sustainability

Review

Lake Atitlan: A Review of the Food, Energy, and Water Sustainability of a Mountain Lake in Guatemala

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Abstract: This paper summarizes the findings of an extensive review of literature that was conducted to understand the historical state of the food, energy, and water nexus in the Lake Atitlan basin and to recommend incentive-based, long-term sustainable policies to become a significant driver to Guatemala's tourism industry and GDP growth. The SWAT (Soil and Water Assessment Tool) was implemented in the basin to work towards the goal of simulating nutrient loading. A key conclusion of this review study is for the local population to have advocacy for the "zero wastewater discharge to Lake Atitlan" initiative to bring long-term benefits to lake water quality. One of the recommended policy decisions is to seek external financing from international agencies like the World Bank at low-cost interest (IDA Loans) to implement waste management systems and pay this external debt by putting a small but affordable tax on tourists visiting the lake. Once a culture of zero municipal effluent discharge to Lake Atitlan is adopted by the local population, the livelihood of residents will become sustainable and the standard of living will increase because of improved water and air quality, making Lake Atitlan a haven of tourism for Guatemala and lifting its economy.

Keywords: algae; eutrophication; food security; water quality; policy; SWAT

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1. Introduction

Lake systems are massively important for the surrounding environment and have been the scene of human development since the dawn of time, providing communities with ample supply of fresh water for consumption, agriculture, and as a habitat for renewable sources of food [1–3]. Today, the ecosystem services provided by lakes have been documented and are largely understood, comprised of categories including the benefits of biodiversity, climate change mitigation, fisheries, recreation, tourism, and nutrient and sediment sequestration [4–7]. Moreover, the economic value of the ecosystem services make them an important asset for a nation's economy [8–10]. These systems make up some of the most prized resources for a nation but are often exploited without considering consequences [11–13]. A rising demand of ecosystem services because of rapidly increasing populations, greater expected quality of life, and increasing anthropogenic activity has put increasing pressure on lake sustainability, where many lake systems have experienced decreasing water quality and quantity [14,15]. Forio and Goethals [16] concluded that the continual monitoring of surface water is a key factor to understanding ecological contributions to meeting sustainable development goals.

Lake degradation has been observed around the globe, many with different sets of challenges depending on a myriad of external and internal factors. A common situation of how a lake becomes impaired is from the input of excessive amounts of phosphorus and nitrogen from wastewater, agricultural runoff, sediment bound nutrients, and other various sources, causing eutrophication [17–19]. The excess nutrients stimulate algae growth leading to uncontrolled algal blooms that dominate the ecosystem. Consequences of algal blooms include stress on aquatic life due to dissolved oxygen depletion, negative impacts on tourism, and some cyanobacteria species, such as *Microcystis* sp. and *Anabaena* sp., can produce harmful toxins [20]. The progression of a lake becoming impaired because of accumulating nutrients occurs over time and can generally be sped up by increasing human activity within a lake basin. For example, a case study by Chen et al. [21] of Lake Biwa in Japan describes a history of untreated sewage and agricultural runoff into the lake, causing eutrophication since 1975. There, a governmental initiative to treat 100% of the domestic sewage began in the mid-1970s and recently met its goal after forty years, showing significant water quality improvement in the lake. Another case study of Lake Erie in the United States depicted how difficult it can be to address eutrophication, documenting that after extensive governmental policies of limiting total phosphorus input into the lake in 1983, the lake experienced its worst ever cyanobacterial bloom in 2011 [22]. Eutrophication rates are also influenced by land use alterations within a drainage basin [23,24]. For example, Lake St. Lucia in South Africa has experienced increased loads of sediment due to the removal of upstream wetlands for sugar cane cultivation, resulting in elevated phosphorus associated with sediment [25,26]. Eutrophication is largely a human-caused problem and can be remedied by removing or limiting anthropogenic inputs of nutrients into the lake system.

