Modeling the Aquaculture Carrying Capacity Of Lake Toba, North Sumatra, Indonesia

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Table of Contents:

Introduction:

Aquaculture is the fastest-growing food production sector in the world (FAO, 2012). Many developing countries, especially in Southeast Asia, are increasingly reliant on this practice in order to meet the economic and dietary needs of a growing population. Since aquaculture is heavily reliant on water resources, it often competes with other water-dependent industries. This can lead to negative impacts on industries such as capture fisheries, agriculture, and tourism. Additionally, the use of environmental resources required for aquaculture can have cascading social and economic implications. For these reasons, it is imperative that the carrying capacities of the water bodies used are considered in order to ensure the sustainability of aquaculture-based food production (Ross et al, 2013).

Although carrying capacity is often solely considered in terms of aquaculture production, it has been further developed into categories in order to aid the ecosystem approach to aquaculture introduced by the Food and Agriculture Organization of the United Nations (FAO) in 2006. This approach aims to integrate aquaculture within the natural ecosystem in order to promote the sustainable development and resilience of social-ecological systems (FAO, 2010). The categories of concern include the physical, production, social, and ecological based carrying capacities (McKindsey et al, 2006). The issue of aquaculture carrying capacity is presently a main concern throughout the Republic of Indonesia, where freshwater aquaculture has experienced exponential growth throughout recent years (Abery et al, 2005).

Lake Toba, with a surface area of 1,103 km^2, and a maximum depth greater than 500 m, is the largest lake in Indonesia, and the largest volcanic-crater lake in the world (Chesner, 2011**).** It is located in the province of North Sumatra, 176 km west of the capital city of Medan. With blue waters surrounded by mountainous peaks over 2,000 meters above sea level, the lakes natural beauty is internationally recognized. Home to the fascinating Batak culture, Lake Toba is one of Indonesia's popular tourist destinations, drawing frequent visitors from within the country as well as global travelers. In addition to lake-based tourism, the natural resources of the lake and its drainage basin sustain local livelihood by supporting rich agricultural lands, industrial uses, and floating cage aquaculture operations (Moedjodo et al, 2003). Despite it's incredible size, the lakes water quality is threatened by a number of activities throughout the drainage basin. Nutrient loading and eutrophication are the main threats to the water body, and therefore local livelihood. Since caged-fish production can contribute substantial amounts of nutrients (Beveridge, 2008), there is a pressing need to determine the ecological carrying capacity for aquaculture production in Lake Toba.

In June of 2014, three separate studies on aquaculture carrying capacity for Lake Toba were presented at the Indonesian Institute of Sciences (LIPI) research center in West Java. These studies were conducted separately by the LIPI Research Center for Limnology, the Environmental Protection Agency of North Sumatra Province (EPANS)**,** and the Indonesian Center for Fisheries Management (CFM). Each of these studies used similar modeling techniques focusing on the amount of phosphorous entering the lake from cage operations. However, the input values to the model and results from these studies varied, providing different acceptable production levels for Lake Toba and thus confounding management decisions.

Purpose:

This report will generate a set of carrying capacity estimates for both the entire lake, and a specific zone within the lake, based on a range of key input values that have been found to vary in previous studies. More holistic estimates will also be created by factoring in a range of potential watershed nutrient inputs from sources such as domestic wastewater and agricultural runoff in addition to aquaculture. Finally, this report will explore alternative approaches to estimating carrying capacity using a zoned approach. Estimates for the carrying capacity of one specific zone, Haranggaol Bay, will be produced in order to illustrate a "hot spot" approach to water quality management.

In-depth analyses are performed on selected prior studies that have estimated the aquaculture carrying capacity of Lake Toba. A literature review of past approaches to similar environmental problems has been conducted to foster recommendations for further studies. Special attention has been given to approaches that recognize zonation within large lakes to reflect conditions that might generate localized eutrophication. The intent of this report is to add value to the body of work that has been developed, and to attain a more comprehensive understanding of such a complex issue. When considering the critical role this lake and catchment play in the livelihoods of local people, efforts to protect the natural resources and associated industries must be thoroughly studied. The goal of this study is to provide guidance on approaches that can foster sustainable aquaculture production, while protecting the environment and continuing to attract tourism.

Estimating Carrying Capacity

To meet the growing demand for fish, in addition to business and employment opportunities, freshwater aquaculture has expanded throughout Indonesia over the last three decades. Due to this rapid expansion, some water bodies have already exceeded their abilities to assimilate the wastes from aquaculture production and sustain water quality. Wastes include benthic deposition of uneaten feed and feces; these excess nutrients can accelerate the process of eutrophication (Beveridge, 2008) deteriorating the water quality and therefore the ability to produce fish.

The FAO Fisheries and Aquaculture Department introduced the Ecosystem Approach to Aquaculture (EAA) as a strategy guided by three key principles (FAO, 2010):

- Aquaculture development and management should take account of the full range of ecosystem functions and services, and should not threaten the sustained delivery of these to society.
- Aquaculture should improve human well-being and equity for all relevant stakeholders.
- Aquaculture should be developed in the context of other sectors, policies and goals.

Carrying capacity is an integral part of the EAA, by helping determine the upper limits of aquaculture production based on environmental limitations and social acceptability. The main purpose is to determine the level of resource use that can be sustained by the natural environment over the long term, while avoiding "unacceptable change" to the functions of the ecosystem and social structures. Assessment of carrying capacity is one of the most important tools for implementing an EAA, and can be applied across a multitude of scales (Ross et al, 2013).

McKindsy et al. (2006) and Ross et al (2013) identified four separate types of aquaculture carrying capacities. Physical capacity is the maximum amount of cages that can physically fit in an area. Production refers to the maximum amount that does not have unacceptable impacts on the farm(s). Social capacity refers to the maximum amount of production that does not inhibit social uses of the water body. Similarly, ecological capacity seeks the magnitude of production that can be supported without unacceptable impacts on ecosystem functions. For example, fish cage culture requires ecosystem services for the degradation of organic matter and nutrients, which in turn affects the oxygen content necessary for fish development. However, beyond a certain level of fish production, the natural system may no longer be able to process the nutrients and provide the necessary oxygen.

Lake Toba's current issue with aquaculture development is mainly concerned with social and ecological carrying capacity. Due to the size of the water body, and naturally limiting factors such as wind and wave exposure, physical and production capacities are less of a concern. The social and ecological carrying capacities are closely tied together due their interdependent relationship. Social uses of the water body are directly affected by ecosystem functions, and these in turn support a variety of stakeholders.

Lake Toba supports a range of interests including small local aquaculture operations for both sale and consumption, large export oriented operations and all of the associated employees, wild capture fisheries, tourism, agriculture, industrial uses such as hydropower and pulp production, as well as cultural significance and local residential use (Moedjodo et al, 2003). With such a diverse range of interests being dependent on this water body, it is critical to determine and implement an ecological, and therefore social, aquaculture carrying capacity.

Background: Setting, Aquaculture Practices and Water Quality of Lake Toba

The formation of Lake Toba is the result of globally significant volcanic activity beginning about 70 million years ago (Chesner, 2012). Because of this the lake is surrounded by precipitous cliffs reaching up to 1,200 m above the water. The surface of the lake sits at 904 meters above sea level, while the waters have a maximum depth of 505 meters (Moedjodo et al, 2003), placing it among the deepest lakes in the world. The lake is oriented in a northwest to southeast direction, and is 87 km long and 27 km wide. The catchment area of Lake Toba covers 3,658 km^2, while the lakes surface makes up 1,103 km^2 of that area, therefore 2,555 km^2 of surrounding land drains into the water body through 202 brooks and rivers (Saragih and Sunito, 2001). This provides a drainage-area to lake-area ratio of approximately 2:1. The lake has a single outlet in the southeast portion of the lake, the Asahan River, which flows east to the Strait of Malacca. Due to the steep surrounding topography, and the limited drainage of the catchment, the lake has a retention time upwards of 81years (Moedjodo et al, 2003). Some argue that the development of a hydroelectric dam at the mouth of the Asahan River has further increased this rate (Lehmusluoto, 2000). This slow flushing rate is cause for concern in regards to nutrient loading within the lake, because prolonged retention times limit the flushing of nutrients from the lake ecosystem.

Figure 1. Map of Lake Toba basin

In the center of the lake lies one of the main tourist destinations, the large peninsula with a thin attachment called Samosir Island. This island is approximately the size of Singapore. Here, a number of ethnic Batak groups subsist primarily on farming and fishing, while many tourist accommodations are situated on the eastern peninsula of Tuk-Tuk among other small coastal towns. Much of this island has been cleared for farmland, while small aquaculture operations take place along the shores.

The tropical, yet cool, environment of this mountainous region combines with fertile volcanic soils to yield highly productive agriculture. Rice paddy fields are very common throughout the drainage basin, as well as fields of corn, onions, chilies, and mangos. Cash crops are commonly grown on higher grounds throughout the watershed. Coconuts, cloves, cinnamon, coffee, and cocoa are the primary source of income for many families. The raising of livestock is also common throughout the basin, however it is not as extensive and is often done by families as an ancillary part of their income (Moedjodo et al, 2003).

Floating cage aquaculture ('karamba' in the local language) in Lake Toba is practiced both by local farmers and two main private enterprises, PT Aquafarm Nusantara, and PT Suri Tani Pemuka that were set up by external investment companies. Local farmers produce fish mainly for domestic markets or consumption, while the external investment companies export most of their produce. Due to the lakes huge size and expansive wind fetches, farm operations are naturally limited to lake areas that are protected from high wind and wave exposure to avoid conditions that can destroy cages. Additionally, the majority of local farms are located close to shore for monitoring and security purposes (Figure 2).

