Nutrient Load Analysis of Lago de Yojoa, Honduras

By

Tia M. Trate
B.S. Environmental Engineering
Manhattan College, 2005

Submitted to the Department of Civil and Environmental Engineering in Partial Fulfillment of the Requirement for the Degree of

MASTER OF ENGINEERING IN CIVIL AND ENVIRONMENTAL ENGINEERING
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
JUNE 2006

© 2006 Tia Trate. All rights reserved.

The author hereby grants to MIT permission to reproduce and distribute publicly paper and electronic copies of this thesis document in whole or in part in any medium now known or hereafter created.

Signature of Author

Tia Trate
Department of Civil and Environmental Engineering
May 12, 2006

Certified by

Peter Shanahan
Senior Lecturer of Civil and Environmental Engineering
Thesis Supervisor

Certified by

Andrew J. Whittle
Chairman, Departmental Committee for Graduate Studies
Nutrient Load Analysis of Lago de Yojoa, Honduras

By
Tia Trate

Submitted to the Department of Civil and Environmental Engineering on May 12, 2006 in Partial Fulfillment of the Requirements for the Degree of Master of Engineering in Civil and Environmental Engineering.

Abstract

Lake Yojoa, Honduras is an important natural resource to the people of Honduras. The lake’s water quality has been a controversial subject. This thesis describes a nutrient load analysis performed to gain a better understanding of the water quality. Loads were calculated for point sources, non-point sources, and other sources. These loads were applied to a trophic model to determine the lake’s trophic status. The results of this study seem to point out that much about tropical limnology is unknown. Lake Yojoa appears to be a mesotrophic lake with nitrogen as the limiting nutrient. However, further field evaluation of the limiting nutrient and nutrient loadings is recommended in order to provide information for better management of the lake.

Thesis Supervisor: Peter Shanahan
Senior Lecturer of Civil and Environmental Engineering
Acknowledgement

There are many people I would like to thank for their help and support on this project. First, Pete Shanahan, whose guidance and input was critical to this project. Eric Adams provided his guidance and assistance in gathering data in Honduras. Also, Chad Cox, who initiated the project and was instrumental in obtaining contacts in Honduras. He also was a crucial member of the team, who taught me much about diplomacy.

I thank Mira Chokshi for her loyalty, enthusiasm, patience, and assistance in this project. I couldn’t have done it without her. Additionally, I thank her for countless games of pool and piña coladas. Ari Herrara deserves many thanks as well. His translating skills and general knowledge about Honduras were extremely helpful during the visit to Honduras. I especially thank him for taking me to Donkey Town to have a warm corn drink.

I would also like to thank the Cox, Herrara, and Adams families for their support, patience, and presence in Honduras. Sylvia Schoenbaum also provided many contacts in Honduras and acted as a translator.

A special thanks to my parents and my brother, who have supported me through my seemingly unending academic career. Also, thanks to Tyson Collazo and Charise Amato for unending support and long phone calls.
# Table of Contents

LIST OF FIGURES .................................................................................................................................................. 6
LIST OF TABLES ...................................................................................................................................................... 7
LIST OF TABLES ...................................................................................................................................................... 7

1 INTRODUCTION .................................................................................................................................................. 8

1.1 INTRODUCTION ........................................................................................................................................... 8
1.2 PURPOSE OF STUDY .................................................................................................................................. 8

2 BACKGROUND INFORMATION ......................................................................................................................... 9

2.1 TOPOGRAPHY ............................................................................................................................................... 9
2.2 BATHYMETRY ............................................................................................................................................. 10
2.3 HYDROLOGY ................................................................................................................................................ 11
2.3 METEOROLOGY ......................................................................................................................................... 12

3 STAKEHOLDERS .............................................................................................................................................. 13

3.1 FISH FARMS .............................................................................................................................................. 14
3.2 MINES .......................................................................................................................................................... 16
3.3 WASTEWATER .......................................................................................................................................... 17
3.4 FISH RESTAURANTS (LA CASETAS) ......................................................................................................... 18
3.5 ENEE DAM – HYDROELECTRIC POWER GENERATION .............................................................................. 19
3.6 LAKE RESIDENTS .................................................................................................................................. 19
3.7 AGRICULTURAL PRACTICES ...................................................................................................................... 19
3.8 NON-PROFIT ORGANIZATIONS .................................................................................................................. 20
3.9 ADDITIONAL ACTIVITIES AROUND THE LAKE ......................................................................................... 20

4 BACKGROUND OF TROPICAL LAKES ........................................................................................................... 22

5 BACKGROUND OF NUTRIENTS ....................................................................................................................... 27

5.1 INTRODUCTION .......................................................................................................................................... 27
5.2 LIMITING NUTRIENT ................................................................................................................................. 28
5.3 PHOSPHORUS ............................................................................................................................................ 29
5.4 NITROGEN .................................................................................................................................................. 29

6 NUTRIENT LOAD ANALYSIS BACKGROUND .............................................................................................. 30

6.1 POINT SOURCES ....................................................................................................................................... 30
6.1.1 Las Vegas ............................................................................................................................................... 30
6.1.2 La Casetas ........................................................................................................................................... 30
6.2 NON-POINT SOURCES ............................................................................................................................... 31
6.2.1 Urban, Agricultural, and Forest Runoff ................................................................................................. 31
6.2.2 Groundwater Infiltration ....................................................................................................................... 31
6.3 OTHER SOURCES ..................................................................................................................................... 32
6.3.1 Fish Farms ........................................................................................................................................... 32
6.3.2 Detergents ........................................................................................................................................... 32
6.3.3 Internal Loading ................................................................................................................................... 33

7 METHODS ....................................................................................................................................................... 35

7.1 POINT SOURCES ....................................................................................................................................... 35
7.1.1 Las Vegas ............................................................................................................................................... 35
7.1.2 La Casetas ........................................................................................................................................... 36
7.2 NON-POINT SOURCES ............................................................................................................................... 36
7.2.1 Runoff .................................................................................................................................................. 36
List of Figures

Figure 2.1: Natural reserves surrounding Lake Yojoa ............................................................. 9
Figure 2.2: Bathymetry for Lake Yojoa .................................................................................. 10
Figure 2.3: Inflow (rivers and tributaries) and outflow (canal) ............................................. 11
Figure 2.4: Weather stations around Lake Yojoa ................................................................... 12
Figure 3.1: Various stakeholders in and around Lake Yojoa .................................................. 13
Figure 3.2: Stages of tilapia fish production at Aqua Finca .................................................... 14
Figure 3.3: Production stages at the AMPAC mine ................................................................. 16
Figure 3.4: Wastewater Treatment Facility, Municipality of Las Vegas ................................. 18
Figure 3.5: Discharge pipe from La Casetas ........................................................................... 18
Figure 3.6: Burning of solid waste at landfill outside Peña Blanca ......................................... 21
Figure 4.1: Thermal stratification in a monomictic or dimictic lake ........................................ 24
Figure 4.2: Relationship between mean depth, surface area, and mixing patterns in lakes ... 24
Figure 4.3: Lake types in the tropics ....................................................................................... 25
Figure 7.1: Subwatersheds of Lake Yojoa, overlain on LANDSAT image ............................... 36
Figure B.1: Sampling locations, green indicates secchi disk depth was taken ....................... 51
Figure B.2: Secchi disk ........................................................................................................... 52
List of Tables

Table 4.1: Lake mixing characterizations ................................................................. 23
Table 5.1: Primary productivity controls for tropical and temperate lakes .......... 27
Table 6.1: Nitrogen concentrations through the groundwater infiltration process .... 32
Table 6.2: Nutrient components in fish feed and absorbed by fish ..................... 32
Table 7.1: Subwatershed names and areas .............................................................. 37
Table 7.2: Land usage characteristics by subwatershed ........................................ 38
Table 7.3: Export coefficients .............................................................................. 39
Table 8.1: Total loads by source .......................................................................... 41
Table 8.2: Percentage of total load by source type ................................................ 41
Table 8.3: Non-point source composition by percentage ...................................... 42
Table 8.4: Trophic characteristics of lakes and reservoirs ..................................... 42
Table 8.5: Trophic status classification system quantitative results ...................... 43
Table A.1: Contacts in Honduras ....................................................................... 50
Table B.1: Secchi disk measurements by location ............................................... 52
1 Introduction

1.1 Introduction

Lake Yojoa is the largest freshwater lake in Honduras, with spectacular beauty and remarkable ecological diversity around the lake. It is located in the central west region of Honduras, 125 kilometers northwest of Tegucigalpa, the capital of the country, and 75 kilometers south of San Pedro Sula, the industrial center of the country. Geographically, it is located between 14°45' and 14°57' degree north latitude, and 87°53' and 88°07' west longitude. It has an elevation of 632 meters above the mean sea level. ("Lake Yojoa")

1.2 Purpose of Study

The water quality in Lake Yojoa is of great interest to the local communities, industries, and municipalities. The locals believe that anthropogenic activities have had an impact on the lake's water quality in the past 25 years. Anthropogenic activities that could have major water quality impacts were identified as untreated wastewater, agriculture, aquaculture, and mining. A field study was conducted in January 2006 for three weeks to obtain comprehensive information on various stakeholders. The practices for small and large-scale industries were observed and are explained in the next chapters. Water quality analyses were performed at various locations in and around the lake. Additionally, historical data was collected from various sources on Lake Yojoa's water quality. This data is used to gain a better understanding of the lake's temperature variation and to quantify anthropogenic influences.