In drier regions, such as the Middle East, natural lakes are the main source of irrigation for agriculture [27]. One of the largest human-caused ecological disasters is the draining of the Aral Sea between the border of Kazakhstan and Uzbekistan [28]. High levels of extraction from the lake water for agricultural irrigation accompanied by no regulations led to a 90% decrease in water volume, which had a massive ecological impact on native species because salinity levels increased 10-fold [29]. A more recent study by Ahmadaali, Barani, Qaderi, and Hessari [14] documented a similar trend occurring in Urmia Lake, Iran, noting that human impact on the drying of the lake is the driving factor, rather than climate change. The socioeconomic impacts of degrading lake resources are compounded when occurring in regions already suffering from poverty, food insecurity, and water stress [30]. The increasing demand on natural resources since the turning of the century has put immense pressure on lake bodies, primarily due to quickly increasing populations. For example, this sudden increase in pressure has been highlighted in case studies from Mexico, where Lake Xaltocan provided life for surrounding communities for over 2500 years but completely dried out in the 1940s due to diversions for agricultural irrigation [11], and from Chad, in the Lake Chad Basin, where the endorheic lake has diminished to 95% of its original volume from 1963 because of overconsumption [12]. In general, many lake authorities are implementing basin-wide policies to help restore the lake systems, with the damage seemingly done. Panagopoulos and Dimitriou [31] described the Lake Karla restoration initiative in Greece to renew the drained lake, emphasizing the need for the investors, mainly governmental authorities, to not only enforce policy and set regulations, but to also continually invest in local lake management groups for the continual monitoring and maintenance of the lake, calling for cooperative water management.

Invasive species can also drastically impact lake ecology, throwing off the balance of the ecosystem by disrupting the food web. For example, Aloo et al. [32] documented the deleterious impacts of introducing Nile Perch (*Lates niloticus*) into Lake Victoria in the mid 1900s, with the goal of enhancing the fishing industry. The process led to the extinction of multiple native species, a shift of socioeconomic reliance on the exotic fish from the native fish yields, and degrading food security because the local community could not compete with the fisheries industrialized for catching and processing the Nile Perch. Invasive species are not always fish—Walsh et al. [33] analyzed the economic costs of the invasive Spiny Water Flea (*Bythotrephes longimanus*) in Lake Mendota, Wisconsin USA. When considering ecosystem services associated with water clarity impacted by the flea, the cost for restoration was at least 86.4 million USD, while the monetized ecosystem services would generate around 140 million USD, economically justifying restoring the lake and protecting lake ecosystems from invasive species at all costs. Moreover, the United States has experienced widespread consequences of invasive zebra mussels (*Dreissena* *polymorpha*), still today grappling with long-term consequences of the alien species with economic impacts exceeding $100 million USD [34].

Lakes lie at the center of the food, energy, and water nexus. They are the foundation of many communities, for example, as in Lake Kinneret in Israel where the country's only freshwater lake provides drinking water to 25–30% of the country, food, and religious importance [35]. Additionally, Erhai Lake in China, known locally as "Mother Lake", supports hydroelectric power, tourism, and resources [36]. The impact of anthropogenic activity on each important lake needs to be understood for a sustainable future. Each situation is unique with unique solutions that will be most effective. Lake Atitlan, located in the western highlands of Guatemala, is a unique case study that has an extensive history with degrading water quality due to challenges with invasive species and eutrophication. As with the previously discussed case studies, the importance of creating sustainable plans to preserve the ecosystem services is of the utmost importance.

1.1. Guatemala

Guatemala is the third largest country in Central America with the tenth largest GDP of Latin America at $78.5 billion USD [37]. The population of more than 17 million people of Guatemala is the fastest growing in Central America [38]. A large proportion of the population consists of indigenous Maya, making up 41.7%, while the majority population demographic is Mestizo, from Spanish descent, at 56% [39]. Guatemala has struggled with poverty alleviation, which is largely seen in the Maya demographic. Nearly 59.3% of the total population lives in poverty, and 40% of indigenous Maya live in extreme poverty [39]. The United Nation's number one sustainable development goal is to eliminate poverty in the world, a goal Guatemala is working towards. Presently, the economy of Guatemala is dominated by the service economy at 63.2%, followed by industry at 23.4% and agriculture at 13.3%, as of 2017 [40]. The World Bank states about Guatemala:

"Guatemala has experienced continued economic stability, but this has not translated into growth acceleration to close the income gap with rich countries. In fact, poverty and inequality in the country are persistently high, with Indigenous Peoples continuing to be particularly disadvantaged".

This summary from the World Bank reflects on the improvement of Guatemala's economy, but that inequality between the indigenous and the wealthy populations remain a challenge that may hamper further economic growth.

Guatemala is a country of contrasts, where one may find themselves walking through an impoverished neighborhood and subsequently walk into a luxurious three-story mall with escalators and dozens of stores selling expensive designer brand accessories (Personal Experience 2019). Since tourism and services are the top economic drivers for Guatemala, it is important for the national government, the local governments, and the local people to protect and preserve natural attractions. Of all the tourist attractions in Guatemala, Lake Atitlan is at the top of the list [41]. Nestled among three towering volcanoes in the western highlands of Guatemala, Lake Atitlan not only draws thousands of tourists every year, but also provides livelihood for the more than 380,000 people surrounding the lake [42]. The lake is the food, energy, and water nexus for the surrounding population. It provides drinking water, fish as source of daily food, and irrigation water for agriculture that sustains livelihoods of people by providing profitable services like tourism, restaurants, and transportation, all of which require reliable energy resources.

