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Feasibility of Wastewater Reuse for Fish Production in Small Communities in a Developing World Setting

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
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ABSTRACT

Eradicating poverty, malnutrition, and the burden of disease have been included as three of the major issues facing the world. The United Nation member countries, having set forth the Millennium Development Goals, have committed themselves to solving these problems. Two major factors which affect solutions to these problems are increasing water stress and implementing improved sanitation. Integration of tilapia aquaculture and reuse of wastewater has been suggested as a solution which addresses both of these factors. The objective of this study is to examine the feasibility, and explore the benefits and drawbacks, to implementing small community wastewater fed (WWF) aquaculture systems in the developing world.

The water quality characteristics of treated effluent from nine wastewater treatment (WWT) plants were compiled from other studies. The concentration of total nitrogen in the effluent and the flow rate were of most importance, as they were used to calculate the nitrogen loading at each WWT plant. The nitrogen loading was then used to estimate the total pond size which could be supported by each WWT plant, the expected yearly yield for tilapia, and the percentage of the population who would benefit from provision of protein associated with the integration a fish farming system with the WWT plant.

Results show that WWF, semi-intensive tilapia culture can provide 10 grams per day of dietary protein for 11% – 52% of the population of the communities in this study when integrated with a community managed wastewater treatment system. To assess potential risks to human health, associated with WWF aquaculture, the level of fecal coliform (FC) contamination was compared to the standard set by the World Health Organization; less than 10^5 FC per 100 mL for reuse in fish ponds. The level of FC

contamination in the WWT plant effluents ranged from 653 to 1.78×10^5 FC per 100 mL, exceeding this standard.

Given the context, the level of fecal coliforms should not rule out integrated reuse and aquaculture as an option. The nutrients found in wastewater are valuable resources in tilapia culture; therefore, allowing their persistence through treatment for reuse, while optimizing wastewater treatment technologies for pathogen removal is an appropriate solution for small communities in developing countries for reducing poverty, malnutrition, and disease burden of waterborne illnesses.

INTRODUCTION

At the turn of the millennium the 189 countries of the United Nations (UN) made a commitment to the improvement of the lives of the world's poor. The UN outlined eight goals to be reached by the year 2015. Among these eight Millennium Development Goals (MDG), the member states of the UN have dedicated themselves to the eradication of extreme poverty and hunger (Goal 1) and assurance of environmental sustainability (Goal 7) (UN, 2000). Aquaculture, the farming of aquatic plants or animals, can play an important role in achieving both of these goals. It can also contribute indirectly to the achievement of the other goals: e.g., improving maternal and child health, combating diseases such as HIV/AIDS, and achieving universal primary education.

Aquaculture has a long history in many parts of the world. In Zambia, extraction of fish from rivers and streams, even traditional methods of fish farming, are widely practiced. Generally, aquaculture in Zambia has been an extensive farming practice and most families keeping traditional style fish ponds have done so for subsistence. Increasing local demand has made catching, transporting, and selling of fish in urban areas a very important economic activity for many families.

Export of fish and fish products accounts for over 25% of the total agricultural export in 14 African nations (Heck et al., 2007). By investing in aquaculture these countries can reduce poverty by adding jobs and growing their economies. Investment in aquaculture can occur at all levels of the economy, from rural farmers to larger commercial farms. In the same way that aquaculture can span all levels of economic development, it can also be integrated with solutions used in other sectors. For example, this integration could combine irrigation systems and wastewater treatment (WWT) systems, or the nutrient rich effluents from fish ponds and vegetable crops which require nutrients and reliable irrigation. Aquaculture education can also be integrated into school curriculums or financing programs for women's groups and cooperatives.

The sections of MDG 1 seek to reduce poverty by increasing incomes, and decreasing unemployment (UN, 2000). Section C of MDG 1 focuses on hunger. Rural aquaculture promotion increases the capacity of rural farmers not only to increase their family income, but also to reliably produce a food like fish, which is rich in protein. Even if families do not use aquaculture for economic gain, the benefits of having a reliable source of protein will improve the family's health, helping to achieve Goal 1.

There are many benefits of integrating aquaculture with other agricultural and environmental efforts. The integration of aquaculture into traditional farming practices, such as keeping livestock and gardening, can raise the productivity per unit of land area by 28 percent (The World Fish Center, 2007). It is likely that integration could also yield similar results for water productivity. Aquaculture systems that reuse wastewater or pond effluents could help to reduce water stress.

Study Objective and Hypothesis

The objective of this study is to examine the feasibility, and explore the benefits and drawbacks, to implementing wastewater fed (WWF) aquaculture systems in the developing world. Some previous studies have investigated at wastewater agriculture and aquaculture as a productive treatment method (Edwards, 1992). However, a general approach to WWF agriculture lacks detail regarding the unique challenges and benefits of reusing wastewater for fish production. Other studies have approached WWF aquaculture directly, focusing on nutrient recovery, economic feasibility, or institutional support for WWF fish farming (Bunting, 2006; Mara et al., 1993). However, the most detailed of these studies focused on the theoretical renovation of a large wastewater treatment (WWT) plant serving an existing aquaculture system – 550,000 cubic meters per day (Bunting, 2006).

The study's author spent two years in Zambia as a Peace Corps volunteer, as part of the Master's International Program in Civil and Environmental Engineering (http://cee.eng.usf.edu/peacecorps/) and the Rural Aquaculture Promotion (RAP) program. He participated in nine weeks of cultural, language (Bemba), aquaculture, and HIV/AIDS training. Following training he moved to his host community where he conducted farmer evaluations, fish farming workshops, farmer site visits, and community based HIV/AIDS education. His direct observation of fish farming practices in Zambia served as a basis for some assumptions made in this study and for recommendations made for future research.

This study will use data obtained from various WWT plant case studies, within a developing world setting, to investigate the feasibility of integrating wastewater reuse with fish pond aquaculture that would support a portion of a community's protein requirements. The study will specifically examine whether the nutrient loading associated with effluent from small community wastewater treatment systems found in the developing world is sufficient to support fish growth. The study will also address whether reusing treated wastewater effluent to produce fish results in the protection of human health. The study will assess the following two hypotheses:

1. Integrating fish aquaculture with small WWT facilities will provide sufficient amounts of water and nutrients to farm fish and provide a significant amount of a community’s protein intake.
2. Wastewater from small scale WWT plants can be safely reused in fish pond aquaculture.

PREVIOUS RESEARCH

The Relationship of Aquaculture to the Millennium Development Goals

The integration of aquaculture into traditional farming practices can be used to directly address MDG Goals 1 and 7 set forth by the UN in 2000. The solutions which will achieve Goal 1, to eradicate extreme poverty and hunger, will involve aquaculture. Already fish products contribute substantially to the economies and diets of many communities in developing countries. Current capture methods from freshwater have depleted natural supplies, and aquaculture could serve as a way to fill the existing gap between supply and demand (Heck et al., 2007). Growth of the industry could, especially among rural small scale farmers, engage these families in an economic sector which has great potential for growth.

By promoting indigenous species and by integrating fish farming with WWT, fish farming programs can also have a direct impact on achieving Goal 7, to ensure environmental sustainability. Natural fish stocks are already under great stress from current demand (Heck et al., 2007). By promoting semi-intensive aquaculture, some of this stress could be relieved, especially where natural stocks have collapsed or have been regulated. Integrated WWF aquaculture can play a role in reducing the number of people without access to improved sanitation. Increasing capacity to treat wastewater provides room for expansion of water treatment facilities that will be designed to supply water to reuse applications, especially if the WWT facilities have other benefits like food production and economic incentives (Bunting, 2006).

Table 1 summarizes these direct links to targets in MDG Goals 1 and 7 and the indirect benefits to all of the other Millennium Development Goals in Africa. The indirect benefits are generally related to the health benefits and increased income associated with families engaged in aquaculture.

Table 1 – Contribution of fisheries to the MDGs in Africa, reprinted with permission from Simon Heck et al. (2007)

MDG Objectives		Contribution of Fisheries and Aquaculture
Goal 1	Eradicate extreme poverty and hunger	Income to 10 million poor households through fish capture, processing, trade and allied industries Food security for 200 million poor, strengthened through affordable, high quality food
Goal 2	Achieve universal primary education	Indirect benefits through increased income for women and improved health of children
Goal 3	Promote gender equality and empower women	Women strongly engaged in artisanal processing and trade, gaining income and power
Goal 4	Reduce child mortality	Fish nutrients (such as fatty acids) improve neural development in the fetus and lower the risk of low birth weight, key factors in child mortality Child nutrition improved through supply of protein and minerals
Goal 5	Improve maternal health	Improved nutritional status of women
Goal 6	Combat HIV and AIDS, malaria, and other diseases	Fishing communities are among the hardest hit by HIV and AIDS; progress here is vital for combating the pandemic regionally Affordable proteins and micronutrients help mitigate the impacts of disease among the poor and are essential for the effective use of drugs Incomes form fisheries and aquaculture enable the poor and HIV and AIDS sufferers in particular to obtain badly needed nutrition and income and thus access further services

Table 1 (Continued)

Goal 7	Ensure environmental sustainability	Good fisheries governance, such as through regulated small scale and large scale aquaculture can contribute to preserving biodiversity and fragile habitats throughout the continent
Goal 8	Develop a global partnership for development	Fish is the leading export commodity helping African nations to improve their trade balance, and offering opportunities for developed countries to promote and adopt good trading practices from the outset The Abuja Declaration on Sustainable Fisheries and Aquaculture in Africa and the pan-African Fisheries and Aquaculture Program by the African Union are strengthening regional cooperation and international partnerships in science and capacity building

Wastewater Fed Aquaculture

Wastewater fed (WWF) aquaculture systems utilize wastewater to irrigate and supply nutrients to aquatic species. Junge (2001) views WWF aquaculture as a part of an integrated method to treat wastewater to acceptable levels of coliforms and other requirements. This integration of wastewater treatment and productive aquaculture has been called a *rational* design by Bunting (2006). A rational design approach views water treatment and aquaculture as a single system to be optimized for maximum fish production and wastewater treatment.

The use of wastewater in agriculture is not a new idea. Wastewater was used in 19th century Europe to irrigate crops at the periphery of the continent's growing cities (Ensink and van der Hoek, 2007). This served not only to irrigate and fertilize crops, but also as an environmental buffer between the raw sewage and the bodies of water which the waste would otherwise be dumped. As the land became more coveted for other forms of development, along with the invention of chemical fertilizers and traditional WWT plants, the practice was abandoned.

Currently wastewater is reused for agriculture in developed and developing countries around the world. Specifically reuse for fish aquaculture is occurring on a rather large scale near Kolkata, India (Bunting, 2006). However, wastewater is also unintentionally reused from polluted surface waters where wastewater is released directly to surface waters (Edwards, 1992).

As water stress becomes an increasingly important concern in many places, more people are exploring the option of WWF aquaculture as part of an integrated wastewater treatment and agricultural scheme (Ensink, 2007). Fish farming falls within the many options which exist for productive wastewater treatment designs. Other engineers and scientists have noted the wide range of aquaculture options which exist for the WWF aquaculture systems (Junge, 2001). Figure 1 presents these various aquaculture products:

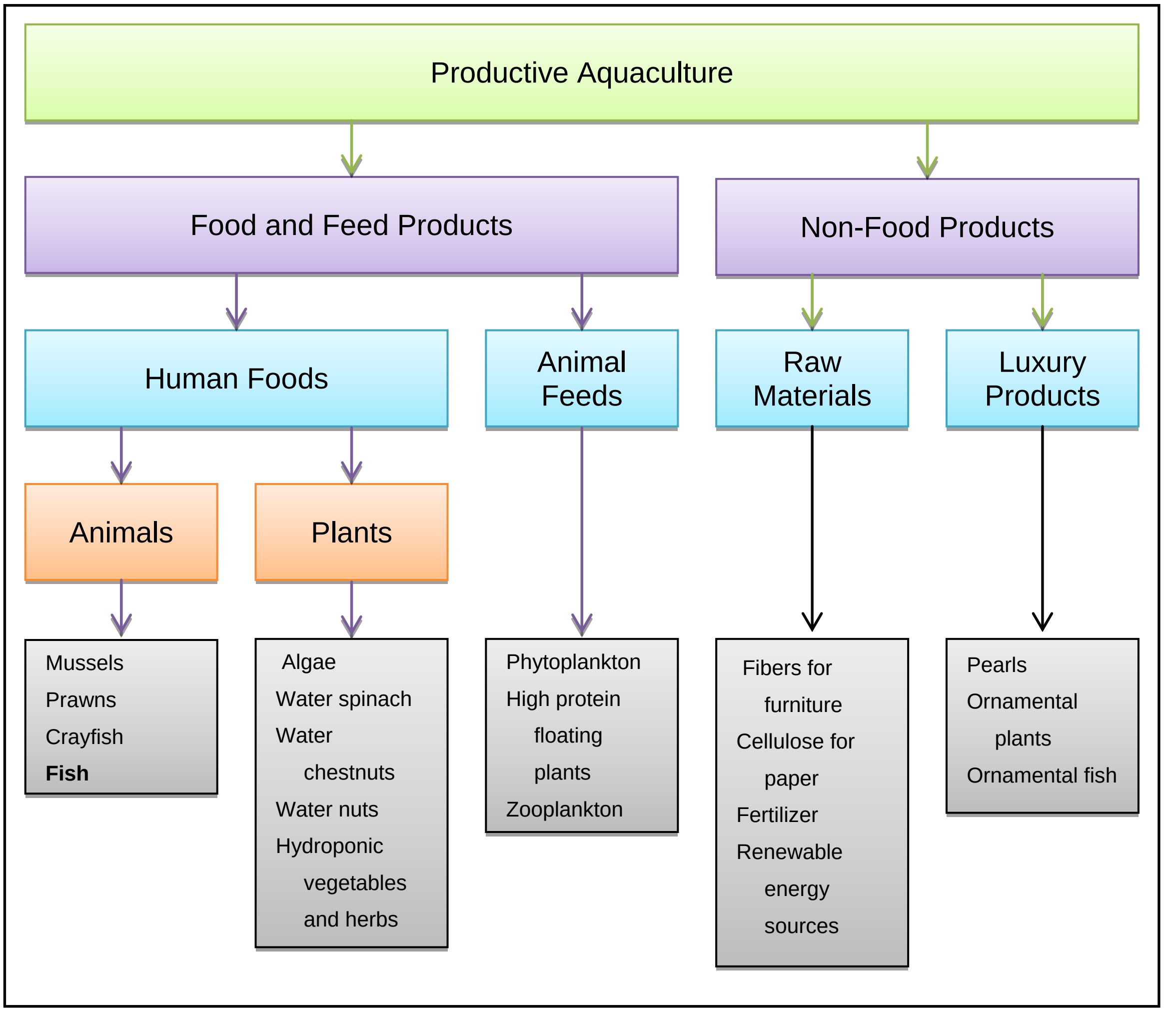

Figure 1 – Schematic showing the various products of aquaculture systems

Adapted from (Junge, 2001)

Wastewater treatment in developed countries has many varied objectives all aimed at protecting the well-being of a nation's residents and the state of the environment. It has been suggested that the main goal for wastewater treatment in developing countries should be the removal of pathogens, since the disease burden for waterborne illness is the largest concern associated with wastewater (Oakley, 2005). By combining this WWT priority with aquaculture, the nutrients and organic matter in wastewater can be viewed as a resource rather than a waste product to be treated (Cavallini, 1996). The financial and health benefits (from increased protein supply) add to the incentives for building and maintaining wastewater treatment systems (Edwards, 1992).

WFA systems can be separated into three groups: first, productive ponds receiving raw wastewater; second, productive ponds receiving wastewater treated by primary treatment system; and productive ponds receiving wastewater treated for pathogens (Cavallini, 1996). This study focuses on the third group, productive ponds receiving wastewater treated for pathogens. Due to the health risks of working directly with raw wastewater in fish ponds and the water quality targets proposed by the World Health Organization (WHO), direct use of raw wastewater is not considered. Since lagoon based systems are promoted for use in small communities in the developing world, the study focused on lagoon systems.

Risks to Human Health in Wastewater Fed Aquaculture

With increasing water stress around the globe, the interest for reuse of wastewater has garnered attention. Many uses for water do not require drinking water quality; for example: irrigation, toilet flushing, cleaning, industrial reuse and environmental enhancement (Jamwal and Mittal, 2010). The reuse of wastewater for production of food for humans poses obvious questions about the risk to human health. What quantities of pathogens should be tolerated for use in agriculture? What risks do these levels pose to those who work in wastewater agriculture? How should the policies be enforced?

Governments have taken various approaches to the regulations set to ensure that the reuse of wastewater is safe. A sample of these regulations for U.S. states and other countries is presented in Appendix A. The approach taken to wastewater reuse varies greatly between developed and developing nations. The United States Environmental Protection Agency takes a conservative approach, stating that wastewater reuse should pose no risk of infection (Ensink and van der Hoek, 2007). In contrast, institutions such as the International Water Management Institute, whose work focuses on poor communities in developing countries, try to balance the benefits and risks of wastewater reuse. The WHO takes a stance somewhere between them, requiring that there should be no additional cases of infection, but also recognizing that different countries face their own unique situation (Ensink and van der Hoek, 2007). In 2006, the WHO revised its guidelines on wastewater reuse. However, it stood by its earlier guidelines for wastewater use in aquaculture.

Some debate has occurred about the 2006 revision of the WHO guidelines for wastewater use in agriculture from those established in 1989. While some argue that relaxation of the WHO guidelines could send the wrong message to practitioners and potentially increase disease risk. It is more likely recognition of the reality of wastewater reuse, especially in developing countries. Each country must take into account the current wastewater reuse practices in their country and asses what kind of policy is appropriate for their nation (WHO, 2006). A summary of these considerations is provided in Appendix B.

The fact that the WHO has asked local governments to adopt guidelines which suit local conditions is paramount to finding solutions for the developing world. Diarrheal diseases already place an incredible burden on global health. As engineers we do not want to increase this burden. However, we must recognize that poor sanitation is the status quo in many communities. To deny access to wastewater because it does not meet requirements that have been deemed appropriate in the United States does not improve the overall situation of the people who choose to use that water. For many, untreated wastewater is the only reliable source of water for irrigation (IWMI, 2006), and for far more polluted surface waters are the best option for irrigation. It is estimated that less than 20% of wastewater is treated worldwide and 3.5 to 20 million hectares is irrigated with wastewater or waste contaminated river water (Scott et al., 2004; IWMI, 2006). This argument is not to be used as an excuse for designing systems that may increase health risks. Rather, looking at the current situation and finding a solution that will be economically, social, and environmentally sustainable is the ultimate goal.

Currently, the WHO states that the geometric mean for fecal coliforms should be no greater than 1,000 per 100 mL of wastewater for crops consumed uncooked. This was relaxed from a geometric mean of 100 coliforms per 100 mL used previously (Ensink and van der Hoek, 2007). The WHO report also urges local governments to adopt guidelines which suit local conditions (Ensink and van der Hoek, 2007). It is important to consider health impacts of these systems, especially the impacts on those who work at wastewater fed farming systems. It is also important to consider the risk associated with consuming fish produced in these systems.

In creating guidelines the WHO had few case studies to use in determining suggested guidelines for allowable levels of fecal coliforms and other contaminants, as there has been little study of wastewater fed aquaculture. The risks associated with WFF aquaculture can be divided into two categories: 1) those which may directly affect workers at the site and 2) those that may affect the consumers of the fish. Risks to the consumers of fish may be due to accumulation of pathogenic bacteria on the skin of fish, in their gills, and in the intestines. These risks may be increased if the fish live in a particularly stressful environment due to overstocking or low dissolved oxygen (WHO, 2006). Trematodes may also pose a health threat if host species, such as aquatic snails, are present in the system. Tests to verify the absence of trematode eggs should be conducted and proper pond maintenance should be followed to combat the survival of host species in the ponds. The risks posed by microbial pathogens can generally be avoided by proper cleaning of the fish gut and cooking. The community and workers should be aware of the risks associated with WWF aquaculture. For example, workers should wear shoes to avoid infection by hookworm and the community should not use the pond water for drinking or allow children to swim in the ponds (WHO, 2006).

One approach for evaluating WWF aquaculture systems is to set guidelines based on health based targets. Health based targets suggested by the WHO are found in Table 2.

