CURRENT ECOLOGICAL STATE OF LAKE ATITLAN AND THE IMPACT OF SEWAGE INFLOW: A RECOMMENDATION TO EXPORT SEWAGE OUT OF THE BASIN TO RESTORE THE LAKE

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Unidos por el Lago Atitlán

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EXECUTIVE SUMMARY

Lake Atitlán, recognized as one of the world's most beautiful lakes, has recently been deteriorating due to increased algae concentrations and reduced lake clarity. This is generally acknowledged as a case of cultural eutrophication, in which excess loading of nutrients from human activities in the watershed causes an accelerated change in lake conditions. The consequences are often serious, with cyanobacterial blooms, pathogens, and toxins in the water posing serious health hazards for local populations and visitors who use the lake as a drinking water supply, and reducing its aesthetic value as a world class tourist destination.

Over 100,000 people rely on Lake Atitlán water as their primary drinking water source. Currently, most wastewater produced by the basin's population (>300,000) is discharged into the lake. The phosphorus and nitrogen in this wastewater is accelerating lake eutrophication, resulting in formation of cyanobacterial and algal blooms. Pathogens from this wastewater are a direct threat to the public health, and the degradation of water quality jeopardizes future economic stability of the region. The need for an integrated wastewater management plan is imperative.

In response to these issues and to help develop both local and national capacity related to training and understanding the current conditions at the lake, a USAID-funded project called United for Lake Atitlan was created. This project has been implementing a program of water quality monitoring, nutrient bioassays, watershed assessments and scientific training to support the development of appropriate strategies for restoring and maintaining the unique characteristics for which Lake Atitlan has long been famous.

Of particular concern are the results from evaluation of biological indicators based on the phytoplankton community composition that show the lake water quality is steadily deteriorating with a worrisome increase in the abundance of two types of cyanobacteria, *Microcystis* and *Aphanizomenon*, which are both known to produce cyanotoxins. Furthermore, decreasing concentrations of dissolved oxygen in the deep waters of Lake Atitlan is likely to lead to a substantial increase in the rate of nutrient release from the sediments in a process known as internal loading. This has often caused a dramatic change in lake condition, such that algal blooms become excessive, persistent and often toxic. Such a dramatic change in lake status would be evident to both residents and visitors, eliminating the drinking water source for over 100,000 persons, seriously affecting the aesthetic qualities of the lake, and thus substantially reducing the lake's economic value to the country.

Nutrient bioassay experiments have shown that sewage input to the lake has a disproportionately large effect on lake algae and bacterial production in the water, compared to other nutrient sources such as fertilizer of soil erosion. Thus, the best and most immediate solution is to export all sewage from out of the Lake Atitlan basin, a remedy that has been applied successfully in a number of other cases around the world where important lakes were similarly threatened by cultural eutrophication.

Wastewater treatment plants with discharge of their effluent to the lake are not a solution for preventing the deterioration of Lake Atitlán, on the contrary, they would contribute to further eutrophication. Wastewater export with treatment and reuse will significantly lower further eutrophication of Lake Atitlán and will be sustainable with positive energy generation from wastewater hydroelectric plants and methane production, and reuse of treated effluents with valuable nutrients in agriculture instead of discharging the nutrients into the lake.

CULTURAL EUTROPHICATION OF WATER BODIES - A GLOBAL ISSUE

Cultural eutrophication is the increased loading of nutrients due to human activity promoting deterioration of aquatic ecosystems. High nutrient input often leads to direct human health risks due to high pathogen loading. In addition, it promotes rapid growth of undesirable algal and cyanobacterial species leading to blooms often accompanied by cyanotoxin production. Alterations to the flow of energy through aquatic food webs and changes to biological composition, and disruption in the aesthetic qualities of ecosystem such as water clarity are common (Chislock et al. 2013). The costs of cultural eutrophication are quite large and can be prevented if systematic measures are taken to reduce point and nonpoint source pollution to aquatic ecosystems. If systematic measures are not taken, then costs can be very high. For example, in the US alone, eutrophication results in the loss of $2.2 billion annually (Dodds et al. 2009).

LAKE ATITLÁN: CULTURAL EUTROPHICATION AND CURRENT ECOLOGICAL CONDITION

In the last decade, there have been dramatic changes to the ecology of Lake Atitlan, a highland mountain lake in Guatemala. Research and observations by the research community and agencies show a rapid degradation of the whole lake ecosystem. In December 2008 the first small algal bloom occurred, followed by a second large bloom in October 2009 (Rejmánková et al 2011). The 2009 bloom lasted about three months before the lake cleared again. A visible increase of cyanobacteria was noted in July 2010, months after a mass-wasting event of sediment was introduced from Tropical Storm Agatha. The increased frequency and size of cyanobacterial blooms has concerned Guatemalan policy makers and local residents who are concerned about a) a decrease in tourism and thus livelihoods for communities and b) health effects from toxins and increased disease prevalence common under these types of blooms. In response to these issues and in order to develop capacity related to training and understanding the current conditions at the lake, a USAID-funded project called United for Lake Atitlan was created. The following science based information has been developed as part of this project with contributions from a wider scientific community and is presented here to document the current conditions at Lake Atitlan.

Light dynamics and the reduction in transparency over time.