1.2. Lake Atitlan

Lake Atitlan (14.6907 N, 91.2025 W) formed around 84,000 years ago when a volcano erupted and the caldera that was left behind was filled with water from the San Francisco and Quiskab rivers that still today flow into the lake [43]. The three surrounding volcanoes are named Atitlan, San Pedro, and Toliman. The volume of the lake is 24 cubic kilometers, with a maximum depth of 300 m [44] and a drainage area of 426 square kilometers, as delineated in ArcMap version 10.4 using SWAT 2012 (Soil and Water Assessment Tool) shown in Figure 1.

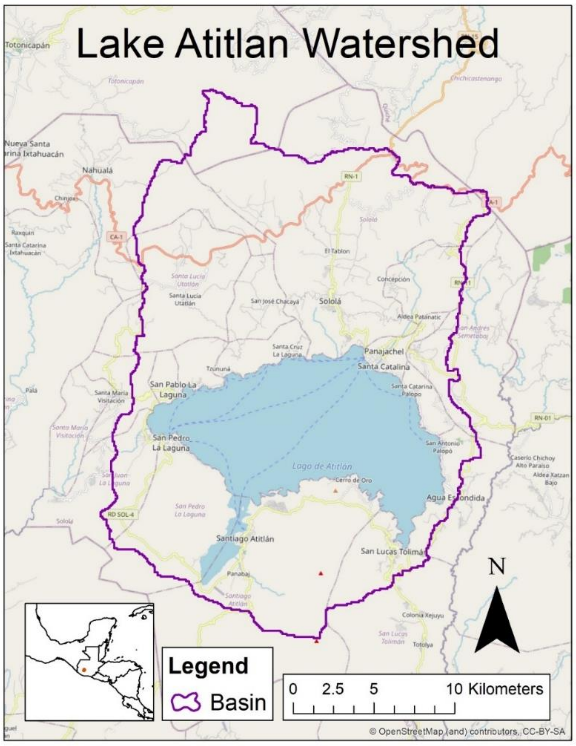

Figure 1. Lake Atitlan watershed in the western highlands of Guatemala. The purple outline is the watershed boundary.

It is the third largest freshwater lake in Guatemala [45]. There are no main outflows of this endorheic lake [46], with the main discharges of water being evapotranspiration and percolation. Due to the fact that the lake has no primary discharge outlet, the hydraulic retention time is unusually high at 80 years [46]. The low nutrient oligotrophic lake has naturally pristine water quality, which has gradually decreased because of human impact [47]. The average annual precipitation of this area is some of the highest in Guatemala at 3203.5 mm per year, computed using data collected from 1979 to 2014 by two local weather stations [48], and presumably contributes greatly to the water recharge of the lake.

Lake Atitlan is home to a large diversity of natural flora and fauna, yet a low diversity of fish species, likely due to the lake having no significant outlet for fish to enter from downstream [49]. It is home to 798 different plant species, 116 different reptile, and amphibian species, 236 different bird species, and 141 different mammal species such as the Black-handed Spider Monkey (*Ateles geoffroyi*) [50]. Of the different species, there are a handful of endemic species that are unique to the basin. Due to its ecological importance, the lake is protected as a Reserve of Multiple Uses of Basin Lake Atitlan and as of the year 2002, is listed as a world heritage site by UNESCO, who recognizes the lake's natural beauty, ancestral importance, and archaeological sites [51].

There are fifteen municipalities surrounding the lake with a total population of 380,400 as of 2017 [42]. Around 70% of these inhabitants live in poverty, and of those in poverty, 32% live in extreme poverty [42]. The largest municipality in the basin is Santiago, a population of 42,267 in 2018 with a growth rate of 2.67% since 2008 [52]. The main economy in the lake is tourism, followed by agriculture and livestock. Coffee, corn, beans, wheat, potatoes, sugar cane, and vegetables are grown in the lake basin. The native Maya are alive and well around the lake, although many live in poverty. There are three Maya groups living in the lake basin, the K'iche'e, Kaqchikel, and the Tz'utuiil. These Maya groups have great influence in the society surrounding the lake, as much of the population have roots connected to these groups. The Maya culture is very important to the people not just near the lake, but in all of Guatemala.

2. Energy Security Challenges

The energy security of a sustainable society is very important to the livelihoods of the citizens and for secure operations of day-to-day services [53,54]. The energy security challenges associated with impoverished communities, like those surrounding Lake Atitlan, are the supply of fuel for transportation, fishing, and tourism, and a reliant supply of electricity for lighting, cooking, and tourist activities [55,56]. Many of the economic boosting activities and services rely on a secure energy source, without which, tourism would decrease, and locals would face unemployment [57]. The benefits of improving energy security range from more affordable energy prices, increased employment, poverty alleviation, and environmental improvement, among others [58].