Table 2 – Health-based targets for waste-fed aquaculture (WHO, 2006)

Exposed Group	Hazard	Health-based target	Health Protection Measure
Consumers, workers and local communities	Excreta-related pathogens	10^{-6} DALY	Wastewater treatment Excreta treatment Health and hygiene promotion Chemotherapy and immunization
Consumers	Excreta-related pathogens	10^{-6} DALY	Produce restriction Waste application/timing Depuration Food handling and preparation Produce washing/disinfection Cooking foods
	Food borne trematodes	Absence of trematode infections	
	Chemicals	Tolerable daily intakes as specified by the Codex Alimentarius Commission	
Workers and Local Communities	Excreta-related pathogens	10^{-6} DALY	Access control Use of personal protective equipment Disease vector control Intermediate host control Access to safe drinking water and sanitation at aquacultural facilities and in local communities Reduced vector contact (insecticide-treated nets, repellents)
	Skin irritants	Absence of skin disease	
	Schistosomes	Absence of schisto-somiasis	
	Vector-borne pathogens	Absence of vector-borne disease	

These targets are based upon a standard metric of disease. For these targets DALYs are used. DALYs are disability adjusted life years; one DALY represents one year lost to ill-health, disability or early loss of life. Using health-based targets can help policy makers and practitioners to evaluate the risks associated with WWF aquaculture; however, they can be difficult to apply when designing a WWF aquaculture system. Performance targets are simpler to use and should be used at three- to six-month intervals to evaluate the risk associated with consumption of fish which is always eaten cooked (WHO, 2006). However, few studies have been done that link expected DALYs to microbial performance targets for wastewaters intended for reuse in aquaculture. Based on limited information, the WHO has settled on a geometric mean of 10^4 fecal coliforms (FC) per 100 mL of fish pond water and less than one helminth egg per liter (arithmetic mean) (WHO, 2006). Influent to the pond may have a geometric mean of 10^5 FCU per 100 mL to take into account the effects of pathogen removal which occur in the fish pond once the wastewater enters the pond (WHO, 2006). This is consistent with the CEPIS report, studying WWF ponds in Peru, which concluded that effluents from wastewater stabilization ponds containing 10^5 FCU per 100 mL were appropriate for reuse in aquaculture (Cavallini, 1996).

Other potentially hazardous constituents, chemicals such as mercury and pesticides are generally of little concern in WWF aquaculture. These toxins do have the potential to bioaccumulate. However, fish should be regularly harvested, so the period in which bioaccumulation may occur is relatively short. Therefore, the expectation is that levels of potential toxins would be low enough to be considered safe for human consumption (WHO, 2006). It should be noted that most studies, including this paper and the WHO report, do not address the reuse of industrial wastewaters for aquaculture.

Due to the short grow out period for tilapia, four to six months, the accumulation of potentially harmful substances, such as mercury, was not a major component of the RAP program. Since it was assumed that unless these substances are present in the water at excessive concentrations, they would not be present in fish at harmful levels. Also the wastewater to be reused, from small community waste treatment systems, is assumed to come from domestic waste which is less likely to contain harmful toxins associated with industrial wastes.

One study found that farmers, sellers, and consumers in Ghana were unaware of the dangers of mercury contamination from local small scale mining (Tschakert, 2010). This suggests that local governments and aquaculture promotion programs should include educational components to create awareness of the dangers of mercury poisoning. The Tschakert study also found that fish from less contaminated waters had higher demand, so the threat to public health may be smaller than suggested by panicked messages about contamination at the mining sites.

Phytoplankton accumulates heavy metals. However, “the contaminants do not appear to be readily accumulated by fish that feed on the algae.” (Edwards, 1992). However, other studies have found fish grown in treated wastewater to exceed the WHO guidelines for safe consumption of fish (Bhattacharyya et al., 2010). The WHO guideline of 1.6 µg per gram bodyweight (of person) per week for methylmercury is set to avoid potential harmful effects of a developing fetus. A person of 50 kg could consume up to 80 µg of methylmercury a week without exceeding this limit (WHO, 2007).

The main methods for removing heavy metals before reuse is to allow plankton to settle out into the sludge layer or use chemical methods such as precipitation. Once these compounds are in the pond heavy metal uptake by fish and plankton is influenced by their concentration and the pH of the water. Lower pH has been shown to increase the accumulation of methylmercury in tilapia (Wang et al., 2010).

For reuse of domestic wastewater there is not much concern with contamination of heavy metals as compared to direct use of surface waters (Edwards, 1992). However, if there is any potential that wastewater is mixed domestic and industrial, testing and monitoring is essential to ensure there is no threat to public health.

The United States Environmental Protection Agency (US EPA) has set action levels for the concentration of copper, zinc, and cadmium in water. These action levels are presented in Table 3. If the metal concentrations exceed these action levels for a given water hardness, measures must be taken to ensure that the quality of fish is not harming the health of its consumers. The fact that the action levels vary with water hardness shows that the threat posed by heavy metals and other chemicals depends very much on the other water chemistry factors, not solely on the compounds' concentrations in water. Therefore, the negative effects of heavy metals and toxins on fish quality should be evaluated for each WWF aquaculture system.

Table 3 – Chronic criteria action levels for copper, zinc, and cadmium in freshwater at various levels of water hardness (US EPA, 2002b)

	Hardness (mg/L as $CaCO_3$)			
	500	100	10	1
Copper (µg/L)	35	9	1.3	0.18
Zinc (µg/L)	460	120	17	2.4
Cadmium (µg/L)	0.75	0.25	0.049	0.01

Studies on Wastewater Fed Aquaculture

Few studies have focused specifically on integrating wastewater reuse with fish farming in the developing world. Two studies identified from India (Bunting, 2006; Mara et al., 1993), use the existing large scale WWT and fish farming system east of Kolkata as a starting point for their analysis. These studies present one perspective for designing a wastewater reuse and aquaculture system; however, they differ in focus from this study. The characteristics of the WWT system used in the Peru study (Cavallini, 1996) did not include data for the average flow rate or nitrogen concentration in the treated wastewater.

Both of the India studies aimed to find the potential benefits of renovating the existing pond system, making it more productive and safer for workers and fish consumers. The ponds were mixed cultures of tilapia and carp. The entire system constitutes about 3,000 hectares of fish ponds fed by 555,000 cubic meters per day of treated wastewater. Wastewater characteristics for treated wastewater entering the pond are presented in Table 4. However, the actual level of fecal coliform (FC) contamination was not measured, but estimated using a model for FC removal.

Table 4 – Treated wastewater characteristics for wastewater effluent entering farming system east of Kolkata, India (Bunting, 2006)

Flow Rate	6,366 L/s
Nitrogen Concentration	50 mg/L
Fecal Coliforms per 100mL (estimated, not measured)	380
BOD Loading	6 kg/ha·day

The study in Peru (Cavallini, 1996) was an experimental fish farm studied over the course of two years. The study found that the dispersion flow model was appropriate for modeling the levels of bacteria in its stabilization ponds and recommended that model be used when designing ponds to meet a permissible level of bacteria. It also supported the WHO's suggestions for guidelines of acceptable levels of fecal coliforms in pond influent and pond water based on the quality of fish harvested from the study's ponds. It also suggested that aquaculture ponds operate with a loading of biochemical oxygen demand (BOD) of 10 to 20 kg per hectare per day.

Protein Requirements for Human Beings

According to a joint report by the WHO, FAO, and the United Nations University, an adult weighing 60 kilograms should consume 50 grams of protein a day. In some countries fish constitutes up to 70% of the animal protein consumed; in Africa over 200 million people eat fish regularly (Heck et al., 2007). Figure 2 shows the per capita intake of fish in kilograms per year. As shown in Figure 3, fish accounts for more than 20% of animal protein in the diets of many African countries, yet the supply of fish is low compared to many countries in Europe, North America, and East and Southeast Asia.

This suggests that many countries, especially where protein consumption is low, have cultures which are already accustomed to preparing and eating fish. Increasing the total dietary protein intake by increasing the supply of fish is an acceptable method for decreasing malnutrition.

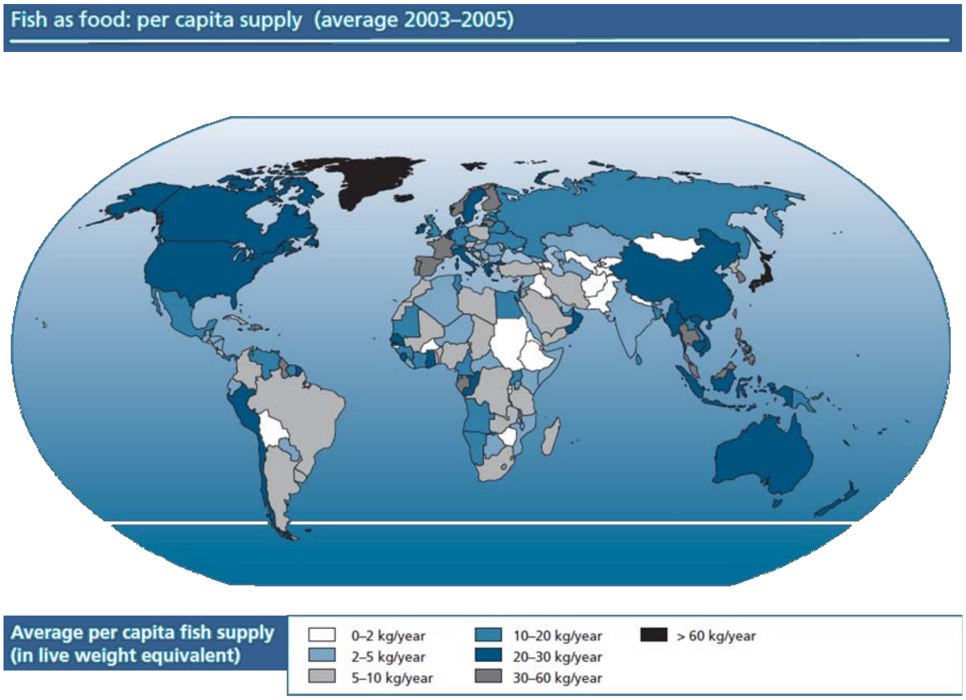

Figure 2 – Global per capita supply of fish to global food supply (average 2003-2005)

Reproduced with permission from the Food and Agriculture Organization of the United Nations (2009, p. 62)

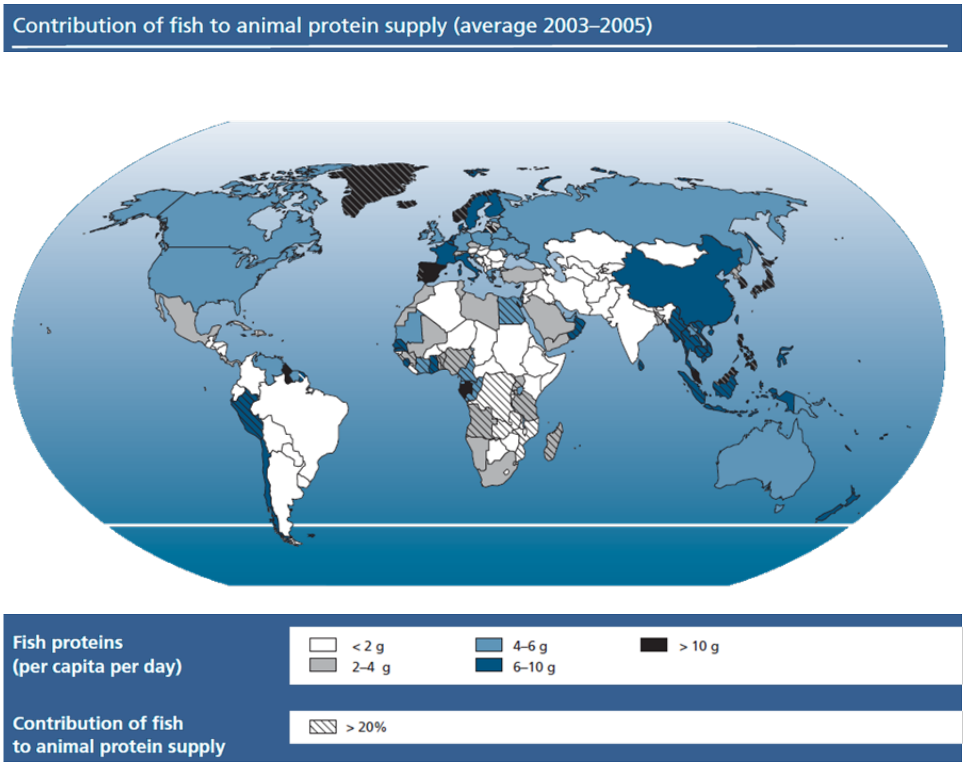

Figure 3 – Global contribution of fish to animal protein supply (average 2003-2005)

Reproduced with permission from the Food and Agriculture Organization of the United Nations (2009, p. 62)

However, there are other sources of dietary protein besides fish and meat. Africa consumes the least protein daily per capita, approximately 60 grams per day (FAO, 2009); Appendix C presents the total supply of dietary protein by food group across six world regions. This actually meets the dietary guidelines for a 60 kilogram adult, but does not take into account the inequalities of protein consumption across the continent. The countries in which daily consumption of fish protein is greater than ten grams per person are coastal countries which have a long history of ocean fishing: e.g. Norway, Iceland, Japan, and the Philippines.

Based on the data for current sources of protein for various world populations depicted in Figure 3, one would expect that fish would account for no more than 10 grams a day in communities which introduce fish farming as part of a food security or economic development plan. A typical serving of fish according to the United States Department of Agriculture is 3 ounces or about 85 grams (USDA , 2006). This is also about the size of one harvested fish in a Zambian fish farm.

FISH FARMING SYSTEMS

Semi-Intensive Tilapia Farming System Overview

The Rural Aquaculture Promotion (RAP) program is a joint venture between the United States Peace Corps (PC) and the Zambian government.

“Rural Aquaculture Promotion (RAP) was developed in 1996 by Peace Corps Zambia in response to a request from the Department of Fisheries (DoF) for human resource assistance in the aquaculture sector. The purpose of RAP is to help rural families and groups to address their livelihood needs, including HIV/AIDS mitigation, by operating integrated aquaculture as small business ventures that are supported by effective fish farmer organizations” (USDS, 2011).

The project coordinators have developed various recommendations for the construction and management of semi-intensive tilapia farming systems. The RAP standard fish pond and farming strategy is intended for rural farming families and co-operatives of rural farmers in Zambia. Utilization of local resources is very important in this context since external inputs such as special digging tools, manufactured fertilizers, commercial feeds, fishing nets, and pipes can be relatively expensive and cost-ineffective.

Most communities host three generations of RAP volunteers. The service of each volunteer builds upon the progress of the previous. Earlier volunteers focus on cultural acclimation of the host community to working with an American and the goals of the PC and the RAP program. This is followed by the identification of project farmers who have ponds or would like to build ponds. This is followed by the construction of ponds, teaching of basic management, stocking, and harvesting concepts. Marketing, business management, co-operative development, and farm integration are introduced on demand and usually after a base of model farmers are identified within the communities.

RAP Standard Pond

The RAP standard pond is the ideal pond for a beginning fish farmer. However, this pond design is by no means the only suitable pond, especially since every farmer's situation differs. Often the pond design is modified to accommodate the land and water supply. The RAP program also promotes three species of native tilapia which are detailed in Appendix D. Nile tilapia (*Oreochromis niloticus*) is also included because it is the most commonly cultured type of tilapia worldwide (El-Sayed, 2006). However, it is now considered an invasive species in Zambia and it is no longer promoted by the Department of Fisheries. Tilapia is cultured in over 100 countries and the production of farmed tilapia nearly quadrupled between 1990 and 2002 from 383,654 metric tons to over 1.5 million metric tons (El-Sayed, 2006). Therefore, the study of semi-intensive tilapia culture will have widespread impact in an agricultural sector which is already experiencing enormous growth.

Ideally, the pond is fed by a furrow. A furrow is a ditch which is often used in Zambia for irrigation and household water supply. A furrow begins where part or all of the flow of a stream has been dammed or diverted into a ditch which follows the contours of the stream valley. The furrow should be able to provide enough water to keep the pond or pond system full year round. This is especially important where infiltration through the pond bottom is high and where rainfall is very seasonal. For example, a farmer must be confident that during October, the end of the dry season, water flows in the stream. Otherwise seasonal farming or groundwater fed ponds may be more appropriate.

The site should also be close to the house to reduce the risk of theft and the amount of energy expended traveling to and from the pond. Often the compost and manure will be produced near the house; reducing the distance between the pond and these resources saves time and energy. The soil should have a high-clay, low-sand content that does not allow for a large amount of infiltration. There should be plenty of space for future expansion, since the family may want to add more ponds; some for household consumption, fingerling-production, or to sell to market. Fingerlings are young fish, 4 to 6 cm long, used to stock a pond.

Figure 4 is a schematic showing an aerial and cross section view of a valley used for fish ponds. Figure 4a shows the furrow, diverted stream, and a system of eight ponds. Each pond has its own inlet to prevent contamination between ponds. Figure 4b is a cross section of the valley. The ponds are built on the valley's slope because it is important that ponds can be gravity-drained so they can be easily harvested and dried between harvests. This draining process is important in maintaining the pond. This process includes the removal of trash fish, removal of settled organic matter, and ease of harvesting fish from an emptied pond. The ponds should also be high enough up the valley wall to prevent flood water from reaching the dike walls, which are shown in orange.

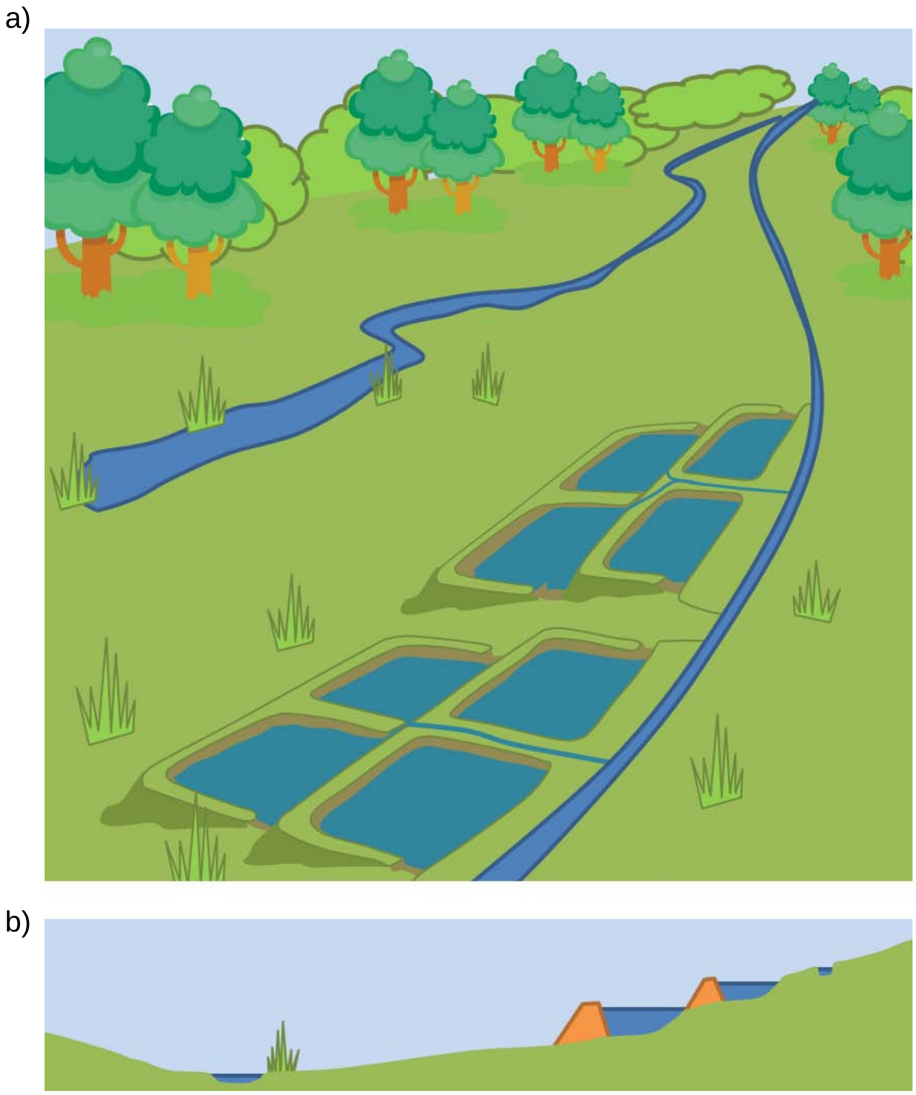

Figure 4 – a) Schematic of a semi-intensive fish farming system showing a system of eight ponds and good placement within a stream valley, b) cross section of a valley utilized for a fish pond system

The physical characteristics for a RAP standard pond are summarized in Table 5. Figure 3 shows a cross section and Figure 4 shows a plan view of a RAP standard pond. They also help to reduce the physical efforts exerted during the construction, management, and harvesting of the ponds. Traditional ponds often feature interior walls which have no slopes, just a vertical wall face. This design does not benefit the fish and actually increases the amount of digging required during construction. Choosing a site with a slope between 5% and 15% the amount of digging and soil movement is lower than on a valley wall with a much shallower or steeper slope.