Light dynamic in lakes is important because it controls the depth the zone of higher plant and algae production that supports fisheries within the lake. Simply stated, plants need light for energy and when light transmission is reduced within a lake, the zones of production that support fish changes. High transparency, or clarity of water, is generally desired by humans and thus changes in water transparency provide an aesthetic measure of water quality. Lake transparency or clarity has traditionally been measured using a black and white disc (Secchi disc) that is lowered into the water until it disappears. Reduced clarity indicates changes in the amount of suspended particles in the water column; these particles can be algae or sediments from run-off. Researchers that have come to Lake Atitlan in the last 100 years have measured transparency using Secchi disc. Thus, comparing values over time allows for an understanding of the change in light dynamics. Figure 1 indicates a dramatic decrease in transparency over time. Note, in the last three years there has been a rapid decline in clarity which we believe is attributable to increased algae concentrations and suspended sediments delivered from the watershed under large storm events.

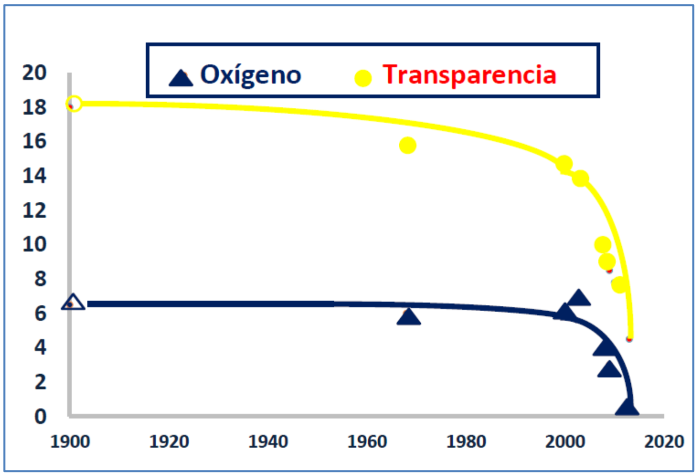

Figure 1. Water transparency (m) and deep-water oxygen levels (mg/L) from Lake Atitlan gathered from historical and our current project over time. Studies for this data include: Juday (1915) and Weiss (1971).

Lake nutrients and sources from waste water discharge.

Lake water is composed of many chemicals from various sources - phosphorus, iron and aluminum from rocks, carbon and nitrogen from microscopic plankton and decomposing plant remnants, etc. In addition, nutrients can get to water from anthropogenic sources like sewage, laundry detergents and fertilizer runoff. Life is dependent upon many of these chemical compounds, therefore it is important to know what nutrients are present in the lake water. Three very important elements for life are carbon, nitrogen and phosphorus. Carbon provides a source of energy, nitrogen is found in proteins and muscles and is excreted in waste; phosphorus is found in DNA, cell walls, and is also used in energy transferring molecules by all organisms. But not all nutrients are needed by organisms at the same concentration. In general, much more carbon is needed than nitrogen, and more nitrogen is needed than phosphorus.

Plants obtain carbon as carbon dioxide from the air, and nitrogen and phosphorus in their inorganic forms from water. That is why we test for nitrate (NO_3), ammonium (NH_4), and phosphate (PO_4). We also measure total nitrogen (TN) and total phosphorus (TP). This is a measurement of all of the possible sources of nitrogen and phosphorus in the water and comes from both living and dead sources. Examples include: live plankton, decomposing leaves, sediment particles in the water column, wastewater in the lake, etc. Although many of these sources are composed of larger organic molecules, they can be a source of nutrition to bacteria and other decomposers which can then release an inorganic and more bioavailable form of nitrogen or phosphorus.

In Lake Atitlan, as in other deep, thermally stratified lakes, nutrient concentrations increase with depth (Figure 2). This is partly because stratification prevents the mixing of nutrients across large depths of water. Algae that are more abundant in the zone of light penetration (about 30 m) are depleting most of the nutrients in the upper layer. Deeper layers are typically richer in nutrients due to sinking and accumulation of dead lake organisms and soil particles, and degradation of particles in deeper water by bacteria or excretion by animals. Ammonium concentrations are near zero everywhere, except between 30 and 50 meters and at the very bottom of the lake. This is likely a result of a large congregation of plankton in the 30-50 m zone releasing ammonium as a waste product. This is also apparent in the nitrate and the phosphate data, where the concentrations are lower in these depths than at the surface and in the deeper waters. This indicates that plankton are taking up nitrate and phosphate at the 30-50 m depths and releasing it as they die and sink to the bottom. In addition discharge of nutrient rich water may be inserted into the lake at these depths depending on the thermal properties and thus, density of the water.

