Master thesis

TVVR 13/5003

Environmental Sustainability of Floating Biodigesters in Tonlé Sap, Cambodia

Minor Field Study

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Abstract

Conditions for humans living in floating villages around the world are usually in the lowest earning bracket. The lack of sanitary facilities pollutes lakes and deteriorates human health. This master thesis evaluates the environmental sustainability of implementing floating biodigesters as a sanitary solution in a village located on the lake Tonlé Sap in Cambodia. The main objectives include assessing the benefits from reduction of waste addition to the lake and biogas produced from the biodigester. The main environmental problems discussed are emissions of greenhouse gases, spreading of pathogens and nutrient pollution.

The objectives were met by gathering local data and complement this with experimental measurements. Three scenarios representing the extent of the biodigester implementation were elaborated to evaluate the improvements on the specific environmental problems. The scenarios were: past situation with no biodigester systems, current situation where the biodigesters are implemented with limitations for the waste management system and the future situation where the biodigesters are introduced with an optimal waste management system and a usage of the digestate.

The past situation mainly affects the health among the villagers due to spreading of pathogens. The current situation has reached a state where the biodigesters degrade pathogens well and the prospects for human health improvements are good. However, there has not been a distinct reduction of nutrient pollutions and greenhouse gas emissions. Finally, the future situation with full implementation of biodigesters shows great potential in reducing pathogen concentrations around the village. Local contribution of nutrients and greenhouse gases are also reduced with this sanitary solution. The multiple benefits of biodigesters contribute very much to the development of living conditions in floating villages.

Keywords: Tonlé Sap, Biodigester, Cambodia, Environmental Sustainability, Phat Sanday, Floating Villages, Anaerobic Digestion, Sanitation

Sammanfattning

Levnadsförhållandena är vanligtvis låga för människor som lever i flytande byar runt om i världen. Avsaknaden av adekvata avfallssystem i flytande byar försämrar både människors hälsa samtidigt som sjöar kontamineras. Detta examensarbete utvärderar hållbarheten av att implementera flytande bioreaktorer som avfallssystem för flytande byar i sjön Tonlé Sap, Kambodja. Det huvudsakliga syftet är att belysa fördelarna med att minska tillflödet av föroreningar till sjön samtidigt som biogas kan produceras från bioreaktorn. De miljömässiga problem som diskuteras är: utsläpp av växthusgaser, spridning av patogener och tillflöde av näringsämnen till sjön.

Lokal data samlades in och kompletterades med egna mätningar. De miljömässiga förbättringarna diskuterades utifrån tre scenarier som beskrev i vilken utsträckning bioreaktorerna blivit introducerade. De tre scenarierna var: dåtida situationen utan bioreaktorer, nuvarande situationen med bioreaktorer introducerade och en begränsad hantering av avfallet samt framtida situationen med bioreaktorer implementerade och en optimal hantering av avfallet.

Den gamla situationen påverkar huvudsakligen hälsan hos byborna på grund av hög spridning av patogener. Den nuvarande situationen har nått ett tillstånd där patogener reduceras väl i bioreaktorerna och förutsättningarna för förbättrad hälsa hos byborna är god. Dock finns det inga system för att minska tillflödet av näringsämnen till sjön och utsläppet av växthusgaser har bara minskat marginellt. Det framtida scenariot visar en mycket god potential för att minska patogenspridningen runt byn. Utsläppet av växthusgaser och näringsämnen kommer också minska kraftigt med detta reningssystem. Introduktionen av bioreaktorer är rekommenderat då flera miljöproblem förbättras vilket leder till att levnadsförhållandena för människorna i byn kommer att kunna höjas avsevärt i framtiden.

Nyckelord: Tonlé Sap, Bioreaktor, Kambodja, Hållbar Utveckling, Phat Sanday, Flytande byar, Rötning, Avfallshantering

Preface

This master thesis "Environmental Sustainability of Floating Biodigesters in Tonlé Sap, Cambodia" was partly performed at the Division of Water Resources Engineering, Department of Building and Environmental Technology, Lund University in Sweden and partly at Live and Learn Environmental Education in Phnom Penh, Cambodia.

Firstly, we would like to thank our supervisor in Cambodia, Mr Robert Hughes. You have helped us with all kind of problems related to this thesis. It did not matter if there were practical or theoretical issues, you have always provided us with good answers. Our gratitude also goes to Ms Gabrielle McGill and the personnel at Live and Learn Environmental Education Cambodia. This study would have been impossible to perform without the help from the delightful people at this organisation.

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Our gratitude should also be given to the following persons for their help throughout this study: Professor Lars-Anders Hansson, Professor Kenneth M. Persson, Emma Kreuger Ph.D., Professor Lovisa Björnsson, Linda Tufvesson Ph.D., Mr Per Svenningsson, Professor Magnus Larson. Docent Jan Ovesen and Mr Kong Channareth

Finally, we would like to thank our families for their support through the project.

Lund 2013

Henrik Carlsson and Kristofer Kiste

Abbreviations

AWMS – Animal Waste Management Systems

CFU – Colony-Forming Unit

CH_4 - Methane

CO_2 – Carbon dioxide

E. coli – Escherichia coli

EWBA – Engineers Without Borders Australia

GERES – Groupe Energies Renouvelables, Environnement et Solidarités

GHG – Greenhouse Gases

GWP – Global Warming Potential

HRT – Hydraulic Retention Time

LLEEC – Live and Learn Environmental Education Cambodia

LMB – Lower Mekong Basin

MRC – Mekong River Commission

NaOH – Sodium Hydroxide

NBP – National Biodigester Programme

NGO – Non-Governmental Organization

NO_x – Nitrogen Oxides

RDI – Resource Development Institute in Cambodia

RUA – Royal University of Agriculture in Cambodia

RUPP – Royal University of Phnom Penh

SRT – Solid Retention Time

TS – Total Solids

VS – Volatile Solids

Table of Contents

1 Introduction

In many places around the world, humans have settled on floating houses and live together in floating villages. The living conditions are usually rough and sanitation hardly exists. On the Tonlé Sap in Cambodia, several floating villages exist and solutions to improve their livelihood are desired. One solution is introducing floating biodigesters to improve village conditions by means of better water quality as well as production of renewable biogas energy for the village. This master thesis is meant to support the development in terms of determining environmental benefits of introducing biodigesters to these communities.

1.1 Background

Cambodia has for a long time been haunted by poverty and illiteracy. With the leadership of Pol Pot, the Khmer Rouge reversed the development further during the end of the 70s (Ovesen, 2012). Even after the Khmer Rouge was dethroned by the Vietnamese in 1979, a decade of non-peaceful conditions made the development stagnate. In early 90s when King Sihanouk assumed the office of Head of State, Cambodia could once again begin to develop. Currently modernization and development mostly occur in urban areas increasing the economical gap between poor and rich. Many habitants in Phnom Penh and other large cities have improved their standard of living, while rural Cambodia still has the same severe conditions of poverty.

Figure 1. Picture over Southeast Asia showing the location of Cambodia (Google, 2013a)

The Tonlé Sap is the biggest lake in Southeast Asia and connects to the Mekong River, thereby providing both the Cambodian and the Vietnamese population with their major supply of fresh water (Keskinen, et al., 2003). On the lake people have settled in floating villages where their houses float assisted by clay pots and plastic containers (see Figure 2; Brown, 2010).

Figure 2. Floating houses in Phat Sanday, Tonlé Sap.

Inhabitants in these villages are very poor and their livelihood is mainly dependent on fishing. In general there are small possibilities for other income sources since infrastructure like an electricity grid and roads in the floating villages are very limited, or non-existent. There are however good prospects for more ecotourism in the area which would stimulate other types of livelihood in the future (Keskinen, et al., 2003). The lack of flexibility in their livelihoods makes the villagers extra sensitive to sudden changes in the environment and economy. These aspects make people living in the floating villages among the poorest in the country. Sanitary conditions in the communities are unhygienic and people are defecating directly in to the water, either from a hole in the floor or from the side of their house (Brown, 2010). At the same time many people use the lake water directly for bathing, washing and drinking so the need for water sanitation in these communities are high.

1.2 Live and Learn Environmental Education Cambodia in Phat Sanday

Live and Learn Environmental Education Cambodia (LLEEC) is a Non-Governmental Organisation (NGO) that the recent years, has been working on development and implementation of floating biodigesters on Tonlé Sap. LLEEC started up the “Floating Latrine Project” to improve sanitation conditions in Phat Sanday (Brown, 2010). Currently, LLEEC is working on different prototypes for testing and future usage in the floating communities. In 2010 the community consisted of five villages with 980 households and 6 954 inhabitants (LLEEC, 2010a). Other general data gathered by LLEEC are presented in Table 1.

Table 1. General information of Phat Sanday (LLEEC, 2010a).

Villages	5
Households	980
Citizens	6 954
Fishermen	95%
Average number of persons per household	7
Volume of human waste per citizen (kg/day)	0.26
Volume of human waste per household (kg/day)	1.3
Average number of pigs for households that are pig owners	2
Volume of pig manure per pig (kg/day)	2.75
Volume of pig manure per household that are pig owners (kg/day)	5.5

Table 1 state that each household consists of an average of seven persons. The waste production per citizen is based on an average adult production. Children do not produce as much waste as the adults and the household production is therefore assumed to equal a production from five humans and two pigs.

Phat Sanday is located in the southeastern part of Tonlé Sap. The location of the lake is shown in Figure 3.

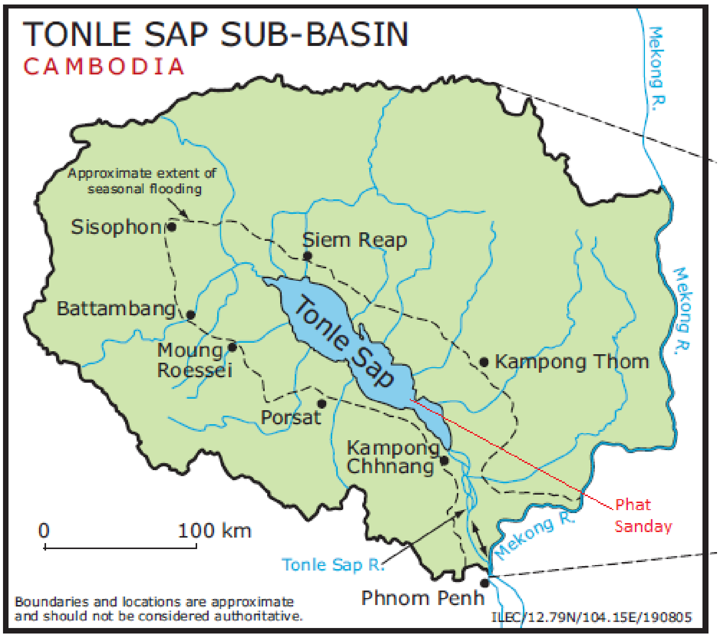

Figure 3. Map of Tonlé Sap sub-basin with Phat Sanday marked in red (modified from Keskinen et al., 2003).

The village was chosen by LLEEC as a result of an early assessment that studied the suitability of different villages in the area. Brown (2010) presented the following main reasons for choosing Phat Sanday:

- High levels of environmental awareness within the village and thereby better chances that they would participate in the project.
- The village was and could be included in several environmental programmes from other key actors in the area.
- Located close to Phnom Penh resulting in practical benefits.

Today the project has developed into several subprojects where one of them focuses on implementing floating biodigesters suitable for water sanitation as well as renewable energy production. The feeds to the biodigester are mainly pig manure and human excrement. Consequently, direct pollution to the lake is reduced since the waste products are used as a resource instead. As a by-product and a secondary benefit, methane gas is produced that can be made available for household services. Currently, people burn wood for cooking which causes health problems as well as deforestation.

Figure 4. A typical hard plastic floating biodigester in Phat Sanday.