Table 5 – Physical characteristics of a standard pond promoted by the Rural Aquaculture Promotion (RAP) program

Feature	Dimension	Rationale
Inside Slopes	3:1 slope	Provides location for breeding nests, creates thermocline (warmer water at shallow edges), easier to enter exit pond for maintenance/harvesting
Pond Bottom	Depth from 0.8m to 1.1m	This creates a slight slope in the pond bottom which can help when draining the pond for harvests
Outside Slopes	2:1, grass covered	Provides structural strength, reduces erosion
Overall Size	10m by 15m	Larger ponds may be too large for a beginning farmer to manage and they require more resources; more small ponds allow for more combinations of production cycling; spreads disease risk over many ponds
Compost Bins	10% of surface area	Size and locations large enough to provide ample compost, prevents spreading out of compost on water surface which would block sunlight
Inlet/Outlet Pipes	1 inlet, 1 outlet per 100m^2	Inlet allows for the control of flow into the pond, outlets allow for overflow control, especially during heavy rains
Pipe Screens	At inlets and outlets	Prevents trash fish from entering the pond from furrow at inlets and prevents fingerlings from exiting at outlets
Wide walls	1m wide all around pond	Ensures the structural strength of walls is sufficient, provides path for easy access around the entire pond during maintenance/harvesting

Figure 5 shows a typical cross section of a pond. The tops of the dike walls and slopes are covered in grass, the maximum depth of the water is just over a meter, and the overall slope of the site is about 5 to 15%.

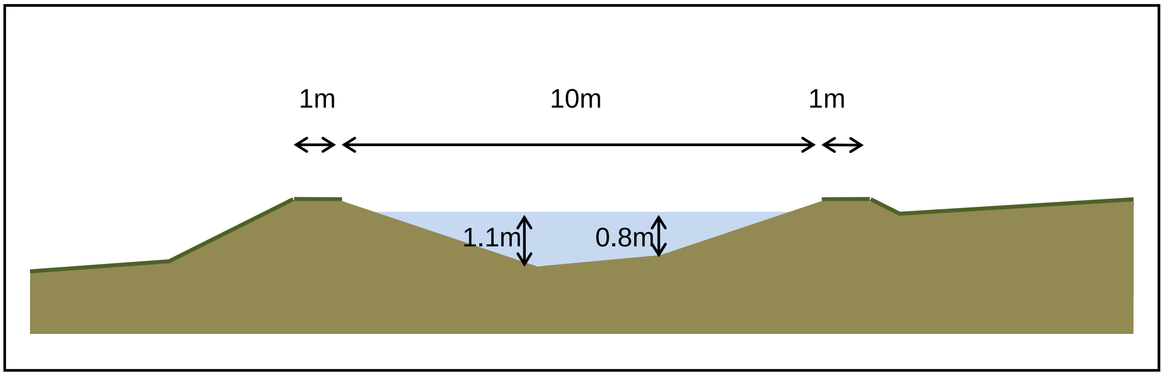

Figure 5 – Cross section view of a Rural Aquaculture Promotion (RAP) standard pond

Figure 6 provides a plan view of a typical RAP standard pond. The furrow is on the upslope side of the pond. It also shows a typical layout for the inlet and outlet pipes, the outside slopes, and the compost bin.

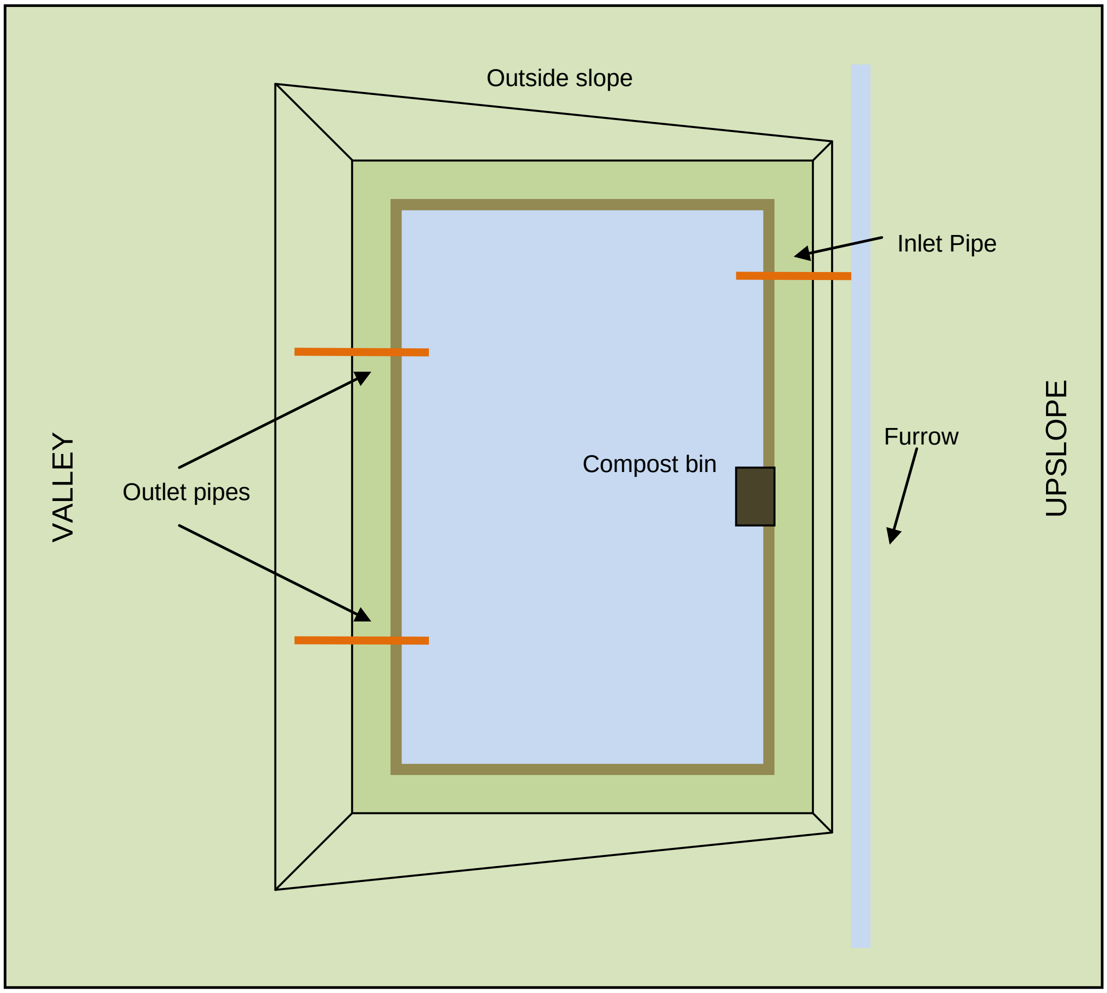

Figure 6 – Plan view of a Rural Aquaculture Promotion (RAP) standard pond showing typical layout of inlets, outlets, furrow, compost bin, and overall orientation in the valley

Environmental Requirements

Studies have been conducted on the effects of various environmental factors on tilapia production. These studies provide useful insights into fish production, they are limited since factors such as temperature, pH, levels of dissolved oxygen, *et cetera* work together in ways that may limit or enhance growth and reproduction, or possibly even cause fatality.

While Table 6 presents guidelines for important factors that could cause fatality or limit production, it is important to keep in mind that various factors may work together to cause undesired effects. Consider the following examples. If the temperature drops over the course of an evening by a few degrees then the fish will tolerate this change. However, if the temperature drops the same amount over a few minutes (perhaps during fingerling transport) than the temperature change could be fatal. Or if one study shows that a certain tilapia species can tolerate a NH_3 concentration of 3.4 mg NH_3 – N/L, then maybe the fish were only capable of tolerating this high concentration because they had been acclimatized to NH_3 previously and the temperature and pH were in ranges which did not compound stress for the fish.

Table 6 – Environmental factors affecting tilapia growth and mortality (El-Sayed, 2006)

Factor	Ideal	Tolerable	Notes
Temperature	20°C – 35°C	7°C – 10°C to 40°C – 42°C	Greatly affects growth rates and reproduction
Salinity	Varies greatly between species; *Oreochromis mossambicus, O. aureus, Tilapia zilii* most tolerant; optimum limits for all species range from 0 $^{0}/_{00}$ to 19 $^{0}/_{00}$		
Dissolved Oxygen	Aeration not conclusively shown to increase growth rates	0.0 – 0.5 mg/L	Affected by many factors such as photosynthesis, respiration, and diel fluctuation
Ammonia	Below 0.1 mg un-ionized ammonia (UIA) – N/L	LC_{50} 48 h: 2.5 – 6.6 mg UIA – N/L	un-ionized ammonia (UIA) is toxic to fish; level of toxicity depends on dissolved oxygen (DO), CO_2, and pH; brief exposures of high concentration have little lasting effect on growth rates
Nitrite	Relatively non-toxic at low levels	LC_{50} 96 h: 4.4g fish: 81 mg/L 90.7g fish: 8 mg/L	Sustained high levels compromise immune systems, causing mortality; tolerance depends on fish size
pH		3.5 – 5 (acidic lower limit range) 11 – 12 (alkaline upper limit range)	Adult fish more resistant to low pH, water pH greatly affect resistance to changes in DO
Turbidity	Below 75 NTU; growth is inhibited for turbidities greater than 75 NTU	Suspended matter which causes turbidity, reduces fertilizer effect, causes water to acidify, and inhibits light penetration; turbidity can be caused by rainwater runoff from dike walls, turbid source water, or re-suspension of particles from pond mud by water and fish movement	

The Bloom

The most important concept which should be understood when farming fish is that pond fertilization and composting are not a direct feeding method for fish. The composting materials and fertilizer (often some kind of manure) is added to the pond to promote the growth of algae. The resulting algal bloom is visible as a greenish color in the water column. The bloom is actually microscopic plankton that use nutrients in the water and sunlight to grow. In turn these phytoplankton are fed on by the fish. The bloom is most important for fingerlings and other young fish since it makes up a large part of their diet. As they become larger the fish begin to feed more frequently on supplemental feeds which are fed directly to fish on the pond's surface.

The most important components in pond fertilization are the levels of carbon, nitrogen, and phosphorus supplied to the pond. Potassium is also important if there are very low potassium levels or the alkalinity of the water is low (El-Sayed, 2006). The optimal C:N:P ratio is 50:10:1. According to Edwards (2000) the average nutrient content for phytoplankton in fish ponds is 45-50% carbon, 8-10% nitrogen, and about 1% phosphorus.

As shown in Figure 7 the source of each of these components is a combination of the compost, ash, and manure. In the case of WWF aquaculture, wastewater will also provide carbon, nitrogen, and phosphorus. However, the carbon and phosphorous, depending on the amount of suspended solids, will likely come from compost materials, meaning that composting will remain an important part of pond maintenance.

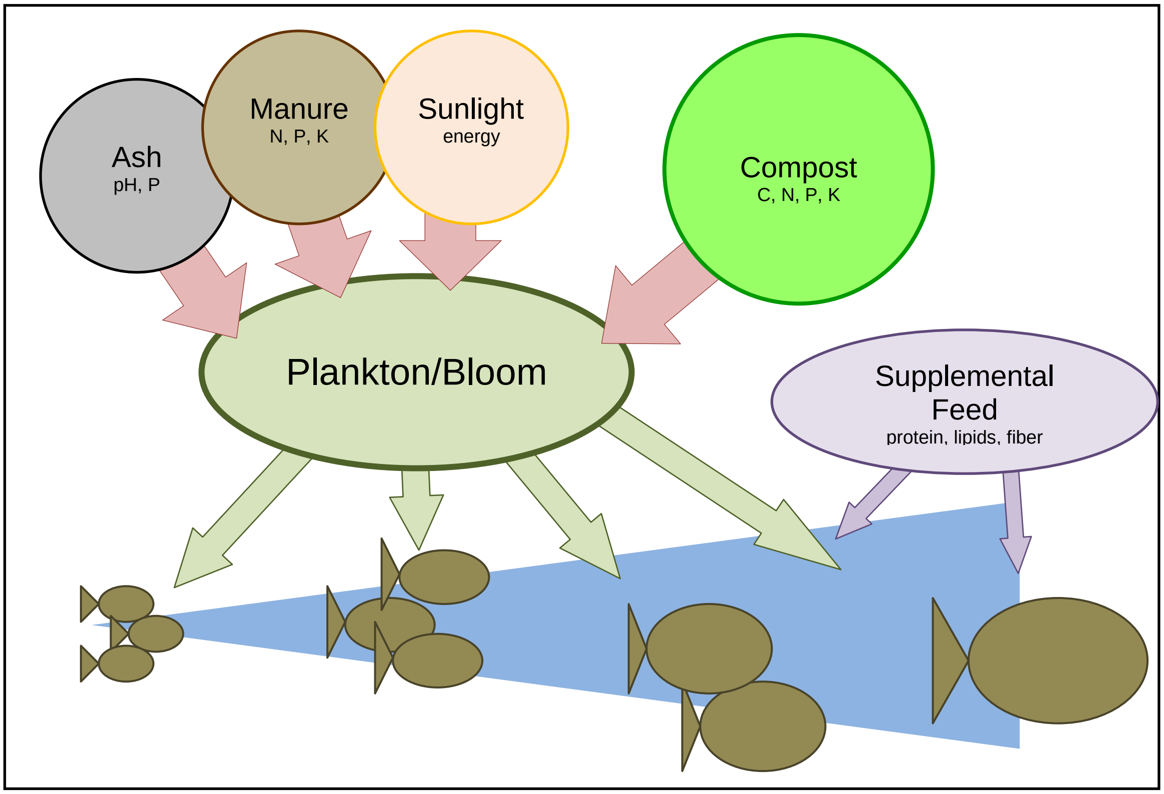

Figure 7 – Schematic showing various inputs for growth of phytoplankton to support the growth of fish

Fish ponds can be optimized for fish reproduction (ponds with mixed-sex cultures designated for the breeding of fingerlings) or for fast growth of adult fish (all-male cultures of a single generation fed with supplemental feeds). These more intensive production methods often require greater skill and resources to change the sex of fish, and required coordinated harvests and stocking times. However, a mixed population consisting of different generations is the norm for rural fish production in Zambia.

Figure 7 was developed by the author as a visual aid to assist farmer's understanding of pond inputs, showing that most pond inputs, while essential for fish growth, are actually used to grow the algal bloom. Ash, manure, sunlight, and compost are related to various pond design features and management techniques promoted by the RAP extension agents.

Adding ash to the pond is promoted in the program for predator control and promoting the growth of the algal bloom. It is suggested in the guide *Fish Farming: Lessons on How to Keep Bream*, that one bucket of ash per 100 square meters be added each week to the pond (Ganther, 2003). Depending on the type of wood which is burned, ash can contain 25 to 45 percent calcium carbonate and is usually less than one percent phosphorus. Adding ash to the pond increases the pH and hardness of the water; therefore, the addition of ash is particularly important where soils that underlie the fish ponds are more acidic. This also increases the biological productivity of the water (Maar et al., 1966). An alkalinity which is greater than 20 mg/L as $CaCO_3$ is required to make the addition of fertilizer effective (El-Sayed, 2006). Ash is found in most rural communities as a waste product from cooking using solid fuels. As an alternative to using commercial lime, ash becomes a valuable resource in semi-intensive fish farming.

Manure provides the main source of nitrogen, phosphorus, and potassium (N, P, K). Appendix E provides the compositions (N, P, K) of various pond fertilizers and compost materials which are commonly found on rural farms in Zambia. The main focus of fertilization and composting schemes are the amounts of nitrogen, phosphorus, and carbon added to the pond as well as the ratio between these inputs (El-Sayed, 2006). Maintaining and adjusting fertilization and composting schemes are often the major focus of RAP in Zambia. Often the concept of fertilizing the pond is new to farmers, since traditional fish ponds were left untended and allowed to develop as a “natural ecosystem,” leaving the fish to fend for themselves. Learning to take ratios of the various fertilizers into consideration is a skill that is focused on with role-model farmers, and at first basic fertilization schemes are promoted, e.g. one 20 liter bucket of chicken manure each week for a 1.5 *are* pond. (One *are* is one one-hundredth of a hectare.)

Sunlight is also included in Figure 7 above (schematic of pond inputs for phytoplankton growth) so that farmers understand the importance of sunlight in the growth of fish. The bloom is made up of autotrophic organisms that depend on sunlight for growth. Growth of fish can be affected by a lack of sunlight during rainy seasons. By understanding the role of sunlight in the system, farmers are receptive to certain pond design features. The following design features and maintenance techniques can all be justified if one understands that phytoplankton in the pond require sunlight to grow: pond depth, ponds do not need to be more than one meter deep since light will not penetrate; location cleared of trees, trees must be cleared from the area to allow for maximum sun exposure; placing compost in a crib, compost materials are kept in a composting crib because if they float over the surface of the pond they shade the water and phytoplankton below; stocking rates based on surface area not volume, stocking rates are based on the area exposed to light since this will dictate how much phytoplankton, and therefore fish, can be supported.

Compost is also a major source of carbon in the pond system. In Figure 7 above, it is set in a larger circle to the side to emphasize its importance. Farmer's often do not put enough compost in their ponds. It also differs from sunlight, ash, and manure because it is placed in the compost crib of the pond not applied directly into the pond. Although compost materials are often readily available to farmers in Zambia, under-composting is often an issue, and extra emphasis is placed on this component to encourage farmers. The compost is kept in compost cribs and should be kept full at all times. The decaying compost should be mixed daily to encourage decomposition and mixing into the pond water. Many plant by products and farm wastes are good composting materials, some of these are listed in Appendix E.

Fish production begins with the stocking of a pond with six-week-old fingerlings. Tilapia fingerlings are typically 4 to 6 centimeters in length. This first generation will mature in about 6 months, having produced two generations of younger fish. When the third generation of fingerlings is 4 to 6 centimeters in length the pond is harvested. First and second generation fish are sold at market. The third generation fingerlings are kept in a 1 by 1 meter holding pond.

The pond is drained during the harvesting process. The mud accumulated on the pond bottom is cleared from the pond and the empty pond is allowed to dry for two weeks. This process helps to prevent any fish, snail, or disease causing organisms from contaminating the next cycle of stocking and harvesting. The pond is refilled, and should be regenerated before stocking the pond with the fingerlings from the holding pond.

The growth of fish is dependent on a proper supply of algae, as well as sufficient dissolved oxygen, proper water temperature, and supplemental feed. Supplemental feeding is especially important for larger fish after about 45 to 60 days from the initial pond stocking. After this time fish tend to rely less on the natural food supply (i.e., algal bloom) and require supplemental feeds to grow larger and increase yield. The timing and formulation of supplemental feeds for semi-intensive tilapia farming is outlined in Appendix F.

Supplemental Feeding

Young tilapia feed mainly on plankton (the pond algal bloom), as they grow their bodies become capable of ingesting larger food and begin to require larger amounts of nutrients and resources to grow. Studies have been done to optimize processed fish feeds which are sold to intensive fish farming operations (El-Sayed, 2006). For smaller scale, semi-intensive fish farming practices though, focus is placed on utilizing locally available resources.

Feed composition, rate of application, and the start time for supplemental feeding have all been studied. However, there is not one single supplemental feeding scheme which will provide the best yields, since yield can be affected by other factors including the fish species.

One study presented in *Tilapia Culture* (El-Sayed, 2006), showed that natural food supply (plankton) was sufficient until the fish matured to about 100 to 150 grams. Beginning supplemental feeding before this point was a waste of resources since it did not produce significantly larger fish. Also feeding until 50% satiation produced similar yields to feeding until 100% satiation, which shows that significant resources can be saved by feeding a smaller quantity (El-Sayed, 2006).

Traditional fish farming practices in Zambia do not include feeding fish. Local farmers are often observed to comment “Fish find their own food, why should I feed them?” This concept is also reflected in local practices of allowing livestock to graze around the family farm to find food. So simply introducing the idea that feeding fish since they are “trapped” in the pond and unable to graze may be challenging. However, once the change is accepted farmers should focus on experimenting with different combinations of feeds.