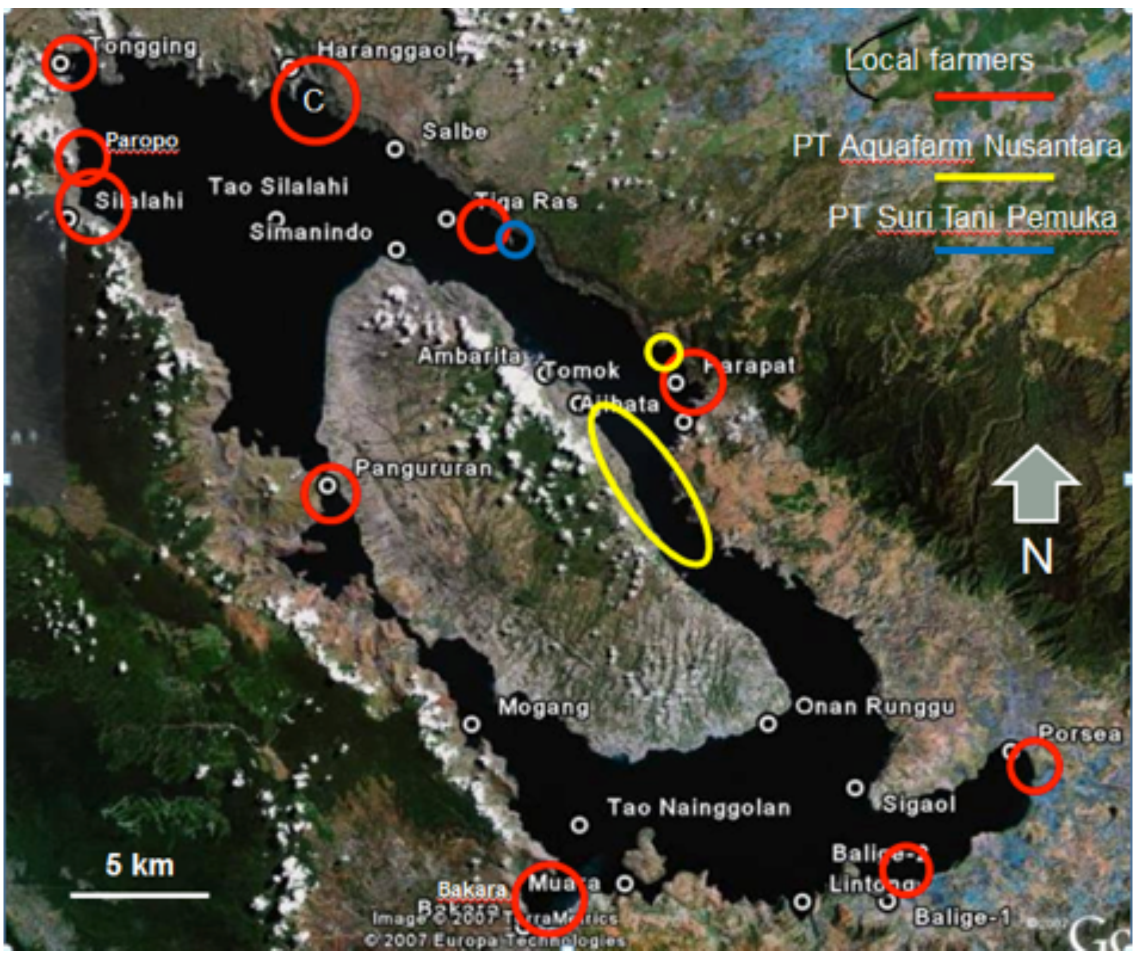


Figure 2. Aquaculture cage locations in Lake Toba

Haranggaol Bay is a large cove located in the northeastern portion of Lake Toba. This bay contains the largest concentration of aquaculture cages throughout the lake, all of which are operated by local farmers. The waters in this bay have a surface area of approximately 3 km^2, based on the terminus of surrounding headlands. The bay has a maximum depth upwards of 200 m. While an average depth has not been officially calculated, this study uses an average depth of 150 m based on visual observations of bathymetric maps (Chesner, 2012). The surrounding mountains provide a sub-drainage basin for this bay with an area of approximately 19 km^2 based on measurements made with Google Earth Pro (Figure 3).

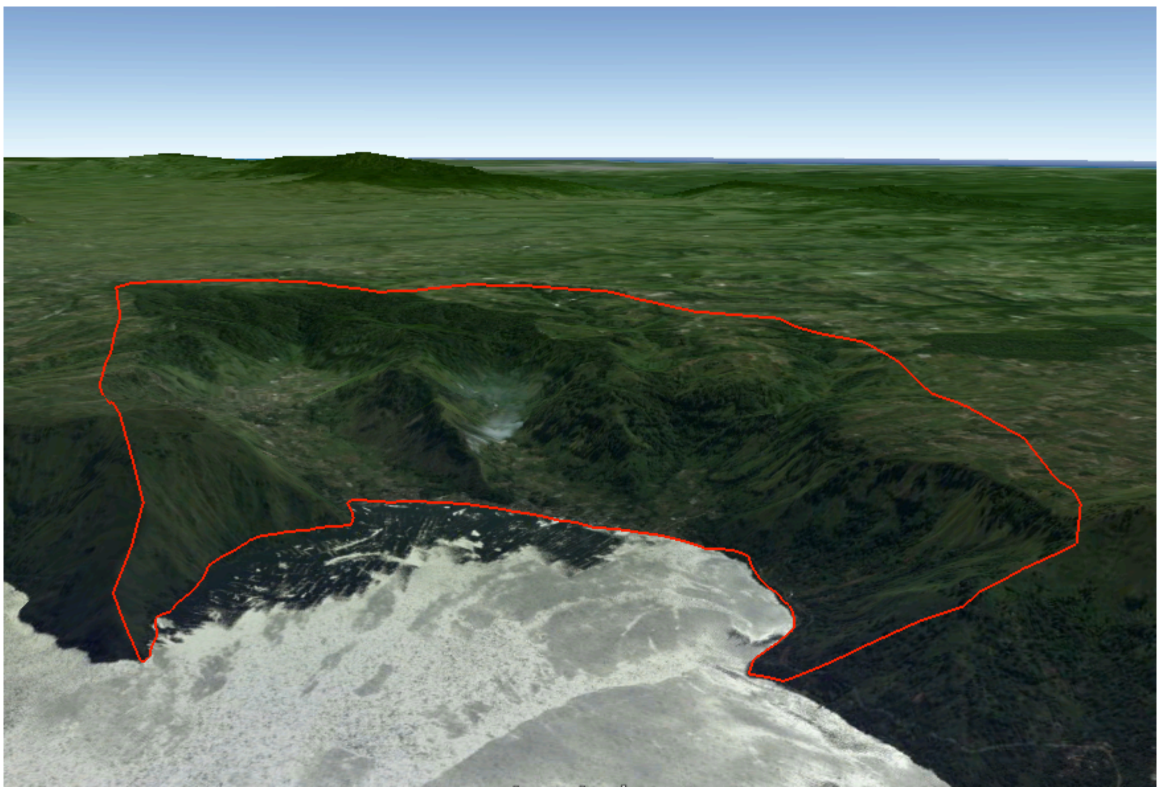


Figure 3. Haranggaol Bay and delineated sub-drainage basin using Google Earth Pro

Aquaculture in Lake Toba began with carp production three decades ago with the help of URI researcher Richard Pollnac (Pollnac and Sihombing, 1996). Today the predominant species produced is *Oreochromis niloticus* (Nile tilapia). While carp, catfish, and a few other species are also produced in the lake, tilapia represents the largest proportion of production, and the main source of profit throughout the lake. Therefore, the carrying capacity calculations in this study were based on figures for Nile tilapia.

Production units are referred to as cages, which vary in size and construction throughout the lake. Typically, cages will have a rectangular shape and will be made with metal frames. Wood and bamboo are also used for construction, however these require more frequent replacement, whereas a metal frame can last as long as 10 years. Units are often joined in groups of two or four in order to better endure wind and wave damage.

Feed types and practices also vary throughout the lake. Typically a sinking pellet feed is used, which is often less expensive than a floating pellet feed. Each feed type has a varying amount of phosphorus, an essential nutrient for fish development, but also a contributor to lake eutrophication. Feeding regimes are for the most part unregulated and spontaneous, with workers dropping handfuls of feed into each cage unit throughout the day. In cases where the efficiency of feed types and practices are considered, a food conversion ratio (FCR) is developed. This is the amount of feed it takes to produce one ton of harvested fish. Ideally, farmers would want the lowest possible FCR of approximately 1:1. However, due to varying practices throughout the lake, a broad range of FCR's have been found to exist. This study will use the average FCR's, and phosphorous contents of feed, found through farmer surveys.

While little data are available on current aquaculture production rates, recent estimates have been made from lake surveys conducted by Dimitar Taskov and Irina Timonina of the University of Stirling. This work is yet to be published, however, previously published data from Anon (2014), Unger (2014), and Indonesian statistics (BPS, 2013) were considered in addition to their calculations. Their estimate of total production for aquaculture in Lake Toba is 76,284 metric tons/yr. Production from Haranggaol Bay alone is approximately 27,000 tons/yr, representing more than 1/3rd of the entire lake production.