1.3 Objectives

The general objective of this master thesis is to establish environmental benefits of introducing floating biodigesters in the village Phat Sanday in Tonlé Sap, Cambodia. The key objectives are:

- Assessing energy production from a household biodigester and establish potential reduction in emission of greenhouse gases.
- Determine the potential reduction of waste added from the community to the lake and draw conclusions of possible impacts on water quality.

1.4 Limitations

The general scope of the thesis is narrowed through the following limitations:

- The applications for the digestate will not be thoroughly studied. However, whenever stated that there is an application for the digestate, it is assumed that this application has no negative impact on the environment.
- Economical sustainability considerations of the biodigester will not be evaluated.
- Modelling or advanced assessment of quantifying water quality improvements will not be performed.
- Microbiological optimisation of the biodigester will not be reviewed.

1.5 Detailed research question formulation

Answers to the questions given in this section are meant to jointly meet the objectives given in section 1.3.

- In terms of nitrogen and phosphorous in waste, how much of the village's addition to Tonlé Sap can be reduced by introducing floating biodigesters?
- Will the reduced input of nutrients reduce the possibility for lake related problems such as eutrophication?
- How much is the pathogen concentration degraded by implementing floating biodigesters?
- How much biogas can be produced by an average household based on their resources and how much energy is that equivalent to?
- What energy sources can be replaced by biogas and what effect does that have on greenhouse gas emissions?

2 Tonlé Sap

Tonlé Sap, also known as the Great Lake, is the largest freshwater lake in Southeast Asia and located in the middle parts of Cambodia (Keskinen, et al., 2003). Tonlé Sap is highly dependent on the interaction with Mekong River which is a large river flowing through Southeast Asia. The Mekong River stretches from China and Myanmar in the north down through Laos, Thailand and Cambodia before discharging in the Vietnam delta to the South Chinese Sea. Hydrological variations of Mekong River highly affect the conditions of Tonlé Sap.

2.1 Hydrology

Annually, the size of the lake varies but always consists of a large northwestern basin connected through Tonlé Sap River to a small southeastern basin (Campbell, 2009). During dry season, the size of the permanent lake is around 2500 km^2 with a mean depth of about 1 m (Kummu, et al., 2006). Figure 5 shows that the larger permanent lake has a width of around 35 km and a length of 120 km (Campbell, 2009).

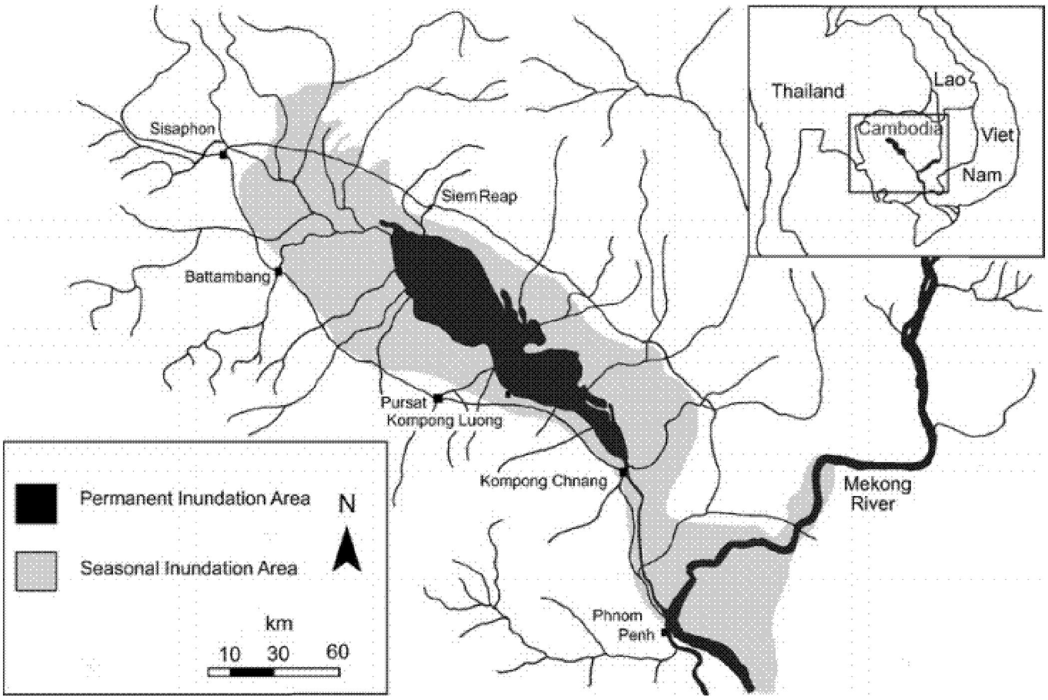

Figure 5. Locations of the permanent Tonlé Sap basins together with the elongation of the lake during wet season (Campbell, 2009).

When the monsoon arrives in May, the size of Tonlé Sap increases. The flooding of Mekong River alters the flow direction towards Tonlé Sap. Hydrological studies have shown that 57 % of the water in Tonlé Sap originates from Mekong River (Kummu and Sarkkula, 2008). The rest of the water is added through tributaries (30 %) and direct precipitation (13 %). In particular, large rice fields and forest areas are inundated. The great inflow of water causes a sevenfold increase of the lake area and the depth reach around 8-10 m (Campbell, 2009). The width and length of the lake is increasing creating a total area of around 17 000 km^2. Inundation of Tonlé Sap is an important factor in reducing the flooding risks in major cities such as Phnom Penh. Tonlé Sap is therefore acting as a storage that decreases the flow downstream of Phnom Penh.

After the monsoon, in November, the flow of the Tonlé Sap River alters direction and water from Tonlé Sap flows back to Mekong River. The majority of water (87 %) is transported via Tonlé Sap River down to Mekong River while the rest is evaporating (Kummu and Sarkkula, 2008). During this time lake area slowly attenuates and the water level decreases back to the permanent lake size. The occurrence of dry and wet season is described in Figure 6.

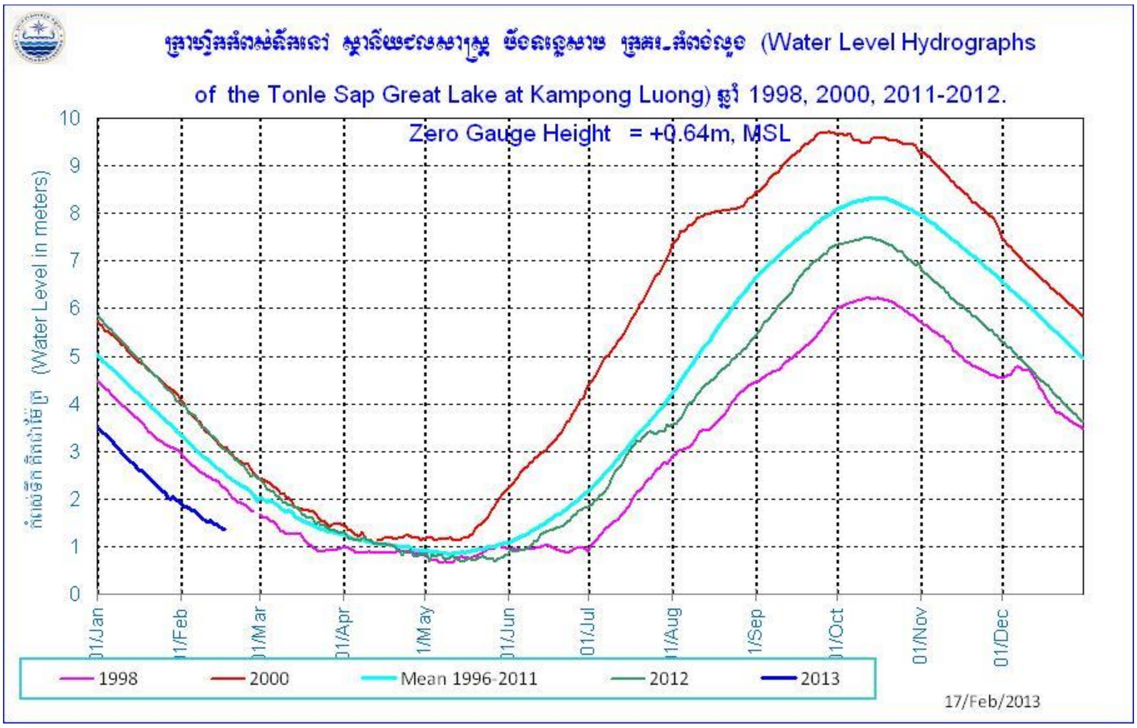

Figure 6. Water level with respect to time for a station located at Kampong Luong in Tonlé Sap (DHRW, 2008). The occurrence of the yearly flooding is clearly visible by the increased water levels.

2.1.1 Local hydrology

Phat Sanday is as shown in Figure 3 located at the southeast corner of Tonlé Sap. A local map (Figure 7) shows that the village is located in a trench. The white dots in Figure 7 are roofs from floating houses.

Figure 7. Extent of Phat Sanday. The white dots are floating houses in the village (Google, 2013b).

The river Stung Sen originating from Kampong Thom acts as an inflow to the village (top right in the picture). The flow in the trench flows in a southwest direction down towards the southwest part of Figure 7 where the water flows out to the southern part of the main water body of Tonlé Sap. The whole community of Phat Sanday has settled along the flow direction of Stung Sen and the village is aggregated at dry season. However, during wet season, the whole area is flooded and Phat Sanday becomes a part of Tonlé Sap's large water body thus spreading the houses.

2.1.2 Hydrological effects

The large hydrological variations have implications on the condition of the lake. In the season with low water level, turbidity is increasing. Wind induced turbulence which stress the water surface becomes more significant as depth is decreasing and conditions at the lake bottom becomes turbulent (Campbell, 2009). On the contrary, turbidity becomes lower during wet season when wind induced turbulence effects on the surface does not suspend sediments from the lake bottom. In addition, the increased quantity of water dilutes the system which further decrease the turbidity.

During flooding season, nutrients are discharged from farmlands causing a highly productive lake situation positive for the fish stock. Many humans in rural societies use fishing as their livelihood making them dependent on the annual flooding of Tonlé Sap. However, with increasing populations living around the lake, the pressure on the fish stock is increased causing a potential extinction of different species. Especially larger fish species are threatened. Presumably because larger species have longer breeding time than smaller ones (MRC, 2010a).

3 Environmental concerns

The present living conditions in Phat Sanday are contributing to decreased environmental quality in the area. Some environmental concerns are currently affecting the area more than others. However, it is also useful to have a precautionary approach for those concerns that in the future might become problematic. The three different environmental concerns that are potentially harmful in the area are:

- Addition of nutrients through waste to the lake.
- Addition of pathogens through waste to the lake.
- Emissions of greenhouse gases from wood fuel in relation to global warming.

3.1 Nutrients in Tonlé Sap

The theory of eutrophication, which is a major environmental effect related to increased nutrients additions, is initially discussed. Thereafter the current water quality status in Tonlé Sap is evaluated.

3.1.1 Eutrophication

The algal productivity of a lake is sometimes used for characterizing the environmental state of the lake. The lake state based on the productivity is divided into three different trophic states, oligotrophic, mesotrophic and eutrophic (Brönmark and Hansson, 1998). Oligotrophic lakes have low productivity with low or no vegetation making them very clear and deep visible. Mesotrophic lakes have intermediate productivity with some vegetation and slightly shallower visibility. The last trophic level, eutrophic, is however a state of a lake characterised by excessive growth of plants. Visibility is becoming even shallower and the amount of vegetation becomes significantly higher.

The trophic state is highly connected to the amount of nutrients in the lake. Phosphorous and nitrogen are important nutrients in lakes and organisms use them for growth. Nutrients are mostly in ionic forms since they dissolve in contact with water. Animals are not capable of absorbing dissolved ions so it is only the smallest organisms that can utilise them (Brönmark and Hansson, 1998).