Data on the primary sources of electricity in the Lake Basin are limited. However, the national usage of energy relies on 41% from fossil fuels, 31% from hydroelectric power, and 28% from renewable energies [39]. Much of the literature on hydraulic electricity generation focuses on reservoirs equipped with hydroelectric power [59–61], which cannot be applied to Lake Atitlan because of its feature of having no overland outlet. Electricity in the Atitlan basin is primarily from the public electricity grid managed by municipalities [62]. The average electricity cost in Guatemala is 0.244 USD/kWh for households and 0.160 USD/kWh for businesses, above the world average of 0.140 USD/kWh and 0.120 USD/kWh, respectively [63,64].

Fortunately, energy harvesting technologies for lake applications are in development, which have the potential to benefit Lake Atitlan if invested in when available. Examples of these are sediment microbial fuel cells tested in Taihu Lake, China, a process of generating electricity from carbohydrate and protein-rich cyanobacteria [65]; a technology added to a wastewater treatment plant to treat dissolved organic matter from raw lake water while simultaneously generating electricity using a microbial fuel cell [66]; or thirdly, a study in Skadar Lake, Montenegro, testing the potential use of floating photovoltaic cells for renewable electricity supply [67]. Another promising renewable energy in the basin is geothermal energy, a resource yet to be exploited, and the Atitlan basin is indicated as an area of interest for investment in the renewable energy [68]. Innovations and opportunities such as these would provide Lake Atitlan with a stable and reliable renewable source of electricity and significantly increase energy security within the basin [69]. Furthermore, Guatemalan legislators must enact policy that complements the efforts made towards energy security to ensure success of innovative strategies, either through governmental subsidies or other incentive programs to offset up-front costs [58].

The energy characteristic in the food, energy, and water nexus is the driver of the other two characteristics. Without energy, crops could not be cultivated, or fish efficiently caught from the lake, and water quality would rapidly decline if wastewater treatment plants (WWTPs) were unpowered by electricity. The importance of energy in the food, energy, and water nexus is interwoven in the solutions to a sustainable future [70,71].

3. Water Quality Challenges

Primarily before the 1900s, the water in Lake Atitlan was of exceptional quality. The low nutrient lake made for crystal clear water with documented measurements of secchi depth reaching nearly 18 m [72]. With a growing population surrounding the lake, it was only a matter of time before man-made nutrient loading into the lake would increase. Presently, the estimated sewage produced in the basin is around 45,500 cubic meters per day, 80% of which is untreated [42], and is primarily responsible for the total nutrient and pathogenic bacteria contamination to the lake [73]. The rapid decrease in water quality of the lake was accelerated in 1958 due to the introduction of the black bass (*Micropterus salmoides*) to the lake in an effort by the local townships to increase tourism and attract anglers from around the world [74]. Sadly, the effects the black bass had on the lake ecosystem were traumatic. The aggressive bass outcompeted native fish for resources, severely decreasing the lake's biodiversity. In addition, the endemic Atitlan grebe (*Podilymbus gigas*) was declared extinct in 1989 because the black bass depleted the supply of crab, which the grebe was dependent on [74]. With the food web thrown off balance and an increasing amount of nutrient buildup from inputs of wastewater and agricultural runoff, the growth of algae and bacteria were left unchecked. In 2009, the lake experienced a bloom of phytoplankton that covered 38% of the lake's surface at its peak [75] (Figure 2).

Figure 2. Lake Atitlan cyanobacteria bloom in November 2009. Photograph from the Earth Observatory, NASA [76].

The lake experienced another significant bloom of phytoplankton in 2015, but not as large as the 2009 algal bloom [77]. These blooms are not only unaesthetic and hurtful to tourism, but certain phytoplankton blooms can consist of cyanobacteria, which produce toxins dangerous to human contact [78]. The algae blooms observed in the lake are primarily made up of *Limnoraphis robusta*, a non-toxin forming cyanobacteria [79], yet continue to negatively affect tourism and disrupt the lake ecology [80]. Cyanobacteria in the lake has been detected since the 1970′s, however it has been present in the lake at considerable levels since the largest bloom in 2009 [81–83].

The water quality issues surrounding the lake are the greatest hurdles to solve Lake Atitlan's challenges for long-term sustainability within the food, energy, and water nexus. The lake itself serves as an untreated source of drinking water for more than 70,000 people, even when the levels of harmful cyanobacteria are known, potentially causing unreported illnesses within local communities [46]. The residents in poverty around the lake have no other choice than to use the water for consumption and for washing. Poorer water quality due to wastewater inputs have widespread impacts on the overall economy of the lake, losses in tourist attraction, reduced biodiversity, and increased health risks for those consuming the water [46].