This work was accomplished as part of a project completed under the Master of Engineering program at MIT with substantial collaboration from my project partner, Mira Chokshi (Chokshi, 2006). Chapters 1, 2, and 3 of this thesis were co-written with Ms. Chokshi.
2 Background Information

2.1 Topography

The Lake Yojoa region is not a single geographic unit that can be delineated with precision. There are two large natural reserves: National Parks of Santa Barbara on the northwest of the lake and Cerro Azul Meambar on the south east of the lake. These two natural preserves form the boundaries of the contributing watershed of the Lake Yojoa, with large part of these preserves outside the watershed.

The topography of the river basin in the northern sector of the lake is flat. In the east and the west side of the lake, the topography changes from undulating to mountainous, with steep slopes as it approaches the two national forests. In the northwestern and southeastern regions around the lake, the topography is undulating.

Figure 2.1: Natural reserves surrounding Lake Yojoa
2.2 Bathymetry

Lake Yojoa is 16.2 km in length (maximum) and 6.2 km wide (maximum), with surface area of 89 square km, and perimeter of 54 km. The maximum depth of the lake ranges from 26 to 29 m, and the average depth of the lake is about 16 m. (Vaux, 1993)

Bathymetry is defined as the measurement of depth of a water body. The bathymetry for this project was derived from Vaux’s report published in 1993. The bathymetry from this report was digitized using the ArcGIS 9.1 ArcScan tool into GIS format. Digital format of the bathymetry allowed efficient calculations for surface area at various lake depths. Since the bathymetry was digitized for automating surface area calculations, the digital data was projected in North America Albers Equal Area Conic projection, which minimizes area distortions.

Figure 2.2: Bathymetry for Lake Yojoa
### 2.3 Hydrology

Six major rivers and tributaries flow into the lake. These are: Helado, Varsovia, Balas, Raices (El Cianuro), Yure, and Cacao. Figure 2.3 shows these inflow channels. The natural outlet of the lake was historically in the south (near the Varsovia); however with the establishment of a hydroelectric dam on the northern end, the water is diverted to the dam via a constructed drainage canal in the north (Drainage Canal ENEE). The outflow in this canal is controlled to meet the flow requirements for hydroelectric power generation.

![Figure 2.3: Inflow (rivers and tributaries) and outflow (canal)](image-url)
2.3 Meteorology

The annual average temperature recorded for the region around the lake is 22.7 °C. The monthly average temperature is the lowest in December and January (20 °C), and highest in May and June (24.8 °C) (Betancourt and Dulin, 1981). The two natural reserves of Azul Meambar and Santa Barbara on either side of Lake Yojoa form a micro-climate for the region. Partially cloudy conditions persist all year round.

Figure 2.4: Weather stations around Lake Yojoa
3 Stakeholders

Figure 3.1 represents various stakeholders around Lake Yojoa. The term “stakeholders” includes industries discharging directly/indirectly into the lake, people depending on the lake for their water needs and livelihood; and individuals and organizations with general interest in the lake’s water quality.

Figure 3.1: Various stakeholders in and around Lake Yojoa
### 3.1 Fish Farms

Lake Yojoa is used extensively for commercial production of tilapia fish, which is a significant part of the lake ecosystem. Additionally, some locals fish tilapia and largemouth bass using nets and harpoons. The catches of the local fisherman average about 150 pounds per day, a majority of which is tilapia. These fish are then sold to local people and fish restaurants along the lake periphery. In addition to local fishermen, two large scale operations exist. The tilapia co-operative formed by locals is operated and managed by local fisherman of the area. The other and significantly larger production is handled by a company called Aqua Finca Saint Peter Fish.

Aqua Finca Saint Peter Fish is owned by a Swiss proprietor, who started the operations in Honduras in 1997, and provides employment to about 700 people. The company has its operations in two reservoirs: El Cajon and Lake Yojoa; El Cajon has 4 hectares of tilapia cages whereas Yojoa has 2.6 hectares of tilapia cages. The main operations center is located in El Borbotón, which is about 25 km. north of Lake Yojoa.

A typical tilapia fish production operation consists of five major stages as explained below and shown schematically in Figure 3.2.

![Figure 3.2: Stages of tilapia fish production at Aqua Finca](image)

**Nursery Fry:** The tilapia fish are cultured in an indoor temperature-controlled room at the El Borbotón plant. When the fish grows to about 1-5 g. in weight, it is transferred to the next production stage.

**Fingerlings:** Fingerlings are juvenile fish that are fed in baffled open channels at the El Borbotón operation center. The water in the open channels is aerated regularly. The fingerlings mature when they attain a weight of about 25-30 g, at which time they are transferred to open cages in Lake Yojoa or El Cajon reservoirs.
**Mature Tilapia:** Tilapia are raised to full maturity in floating cages in Lake Yojoa and El Cajon. Aqua Finca uses Norwegian-type circular cages, each of 250 m² area and 6m depth, which are constructed on-site. Lake Yojoa has three cables of about 15-18 cages each. The total area of all cages is about 2.6 hectare, which is within the permitted 4.0 hectare limit. Present production in Lake Yojoa is about 4000 tonnes/year with about 1300 tonnes of standing crop at any given time. Tilapia are harvested when they weigh about 250 g.

Tilapia require proteins, lipids, vitamins and minerals in their diet for efficient growth. Alcon, a Honduran feed company, produces this feed with ingredients like animal tissue, dried powdered solid waste recycled from the descaling operation, by-products from vegetable farming like maize, soya, wheat, etc. (Snir et al., 2006) The feed is extremely efficient and environmental friendly; 100% of it floats so there is no settling. The tilapia fish production cycle generally has a duration of eight months, where 2.2 kilograms of feed produces about 1000 grams of fish. (Schmittou, 2003)

**Descaling/Cleaning:** The mature fish are descaled and cleaned to produce fillet at the El Borbotón operations center. The company indicates they provide a very high level of quality control, plant safety, and hygiene. The solid waste is completely reused for biofuel, feed production and other purposes.

**Export:** The fillet is transferred from the Yojoa region to San Pedro Sula airport on a daily basis, and it is exported to the U.S. under the brand of Regal Springs.

Aqua Finca monitors the water quality of Lake Yojoa on regular intervals and reports the results on a quarterly basis. Physical water quality parameters including temperature, pH, DO, and conductivity are monitored at three sampling locations at a depth interval of 1 m. Chemical and biological parameters including nitrogen, phosphorus, total sediment, BOD, COD, and algae are sampled at larger depth intervals at the same locations.
During October 2003 and October 2005, the fishing industry (Aqua Finca and the co-operative) observed sudden fish kills at Lake Yojoa and El Cajon reservoirs. In October 2005, the incident occurred overnight, and Aqua Finca lost up to 260 tonnes of fish in the two reservoirs combined and suffered a major financial blow. (Snir et al., 2006) For detailed explanation of the lake overturn phenomenon see Chokshi (2006).

### 3.2 Mines

AMPAC mine is located in the El Mochito region, northwest of Lake Yojoa. The mine's operations began in 1948; it was acquired by American Pacific Mining Corporation in 1987, and by a trans-Canadian organization, Breakwater, in 1990. It is the biggest mine in Central America and provides employment to more than 200 people from the neighboring village of Las Vegas, one of the largest villages close to the mine. The AMPAC mine currently produces zinc, lead and trace quantities of silver. It mines about 1850 tonnes/day of ore, from which 6.94% is zinc, 1.7% is lead and 0.0087% is silver. (“Operations: El Mochito”; Lago, 2006)

The different stages of the mining operation were observed during the field visit, and are explained in Figure 3.3.

---

![Figure 3.3: Production stages at the AMPAC mine.](image)

**Dry grinding:** The first stage of production involves dry grinding of large sized rocks extracted from the quarry to produce small size pellets.