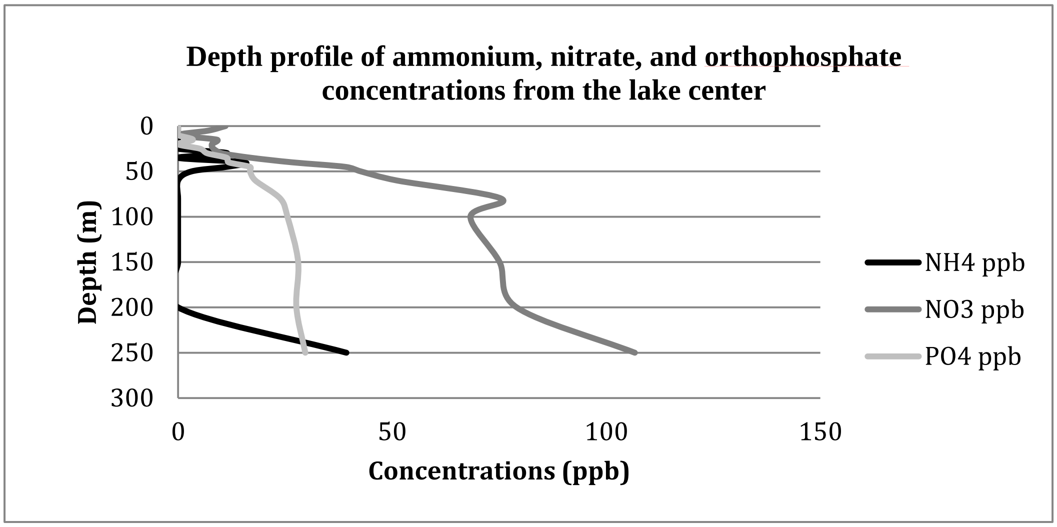

Figure 2. Nutrient profiles from the lake showing that deeper waters accumulate nutrients over time and these are redistributed to the surface layers when the lake mixes.

Wastewater discharge

Despite all the rhetoric about the necessity to deal with sewage inflow to the lake, there is still direct sewage inflow at many locations such as Panajachel, Santa Catarina and Santa Cruz, and at other locations partially treated wastewater is still contributing substantial amounts of nutrients. Rivers San Francisco and Quiscab are also significantly contributing to the lake nutrient loading. Table 1 provides average nutrient concentration in sewage effluent and river water. Waste water has significantly higher concentration of nitrogen and phosphorus forms that we believe are directly resulting in the production of algae and bacteria including potentially harmful cyanobacteria.

Table 1. Examples of concentrations of nutrients in sewage effluent and river water, all in µg/L. Data from measurements taken in irregular intervals during 2010-2012. Note: The total nitrogen (TN) and total phosphorus (TP) values in this table are below the typical values of the wastewater, probably due to the infiltration into sewer.

		PO_4-P	TP	NO_3-N	NH_4-N	TN
WASTEWATER						
Panajachel		2846	7200	5022	4819	10032
Santa Cruz		3200	na	26	3240	na
Santa Catarina		5555	6350	43	6149	7792
RIVER WATER						
San Francisco		138	2958	1702	54	2495
Quiscab		160	1508	1009	83	1635
other rivers		92	370	692	40	1197

Lake phytoplankton

The term plankton refers to the assemblage of free floating or weakly swimming organisms that are predominantly microscopic and adapted to spend their lives in the water column of aquatic habitats. Algae and cyanobacteria are the autotrophic components of plankton, also called phytoplankton, which means that they have the capability to utilize sun energy and carbon dioxide from the air to produce organic carbon. There are several important differences between algae and cyanobacteria: a) many cyanobacteria are capable of fixing nitrogen, i.e., utilizing nitrogen from the air. This gives cyanobacteria an advantage over other species of algae in lakes that have low proportion of nitrogen relative to phosphorus; b) zooplankton feeds preferentially on algae and thus dominance of cyanobacteria can be detrimental to zooplankton growth and consequently fish production; c) many cyanobacteria are known to produce toxins that can be extremely harmful to animals and humans.

In addition to algae, cyanobacteria and zooplankton, the heterotrophic bacterial community forms an important component of plankton. The term heterotroph refers to an organism that cannot utilize the sun energy but depends on an external organic carbon source such as sugar to fuel its activities. In the process of utilizing the organic carbon, heterotrophs consume oxygen. Heterotrophic bacteria represent the most important biological component in the breaking down of organic material in aquatic systems, and their biomass constitutes a large fraction of the total plankton biomass. Organic carbon for heterotrophic bacteria can originate either from dead lake organisms or from external sources. One example of an external source is untreated sewage, which has been shown to highly promote growth of heterotrophic bacteria (see Fig. 5). **When the consumption of oxygen due to the rapid growth of heterotrophs exceeds the production of oxygen by autotrophs, the resulting anoxic (= no oxygen) conditions may lead to many serious consequences including fish kills, increase in release of phosphorus from sediments, etc.**

Cyanobacteria and their increase over time

One planktonic filamentous cyanobacterium that has recently increased in abundance in Lake Atitlán and formed a major bloom in 2009 was first tentatively identified as *Lyngbya robusta* (Rejmánková et al 2011). Further evaluation of *Lyngbya robusta* from Lake Atitlan based on phylogenetic, morphological and ecological criteria resulted in the establishment of a new genus *Limnoraphis* (Komárek et al 2013). The unique feature that sets *Limnoraphis* apart from *Lyngbya* species includes formation of special aerotopes (gas vacuoles that allow cyanobacteria to control their buoyancy) irregularly spaced in cells. In addition, *Limnoraphis robusta* does not have genes for toxin production and it is capable of nitrogen fixation, despite the lack of heterocytes. It contains high amounts of carotenoid pigments, which cause the unusual brown color of macroscopic scum on the water surface.