Several authors have described the deteriorating ecological state of Lake Toba over the last few decades (Saragih and Sunito, 2001; Lehmusluoto, 2000; Lukman, 2014, Anon, 2014). Decreasing water quality, as evidenced by declining

Secchi-depth readings, and an increase in the abundance of water hyacinth throughout the lake indicate an excess of nutrients. Some tourists even complain of itchy skin after swimming. Questions surround the role of aquaculture wastes as the driver of eutrophication (Anon, 2014). This linkage has been documented in smaller lacustrine (i.e., lake) systems due to the excessive phosphorous (P) added to the water through sinking-pellet fish feed and feces (Pollnac and Sihombing, 1992). The increased phosphorus inputs accelerate algae growth, and subsequent death due to the short life span, which can lead to rapidly deteriorating water quality and large fish mortality rates from the consumption of dissolved oxygen due to the decomposition and decay of algae in the water.

A number of land use practices throughout the drainage basin also threaten the water quality of Lake Toba through excessive nutrient contributions. Many of the farmers use fertilizers and pesticides on their crops, some of which make their way into the lake. Nutrient-rich wastes from livestock also enter the lake through overland runoff. One of the more significant concerns throughout the watershed is the lack of wastewater management (Lehmusluoto, 2000). Many of the small villages discharge domestic sewage directly into streams and rivers that feed into the lake (Saragih and Sunito, 2001), while some use outdated cesspools and storage tanks that may also leach into the lake via groundwater.

The management of these issues is complicated by the political dynamics of such a large lacustrine system. The watershed embraces seven different governmental districts (“Kabupatens”), each having a number of sub-districts (“kecamatans”). Each of these administrations (Figure 4) governs varying portions of the watershed. Kabupaten Toba Samosir, with its twelve Kecamatans, is responsible for the largest portion of the watershed, approximately 64% (Moedjodo, 2003). With varying populations, land use types, and levels of aquaculture throughout the lake, the management of environmental issues is further complicated by the multitude of administrations. Addressing such issues will require strategic planning, clear communication, and the delegation of appropriate levels of responsibility for each Kabupaten.

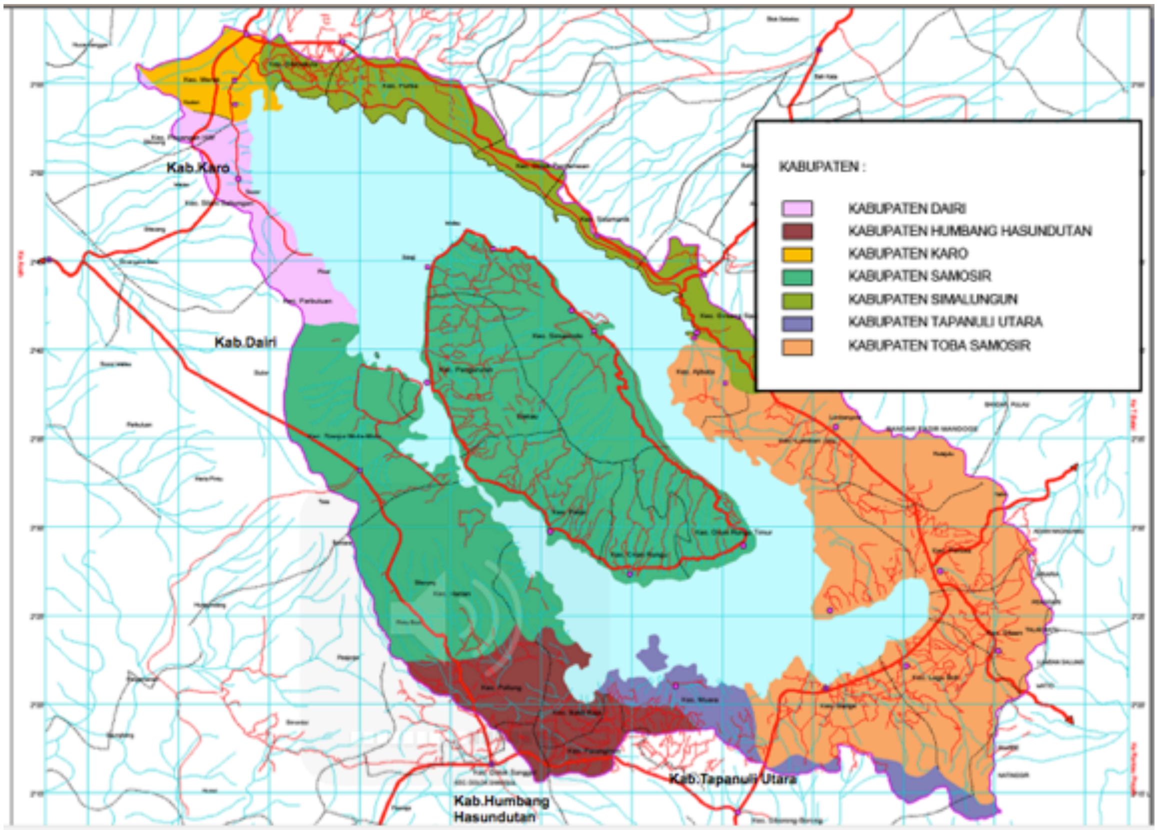


Figure 4. Administrative boundaries of Lake Toba basin

Estimating Carrying Capacity of Lake Toba:

Approach:

A number of modeling approaches are used to address the ecological carrying capacity of aquaculture. In situations without extensive water quality data estimates geared towards local needs can be determined through systems modeling of inputs and fates of major limiting nutrients. Being a freshwater lake, phosphorous (P) is assumed to be the limiting nutrient of concern. A mass balance approach can be used to estimate total aquacultural wastes lost to the lake environment Using data on P-content of feeds, food conversion ratios (FCR), and carcass P-content, it is possible to estimate the total-P loadings to the lake per metric ton of caged fish production (Beveridge, 2008). The number of acceptable cages can then be calculated based on desired water quality standards (expressed as a specific in-lake concentration of P), or the desired trophic status, which can vary based on local goals. With the goal of sustaining tourism in the region, the desired trophic state standard for Lake Toba is set as oligotrophic. Oligotrophic waters have high clarity, infrequent or a comlete absence of algal blooms and sustain well oxygenated conditions throughout much of the lake environment.

The rationale behind this mass balance model approach is based on the assumptions that algal densities are negatively correlated with water quality, particularly dissolved oxygen (DO) levels, and therefore the growth and survival of fish. P is assumed to be the limiting nutrient that controls phytoplankton (i.e., algae within the water column) abundance in freshwater environments (Beveridge, 2008). A challenge with aquaculture is that P is an essential element required for fish growth and bone development, which is typically derived from dietary sources. Despite P requirements being species-specific, most diets for fish culture contain a surplus that can enter the lake and potentially change water quality.

The Beveridge model for intensive cage aquaculture used in this study, and the prior Lake Toba carrying capacity studies (LIPI, EPANS, CFM, 2014), ultimately stem from one of the most widely used empirical models developed to predict the response of aquatic ecosystems to increases in P loadings, that of Dillon & Rigler (1974). This is a modification of Vollenweider's original model (Vollenweider, 1968), which states that the total-P concentration in a water body is determined by the P loading, the lakes area and mean depth, the flushing rate, and the fraction of P lost to the sediment.

The key inputs required for this model to be used for aquaculture include the food conversion ratio (FCR), and the total-P percentage of the feed used. The product of these provides the amount of total-P required to produce one metric ton of fish. From this value, the percentage of P retained by the fish (species-specific) is subtracted to provide the amount of total-P lost to the environment per ton of fish produced. Next, the permissible change in total-P concentration for the entire water body is determined by subtracting the lake's initial P concentration from the desired concentration after aquaculture production. This figure is based on Carlson's trophic index, where less than 10 parts per billion (ppb or mg m^3) is considered the upper limit to sustain oligotrophic conditions. The permissible loading from fish is then determined by multiplying the change in P by the lakes depth and the flushing rate, then dividing this by 1-R (the coefficient for P lost to sediment). This figure is then multiplied by the lake surface area and divided by the total-P lost to the environment per ton of fish produced. The final result is the permissible amount of fish production in metric tons per year.

Figures		Values	Units
FCR (food conversion ratio)		1.2	
Phosphorous in Feed (P_food)	1.02% -> to kg	10.20	kg P/ton feed
FCR x P_food		12.24	kg P /ton fish
P in fish species (P_fish)	Nile tilapia = 0.34%	3.4	kg P/ton fish
P lost to the environment (P_env)			
P_env = P_food - P_fish	(kg/ton produced)	8.84	kg of P/ton produced
	-> grams	8840	g of P/ton produced
Average Depth (Z)		225	m
Flushing rate (p)		0.014	yrs
R_fish (P lost to sediment)		0.96	
Surface Area (A)		1,240,000,000	m2
P_f (Desired P level after Aq)		10	mg/m^3
P_i (Initial/ ambient P level)		5	mg/m^3
Delta P (permissible change to in-lake total-P levels)		5	mg/m^3
L_fish (loading from fish)		393.75	$mg/m^2/yr$
= Delta P*Z*p /(1-R)	to grams ->	0.39375	$g/m^2/yr$
L_fish x Surface Area	$g/m^2/yr * m^2$	488,250,000	g/yr
Total Permissible Production			
= L_fish x A / P_env	(g/yr) / (g/ton)	**55,232**	metric tons/yr

Table 1. Example of Beveridge Model used in this study.