**Wet grinding:** The next stage involves grinding of the pellets with water to form a wet slurry. Next, chemical compounds including copper sulfate, sodium isopropionate, isobutyl carbinol, calcium oxide, sodium cyanide and zinc sulfate are added. These additives cause the metals to rise at different rates, thus allowing mechanical skimmers to separate them from the slurry. Skimmed metals are further processed for export; residual slurry is taken to next stage.
On-site settling tank: The mining operations have primary setting ponds at the main center in El Mochito, where the residual slurry is pumped. Approximately 40% of the effluent from the settling tank is used to backfill the mine, while the remaining 60% is pumped to a tailings pond located a few miles from the central mining operations.

Off-site tailings pond: The first tailings retention pond was built in 1960. It was replaced with a new one in 1971, and the newest tailings pond will be opened in 2006. The old tailings ponds are vegetated and regularly monitored.

Final disposal: The residual from the tailings pond is discharged in the Raices River about 8 km upstream of Lake Yojoa. The water quality in the Raices River is monitored on a monthly basis at several points upstream and downstream of the discharge point by Dirección de Fomento a la Minería (DEFOMIN). DEFOMIN is the department of the government of Honduras responsible for administration of the country's mineral resources. The comprehensive water quality tests include manganese, zinc, copper, aluminum, arsenic, silver, cadmium, nickel, total chromium, iron, mercury, lead and cyanide. Additionally, DEFOMIN also reports the pH and temperature at these monitoring points. ("Operations: El Mochito", Lago, 2006)

No communication was established with DEFOMIN during the field visit to obtain the water quality reports on the heavy metals listed above.

3.3 Wastewater

One of the major problems plaguing most developing countries is water and wastewater treatment, and Honduras is no different. The largest municipality surrounding the lake is Las Vegas. The municipality discharges its waste to an Imhoff tank, a system that includes primary settling and a septic tank (Figure 3.4). The Las Vegas treatment plant, however, is ineffective, and the wastewater of 600 families is discharged essentially untreated to Raices River about 8 km upstream of Lake Yojoa. (Flores, 2006) Discharge of raw wastewater into a river contributes nutrients to the system, thus having an impact on water quality.
3.4 Fish Restaurants (La Casetas)

The fish restaurants (known as La Casetas) are a tourist attraction, serving approximately 15,000 tourists per month. There are approximately 50 fish restaurants along the south-eastern periphery of the lake. Wastewater from these restaurants, which includes cooking oil, sanitary wastewater and grey water, is directly discharged into the lake. (Santos, 2006) Figure 3.5 shows pipes leading from one of these restaurants directly to the lake.
3.5 ENEE Dam – Hydroelectric power generation

The Empresa Nacional de Energía Eléctrica (ENEE) is the organization in charge of generating and transmitting 1,392 MW of electricity throughout Honduras. The largest hydroelectric generation occurs at El Cajon, at a capacity of 300 MW. (“Descripción del Sistema Interconectado”) The water that is used at this hydropower generation plant is withdrawn from Lake Yojoa through the Drainage Canal ENEE (known as the Artificial Canal). Since the flow rate in this canal is controlled by water requirements at the ENEE plant, the lake water levels severely fluctuate with the withdrawal. Varying lake levels can cause periodic wetting and drying of the lake shoreline, which can induce release of nutrients.

3.6 Lake Residents

Residents of the surrounding towns and villages have a vested interest in the water quality of Lake Yojoa, as well. Although Yojoa is not a drinking water source for the residents, the locals take pride in the aesthetics of the lake. Additionally, locals use the lake for recreational purposes like swimming and boating. Locals also fish the lake for its bass and tilapia. The local economy is highly dependent on the lake and many locals are employed by the fish farms, plantations, hotels, restaurants, etc.

3.7 Agricultural Practices

There are several types of agricultural land uses surrounding the lake, including animal husbandry and crop production. The most common types of crops planted in the region are coffee, yucca, pineapple, and sugar cane (Coello and Pineda, 2006). The types of fertilizers used and application rates for the crops in this region could not be determined as a part of this study. However, rainfall runoff entering Lake Yojoa could contain fertilizers used on these plantations. Slash and burn farming is a common agricultural practice for the sugar cane plantations. The effects of slash and burn farming on water quality are not documented in the technical literature; however, increased sedimentation is a possible impact on the lake’s water quality. Additionally, cattle and chickens are raised on land adjacent to the lake.
Manure from these animals can also find its way into the lake water via rainfall events. Overgrazing of pastures can also lead to increased sedimentation.

### 3.8 Non-profit Organizations

The Asociación de Municipios para la Protección del Lago de Yojoa (AMUPROLAGO) is a non-profit organization supporting the environmental quality of Lake Yojoa. AMUPROLAGO is directed by the mayors of the lake’s surrounding municipalities. The goals of the organization are to conserve the natural resources in the Lake Yojoa watershed.

### 3.9 Additional Activities Around the Lake

In the absence of adequate wastewater collection systems, other villages in the area discharge waste to septic systems. These septic systems are very old and most likely have never been pumped. It is possible that these systems are leaking into the lake through groundwater infiltration. Additionally, septic tanks are used by the three resort hotels along the lake: Agua Azul, Las Glorias, and Las Brisas. (Boesch, 2006)

Open land disposal of solid waste and use of tributary water for washing and bathing are a few examples of the lack of general environmental awareness, lack of infrastructure, and general poverty of the community around Lake Yojoa. Since the infrastructure does not support weekly trash collection and appropriate disposal, small open landfills have been created on the outskirts of villages and towns. For example, the landfill in Figure 3.6 was found outside of the village of Peña Blanca near the ENEE Canal during the field visit. It is not uncommon to see garbage along the sides of the road. Since there are not proper disposal methods, this is a common way to get rid of garbage. The garbage piles may contain liquid wastes that were improperly disposed. The liquid wastes, as well as leachate from these garbage piles, can easily enter nearby surfaces waters, possibly impacting those waters. Also, villagers around Lake Yojoa wash their clothes and bathe in the tributaries to the lake. Detergents used for clothes washing may contain phosphorus, thus contributing nutrients to the lake.
Figure 3.6: Burning of solid waste at landfill outside Peña Blanca
4 Background of Tropical Lakes

Tropical lakes have not been studied to the same extent as temperate lakes. This is primarily because temperate lakes make up about 90% of the world’s natural lakes, while tropical and subtropical lakes fill out the remainder. (Lewis, 2000) The studies that have been conducted are fragmentary and diffuse. Additionally, all limnological principles applied to temperate lakes do not apply to tropical or sub-tropical lakes. (Lewis, 1989) This makes studying a tropical lake difficult.

One of the most popular ways to classify a lake is by the frequency of its mixing. There are several major categories under this classification system: amictic, holomictic, monomictic, dimictic, oligomictic, and polymictic. (Schmid-Araya) Each of these mixing categories are described in Table 4.1.
The most common types of mixing characteristics are monomictic, dimictic, polymictic. A monomictic lake is generally characterized by no ice cover and one annual mixing period. Tropical lakes are generally classified as monomictic lakes. A dimictic lake generally has a seasonal period of ice cover, fall and spring mixing, and a season of stable thermal stratification (Figure 4.1). Dimictic lakes are for the most part found in temperate regions; although other regions have been known to contain dimictic lakes. A polymictic lake generally does not stratify and is usually characterized as a shallow lake. In contrast, very deep lakes can be meromictic. A meromictic lake mixes without mixing the hypolimnion. (Lewis, 2000) Figure 4.2 illustrates the relationship between mean depth, surface area, and mixing patterns in lakes (including five case studies in the tropics). According to this figure, Lake Yojoa would be characterized as a warm monomictic lake.

Table 4.1: Lake mixing characterizations

Source: Schmid-Araya

<table>
<thead>
<tr>
<th>LAKE TYPE</th>
<th>CHARACTERISTICS</th>
<th>GEOGRAPHICAL AREA</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMICTIC LAKES</td>
<td>No vertical mixing, sealed off perennially by ice.</td>
<td>Antarctica, altitude mountains.</td>
</tr>
<tr>
<td>HOLOMICTIC LAKES</td>
<td>Complete vertical mixing at least once a year.</td>
<td></td>
</tr>
<tr>
<td>COLD MONOMICTIC</td>
<td>Water temperatures never greater than 4°C and with one circulation in the summer at or below 4°C.</td>
<td>Arctic and high mountains lakes.</td>
</tr>
<tr>
<td>WARM MONOMICTIC</td>
<td>Water temperatures never drop below 4°C, they circulate freely in the winter at or above 4°C and stratified in summer.</td>
<td>Coastal areas of Northern Europe and North America.</td>
</tr>
<tr>
<td>DIMICTIC</td>
<td>Two periods of mixing, one spring and one autumn.</td>
<td>Cool temperate regions, high elevations in sub-tropical regions.</td>
</tr>
<tr>
<td>OLIGOMICTIC</td>
<td>Tropical, with rare circulation at irregular interval, and temperatures above 4°C</td>
<td>Equatorial regions with high humidity</td>
</tr>
<tr>
<td>POLYMICTIC</td>
<td>Lakes with frequent or continuous circulation.</td>
<td>Shallow lakes</td>
</tr>
</tbody>
</table>
Figure 4.1: Thermal stratification in a monomictic or dimictic lake
Source: “Thermal Stratification”