According to our results, *Limnoraphis* develops in large, oligo- to mesotrophic lakes or reservoirs with increased content of phosphorus. Concentration of nitrogen in the epilimnion is typically quite low. It is interesting to point out that the first record of the planktonic *Lyngbya* (*Limnoraphis*) in Guatemala is from September 1983 from Lake Amatitlán (unpublished records of WHO; Cronberg, personal communication). Apparently this species in Amatitlan was later replaced by *Microcystis*, another cyanobacteria that is known to produce algal toxins. We have been working with cyanbacterial experts to understand the ecology and distribution of taxa to determine if the frequency of blooms may increase.

Phytoplankton in general has shown dramatic increases in abundance over time, from only 354 organisms per liter in July 1968 (Weiss, 1971) to over 400,000 organisms/L in November 2009 (Dix et al. 2012), Fig. 3. Cyanobacteria were not observed by Weiss (1971), but the cyanobacteria *Microcystis* was present in 1976, representing a small percentage of the total (Dix *et al*. 2003). Over time, the numbers increased exponentially (see Figure 3) to over 400,000 organisms per liter in 2009.

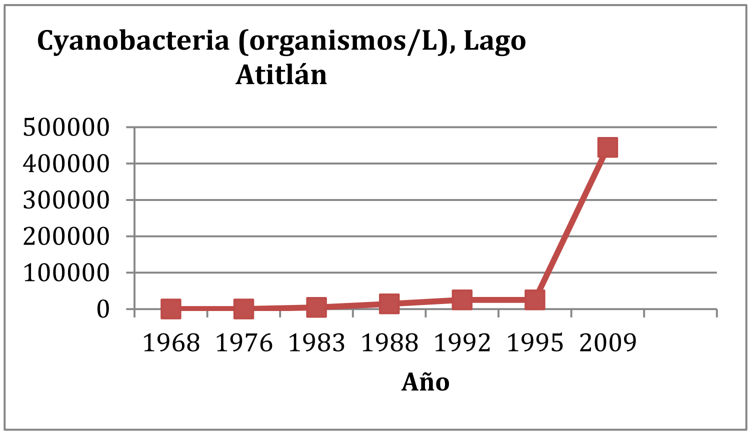

Figure 3. Change in the cyanobacterial count (cells per liter) between 1968 and 2009.

In July 2013 (unpublished data, Dix *et al.*) a bloom with over 8 million cyanobacterial cells per liter, representing 3 genera, *Limnoraphis*, *Aphanizomenon and Microcystis*, was observed in Santiago Atitlán (see Figure 4).

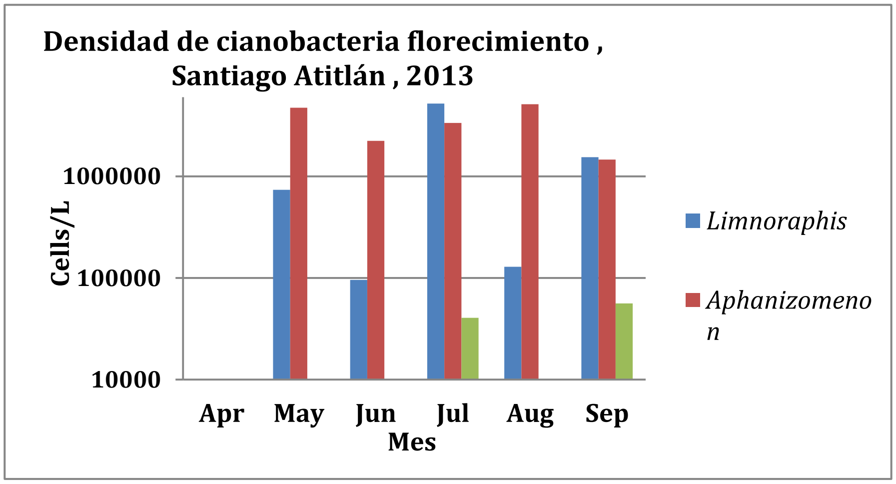

Figure 4. Cyanobacterial counts in Santiago Bay. Note the logarithmic scale.

Aphanizomenon had been observed in San Lucas Tolimán in March 2009 (Castellanos & Dix 2009), but numbers were insignificant until 2013. Like *Limnoraphis*, this genus can fix nitrogen. Both *Limnoraphis* and *Microcystis* are capable of producing cyanotoxins. Fortunately, no cyanotoxins were detected in water samples analyzed in the summer of 2013, but as abundances of *Microcystis* and *Aphanizomenon* increase, toxin production is bound to occur.

The biological indicators based on the phytoplankton community composition show that the lake water quality is steadily deteriorating, and especially worrisome is an increase in *Microcystis* and *Aphanizomenon* abundance, which are both cyanobacteria known to produce

cyanotoxins. The abundance of *Aphanizomenon* reached bloom concentrations (>2 million cells/L) between May and July, 2013. The major source of nutrients contributing to lake eutrophication is the untreated or only partially treated sewage that contributes large quantities of nitrogen.