This model, however, does not typically account for nutrient contributions from the watershed. Yet this can be accomplished by factoring in estimated watershed-P inputs into the permissible change in total-P for the water body (EPANS, 2014). By subtracting both the initial-P level and the watershed-P inputs from the desired-P level after aquaculture, a lower, but more accurate estimate of the carrying capacity of aquaculture production will be generated.

In this study, watershed P inputs will include estimated domestic wastewater contributions, as well as figures for agriculture, livestock, and other land use contributions found in one of the previous studies (EPANS, 2014). Domestic wastewater will be calculated by first estimating the population living within the drainage basin, since all of the surrounding regencies extend far beyond the watershed boundary. Population is then multiplied by a total-P loading factor and by a runoff coefficient to more accurately represent the portion of wastewater entering the lake. The World Health Organization suggests that the composition of untreated domestic wastewater includes a total-P production of between 1 and 3 grams per capita per day (WHO, 1997). Since the majority of wastewater in the Lake Toba watershed is untreated, or inadequately treated, this study will estimate wastewater at both 2 and 3 g/cap/day in order to examine the results from a range of possible contributions. A runoff coefficient of 0.5 will be used to represent the multi-unit, detached, residential environment (EPANS, 2014). The sum of domestic wastewater and land use inputs (i.e., loading as mass/time) are then divided by the volume of lake (volume/time) to generate an estimate of lake P concentrations from the watershed inputs. This approach assumes that the water retention time is corresponding to the time unit of the loading estimate.

This approach includes two major assumptions that could influence the effects of watershed loading on lake trophic status. First, only a portion of the watershed P load is likely to be bioavailable to primary producers (Seitzinger, 2005). Thus, the effects of watershed P loading on chlorophyll a levels are likely to be overestimated. In contrast, the approach obtains concentrations based solely on annual loading and lake volume and ignores the actual retention time. With the long retention time of Lake Toba, any P loading can accumulate within the water column and thus the resulting lake P concentrations are likely to be underestimated.

Previous studies have approached aquaculture carrying capacity by using the Beveridge model to address the entire water body as one homogenous unit. However, when dealing with a large lacustrine system with a diverse coastline and bathymetry; local winds, currents, circulation, and turnover rates may play an important role in the fate of lake nutrients. Therefore, trophic status can vary throughout the lake and its many bays. The spatial heterogeneity can result in localized "hot spots" where P concentrations are more elevated than the majority of the lake and thus are more likely to generate algal blooms than predicted by whole lake analyses. For Lake Toba, this consideration could drastically alter the actual ecological carrying capacity of aquaculture. Since the majority of cages are naturally limited to small bays, some of these areas may have already reached or surpassed their ecological carrying capacity. For these reasons, a zoned approach to eutrophication management may be more applicable to a lake of this size.

Zoned approaches to managing eutrophication have been used on Lake Champlain, in the U.S.A. and Canada. Lake Champlain is a 170km-long natural lake shared by the U.S.A. states of New York, Vermont, and the Canadian Province of Quebec. This lake is rich in historic value and serves mainly as a source of recreation and as a water supply. The lake has a surface area of 1,130km^2 and is made up of numerous bays and open water segments. A variety of trophic conditions exist throughout the lake, with much of the open and deeper areas in the low-mesotrophic to oligotrophic range, while eutrophic conditions exist in shallower locations such as St. Albans Bay (Smeltzer and Quinn, 1996). Since the watershed includes almost half the state of Vermont, and large areas of northeastern New York and southern Quebec, a large variety of point and non-point sources are responsible for nutrient inputs. In 1996, a phosphorous budget and mass balance model was developed for Lake Champlain in order to identify necessary load reductions required to attain total-P concentration criteria established in water quality agreements.

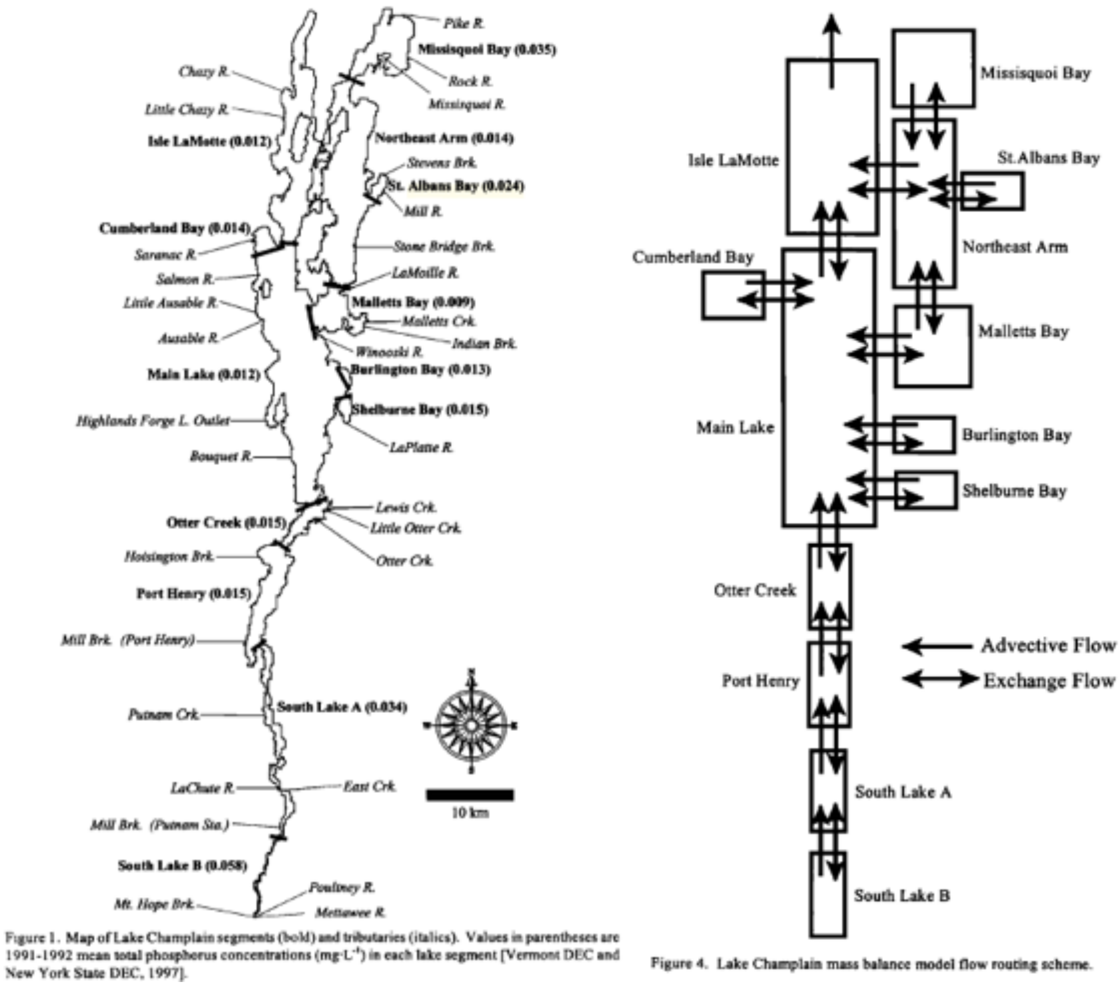


Figure 5. Lake Champlain map and zonation example

Due to the size and diversity of the lake and its watershed, the criterion for in-lake total-P was developed for 13 segments (i.e., zones) of Lake Champlain (Smeltzer and Quinn, 1996). Extensive water quality sampling for each of these zones was used to support the development of a zoned approach to whole-lake mass balance modeling. By modeling each zone individually (Figure 5), necessary load reductions were identified for each sub-watershed in order to meet the established criteria for the segment, and ultimately the entire water body. Agreements on desired in-lake water quality goals could then be made between the various government jurisdictions, and responsibilities divided appropriately. The implementation of point and nonpoint source controls resulted in a P load reduction of 20% between 1991 and 1995 (Lake Champlain Management Conference, 1996).

Similarly, Lake Toba has a variety of point and nonpoint sources throughout its expansive watershed, and respective sub-watersheds, that must be considered in order to accurately estimate nutrient loading. These sources must be identified and quantified before aquaculture wastes can be considered the primary source of eutrophication**.** Therefore, a zoned approach to modeling may better represent the loading occurring throughout the lakes many bays. By setting an appropriate criterion for each zone, this approach could also aid the challenging task of dividing responsibilities amongst the seven governmental districts (Kabupatens). As an example, the aquaculture carrying capacity will be estimated for Lake Toba's Haranggaol Bay, where the highest concentration of aquaculture cages can be found.

Methods:

Qualitative methods:

In June of 2014, fieldwork was conducted throughout portions of the Lake Toba basin. Informal surveys and interviews were conducted with local farmers and hoteliers throughout the eastern portion of Samosir Island, as well as the towns of Parapat, Haranggaol, and Tongging. GPS positions were collected and observations on land use were noted.

Quantitative methods:

Some prior studies of aquaculture carrying capacity did not consider watershed inputs. I therefore developed carrying capacity estimates with and without watershed inputs. For carrying capacity analyses based on aquaculture as the primary P input (not including watershed inputs). The key figures necessary to model ecological carrying capacity of aquaculture production include the food conversion ratio (FCR), the amount of phosphorous in the feed (P_food), lake depth (z), lake area (A), lake volume (v), flushing rate (p), residence time, and the permissible change to total in-lake phosphorous (Delta P), which is determined by the difference between the maximum acceptable P level after aquaculture and the initial/ ambient P level.