Figure 4.2: Relationship between mean depth, surface area, and mixing patterns in lakes
Source: Lewis, 2000
Natural tropical lakes, unlike those from temperate regions, have been found to be mostly of river origin (Figure 4.3). River lakes generally receive water from large areas relative to their size (river drainages), thus they are especially sensitive to any changes in the hydrology or water quality of these rivers. (Hairston and Fussman, 2002) Lake Yojoa was formed in a volcanic field; however, this volcano is now extinct. ("Lake Yojoa")

![Figure 4.3: Lake types in the tropics](image)

Source: Lewis, 2000

Tropical lakes differ from those in other parts of the world in that stratification may change and mixing may occur on a daily basis. (Hairston and Fussman, 2002) However, it should be noted that even though there have been well documented studies on tropical lakes, there is still much confusion about the seasonality of mixing cycles in tropical lakes. (Lewis, 2000) Lake Yojoa, however, appears to have one overturn per year. (Chokshi, 2006)

Tropical lakes also typically have a small temperature gradient, which makes it difficult to identify the epilimnion. (Lewis, 1989) Lake Yojoa also has a small temperature gradient most of the year. (Chokshi, 2006) Additionally, tropical lakes are more vulnerable to changes resulting from wind and heat than temperate lakes. This is primarily because of the minimal Coriolis effect, low maximum stability, and high response of stability to changes in heat content. Tropical lakes should be viewed as less stable than temperate lakes because of large, unpredictable, and biotically potent changes in the size of the epilimnion. (Lewis, 1989)
Tropical lakes are much more likely to be oxygen depleted than temperate lakes. Low oxygen concentrations are generally accompanied by large changes in the chemistry of freshwater, especially at the sediment-water interface. (Lewis, 1989) It is difficult to retain oxygen in the hypolimnion of tropical lakes because stratification usually lasts longer (i.e. 10-11 months, rather than 6-9 months in a temperate lake), the water’s ability to hold oxygen at a high temperature is poor, and there are higher rates of microbial metabolism due to increased temperatures. Therefore, because of these factors, anoxia caused by eutrophication or nutrient enrichment will be more significant and will occur more rapidly in a tropical lake. Thus, a small increase in oxygen demand can lead to anoxic conditions in the hypolimnion. (Lewis, 2000)

Stratified lakes lose nutrients in the epilimnion during peak growth periods due to sedimentation. Thus in a tropical lake, because mixing the depth of the epilimnion can be highly variable, the recycling of nutrients from deep water can be large. In the case of a relatively shallow epilimnion, a period of growth may cause nutrient depletion. On the other hand, a thick epilimnion accompanied by cool, windy weather will return nutrients from deep water to the mixed layer. This will, thus, allow higher rates of production to be established near the water surface. (Lewis, 1989)
5 Background of Nutrients

5.1 Introduction

Lake eutrophication (the excessive growth of aquatic plants) is caused by several stimulants including excess nutrients (phosphorus and nitrogen). Table 5.1 compares the stimulants that are responsible for the control of primary production in temperate and tropical lakes. (Lewis, 1989) It is apparent that nutrients are the major cause of deviation from the global maximum in tropical lakes. The global maximum is the primary production when nutrient-sufficient conditions occur at a maximum temperature for a maximum incident irradiance. This scenario occurs at latitudes of 20° to 30°. (Lewis, 1989) Also, it should be noted that biomass nutrient renewal is higher in a tropical lake than a temperate lake. Lewis (2000) attributes this to two factors, the speed with which the limiting nutrient is released and the rate at which nutrients are returned to the growth zone from the hypolimnion to offset sedimentation losses.

Table 5.1: Primary productivity controls for tropical and temperate lakes

<table>
<thead>
<tr>
<th>Causes of deviation from global maximum</th>
<th>Tropical lakes (0–20°)</th>
<th>Temperate lakes (30–60°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incident irradiance (%)</td>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>Temperature (%)</td>
<td>7</td>
<td>49</td>
</tr>
<tr>
<td>Nutrients (%)</td>
<td>48</td>
<td>10</td>
</tr>
<tr>
<td>Total (%)</td>
<td>61</td>
<td>79</td>
</tr>
</tbody>
</table>

Trends in nutrient effects

As a cause of deviation from latitudinal production maximum (%)

<table>
<thead>
<tr>
<th>Biomass nutrient renewal, yr⁻¹</th>
<th>Tropical lakes (0–20°)</th>
<th>Temperate lakes (30–60°)</th>
</tr>
</thead>
</table>

Nutrients can enter surface waters via municipal and industrial discharges and agricultural, urban, and forest rainfall runoff. A direct correlation has been observed between the amount of nutrients entering a water body and the frequency and severity of algal blooms. Increased primary productivity (i.e. algal blooms) can have several impacts on water quality. These
impacts include, but are not limited to, aesthetics, including color and odor; large diurnal dissolved oxygen (DO) variations, resulting in fish kills; and settling of phytoplankton and other aquatic vegetation, causing increased sediment oxygen demand (SOD) and lowering DO in the hypolimnion. (Thomann and Mueller, 1987)

The nutrients described above do not necessarily enter the system in the most bioavailable form. Total phosphorus is made up of a dissolved form and a particulate form. The dissolved form is also composed of several forms including dissolved reactive phosphorus, which is bioavailable. Particulate phosphorus includes both the organic and inorganic forms of phosphorus. Total nitrogen includes organic nitrogen and inorganic nitrogen, which is composed of ammonia, nitrate, and nitrate. During nitrification, ammonia is converted to nitrite, which is quickly converted to nitrate. Also, during denitrification nitrate is converted to nitrogen gas. Inorganic nitrogen is the bioavailable portion of nitrogen. Additionally, nitrogen also has a particulate and dissolved form; however, the particulate form is generally comprised of detritus and phytoplankton. (Thomann and Mueller, 1987)

5.2 Limiting Nutrient

Carbon, nitrogen and phosphorus are required in relatively large amounts for primary production to occur. If one of these three nutrients is unavailable, primary productivity will be limited. The limiting nutrient is the nutrient that is least bioavailable. Usually, either phosphorus or nitrogen is the limiting nutrient; this is because carbon is naturally available. Alkalinity, atmospheric carbon dioxide, and decaying organic matter are all potential sources of carbon. (Masters, 1998) It has been suggested that tropical lakes are nitrogen limited. However, phosphorus limitation can occur in tropical lakes. Some lakes have even been found to have a balance between phosphorus and nitrogen limitation. There is evidence that nitrogen limitation occurs more often in tropical systems. Nitrogen-fixing algae are more prevalent in “unpolluted” tropical lakes than in “unpolluted” temperate lakes. Additionally, tropical lakes contain more reactive phosphorus than temperate lakes. (Lewis, 2000)
5.3 **Phosphorus**

Phosphorus is an essential part of nucleic acids, phospholipids, adenosine triphosphate (ATP) and other building blocks of life; however it is rarely found naturally in bioaccessible forms in freshwater lakes. Phosphorus is the limiting nutrient in most temperate freshwater systems because its only natural supplier is the weathering of rocks. (Hairston and Fussman, 2002) The bioavailability of phosphorus is an important factor in the determination of a lake’s water quality. If the phosphorus is very bioavailable (i.e. there is lots of inorganic phosphorus), it is easier for the phytoplankton to use, thus creating eutrophic conditions. If phosphorus is not bioavailable, it is the limiting nutrient in the lake. Research has shown that high phosphorus loading can lead to high phytoplankton biomass, turbid water, and unwanted biological changes (including but not limited to loss of diversity, disappearance of submerged macrophytes, changes in fish stock, and decreases in top-down control by zooplankton on phytoplankton). (Søndergaard et al., 2003)

5.4 **Nitrogen**

Nitrogen may be more important to water quality in the tropics than in temperate latitudes. The elevated temperatures of the tropics enhance the rock weathering process. This process forms phosphorus, thus more inorganic phosphorus is naturally available in a tropical lake. It may appear that nitrogen-fixing bacteria, which benefit from high temperature at tropical latitudes, would fix nitrogen as such a rapid rate that they would dominate the nitrogen budgets of some tropical lakes. However, nitrogen fixers, while widespread in the tropics, generally supply only a small proportion of the total nitrogen for a tropical lake. Denitrification is also important to the nutrient balance of lakes. In a tropical lake, because the hypolimnion characteristically has high temperatures and anoxia, one may infer that denitrification (i.e. loss of a large proportion of inorganic nitrogen) occurs more often than in a temperate lake. This, however, has not been proven. (Lewis, 2000)
6 Nutrient Load Analysis Background

A nutrient load analysis is typically carried out to identify sources of lake eutrophication. These sources are characterized as point sources, non-point sources, and other sources. A point source is a source that is directly discharged to the water body via a pipe. For Lake Yojoa these include the wastewater from the Municipality of Las Vegas and the waste discharges from La Casetas. A non-point source is a source which is not directly discharged into the water body, but enters the system via an indirect route like rainfall runoff. At Lake Yojoa non-point sources include urban, agricultural, and forest runoff, as well as groundwater infiltration from septic systems. Other sources identified include inputs from fish farms, detergents used for washing clothes in the tributaries, and internal phosphorus loading.