Connection of sewage loading to algae and bacterial growth using nutrient bioassays

As mentioned earlier, macronutrients of phosphorus and nitrogen are very important for plant growth. The optimal production of plants is often dictated by how the ratio of these nutrients changes over time, dependent on the demand (amount used by the plant community) or on supply from river and sewage inputs into the lake or internal redistribution when the lake mixes. At any given point in time or season, the nutrient requirements of algae and bacteria can be determined by adding nutrients to test containers and observing how those nutrients stimulate their production. In addition, we can determine the reaction of algae to different sources of nutrients supplied from the watershed (e.g. river inputs, sewage, or atmosphere) by placing additions of these nutrient sources into bottles and watching the production of algae over time. We conducted seasonal incubation experiments using lake water from the center of the lake amended with nitrogen, phosphorus, sewage water, or surficial sediment soil particles from various land-based activities. In every incubation, the algae and bacteria growth dramatically increased with sewage introductions, compared to growth from background control levels, nutrient incubations, or soil particles. For example, in Figure 3, algae production increases 333% compared to the background level of nutrients (control). In addition, heterotrophic bacterial demand for oxygen increases with addition of sewage water by 450%. This likely explains part of the resulting decline of oxygen at the bottom of the lake (see below). **These experiments clearly link the sewage to the changes in the lake algae and bacterial production in the water**.

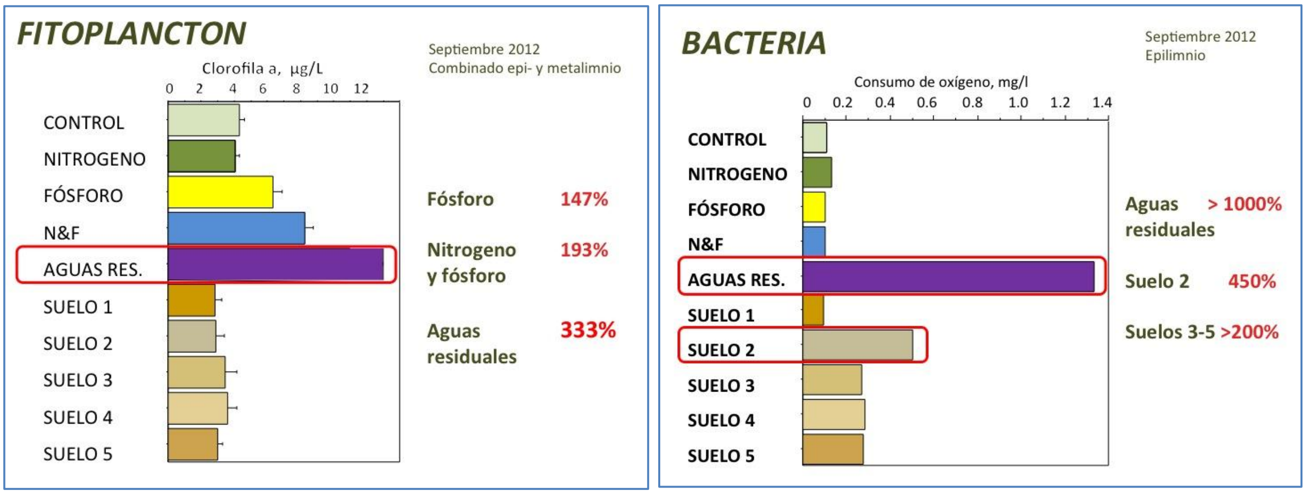

Figure 5. Nutrient bioassays that suggest (a) the lake algal production is limited by nitrogen and phosphorus and sewage production increases algae production by 333% compared to bottles with only lake water, and (b) heterotrophic bacteria production or consumption of oxygen is increased by 450% compared to bottles with lake water and no additions.

Decrease of oxygen levels in the deep waters raise a major concern for the internal health of the lake and potential for future algal blooms.

Dissolved oxygen is a critical component of aquatic ecosystems. First, oxygen levels determine the habitat and survival for higher level consumers such as fish or their food sources (e.g. invertebrates). Oxygen levels also control the form and availability of nutrients that are utilized by algae for their growth. Oxygen levels are lowered in water when there is an increase in production of organic matter which is subsequently decomposed by heterotrophic bacteria (see above). Under these lower oxygen conditions (<2 mg/L), for example, forms of phosphorus become more labile (PO4) and available for algae to grow. When oxygen levels are lowered in the deep water, this can lead to a large volume of available nutrient build up that becomes available to algae living at the surface when the lake mixes. The nutrients released under reduced oxygen conditions in the deep waters results in a phenomenon called internal lake loading, where a lake is no longer entirely reliant on external watershed sources to stimulate algae production, but instead relies on increased availability of nutrients released from the sediments and distributed to upper waters during lake mixing. At Lake Atitlan there is strong seasonal pattern to oxygen, but overall the surface waters continue to remain oxygenated. However, in May to September in 2012 we observed that dissolved oxygen levels from about 80 m to the deeper waters were below 2 mg/L, indicating deteriorating lake condition (Fig. 4). In addition, evaluation of historical information collected from the lake suggests a rapid deterioration of oxygen levels from the lake's deep water (Figure 1). **This indicates that in the last three years, the lake has been undergoing a dramatic shift in deep water dissolved oxygen, with increased potential for internal loading and increased algal/cyanobacterial blooms.**