Finding a good combination of feeds is important since not all of the dietary needs can be met by simply adding maize meal. An exercise for combining different feeds to create a well-rounded diet that includes protein, carbohydrates, fiber, and lipids is presented in Appendix F.

Farm Integration

Farm integration and permaculture are components of many organizations' agriculture programs in Zambia, including the United States Peace Corps. It is promoted as a way to gain benefits of synergistic farming practices including: saving time, labor, reducing water consumption, and utilizing farm waste. Farm integration does not focus simply on water and waste reuse. It takes a larger perspective of the farming system including the various roles of family members, spatial planning and farm layout, and permaculture techniques. Permaculture is a method of farming which plans for the highest yield of all farming products by minimizing labor, land area, and materials. Here are some examples of farm integration:

- Chicken cages built over a fish pond so that manure is dropped directly into the pond. 10 -15 chickens per *are*.
- Utilizing nutrient-rich pond effluent to irrigate cash crops.
- Using brewery waste or maize bran in fish feeds.
- Organizing farm layout so that daily high intensity activities are located closer to the home, while semi-managed and agro-forestry areas are located farther from the home.
- Utilizing agro-forestry crops to improve soil, while harvesting leaves for animal fodder and fish feed.

Expected Yields

Yields from fish ponds vary widely. Depending on methods of pond fertilization, stocking densities, and temperature the yields have been observed to be less than one metric ton per hectare annually to over 12 metric tons as observed in a study in Thailand (El-Sayed, 2006). Figure 8 shows results of expected yields of tilapia from various studies which varied in stocking rates and fertilization schemes.

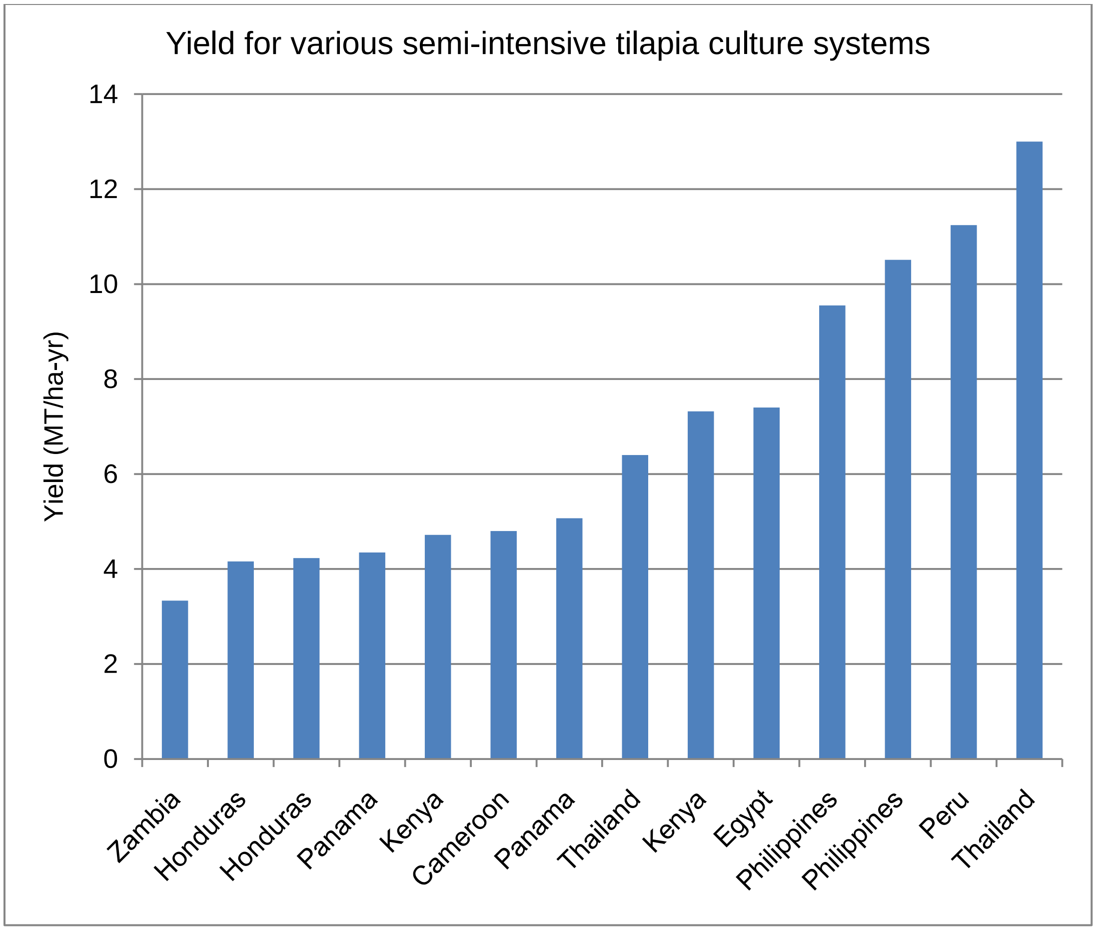

Figure 8 – Yields in metric tons per hectare per year for various semi-intensive tilapia cultures (El-Sayed, 2006; Bweupe, 2011)

Table 7 presents more details about the fertilization scheme and sexing of the fish in each study. All of the studies which observed yield greater than 6.4 metric tons per hectare per year, except one of the studies in the Philippines, were on fish cultures that had been sexed; i.e. only males were grown to harvest.

Also the yield presented here for Zambia, 3.33 metric tons per hectare per year, is based on actual farmer data provided from the RAP program. Traditional fish farming in Zambia does not involve fertilization and supplemental feeding. So this yield captures drawbacks associated with improper harvesting schedules, poor fertilization, and lack of supplemental feeding.

Table 7 – Yearly pond yields in weight of fish harvested for various semi-intensive tilapia cultures

Species	Country	Stocking Density (ha^{-1})	Yield (Mt/ ha·yr)	Sex	Stocking Rate (fingerlings/ m^2)	Fertilization Scheme
Tilapia	Zambia	11,000	3.33	mixed	1.1	Various[a]
O. n*	Honduras	10,000	4.16	mixed	1	chicken manure 1000 kg/ha·wk[b]
O. n	Honduras	10,000	4.23	mixed	1	chicken manure 1000 kg/ha·wk[b]
O. n	Panama	10,000	4.35	mixed	1	chicken manure 1000 kg/ha·wk[b]
O. n	Kenya	1,000	4.72	males	0.1	diammonium phosphate + urea, 20kg/ha·wk[b]
O. n	Cameroon	7,600	4.8	mixed	0.76	dry cattle manure, 226 kg/ha·wk[b]
O. n	Panama	10,000	5.07	mixed	1	chicken manure 1000 kg/ha·wk[b]
O. n	Thailand	20,000	6.4	males	2	280 kg chicken manure + 56.3 kg urea + 17.5 kg TSP/ha·wk[b]
O. n	Kenya	1,000	7.32	males	0.1	diammonium phosphate + urea, 20kg/ha·wk[b]
O. n	Egypt	20,000	7.4	males	2	chicken manure 1000 kg/ha·wk for 60 days, 54.4 kg urea + 92.4 kg superphospahte/ ha·wk[a]

Table 7 (Continued)

O. n	Philippines	40,000	9.55	males	4	ammonium phosphate (28 kg N + 5.6 kg P)/ha·wk[b]
O. n	Philippines	20,000	10.51	mixed	2	chicken manure 500 kg/ha·wk[b]
O. n	Peru	20,000	11.24	males	2[c]	
O. n	Thailand	30,000	13	males	3	urea + TSP; 28 kg N + 7 kg P / ha·wk[b]

* *O. niloticus* a – (Bweupe, 2011), b – (El-Sayed, 2006), c – (Cavallini, 1996)

The average yield for all studies reported in Table 7 is 6.53 metric tons per year per hectare, while the median is 5.07. Based on this, the expected yield used in this study was 5.0 metric tons per hectare per year. The average here is augmented by the high yields associate with single-sex cultures and fertilization schemes which utilized synthetic fertilizers. The median was chosen as a more conservative estimate based on the authors experience in Zambia. The Zambian scenario, while having the lowest yield, does capture many of the realistic challenges expected in adopting fish farming technology in a community for which it may be a novelty.

TREATMENT PLANT CHARACTERISTICS AND LOCATIONS OF CASE STUDIES USED TO PROVIDE WASTEWATER CHARACTERISTICS

The study uses results of effluent water quality obtained from community based wastewater treatment facilities located in Bolivia, South Africa, Tanzania, Arizona, Zimbabwe, Honduras and Argentina. The wastewater characteristics are secondary data compiled from the various studies to offer a wider view of various loading and treatment plant scenarios than those used in previous aquaculture research (Bunting, 2006). The data from the WWT plants in Bolivia were collected by other University of South Florida researchers, while the other data was collected by the authors of the studies cited in Table 8.

All of the wastewater treatment systems utilize some combination of facultative lagoons and maturation lagoons to treat the wastewater. In the United States, these systems are no longer a top choice since it is difficult to meet the strict requirements set by the U.S. Environmental Protection Agency (EPA) (Oakley S. M., 2005). Removal of biochemical oxygen demand (BOD) can reach 95%, but total suspended solids (TSS) in effluent can reach 150 mg/L (US EPA, 2002a). Also, the performance of lagoons in cold climates can be compromised, which has lead to some states to prohibit discharge from lagoons during the winter (US EPA, 2002a). However, the systems are appropriate for communities in the developing world where the most pressing issues are those related to reducing and preventing the spread of waterborne infectious diseases and the climate is conducive to their operation (Oakley, 2005).

It is also worth noting that many of the countries in which these WWT plants are located are countries which currently have low fish protein supplies, shown in Figure 3 of the

Protein Requirements for Human Beings section. The daily per capita supplies of dietary protein from fish are less than 2 gram per person per day in Bolivia, Zimbabwe, Honduras, and Argentina. Of the remaining developing countries Tanzania and South Africa have supplies between 2 and 4 grams per person per day.

Table 8 provides data reported in various studies of the nine WWT plants used in this study. The approximate population for each community, the flow rate and nitrogen concentration for the wastewater effluents are given.

Table 8 – Flow rate and nitrogen concentration of wastewater at each case study location

	Approximate Population Served	Flow Rate (L/s)	Nitrogen Concentration (mg – N/L)	Source
Bolivia, Sapecho	1,160	0.77	33.6	Muga et al. 2009 Reents, 2011
Bolivia, San Antonio	777	0.82	22.4	Mihelcic et al., 2010 Reents, 2011
South Africa	9,788	23.1	11.9	Igbinosa and Okoh, 2009
Tanzania	6,500	9.7	58.4	Mbwele et al., 2003
Arizona	27,271	42.9	25.0	Gerk et al., 2001
Zimbabwe, Nemanwa	5,000	2.31	39.0	Nhapi et al., 2003
Zimbabwe, Gutu	10,000	4.63	39.0	Nhapi et al., 2003
Honduras	10,000	24.5	12.3	Oakley, 2010
Argentina	500,000	1,597	27.0	Mendoca, 2006 via Oakley, 2010

Sapecho

Two community WWT plants in Bolivia were used in this study. Both have been well studied by a research group from the University of South Florida. The wastewater treatment plant in Sapecho serves a community of 1,168 residents as of 2010. The system has been design to treat up to 2.97 L/s. The wastewater enters the system and passes through a grit removal chamber. It then passes into an upflow anaerobic sludge blanket (UASB) reactor. Water continues into a series of two maturation lagoons and sludge is removed from the UASB reactor to two sludge drying beds (Muga et al., 2009).

The flow rate from the final maturation lagoon was reported to be 0.77 L/s and the total nitrogen concentration in the wastewater exiting the final lagoon was 33.6 mg – N/L (Mihelcic et al., 2010).

San Antonio

The wastewater treatment plant in San Antonio serves 777 residents as of 2010. The system has been designed to treat up to 1.34 liters per second. The wastewater enters the system and passes through a grit removal chamber. It then passes into a facultative lagoon. Water continues into a series of two maturation lagoons (Mihelcic et al., 2010).

The flow from the final maturation lagoon was reported to be 0.82 L/s and the total nitrogen concentration in the wastewater exiting the final lagoon was 22.4 mg – N/L (Reents, 2011).

South Africa

The treatment facility near Alice, South Africa receives a mix of domestic, light industrial, and runoff wastewater and treats it using an activated sludge system (Igbinosa and Okoh, 2009). No additional information about the treatment facility was described.

The measurements were taken for nitrate and nitrite were determined in the lab using the standard photometric method and reported as averages for each of four seasons (Igbinosa and Okoh, 2009). The sum of the averages for nitrate and nitrite were used in this study, 11.9 mg – N/L. The flow was reported in the Methods chapter as the average flow treated by the plant, 23.1 L/s.

Tanzania

The treatment system in Tanzania handles wastewater mainly from domestic sources for a population of about 6,000; although the system was designed to treat waste for a population of 2,000 to 5,000 people. The wastewater enters a primary facultative pond and then splits into two parallel flows, each of which enters a series of two facultative ponds and finally a maturation pond (Mbwel et al., 2003).

Sampling of the wastewater was performed once every two weeks over a period of six months. The samples were analyzed according to procedures described in *Standard Methods for the Examination of Water and Wastewater* (1995).

Arizona

This study examined the effectiveness of a constructed wetlands treatment facility. The main goal of the wetland was to reduce nitrogen content in the water so that it could be used as part of an aquifer recharge system. Influent to the wetlands is non-nitrified effluent from aerated treatment lagoons (Gerke et al., 2001). The characteristics of this non-nitrified effluent are used because the nitrogen in this effluent is valuable for reuse in aquaculture.

The average daily effluent flow from the WWT plant was reported as 3,710 cubic meters per day. Monthly average flows ranged from 3,300 to 4,500 cubic meters per day. The average total nitrogen for WWT plant effluent was reported in the Methods chapter 25 mg – N/L and the inflow of BOD was 50 mg/L.

Zimbabwe

In Zimbabwe two water reuse systems were analyzed. The system in Nemanwa and Gutu treated wastewater from populations of 5,000 and 10,000 people, respectively. The plant at Nemanwa was report to treat a flow of 2.3 L/s, while the plant at Gutu treated 4.6 L/s. Both systems received mixed wastewaters of residential and commercial sources (Nhapi et al., 2003).

At Gutu the untreated wastewater entered a primary treatment pond followed by two duckweed ponds in series and then a final maturation lagoon. The effluent characteristics from this pond were used. At Nemanwa the untreated wastewater entered two anaerobic ponds followed by two duckweed ponds in series and finally a maturation lagoon. Water characteristics for the final effluent from this plant were not reported so the wastewater characteristics after the first duckweed pond were used.

The authors used the micro-Kjeldahl method followed by distillation with sodium hydroxide and sodium thiosulphate solution to determine the total nitrogen concentration. The total concentrations for nitrogen in the wastewater at Gutu and Nemanwa, at the points described above, were both reported to be 39.0 mg – N/L (Nhapi et al., 2003).

Honduras

The WWT plant in Tela, Honduras treats an average of 24.5 L/s, serving an estimated population of 10,000 people. The WWT plant consists of a facultative lagoon followed by two maturation lagoons in series. The mean effluent total nitrogen was reported as 12.3 mg – N/L (Oakley, 2010).

Argentina

The WWT plant in Mendoza, Argentina treats an average of 1,597 L/s, serving an estimated population of half a million people. The mean effluent total nitrogen is 27 mg – N/L. The WWT plant consists of twelve batteries of one facultative followed by two maturation lagoons in series. The area of the entire lagoon system is 278 hectares (Medoca, 2006 via Oakley, 2011).

METHODS

This chapter provides the rationale behind the assumptions used for the study calculations. The analysis performed in the study is summarized in Figure 9. Measured quantities are depicted in green (and described in Table 8 of the previous chapter), while calculated values are shown in red.

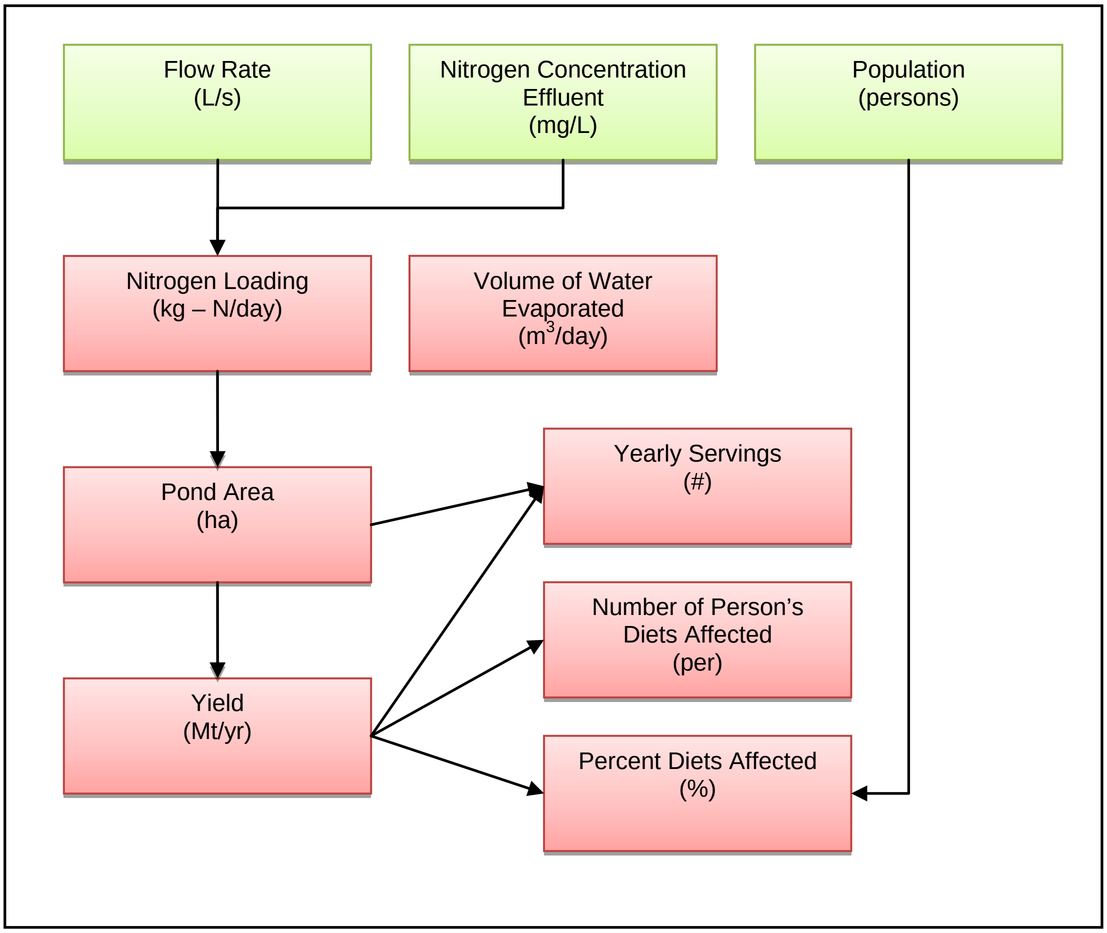

Figure 9 – Flowchart of calculations for nitrogen loading, estimated total pond area, amount of water evaporated, estimated yearly pond yield, number of tilapia servings, number of persons affected

Nitrogen Loading, Pond Area, and Evaporation

As discussed earlier in this thesis, the rate of nitrogen loading is the most important design factor for an aquaculture system. The pond sizes are determined to provide a nitrogen loading rate of 4 kg – N per hectare per day, which was indicated by previous research to be the optimal nitrogen loading rate (El-Sayed, 2006; Bunting, 2006; Mara et al., 1993).