6.1 Point Sources

6.1.1 Las Vegas

As previously mentioned, the Municipality of Las Vegas discharges its treatment plant effluent into El Raices. The raw waste from approximately 3000 people is treated in an Imhoff tank. According to the municipality’s environmental department, the water leaves the system virtually untreated. (Flores, 2006) Municipal wastewaters contain nitrogen and phosphorus. The average municipal domestic wastewater contains approximately 40 mg/L nitrogen and 10 mg/L phosphorus. ("Wastewater characteristics and effluent quality parameters")

6.1.2 La Casetas

La Casetas directly discharge wastewater into Lake Yojoa. This wastewater is comprised of domestic wastewater, as well as grease from the restaurants. Approximately 300 people reside in La Casetas, a popular tourist attraction along the lake, which attracts about 15,000 visitors per month. (Santos, 2006) The domestic wastewater portion of the wastewater is very
similar to that of the Municipality of Las Vegas. However, the used cooking oil is typically composed of hydrocarbons, and would not be a concern in terms of nutrient loading.

6.2 Non-Point Sources

6.2.1 Urban, Agricultural, and Forest Runoff

Rainfall runoff from urban, agricultural and forested areas can contribute nutrients to the lake system. This runoff can contain nutrients from soils, fertilizer, and detritus. Loading from forests has been approximated at 0.4 kg/ha/yr for phosphorus and 3 kg/ha/yr for nitrogen. Similarly urban runoff loads have been approximated for phosphorus and nitrogen at 1 kg/ha/yr and 5 kg/ha/yr, respectively. Additionally, agricultural runoff for phosphorus has been approximated at 0.5 kg/ha/yr and for nitrogen at 5 kg/ha/yr. (Thomann and Mueller, 1987)

6.2.2 Groundwater Infiltration

The remainder of the Lake Yojoa water basin population, approximately 67,000 people, uses septic systems to dispose of their wastes. Additionally, the three hotels along the lake use septic systems. These septic systems are very old and have probably never been pumped. (Boesch, 2006) Valiela et al. (1997) have determined that nitrogen leaving a septic system and entering a freshwater system from a groundwater aquifer has an approximate concentration of 9.8 mg/L. Table 6.1 displays the degradation of nitrogen as it passes through the septic system to the aquifer and after it finally leaves the aquifer.
Table 6.1: Nitrogen concentrations through the groundwater infiltration process

Source: Valiela et al., 1997

<table>
<thead>
<tr>
<th>Steps along path of wastewater flow</th>
<th>Components</th>
<th>Total dissolved nitrogen concentration (mg/L)</th>
<th>Percentage loss of TDN that enters each component</th>
<th>Percentage loss of TDN that occurs in each component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw wastewater entering septic tanks</td>
<td>Septic tanks</td>
<td>72 ± 12</td>
<td>0</td>
<td>6.4</td>
</tr>
<tr>
<td>Effluent leaving septic tanks</td>
<td>Leaching fields</td>
<td>68 ± 7</td>
<td>35</td>
<td>38.6</td>
</tr>
<tr>
<td>Effluent leaving leaching fields</td>
<td>Plumes</td>
<td>44</td>
<td>34</td>
<td>46.6</td>
</tr>
<tr>
<td>Effluent leaving plumes</td>
<td>Aquifer</td>
<td>15</td>
<td>33</td>
<td>8.4</td>
</tr>
<tr>
<td>Wastewater nitrogen leaving aquifer</td>
<td>Total loss relative to raw wastewater nitrogen inputs</td>
<td>9.8</td>
<td>86</td>
<td>100</td>
</tr>
</tbody>
</table>

6.3 Other Sources

6.3.1 Fish Farms

The fish farms contribute nutrient to the system through the fish feed and the feces of the fish. Since the fish farms use floating feed, the amount of feed that is not consumed is negligible. Thus, the primary source is the fish feces. Table 6.2 displays the percentages of nutrients found in the feed. The second column illustrates how much of the nutrient is absorbed by the fish; the remainder exits the fish as waste.

Table 6.2: Nutrient components in fish feed and absorbed by fish

Source: Schmittou, 2003

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>% in Feed</th>
<th>% absorbed by fish</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>5.6</td>
<td>8</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.9</td>
<td>1.4</td>
</tr>
</tbody>
</table>

6.3.2 Detergents

Residents of the lake region were observed laundering clothes in the tributaries to Lake Yojoa. Detergents such as Tide have been found to be composed of approximately 11% phosphate. (Knud-Hanson, 2006)
6.3.3 Internal Loading

Under steady-state conditions a portion of the phosphorus inflow into a lake is retained in the sediment. Retention of phosphorus is measured by the difference between the downward and upward fluxes of phosphorus. The downward flux is mostly caused by sedimentation of particles either entering the lake or being produced in the water column (i.e. algae and detritus). The upward flux (also, gross release of phosphorus), on the other hand, is primarily driven by the decomposition of organic matter (OM) as well as the concentration gradients and transport mechanisms in the sediment. This process is termed internal loading.

Internal loading is a concern in polluted lakes because it can persist for at least ten years (in some cases as much as 20 years or more) after an external nutrient loading reduction has occurred. Several mechanisms may be responsible for internal loading of phosphorus including resuspension, chemical diffusion and bioturbation, and mineralization and microbial processes. Additionally, temperature, redox conditions, iron to phosphate ratio, and pH are several factors that can affect internal loading. Biologically mediated processes are more likely to occur at higher temperatures. Phosphorus internal loading and retention capacity strongly exhibit seasonality, therefore signifying that release mechanisms may both be associated with temperature and biological activity. Thus, internal phosphorus loading can become a problem because of the continually elevated temperature in a tropical setting. (Søndergaard et al., 2003)

The most common interpretation of internal phosphorus loading is explained by redox conditions at the sediment-water interface. The redox conditions are as follows: when dissolved oxygen (DO) is present, the phosphate ion ($\text{PO}_4^{3-}$) tends to form an insoluble salt with iron (Fe). The salt then sinks to the hypolimnion, binds to the sediment, and makes the phosphorus even less bioavailable. (Hairston and Fussman, 2002)

Phosphate can bind to iron and calcium contained in the sediments. Iron binds with phosphate through adsorption of inorganic phosphorus on to FeOOH. Equation 6.1 illustrates this chemical reaction.
\[ \text{FeOOH} + H_2PO_4^- \Leftrightarrow \text{Fe}(O\text{HPO}_4) + OH^- \]  

Binding with calcium occurs when Apatite (Ca$_5$(PO$_4$)$_3$) is available. Ca$_5$(PO$_4$)$_3$ is commonly found in rocks, skeletal materials, and fossil limestone. It can also be created by precipitation with calcium carbonate. Because apatite has a low solubility, it is known to control the solubility of inorganic phosphorus and cause it to bind with calcium carbonate, thus forming apatite. (Golterman, 2004)

In the sediments, if the conditions are anoxic, PO$_4^{3-}$ can become soluble again through bacterial and chemical processes. (Hairston and Fussman, 2002) This is an important “recycling mechanism” for phosphorus in the lake nutrient cycle. In addition, enzymatic hydrolysis can form alkaline phosphatase (APase) another significant method of phosphate regeneration. (Barik et al., 2001) In tropical lakes, the surface sediments are generally anoxic and do not readily bind phosphorus. pH is important in this reduction process because the binding capacity of the oxygenated sediment layer decreases as the pH increases. The ratio of iron to phosphate is also important in internal phosphorus loading. It has been shown that the retention capacity of phosphorus is high as long as the iron to phosphorus ratio exceeds 15 (others say 10); when the ratio is above this, the sediments should be oxidized and reduce the internal loading rate. In addition, perturbation through bubbles produced in deeper sediment layers during decomposition of OM by microbes may enhance the internal loading process. (Søndergaard et al., 2003)

The nutrient load analysis for Lake Yojoa must include point sources, non-point sources, and the other aforementioned sources. The impact of each source type varies for every water body. The following chapter describes in detail the methods for calculating these loads for Lake Yojoa.
7 Methods

7.1 Point Sources

For all point sources, the domestic wastewater discharge was calculated using the following equation:

\[ Q_{ww} = 10^{-3} k q P \]  
(Equation 7.1)

where \( Q_{ww} \) is the domestic wastewater flow (\( m^3/day \)); \( q \) is the water consumption (L/person/day); \( P \) is the population connected to the system; and \( k \) is a “return factor”. The “return factor” is defined as the fraction of consumed water that is returned to the system. This value is in the range of 0.8-0.9. In higher-income areas, the value is lower primarily because more water is used for activities that do not return the water to the sewer (i.e. car washing and watering the lawn). (Mara, 2003) Thus, for the Lake Yojoa region a \( k \) value of 0.9 was applied. The water consumption was calculated using data from The UN’s AQUASTAT database. The database reveals a total population for Honduras on the order of 6 million people. Also, according to AQUASTAT, the average yearly domestic water consumption in the period from 1998 to 2002 was approximately 70 million \( m^3/year \) for the entire country. This equates to about 32 L/person/day. The point-source loading to the lake can then be calculated by multiplying the flow calculated using Equation 7.1 by the nutrient concentration found in Table 6.1.