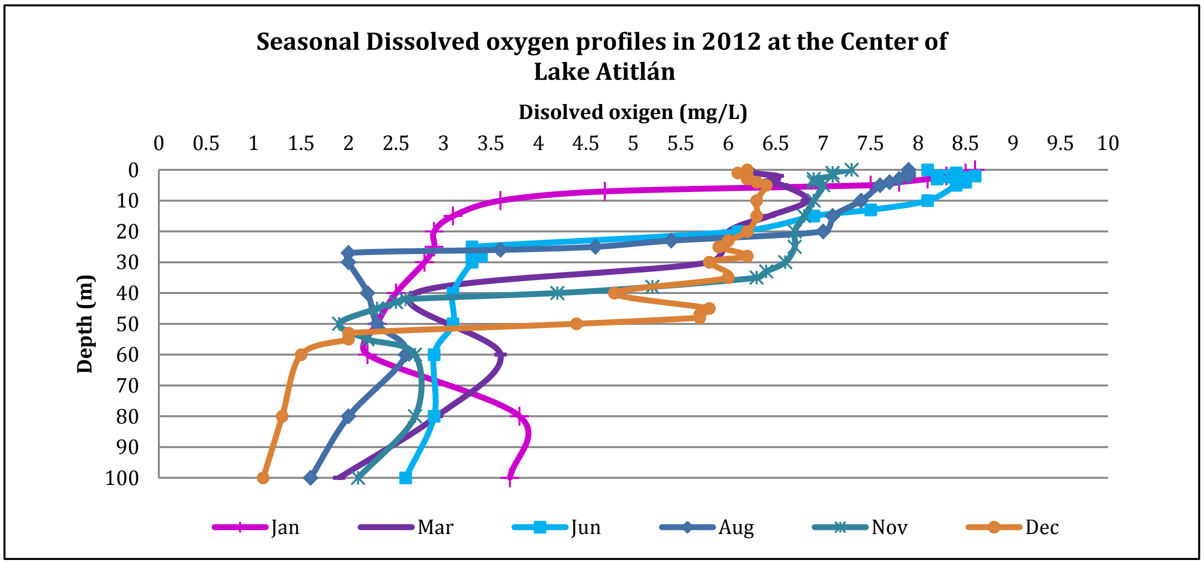

Figure 6. Dissolved oxygen profiles from the center of the lake in 2012.

Pathogens and conditions in the lake

There are several records documenting widespread pathogen infections among people in towns that use lake water as their source of drinking water. Bentley et al (2004) recorded 31% of *Cryptosporidium* infections in residents from villages around the lake and postulated that the lake water was responsible for transmission of the disease. The prevalence of cryptosporidiosis in Latin

American countries varies from 2% to 31%, suggesting a high level of infection in Guatemalan villages. Water and sanitation–related diseases such as diarrhea, dysentery, and intestinal parasites comprised 22% of medical cases among males and 19% of medical cases among females reported at the Ministry of Health post in Santiago Atitlán, Guatemala, in 2007 (Nagata et al 2011). Similar results were reported by Molbey (pers. communication) whose medical team tested 220 school aged children from the same town for giardiasis. The overall incidence of giardiasis was approximately 38%. A report from Tzununa confirms that most of the medical cases are related to waterborne illnesses (Allam et al. 2010). High concentrations of fecal and total coliforms (> 16.10^3) have been reported by Padilla Cámbara et al (2010) in Rio Quiscab.

Public health data for Sololá suggest that 18% of all tap water sampled is contaminated.

Data from March 2013 (Figure 7) indicate that coliforms are distributed all over the lake, with high counts being found in the rivers and the lake area near Panajachel. All sites sampled exhibited counts above acceptable levels for potable water. **The health impact of high pathogen loading from untreated sewage is a major concern.**

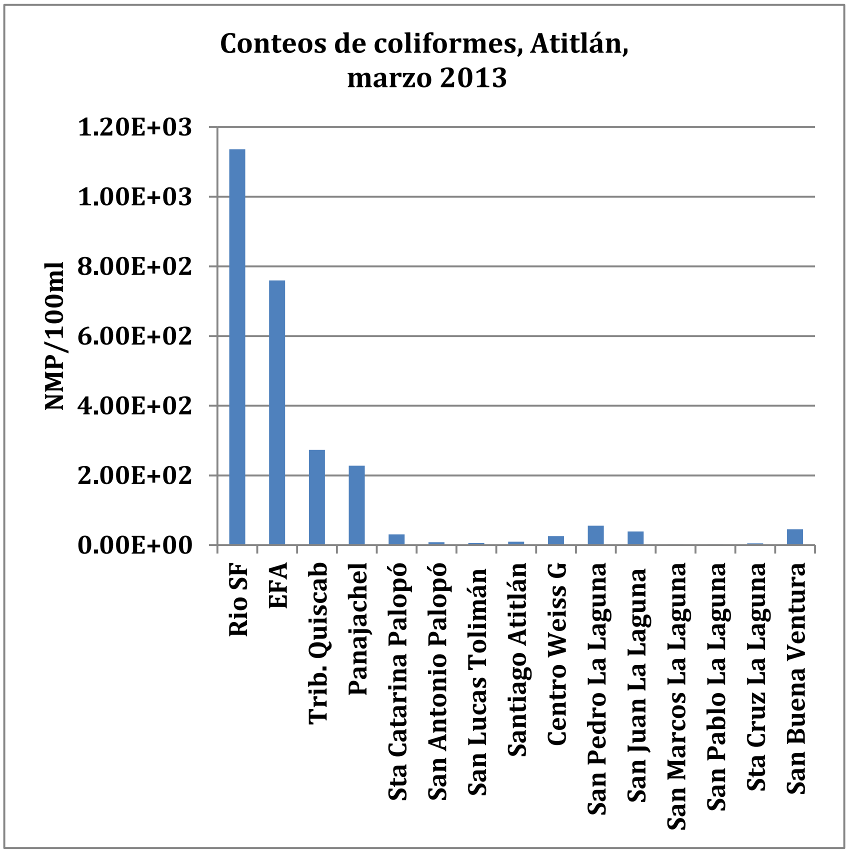

Figure 7. Counts of coliform bacteria from various locations in the lake and rivers. EFA stands for Escuela de formacion Agricola.