First, the nitrogen loading, in kilograms N per day, was calculated for each plant using Equation 1, where Q is the flow rate in L/s and C_N is the nitrogen concentration in mg – N/L in the treatment plant effluent:

Equation 1 – Nitrogen loading

$$Nitrogen\ Loading, \qquad N = Q \times C_N \times 86{,}400 \frac{s}{day} \times 10^{-6} \frac{kg}{mg}$$

Equation 2 provides an example calculation of nitrogen loading for the data obtained from the wastewater treatment effluent of Sapecho, Bolivia:

Equation 2 – Nitrogen loading, Sapecho

$$\begin{aligned} N_{Sapecho} &= Q \times C_N \times 86{,}400 \frac{s}{day} \times 10^{-6} \frac{kg}{mg} \\ &= 0.77 \frac{L}{s} \times 33.6 \frac{mg - N}{L} \times 86{,}400 \frac{s}{day} \times 10^{-6} \frac{kg}{mg} \\ &= 2.24 \ \frac{kg - N}{day} \end{aligned}$$

Secondly, the total pond area of a fish farming system that can be supported by the calculated daily nitrogen loading from the plant is determined using Equation 3:

Equation 3 – Pond area

$$Pond\ Area, \qquad A = \frac{N}{4\ \frac{kg-N}{ha \cdot day}}$$

Equation 4 is an example calculation for the expected fish pond area that could be supported from the wastewater effluent associated with the treatment plant in Sapecho, Bolivia:

Equation 4 – Pond area, Sapecho

$$A_{Sapecho} = \frac{N}{4\ \frac{kg-N}{ha \cdot day}}$$

$$= \frac{2.24\,\frac{kg-N}{day}}{4\ \frac{kg-N}{ha \cdot day}}$$

$$= 0.56\ ha$$

To evaluate whether the quantity of water is sufficient to keep ponds of the estimated size filled, the amount of water which would evaporate daily was calculated using Equation 5, where R_{evap}, is the rate of evaporation. Two rates of evaporation where chosen to represent a range of range of climates, 3mm per day and 9mm per day. The value used in the Kolkata, India study, 5mm per day falls within this range.

Equation 5 – Volume of water evaporated from a fish pond system

$$Volume, \qquad V_{evaporation} = R_{evap} \times A \times \frac{10{,}000m^2}{ha} \times \frac{m}{1{,}000mm}$$

Equation 6 is an example calculation for the expected amount of evaporation occurring from a pond system associated with the treatment plant in Sapecho, Bolivia at a rate of 3mm per day:

Equation 6 – Volume of water evaporated from a fish pond system, Sapecho

$$\begin{aligned} \mathrm{V}_{Sapecho} &= R_{evap} \times A \times \frac{10{,}000m^2}{ha} \times \frac{m}{1{,}000mm} \\ &= 3\frac{mm}{day} \times 0.56ha \times \frac{10{,}000m^2}{ha} \times \frac{m}{1{,}000mm} \\ &= 16.8\ \frac{\mathrm{m}^3}{\mathrm{day}} \end{aligned}$$

Nitrogen in Human Urine

Nitrogen which enters a WWT system can be estimated based on the number of people it serves. Studies have found that people excrete between 2.7 and 4.5 kilograms of nitrogen each year in their feces and urine. Other characteristics of nutrient content in excrement are presented in Appendix G. It is important to note that 81 – 90% of nitrogen excreted by humans is found in the urine (Kvarnström, 2006). Since a majority of the nitrogen associated with the feces would likely settle out as part of the sludge, only the portion of nitrogen associated with urine is used in this calculation, up to 4.0 kg nitrogen per person per year.

The following calculation will estimate the amount of nitrogen one could expect to see entering the WWT plants in this study. Since the studies reported that nitrogen removal does occur in these treatment systems we would expect only a portion of this nitrogen to be represented in the nitrogen loading obtained from wastewater effluent that was calculated in the Nitrogen Loading section. The results for the amount of nitrogen excreted in urine will be compared to the nitrogen loadings calculated with the flow rates and WWT plant effluent concentrations of nitrogen to ensure that the wastewater nitrogen loadings are reasonable.

The amount of nitrogen (from urine) entering the WWT plants was calculated using Equation 7:

Equation 7 – Nitrogen excreted in urine per day by a population

$$Total\ Nitrogen_{excrement},\ N_{excrement} = Population \times 4.0\ \frac{kg}{per \cdot yr} \times \frac{1\ yr}{365\ days}$$

Equation 8 is an example calculation for the amount of nitrogen in kilograms per day excreted by the population in Sapecho, Bolivia:

Equation 8 – Nitrogen excreted in urine per day by a population, Sapecho

$$N_{excrement} = Population \times 4.0\ \frac{kg}{per \cdot yr} \times \frac{1\ yr}{365\ days}$$

$$= 1{,}160\ per \times 4.0\ \frac{kg}{per \cdot yr} \times \frac{1\ yr}{365\ days}$$

$$= 12.7\ \frac{kg}{day}$$

The results for nitrogen loading based on nitrogen found in human urine will be compared to the result for nitrogen loading based on the WWT plant effluents.

Expected Yields and Number of Diets Affected by Fish Ponds

Using the value of 5 Mt of fish per hectare per year determined in the Fish Farming Systems chapter, the total expected fish yields, in metric tons per year, for a pond system constructed at each of these plants was determined using Equation 9:

Equation 9 – Pond yield in metric tons of fish per year

$$Yield, \qquad Y = A \times 5\frac{Mt - fish}{ha \cdot yr}$$

Equation 10 provides an example calculation for the expected fish yield for a pond system integrated with the wastewater treatment plant effluent from Sapecho, Bolivia:

Equation 10 – Pond yield in metric tons of fish per year, Sapecho

$$Y_{Sapecho} = A \times 5\frac{Mt - fish}{ha \cdot yr}$$

$$= 0.56ha \times 5\frac{Mt - fish}{ha \cdot yr}$$

$$= 2.79\ \frac{Mt - fish}{yr}$$

The total number of 85 gram servings of tilapia was also determined for the effluent from each treatment plant using Equation 11:

Equation 11 – Servings of tilapia per year from yield

$$Servings, \qquad S = Y \times \frac{10^6\,\frac{g}{Mt}}{85\,\frac{g}{serv}}$$

In Equation 11, the value of 85 grams per serving was obtained from the United States Department of Agriculture (USDA, 2006). Equation 12 provides an example calculation for the number of 85 gram servings produced by fish ponds each year that is integrated with the wastewater effluent for the Sapecho treatment system:

Equation 12 – Servings of tilapia per year from yield, Sapecho

$$S_{Sapecho} = Y \times \frac{10^6\,\frac{g}{Mt}}{85\,\frac{g}{serv}}$$

$$= \ 2.79\frac{Mt}{yr} \times \frac{10^6\,\frac{g}{Mt}}{85\,\frac{g}{serv}}$$

$$= 33{,}000\frac{serv}{yr}$$

Based on the rationale presented along with Figure 3, one person would reasonably add an average of 10 grams of protein from fish to their diet, or 3.65 kilograms of protein per year. However, these 10 grams of dietary protein do not correlate directly to 10 grams of harvested tilapia. All foods are made up of many different components. Therefore, we must know how much dietary protein is contained in tilapia. For every 85 gram serving of tilapia, 17 grams of protein are consumed (Fat Secret, 2011). Equation 13 was used to calculate the number of people who would be impacted by the installation of the fish ponds through access to greater amount of protein in their diet:

Equation 13 – Number of person's diets affected by integration of wastewater fed aquaculture

$$Persons\ affected, \qquad P = Y \times \frac{1000\ kg}{1\ Mt} \times \frac{person \cdot year}{3.65\ kg \cdot protein} \times \frac{17\ g - protein}{85\ g - tilapia}$$

Equation 14 is an example calculation for the number of person's diets affected in Sapecho, Bolivia by the installation of the fish ponds:

Equation 14 – Number of person's diets affected by integration of wastewater fed aquaculture, Sapecho

$$P_{Sapecho} = Y \times \frac{1000\ kg}{1\ Mt} \times \frac{person \cdot year}{3.65\ kg \cdot protein} \times \frac{17\ g - protein}{85\ g - tilapia}$$

$$= 2.79 \frac{Mt}{yr} \times \frac{1000\ kg}{1\ Mt} \times \frac{person \cdot year}{3.65\ kg \cdot protein} \times \frac{17\ g - protein}{85\ g - tilapia}$$

$$= 153\ persons$$

RESULTS

The feasibility of supporting fish farming from the treated wastewater effluent associated with nine geographically diverse treatment plants was analyzed in this study. The selected communities range in population from 777 people in San Antonio, Bolivia to half a million people served by the plant in Argentina. However, the average population of seven communities in this study other than Argentina is 8,800, reflecting the focus of this study on small scale WWT plants. The associated concentrations for total nitrogen in the treated effluent ranged from a low of 11.9 mg – N/L at the South Africa plant to a high of 58.4 mg – N/L at the plant in Tanzania. The flow rate at each plant was different and related to the population served. It ranged from a low of 0.77 L/s at the Sapecho, Bolivia plant to 1,597 L/s at the WWT plant in Argentina. Excluding the largest WWT plant (Argentina) the average flow rate for the other eight WWT plants is 13.6 L/s.

Nitrogen Loading, Pond Area, and Evaporation

Following the flow chart provided previously in Figure 9 of the Methods chapter, the first calculation performed was the effluent nitrogen loading per day at each WWT plant. This was calculated from the flow rate, in L/s, and the total nitrogen concentration, in mg – N/L. These concentrations were measured in the effluent of the WWT facilities, where an aquaculture system would likely be integrated. Table 9 presents calculated results for nitrogen loading at each of the nine locations along with the measured flow rate and nitrogen concentration.

Table 9 – Flow rate, nitrogen concentration, and nitrogen loading at each plant

	Flow Rate (L/s)	Nitrogen Concentration (mg – N/L)	Nitrogen Loading (kg – N/day)
Bolivia, Sapecho	0.77	33.6	2.24
Bolivia, San Antonio	0.82	22.4	1.59
South Africa	23.1	11.9	23.7
Tanzania	9.7	58.4	49.0
Arizona	42.9	25.0	92.8
Zimbabwe, Nemanwa	2.31	39.0	7.80
Zimbabwe, Gutu	4.63	39.0	15.6
Honduras	24.5	12.3	26.1
Argentina	1,597	27.0	3,730

The nitrogen loadings used in this study thus ranged from a low of 1.59 kg – N/day at the San Antonio, Bolivia WWT plant, to a high of 3,730 kg – N/day at the Argentina plant. Because the nitrogen concentrations in the treated effluents are of similar magnitude for all the plants, this large range of nitrogen loadings can be attributed mostly to the large range of flows amongst these plants. However, some variation can be attributed to the differences amongst nitrogen concentration. For example, if one compares the flow rate of the two Bolivian treatment plants it can be noted that while the flow rate at the Sapecho plant is lower than the San Antonio plant (0.77 L/s vs. 0.82 L/s), the nitrogen loading at the Sapecho plant is actually greater than at the San Antonio plant (2.24 kg – N/L vs. 1.59 kg – N/L). This is due to the higher total nitrogen concentration measured in the effluent at the Sapecho plant (33.6 mg – N/L vs. 22.4 mg – N/L).

These results are now compared to the estimation for the nitrogen found in the urine of a population, calculated earlier using Equation 7. The nitrogen loading expected at each plant, based on reported values for nitrogen found in human urine, is provided in the column labeled: N_{urine}. The nitrogen loading in the treated wastewater, calculated with the flow rate and nitrogen concentration, is given in the column labeled: N_{WW}. These values are then compared in the final column labeled N_{WW}/N_{urine}.

Table 10 – Comparison of nitrogen loading in wastewater treatment plant effluent and nitrogen loading expected from human urine

	N_{urine} (kg – N/day)	N_{WW} (kg – N/day)	N_{WW}/N_{urine} % Nitrogen Found in Wastewater vs. Estimated Nitrogen Found in Urine
Bolivia, Sapecho	12.7	2.24	17.6%
Bolivia, San Antonio	8.52	1.59	18.6%
South Africa	107	23.7	22.1%
Tanzania	71.2	49.0	68.8%
Arizona	299	92.8	31.0%
Zimbabwe, Nemanwa	54.8	7.80	14.2%
Zimbabwe, Gutu	110	15.6	14.2%
Honduras	110	26.1	23.8%
Argentina	5,479	3,730	68.0%

Some nitrogen which enters the WWT plant either settles out into the sludge, is converted to biomass which then settles, or is released to the air via denitrification. The results show that the amount of nitrogen measured in the WWT plant effluent as a percentage of the amount of nitrogen expected to be produced by the population ranges from a low of 14.2% at the Zimbabwe plants to a high of 68.8% at the Tanzania plant. This difference may be because the actual nitrogen removal varies at each plant, affecting the effluent concentration of nitrogen. In addition, the type of populations served by the plants varies from entirely domestic in Bolivia to a more mixed domestic/commercial type in Tanzania. In addition, this analysis showed that the nitrogen loadings used in this research that were based on the measured WWT plant effluents appear reasonable because the amount of nitrogen found in the WWT plant effluent contains less nitrogen than the estimated amount of nitrogen produced by the population.

The total area of fish ponds that could be integrated with each wastewater effluent stream was determined from the nitrogen loading rates specific to each WWT facility. The total number of fish pond hectares which could be supported in each community is provided in Table 11. This area represents the total area of ponds, and does not directly imply the number of ponds. RAP standard ponds are generally 150 square meters, but each system could utilize ponds of various sizes to suit the landscape and development plan of each community.

Table 11 – Estimated total area of fish ponds at each wastewater treatment plant

	Estimated Total Pond Size (ha)
Bolivia, Sapecho	0.56
Bolivia, San Antonio	0.40
South Africa	5.93
Tanzania	12.3
Arizona	23.2
Zimbabwe, Nemanwa	1.95
Zimbabwe, Gutu	3.90
Honduras	6.52
Argentina	932

To evaluate whether the quantity of water is sufficient to keep the pond system filled the amount of water which would evaporate from the ponds was calculated and compared with the flow rate of each WWT plant. The resulting estimation for total water evaporating for the pond system in cubic meters per day at rates of 3 mm per day and 9 mm per day are provided in Table 12, along with the flow rate for each WWT plant in cubic meters per day. The range of percentages of the WWT plant's flow rate which is estimated to be lost by evaporation is provided in the final column of Table 12.

Table 12 – Flow rate, estimated amount of water evaporated daily from pond system and percentage of flow lost to evaporation

	Flow Rate (m^3/day)	Range of Volumes of Water Evaporating from Fish Pond System (m^3/day)		Range of Percentages of Flow Lost from Fish Ponds Through Evaporation	
Bolivia, Sapecho	66.5	16.8	50.3	25%	76%
Bolivia, San Antonio	70.9	11.90	35.7	17%	50%
South Africa	2,000	178	534	9%	27%
Tanzania	840	368	1,100	44%	131%
Arizona	3,710	696	2,090	19%	56%
Zimbabwe, Nemanwa	200	58.5	176	29%	88%
Zimbabwe, Gutu	400	117	351	29%	88%
Honduras	2,121	196	587	9%	28%
Argentina	138,000	27,900	83,800	20%	61%

The estimated percentage of effluent water lost through evaporation from the pond surface ranges from 9% at the Honduras WWT(rate of 3 mm per day) plant to 131% at the Tanzania WWT (rate of 9mm per day) plant. This is a reflection of the concentration of nitrogen in the treated wastewater effluent. For WWT plant with a high concentration of nitrogen in the wastewater effluent, such as Tanzania (58.4 mg – N/L), the design is for a relatively larger pond system compared to a WWT plant with lower effluent concentrations of nitrogen, such as the plant in Honduras, (12.3 mg –N/L).

Expected Yields and Number of Diets Affected by Fish Ponds

The expected yields for the fish ponds at each WWT plant are presented in Table 13. For each WWT plant the expected yield is given in metric tons produced each year. As shown in the flowchart in Figure 9 of the Methods chapter, the expected yield is used to calculate the number of 85 gram tilapia servings and the number of persons whose diet could be affected by the integration of an aquaculture system. The results of those calculations are provided in Table 13. The expected yield ranges from a low of 1.98 metric tons of tilapia per year, at the San Antonio plant, to over 4,000 metric tons at the plant in Argentina. This is mainly a reflection of the differing sizes of those plants.

Table 13 – Expected aquaculture system yield, number of tilapia servings produced each year, and the percentage of the population affected by aquaculture integration

	Yield (Mt/yr)	Number of Servings (85g) of Tilapia (per year)	Number of Person's Diets Affected (per year)	Percent Population Affected by Aquaculture Integration
Bolivia, Sapecho	2.79	32,900	153	13.2%
Bolivia, San Antonio	1.98	23,300	109	14.0%
South Africa	29.7	349,000	1,625	16.6%
Tanzania	61.3	721,000	3,357	51.6%
Arizona	116	1,360,000	6,353	23.3%
Zimbabwe, Nemanwa	9.75	115,000	534	10.7%
Zimbabwe, Gutu	19.5	230,000	1,068	10.7%
Honduras	32.6	384,000	1,787	17.9%
Argentina	4,660	54,800,000	255,205	51.0%

The number of tilapia servings produced by this expected yield ranges 23,300 at the San Antonio plant to approximately 55 million servings at the Argentinean treatment plant. Similarly, the number of person's diets affected by this new supply of protein is presented and ranges from 109 in San Antonio to over a quarter-million in Argentina.

The number of diets affected as a percentage of the populations served by each plant, ranges from a low of 10.7% at the Zimbabwean plants to a high of 51.6% at the Tanzania plant. The Tanzanian plant had the highest nitrogen concentration by far at 58.4 mg – N/L. This high concentration accounts for the large pond area and high yields at this plant; therefore, the high concentration can also explain why a large portion of the population would be affected by the integration of an aquaculture system.

Since the Zimbabwean plants do not have exceptionally low nitrogen concentration, 39.0 mg – N/L, in their wastewater another factor must account for the low percentage of the population which could be affected. One explanation could be the low flow rate at these plants. The portion of the wastewater flow accounted for by one person at these plants is 40 liters per person per day. At other plants it ranges from 57 L/per·day to over 200 L/per·day. This low flow rate means causes low nitrogen loading, in turn lowering the area of ponds that could be supported by these WWT plants.

Evaluating Other Environmental Requirements

Based on the environmental factors outlined in Table 6 of the Fish Farming Systems chapter, Table 14 was compiled to compare the environmental limits or recommendations for tilapia farming to the actual measurements taken at the WWT plants. Not all studies provided detailed wastewater effluent measurements for each of the factors. For those plants that did report relevant data, the measurements are provided below alongside the limits or ideal factors.

Of the treatment plants which reported dissolved oxygen (DO) levels in the WWT plant effluents, nearly all are within and acceptable range for the growth of tilapia. Only the treatment plant effluent for the Nemanwa, Zimbabwe plant showed a DO level of zero for its lowest measurement. The mixing action of water entering the ponds and the production of oxygen by photosynthesis should produce a sufficient amount of oxygen to support the respiration of fish.

The temperature of the wastewater effluent at the various plants ranges from 11 °C in Arizona to 25 °C in Gutu, Zimbabwe. Because some of the temperatures are lower than the optimal range of 20 to 35 °C, attention will need to be paid to the planning of reproduction. Since many tilapia species will not reproduce unless the water is greater than a certain temperature, stocking and harvesting will need to be seasonally planned so that reproduction coincides with the warmest part of the year. The temperature the wastewater effluents do not even approach the lethal limits for tilapia, less than 7°C or greater than 42°C.

Table 14 – Wastewater characteristics which could affect tilapia growth at each wastewater treatment plant

	Bolivia, Sapecho	Bolivia, San Antonio	South Africa	Tanzania	Arizona	Zimbabwe Nemanwa	Zimbabwe Gutu	Limit/Ideal
Dissolved Oxygen (mg/L)	7.7	9.6	4.2 – 5.4	8.9	-	0 – 13.1	2.9 – 11.7	0.0 – 0.5
Temperature (°C)	22.5	22.0	15.2 – 24.7	-	11 – 16	14 – 26	13 – 25	20 – 35
Nitrite (mg – N/L)	-	-	0.12 – 1.30	3.52	-	< 0.02	< 0.03	8
pH	7	6.93	6.10 – 7.03	9.2	-	6.8 – 8.0	7.1 – 8.1	4.3 – 11.5
Turbidity (NTU)	43.5	90.4	3.68 – 9.64	-	-	11 – 77	31 – 73	75
BOD Loading (kg/ha·day)	3.47	5.30	-	12.6	8.0	-	-	10 – 20
Fecal Coliforms (FCU/100mL)	1.78×10^5	1.21×10^5	-	653	-	-	-	10^5
Orthophosphate Loading (kg/ha·day)	0.41	0.50	0.11 – 1.6	1.5	-	0.51 – 1.0	0.51 – 1.0	2

A nitrite concentration of 8 mg – N/L is 50% lethal at 96 hours for certain tilapias weighing more than 90.7 grams (El-Sayed, 2006). The tolerance to nitrite increases for smaller fish. The highest reported level of nitrite was at the WWT plant in South Africa: 1.3 mg – N/L. This is well below the LC_{50} of 8 mg/L; therefore, nitrite entering the pond in treated wastewater is likely not of major concern.