Productivity in the lake is caused by growth of organisms in the lake. The smallest organisms called primary producers (bacteria, algae, etc.) require nutrients for reproduction. The assimilated nutrients are then transported upwards through the food web when larger organisms consume smaller ones. Animals such as fish also require nutrients and receive them by consuming primary producers or organisms below them in the food web. According to Brönmark and Hansson (1998) most nutrients exist in excess in a normal lake (Si, K, Ca, C, etc.). The growth and primary productivity is therefore determined by the limiting nutrient. This is normally phosphorous or nitrogen and the risk for eutrophication are often related to these.

Only dissolved compounds can be used for algal growth meaning that orthophosphate is representative for phosphorous while ammonia, nitrate and nitrite are representative for nitrogen (Deas and Orlob, 1999). The total concentration of these compounds is therefore a suitable measurement in terms of an eutrophication risk analysis.

Problems have arisen because human activities add phosphorous and nitrogen lakes. Human sewage, industrial waste and farming fertilizers are some examples of human activities increasing the input of phosphorous and nitrogen to water bodies. This results in an excessive growth of primary producers (Brönmark and Hansson, 1998). Increased biomass among species of primary producers can cause a green surface layer, thus inhibiting sunlight to penetrate lake's surface. Consequently, sub-merged plant species will not obtain any sunlight making them unable to photosynthesise. The plants and other light dependent organisms living deeper then dies and more dead organic matter is produced. This causes a significant oxygen reduction in the lake since oxygen is consumed while breaking down the organic matter. Fish and other living organisms require oxygen for living meaning that they will suffer from low oxygen conditions. Ultimately, the conditions in the lake have greatly been altered by larger nutrient additions. In addition, toxic conditions often occur during eutrophication due to many cyanobacteria species producing toxins that are harmful for humans.

It is not only excessive phytoplankton growth that causes eutrophication. Additional input of phosphorous and nitrogen also alters the environmental circumstances in the lake in terms of modified competition conditions. Species adapted to a certain condition might be outrivaled by another species. The invasive species are better adapted to the new conditions and outcompete the former (Brönmark and Hansson, 1998).

A common species invading new environments is the water hyacinth (*Eichhornia Crassipes*) (Brönmark and Hansson, 1998). It doubles its mass in around 14 days and this makes it very fast growing and competitive in a new environment. Water hyacinth is a surface floating species that can spread to cover the entire water surface. Similar to the phytoplankton coverage, no sunlight can penetrate through the layer of water hyacinth leading to poor oxygen conditions in the lake.

3.1.2 Mekong River quality

Water conditions in Tonlé Sap are demonstrably affected by Mekong River. Quality variations in Mekong River are therefore important to consider regarding Tonlé Sap conditions. There are generally no acute threats to the river conditions, but higher population density in the region is increasing the pressure on the ecosystem (Campbell, 2009).

3.1.2.1 Phosphorous

A water quality assessment of Mekong River performed by MRC (2010b) shows a small annual increase in total phosphorous concentration. For the mainstream stations in the Lower Mekong Basin (LMB), a steady increase in total phosphorous concentration from 1998 until 2008 was discovered. Mainstream stations are located along the main flow of river; hence Tonlé Sap is defined as a tributary station. Among the tributary stations, no significant trend of increasing phosphorous concentrations has yet been found. Instead the largest phosphorous increase is located close to Vietnam Delta. This is likely a result of growing urban populations with poor sanitation facilities.

Different phosphorous forms show high affinity for suspended solids and are therefore bound to the particles. This leaves less phosphorous forms available for plants and the risk for eutrophication is decreased. It is mainly orthophosphates that are available for plant uptake (MRC, 2008). The ratio between phosphate and total phosphorous is low in Mekong River with median values around 0.3. In Tonlé Sap, the ratio is slightly lower with median value around

0.25. Campbell (2009) explains the low ratios by a large suspended solids concentration in Mekong River.

According to MRC´s State of Basin Report (2010b), the elevated levels of phosphorous close to Vietnam Delta are high enough to cause algal blooms. The median phosphorous levels are though much larger in the delta compared to the tributaries. However, the trend of increasing phosphorous levels in the delta shows that elevated phosphorous level also might be a problem further upstream.

Kampong Luong is located on the southwest part of Tonlé Sap not directly in contact with Phat Sanday. The data from Kampong Luong was presumed to be representative as background levels for the water outside Phat Sanday. This data was compared with the measurements from Brown (2010) which verified the assumption to be valid. Total phosphorous concentration variations from Kampong Luong are presented in Figure 8.

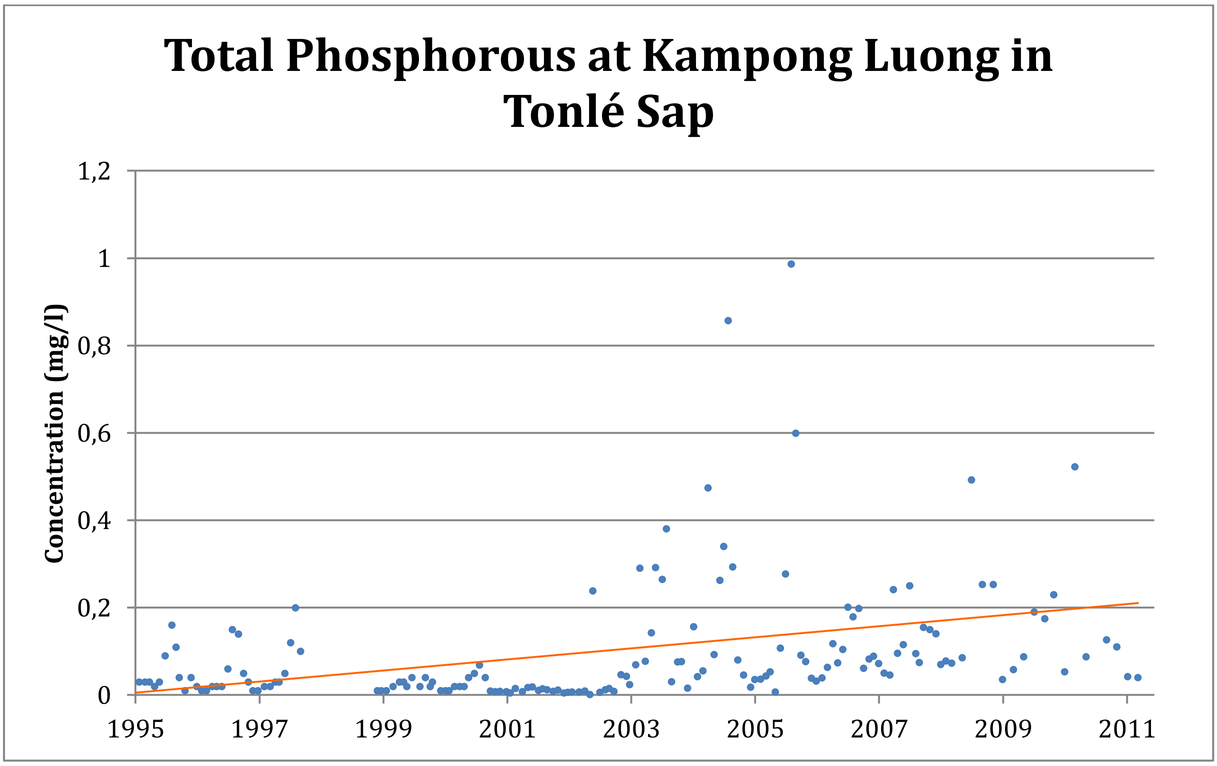

Figure 8. Monthly total phosphorous measurements are given by the blue dots. The orange line represents a trendline for total phosphorous. Time period stretches from 1995-2011 (MRC, 2012).

An increase in phosphorous concentration can clearly be seen in the area. The increase seems to follow the same pattern as the trend given for the whole Mekong River. Thus, rising levels of phosphorous also poses a potential health risk for tributaries such as Tonlé Sap.

3.1.2.2 Nitrogen

Until recently, total nitrogen has not been measured by MRC. Instead measurements have been made for nitrogen compounds such as, nitrate and ammonia. Increasing levels of nitrogen compounds in Mekong River have been discovered. However, for nitrate no significant change has been seen (MRC, 2010b). This means that the levels of nitrate are still low, somewhat around 0.3 mg/l, which is way below the threshold value of 0.7 mg/l (Campbell, 2009). Illinois Environmental Protection Agency states that values above 0.3 mg/l are able to cause algal blooms (IEPA, 1998). With this guideline it is potentially a risk for algal blooms in Mekong River. The concentrations are significantly higher closer to the delta, but still the majority of measurements are below the threshold level (MRC, 2008). The reason for increased concentration in the delta is probably larger loads of sewage from rapidly developing urban areas.

Ammonium concentration was also measured from 2000-2008 and the trend is a small increase (MRC, 2010b). Most stations showed the same results and there is no trend of higher concentrations further downstream. Ammonium itself is not especially hazardous but its unionised form (ammonia) is toxic for many species in lakes. According to Campbell (2009), the concentrations of ammonium and ammonia are low and not causing any problems for lake organisms.

Total nitrogen concentration in Kampong Luong has only been measured from late 2007 and ahead. It is considered to be a too short period for establishing a trend. The measurements are given in Figure 9.

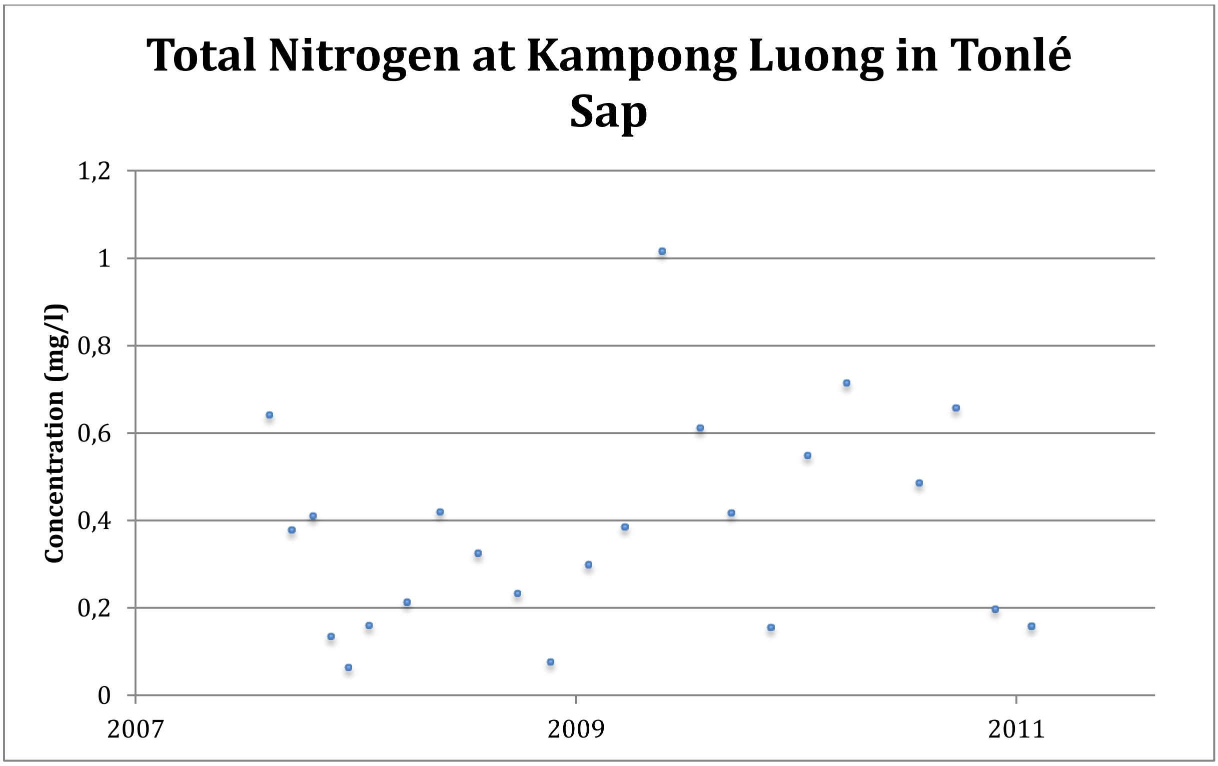

Figure 9. Total nitrogen at Kampong Luong. The time period stretches from 2007-2011 (MRC, 2012).