7.1.1 Las Vegas

Using the above information and the population size of the municipality provided by Flores (2006), the domestic wastewater load for Las Vegas was calculated. This load does not include any industrial waste inputs into the sewer system. The information about discharges from industry is currently unavailable. Additionally, transport through El Raices was not considered in the load calculation, thus, the municipality’s load was assumed as a direct discharge.
7.1.2 La Casetas

The load for La Casetas was carried out in a similar manner. The exception being that additional discharge was included for the 15,000 tourists who visit the restaurants each month. For the tourists, a water consumption value of 5 L/person/visit was assumed. Also, the fish restaurants are directly discharging into the lake; therefore, transport calculations are not necessary.

7.2 Non-Point Sources

7.2.1 Runoff

To calculate the load from agricultural, urban, and forest runoff, the watershed was delineated into 25 subwatersheds (Figure 7.1). Table 7.1 illustrates the names and areas of each subwatershed.

Figure 7.1: Subwatersheds of Lake Yojoa, overlain on LANDSAT image.
Table 7.1: Subwatershed names and areas

<table>
<thead>
<tr>
<th>Watershed Name</th>
<th>area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rio Blanco</td>
<td>1570</td>
</tr>
<tr>
<td>Lago De Yojoa</td>
<td>8160</td>
</tr>
<tr>
<td>Quebrada de Sabanetas</td>
<td>830</td>
</tr>
<tr>
<td>Quebrada la Quebradona</td>
<td>2190</td>
</tr>
<tr>
<td>Quebrada La Joya</td>
<td>950</td>
</tr>
<tr>
<td>Las Cañeras</td>
<td>410</td>
</tr>
<tr>
<td>Quebrada del Cianuro</td>
<td>4360</td>
</tr>
<tr>
<td>Quebrada del Palmar o de Poza Azul</td>
<td>2150</td>
</tr>
<tr>
<td>Quebrada de Balas</td>
<td>1150</td>
</tr>
<tr>
<td>La Guama</td>
<td>650</td>
</tr>
<tr>
<td>Quebrada de los Jutes</td>
<td>550</td>
</tr>
<tr>
<td>Quebrada del Novillo</td>
<td>170</td>
</tr>
<tr>
<td>Quebrada del Aguacate</td>
<td>820</td>
</tr>
<tr>
<td>Monteverde</td>
<td>280</td>
</tr>
<tr>
<td>Buenos Aires</td>
<td>210</td>
</tr>
<tr>
<td>Peñitas</td>
<td>150</td>
</tr>
<tr>
<td>Peñitas 2</td>
<td>190</td>
</tr>
<tr>
<td>Quebrada de Jutiapa</td>
<td>750</td>
</tr>
<tr>
<td>Quebrada del Cacao</td>
<td>840</td>
</tr>
<tr>
<td>El Playon</td>
<td>260</td>
</tr>
<tr>
<td>Horconcitos</td>
<td>4720</td>
</tr>
<tr>
<td>Las Marias</td>
<td>220</td>
</tr>
<tr>
<td>Canal Artificial</td>
<td>1930</td>
</tr>
<tr>
<td>Los Andes</td>
<td>250</td>
</tr>
<tr>
<td>Quebrada de la Pita</td>
<td>1580</td>
</tr>
<tr>
<td>Las Conchas</td>
<td>180</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>35500</strong></td>
</tr>
</tbody>
</table>

Using this information the land uses of each subwatershed were approximated. Table 7.2 gives the land use breakdown of each subwatershed.
Table 7.2: Land usage characteristics by subwatershed

<table>
<thead>
<tr>
<th>Subwatershed Name</th>
<th>Percent Land Usage</th>
<th>Total Land Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Forest</td>
<td>Agriculture</td>
</tr>
<tr>
<td>Rio Blanco</td>
<td>85</td>
<td>5</td>
</tr>
<tr>
<td>Quebrada la Quebradona</td>
<td>90</td>
<td>8</td>
</tr>
<tr>
<td>La Caneras</td>
<td>70</td>
<td>25</td>
</tr>
<tr>
<td>Quebrada de Balas</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Quebrada del Cianuro</td>
<td>60</td>
<td>15</td>
</tr>
<tr>
<td>Quebrada del Palmar o de Poza Azul</td>
<td>60</td>
<td>35</td>
</tr>
<tr>
<td>Quebrada de los Jutes</td>
<td>70</td>
<td>25</td>
</tr>
<tr>
<td>Quebrada del Novillo</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Quebrada del Aguacate</td>
<td>75</td>
<td>25</td>
</tr>
<tr>
<td>Quebrada de Jutiapa</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Horconitos</td>
<td>35</td>
<td>60</td>
</tr>
<tr>
<td>Quebrada de la Pita</td>
<td>90</td>
<td>5</td>
</tr>
<tr>
<td>Las Conchas</td>
<td>95</td>
<td>5</td>
</tr>
<tr>
<td>Las Marías</td>
<td>98</td>
<td>2</td>
</tr>
<tr>
<td>Los Andes</td>
<td>97</td>
<td>3</td>
</tr>
<tr>
<td>El Playon</td>
<td>98</td>
<td>2</td>
</tr>
<tr>
<td>Quebrada del Cocoa</td>
<td>90</td>
<td>10</td>
</tr>
<tr>
<td>Penitas 2</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Penitas</td>
<td>89</td>
<td>11</td>
</tr>
<tr>
<td>Buenos Aires</td>
<td>93</td>
<td>7</td>
</tr>
<tr>
<td>Monteverde</td>
<td>98</td>
<td>2</td>
</tr>
<tr>
<td>La Guama</td>
<td>75</td>
<td>20</td>
</tr>
<tr>
<td>Quebrada La Joya</td>
<td>80</td>
<td>12</td>
</tr>
<tr>
<td>Quebrada de Sabanetas</td>
<td>80</td>
<td>5</td>
</tr>
<tr>
<td>Canal Artificial</td>
<td>50</td>
<td>5</td>
</tr>
</tbody>
</table>

Using the percent land use information, areas of each land use were calculated. The total mass loading due to watershed runoff can be expressed by the following equation:

\[
M = (Ec_f \times A_f) + (Ec_{ag} \times A_{ag}) + (Ec_u \times A_u) \]  (Equation 7.2)

where M is the total mass loading due to watershed runoff (kg/yr); Ec\(_f\) is the export coefficient for forest land (kg/ha/yr); A\(_f\) is the area of the forest land (ha); Ec\(_{ag}\) is the export coefficient for agricultural land (kg/ha/yr); A\(_{ag}\) is the area of the agricultural land (ha); Ec\(_u\) is the export coefficient for urban land (kg/ha/yr); and A\(_u\) is the area of the urban land (ha). The export coefficients can be found below in Table 7.3. (Reckhow et al., 1980)
Table 7.3: Export coefficients

Source: Reckhow et al., 1980

<table>
<thead>
<tr>
<th>Land Use Type</th>
<th>Phosphorus</th>
<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>high</td>
<td>most likely</td>
</tr>
<tr>
<td>Forest</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Agriculture</td>
<td>1.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Urban Runoff</td>
<td>2.7</td>
<td>0.9</td>
</tr>
</tbody>
</table>

7.2.2 Groundwater Infiltration

The groundwater infiltration discharge from septic systems is calculated using the following equation:

\[ Q_{gw} = kqP \] (Equation 7.3)

where \( Q_{gw} \) is the domestic wastewater flow into septic systems (\( \frac{m^3}{day} \)); \( q \) is the water consumption (\( \frac{L}{person/day} \)); \( P \) is the population connected to septic systems; and \( k \) is a "return factor". The water consumption and "return factor" have been assumed to be the same as previously discussed. The total population of the Lake Yojoa watershed has been approximated at 70,000 persons, of which approximately 67,000 do not have access to sewer systems. These residents rely on septic tanks for their sanitation purposes. (Santos, 2006 and Boesch, 2006) The flow calculated in Equation 7.3 is then multiplied by the concentration of the nutrients escaping the aquifer. This concentration has been approximated by Valiela et al. (1997) as 9.8 mg/L. This calculation is very conservative in that it assumes all the waste discharged into the septic system eventually makes it to the lake during the year.