HOW TO SOLVE THE SEWAGE LOADING AND LAKE PRODUCTION ISSUES AT LAKE ATITLÁN: INVESTIGATIONS FROM OTHER LAKE ECOSYSTEMS

The pollution of lake and reservoirs by different types of contaminants constitutes a major environmental concern in many parts of the world and a major threat for the world's freshwater resources. As documented above, effluent waters from wastewater treatment plants (WWTPs) represent major sources of contamination for aquatic environments. Among available management practices for lakes, the wastewater effluent diversion out of a watershed is the most effective and in many cases, the only solution. As a result, many countries have implemented research and engineering programs to restore and protect their lake ecosystems by exporting sewage from the basin. There are now multiple examples demonstrating that both total algal biomass and algal/ cyanobacterial blooms occurrence decreases after reduction in nutrient input. One of the classic examples involving decreases in cyanobacterial blooms is that of the removal of sewage discharges from Lake Washington within metropolitan Seattle, Washington (Edmondson, 1970). This lake had sustained noxious cyanobacteria blooms from the 1920s through the 1960s because of sewage effluent inputs, despite prevalent use of wastewater treatment facilities. An elimination of sewage and treatment discharges to Lake Washington was imposed in 1968, and the cyanobacterial blooms declined.

In a much larger system, Lake Erie, the green macroalga *Cladophora* had dominated much of the west basin with massive growth until improved wastewater treatment and detergent phosphate bans in the early 1980s led to significant reduction in the nuisance blooms (Ashworth, 1986). In the Potomac River, a tributary of Chesapeake Bay, phosphate removal from sewage in the late 1970s was related to significant reductions in the frequency and intensity of *Microcystis* blooms that had been problematic in the previous decade (Jaworski, 1990).

Even with successful sewage diversion, the recovery can be long and continuous monitoring and management are needed to prevent lake deterioration due to other causes such as erosion and fertilizer runoff (Verdonschot et al 2012; Hering et al. 2013). The best approach is a well-defined and well-executed program for water quality protection such as, e.g., the European Union Water Framework Directive. It represents the basic legal framework for water quality protection in the states of the European Union and defines the main requirements for water quality monitoring in inland waters, coastal waters, estuaries and lagoons (Premazzi et al. 2003).

Bellow we describe case studies from lake basins that a) conducted similar assay experiments to understand the nutrient limitation for algae growth and influence of (treated and untreated) sewage to lake production and b) determined that export was the primary approach to promoting a healthy lake ecosystem.

Case Studies

***Lake Tahoe**: A case study showing how water export can conserve a lake and the sewage water can be utilized for agricultural interests. Lake Tahoe is a mountain lake located in the Western United States known for its remarkable blue color due to the lack of algae and sediment particles in the water. Water transparency has historically been measured between 23 to 33 meters. Scientific studies utilize nutrient bioassays and monitoring of algae production in the lake over time. Notable increases in algae production over time concomitant with decrease in water clarity measured by Secchi disc had been recorded in Lake Tahoe in the 1960's and 70's. Nutrient assays suggested the introduction of nutrients from sewage were stimulating the algae growth and future input would result in a marked decrease in water clarity and ecological function. Researchers shared this information with the members of the community in the watershed but also with their state and federal, elected officials. There was discussion that increasing the treatment of sewage using waste water treatment plants was the best solution to solving the nutrient loading issue in the lake. However, given the lake's long residence time (650 years), estimation of nutrient budgeting for the lake, and potential longer-term costs of using tertiary, high capacity treatment, it was determined that the export of sewage was the best long term plan for restoring and preserving the lake. As a result, all of the sewage in the basin was collected and exported from the basin in the 1970s* *resulting in the marked decrease in the rate of the loss of clarity and increase in primary algae production. It should be noted that the treated water exported from the basin has high commercial value and is utilized by private farmers growing crops outside of the basin. They value the nutrient rich water as a supply to their crops which allows them to reduce their fertilizer applications.*

Lower Madison Lakes, Wisconsin: *Another case study comes from the Lower Madison Lakes, Wisconsin, which are among the most studied lakes in the world in terms of their response to reduced nutrient loading resulting from diversion of wastewater effluent (Sonzogni et al. 1975). In 1958, after running to the lakes for about 20 years, the treated wastewater from metropolitan Madison was diverted from entering the two lower Madison lakes. This case was unique in that, for the first time, a detailed nutrient budget was determined by measuring the amounts of nutrients entering a lake from various sources. Sawyer et al. (1944, cited in Sonzogni et al. 1975) found that 88 percent of the inorganic phosphorus loading received by Lake Waubesa came from the WWT Plant effluent. These studies were followed by a series of hydrological and chemical investigations of the Madison lakes by a variety of researchers at the University of Wisconsin. These investigations demonstrated that wastewater was a major source of aquatic plant nutrients (such as phosphorus) for the Lakes. Finally, after much public debate and community arguing, it was decided that Madison's treated wastewater effluent should be completely diverted out of the lakes. In December 1958, this diversion was completed. The phosphorus contents of both lakes responded rapidly and permanently to the decreased phosphorus loading. Of considerable importance is the fact that during the period before diversion (1955-1957), the algae of Lake Waubesa consisted of 99% Microcystis. Soon after diversion, there was a striking change in the number of algal species, as Microcystis decreased during the first summer following diversion. Recent evidence indicates that the algal population has remained much more diverse than during the period of wastewater discharge (Sonzogni et al. 1975).*

What happens if you do not export sewage from a basin?