Variations of nitrogen are probably a result of the annual hydrological variations. However, this dataset seems to show a small nitrogen increase that could imply a long-term trend of rising concentrations.

3.1.2.3 N:P Ratio

Algae are dependent on uptake of both phosphorous and nitrogen. Lakes are often limited by one nutrient and an addition of the limited nutrient causes excess growth. Establishing a ratio between nitrogen and phosphorous shows whether a lake is nitrogen or phosphorous limited. MRC (2010b) states that N:P ratio from 7-10 is optimal for algal growth. The ratio at mainstream stations has its median value within 7 and 10 implying optimal growth conditions. However, the potential growth relationship depends on several other parameters and the values of 7-10 should not be taken as defaults (Campbell, 2009). Currently, eutrophication is not widespread implying that the lake can handle the current concentrations. In the tributaries where Tonlé Sap is included, the ratio is higher than 10 (MRC, 2010b). The median lies around 12 indicating that phosphorous is the limiting nutrient. An external phosphorous addition might increase the risk for eutrophication effects.

3.1.3 Eutrophication in Mekong River – A threat?

The risk for eutrophication in Mekong River and Tonlé Sap is by many authors reported to be low (Sarkkula, et al., 2003; Hart, 2004; MRC, 2010b). The simple explanation is that the nutrient levels are held relatively low. This is reflected by the fact that concentrations of phosphorous and nitrogen are in most cases kept below the threshold values. Tonlé Sap also has a slightly higher resistance to high nutrient concentrations than many other lakes. The reason is the high amount suspended solids and the high turbidity (MRC, 2008). Algal growth is decreased when less light can penetrate due to the low visible conditions (Campbell, 2009). Still, small local eutrophication problems have been detected, mainly closer to the Vietnam Delta (MRC, 2010a).

Eutrophication effects can also be a serious consequence if the implementation of hydropower dams in Mekong River becomes reality. Lanza (2011) discusses the potential environmental impacts on Tonlé Sap by dam constructions. During low water season, a primary productivity increase has been discovered due to less turbid water and more light penetration. The increased dry year productivity is balanced by the yearly flow pattern where the increased flow during rainy season reduces primary productivity. Building dams alters the flow pattern and sediment transport that likely will modify lake living conditions. Lower flow is a possible effect of dams and the current primary productivity during low water season cannot be balanced enough during wet season.

Eutrophication is not currently a major problem in Mekong River and Tonlé Sap. However, localised problems may be present under certain conditions, particularly with high input of nutrients combined with other stresses (Hughes, 2013).

3.1.3.1 Previous eutrophication of large lakes

Some large lakes around the world have started to suffer from problems with eutrophication. Some examples are presented below:

- Lake Victoria in East Africa is probably the most well known example where increased nutrient additions caused algal blooms. Typically, the increased nutrients originated from industrial and domestic human activities (Ochumba and Kibaara, 1989). Another problematic consequence was that water hyacinth was introduced. Conditions favoured water hyacinth growth in Lake Victoria and the endemic species was outcompeted (Albright, Moorhouse and McNabb, 2004).
- Lake Erie in North America is another lake that has been exposed to eutrophication. Similar to Lake Victoria, human activities increased the nutrient levels and the result was elevated algal growth (EPA, 2011). Hence, anoxic conditions prevailing low oxygen availability for lake organisms was created.
- Lake Tai (Taihu), which is the third largest lake in China, is also highly affected by eutrophication (Wilhelm, et al., 2010). Lake Tai is a shallow lake and the nutrient

additions have caused a hypoeutrophic status. Once again, the sources were anthropogenic additions of nutrients.

3.1.4 Other important parameters in a lake

Dissolved oxygen is a parameter giving the amount of oxygen available for organisms. A low concentration of dissolved oxygen cause problems for many living organisms such as fish and is often a secondary consequence of eutrophication. Michigan Water Quality Standards (DEQ, 2006) states a minimum of 5 mg/l of dissolved oxygen in warm water bodies. Data from Kampong Luong collected by MRC (2012) gives a dissolved oxygen concentration as shown in Figure 10.

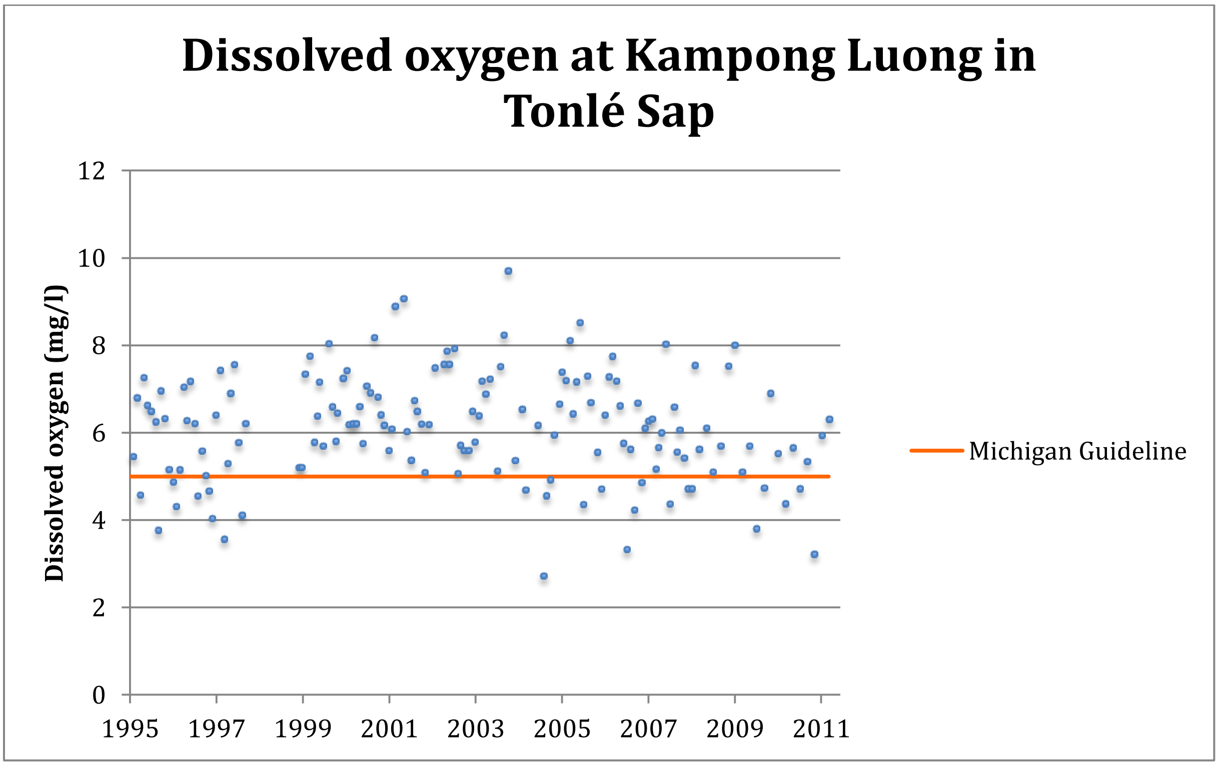

Figure 10. Dissolved oxygen concentrations measured by MRC (2012) from 1995-2011 at Kampong Luong in Tonlé Sap. The red line represents Michigan Water Quality Guideline for dissolved oxygen (DEQ, 2006).

The majority of values are higher than the guideline value stated for warm water lakes. Dissolved oxygen concentration in Phat Sanday is around 5.4 mg/l both for high water level and low water level season (Brown, 2010).

The pH is also a parameter related to the environmental quality of a water body. Problems with acidification are reflected by a pH decrease. MRC (2008) reported that Mekong River in general has low problems with acidification, except for some parts close to Vietnam Delta. In Tonlé Sap, no pH related complications have been stated. Measurements taken by MRC (2012) in Kampong Luong, located in the southwest part of Tonlé Sap, show a stable pH during the last 20 years as presented in Figure 11.

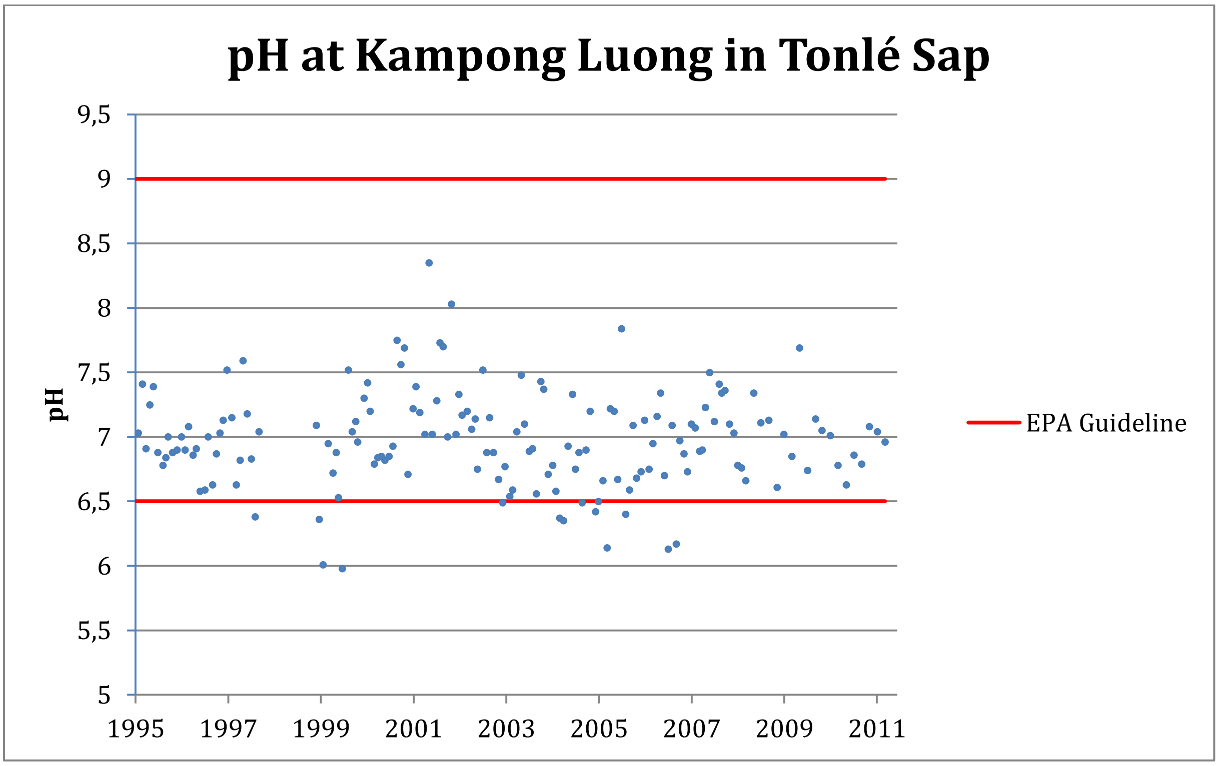

Figure 11. Observed pH data by MRC (2012) from 1995-2012 at Kampong Luong. EPA freshwater bodies guideline (2009) is added as reference value.

EPA (2009) guidelines given for freshwater bodies have been included in Figure 11. Most measurements lies within the EPA guideline and the medium value is fairly close to neutral pH. No significant trend is clear over time and the variations might be a result of the annual flooding. Measurements taken by LLEEC in Phat Sanday also lie within the EPA guideline with pH slightly higher than 7 at high water level and pH slightly lower than 7 at low water level (Brown, 2010).

Temperature in the region varies since Mekong River is stretching over different temperature regions. The climate at the northern part of Mekong River is cooler than in the LMB. In Tonlé Sap, annual variations are moderate due to the tropic climate conditions. In Kampong Luong, MRC measurements (2012) show a stable water temperature (Figure 12).