There is also no indication that the pH of wastewater entering the ponds should have a direct effect on the health of the fish. Tilapia tolerate a large pH range and all of the pH measurements recorded at the treatment plants (i.e., 6.1 to 9.2), fall within the tolerable limits for tilapia of 4.3 to 11.5 (El-Sayed, 2006).

The turbidity of WWT effluents ranged from 3.7 NTU to 90.4 NTU. Excluding the one high value of 90.4 NTU reported at the San Antonio treatment plant in Bolivia all of these values fall below the turbidity limit of 75 NTU for good tilapia growth. It is likely that sedimentation that occurs in the fish ponds and this sedimentation of suspended solids from the wastewater stream into the pond would cause the turbidity of the pond water to be lower than that of the WWT plant effluent.

The Cavallini study in Peru suggested BOD loading to the pond should be between 10 and 20 kilograms per hectare per day (Cavallini, 1996). The four WWT plants which reported BOD concentration in the WWT plant effluent resulted in BOD loadings ranging from 3.47 to 12.6 kilograms per hectare per day. All of these BOD loadings fall within Cavallini's suggested range.

Some of the studies reported the orthophosphate or total phosphorus concentration in the effluent. The phosphorus loading to the fish pond systems were determined and found to ranged from 0.11 kg – P/ha·day at the WWT plant in South Africa to 1.5 kg – P/ha·day at the WWT plant in Tanzania. One study suggested an application of 2.0 kg –

P per hectare per day (El-Sayed, 2006). The pond bottom soil influences the amount of phosphorus available in pond water for plankton growth (El-Sayed, 2006). Because none of the WWT plants exceeded 2.0 kg – P per hectare per day, the ponds will likely require supplemental fertilization, especially with fertilizers/compost materials high in phosphorus: e.g. chicken or pig manure, soya or lantana leaves, or D-compound. Since the availability of phosphorus is affected by the acidity of the pond bottom, adding ash, can adjust the pond bottom pH, allowing the phosphorus to remain available for plankton growth.

Of the wastewater treatment systems presented in this study, three reported fecal coliform counts in the WWT plant effluent. At the Bolivian WWT plants the number of fecal coliforms per 100 mL was 1.78×10^5 and 1.21×10^5, at the Tanzania WWT plant it was 653. The two WWT plants in Bolivia do not meet the WHO standard of less than 10^5 for fish pond influent. Fecal coliform counts for WWT treatment plants in the United States range from 7.0 to 3.6×10^5, suggesting that the regulation could be met with lagoon style wastewater treatment (Crites & Tchobanoglous, 1998).

DISCUSSION AND CONCLUSIONS

Discussion

This objective of this study was to evaluate the integration of small wastewater treatment facilities with aquaculture in a developing world setting to determine whether treated wastewater effluent can provide a sufficient amount of water and nutrients to farm fish and provide a significant amount of a community's protein intake. The study evaluated data obtained from nine locations: two in Bolivia, one in South Africa, one in Tanzania, one in Arizona, two in Zimbabwe, one in Honduras, and one in Argentina. All of these locations utilize lagoon style treatment methods, which have been promoted for tropical locations in the developing world because of their simple design, low cost, and effectiveness at pathogen removal (Oakley, 2005).

The amount of nitrogen available for utilization in semi-intensive tilapia culture was determined to be sufficient to support fish pond systems at each of the WWT facilities. The total size of the resulting fish ponds ranged from about half a hectare to over 900 hectares, assuming that the fish ponds would require a nitrogen loading of 4 kg – N/ha·day. Estimations of the amount of evaporation from the fish pond systems were used to assess whether the flow was sufficient to maintain adequate water level in the ponds. This water loss was estimated to range from 15% to 73%.

For a WWT plant with a high concentration of nitrogen in the wastewater effluent, the size of the pond system designed should be carefully assessed. The system must be supported by a wastewater effluent flow rate large enough to account for water loss through evaporation and subsurface infiltration based on the local condition of climate and soil type.

Based on data for protein consumption and sources of dietary protein, the number of people who would have access to increased servings of protein through the integration of a tilapia farming system with the existing WWT plant effluent was determined for each of the study sites. The analysis showed that the integration of tilapia aquaculture with the existing WWT plant effluent could improve the diets of 11% to 52% of the persons served by the WWT plants. The average percentage of persons whose diets would be affected is 23%. For example, the city of Kolkata (India) has approximately 4.6 million residents (2001) and the current fish production of the Kolkata fish farms is 1,560 metric tons of fish annually (Bunting, 2006; Brinkhoff, 2011). This is enough fish to affect the diets of 12% of the city's population. Comparing the percentage of people who are affected by this existing integrated WWF aquaculture system shows that the amount of added protein is significant in all the communities studied.

The aim of UN Millennium Development Goal 1 is to reduce by 50% the number of people living in extreme poverty and hunger by 2015. It is unlikely that the additional dietary protein produced by integrating a WWF aquaculture system would be evenly distributed among the population or benefits the neediest persons with in the population. However, if the neediest 23% (average number of diets affected) of the population of these communities experienced improvements to their diets, then significant progress towards achieving the MDGs could be made.

By linking the benefits of aquaculture with wastewater treatment a community may be inclined to support the construction and maintenance of wastewater treatment systems. This is because the social and economic benefits of solely treating wastewater may not be perceived as a large enough incentive. For example, at the treatment WWT plant in Tanzania, the lagoons had not been desludged in 16 years (Mbwele et al., 2003). The associated incentives of tilapia aquaculture could be very helpful in poorer communities, where a major problem was the inability or desire for beneficiaries of wastewater treatment to support the WWT technology (Edwards, 1992).

The study found that the current level of fecal coliform contamination in wastewater effluent did not meet the WHO standard of 10^5 FCU per 100 mL. There are two options to deal with this shortcoming. Either the design of WWT lagoons could be adjusted to meet this target, or the target could be revised to allow for use of wastewaters which have a higher number of FC. To optimize lagoon treatment for pathogen removal the main mechanism for their removal must be considered. Natural die-off of pathogens, as well as predation, sedimentation, and adsorption occur in lagoons (Crites and Tchobanoglous, 1998). Models for the removal of fecal coliforms in lagoon systems are dependent on temperature of the water and the retention time of the lagoon (see Appendix H). This suggests that increasing retention times during lagoon design could help in achieving greater removal of FC. It would also be important that the systems are not under-designed for the amount of wastewater created by the community.

Future Research

Future studies should be done to assess the level of FC contamination in ponds which received WWT effluents containing greater than 10^5 FCU per 100 mL. The WHO already sets different standards for the wastewater intended for reuse in fish ponds and actual pond water itself: 10^4 FCU per 100 mL and 10^5 FCU per 100 mL, respectively (WHO, 2006). This differentiation is to account for the effects of pathogen removal which occurs within the fish pond. The removal mechanisms for maturation lagoons are also happening in fish ponds, hence the suggestion by some to use them as part of the “treatment” phase (Cavallini, 1996). Even though the pond influent may not meet the current standard set by the WHO, the pond water itself could test to show less than 10^4 FCU per 100 mL: the standard level to protect the help of fish pond workers and consumers.

Since the specific standard for FC contamination by the WHO follows from its health based targets, which are measured in DALYs, it is possible that the current limits are stricter than necessary. By using WWT effluents in aquaculture or other agriculture projects the practitioners may be more aware of proper preparation of fish since it is directly related to known pathogens. The health impacts associated with fish grown in WWT plant effluents may be lower compared to indirect reuse (releasing highly contaminated wastewater to surface waters, which are then in turn used for agriculture or even drinking water supply). This indirect reuse may present detachment in the perception of the users from the contamination source and the point of reuse, causing users to take fewer precautions to prevent waterborne disease. This reasoning might turn out to show a lower disease burden associated with direct wastewater reuse, even if it does not meet current standards suggested by the WHO. Further studies using this health based target perspective, especially at the national level as suggested by the WHO, would be required to determine if this is the case.

Studies should be made to see if there are significantly higher numbers of helminth eggs in fish pond sediments from wastewater reuse systems as compared to surface water systems. No data was found for helminth egg contamination in the effluent of the WWT plants used in this study. The WHO requirement for helminth eggs found in wastewater intended for reuse is an arithmetic mean of less than one egg per liter or per gram total solids (WHO, 2006). Pond bottoms should have all muddy deposits removed after each harvest period. The pond bottom should then be allowed to dry and crack for two weeks.

Currently the RAP program suggests that this mud be spread in gardens to fertilize the soil. Using the results of these studies a proper disposal or reuse method for pond mud can be developed.

Following the RAP suggestion to reuse pond mud for gardening, RAP also suggests using pond effluents to irrigate vegetable crops. This leads to the question of how to treat fish pond effluent. In Zambia, regulating fish pond effluents is not of concern. It is assumed that the density of farmers who discharge effluent to local streams is so low that it is unlikely to have major impacts. This does not mean that it should not be a concern for the Department of Fisheries in Zambia. As aquaculture expands with demand the nutrient-rich effluents from fish ponds could pose a threat to waterways as it has in other countries (El-Sayed, 2006).

Field studies on systems such as those proposed in this study should be conducted to characterize the effluents of semi-intensive tilapia production. If these effluents are of very high-strength or are discharged in such a quantity that they may compromise the quality of local waterways, farmers in Zambia and the agencies required to regulate the quality of waterways will be forced to implement policies mitigate the effects of aquaculture. For now farm integration is promoted as a way to capture the nutrients in fish ponds effluents. Farmers divert discharges from directly entering streams and lakes for irrigation in garden for cash crops such as cabbages and tomatoes. The effectiveness of this practice for protecting surface water from high nutrient loading should be investigated. Other wastewater polishing treatments could also be implemented for nutrient removal if this practice is not sufficient. These treatments could be biological treatments such as duckweed ponds, maturation lagoons and WWT wetlands.

Studies on the social acceptance of fish produced in wastewater fed ponds should be done in the countries where WWF aquaculture systems are promoted to evaluate the acceptance of fish produced in treated wastewater. For example, in a report about wastewater fed aquaculture in Lima, Peru the authors found that there was complete acceptance for the fish produced in wastewater fed ponds, even when the consumers knew where the product came from (Cavallini, 1996). The existence of the wastewater fed fishponds outside of Kolkata, India (the largest in the world) (Cavallini, 1996), indicates that acceptance of fish produced in ponds fed with wastewater effluent may be generally acceptable in an area where demand for cheap protein is high and the use of wastewater in agriculture already exists. However, a major loss in capital, time, and labor could occur if the market for WWF aquaculture product is not studied before the implementation of these systems.

Conclusion

This study has shown that small lagoon based WWT plants in the developing world can provide enough water and nutrients for an integrated WWF aquaculture system. It has also been shown that other wastewater characteristics important for the health of tilapia, such as the concentration of dissolved oxygen, temperature, nitrite concentration, and pH do not appear to pose any risk to the health of the fish. However, phosphorus loading from the WWT plants does not appear to be sufficient because the phosphorus loading from treated wastewater did not exceed 2.0 kg – P/ha·day. Therefore, addition of compost to the fish ponds should focus on provision of phosphorus. Conservative estimates obtained from this study suggest that the productivity of these WWF fish ponds would affect on average 23% of the population of these communities served by the wastewater treatment systems. Estimations for the amount of protein produced by this integrated farming technique should be able to play an important role in the achievement of the Millennium Development Goals.

This study has shown that reuse of WWT plant effluents will require more effective removal of fecal coliforms in order to meet standards set by the WHO. However, given the context, the level of fecal coliforms in these treated wastewaters should not rule out WWF aquaculture as an option for small communities in developing countries to reduce poverty, malnutrition, and disease burden of waterborne illnesses.

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APPENDICES

Appendix A: Summary of Water Recycling Guidelines and Mandatory Standards in the U.S. and Other Countries

Many countries have set guidelines or mandatory performance targets for the treatment of wastewater intended for reuse. The following table presents some of these guidelines (g) and mandatory performance targets (m). (US EPA, 2002)

Country/ Region	Fecal Colifroms (CFU/100 mL)	Helminth Eggs	BOD_5 (ppm)	Turbidity (NTU)	Total Suspended Solids (ppm)	pH	Chlorine Residual (ppm)
Arizona	< 1	–	–	1	–	4.5 – 9	–
California	–	–	–	2	–	–	–
Cyrpus	50	–	10	–	10	–	–
France	<1,000	<1	–	–	–	–	–
Florida	25 for any sample 75% (m)	–	20 (m)	–	5 (m)	–	–
Germany	100 (g)	–	20 (g)	1 – 2 (m)	30	6 – 9	–
Japan	10 (m)	–	10 (m)	5 (m)		6 – 9 (m)	–
Israel	–	–	15	–	15	–	0.5
South Africa	0 (g)	–		–	–	–	
US EPA	14 for any sample, 0 for 90% (g)	–	10 (g)	2 (g)	–	6 – 9 (g)	1 (g)

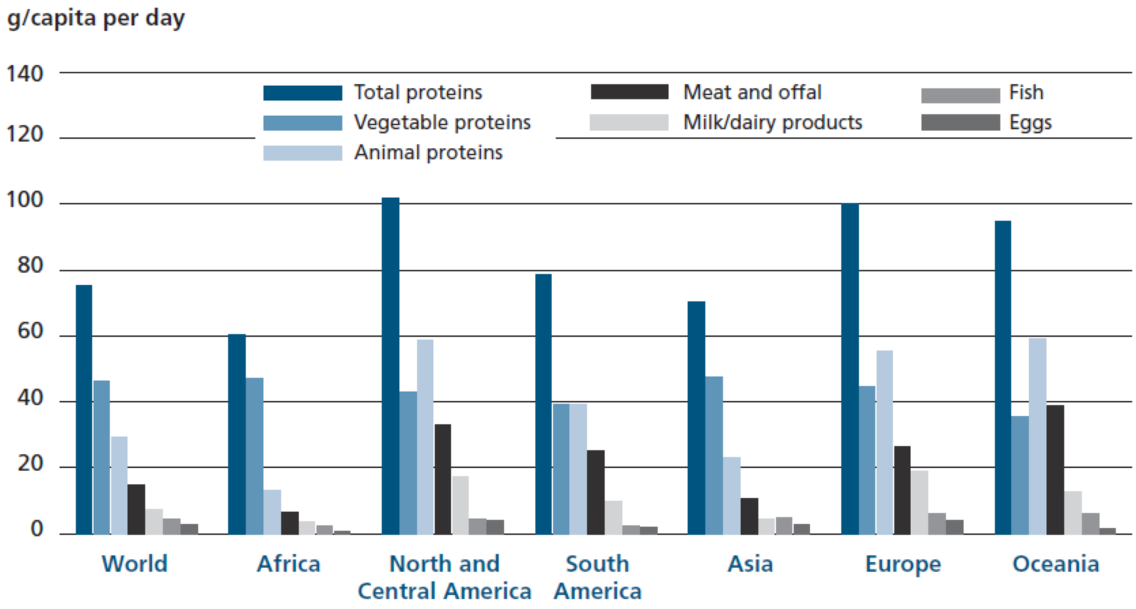
Appendix B: Considerations for National Wastewater and Excreta Use Policies Presented in the WHO Report on Wastewater Reuse in Aquaculture

Policy priorities for each country are necessarily different to reflect local conditions. National policy on the use of wastewater and excreta in aquaculture needs to consider various issues, including:

- the health implications of wastewater and excreta use in aquaculture (requirement for a health impact assessment prior to large scale project implementation and setting of appropriate standards and regulations
- water scarcity
- the amount of wastewater and excreta generated now and in the future
- the locations where excreta are generated
- the acceptability of wastewater and excreta use in aquaculture
- the extent and types of wastewater and excreta use currently practiced
- the ability to effectively treat wastewater and excreta and implement other health protection measures
- downstream impacts if wastewater and excreta are not used for aquaculture
- number of people dependent upon wastewater and excreta use in aquaculture for their livelihoods
- trade implications of exporting fish or plants produced with wastewater and excreta

Reproduced from the World Health Organization (WHO, 2006)

Appendix C: Total Protein Supply by Continent and Major Food Group



Reproduced with permission from the Food and Agriculture Organization of the United Nations (2009, p. 63)

Appendix D: Characteristics of Commonly Cultured Tilapia Species in Zambia

Table A – Characteristics of reproduction, feeding, and markings for commonly cultured tilapia species in Zambia (Froese & Pauly, 2010)

Species	Reproduction	Feeding	Markings/Notes
Nile Tilapia *Oreochromis niloticus*	Female mouth-brooder Shallow nests	All: phytoplankton, algae Adults: plants	Young: Tilapia spot 3 anal spines Vertical stripes throughout caudal fin Dark spot on gill cover
Redbrested Bream *Tilapia rendalli*	Both parents guard nest More eggs are laid than mouth-brooders Substrate spawner	Young: plankton Adults: wide range including plants, algae, insects, crustaceans	Red breast 3 to 5 vertical bars on body Tilapia spot Shallow head
Greenheaded Bream *Oreochromis macrochir*	Volcano shaped mound with concave top Female mouth-brooder	All: detritus, algae, diatoms Young: invertebrates, zooplankton	Fairly plain greenish-gray body Red eye Speckling on body
Threespotted Bream *Oreochromis andersonii*	Female mouth-brooder Saucer-shaped nests, paternal care after hatching	All: detritus, diatoms, zooplankton Adults: insects, invertebrates	Three dark spots on sides of body Red edge on dorsal and caudal fin Dark spot on gill cover

