatest contributor of point-source contamination. The two watersheds generate 107.01 kg year^{-1} of N, 24.54 of which come from point sources (22.93%) and 82.47 kg come from non-point sources (77.07%). They also generate 14.78 kg/year^{-1} of P, 2.36 kg of which are from point sources (15.99%) and 12.42 kg from non-point sources (84.01%). Regarding total N input (point- and non-point source), the subwatershed of the river generates 53.66 kg year^{-1} (50.14%) and the subwatershed of the lake generates 53.35 kg year $^{-1}$ (49.86%).

The USLE (Universal Soil Loss Equation), the 20 samples of the soil units, the topographic maps, hydrology, water erosion, erosivity factor, soil elevation model, main land uses, sediment production, and vegetation of the 32 microwatersheds show that the subwatershed of the Tomatal River produces an average of 18.7 T year^{-1} of sediments that arrive in the lake, which equals in average 7.45 T year^{-1} of soil loss. The pH of the lake varied between 7.94 and 8.40. Total alkalinity was within the permissible limits, with an average of 146 mg/L. the Ω between 421 and 445 μS/cm, resulted relatively low, and reflected a low concentration of chlorides and sulphates. DO (5.97–7.34 mg/L) exceeds the lower permissible limit for the protection of aquatic life (CE-CCA-001-1989; PVA). BOD_5 indicates that the quality is acceptable to good, and according to the COD, with a low contamination level. Hardness values show soft to slightly hard water (114 to 140 mg/L) with the highest values in the dry seasons. Greases and oils showed low values in the rainy season and high variations upwards of 20 mg/L in the dry season. The physicochemical parameters that no not meet the limits established by the Ecological Criteria for PVA were: total P, $N\text{-}NH_4$, and fecal coliforms (in September, stations E-1 and E-2).

XVI
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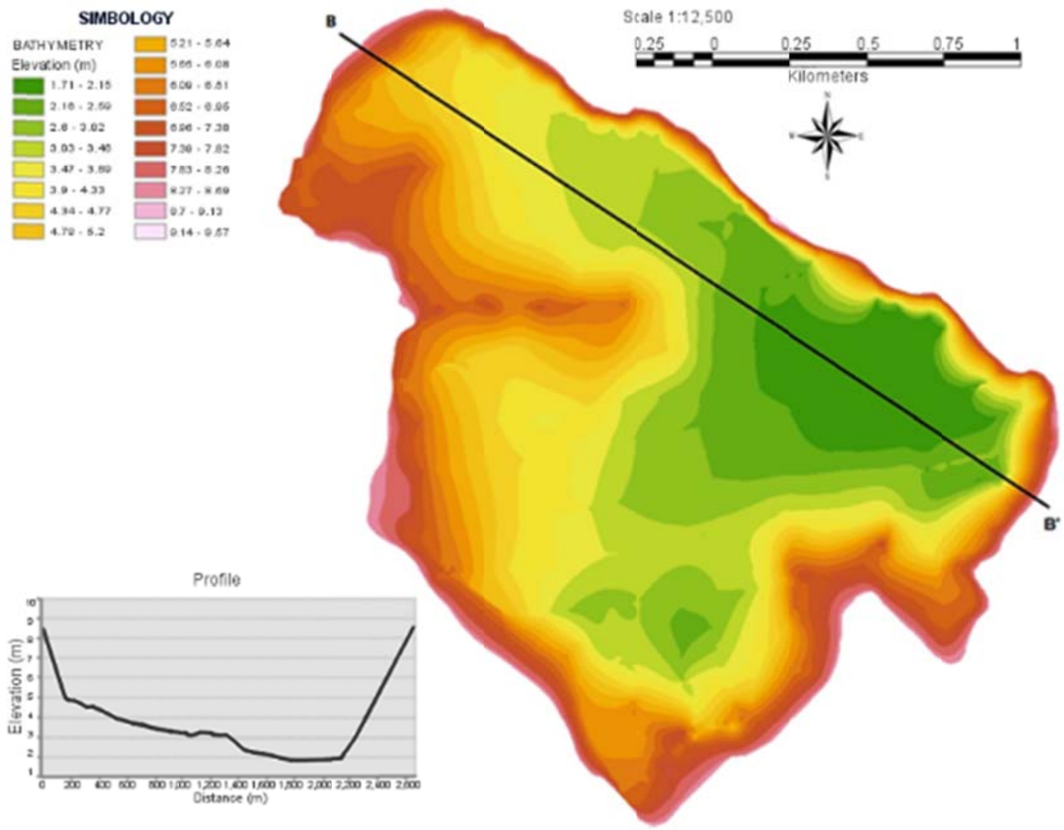

Figure 2. Bathymetry of the Lake Tuxpan (Gro.)