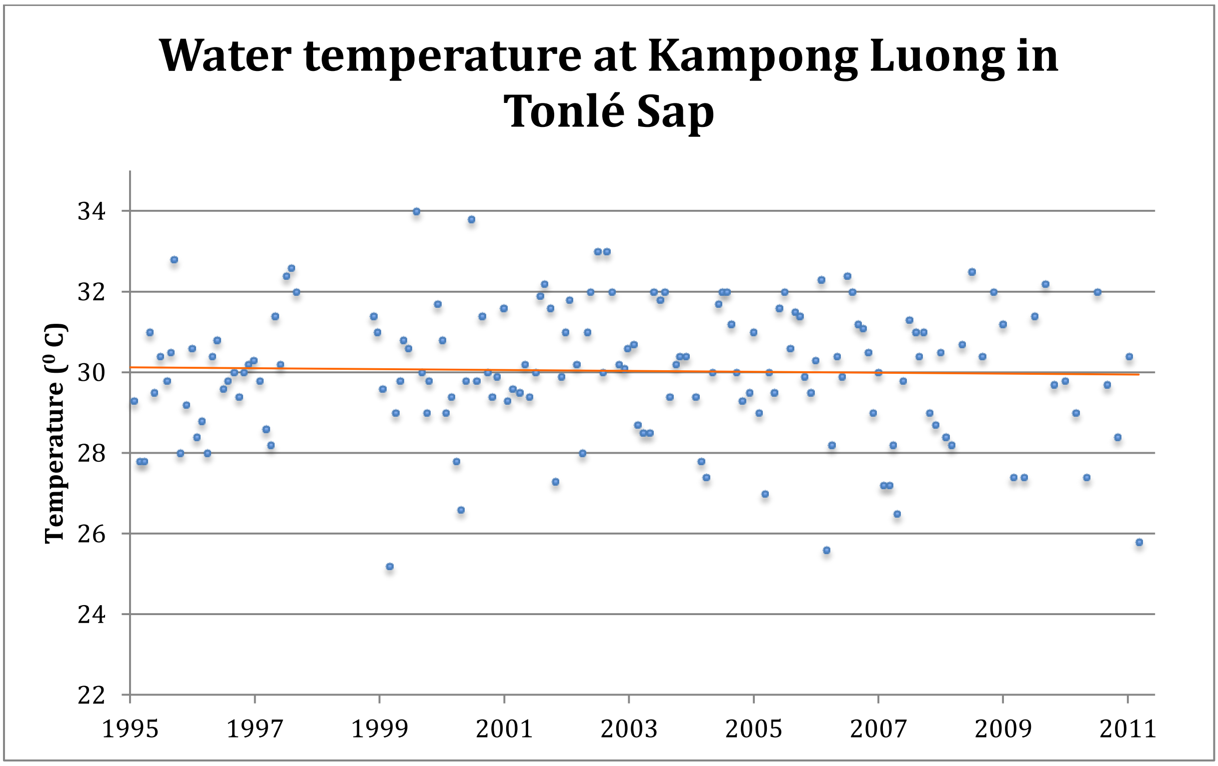

Figure 12. Water temperature variations at Kampong Luong in Tonlé Sap. The orange line represents the temperature trend over time. Time period stretches from 1995-2011

The orange line, representing a trend, shows that the water temperature in Tonlé Sap is stable. The differences are probably due to annual variations of water temperature.

The effect that increased waste additions have on temperature, pH and dissolved oxygen is difficult to establish. However, Hughes (2013) states that it would be extremely unlikely any wastewater input would influence pH or temperature, but localised DO levels could be impacted from excess inputs.

3.2 Pathogens

Pathogenic organisms are divided into bacteria, protozoa and viruses. In fresh water bodies like Tonlé Sap, the existing populations of pathogens mainly origins from human and animal excreta. Therefore, many infectious diseases are spread through the water to other people using it for drinking (UNESCAP, 2000). Coliforms are groups of bacteria growing in the intestines of humans and animals. Escherichia coli (*E. coli*) is one of the most common coliform species. Most of the *E. coli* bacteria are harmless to humans except the group *E. coli O157:H7* which usually causes diarrhoea, abdominal pain, nausea, fever and fatigue (EPA, 2012). Since *E. coli* is a major coliform bacteria it is frequently used as an indicator for pathogen occurrence in drinking water (WHO, 2011). Other bacteria that commonly cause diseases in Cambodia are species of *Salmonella, Cholera,* and *Shigella.* In Cambodia the lack of good water treatment enables pathogens in the drinking water to give rise to diarrhoea, dysentery, typhoid fever, cholera and gastro-enteritis (UNESCAP, 2000). There is also a risk that virus like influenza and HIV are spread through water containing high concentrations of human excrements (WHO, 2011).

Beyond pathogens there are species of parasites that spread through excrements and cause severe problems among the rural population. From a study of human faeces from 2170

Cambodian men and women, the United Nations organisation UNESCAP (2000) found that 30.7 % of them had one or several parasites.

Pathogens in lake water can either be prevented by pre-treatment of the waste from humans and animals through anaerobic or aerobic digestion before it is used as fertilizer or directly discharged in lakes and rivers. To do so it is necessary to collect the waste. One solution is to use Ecosan toilets where the waste is collected in a plastic container, see Figure 13.

Figure 13. A sanitation solution developed by Live and Learn Environmental Education

Alternatively or complementary, the drinking water collected from Tonlé Sap should be boiled or processed through ceramic water filters to reduce pathogen concentrations (RDI, 2011). The ceramic water filter reduces *E. coli* concentrations by up to 95.1 % on average through physical filtration by the tiny pores of the filter as well as chemical treatment by silver ions embedded into the filter. There are other methods for pathogen treatment, for instance solar heating, UV-light, chlorine disinfection or sedimentation through either membrane filters or natural filters. The efficiency and costs of these methods varies and they are not very common in rural Cambodia (WHO, 2011).

3.2.1 Sanitation in floating communities

LLEEC made a study with interviews and workshops in 2010 to map the sanitation conditions in the floating villages in Tonlé Sap (Brown, 2010). Sanitation options in villages like Phat Sanday are very bad if not inexistent. People defecate and urinate directly into the water from either a hole in the floor or from the side of their house. For men this has been convenient for a very long time and can explain the little concern for sanitation development. However, both women and men seem to have a will to improve water quality in their village and were positive to invest in toilet solutions if the price and convenience where acceptable. The main reason is health improvement which is a big concern in the community. Many people suffer from diarrhoea and other intestine, stomach and blood diseases which also lead to high health care costs. This is directly connected to the water quality since the villagers use lake water for bathing, cooking, washing and drinking. Surveys by LLEE have shown that many, but not all, households boil or filter water, however not all the time. The risk of exposure to water-borne pathogens is very high (Hughes, 2013).

Women suffer more than men with the poor sanitation conditions, both during their daily needs as well as during the menstruation period when they often stay at home for the whole time. Also many men are fishermen and travel with boat far away from the village during daytime. There they defecate and urinate directly from the boat into the water. This pollution to Tonlé Sap will not be reduced when introducing either floating toilets or biodigesters as sanitary solutions.

In 2010, LLEEC established the pathogen concentration at several locations in Phat Sanday (LLEEC, 2010b). It was concluded that the incoming concentration of total coliforms and *E. coli* was 5-10 times lower than concentrations at sampling points within or downstream the village. The sampling point representing incoming concentration had an *E. coli* concentration of 195 CFU/100ml and a total coliforms concentration of 1380 CFU/100ml. Incoming concentration was assumed to be representative as background levels.

3.3 Global warming

Global warming has become a major environmental concern and has effects on many levels of all societies and ecosystems. These effects and their impact on local areas are extremely difficult to estimate. All ecosystems will be affected to some degree and whether these effects will be considered positive or negative depends on what parameter that is in focus.

3.3.1 Expected effects from global warming on floating communities in Tonlé Sap

For LMB, which includes the Tonlé Sap, the temperature is expected to rise with 0.68 – 0.81 ^{0}C before 2030 (Eastham, et al., 2008). This will affect the water cycle in the region. Annually evaporation will on average increase with 2 %. Perhaps more significantly for the people around Tonlé Sap, is that the annual precipitation will increase by 13 % on average. However, the increased rainfall will most probably happen during the wet season while the dry season should expect less precipitation. This will increase the expected runoff to Tonlé Sap by 21 % annually and thereby the amount of water in the lake will increase during wet season.

Most problematic for the Tonlé Sap ecosystem as well as the floating communities is probably not the expected changes in amount of precipitation, evaporation, runoff etc. between today and 2030, but instead the more dramatic changes between wet- and dry season in 2030 compared to today. Nuorteva, et al. (2010) predicts that the annual changes will be very problematic for poor people in the floating communities since they mainly depend on fishing and do not have other livelihood alternatives to earn an income from. Since some species generally have problems with adapting to drastically changing environments, an uncertainty has arisen on how the fish population in the lake will be influenced. This could have severe effects on the floating communities as well as the rest of Cambodia that depends on fish from Tonlé Sap.

A major problem with the increased water volumes during the wet season is flooding of nearby areas to the lake. This can lead to severe economic costs of damaged properties in stilted communities and land-based villages. Agriculture and food production could also be expected to damage from these extreme types of flooding (Eastham, et al., 2008). Perhaps flooding will not be as problematic for floating communities since their houses already are prepared to handle higher water levels, and are generally more adapted to the water. But these communities are also depending on the land-based communities and agriculture, for example to buy rice and sell their fish. Floating communities will be affected if the land-based communities are destroyed or moved with increased flooding. There is also a risk that the nearby flooded forests will become permanently submerged and thereby damaged which results in habitat loss. Increased and more severe storms are also expected, which can cause problems for the floating houses and boat transport.

A predicted positive effect from the increased abundance of freshwater due to global warming will be that the future irrigation need in the nearby agriculture could be met without severely draining the hydrological ecosystem in the Tonlé Sap region (Eastham, et al., 2008).

3.3.2 Phat Sanday's contribution to global warming

The expected contributions of greenhouse gas pollution from the floating villages in Phat Sanday are mainly due to:

1. Combustion of fossil fuels for electricity production, which emits CO_2 and NO_x.
2. Combustion of fossil fuels in boat engines which emits CO_2 and NO_x.
3. Emissions from the production and transport of products bought by the villagers.
4. Combustion of wood for cooking, which emits CO_2 and NO_x.
5. Deforestation for wood to either cooking or building material, which reduces ability of earth to absorb CO_2.
6. Anaerobic digestion of human waste, which emits CH_4, N_2O and CO_2.
7. Anaerobic digestion of pig manure, which emits CH_4, N_2O and CO_2.
8. Anaerobic digestion of digestate, which emits CH_4, N_2O and CO_2.
9. Combustion of biogas for cooking, which emits CO_2 and NO_x.

Numbers 4-9 are directly related to the biogas system and dependent on the villager's living conditions and habits. The pollution from these activities vary for different scenarios, see chapter 6.2.

3.3.3 Living conditions

The main field of application for biogas in Phat Sanday is cooking since it is a vital activity for the people to remain in good health.

3.3.3.1 Wood fuel for cooking

In Cambodia, 97 % of the rural population use firewood for cooking (Van Mansfelt , Sras and Pino, 2008). In floating villages like Phat Sanday, nearly 100 % use firewood for cooking. Sometimes the villagers also use charcoal and gas, but wood is definitely the main fuel (LLEEC, 2011).

Several studies giving different results, shows that there are difficulties in estimating average daily wood demand for each household. A survey carried out in Siem Reap, just north of Tonlé Sap, estimated that the average daily wood demand for each household is 14 kg. This is also confirmed by other surveys (SNV, 2005). Provinces in south Cambodia have estimated daily wood fuel demand as 6.34 kg per household (Van Mansfelt and Buysman, 2006). It is uncertain whether it is wood fuel demand that differs between the provinces or the used methodology in the different surveys that differs. It is also important to remember that floating villages have different conditions and opportunities than villages on land.