Previous studies that address Lake Toba's ecological carrying capacity of aquaculture used varying values for a number of these key inputs to the model.

Accordingly, the final results from these different studies also varied. Input variations that exerted large influences on model outputs included lake depth, FCR, P_food, and Delta P. In order to determine the effects of these inputs on the final outcome, I used a range of each of these input values to examine the effects of variation on model output estimates of carrying capacity. For these calculations, the remaining variables were kept static at values similar to previous studies or at the lake-wide average found from lake surveys conducted by Dimitar Taskov and Irina Timonina of the University of Stirling (personal communication, unpublished data).

To examine watershed P loading, a land cover classification was conducted using ERDAS IMAGINE 2014 Satellite imagery was acquired from USGS Earth Explorer. Due to the size of the watershed, 2 remotely sensed images were required. After a mosaic image was created, a supervised classification was developed in order to determine the spectral bands that represent various land covers. GIS was then used to clip the imagery by the watershed boundary and to calculate the total percentages for each category.

Watershed population was calculated by first determining the sub-districts (Kecamatans) of each district (Kabupaten) that fall within the watershed boundary. Census data from 2012 was then acquired through Statistics Indonesia (Badan Pusat Statistik (BPS)) for each Kecamatan. However, a number of these Kecamatans extend well beyond the watershed boundary. For these instances, measurements and estimates were made using GIS and Google Earth Pro. Populations for these areas were then divided appropriately before a sum was determined.

With these estimates, two levels of domestic wastewater P loads were calculated using WHO figures. After unit conversions, these were added to figures for P contributions from livestock, agriculture, and other land uses found in the study by the EPANS. These final values represent the total-P contributions from the watershed at two levels to indicate a range of possibilities. Both figures were used in the calculations of carrying capacity for the whole lake.

For the zoned approach, a number of figures needed to be determined before the model could be run. GIS and Google Earth Pro were used to delineate both the lake surface and sub-watershed area for Haranggaol Bay. Average lake depth for this bay was approximated using the raster-based bathymetric map developed by Chesner (2011). Watershed contributions were determined in a similar manner as described above, yet only the population of the surrounding Kecamatan was used for domestic wastewater calculations. This Kecamatan, however, extended beyond the delineated sub-watershed, so this population was halved in order to create a conservative estimate. Only the lower wastewater factor of 2 g/p/d was used in order to keep estimates conservative, the larger figure dramatically lowered the total permissible production to the point where aquaculture production was unattainable. A percentage of the land use inputs were used based on the proportion of the entire watershed that the Haranggaol Bay drainage area occupies.

Results:

This land cover classification (figure 6) helps to understand the nature of the watershed. A margin of error does exist due to the temporal resolution of the satellite imagery. For more precise results, multiple images from a variety of seasons should be classified and compared. However, for the purposes of this study, the results are congruent with data from the EPANS as well as field observations. A large potion of the watershed consists of agricultural lands, while developed areas are concentrated near the shores of the lake.

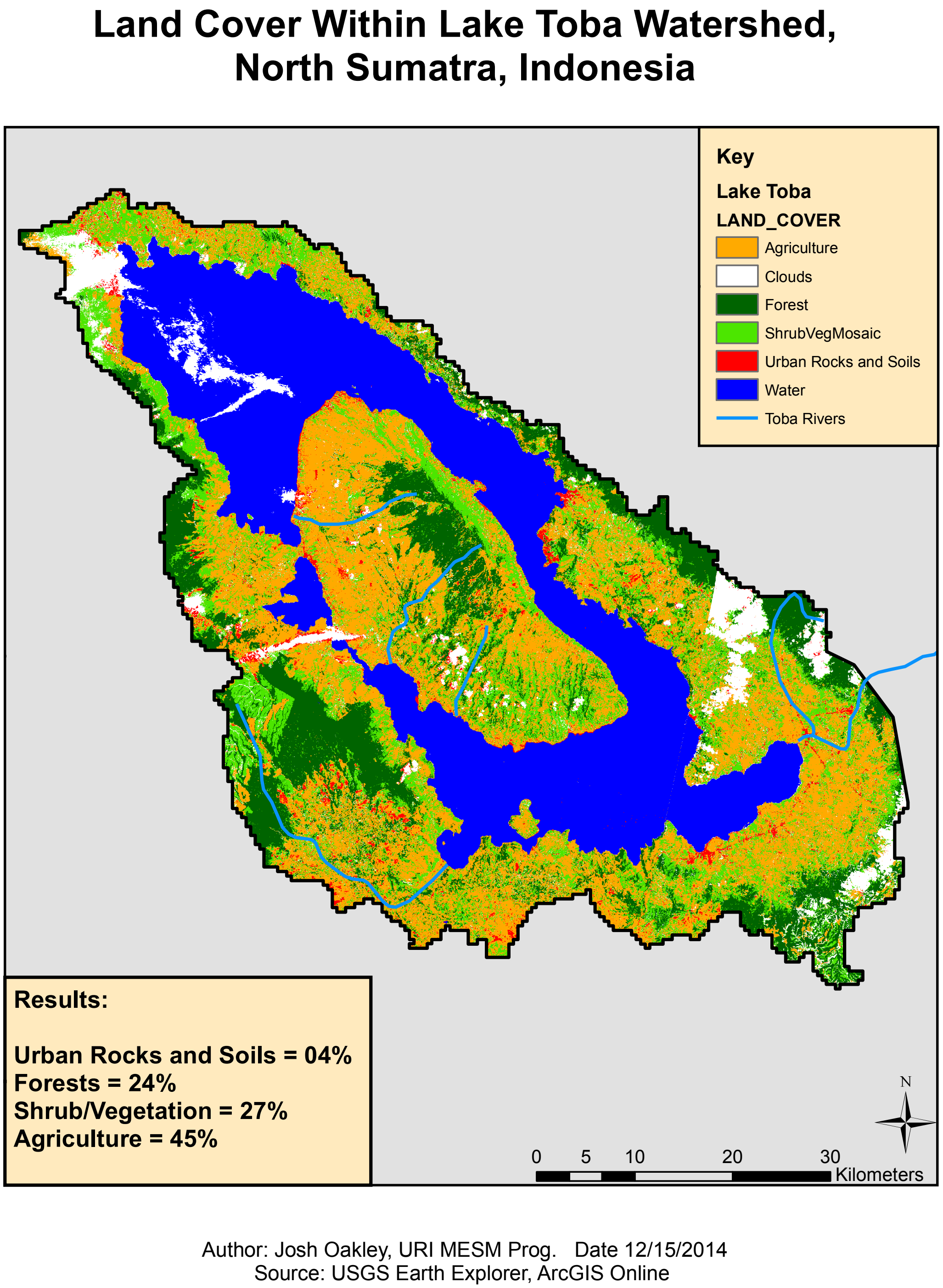
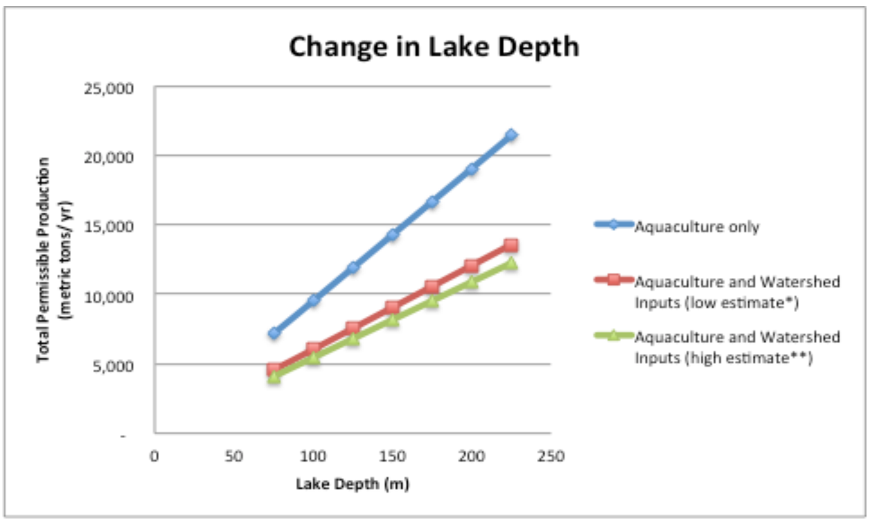
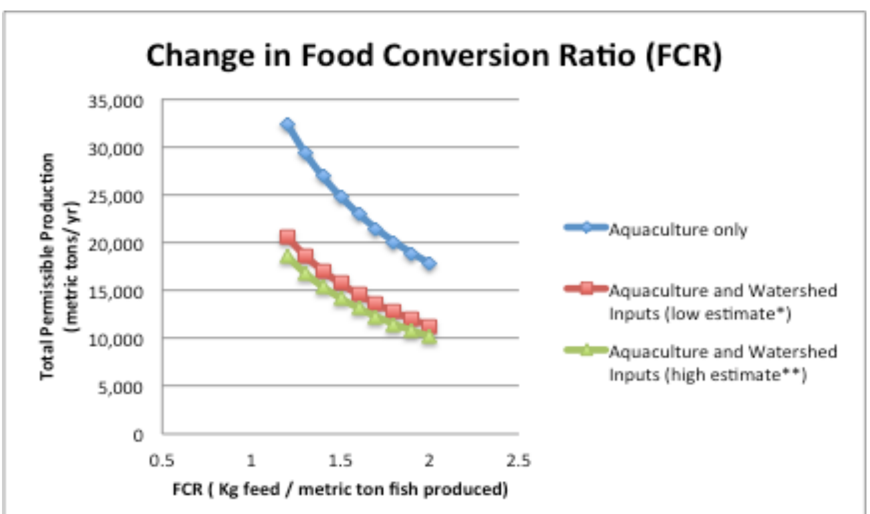


Figure 6. Land cover classification for Lake Toba basin

The range in carrying capacity estimated generated by using a range of input values for key variables demonstrates the importance of these inputs to the model results. A clear relationship between change in carrying capacity and change in input values exists for all of these variables (Figure 7). As lake depth increases, total permissible production also increases. Conversely, as FCR and the P content of feed increase, production decreases. The affects of watershed contributions are also evident by the substantial reduction in total permissible production, especially in the optimal portions of each variable.