7.3 Other Sources

7.3.1 Fish Farms

The loading from the fish feed was calculated by multiplying the aforementioned nutrient composition (Table 6.2) of the feed by the amount of feed used annually. Aqua Finca, according to their data, used approximately 9.8 million kg of food in 2005. (Aqua Finca, 2006) Then to get the actual loading from the fish into the lake the amount of nutrient absorbed by the fish (Table 6.2) must be subtracted from the loading of the fish feed.
7.3.2 Detergents

The total load of phosphorus from detergents was calculated using the assumption that about 1/8 of the population washes clothes in tributaries to Lake Yojoa. It was also assumed that each family (average family size of 5) washes about 2 loads of laundry per week, using one half cup of detergent per load. Vollenweider (1968) reported that detergents contain about 7 to 12% phosphorus. For this calculation, 10.9% was used, as this is the amount of phosphorus in Tide detergent.

7.3.3 Internal Loading

The internal loading can be calculated by the following equation:

\[ L_i = A \times T \times RR \]  

(Equation 7.4)

where \( L_i \) is the load resulting from internal loading (kg/year), \( A \) is the anoxic area (m\(^2\)), \( T \) is the anoxic period (days/year), and \( RR \) is the phosphorus release rate (kg/m\(^2\)/day). (Nurnberg, 1984) The anoxic area is defined as the portion of the lake bottom that is anoxic; for Lake Yojoa this was approximated as 38 km\(^2\). The anoxic period is the length of time that the anoxic area is without oxygen; for Lake Yojoa this was approximated as 210 days/year. The P release rate is the rate at which phosphorus is released from the sediments. For this calculation the mean P release rate of 14 mg/m\(^2\)/day reported by Nurnberg (1984) was applied.
8 Results and Discussion

Table 8.1 displays the load contribution by nutrient type from each of the sources previously identified.

<table>
<thead>
<tr>
<th>Source</th>
<th>Phosphorus (kg/year)</th>
<th>Nitrogen (kg/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Point Sources</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Las Vegas</td>
<td>320</td>
<td>1300</td>
</tr>
<tr>
<td>La Casetas</td>
<td>41</td>
<td>160</td>
</tr>
<tr>
<td>Total Point Sources</td>
<td>360</td>
<td>1400</td>
</tr>
<tr>
<td>Non-Point Sources</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td>3500</td>
<td>4900</td>
</tr>
<tr>
<td>Agricultural</td>
<td>2700</td>
<td>14000</td>
</tr>
<tr>
<td>Urban</td>
<td>2700</td>
<td>890</td>
</tr>
<tr>
<td>Ground Water Infiltration</td>
<td>8900</td>
<td>6900</td>
</tr>
<tr>
<td>Total Non-Point Sources</td>
<td>87000</td>
<td>500000</td>
</tr>
</tbody>
</table>

As expected, the nitrogen loading from the point sources exceeds the phosphorus loading. Again, in the non-point sources and other sources the nitrogen loading exceeds the phosphorus loading. Overall, there is approximately 5 times as much nitrogen loading as phosphorus loading. Table 8.2 shows the percentage of the total load for each source type. Fish farms appear to be the largest contributor of nitrogen and phosphorus by far, comprising 95% and 83% of the respective loads. This estimation of loading from the fish farms can be confirmed in the report by Schmittou (2003), where the loads for phosphorus were calculated to be 115,000 kg/year.

<table>
<thead>
<tr>
<th>Source</th>
<th>% of Total Phosphorus Load</th>
<th>% of Total Nitrogen Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Point Sources</td>
<td>0.34</td>
<td>0.27</td>
</tr>
<tr>
<td>Total Non-Point Sources</td>
<td>8.5</td>
<td>5.0</td>
</tr>
<tr>
<td>Fish Farms</td>
<td>83</td>
<td>95</td>
</tr>
<tr>
<td>Detergents</td>
<td>4.1</td>
<td>--</td>
</tr>
<tr>
<td>Internal Loading</td>
<td>4.1</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 8.2: Percentage of total load by source type
Additionally, the percent composition of the total non-point sources can be found in Table 8.3. Forest runoff dominates the phosphorus non-point source loading, comprising approximately 40% of the load. Meanwhile the non-point source loading for nitrogen is primarily dominated by agricultural runoff, which comprised about 52% of the load.

Table 8.3: Non-point source composition by percentage

<table>
<thead>
<tr>
<th>Non-point Source</th>
<th>% of Total Non-point Phosphorus Load</th>
<th>% of Total Non-point Nitrogen Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>39.8</td>
<td>18.4</td>
</tr>
<tr>
<td>Agriculture</td>
<td>30.1</td>
<td>52.5</td>
</tr>
<tr>
<td>Urban</td>
<td>30.1</td>
<td>3.31</td>
</tr>
<tr>
<td>Groundwater Infiltration</td>
<td>--</td>
<td>25.8</td>
</tr>
</tbody>
</table>

The trophic status of the lake is still under question; Schmittou (2003) concludes that Lake Yojoa is oligotrophic, but a trend toward eutrophication may be occurring. Boyd (2005) concludes that the lake is mesotrophic. Trophic status for a temperate lake is described by Table 8.4. Additionally, Salas and Martino (1991) have published a model that relates trophic status to mean phosphorus concentration (Table 8.5).

Table 8.4: Trophic characteristics of lakes and reservoirs

Source: Vollenweider (1983)

<table>
<thead>
<tr>
<th></th>
<th>Ultra-oligotrophic</th>
<th>oligotrophic</th>
<th>Mesotrophic</th>
<th>Eutrophic</th>
<th>Hypertrophic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass</td>
<td>Very low</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>Very high</td>
</tr>
<tr>
<td>Green and/or blue-green algae fraction</td>
<td>Low</td>
<td>Low</td>
<td>Variable</td>
<td>High</td>
<td>Very high</td>
</tr>
<tr>
<td>Macrophytes</td>
<td>Low or absent</td>
<td>Low</td>
<td>Variable</td>
<td>High or low</td>
<td>Low</td>
</tr>
<tr>
<td>Production dynamics</td>
<td>Very low</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>High, unstable</td>
</tr>
<tr>
<td>Oxygen dynamics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Epilimnic</td>
<td>Normally saturated</td>
<td>Normally saturated</td>
<td>Variably over-saturated</td>
<td>Often over-saturated</td>
<td>Very unstable varying from high over-saturation to</td>
</tr>
<tr>
<td>Hypolimnic</td>
<td>Normally saturated</td>
<td>Normally saturated</td>
<td>Variably under-saturated</td>
<td>Under-saturated to complete depletion</td>
<td></td>
</tr>
<tr>
<td>Impairment of multi-purpose uses</td>
<td>Low</td>
<td>Low</td>
<td>Variable</td>
<td>High</td>
<td>Very high</td>
</tr>
</tbody>
</table>
In order to gain an understanding of the trophic status of Lake Yojoa, the model provided by Salas and Martino (1991) was applied. Equation 8.1 describes this model:

\[
P_n = \frac{L(P)}{\bar{Z}/T_w (1 + 2\sqrt{T_w})}
\]  

(Equation 8.1)

where \(P_n\) is the total phosphorus (g/L); \(L(P)\) is the areal total phosphorus loading rate (g/m\(^2\)/yr); \(\bar{Z}\) is the average depth of the lake (m); and \(T_w\) is the detention time (yr). (Salas and Martino, 1991) For Lake Yojoa the areal total phosphorus loading rate is approximately 350 g/m\(^2\)/yr, the average depth is 8.5 meters, and the detention time is 3.17 years. Thus the total phosphorus is approximately 29 g/L. Referring to Table 8.5, this puts Lake Yojoa in the oligotrophic category, however, it is trending towards the mesotrophic category.