Average values of total P (0.056 mg/L) and total N (2.493 mg/L) point to P as the limiting nutrient, but according to the Trophic State Index (TSI: Carlson 1977), the lake is eutrophic (63.4 units). Turbidity (DS = 0.59 m) suggests a high input of suspended solids and/or abundance of phytoplankton, which, together with human activities (laundering, pouring in touristic wastes, and watering cattle), contribute to its contamination; combined with silt, which reduces the capacity of the lake basin, in increases the trophic grade. During the dry season, T, pH, Ω, and sulfates increase, and DO decreases in the mouth of the river and the restaurant zone of the town of Tuxpan, which can stress aquatic life, an effect which is exacerbated by the higher concentrations of BOD_5 , $N\text{-}NH_4$, organic N, total N, and total coliforms in the laundering area.

Eleven species of phytoplankton were found: *Chroococcus merismopedia* (Bourely, 1970), *Gomphosphaeria* sp., *Microcystis* sp., *Gleocapsa punctata* (Nägeli 1879), *Pediastrum simplex* (Meyen 1829), *Pediastrum duplex* (Meyen 1829), *Ceratium furca* (Ehrenberg) Claparède & Lachmann, 1859, *Ceratium lineatum* (Ehrenberg) Cleve 1899, *Ceratium hirundinella* (O.F.Müller) Dujardin 1841, *Peridinium ovatoides* or *Peridinium cinctum* (O.F.Müller) Ehrenberg, *Coscinodiscus radiatus* (Ehrenberg 1840), as well as six species of zooplankton: *Trachelomonas sp. (Ehrenberg, 1835)*, *Brachionus havanaensis* (Rousselet), *Bosmina longirostris*, *Diaphanasoma birgei* (Korinek 1981), *Keratella cochlearis* and *Limnocalanus macrurus* (G. O. Sars, 1863), which indicate a community characteristic of warm mesotrophic lakes with eutrophication tendency. Due to the content of chlorophyll *a* and the number of cyanophyta cells per milliliter (WHO), there is a relatively moderate to low probability of acute health effects in the rainy season. The cyanotoxin microcystin-LR was not detected anywhere, and toxicity assessed with *Vibrio fischeri, Daphnia magna,* and *Selenastrum capricornutum* indicates that the lake does not have toxins that might damage aquatic flora and fauna development, nor that of humans. However, the presence of six types of phthalates and of the pesticide atrazine point to trash and agricultural activities in the zone as contamination sources.

DISCUSION

The types of soil and the vegetation of the lake basin propitiate a high infiltration, since of the 977.5 mm of average annual rainfall, only from 41 to 52 mm run off through the river subwatershed, which is equivalent to 1.058 hm^3 of water. However, the population lacks a conservationist culture, especially in agricultural areas, where hydric erosion problems occur; thus, the sediments produced in the farms near the streams immediately integrate into the runoff, affecting the hydro-agricultural infrastructure and silting the lake.

Nine point ninety-four percent of the agricultural area of the watershed, without conservationist practices and moderate slope, and the areas with low jungle and gullies that deplete the plant cover, showed moderate to high hydric erosion rates (10–50 T ha^{-1} $year^{-1}$), while in 13.5% of the watershed, with agricultural land in hillsides with over 15% slopes, and grazing or low jungle zones with scant plant cover, the erosion exceeds 50 T ha^{-1} $year^{-1}$, indicating high soil degradation with loss of the arable layer.

Including erosion in the rest of the watershed (73.84% of areas with woods, low jungle and agriculture in soft slope) and the accumulation of sediment transported by the river results in a 2-m reduction of the lake's depth at the mouth, with the progressive loss of its storage capacity and the accumulation of nutrients (80.01% of N and 11.99% of P), which eutrophicate the system.

In average, both subwatersheds release 11.22 T ha^{-1} $year^{-1}$ of sediments, which represent an output of 56,600 T to the lower parts. If the river transports some 18.7 x 10^3 T $year^{-1}$ in a volume of 24.494 x 10^6 m^3, and if the annual runoff volume inflowing to the lake is considered, the morphometry change due to silt will give place to the total loss of the lake in some 127 years, a very short time, geologically speaking, if one considers that the lake is 3,000 years old (Piperno et al. 2007). On the other hand, if one takes into consideration water inflow from all the microwatersheds, the hydraulic residence time of water in the lake is estimated in 6.8 years. This, considering that outflows due to pouring or extraction, evaporation, and fluctuations between more humid or drier years should be balanced with inflows so as to conserve the water body.