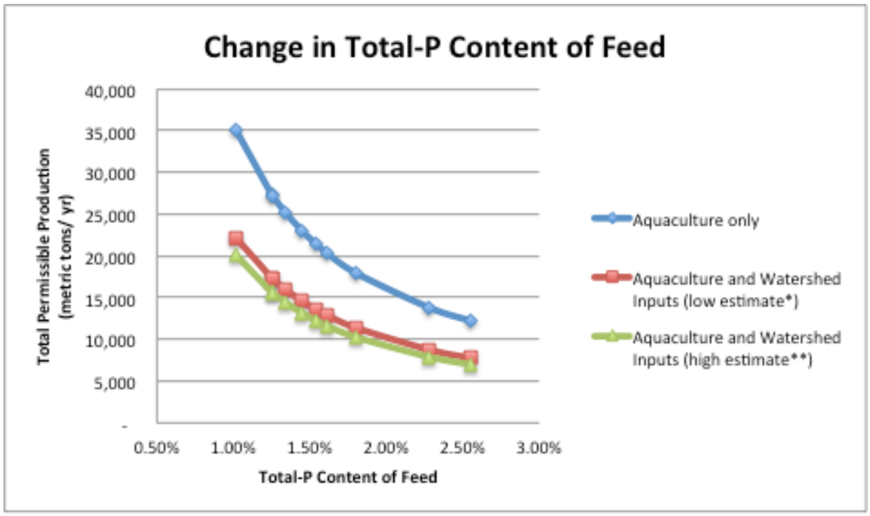


Figure 7. Charts of total permissible production results from altered model inputs for whole lake approach resulting in Oligotrophic waters (Total-P at 10ppb).

As the permissible change to total in-lake phosphorus is altered, and therefore the resulting trophic status following aquaculture, this reveals a substantial impact on total permissible production. An increase by 5 mg/m^3 (or ppb) to the desired total-P level after aquaculture results in approximately double the permissible production total. However, these increases to desired P levels equate to rapidly deteriorating water quality, which would ultimately have negative effects on aquaculture production.

The influence of watershed P contributions on aquaculture production carrying capacity is very evident (Figure 7) with a whole lake model**.** Total permissible production experienced a 36.6% reduction from the lower watershed estimate (Table 2), and a 42.8% reduction after factoring in the higher watershed estimate. The difference between results for aquaculture production alone and with the higher watershed estimate ranged in reductions of approximately 3,000 tons/yr for less desirable inputs, to almost 15,000 tons/yr for optimal inputs. The difference represented by the range of watershed estimates is also significant for each variable. Reductions to total permissible production from the two watershed estimates ranged from approximately 500 tons/yr for less desirable variables to reductions upwards of 2,000 tons/yr for optimal variables.

For Whole Lake Model:

Sources of Watershed Total-P Inputs	**Amount**		**Conversion**	
Domestic wastewater (low estimate[1])	157.35	ton/yr	157,350,000,000	mg/yr
Livestock	292.72	ton/yr	292,720,000,000	mg/yr
Land Use (includes agriculture)	19.10	ton/yr	19,100,000,000	mg/yr
Total of watershed sources	469.17	ton/yr	469,170,000,000	mg/yr
Estimate of Total-P Inputs from Watershed =				
Total / Volume of Water body (256,200,000,000 m2)			**1.83**	**mg/m3/yr**

Sources of Watershed Total-P Inputs	**Amount**		**Conversion**	
Domestic wastewater (high estimate[2])	*236.03*	*ton/yr*	236,030,000,000	mg/yr
Livestock	292.72	ton/yr	292,720,000,000	mg/yr
Land Use (includes agriculture)	19.10	ton/yr	19,100,000,000	mg/yr
Total of watershed sources	547.85	ton/yr	547,850,000,000	mg/yr
Estimate of Total-P Inputs from Watershed =				
Total / Volume of Water body (256,200,000,000 m2)			**2.14**	**mg/m3/yr**

1- Based on estimated watershed population of 431,098 x 2g of P/ capita/ day
2- Based on estimated watershed population of 431,098 x 3g of P/ capita/ day

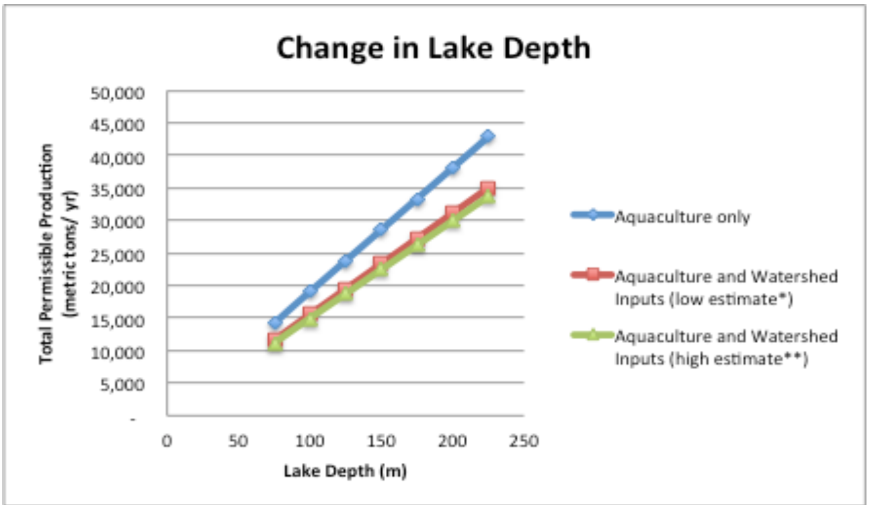
For Haranggaol Bay (zoned) Model:

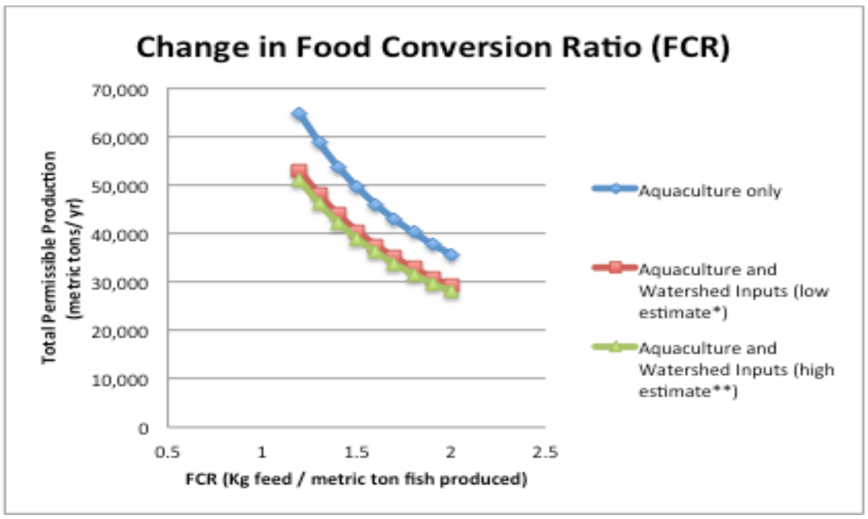
Sources of Watershed Total-P Inputs	**Amount**		**Conversion**	
Domestic wastewater (low estimate[1])	*0.91*	*ton/yr*	912,500,000	mg/yr
Livestock x .0073*	2.14	ton/yr	2,140,000,000	mg/yr
Land Use (includes agriculture) x .0073*	0.14	ton/yr	140,000,000	mg/yr
Total of watershed sources	3.19	ton/yr	3,192,500,000	mg/yr
Estimate of Total-P Inputs from Watershed =				
Total / Volume of Water body (450,000,000 m2)**			**7.09**	**mg/m3/yr**

1- Based on estimated sub-watershed population of 2,500 x 2g of P/ capita/ day
** Proportion of entire watershed that Haranggaol Bay represents*
***Volume based on an average depth of 150m and surface area of 3,000,000*

Table 2. Watershed-P input calculations for Whole Lake Model and Zoned Model

Similar patterns are evident when the model is run with the target trophic status in the low-mesotrophic range of 15 mg/m^3 (or ppb). Permissible production, however, is more than doubled in all categories under these allowable water quality standards (Figure 8). The influence of watershed inputs is parallel to the previous model, despite the increase in acceptable nutrient levels. Each altered variable experienced an 18.3% reduction from the lower watershed estimate, and a 21.4% reduction from the higher watershed estimate. The results of these models indicate the significant potential of watershed influences on aquaculture production, and necessitate the need to more accurately quantify watershed P contributions.