The primary contaminants in the lake are nutrients and pathogens [46]. For Lake Atitlan, that means addressing wastewater management. The wastewater treatment plants (WWTPs) in the surrounding municipalities of Lake Atitlan exist, but are in poor condition. There are 12 WWTPs in the basin, however, 80% of the sewage is left untreated, which ends up discharged directly into the lake [42]. The direct inputs into the lake are further leading to the cyanobacteria blooms, which is even more of a concern because of the endorheic nature of the lake with the 80-year hydraulic retention time. As a result of the long retention time, nutrients can stay in suspension in the water column for an extended period of time and mix into the overall upper layer during a natural event like a hurricane or tropical storm and create a eutrophication event, known as cultural eutrophication [84]. Due to this, the need to reduce the input of raw sewage into the lake is more important than ever.

Soil and Water Assessment Tool (SWAT) Assessment

The Soil and Water Assessment Tool 2012 (SWAT) is used for predicting land management practice effects on water quantity and quality in a basin and could be useful in addressing the water quality issues impacting Lake Atitlan [85,86]. The model could predict where the phosphorus contributing to eutrophication is coming from and the effectiveness of best management practices that can minimize it [87]. For example, the SWAT model can determine where installing a wastewater treatment plant would have the most impact on reducing phosphorus loading to Lake Atitlan. It could also be used to understand the contribution of sediment from the drainage basin to eutrophication in the lake [88]. A first step towards evaluating these goals is to make a hydrologic assessment of the water balance in the basin.

The SWAT model incorporates various input parameters that can either be from directly measured data from the study location or simulated by generalized internal databases [85]. The input parameters unique to the Lake Atitlan basin added to the model were elevation [89], soil type [90], land use [91], and weather data [92]. The elevation data were a Shuttle Radar Topography Mission 90 m digital elevation map, providing enough resolution to effectively delineate the basin and create flow pathways. The soil in the basin was generalized to a eutric cambisol soil type with 48% sand, 36% clay, 2% organic matter, and a saturated hydraulic conductivity of 150 mm/hr [93]. The land use layer area is detailed in Table 1. The weather data are from two local weather stations (14.831 N, 91.250 W and 14.5186 N, 91.250 W), providing daily time-step precipitation, wind speed, temperature, solar radiation, and relative humidity data [48]. The slope classification was set to 0–5%, 5–15%, 15–25%, and 25%+ (Figure 3).