Appendix D Continued

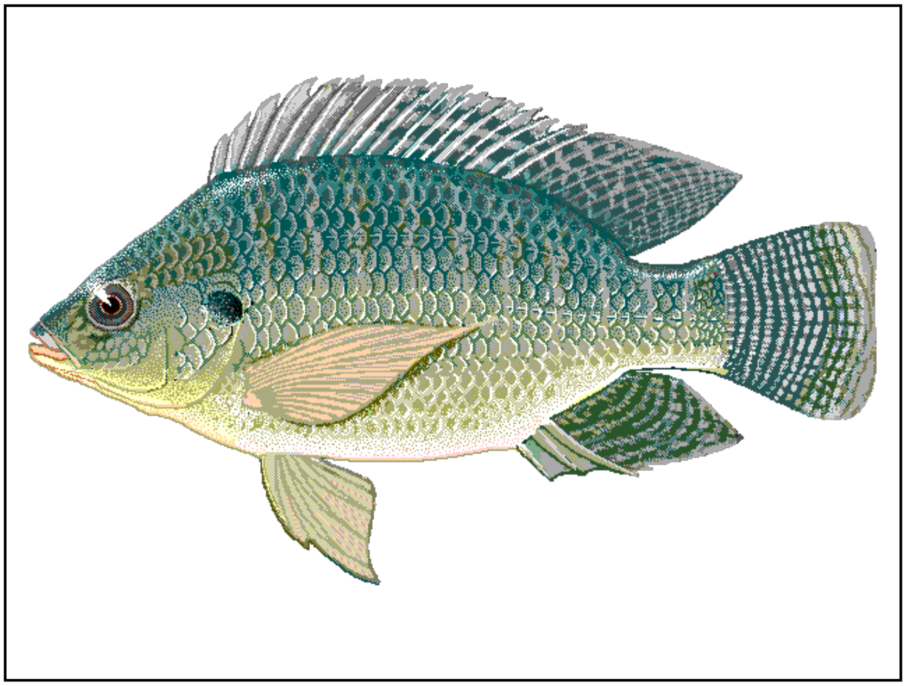


Figure A – Nile Tilapia *Oreochromis niloticus*

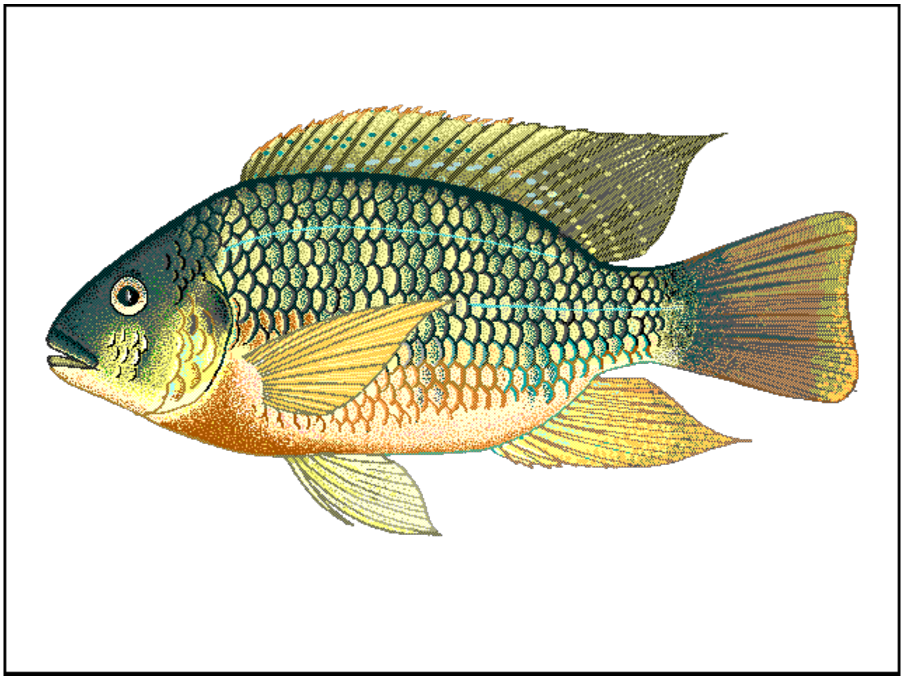


Figure B –Redbreasted Bream *Tilapia rendalli*

Appendix D Continued

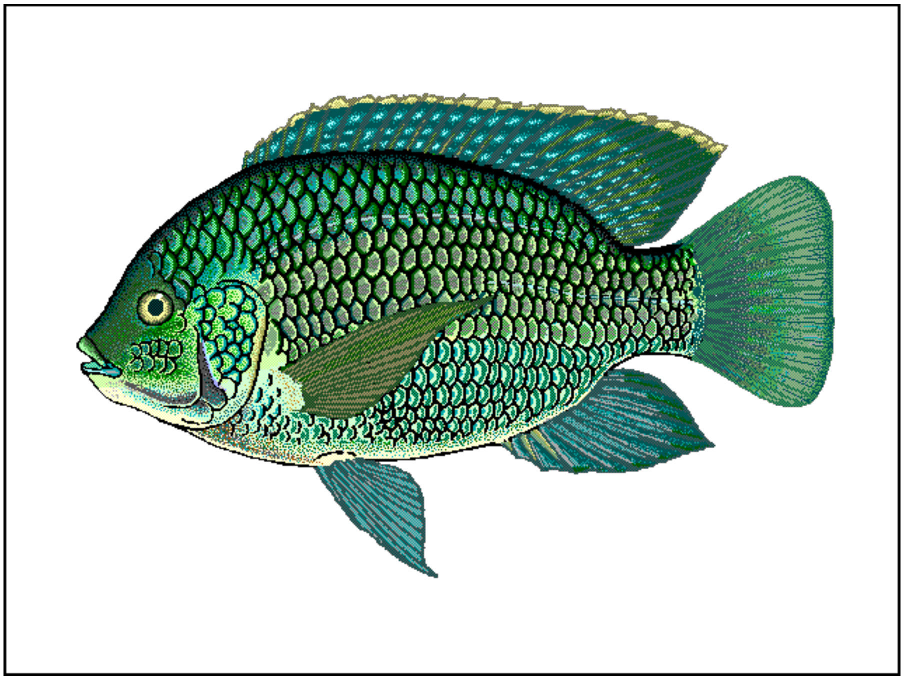


Figure C – Greenheaded Bream *Oreochromis macrochir*

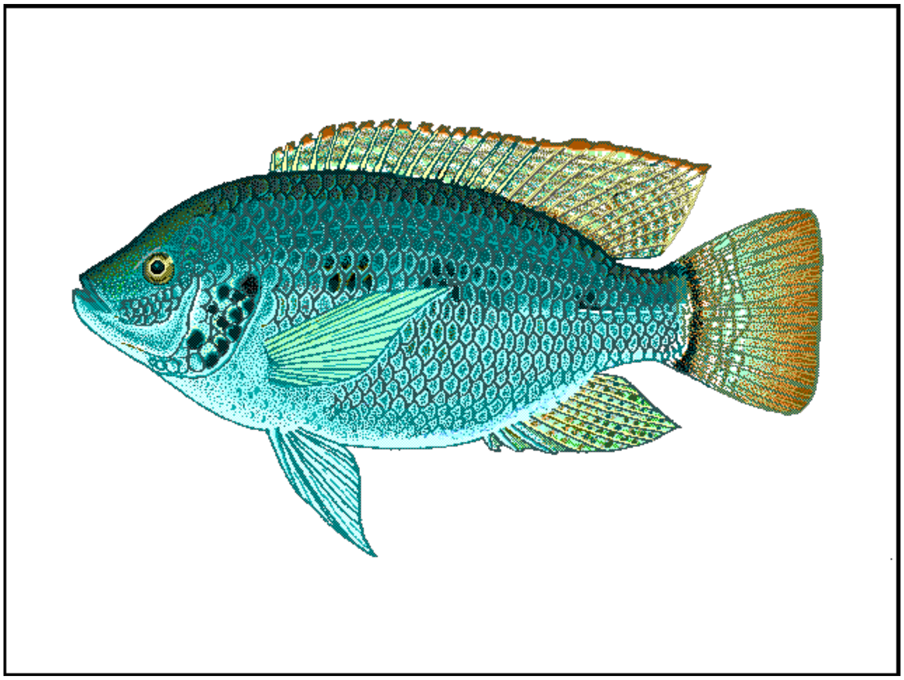


Figure D – Threespotted Bream *Oreochromis andersonii*

Appendix E: Composition of Fertilizer Used in Semi-Intensive Aquaculture

MANURE	Nitrogen (N)		Phosphorus (P)		Potassium (K)		C:N ratio
	%	pts.	%	pts.	%	pts.	
cow	1.91	5	0.56	3	1.4	2	19
sheep	1.87	5	0.79	4	0.92	2	29
goat	1.5	5	0.72	4	1.38	2	
pig	2.8	7	1.36	5	1.18	2	13
chicken	3.77	8	1.89	6	1.76	3	9
duck	2.15	7	1.13	5	1.15	2	10
rabbit	1.72	5	1.3	4	1.08	1	
bat	10	10	4	6	2.5	2	

ASH	Nitrogen (N)		Phosphorus (P)		Potassium (K)		C:N ratio
	%	pts.	%	pts.	%	pts.	
banana fodder		3		6		10	
maize cobs		2		6	50	20	
maize stalks	0.3	2	0.13	3	0.33	2	
groundnut shells		2		4		5	
orange/lemon peels		2		6		8	
cucumber skins		1		5		2	
wood - ifimuti		3	1.8	6	5	8	
peapods		2		4		8	
grass		2		3		3	
charcoal (from brazier)		2		4		5	

WASTES	Nitrogen (N)		Phosphorus (P)		Potassium (K)		C:N ratio
	%	pts.	%	pts.	%	pts.	
banana peels		1		5		10	
cassava peels		1		2		1	
sweet potato peels		1		2		4	

Appendix E Continued

bone meal		3		5		1	
coffee grounds	1.79	2	0.12	1	1.8	2	
eggshells		1		1		1	
feathers		5		0		0	
fish bones		2		5		2	
groundnut shells		3		3		2	
soya meal	7	1	2.28	0	1.02	1	
blood		2		5		2	
ground/dried fish		2		5		2	
maize cobs		0		1		10	
groundnut hulls	0.59	5		4		1	
soya oil cakes	6.95	5	2.88	3	1.02	1	

LEAVES AND STEMS	Nitrogen (N)		Phosphorus (P)		Potassium (K)		
	%	pts.	%	pts.	%	pts.	C:N ratio
cowpea fodder		3		2		2	
maize stalks	0.3	1	0.13	2	0.33	1	55
maize straw	0.59	1	0.31	2	1.31	2	55
rice straw	0.58	1	0.1	1	1.38	2	105
rice husks		1		1		0	
soya straw	0.59	1		2		1	19
soya leaves	1.3	2		11		0	32
groundnut leaves	2.8	2	0.2	2		1	
groundnut straw		1		2		1	
tobacco leaves		5		2		1	
tobacco stems/stalks		4		1		6	
banana leaves		1		5		8	
banana stalks		1		4		8	

Appendix E Continued

grass	0.41	1	0.03	0	0.26	1	20
green weeds	2.45	4		3		3	13
leucaena	2.45	6	0.07	3		2	
sugar cane hulls	0.35	1	0.04	1	0.5	1	116
senna		10		4		2	
blackjack		6		5		6	
beans leaves		2		2		1	
sweet potato leaves		1		2		1	
pigeon pea		1		2		3	
lantanna		8		6		8	
tomato leaves		1		1		1	
sunflower leaves		1		2		1	
velvet beans leaves		4		2		2	

COMMERCIAL FERTILIZERS	Nitrogen (N)		Phosphorus (P)		Potassium (K)		
	%	pts.	%	pts.	%	pts.	C:N ratio
D Compound	10	15	20	25	10	15	
Ammonium Nitrate	34	20	0	0	0	0	
Urea	46	30	0	0	0	0	

Appendix F: Guide to Supplemental Feeding and Formulating Tilapia Feeds

Table B provides many resources which are locally available in Zambia. Often these are plants, tree leaves, farm wastes, and kitchen wastes that can be obtained for free. Formulating fish feeds for semi-intensive fish farming system is never an exact science, but having a set of guidelines can help while experimenting with different feed combinations.

The four main components of fish feeds are carbohydrates, fiber, protein, and lipids. At the very end of the table, point requirements are listed depending on the age of the fish, the farmer selects the total point values for each of the four components. The farmer then combines various available resources to meet these values as closely as possible.

The point values are based on the weight of the substance. Therefore, if one kilogram of termites is used in the feed, then one kilogram of fresh cassava leaves should be used (unless the substance is stated as dried). When adding equal parts by weight, the point values for each can be added together to evaluate the ratio of different feed components. Examples are given after the table to demonstrate this process.

Table B – Supplement feeds: components and point values

CEREALS AND GRAINS

	Protein		Carbohydrates		Fiber		Lipids	
	%	points	%	points	%	points	%	points
sorghum (grain)	10.6	8	71.4	50	1.9	1	3	2
sorghum (bran)	7.8	5	65.7	48	7.6	5	4.8	3
maize (meal)	9.6	6	70.8	50	2	1	3.9	2
maize (bran)	2.1	1	57.8	42	36.5	25	0.8	0
millet (grain)	11.2	8	64.6	48	6.3	5	3.9	2
millet (hulls)	4.8	3	41.2	30	38.3	30	1.3	1

Appendix F Continued

Table B Continued

wheat (grain)	12	10	70	50	2.5	2	1.7	1
wheat (bran)	14.7	11	53.5	40	9.9	6	4	2
rice (mill sweepings)	8	8	40	30	32	10	5	6
rice (bran)	11	6	43	30	14	24	10	3

ROOT CROPS AND PRODUCTS

	Protein		Carbohydrates		Fiber	Lipids		
	%	points	%	points	%	points	%	points
sweet potato (fresh tuber)	1.5	1	25.6	20	0.8	0	0.3	1
sweet potato (dried tuber)	4.2	3	74.9	55	4.2	1	0.7	5
sweet potato peelings	0.7	0	10.2	6	0.1	5	0.2	6
cassava (fresh tuber)	0.9	0	30.9	20	1	2	0.2	2
cassava (dried tuber / meal)	2.1	1	77.9	55	3.8	1	0.5	2
cassava peelings	1.6	1	20.1	15	4.4	2	0.4	5
Irish potato (fresh tuber)	1	1	17.7	12		3		3

INSECTS AND ANIMAL PRODUCTS

	Protein		Carbohydrates		Fiber	Lipids		
	%	points	%	points	%	points	%	points
blood meal	81.5	60	1.6	1	0.7	0	1	1
waste fish	67	50	14.9	10	1	1	9.1	5
termites	15	40		10		5		6
locusts		30		5		2		2
earthworm	50.2	35		5		1	1.4	2
maggot	48.7	35	12	5	5	2	8.1	5
crab meal	50	35		10		3	5	3
frog (pieces)		30		5		2		4

Appendix F Continued

Table B Continued

OIL SEEDS/CAKES AND BEANS

	Protein		Carbohydrates		Fiber		Lipids	
	%	points	%	points	%	points	%	points
coffee meal	10	8	48.6	35	25	18	15	10
cowpea bean	23	15	67	50	6	4	5	3
velvet beans	3.4	2	7.2	5	5.8	4	0.5	0
groundnut (seed)	28.4	20	15.9	10	2.2	1	45	30
groundnut (shells)	6.2	4	21.4	15	54.3	40	1.6	1
groundnut oil cakes	46.2	35	24.8	18	7.5	5	6.7	5
sunflower (seed)	25.7	20	16.3	12	5	3	44	30
sunflower (hulls)	9.8	8	38.1	25	36.4	25	1.7	1
sunflower head and seed	13.1	10	32.8	25	23.4	15	13	8
sunflower oil cakes	37.1	28	27.2	20	12.7	8	9.3	6
soya (seed)	37.8	28	25.6	20	4.9	3	18	12
soya (hull)	9.8	6	38.1	30	36.4	26	1.7	1
soya oil cake	41.6	30	30.1	22	5.9	4	5.3	4
soya (meal)	35	25		20		4		2
pigeon pea	20	15	58	40	7	5	2	1

WASTES

	Protein		Carbohydrates		Fiber		Lipids	
	%	points	%	points	%	points	%	points
beer waste	22	15		20	6.75	10	3.96	5
leftovers (nshima)		1		30		5		5

Appendix F Continued

Table B Continued

LEAVES

	Protein		Carbohydrates		Fiber		Lipids	
	%	points	%	points	%	points	%	points
cassava leaves	25	20	7.7	5	2.1	2	0.8	0
leucaena(soaked and dried)	29.1	22		20	12.6	10	6.2	5
soya leaves	4.7	3	5.7	4	1.1	1	0.6	0
pumpkin leaves		5		5		2		0
beans leaves		3		4		1		0
cabbage	1.7	3		4		2		0
sweet potato leaves	2	10		8		2		0
blackjack		8		8		2		0
pawpaw leaves		10		5		1		0
groundnut leaves		3		4		1		0
rape	3	2		5		2		0
okra	2	1	6	4	1	1	0	0
squash leaves		2		4		1		0
cocoyam leaves		2		4		1		0
chinese cabbage		3		5		2		0

FRUITS

	Protein		Carbohydrates		Fiber		Lipids	
	%	points	%	points	%	points	%	points
avacado		10		15		2		15
banana		2		15		3		2
pawpaw		1		2		4		0
mango		2		2		5		0
guava		2		2		4		0
impundu		1		1		3		0
imfungo		1		1		3		0

Appendix F Continued

Table B Continued

PLANKTON

	Protein		Carbohydrates		Fiber		Lipids	
	%	points	%	points	%	points	%	points
phytoplankton	20	15		20		10		5
zooplankton	65	45		20		5		5

FEED REQUIREMENTS FOR TILAPIA

Size	Approximate age	% Protein	%Carb	% Fiber	% Lipids
0-0.5g	0-2 weeks	50	25	8	10
0.5-1.0g	2-6 weeks	35-40	25	8	10
10-35g	2-3 months	30-35	25	8 to 10	6 to 10
35g-adult	3 mts - adult	25-30	25	8 to 10	6

POINT REQUIREMENTS

Size	Age	Protein	Carbohydrate	Fiber	Lipids
0-0.5g	0-2 weeks	100	45	15	15
0.5-1.0g	2-6 weeks	120	70	25	25
10-35g	2-3 months	130	90	45	45
35g-adult	3 mts - adult	170	130	60	40

Appendix F Continued

Ba Chilufya is feeding his fish - which are 2-3 months old – maize meal, sweet potato leaves, and beer waste. Are these feeds adequate?

For fish that are 2-3 months old, our goals are:

- Goals: Protein 130, Carbohydrates 90, Fiber 45, Lipids 45

His feeds have the following point values:

- Maize meal: Protein 6, Carbohydrates 50, Fiber 1, Lipids 2
- Sweet potato leaves: Protein 10, Carbohydrates 8, Fiber 2, Lipids 0
- Beer waste: Protein 15, Carbohydrates 20, Fiber 10, Lipids 5
- Total: Protein 31, Carbohydrates 78, Fiber 13, Lipids 7

You can see that these feeds do not meet the necessary ratios. Ba Chilufya is close for carbohydrates, but he needs to look for more fiber, lipids, and a lot more protein. If his pond is well fertilized, we can add phytoplankton and zooplankton:

- Previous total: Protein 31, Carbohydrates 78, Fiber 13, Lipids 7,
- Phytoplankton: Protein 15, Carbohydrates 20, Fiber 10, Lipids 5
- Zooplankton: Protein 45, Carbohydrates 20, Fiber 5, Lipids 5
- Total: Protein 60, Carbohydrates 118, Fiber 28, Lipids 17

You can see that this still does not meet our goals. He has too much carbohydrates and not enough protein, fiber, or lipids. Ba Chilufya should look for feeds that have these things (especially protein).

Appendix F Continued

Ba Kabaso has fish that are 2-6 weeks old. He is feeding them termites, sunflower oil cakes, cassava leaves, and pigeon pea. Are his feeds adequate?

For fish that are 2-6 weeks old, our goals are:

- Goals: Protein 120, Carbohydrates 70, Fiber 25, Lipids 25

His feeds have the following point values:

- Termites: Protein 40, Carbohydrates 10, Fiber 5, Lipids 6,
- Sunflower oil cakes: Protein 28, Carbohydrates 20, Fiber 8, Lipids 6
- Cassava leaves: Protein 20, Carbohydrates 5, Fiber 2, Lipids 0
- Pigeon pea: Protein 15, Carbohydrates 40, Fiber 5, Lipids 1
- Total: Protein 103, Carbohydrates 75, Fiber 20, Lipids 13

You can see that, although not perfect, these feeds come close to the necessary ratios. If we were to add plankton to the feeds, Ba Kabaso would be doing quite well:

- Previous total: Protein 103, Carbohydrates 75, Fiber 20, Lipids 13
- Phytoplankton: Protein 15, Carbohydrates 20, Fiber 10, Lipids 5
- Zooplankton: Protein 45, Carbohydrates 20, Fiber 5, Lipids 5
- Total: Protein 163, Carbohydrates 115, Fiber 35, Lipids 23

Here, Ba Kabaso has more than enough of everything except lipids. He could probably even remove one of the feeds, like pigeon pea, to bring the numbers closer to the proper ratios:

- Previous total: Protein 163, Carbohydrates 115, Fiber 35, 23,
- Removing pigeon pea: Protein -15, Carbohydrates -40, Fiber -20, Lipids -1
- Total: Protein 148, Carbohydrates 75, Fiber 15, Lipids 22

These totals are a bit closer to our goals.

Appendix F Continued

Ba Mumba has fish that are 0-2 weeks old. He is feeding them millet (grain), cassava peelings, mangos, and pumpkin leaves. His pond is poorly fertilized and has very little plankton. Are his feeds adequate?

For fish that are 0-2 weeks old, our goals are:

- Goals: Protein 100, Carbohydrates 45, Fiber 15, Lipids 15

His feeds have the following point values:

- Millet (grain): Protein 8, Carbohydrates 48, Fiber 5, Lipids 2,
- Cassava peelings: Protein 1, Carbohydrates 15, Fiber 2, Lipids 5
- Mangos: Protein 2, Carbohydrates 2, Fiber 5, Lipids 0
- Pumpkin leaves: Protein 5, Carbohydrates 5, Fiber 2, Lipids 0
- Total: Protein 16, Carbohydrates 70, Fiber 14, Lipids 7

Because his pond is poorly fertilized and has very little plankton, we should not allow Ba Mumba to claim the points from plankton. You can see here that Ba Mumba is not even close to reaching the ratios needed for his fish to grow properly. He has too many carbohydrates, but is very much short on protein and lipids. He needs to improve his management to get a good plankton bloom and look for foods with more protein.

Appendix F Continued

Ba Bunda has fish that are more than 3 months old. He is feeding them termites, soya meal, leucaena leaves, sunflower seeds, rice bran, and avocados. His pond is very well fertilized and has an excellent plankton bloom. Are his feeds adequate?

For fish that are 3 months old, our goals are:

- Goals: Protein 170, Carbohydrates 130, Fiber 60, Lipids 40

His feeds have the following point values:

- Soya oil cakes: Protein 30, Carbohydrates 22, Fiber 4, Lipids 4
- Leucaena leaves: Protein 22, Carbohydrates 20, Fiber 10, Lipids 5
- Sunflower seed: Protein 20, Carbohydrates 12, Lipids 3, Fiber 30
- Rice bran: Protein 6, Carbohydrates 30, Fiber 24, Lipids 3
- Avocados: Protein 10, Carbohydrates 15, Fiber 2, Lipids 15
- Phytoplankton: Protein 15, Carbohydrates 20, Fiber 10, Lipids 5
- Zooplankton: Protein 45, Carbohydrates 20, Fiber 5, Lipids 5
- Total: Protein 148, Carbohydrates 139, Fiber 58, Lipids 57

Because his pond is very well fertilized and has a lot of plankton, we should include the points for plankton. You can see here that Ba Bunda is doing very well in his ratios. He is just a bit short on protein but all of the other nutrients are close to their goals. His fish should grow very nicely and he will have a successful harvest.