The presence of six types of phthalates, derived from oil to produce polyethylene, polyvinyl, polystyrene, polypropylene, and other polymers used for the manufacturing of toys, food containers and drink bottles, as well as for cosmetic and personal care products (such as fragrance fixatives), implies plastic contamination. Phthalates are considered high-risk contaminants for the aquatic environment and human health, due to the damage that they cause in the endocrine system of species in reproduction

(Oppenheimer et al. 2008 and Miège et al. 2009). Together with the incidence of the pesticide atrazine (triazine) they point to trash and agricultural activity in the zone as contamination sources.

Water contamination comes from laundering at the banks of the lake by visitors and residents of Tuxpan, from the inflows of wastes from restaurants, and from non-point-source contamination from the microwatersheds due to farming activities. In addition, the lack of planning and integrated management of the watershed affects the sustainability of the ecosystem, causing erosion, deforestation, contamination, and biodiversity loss.

Most lake planktonic species are frequently found in warm waters, tolerant to salt concentration. Some can feed themselves autotrophically or heterotrophically, depending on the characteristics of the environment. Generally, these are found in mesotrophic to eutrophic waters (Saratonov 1995), an aspect that places the lake in the limit between both grades due to the high content of nutrients. *Ceratium* may compete well with other species of phytoplankton under stress conditions due to its ability to search for the best conditions for its nourishment and photosynthesis (Heaney and Talling 1980), and can be associated with levels of chlorofill under 15 µg l-1 (Hart y Wargg 2009). The abundance of *Ceratium* is related to high concentrations of total N and P or SRP, an aspect that contrasts with the perception that this genus is an indicator of clear waters, which may be the case for certain species.

The restructuring of planktonic communities associated with sudden blossoming of *Ceratium* could be linked to an unstable trophic state, reflecting the possibility of a transcending threshold change in the ecosystem, as could have happened due to the abrupt human-induced changes that lead to unexpected and sudden conditions (alternation of ecological states), and which can be unfavorable with respect to the ecological services evaluated by society. Underlining this aspect, Alva (2007) notes that *Microcystis aeruginosa* is a highly toxic cyanobacteria that affects several groups of animals (from zooplankton to mamals). The permanent monitoring of the lake is therefore suggested.

The introduction of exotic species, accidentally or intentionally, also causes changes in the ecologic relations of competence, predation, hybridization, and the introduction of fish illnesses. The presence of *Hpostomus* sp in the lake may abate the diversity of flora and fauna due to the fact that it is an invasive species that inhabits shallow fresh waters and feeds on the eggs and/or larvae of native or introduced species, exterminating them, because it also competes with them for food, refuge zones, breeding, laying of eggs, and spawning, and is considered as "one of the greatest threats for the biodiversity of continental aquatic ecosystems and for fresh-water fisheries" (Mendoza et al. 2007). Therefore, the following actions are suggested: 1) To Manage the microwatersheds that contribute with sediment due to agricultural activities, by means of programs for the promotion and adoption of conservationist practices for hillside lands, together with dams within streams and rivers in order to control the sediments and runoffs and help infiltration for aquifer recharge; 2) To control agrochemical substance and make a better management of wastes produced by the population; 3) To reforest the river corridor with adequate vegetation in order to regulate the natural flow of the Tomatal River and its water quality; 4) to control human invasion in river corridors and of the concomitant anthropogenic contamination; 5) To return the Tomatal River to its original riverbed; 6) To control wastewater from touristic activities and from the population that contributes to the contamination of the water body due to the input of solids and nutrients; 7) To control livestock in order to avoid the use of the water body as a watering site; 8) Permanent seasonal monitoring of the lake's water quality in order to assess silting and nutrient input and their dynamics in the watershed, by the processes of point-source- and non-point-source contamination, erosion, and the development of toxic algae blooming; 9) To Study the composition, structure, and function of the local population of the exotic species *Hypostomus* and its relationship with fisheries; 10) To Installation a drainage system of home water harvesting in the town for treating it before it reaches the water body; and 11) To evaluate the strategies for the management, conservation, and rehabilitation of the water bodies.

CONCLUSIONS

Disturbances to the environment generated at the El Tomatal River were induced by human activities in the early 40s related to the expansion of cultivation areas and the diversion of the natural riverbed towards Lake Tuxpan, which modified the frequency, magnitude and periodicity of river flows and hence the structure and function of the river corridor. This alteration was compounded by human invasion, which modified the ecological functions of the El Tomatal River and by the natural disturbances (storms, hurricanes, landslides, etc.) that also exert stress on the river corridor. Therefore, erosion control of hillsides, reforestation of the river corridor with adequate vegetation for regulating the natural flow of the river and its water quality, the rechanneling of the river, and the control of human invasion of river corridors and associated contamination are necessary measures to conserve the water quality of the river and avoid the of a great amount of sediment, nutrients, fecal coliforms, and trash into the lake.

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