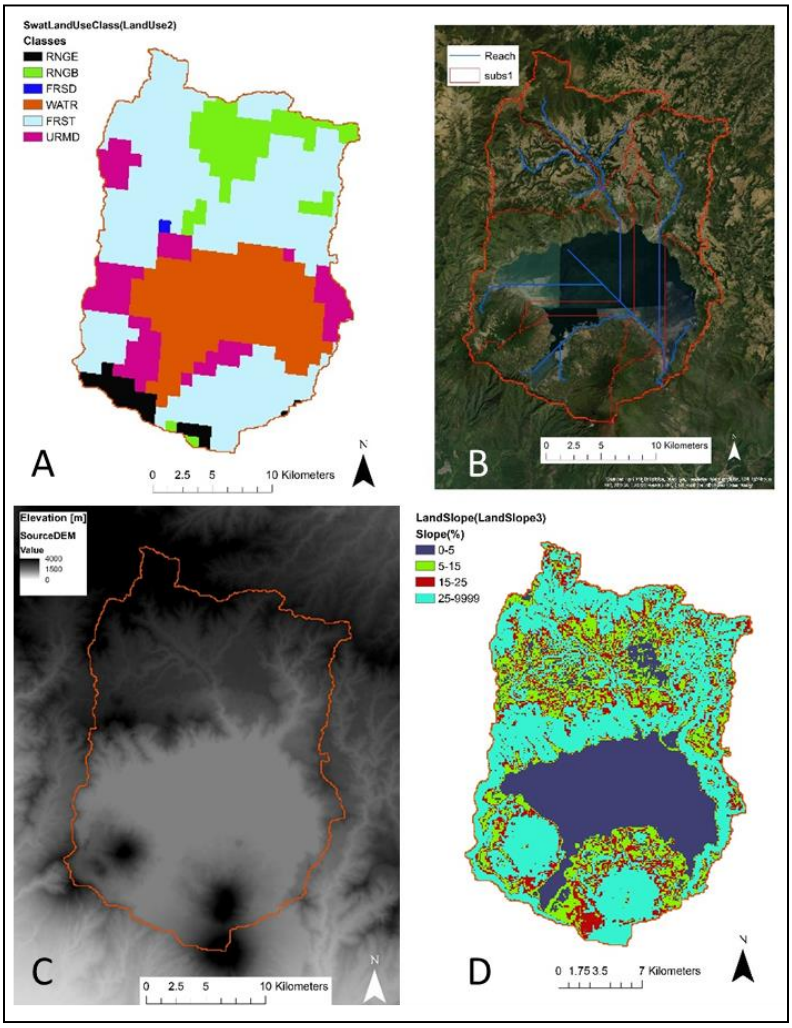

Figure 3. Soil and Water Assessment Tool 2012 (SWAT) input parameters. (**A**): Land use extent; range-grasses (RNGE), range-brush (RNGB), forest-deciduous (FRSD), water (WATR), forest-mixed (FRST), residential-medium density (URMD). (**B**): Basin stream segments and sub-basin delineation. (**C**). Digital elevation map and basin. (**D**). Hillslope map.

Table 1. Land use classification and areal extent.

Label	Name	Area (m^2)
FRST	Forest-Mixed	50.06
WATR	Water	24
URMD	Residential-Medium Density	12.36
RNGB	Range-Brush	10.26
RNGE	Range-Grasses	3.14
FRSD	Forest—Deciduous	0.18

The SWAT model was simulated for a 36-year period, 1979–2014. The water balance of annual water yield is displayed in Figure 4, showing an average annual water yield of 1736.32 mm. The predicted average annual precipitation was 3203.5 mm. The large portion of outflow from lateral soil simulated is likely higher than realistic due to the generalized saturated hydraulic conductivity for the entire basin. A more detailed analysis of the soil properties and land use description specific to the region would provide more fidelity to the model. This first analysis was done to understand the limitations of the available data. The SWAT assessment has computed a water balance for the basin that next needs to be calibrated and validated using existing monitoring data [94]. When optimized with field data, the model can serve as a tool to predict how land use change will impact nitrate, phosphorous, sediment, and bacteria loading into the lake [95]. This tool would serve as a cost-effective way to justify management projects before major investment [96].