There have been no studies on exact amounts of daily wood used in Phat Sanday. However, a focus group survey conducted in 2010 showed that each household on average gather 2 m^3 wood every time they go to collect. The average value do however represent that most people who collect wood use it all for themselves, but some people who collect are regular wood-sellers to those households who do not collect it themselves (Hughes, 2013). GERES (2012) conducted a survey in other floating communities in Tonlé Sap showing that each household use 3.4 kg of wood per day. This is much lower than the previous data from land-based households but more representative for conditions in Phat Sanday.

About 77% of this wood is considered non-renewable because of unsustainable logging and this has effects on deforestation (Arazo, et al., 2009). The Cambodian human development report states "Rates of deforestation and associated land use changes have been the major driving force behind Cambodia becoming a net emitter of GHG" (Ministry of Environment, 2011). However, it should in this context be considered that most of the fuel wood usually is collected from non-forest areas and that instead of unsustainable logging, shifts in land use are the main reasons for deforestation in the country (Burgess, 2000). People in Phat Sanday get their wood from both forest- and non-forest areas (Buntha, 2013). Since there is no planting of new trees in the nearby regions, independently of origin the burning of wood still emits carbon dioxide. If the origin of wood is from renewable forests, the CO_2 emission should not be considered as a net addition of GHG to the atmosphere. If the wood originates from non-renewable forests, then there will be no replacement of the tree that is cut down. The wood burning is thereby contributing to the global warming (Van Mansfelt and Buysman, 2006).

If a household produces biogas, the need to collect or buy firewood can be reduced or removed completely depending on how much gas that is produced. Land-based households that install a biodigester are on average reducing the time spent collecting firewood from 3 hours/day to 45 min/day (Van Mansfelt, Sras and Pino, 2008). The time spent for households in floating villages is uncertain since they go by boat and collect wood. Sometimes driftwood is also collected. More studies need to be done to estimate how much time that is spent, but it is certain that it takes several hours a week.

3.3.3.2 Cooking stoves and combustion

In the floating villages of Tonlé Sap the most common woodstove used is the Traditional Lao Stove (TLS) which has an efficiency of 25 %, see Figure 14 (GERES, 2013). Other stove models exists in Cambodia but are more unusual. An NGO called GERES are currently working on marketing a new woodstove model that will improve both efficiency and combustion. The main reason behind their project is to reduce deforestation and CO_2 emissions. Other issues are that the combustion in the current stoves is usually incomplete thereby causing unhealthy smoke containing Carbon Monoxide (CO), soot and particles. This can cause health hazards such as acute respiratory infections (ARI), coughs, bronchitis and eye problems. Once again women get more exposed to these hazards (Moeung, 2001). In Phat Sanday many households cook outside which results in better ventilation and they are perhaps less exposed to the smoke than land-based households. However, no study has been done on how many households that cook inside. The degree of exposure of outside cooking is also difficult to estimate. Unhealthy smoke from burning wood should thereby still be considered as a problem.

Figure 14. Kitchen in a household in Phat Sanday. A typical Traditional Lao Stove is shown to the right.

The biogas owners will use a biogas stove for cooking. This is a quite simple model that is bought in Phnom Penh and distributed through LLEEC. A similar biogas cooking stove was tested by SNV (2005) in an in-depth research study that showed an average stove efficiency of 49 %.

Figure 15. Typical gas stove in Phat Sanday.

3.3.3.3 Lighting

There is a potential to use biogas for secondary purposes such as lighting. SNV made some testing of a typical biogas lamp from Cambodia in 2009 showing that the design of the lamps need improvement to make it less fragile and to improve airflow regulation to the lamp (SNV, 2009b). The lamp consumed 56 L of biogas/hour. In rural Cambodia, the main source for lighting is electricity from car batteries which are used by 77 % of the villagers (Van Mansfelt, Sras and Pino, 2008). In Phat Sanday conditions are different, and about 90 % get electricity to their lamps from car batteries that can be recharged by diesel generators. 10 % of the people sometimes use the diesel generators directly to produce electricity for their lamps. There are also a few households that have installed solar panels to receive electricity to their lamps. Some households use kerosene lanterns which has an open flame and can be a dangerous fire risk. None of the households use gas lamps (LLEEC, 2011).

Figure 16. Cambodian biogas lamp (SNV, 2009b)

3.3.3.4 Animal waste management systems

The use of dung and manure as fertilizer is very common for rural Cambodia. Since the manure is thought of as substrate to the biodigesters it is a perfect substitute to use the output from the biodigesters as fertilizer instead. In the floating villages of Phat Sanday, access to farming land is very scarce so the manure is dumped directly into the water where it is degraded. If this degradation is anaerobic, methane is produced which will be released to the atmosphere. With aerobic degradation, mainly carbon dioxide is produced. During dry season some nearby land appears and are used for growing vegetables on. People also grow small amounts of vegetables directly on their porch. An upcoming project in LLEEC is to establish floating gardens where the villagers receive a couple of square meters more to grow vegetables on. The current access to farming land should still be considered very low and also means that there is not a great need of digestate from the biodigesters at the moment. Further away from the villages, in the surrounding land areas of Tonlé Sap, the farmers usually grow rice. A potential idea is to establish a market for trading digestate with the rice farmers, which currently not exist. If this could be established then the digestate could be used more sustainably. When the digestate is dumped in the water, there is no replacement of chemical fertilizers and the biodigester loses some of its GHG-reduction potential. It should though be considered that if rice farmers get access to digestate they might not necessarily replace any chemical fertilizers. A survey by National Biodigester Programme (NBP) showed that only 6 % of the farmers replaced chemical fertilizers completely for digestate (Van Mansfelt, Sras and Pino, 2008). Most of the respondents instead use the digestate in addition to their chemical fertilizer to improve their yield from the land

3.4 Other environmental concerns

There are some other environmental concerns not discussed within this study. Implementation of biodigesters is affecting some of the following concerns but the extent will not be evaluated.

Incomplete combustion of wood particles creates soot that is hazardous for humans. In many rural areas, indoor cooking with wood as fuel source causes unhealthy conditions in their houses. On the other hand, biogas is much cleaner and combustion is more or less complete. Soot related health problems are therefore improved by introducing biodigesters.

Water hyacinth is growing in the lake but its growth is so far moderate and complete invasion of water hyacinth does currently not seem to be a problem. However, many lakes around the world have suffered from invasion of water hyacinth so care should be taken to make sure that it is not becoming problematic. A possible control could be to use water hyacinth as a substrate to the biodigesters but that potential should be further studied.

Tonlé Sap has, based on the large fish catch, been termed “one of the most productive lakes in the world” (Campbell, 2009). The biodiversity in the lake is high but is reducing mainly due to overfishing. In addition, increased nutrient levels might affect the biodiversity either by problems related to decreased oxygen levels or alteration of competition conditions eradicating some species.

Many other environmental concerns might appear in Tonlé Sap but only those directly related to an implementation of biodigesters are evaluated in this study. Hence, problems such acidification and sediment transport are not at all considered.

4 Biodigesters

4.1 Background of small-scale biodigesters

Biodigesters in floating communities is a rather new topic worldwide. Until now, biodigesters in rural areas have mainly been land-based. Some trials of water-based biodigesters have been performed in Vietnam in the 1990s but no results or evaluations have been published (An, et al., 1996). However, promising environmental benefits from rural land-based anaerobic digestion have been shown in many places around the world.

Figure 17. Early design of a floating biodigester in Vietnam (An, et al., 1996).

4.1.1 Rural anaerobic digestion

Stichting Nederlandse Vrijwilligers (SNV) is a non-profit organisation from the Netherlands that since 1989 has worked with rural anaerobic digestion in Asia and has lately expanded to parts of Africa (SNV, 2012a). Nepal was the pilot country and the national ministry responsible for anaerobic digestion has widely implemented biodigesters in many counties around the country. The average family that own a biodigester consists of six humans, three cattle and some smaller animals (CMS, 2008). Results show that the average household feed their 6 m^2 biodigester with 20 kg/day producing enough energy to reduce the need for fuel wood by 51 %. Equivalent in mass of fuel wood, this corresponds to an annual saving for each household of 3.2 tons/household. Consequently, the reduced use of non-renewable fuel wood decreases the GHG emissions with 1.33 tons/year from 500 households.

Van Mansvelt, Sras and Pino (2012) have through NBP performed a study showing that 86 % of the biodigester owners produce enough biogas to use for their household services (lightning and cooking). On average, 36 kg/day, produced by 3.6 cattle and 2.6 pigs, is fed in a 5.4 m^2 biodigester. With a total amount of 14 000 registered biodigesters throughout the country, the reduced effect on deforestation is substantial. Before the biodigesters were installed, 94 % used firewood as their main energy source.

In Laos, the biodigesters produced enough gas to use the stove for 116 minutes per day (Rietzler, 2009). The feed were 20 kg manure/day and the sizes of the biodigesters were 4 m^3. With this amount of biogas, 86 % of the household owners felt that they received enough gas for cooking. Throughout the community, the average amount of wood saved by instead using biogas was 4.8 kg/day.

All these implementations have been accomplished in areas where the farmers have enough cattle to feed the biodigester with at least 20 kg per day. Lower feeds have been shown in models from Dominican Republic which was based on the feed from one pig and six poultries (Rowse, 2011). The resulting biogas production from the model comprised to half of the actual energy need.

Small-scale anaerobic digestion using only human waste as input has not been widely evaluated. A problem arising with biodigesters using only human waste is that the daily household waste production is pretty low and will not be enough to produce sufficient gas amounts. Therefore, small-scale biodigesters are additionally fed with livestock manure. Another typical problem is that there is a high amount of nitrogen in human waste that requires an additional carbon input to prevent ammonia inhibition (Kreuger, 2012).

In India, a trial of anaerobic digestion at psychrophilic temperatures was performed with human waste as input (Meher, Murthy and Gollakota, 1994). Temperature was held at 15 °C and three bench-scaled sized (20 L) biodigesters gave a production of 0.19 L biogas/L bioreactor and day. In a similar way, a pilot scaled biodigester test was performed. However, the efficiency of this biodigester was only 50% of the bench-scaled biodigesters.

4.2 Theory of anaerobic digestion

The purpose of anaerobic digestion is to convert organic matter to biogas whose main constituents are methane (CH_4) and carbon dioxide (CO_2). The latter is not possible to combust so the desired product is methane. A series of microbiological processes is required for production of methane implying that many different microorganisms must live and grow in the system. Collaboration between the organisms is therefore necessary. Due to the complexity in anaerobic digestion, a lot of knowledge is required to create an efficient process with conditions suitable for all different types of organisms.

4.2.1 Microbiology of anaerobic digestion

Biogas is produced in anaerobic digestion of organic matter (substrate) by microorganisms which utilise the organic matter for reproduction of new cells and energy production. After the first degradation of substrate, the end products will serve as substrate for new types of microorganisms in a second degradation (Schnürer and Jarvis, 2009). The digestion of a specific substrate to methane involves many sorts of organisms that sequentially digest the incoming matter. It is therefore important that the microorganisms live simultaneously and not outcompete each other.

The substrate usually consists of longer organic molecules such as proteins, sugars and fats. These are successively broken down to smaller constituents and finally to methane. Through this sequence, the substrate undergoes the following four major processes: hydrolysis, fermentation, anaerobic oxidation and methanogenesis.

4.2.1.1 Hydrolysis

Substrate entering the anaerobic digestion process is firstly exposed to microorganisms performing hydrolysis. Longer organic molecules are splinted to smaller molecules such as amino acids, shorter sugar chains, alcohols and fatty acids (Schnürer and Jarvis, 2009). Large size molecules cannot directly be degraded by microorganisms so instead enzymes are secreted to break the bonds in the molecules. Depending on the substrate (proteins, sugars, etc.), different microorganisms can produce the necessary enzymes for degradation of the specific substrate.