Lake Amatitlán is located in the department of Guatemala and its basin includes not only the capital but also other cities like Villa Nueva, Mixco, Amatitlán, and San Miguel Petapa, among others. Seventy-six percent of the population in the basin lives in urban areas and none of the cities mentioned above has a municipal wastewater treatment plant that would completely treat its wastewater. Due to continuous input of untreated domestic and industrial wastewater, Lake Amatitlán has reached a hypereutrophic status decades ago. Ever since 1967, the progressive deterioration of Lake Amatitlán has been observed, starting with a report from USAC-ERIS and IGN. In 1987 with cooperation of the Mexican Government, a study was published as a master plan for the rescue of Lake Amatitlán. In this study certain projects were identified as priority and urgent, such as: wastewater treatment plants and recollection system for towns around the lake and in the basin, urban planning and recovery of important springs. This plan was not executed completely but certain efforts were completed, like the construction of a couple of wastewater treatment plants around the basin. Since the situation of the lake did not improve, the Authority for the Sustainable Management of Lake Amatitlán (AMSA) was established in 1996 with the objective to rescue the lake. In 2003 AMSA had seven wastewater treatment plants working around the basin and reported 25 more, all except one limited to secondary treatment. The exception is the WWTP, which has wetlands as tertiary treatment treating up to 33% of Rio Villalobos (main superficial inflow) discharge in the dry season. Despite all these efforts, Lake Amatitlán has almost year round blooms of cyanobacteria, transparency is less than 1 meter, coliforms are detected at every lake site, high levels of heavy metals like lead and chromium are present and the huge amount of sediments coming from the river is lowering the depth of the lake at very high rates. ***<u>Thus Lake</u>***

***Amatitlan is a sad proof of the fact that WWTP discharging water to the lake are not a solution*.**

WASTEWATER TREATMENT PLANTS ARE NOT A SOLUTION FOR THE PROBLEM

The above case studies demonstrate that slowing down or reversing the eutrophication process in the lakes can only be achieved by preventing the input of sewage effluent. Existing treatment plants, however, were not designed for total nutrient removal or pathogen removal. The plant at Santa Catarina only removes organic matter. The plant at Panajachel was designed to remove organic matter and some phosphorus, but not nitrogen; it is currently not removing phosphorus because operators do not have a laboratory or the training to be able to dose with aluminum sulfate for phosphate precipitation, while continuously monitoring dosing and removal efficiencies. Neither plant was designed for pathogen removal, which is extremely difficult in wastewater treatment without a very high effluent quality. In all of Latin America it is estimated that less than 10% of generated wastewaters receive any form of treatment, and only approximately 4% receive secondary treatment (WHO/UNICEF, 2013). So-called tertiary treatment, needed for nutrient removal from wastewaters, is nonexistent in Latin America and is only common in the US in the region of the Great Lakes, Florida and Chesapeake Bay (Metcalf & Eddy, 2014).

Although affordable ways for pathogen treatments exist, e.g., in the form of maturation lagoons where pathogens in water are exposed to and eventually eliminated by UV light, these lagoons require a lot of space, which is not available in the basin. Finally, the proper maintenance of a WWTP, especially those based on activated sludge principle which require a lot of electrical energy to operate, is prohibitively expensive and beyond the capabilities of the municipalities to operate. **The bottom line is that wastewater treatment plants are not a solution for preventing the deterioration of the lake**.

OTHER MODELS

A feasible alternative to WWTP is based on the model of Lake Tahoe (see above) with a pressure sewer that would pump all wastewater to a biological treatment facility (stabilization lagoons) outside of the basin where methane can be generated. Additional benefits would include the generation of electricity in the downslope stretches of the sewer, as well as the reuse of treated, nutrient rich water for irrigation of agricultural crops. **Wastewater export with treatment and reuse is expected to significantly lower further eutrophication of Lake Atitlán and will be sustainable with positive energy generation from wastewater hydroelectric plants and methane valorization**, **and reuse of the valuable nutrients (nitrogen and phosphorus) in agriculture instead of discharging them to the lake**.

The proper technology and experience to build a pressure pipe exists in Guatemala (examples)

- Pressure wastewater pipeline for Flores at Lago Peten-Izta.
- Hydroelectric project at Choloma, Guatemala: 7,000 m of HPDE pipe for pressure line.
- Anaerobic ponds with methane generation with carbon credit certification: treatment plant of Agrocaribe near Puerto Barrios, Guatemala.
- Reuse of wastewater in agriculture: common throughout Guatemala in the informal sector without environmental control. This project would remove pathogens to meet the WHO

guidelines for reuse, and valorize the nutrient value of the wastewater for fertilizer.

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