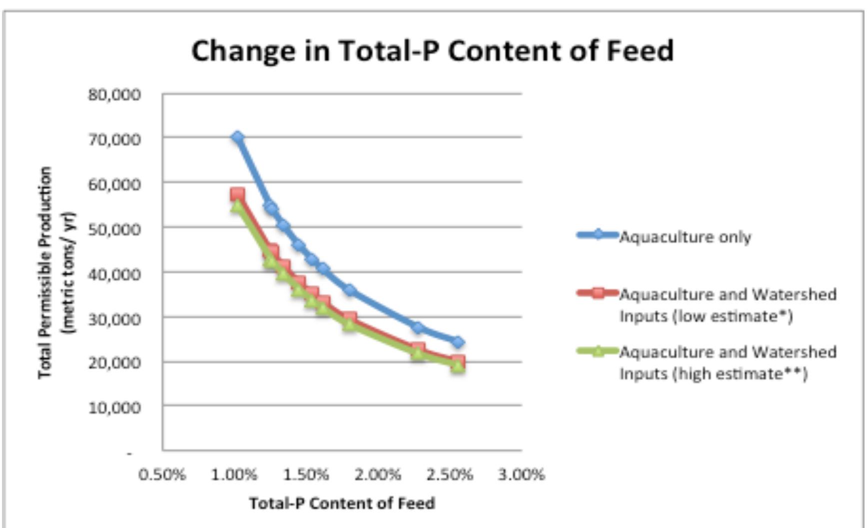


Figure 8. Charts of total permissible production results from altered model inputs for whole lake approach resulting in Mesotrophic waters (Total P at 15ppb).

In order to show a range of possibilities based on the whole lake model, the following tables were created using two main combinations associated with a change to the desired in-lake total-P levels following aquaculture production. Table 3 shows the combination of average inputs found in previous studies, while table 4 combines all of the variables that result in optimal production. The results show a range in the absolute total permissible production for the entire lake, based on desired trophic status.

	Desired In-Lake Total-P Levels (mg/m³ or ppb) After Aquaculture				
Desired Total-P level after aquaculture production (P_f)	10	15	25	50	50
Initial Total-P level (P_i)	5	5	5	10	5
Delta P (ΔP = P_f - P_i)	5	10	20	40	45
Trophic status after production	Oligotrophic waters	Mesotrophic waters	Mesotrophic waters	Eutrophic waters	Eutrophic waters
	Total Permissible Production Based On Average Inputs[1] (metric tons/ yr)				
Aquaculture only	21,433	42,867	85,733	171,466	192,899
Aquaculture and Watershed inputs [2]	13,589	35,022	77,889	163,622	185,055
Aquaculture and Watershed inputs [3]	12,260	33,693	76,560	162,293	183,726

1 - Average imputs based on previous studies by EPANS and D. Taskov & I. Timonina

2 - Based on domestic wastewater rates of 2g/p/d and EPANS figures for land use

3 - Based on domestic wastewater rates of 3g/p/d and EPANS figures for land use

Table 3. Range of total aquaculture permissible production (metric tons/yr) for average key input values and various desired trophic states using the Beveridge whole lake model.

	Desired In-Lake Total-P Levels (mg/m³ or ppb) After Aquaculture				
Desired Total-P level after aquaculture production (P_f)	10	15	25	50	50
Initial Total-P level (P_i)	5	5	5	10	5
Delta P (ΔP = P_f - P_i)	5	10	20	40	45
Trophic status after production	Oligotrophic waters	Mesotrophic waters	Mesotrophic waters	Eutrophic waters	Eutrophic waters
	Total Permissible Production Based On Optimal Inputs[1] (metric tons/ yr)				
Aquaculture only	55,232	110,464	220,928	441,855	497,087
Aquaculture and Watershed inputs [2]	35,017	90,249	200,713	421,640	476,872
Aquaculture and Watershed inputs [3]	31,593	86,825	197,288	418,216	473,448

1 - Optimal imputs based on previous studies by EPANS and D. Taskov & I. Timonina

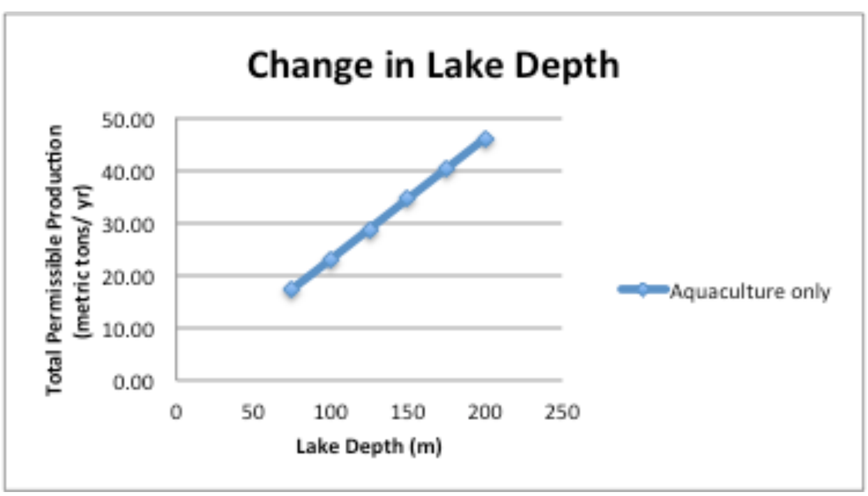
2 - Based on domestic wastewater rates of 2g/p/d and EPANS figures for land use

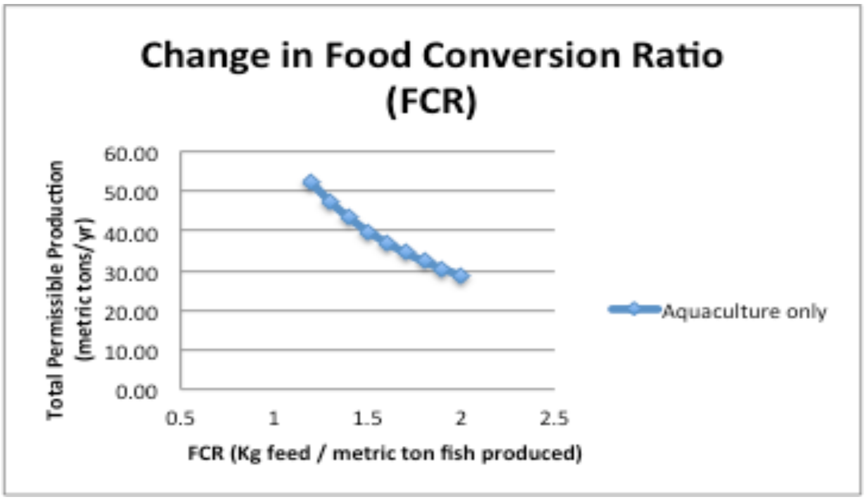
3 - Based on domestic wastewater rates of 3g/p/d and EPANS figures for land use

Table 4. Range of total aquaculture permissible production (metric tons/yr) for optimal key input values and various desired trophic states using the Beveridge whole lake model.

When compared to the current estimated aquaculture production for Lake Toba of approximately 76,000 tons/yr, table A suggests that the current status of water quality is in the high-mesotrophic range based on the lake-wide average FCR and total-P content of the feed used. However, eutrophic conditions are suggested by the abundance of lesser quality inputs and water quality data suggesting an average total-P content of 62 mg/m^3 (EPANS, 2012).

As the model was adapted for the zoned approach, the same linear relationships of the altered variables were found to exist. However, the effects of watershed inputs are substantially higher due to a smaller surface area of the bay and its more shallow average depth. Even though the estimates of total-P from the watershed are substantially lower for this small bay compared to the entire lake, a much smaller volume divides this figure. For these reasons, an oligotrophic status following aquaculture production was unattainable after watershed contributions were factored in. This suggests that this bay is more sensitive to eutrophication due to the lesser water volume. Despite the lack of consideration for water flow and circulation to and from this bay, the limited results for total permissible production remain telling when compared to current production rates.