4.2.1.2 Fermentation

In fermentation, also known as acidogenesis, the end products from the hydrolysis serves as incoming substrate for the fermentation organisms. Small sugars and alcohols are degraded to organic acids, alcohols, carbon dioxide and hydrogen gas (Schnürer and Jarvis, 2009). Fermenting organisms are mostly facultative meaning that they can grow both in presence and absence of oxygen. Therefore, anaerobic digestion can handle low occasional additions of oxygen. It is mainly the fermentation microorganisms that are facultative in anaerobic digestion.

4.2.1.3 Anaerobic oxidations

Fatty acids from the hydrolysis together with alcohols and organic acids from the fermentation process are oxidized anaerobically to hydrogen gas, carbon dioxide and acetate. This process is also called acetogenesis. Too high production of hydrogen gas by the acetogenesis organisms could lead to hydrogen inhibition. Hence, organisms will inhibit themselves. Luckily the next process, methanogenesis, consumes hydrogen gas. The syntrophy between these processes is crucial to maintain an efficient anaerobic digestion.

4.2.1.4 Methanogenesis

The final process of anaerobic digestion is called methanogenesis. Hydrogen gas, carbon dioxide and acetates are the most important substrates for this process. As previously described, collaboration between the microorganisms of methanogenesis and anaerobic oxidation is necessary to have a decent level of hydrogen gas. In contrast to the other microorganisms in anaerobic digestion, organisms in methanogenesis are Archaea (Schnürer and Jarvis, 2009). Unfortunately, Archaea are less robust to changes than bacteria meaning that methanogenesis is normally most affected by disorders such as varying pH or addition of heavy metals. It is therefore important to maintain favourable conditions for Archaea since methanogenesis is the most crucial process for producing biogas.

4.2.2 Chemical conditions

The efficiency of the biogas process is dependent on several factors inside the biodigester such as pH, temperature and oxygen content. All microorganisms working in the anaerobic digestion process are affected by alteration of these conditions, however to what extent is varying. An ideal condition for each and every organism is impossible to create; instead one has to find for what conditions, the whole process is optimal.

4.2.2.1 Temperature

The temperature of the process determines the rate of which biogas is produced. Microorganisms are normally adapted to different temperatures. Organisms working at low temperature (lower than 15°C) are called psychrophiles (or cryophiles), medium temperature (15°C-45°C) are called mesophiles, high temperature (above 45°C-65°C) are called thermophiles and very high temperatures (over 65°C) are called hypothermophiles (Schnürer and Jarvis, 2009). In anaerobic digestion, mesophilic and thermophilic temperatures are most common where the latter work faster which means that a shorter retention time can be used. On the other hand, thermophilic organisms often require input of heat which will be energy consuming. Small-scale systems are meant to be simple meaning that mesophilic temperatures are easier to adapt in tropic climates. In addition, mesophilic microorganisms have the widest range of temperature where they can survive.

For most microorganisms, the optimal rate of production lies very close to the maximum temperature that the microorganisms can survive in (Schnürer and Jarvis, 2009). Hence, the microorganisms will probably die if the temperature is raised slightly above the optimum temperature.

4.2.2.2 pH

pH is an important factor in anaerobic digestion and microorganisms are adapted to function within different pH-intervals. Most organisms are working best at neutral pH in anaerobic digestion. However, some have the possibility of producing at lower pH. Methanogens are the organisms that are most sensitive to changes in pH. Similarly to temperature conditions, another problem when optimising biodigesters is that most organisms have their optimal pH level close to their mortality level.

A pH increase can be a secondary consequence of a high ammonia production in the anaerobic digestion process. The major reason for producing ammonia is breakdown of proteins. A problem with too high ammonia concentrations is that microorganisms, especially methanogens, are inhibited (Schnürer and Nordberg, 2008). In addition, the high ammonia concentration facilitates a pH increase since ammonia is a strong base. This will in turn create more ammonia since the unprotonated form becomes more common at higher pH than the protonated form (ammonium). Too low C:N ratio in the substrate fed to the biodigester means a high content of nitrogen compounds and a high risk of ammonia inhibition. Urea contain high amounts of ammonia and should preferably be mixed with substrates that have very high C:N ratio such as straw (Kreuger, 2012).

4.2.2.3 Oxygen

Anaerobic digestion is a process in the absence of oxygen in the system. Methanogens are especially anaerobic and their cells will be destroyed when oxidized by oxygen (Schnürer and Jarvis, 2009). Microorganisms can usually handle a low concentration of oxygen in a anaerobic digestion system since fermenting bacteria normally are facultative. This means that they can reproduce both with and without oxygen. They favour aerobic breakdown so their efficiency is somewhat higher in the presence of oxygen. Hence, a small leakage or input of oxygen does not necessarily destroy the anaerobic digestion since fermenting bacteria can degrade oxygen.

4.2.2.4 Salts

Microbial organisms are to some extent built up by different salts such as potassium, sodium and calcium (Schnürer and Jarvis, 2009). For growth, it is necessary to have some input of salts into the anaerobic digestion system. Normally, enough salts are supplied through the substrates added to the biodigester and no additional salt input is required. In excess, salt is inhibitory for the microorganisms since it can dry the cell out through osmosis. Similar to other changes of conditions, methanogens is the most sensitive group for differences in salt concentrations.

4.2.3 Pathogen reduction

Anaerobic digestion is an efficient method for reducing pathogens in biological wastes. Microorganisms from human waste and manure have to compete with the microorganisms present in anaerobic digestion. Conditions are adapted to conditions suitable for the "good" organisms in the biodigester meaning that pathogens become outcompeted. Obviously, all pathogens are not removed in anaerobic digestion so the effluent is not completely sanitized.

Thermophilic digestion is more efficient in removal of pathogens than mesophilic digestion. An explanation is that pathogens in manure and human waste are mostly adapted to mesophilic temperatures (between 35-40°C). Hence, most pathogens in biological waste cannot live at thermophilic temperature.

Pathogen reduction at mesophilic temperatures is fairly well tested. Unfortunately, most of the studies are performed at temperature around 37°C and not at 30°C which is typical for tropical conditions. Pathogen reduction efficiency at 37°C will not necessarily equal the efficiency at 30°C. Yen-Phi, et al. (n.d.) replicated tropical conditions in their study of pathogen reduction on cattle and pig slurry added into a continuous reactor with retention time of 45 days. The study was performed in a German laboratory. Results showed that *E. coli* and *Salmonella spp*. were reduced by 90 % after 2-4 days and were completely removed after 8 days. The coliform *Enterococcus spp.* survived longer and the 90 % reduction was reached after 15-25 days. For this coliform bacteria, 45 days was not enough to completely remove the pathogen. A completely sanitized digestate was therefore not acquired.

Poly-ethylene biodigesters have also been introduced in provinces outside Ho Chi Minh City, Vietnam (An, et al., 1996). Inputs to the biodigesters were mainly pig and cattle manure. In this study, carried out at tropical conditions, *E. coli* was almost completely reduced with only 0.1 % left in the effluent. For other coliforms, the reduction was even better with less than 0.1 % left in the effluent.

4.2.4 Reactor models

Biodigesters used for anaerobic digestion are built up in different ways depending on the feeding method. There are three ideal reactor models namely, batch reactors, continuous stirred tank reactors and plug-flow reactors (Warfvinge, 2010). In theory, the ideal case for the two latter ones includes open exposure to air but they can be used in anaerobic applications as well.

A batch reactor is a closed system, with no input or output during the digestion. All waste is added at the beginning of the process stage and the digestion proceeds by itself. The batch reactor can be mixed in order to increase the digestion by making the microorganisms come in more frequent contact with the substrate. Molecular diffusion is always mixing the substrate but to a very low level so normally macroscopic external mixing is necessary for sufficient mixing. It is however important to make sure that no (or very little) oxygen is added. If low amounts of oxygen are added, facultative organisms such as fermenting microorganisms can digest it.

Continuous stirred tank reactors (CSTR) have an inflow and outflow and are in the ideal case perfectly mixed. Perfect mixing means that the concentration is the same everywhere in the system. It is possible to use CSTR in anaerobic digestion but it is obviously important to keep the reactor airtight. The continuous addition comes from an "outside" source that can add oxygen to the system. Special care must be taken to keep the system anaerobic at the inflow and outflow sections. Once again, the system can handle some oxygen due to the facultative organisms. An important parameter in continuous anaerobic digestion is the hydraulic retention time (HRT). This is the average time a molecule spends in the system. Solid retention time (SRT) is also a concept coupled to the average time a particle is in the system. Often, these parameters are equal but exceptions occur. For instance, SRT becomes larger than HRT when sludge is recirculated (Schnürer and Jarvis, 2009).

The ideal plug flow reactor consists of a long cylinder with an inlet and an outlet. No mixing occurs in the flow direction and the particles will move with the same velocity (Warfvinge, 2010). When used in anaerobic digestion, no oxygen should be added at the inlet or outlet. HRT and SRT are important parameters in plug flow reactors to make sure that each individual particle is in the reactor an adequate time.

4.2.5 Total solids and volatile solids

Total solids (TS) and volatile solids (VS) are measurements useful for assessment of the energy content in a specific substrate. Total solids represents the amount of dry matter in a substrate. Another term often used for the total solids is "dry matter content". Volatile solids is a measure of the organic substances that becomes volatile when heating the substrate. It is the volatile solids that are combustible and hence possible to obtain energy from.

Theoretical methane yield of a substrate is often given as m^3 CH_4 / kg VS (Schnürer and Jarvis, 2009). It represents the total possible production of energy possible to gain from a known substrate. Potential methane yield is also a concept used in anaerobic digestion and it represents the "average" methane yield from a substrate (Van Haren and Fleming, 2005). Knowing the VS content of a substrate is therefore useful when trying to assess the potential energy production.

Total solids is also important for the energy yield since it is coupled with VS. TS is normally expressed as percentage of the total weight of substrate while VS is expressed as percentage of TS. In general, the adequate content of TS in a sample is around 10-12% (SGC, 2009; Frandsen, et al., 2011). A too high TS content can cause problems with low flow situations for the substrate while too low dry matter content requires more space because there is an unnecessary large amount of water.

Organic loading rate (OLR) is another important parameter in anaerobic digestion. It is defined as the weight (or load) of VS per added volume substrate and day. Too high addition of VS could cause acidification. The reason is that the substrate is broken down quickly in hydrolysis and fermentation that produces a high amount of acids (Schnürer and Jarvis, 2009). Methanogens require a long time for growing meaning that all the acids cannot be further broken down. This will create a pH drop in the system and inhibit microorganisms. Conversely, too low addition of VS is not advantageous either because this implies that the reactor has been over-sized. Therefore, the organic loading rate should be considered when designing a biodigester.

4.2.6 Substrates

Several types of substrates are possible to use in anaerobic digestion. The amount and relationship between the substrates decides the efficiency of the system. Mixtures of substrates can therefore optimise the process and a larger yield is produced. For this study, three different substrates are used namely, human waste, pig manure and water hyacinth. Human waste and pig manure are pretty common substrates used in anaerobic digestion while water hyacinth is less often used but currently becoming more common.

4.2.6.1 Human waste

Human waste is often divided into faeces and urine and many systems separate them since they can be used for different purposes. Especially, urine is useful since it is rich in nitrogen and can act as a fertilizer on farmlands.

The constituents of human waste differ between urine and faeces. Close to 99% of the urine is water whereas faeces contain around 70-80% water (Torondel, 2012). The rest is in mostly organic and in solid form. Among the nutrients, urine is richer in nitrogen while the phosphorous content is quite equal. The larger organic content in faeces is verified by a substantially higher COD value around 50 g/L compared to 10 g/L for urine. C/N ratio for human waste is normally around 10 but can also be a bit lower depending on the nitrogen content (SNV, 2009a).

It should though be noted that the diet affects the waste composition. A high diet of meat results in more nitrogen in the waste. Also, the moisture content is varying with diet. Therefore, for adequate and accurate determination of human waste composition, on-site measurements are recommended.