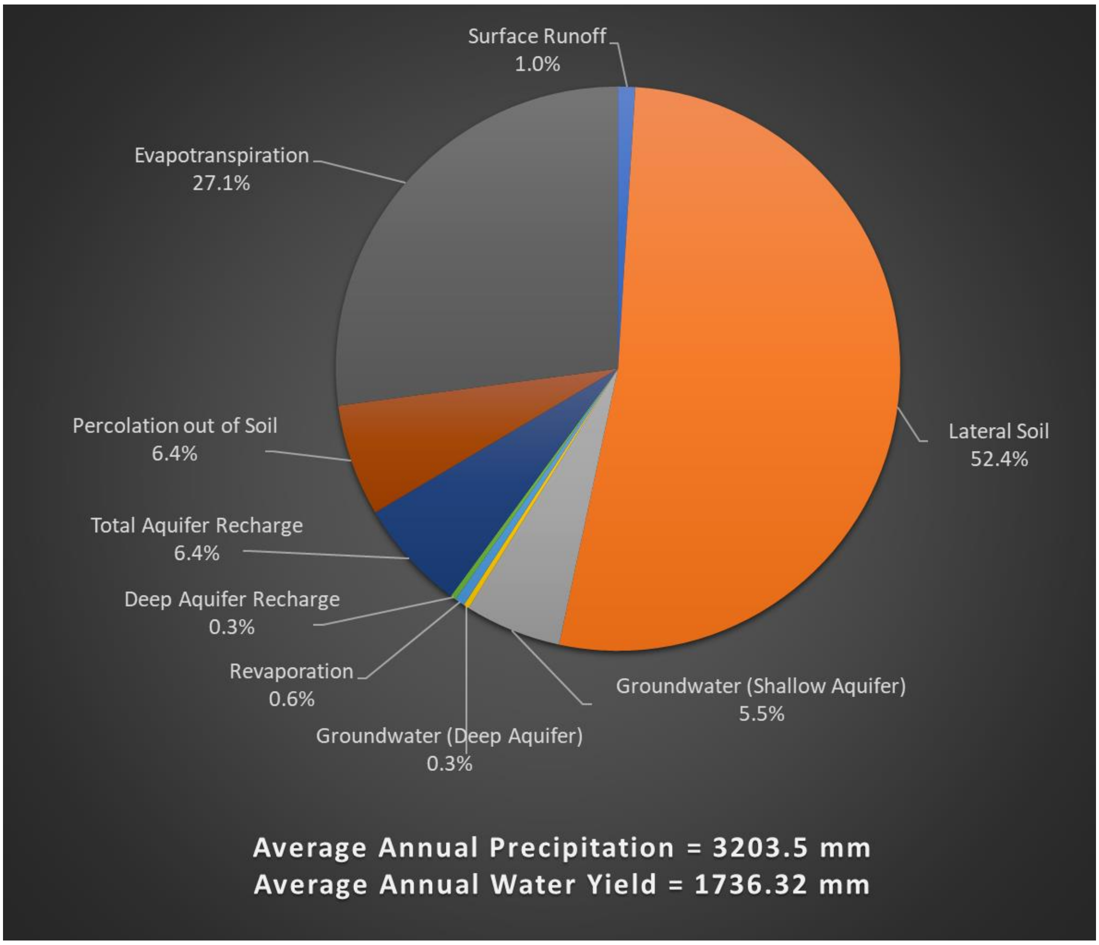

Figure 4. Water balance from the SWAT assessment in the Lake Atitlan basin.

4. Food Security Challenges

The food security in the food, energy, and water nexus is a critical component for a sustainable system. Food security needs to meet four requirements for a region to be totally food secure: availability, accessibility, use, and stability [97]. Most of the agricultural land in the basin is owned by Mestizos, nonindigenous people, while the local Maya tend to land less than half one acre [98]. The main crops grown by the larger Mestizo monocultures are grains, vegetables, coffee, and avocadoes, using green revolution inputs such as fertilizers and pesticides [98]. These inputs have a direct negative impact on lake water quality when eventually drained into the lake, contributing to eutrophication and fish toxicity [99,100]. The SWAT model could prove useful here to help better inform the fate and transport of these pollutants and evaluate the overall impact of agricultural inputs in the lake.

The future of agriculture and food security in the basin may need to look to the past for clues on how to be sustainable. Native Maya used terracing, irrigation, tree culture, and intensified shifting of cultivation, which are unlike those techniques implemented by intensive monocultures today [101]. Moreover, an argument can be made that the introduction of large food chains can reduce food security because locals may rely on fast food more than producing fresher food closer to home that is likely more sustainable, especially in a poverty struck area. It is important for the local people to continue to cultivate their land for nutritious food to sell in the local markets, rather than rely on big businesses to provide food that can lead to worsening health effects [102]. The food challenges associated with the lake itself are whether it can supply enough and healthy fish for selling and consumption. The aversion to eating fish from the lake can hurt tourism and may leave the local people searching for protein elsewhere [103]. Improving the water quality of the lake will lead to sustainable and good quality fish that will subsequently assure a stable food supply to the local population and serve the tourism industry.

5. Policy-Related Issues of Past and Current Work, and Recommendations for the Lake Atitlan Basin

The challenges of the food, energy, and water nexus in Lake Atitlan are imminent, and, the local population, local government, and federal government are aware of the situation, understanding the science of the challenges needing addressed. Many solutions to the food, energy, and water challenges discussed above would theoretically work, however, finding a source of funding for it is difficult. For example, to manage the accumulating trash, a project was implemented to create a garbage disposal system [82] for solid waste. These systems are generally very expensive and cost money to maintain the use of trucks and other needed infrastructure. The garbage disposal system remains in business, however, it is lacking sufficient services to keep up with the increasing rates of trash build-up [46]. With the rapid growth of the population around the lake, the need for a solid waste treatment program is high and investments are needed in solid waste management to improve the living environment for local population and tourists visiting the lake [82]. This certainly will improve the air and water quality in and around the lake due to decreased trash burning and solid waste pollution to the lake.

As far as sewage management is concerned, two proposed solutions have been recommended in the past to clean up the lake's wastewater. A study by Chandra et al. [104] recommended complete raw sewage to be exported out of the basin, for zero contamination to the lake, modeled after a successful case study of Lake Tahoe in California. Another proposed solution was to treat 100% of the wastewater before it was discharged into the lake [98]. The solution to treat 100% of the wastewater was deemed unfeasible because of the limitations to WWTP capacity and the technical maintenance required for the treatment plants. However, funding was available from the Guatemalan government in 2015 to upgrade existing WWTPs, although bureaucracy and clearance issues have slowed the process [77]. The recommendation to export the sewage outside of the watershed is currently being advocated by the governmental group Authority for the Sustainable Management of the Lake Atitlan Basin and its Surroundings (AMSCLAE). The AMSCLAE is the leading organization for monitoring and protecting Lake Atitlan. Unfortunately, the export project is viewed unfavorable within the local community. Aside from the cost, the wastewater is planned for export outside of the watershed to irrigate a monoculture production in the southern region of the country [83], rather than being used as fertilizer for local crops. Additionally, locals are worried about the potentiality for a malfunction with the sewage line, in which the locals would experience the brunt of the negative effects, not the managers of the project [98].