Appendix G: Nutrients Found in Human Excrement

Table C characterizes nutrients typically found in the urine and feces of humans.

Table C – Nutrients found in human feces and urine

Nutrient	Urine (kg/per·yr)	Feces (kg/per·yr)	Total (kg/per·yr)	% of Nutrient Found in Urine
Nitrogen	4.0	0.5	4.5	89%
Phosphorus	0.4	0.2	0.6	67%
Potassium	0.9	0.3	1.2	75%

Source: Swedish data (Drangert, 1998:161)

Nitrogen	2.4	0.3 – 2.7	2.7 – 3.9	81 – 89%
Phosphorus	0.2 – 0.37	0.1 – 0.2	0.3 – 0.57	65 – 67%

Source: (Kvarnstrom et al., 2006:3)

Appendix H: Equation for the Modeling of Fecal Coliform Removal in Lagoons

Modeling of fecal coliform removal in lagoons and fish ponds was performed in the study of the Kolkata wetlands study (Bunting, 2006). The removal was dependent on the temperature and the retention time of the lagoons Equation A, where N_p is the fecal coliforms (per 100 mL) in fishpond; N_i the fecal coliforms (per 100 mL) in untreated wastewater; k_T the rate constant for fecal coliforms removal (per day); θ_a the anaerobic retention time (day^{-1}); θ_f the facultative retention time (day^{-1}); θ_p the fish pond retention time (day^{-1}) (Bunting, 2006):

Equation A – Estimation of fecal coliform removal in lagoons

$$\frac{N_p}{N_i} = \frac{1}{(1 + k_T \emptyset_a)\left(1 + k_T \emptyset_f\right)\left(1 + k_T \emptyset_p\right)}$$

$$k_T = 2.6(1.19^{T-20})$$

Longer retention times and higher temperatures reduce the number of fecal coliforms expected in the fish pond.

Appendix I: World Health Organization Reported Safe Levels of Protein Intake for Adult Men and Women

Body Weight (kg)	Safe Level (g/kg·day)[b]
40	33
45	37
50	42
55	46
60	50
65	54
70	58
75	62
80	66

[a] all ages >18 years

[b] 0.83 g/kg per day of protein with a protein digestibility-corrected amino acid score value of 1.0

Reproduced with permission from the World Health Organization (WHO; FAO, 2007, pp. 243)

Appendix J: Concise Rural Aquaculture Promotion (RAP) Program Pond Construction Manual

Site Selection

Water

The most important factor in choosing a site for a fish pond is water supply. The most ideal source of water will be from a furrow. The furrow should have a flow that is able to sustain the level of water in the pond even during the driest months of the year. Generally farmers will know their land well enough to make this judgment on their own. However, measurements can be made during the driest month to conclude whether the furrow can support a pond or system of multiple ponds.

To ensure that one pond can be filled the flow rate of the furrow should be at least 5 liters per minute per *are*[1]. Fill a large bucket, timing how long it takes to fill. Then calculate the flow rate using the following equation.

$$\frac{Size\ of\ bucket\ (liters)}{Time\ to\ fill\ (seconds)} \times 60\,\frac{seconds}{minute}$$

$$= Flow\ rate$$

Example:

$$\frac{10\ liters}{22\ seconds} \times 60\,\frac{seconds}{minute} = 27.3\ {}^{liters}/_{seconds}$$

Figure E – Calculation for flow rate from a furrow

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[1] *are* – 100 meters square, a 1.5 *are* pond is 10 by 15 meters

Appendix J Continued

You must also consider the quality of the water. If the water is potentially contaminated by upstream farming practices then communication between the farmers will be important. The downstream farmer will have to manage the flow of water into the pond to prevent harming the fish. For example, if the upstream farmer will be spraying pesticides on his crops, than the downstream farmer will want to consider blocking the flow into the pond for a period of time after the spraying.

The farmer will also want to ensure that they have the rights to use the water for farming practices. Water disputes are a common problem in Zambia. Local methods of ensuring that the farmer will have continued rights to using the water should be pursued before the pond is built. The farmer should also maintain a good relationship with other stakeholders in the water source to reduce the possibility of sabotage due to jealousy.

Slope

The slope of the land at the site should be between 2 and 15 percent. This will ensure that the pond is drainable for harvesting. If the land is flat the pond will not be able to drain. If land is too steep the pond will require too much digging and be difficult to construct. The following illustrations show a method for measuring and calculating the slope of the land.

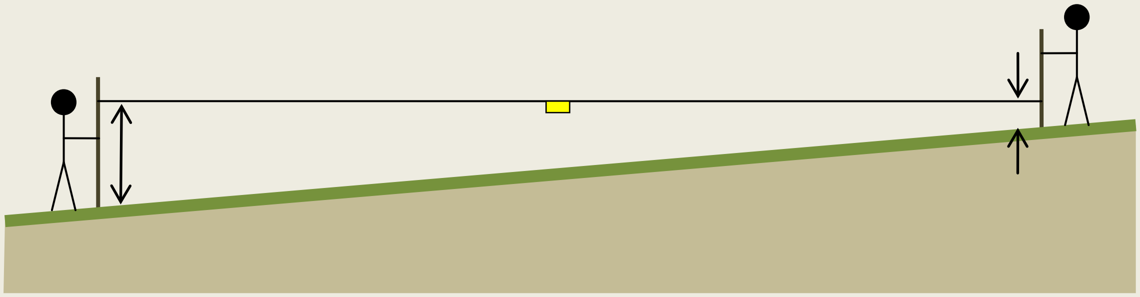
Appendix J Continued

Tools:

- two large sticks about 2 meters long
- 10 meters of string
- measuring tape
- line level

Technique:

1. Tie one end of the twine to one of the sticks.
2. Have one person hold this stick vertical.
3. A second person should walk down the slop of the land and pull the string taught. Ensure that vegetation does is cleared away from the string so there is a good reading.
4. A third person should mount the line level in the middle of the string and have the second person adjust the height of the string until it is level.
5. The third person should measure the height of the string from the ground at both ends of the string. These are A and B as shown in the picture.



Calculation:

$$Slope\ = \frac{B - A}{10\ meters} \times 100\%$$

Example:

$$Slope\ = \frac{1.6\ meters - .7\ meters}{10\ meters} \times 100\% = 9\%$$

Figure F – Measuring the slope of a valley

Appendix J Continued

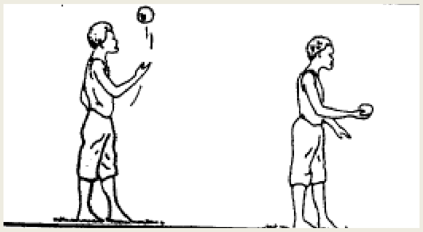
Soil

Having the proper type of soil will keep the pond from leaking too much. If the pond is built on very sandy or rocky soil then water seepage out of the pond will require continuous filling of the pond which is not ideal. Rocky soil is also difficult to dig in. Soil that is high in clay content is best. To check the soil texture and rate of seepage the two following methods can be used.

Appendix J Continued

Ball Test:

1. Dig to the layer of soil below the top soil.
2. Wet the soil.
3. Collect a piece of soil and form a ball.
4. If you can toss the ball into the air and catch it then the soil has a sufficient amount of clay. If the ball breaks apart then the soil may be too sandy.



Hole Test:

1. Dig a one-meter deep hole in the ground at the site.
2. Fill this hole with water.
3. Allow the water to go down then refill it.
4. Repeat this filling three times.
5. If the hole seems hold water well after this process than the site is likely a good location for a pond.

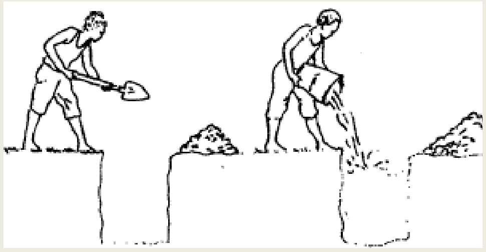


Figure G – Methods for testing soil

Appendix J Continued

Vegetation

The pond should be located in a place where it can have direct sunlight all day. If the site requires that you clear many trees this is work which could be avoided by choosing a site that is already in an open area. Also tree roots may be difficult to remove. If they rot there is a risk that leaks could form in the pond bottom or dike walls.

Planning

Farmers' fields are often located far from their homes. The RAP standard encourages farmers to locate their pond within a 10 to 15 minute walk from the home. This reduces the risk of theft and makes it easier for the family to visit the pond daily for maintenance and monitoring.

The farmer should consider whether they would like to add more ponds in the future. If so the location should be able to accommodate future constructions.

Family and farm integration is an important part of rural aquaculture extension in Zambia. A good example of pond integration would be use pond effluent to irrigate and fertilize vegetable gardens. This type of integration should be considered when locating the pond. If it is placed as high as possible on the valley wall then the effluents could be easily directed into a vegetable garden.

Pond Design

The pond design promoted by the Zambian Department of Fisheries has specific features which they have deemed optimal for fish production in rural Zambia. These features are called the rural aquaculture project standard, or RAP standard. Many of these features are different from traditional ponds found throughout the country.

Slopes

Traditional ponds walls are dug vertically into the ground. The RAP standard pond has inner and outer dike walls that are sloped. The slopes on the inside of the pond are used as breeding locations. The slope also creates a varying depth of water across the pond. This allows for the formation of a thermocline. Along the pond edges the water will be warmer; at the center of the pond the water will be cooler. This helps the fish to find an optimal temperature, especially during the cooler months.

The slopes on the inside and outside of the dike walls ensure the strength of the walls, which is especially important during heavy rainfall. The slopes also make the pond easier to harvest since one can simply walk from the top of the wall into the pond. Having slopes also makes the pond safer since children are not likely to fall into the water or of the outside edge of the wall.

Appendix J Continued

The following illustration describes the RAP standard slope for inner and outer dike walls.

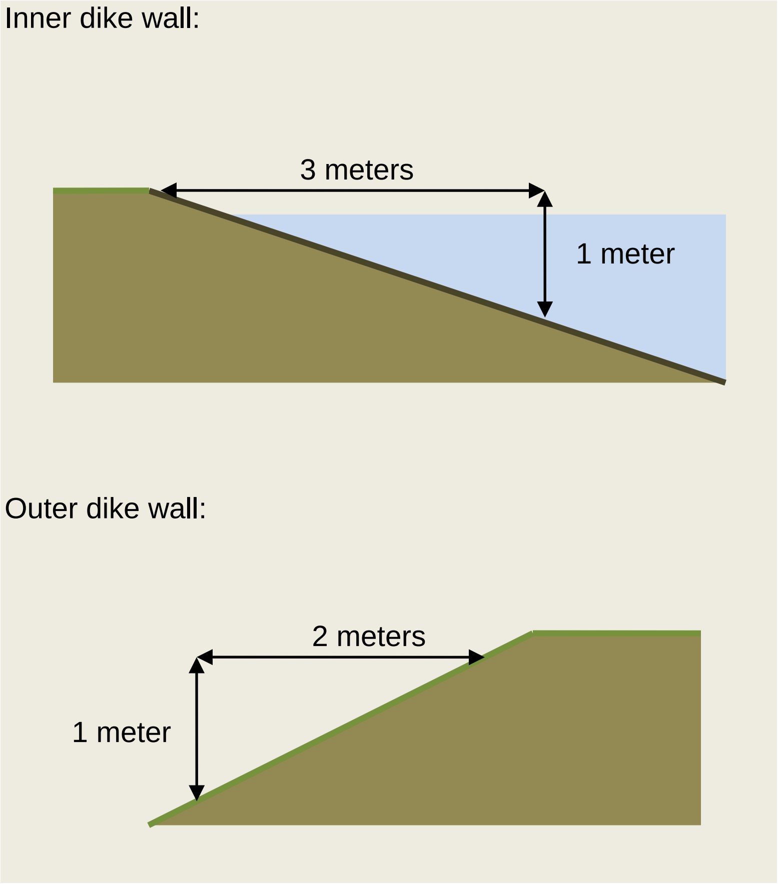


Figure H – Schematic showing interior and exterior slopes of a RAP standard pond

Inlets and Outlets

The most common inlets and outlets for ponds are recycled pipes. Since pipes can sometimes be difficult to find in the rural setting other methods may need to be improvised for controlling the entrance and exit of water from the pond.

Appendix J Continued

Inlet pipes are important because they allow the farmer to control the flow of water into the pond. The exit or overflow pipes prevent water from spilling over the top of the dike walls. This is especially important during heavy rainfall events when water running over the top of the wall could erode the wall, compromising its strength and possibly leading to its collapse and the loss of fish.

If pipes are used the framer may want to add a hard surface to buffer the flow of water, preventing erosion of the dike wall. The pipes should also be screened to prevent “trash fish” from entering the pond, or good fish from exiting the pond.

A pond generally has one inlet. However, the number of overflow pipes is based on the size of the pond. For each *are* the pond should have one overflow pipe. A 10 x 15 meter pond is 1.5 *ares* and would require to pipes to ensure that enough water could exit in a heavy rain event. These overflow pipes should be buried 30 centimeters below the top of the dike wall. This way water can never reach the top of the wall. This buffer zone is called the freeboard.

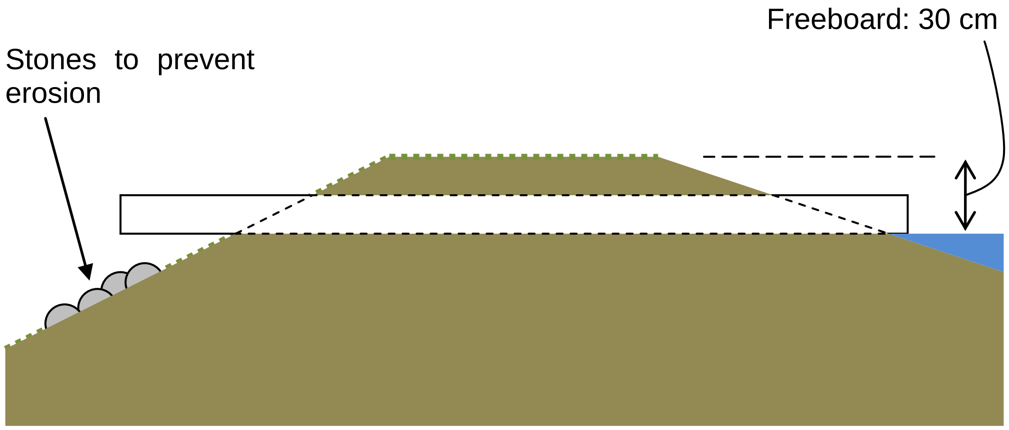


Figure I – Typical setup of an overflow pipe

Appendix J Continued

Size

The size of the pond depends on the resources available and the amount of time the farmer can dedicate to maintaining. Some farmers have constructed a pond of one hectare. However, new farmers are recommended to start with a 10 meter by 15 meter pond. This allows the farmer to gauge how much time and the amount of resources they will require to maintain the pond.

Smaller ponds also reduce the risks associated with disease and theft. If a disease enters the pond or somebody poisons the fish in the pond, the loss associated with one 1.5 are pond is much less than a 100 *are* pond.

Pond Measurement and Construction

The following steps outline the process for constructing a RAP standard fish pond.

- Clear the site of debris and large trees.
- Stake the four corners of the pond. After this stake the four outside corners of the dike walls.
- Determine height of dike walls with level. Choose the height just above the earth at the highest corner. Then using a line level tie the string from corner to corner so that the height of the dike wall on the inner perimeter can by visualized and used as a guide for wall construction.

Appendix J Continued

- The inner box must be determined. Using the RAP standard slopes, two corners of the inner box will be 3.3 meters (1.1m × 3 slope) from the up-slope corners. The other two will be 3.9 meters (1.3m × 3 slope) from the down-slope corners. This is shown in Figure J:

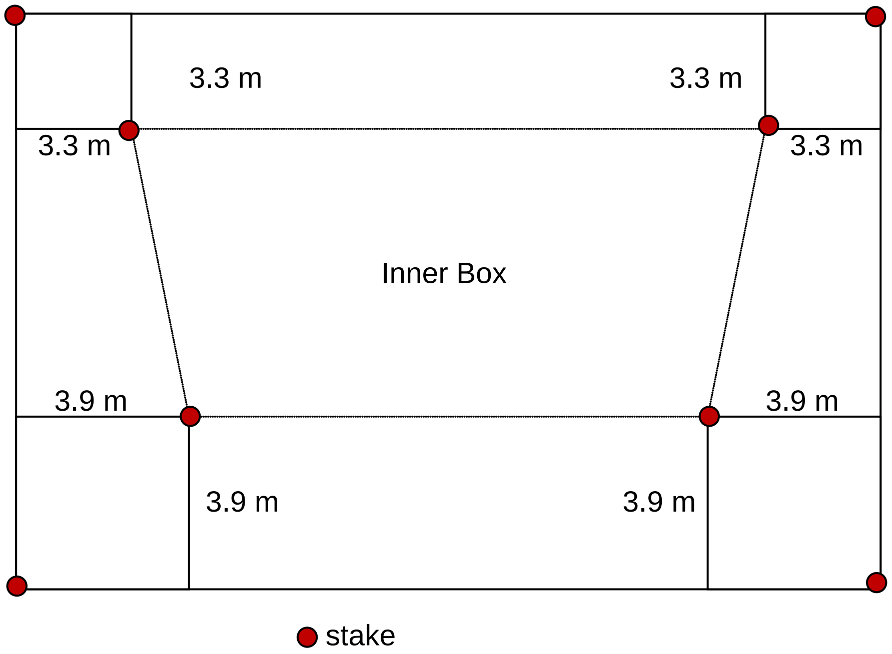


Figure J – Layout for staking of a fish pond and its inner box

- Remove the top soil from the entire construction area.
- Determine the depth which must be dug out at each corner of the inner box.
- Begin by digging the inner box. Figure K shows progress after having completed this step.

Appendix J Continued

Figure K – Photo of pond construction after completion of the inner box

- After completing the inner box, soil is removed to form the inner pond slopes. This soil is used to build the dike walls.
- For every 30 cm of wall construction, the soil must be compacted.

Figure L – Photo showing the completion of pond slope construction and leveling of dike walls

Appendix J Continued

- Figure L shows the completion of the dike walls. The inner slopes and walls must be well compacted.
- Place the inlet and outlet pipes in the dike walls.
- Build compost bins.
- Screen the inlet and outlet pipes.
- Plant grass on the top and outside slopes of the dike walls.

Pond Management

Basic pond management was taught as the 7-1-2 method of pond maintenance. This helps to remind farmers that there are seven, one, and two tasks to be performed each day, week, and month respectively.

Daily

1. Feed and observe fish.
2. Clear frog eggs and check for predators.
3. Stir compost and remove twigs and sticks.
4. Speeds the release of compost nutrients into the water.
5. Check water level.
6. Check walls for leaks.
7. Check the furrow for blockages.
8. Clear pipes and screens.

Weekly

1. Fill compost.

Monthly

1. Cut grass on dikes and around pond.

Remove grass form inside pond.

ABOUT THE AUTHOR

Joshua Girard is a graduate student in the Department of Civil and Environmental Engineering at the University of South Florida (Class 2011). As a Master's International student his academic interests include the many environmental engineering challenges facing the developing world. His course of study has included a range of topics from conventional water/wastewater treatment, air quality, sociology of the environment, general sustainability, and appropriate technology.

From July 2008 to April 2010, Joshua served as a Rural Aquaculture Extension agent with the United States Peace Corps in Zambia. He participated in nine weeks of cultural, language (Bemba), aquaculture, and HIV/AIDS training. Following training he moved to his host community where he conducted farmer evaluations, fish farming workshops, farmer site visits, and community based HIV/AIDS education.

Joshua grew up in southern Maine, USA. He completed his Bachelor of Science in Mechanical Engineering at Boston University in 2007. He has studied abroad in Germany in 2005, where he began learning German. Outside of engineering and academics his interests include traveling, gardening, and current events. He would like to return to Zambia in the future to work in fields relating to aquaculture, transportation, or water/sanitation, incorporating his passion for people and the environment through sustainable technologies.