Another indicator of trophic status of a lake is the amount of algae in the lake. According to Beeton (1971), every pound of phosphorus is capable of creating 700 pounds of algae. For Lake Yojoa, this would amount to about 150,000,000 pounds of algae per year. In January 2006, floating scum, indicative of excessive algae, was observed in one location, near the discharge of the Raices River. To quantify algae, Secchi disk depths were also measured for various locations in the lake (See Appendix B for more details). Secchi disk depths from 3 to 5.5 meters were observed, the average was 4 meters. The Carlson Trophic State Index is commonly used in limnology to relate Secchi disk depth to trophic status. Equation 8.2 represents this relationship:

\[
TSI = 60 - 14.41 \ln(SD)
\]  

(Equation 8.2)

where TSI is the trophic state index; and SD is the Secchi disk depth (m). A TSI of 0-20 is considered oligotrophic, 30-40 is considered mesotrophic, and above 50 is considered eutrophic. ("Carlson’s Trophic State Index") Thus according to this method, the TSI is approximately 40, making Lake Yojoa mesotrophic.

### Table 8.5: Trophic status classification system quantitative results

<table>
<thead>
<tr>
<th>Classification</th>
<th>Geometric mean, P (mg/m(^3))</th>
<th>Log mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eutrophic</td>
<td>118.7</td>
<td>2.074±0.316</td>
</tr>
<tr>
<td>Mesotrophic</td>
<td>39.6</td>
<td>1.598±0.137</td>
</tr>
<tr>
<td>Oligotrophic</td>
<td>21.3</td>
<td>1.328±0.165</td>
</tr>
</tbody>
</table>
Thomann and Mueller (1987) indicate that temperate lakes are phosphorus limited if the nitrogen to phosphorus (N/P) mass ratio is greater than 10; if it is less than 10, the lake is nitrogen limited. Lake Yojoa is clearly not point source dominated, nor is it non-point source dominated, in a traditional sense. Thomann and Mueller do not provide an N/P ratio for lakes dominated by lake loads like internal phosphorus loading or fish farming. However, Sandoval (2003) reports a nitrogen concentration of 130 µg/L and a phosphorus concentration of 70 µg/L. From this data the N/P mass ratio can be computed. The N/P ratio is 2:1, indicating that the lake is nitrogen limited.
9 Conclusions and Recommendations

The calculations conducted for this analysis were based on many assumptions. To gain a better understanding of the nutrient loading into the lake more data must be collected. Accurate data like the agricultural areas broken down by type of crop or animal raised would make the calculation more exact. Additionally, concentrations of waste effluents from Las Vegas and La Casetas would also improve estimates.

Many of the limnological parameters used were primarily for temperate lakes. Similar parameters for tropical lakes would make for better theoretical estimations of the load. The literature does not address tropical lakes and their processes to the extent that it addresses temperate lakes. Little is really known about tropical lakes, there is much room for research in the field of tropical limnology.

Also, more information about slash and burn farming techniques and how this affects lake water quality would improve the study. More research on the impact of this type of agriculture is necessary for a better understanding of the Lake Yojoa watershed. Several questions remain about the effects of slash and burn farming on water quality. These include, but are not limited to: how much impact is there on sedimentation; how is rainfall runoff affected; and how is the nutrient load affected?

It is clear from the analysis of the trophic state of Lake Yojoa that the determination of trophic status has not been perfected. Various analyses can yield different states, this is probably the reason that scientists involved in previous studies on Lake Yojoa have not been able to agree upon a trophic status for the lake. Methods for defining trophic status of lakes should be improved if these characteristics are going to define the health of lakes. Additionally, these methods have mostly been correlated for use on temperate lakes. Thus, it may be that a different set of characteristics for trophic status of tropical lakes should be constructed.
The classification from this study is oligotrophic trending towards mesotrophic. Averaging this classification with those of other studies, Lake Yojoa appears to be mesotrophic. Additionally, it seems that nitrogen may be more important to the water quality of Lake Yojoa. This classification is positive for Lake Yojoa, the lake still has the potential to be protected. However, the high nutrient loads are a threat to the lake’s water quality and if they remain high, the lake may become eutrophic quickly. The proper management of these loads is crucial to the water quality in the lake. Controls must be applied to the nutrient load sources. Additionally, a more careful study on the lake’s nutrient limitation should be conducted prior to acting solely on nitrogen as the limiting nutrient.

Although it appears that the fish farms are the largest contributor of nutrients to the lake, it does not mean that other nutrient sources should not be held responsible for their share of the loading. Whether or not the lake is eutrophic is of little consequence; proper management of the watershed is essential to the health of Lake Yojoa. It is quite necessary for the stakeholders involved to keep an open dialogue and work together to better manage the lake. There are many solutions that could improve and maintain the water quality of Lake Yojoa. First, locals must be educated about proper waste disposal methods. Secondly, there is room for improved infrastructure: wastewater treatment facilities should be built and effective, septic tanks should be pumped on a regular basis, and regular garbage disposal should be enacted. With regards to the fish farm load, possible improvements to lessen the load could include a system to capture fish feces or improved feed which is better absorbed by the fish.
10 References


Betancort, J, and Dulin P. “Plan de Uso Multiple Del Lago Yojoa, Honduras, Segunda Fase,” AMUPROLAGO, 1981.


Mara, Duncan, Domestic Wastewater Treatment in Developing Countries, London: Earthscan, 2003.


GIS Data Sources:
GeoCommunity http://data.geocomm.com/catalog/HO/datalist.html
The Municipality of Las Vegas
## Appendix A: Contacts

Table A.1: Contacts in Honduras

<table>
<thead>
<tr>
<th>Name</th>
<th>Position</th>
<th>Organization</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gladys Fasquelle</td>
<td>President</td>
<td>Museum of Nature</td>
<td>San Pedro Sula</td>
</tr>
<tr>
<td>Juan Carlos Sarto</td>
<td>Boatmen</td>
<td>AMUPROLAGO</td>
<td></td>
</tr>
<tr>
<td>Dimas Zuniga</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mario Santos</td>
<td>President</td>
<td>Playas de Marfa Patronata</td>
<td>Las Casetas</td>
</tr>
<tr>
<td>Antonio Lago</td>
<td>Engineer</td>
<td>Ampac Mine</td>
<td>El Mochito</td>
</tr>
<tr>
<td>Gustavo Torres</td>
<td></td>
<td>DEFOLM</td>
<td>Tegucigulpa</td>
</tr>
<tr>
<td>Javier Flores</td>
<td></td>
<td>AMU of Las Vegas</td>
<td>Las Vegas</td>
</tr>
<tr>
<td>Angel Bosch</td>
<td>Owner</td>
<td>Agua Azul Hotel</td>
<td>Agua Azul</td>
</tr>
<tr>
<td>Hegel Velasquez</td>
<td>Engineer</td>
<td>ENEE</td>
<td></td>
</tr>
<tr>
<td>Ricardo Pineda</td>
<td>Gerente de Procesamiento</td>
<td>USAID-RED</td>
<td>La Lima</td>
</tr>
<tr>
<td>Antonio Coello</td>
<td>Sub-Director</td>
<td>USAID-RED</td>
<td>La Lima</td>
</tr>
<tr>
<td>Peter A. Hearne</td>
<td>Oficial de Desastres y Medio Ambiente</td>
<td>USAID-Honduras</td>
<td>Tegucigulpa</td>
</tr>
<tr>
<td>Gregory B. Kimmet</td>
<td>Especialista en Produccion Mas Limpia</td>
<td>USAID-Honduras-MIRA</td>
<td>La Ceiba</td>
</tr>
</tbody>
</table>
Appendix B: Secchi Disk Depth Methods and Results

Secchi disk depth, an indicator of algal growth and turbidity, was taken at 8 locations in Lake Yojoa (Figure B.1). The secchi disk (Figure B.2) was slowly lowered until it was no longer visible. This depth was recorded, then the disk was slowly raised until it again became visible, this was also recorded. The secchi disk depth is the average of these two numbers. In order to introduce less error into the measurement, each reading was taken by the same person and was conducted two times for each location. The results for these measurements are presented in Table B.1.

Figure B.1: Sampling locations, green indicates secchi disk depth was taken
![Secchi disk](image)

**Figure B.2: Secchi disk**

**Table B.1: Secchi disk measurements by location**

<table>
<thead>
<tr>
<th>LocationID</th>
<th>Secchi Depth Obs 1(m)</th>
<th>Secchi Depth Obs 2(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RR1</td>
<td>3.4</td>
<td>2.7</td>
</tr>
<tr>
<td>ACS</td>
<td>3.0</td>
<td>3.4</td>
</tr>
<tr>
<td>ALL</td>
<td>4.9</td>
<td>4.9</td>
</tr>
<tr>
<td>SMT</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>NES</td>
<td>3.4</td>
<td>3.7</td>
</tr>
<tr>
<td>PGC</td>
<td>4.6</td>
<td>4.3</td>
</tr>
<tr>
<td>NLM</td>
<td>3.7</td>
<td>3.7</td>
</tr>
<tr>
<td>NAA</td>
<td>4.3</td>
<td>4.3</td>
</tr>
</tbody>
</table>