The Guatemalan government has addressed concern about the raw sewage input into the lake. They proposed a multipart plan in 2009 after the large cyanobacteria bloom, to cut all phosphorous entering the lake [81]. Phosphorous is typically the culprit for episodes of eutrophication. The plan called for the construction of multiple new WWTPs in the basin, and a switch to organic farming, meaning without the use of pesticides and fertilizers. The plan was to raise 350 million USD, but the funding goals were not met and the project came to a halt. Likewise, the government protection group for Lake Atitlan, AMSCLAE, provides recommendations for businesses on how to treat wastewater independently to minimize impact to the lake. Whether this strategy will be successful in convincing independent parties to invest in wastewater treatments is uncertain. For example, AMSCLAE recommended a restaurant owner to build a biodigester system, but AMSCLAE would not help subsidize any of the expenses and the business owner simply could not afford the capital costs or loss of business during construction [103]. Nevertheless, the AMSCLAE group continues to do important work monitoring water quality and implementing conservation practices. They hold workshops on sustainability, collect information about population-dense areas that would benefit most from a WWTP, and they create proposals for the management of water in the lake basin.

Two notable pieces of AMSCLAE's strategy are to increase water treatment facilities and advocate for the "zero wastewater discharge to Lake Atitlan" project [105]. The problems in the lake are well known to the government and local people, however, finding the money to implement and maintain projects is the major hurdle. Options to seek financing without hurting local communities could be quickly adopted, for example, initiating a small tax on tourists visiting the lake to create a source of income used to pay off borrowed money from international agencies like the World Bank at low-cost interest (IDA Loans). The funding from international organizations could be allocated to local community projects or to help subsidize federal projects targeted at improving water quality.

The most successful initiatives so far have arisen from initiatives by local communities surrounding the lake, out of necessity to improve conditions quickly without bureaucratic roadblocks. A clearly positive example is the decision by the community in San Pedro La Laguna to ban all single-use plastic in 2016. The town's tourism increased by 40% in 2018 because of this locally led initiative [106,107]. Since then, ten other municipalities around the lake have adopted this practice, resulting in an increase in water quality because of the reduced plastic waste entering the lake. There are other nongovernmental organizations (NGO) that have tried to implement lake restoration programs in the lakeside communities, such as Tul planting by the Ati'tAla' NGO. Their goal was to install strips of the plant Tul (*Scirpus californicus*) to facilitate the filtering of nutrients before entering the lake, as well as providing cultural importance of the plant, which was used in sacred rituals by the Maya [108]. The local communities have also come together to clean buildups of algae on the surface of the lake [83]. Funding in the hands of the local community may lead to the most effective change.

6. Conclusions

Lake Atitlan is the food, energy, and water nexus for the communities living within its basin. It is the lifeblood of many locals who live off the water, fish, crabs, and restoring properties of the lake [83]. It is more than important for the country of Guatemala to protect and restore their most beautiful lake that draws in numerous tourists every year who spend money on venders, restaurants, and services all across the lake, bringing an unmatched economic stimulus to the country. The locals and local experts are fully aware of the water quality issues in the lake. It is only a matter of developing a unified approach backed by secure funding from the national government to make lasting positive and sustainable change.

It is highly recommended for the Guatemalan federal government to recognize Lake Atitlan as one of their country's top priorities to market and invest in. The need for enforceable but incentive-based policies to limit the use of pesticides, fertilizers, and sewage waste around the lake and garbage disposal entering the lake continues to grow. Presently, there are no enforceable policies on lake cleanup and little to no maintenance for existing WWTPs [83]. National and international funding must be sought to address sewage management and maintenance for a unified approach to balance the food, energy, and water nexus in Lake Atitlan. The limited data and formal scientific investigation in the lake basin make it challenging to make informed decisions about balancing the food, energy, and water nexus. There are currently little to no data on food security indicators or on electricity consumption in the surrounding towns. Monitoring of water quantity and quality in the basin would help develop water quality models like SWAT to inform better decision making. Consistent data collection and data availability will be key in making progress towards improving water quality.

As one of the main reasons why Lake Atitlan is polluted, the consistent functioning of local WWTPs must be prioritized. Focusing on small-scale treatment of wastewater may have a better result than attempting to treat all wastewater from around the basin at once. Investing in the sewage wastewater cleanup and solid waste management will lead to immeasurable benefits to the Guatemalan economy and boost the quality of life for all living in poverty or extreme poverty within and around the lake basin.

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