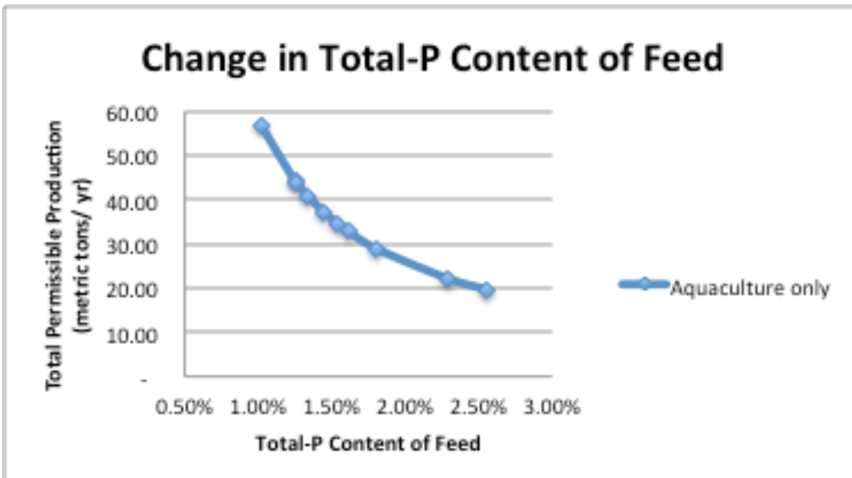
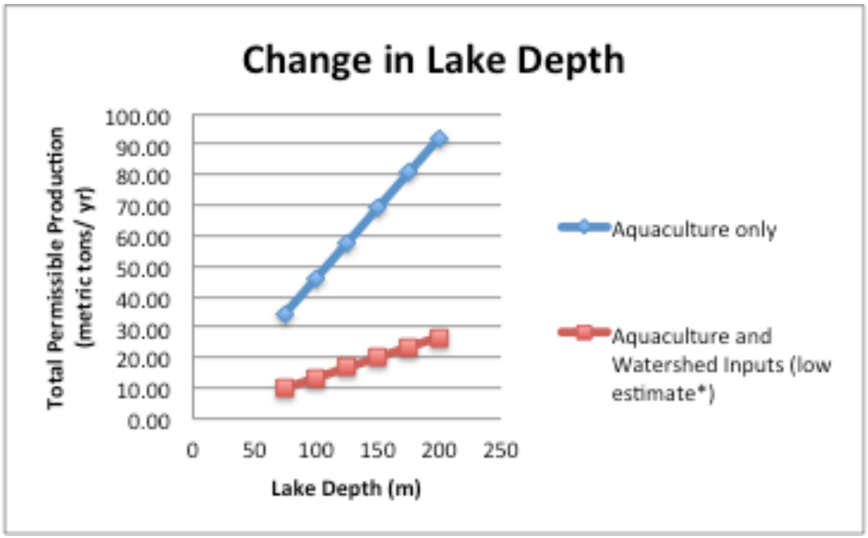
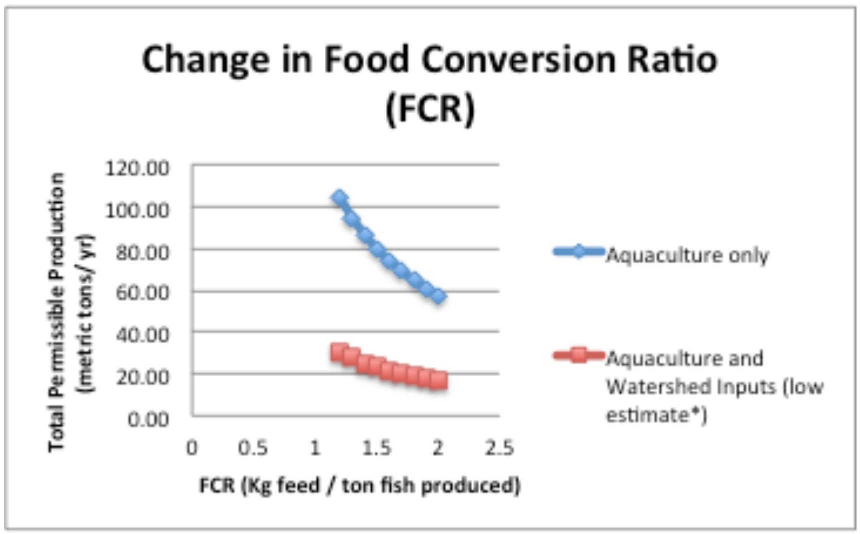


Figure 9. Charts of total permissible production results from altered model inputs for the zoned Harranggaol Bay approach resulting in Oligotrophic waters (Total-P at 10ppb).

When the target trophic status was altered to the low-mesotrophic level, the carrying capacity for aquaculture production alone nearly doubled as it did in the whole lake model (Figure 10). After the addition of the sub-watershed estimates, the total permissible production at carrying capacity experienced a 70.9% reduction. The difference between production before and after watershed considerations ranged in reductions from approximately 25 tons/yr for less desirable variables, up to 80 tons/yr for optimal variables.





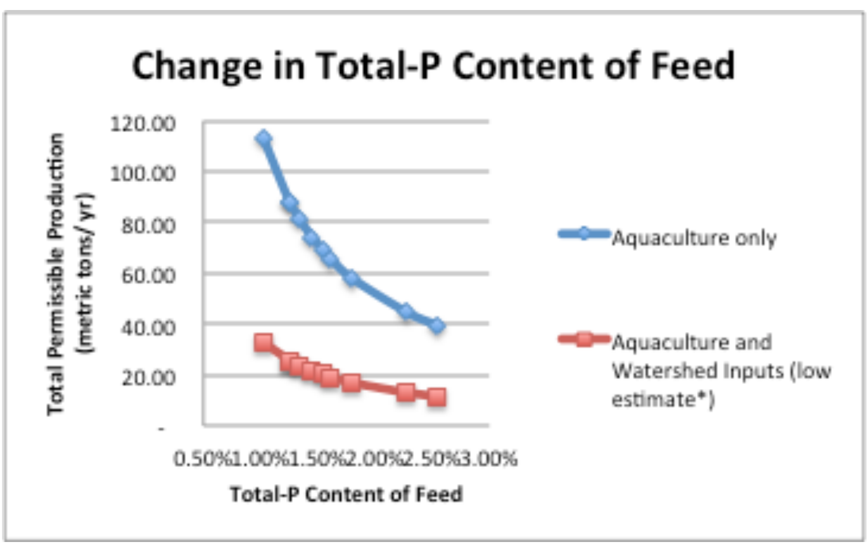


Figure 10. Charts of total permissible production results from altered model inputs for the zoned Harranggaol Bay approach resulting in Mesotrophic waters (Total-P at 15ppb).

The combination tables also show extremely low totals for total permissible production after watershed contributions are considered. These calculations suggest that even if all of the optimal inputs are used, the best results would involve low-mesotrophic waters and the permissible production of only 51.85 tons/yr. Current production is estimated to be upwards of 27,000 tons/yr in this small bay, while water quality data suggests hyper-eutrophic conditions with an average total-P concentration of 110 mg/m3 (EPA, 2012). According to this basic mass-balance model, without considering water circulation, these results place Haranggaol Bay well beyond hyper-eutrophic status.

	Desired In-Lake Total-P Levels (mg/m^3 or ppb) After Aquaculture				
Desired Total-P level after aquaculture production (P_f)	10	15	25	50	50
Initial Total-P level (P_i)	5	5	5	10	5
Delta P (ΔP = P_f - P_i)	5	10	20	40	45
Trophic status after production	Oligotrophic waters	Mesotrophic waters	Mesotrophic waters	Eutrophic waters	Eutrophic waters
	Total Permissible Production Based On Average Inputs[1] (metric tons/ yr)				
Aquaculture only	*34.57*	*69.14*	*138.28*	*276.56*	*311.13*
Aquaculture and Watershed inputs [2]	*NOT ATTAINABLE*	*20.12*	*89.26*	*227.54*	*262.11*

1 - Average imputs based on previous studies by EPANS and D. Taskov & I. Timonina

2 - Based on domestic wastewater rates of 2g/p/d and EPANS figures for land use

Table 5. Range of total aquaculture permissible production (metric tons/yr) for average key input values and various desired trophic states using the Beveridge model for a zoned approach to Haranggaol bay.

	Desired In-Lake Total-P Levels (mg/m^3 or ppb) After Aquaculture				
Desired Total-P level after aquaculture production (P_f)	10	15	25	50	50
Initial Total-P level (P_i)	5	5	5	10	5
Delta P (ΔP = P_f - P_i)	5	10	20	40	45
Trophic status after production	Oligotrophic waters	Mesotrophic waters	Mesotrophic waters	Eutrophic waters	Eutrophic waters
	Total Permissible Production Based On Optimum Inputs[1] (metric tons/ yr)				
Aquaculture only	89.08	178.17	356.33	712.67	801.75
Aquaculture and Watershed inputs [2]	*NOT ATTAINABLE*	51.85	230.01	586.35	675.43

1 - Optimum inputs based on previous studies by EPANS and D. Taskov & I. Timonina

2 - Based on domestic wastewater rates of 2g/p/d and EPANS figures for land use

Table 6. Range of total aquaculture permissible production (metric tons/yr) for average key input values and various desired trophic states using the Beveridge model for a zoned approach to Haranggaol bay.

Discussion:

With aquaculture concentrated into select, more protected bays of Lake Toba, the zoned approach to estimating ecological carrying capacity merits further attention. However, due to the complexities of this large and deep lake, more advanced full ecosystem models may be more applicable. In addition to insights gained from the zoned approach, this study also provides valuable insight on the importance of watershed considerations. Since the conservative watershed estimates used in this study revealed such large impacts to overall estimates of the carrying capacity for aquaculture production and lake eutrophication, it is evident that these nutrient sources require attention. The watershed contributions of P pose a genuine threat to water quality. Improving watershed management can result in a higher carrying capacity for aquaculture production.

As populations continue to rise within the Lake Toba basin, the demand for ecosystem goods and services will as well. In addition to an increase in the need for sustenance, employment opportunities across many fields will continue to be dependent on the lake. If the issue of ecological carrying capacity is not thoroughly addressed, many lives will be affected. Therefore, further study is required throughout the watershed. Water quality sampling should be increased throughout the entire lake in order to accurately determine the current state. A thorough inventory of land use practices should be conducted throughout the watershed. This should include quantifying nutrient contributions from agricultural practices such as the use of fertilizers and pesticides, as well as an inventory of livestock. Most importantly, the issue of domestic wastewater should be a top priority for all of the Kecamatans in the drainage basin. The development of treatment facilities should be explored, as well as public outreach and education programs geared towards more sustainable practices.

With such additional research, and the development of watershed scale management practices amongst the various administrations, Lake Toba can continue to support a variety of industries, while sustaining it's natural resources and the people who depend on them.

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