4.2.6.2 Pig manure

Pig manure is often very useful in small-scale anaerobic digestion since a decent amount is produced every day. Both faeces and urine are included in the pig manure. Dry matter content is normally around 5 % in its liquid phase and up to 15 % in its solid phase (SSCA, 2000; ASAE, 2003). Volatile solids is about 80 % of the total solids. Methane yield is reported by Bond, et al. (2012) to range from 275 to 400 L CH_4/kg VS. The C/N ratio for pig manure is around 20 which is close to optimum for anaerobic digestion (SNV, 2009b). As for human waste, pig manure characteristics change depending on diet and for accurate determination of the composition, on-site measurements should be performed.

4.2.6.3 Water hyacinth

Water hyacinth (*Eichhornia Crassipes*) is a free-floating plant with short reproduction time. It is therefore abundant in many lakes. TS content of water hyacinth is around 5-7 % and VS content is about 80 % of TS (Nigam, 2002). Methane yield for water hyacinth is normally varying between 140-200 L CH_4/kg VS (O'Sullivan, et al., 2010). Water hyacinth mainly consists of cellulose, hemicellulose and lignin. Lignin content is low (10%) compared to land living plants and that is a major benefit in anaerobic digestion (Bhattacharya and Kumar, 2010). Lignin is hardly degraded but lignin polymers such vanillin have been reported to be converted to methane (Barakat, et al., 2012). The high cellulose (25%) and hemicellulose (35%) content is however beneficial and together with a fairly high nitrogen content, the C/N ratio becomes 25 which is substantially lower than other plants (SNV, 2009b). The nitrogen is taken up from the lake leading to a slight decrease of nitrogen compounds concentrations. Utilising water hyacinth in anaerobic digestion has consequently double values; reducing nitrogen concentrations in the lake and enhanced energy production.

4.2.7 Digestate

Not all materials are broken down in anaerobic digestion. The effluent material, known as digestate, must be handled and taken care of in a safe way to make sure that the process is environmentally sustainable. For instance, heavy metals, nutrients etc. are substances that are not broken down in the process (InSource Energy, 2010). The quality of the digestate is thereby dependent on the input into the biodigester.

4.2.7.1 Fertilizer

The digestate has often good capability of being used as a fertilizer. In the influent to the biodigester, nutrients are mostly bound to proteins, organic compounds or other complex molecules (InSource Energy, 2010). Many of the larger molecules are broken down by the microorganisms during the hydrolysis step and the nutrients become available in smaller forms. It is therefore suitable to spread the digestate on a field since the soil can access the nutrients easily. It is though important to remember that the digestate can contain other harmful materials, such as heavy metals, that can damage the environment.

4.3 Anaerobic digestion in Phat Sanday

Introducing biodigesters in Phat Sanday has a potential of being successful. Some prototypes have been shown to work well with the available substrate and have been implemented in the village.

4.3.1 Available substrate

Originally, the main objective for introducing the biodigester was to deal with human waste meaning that this would be the main substrate for all households. Another important argument for installing biodigesters was also to treat larger volumes of pig manure that are dumped from households.

On average, pig-owning households in Phat Sanday usually have two pigs. Pig manure is produced in much larger volumes than human waste (5.5 kg manure compared to 1.3 kg of human waste for a family of five that own two pigs) (LLEEC, 2012). Pig manure also has greater biogas potential than human waste, partly because the C/N ratio is around 20 for pig manure compared to 10 for human waste (SNV, 2009b). Basically all organic material can be used as substrate in the biodigester, but it is important to know what effects different substrate have on the microbiological balance in the biodigester. Food waste is another excellent substrate that can be used. Unfortunately the amounts are so small from the villagers since much of it is given as food to pigs, fish or other animals (Arazo, et al., 2010).

Another important substrate that exists in abundance in Tonlé Sap and has a beneficial C/N ratio (25) is water hyacinth. There are three downsides with only using water hyacinth. Firstly, it would not solve the main problem which is to deal with wastes from animals and humans. Secondly, it would need to be collected which takes time and effort. Thirdly, it has a solid texture since the plant contain much lignin. In too large amounts, this can be difficult for the hydrolytic bacteria to break down, thereby clogging the biodigester as well as decreasing the pH (Katima, 2001). Co-digestion of water hyacinth with human waste and manure could be beneficial. This can balance the overall C/N ratio in the biodigester to optimum levels. For people without access to pig manure, co-digestion of human waste and water hyacinth can be suitable for biogas production.

Agricultural wastes from the rice fields would in general be a better source for carbon than water hyacinth since it has much higher C/N ratio and would need less volumes (Kreuger, 2012). For example rice straw has a C/N ratio of 70 (SNV, 2009b). Unfortunately the villagers usually do not own any rice fields and it could therefore be an unnecessary cost. It is also uncertain how regularly there is access to by-products from rice farming since harvesting only occurs a few times a year.

Some biodigester users purchased cow dung from farmers on land. Cow dung has a high biogas potential and could improve the anaerobic digestion a lot (SNV, 2009b). However, the access to cow dung in the wet season as well as the extra costs (purchasing and transports) limits the potential for this substrate. There are low possibilities of having cows in the floating villages.

4.3.2 Biodigester prototypes

LLEEC has together with Engineers Without Borders Australia (EWBA) developed a few different types biodigesters. Main criteria's for the designs of the digesters are (Arazo, et al., 2010):

- Economic viability for the villagers.
- Practical to implement in that kind of aquatic environment.
- Have a potential for a local market and thereby use local material as long as possible.
- Pathogen reduction.
- Durability of the construction.

4.3.2.1 Soft plastic tube digester

Originally EWBA arranged a contest for engineers across Australia in 2009 called EWBA challenge. A few students from The University of Western Australia won and they developed a soft plastic tube digester with cheap material costs. It also had a simple design for villagers to construct when materials were accessed. Even though the expected lifetime for the digester is supposed to be between 5-10 years, they usually have lifetime not longer than a year (Arazo, et al., 2010). The reason is that the material is pretty easily punctured and also sensitive for UV-radiation. However, Hughes (2012) claims that soft plastic tube digesters can be worth implementing since they have low investment costs and can be repaired or replaced easily. Additionally they are easily scalable to produce large systems with little additional cost or effort. The largest tubular biodigester installed by LLEE so far is 4000 L.

Figure 18. Soft plastic tube biodigester (Arazo, et al., 2010).

4.3.2.2 Hard plastic tank digester

At the moment LLEEC are mainly focusing on hard plastic tank digesters of the material HDPE (Hughes 2013). The smallest have a volume of 200 L and the largest have a volume of 2000 L. They are also discussing implementation of even larger digesters for households with many pigs who live in stilted houses on Tonlé Sap. Because the hard plastic dome digester is solid, it has a longer lifetime that excuses the higher investment cost. The exact lifetime expectancy is not currently known since they have been installed in the recent year (McGill, 2012). A problem that has occurred during testing is clogging in the inlet and outlet (Buntha, 2012). There is also a risk of too low hydraulic retention time due to the basic hydraulic dimensions of the system and locations of the inlet and outlet. LLEEC are investigating improvements such as using a baffled wall inside the digester to change the flow direction (Hughes, 2012). The reason for using this shape is currently because it is easy accessible from a supplier in Cambodia. Currently there are not many suppliers who can provide LLEEC with cost effective options for biodigester vessels since there are limited manufacturing capability available.

Figure 19. Hard plastic dome biodigester.

4.3.2.3 Tyre tube biodigester

A simple construction for a biodigester which uses local, accessible and recycled material is the tyre tube biodigester. The construction simply uses old tractor tyres connected to PVC-pipes for inlet and outlet. The model has not been implemented for testing in the village yet, but some testing has been done at LLEEC office showing problems with leakages and clogging. However, the design has still potential because of its simplicity and low costs. Due to the small volumes, these biodigesters may be best suited to high-energy content fuels, such as food waste.

Figure 20. The two tyres at the lowest position on the wall connected with blue pipes are the digester. The two tyres above function as gas reservoirs.

5 Methodology

This section presents the methodology used for meeting the objectives of the study. The main approach is to perform a scenario analysis that assesses the improvements in the community based on the extent of the implementation of the biodigesters. The three following scenarios have been used:

1. What will be the status of the human health and environment if no biodigesters are implemented? This means that no sanitary systems are introduced. The scenario is a baseline for the pollution.
2. What will be the status of the human health and environment if biodigesters are introduced in all households of the village with limitations for waste management that reflect the current situation?
3. What potential does the full implementation of biodigesters in Phat Sanday have on the human health and the environment? For this scenario, waste management are functioning optimally and there is a usage of the digestate.

The three scenarios are the benchmark to answer the questions given in section 1.5 and consequently, meeting the objectives of the study. Analysis of previous information and data were complemented with own measurements to be as locally applicable as possible. The following description of sample collection method is presented to give an understanding of the lab procedure. The lab results themselves are not the main results; instead the findings from the scenario analysis are the primary results for this study.

5.1 Data collection

General information of the village was collected by using data from old focus groups between the villagers and LLEEC. Size of the village, household sizes, number of animals and other important information were included in this data. Phat Sanday was also visited to gain a personal perception of the habits within the community. This included energy use, excretion habits, livelihood and so forth. Data collected from earlier focus groups about community habits were taken into consideration and compared with the personal perception.

Lab-scale setups as well as full-size setups were designed for assessing biogas production from different substrates. No detailed optimisation of the system was carried out since the aim is to replicate conditions expected in the community, but different fractions of the substrates were tested to see if an extra carbon source would increase the biogas production. TS and VS were measured for the pure substrates to give an understanding of the potential each substrate has to produce energy. It is important that the design, maintenance and daily operation of the real biodigester is as simple as possible. Villagers and future biodigester owners might in general not have the same knowledge as the people within LLEEC and therefore the organization is very keen to keep everything as simple.

For assessment of the potential impact the waste has on the water quality, components of the waste were determined for phosphate, total phosphorous, nitrate, ammonia, ammonium and pathogens. These measurements were conducted in Cambodia to, as much as possible, replicate the diet and conditions of Phat Sanday. The waste components were then applied on a larger scale to establish the total addition of nutrients and pathogens from the village to the lake. Comparison between the addition from the village and the lake concentrations will give a decent framework for further discussion of the environmental impact from the village.

Current concentrations in the lake are to some extent already measured by LLEEC. The older data together with water quality data found from other resources were processed to give an understanding of the water quality in Tonlé Sap.

5.2 Lab-scale anaerobic digestion

Six lab-scale biodigesters were set up with three different substrate fractions as batch reactors. Duplicate tests were conducted for safety reasons to make sure that no test would be ruined. The substrate tanks had a volume of 3000 mL and the incoming substrate was distributed accordingly. The feed to the biodigester was 90 % pig manure and 10 % human waste, based on the same ratio put into a similar but larger biodigester test at Royal University of Agriculture (RUA). In reality, all available human waste will be added changing the percentage to 80 % pig manure and 20 % human waste but that was considered to not be feasible in the existent experimental setup at RUA. It was therefore, for comparable purposes, chosen to in the lab-scale experiment have two tests with the same fractions as RUA (1 and 1*). Two tests contained human waste and water hyacinth (2 and 2*) for representation of the villagers without pigs. The water hyacinth was added to raise the C/N ratio for better digestion. The final two samples had the same contents as the first two samples, however water hyacinth was added to see if the digestion could improve (3 and 3*). The used substrate fractions are presented in Table 2.

Table 2. Fractions of waste put into the lab-scale biodigesters.

	Wet Weight (%)					
Setup	**1**	**1***	**2**	**2***	**3**	**3***
Pig manure	90	90	-	-	62	62
Human waste	10	10	30	30	6	6
Water hyacinth	-	-	70	70	32	32

The system consisted of a substrate tank, connected to a tank with NaOH-solution that in turn was connected to a gasbag. The bag was regularly emptied with a glass syringe. NaOH was added to scrub carbon dioxide and hydrogen sulphide from the biogas meaning that only methane was transported to the gasbag. A thorough lab description and theory behind carbon dioxide scrubbing are given in Appendix A. Figure 21 shows the lab setup.

Figure 21. Setup of the lab scale anaerobic digestion. The right cylinder in the left picture consists of the substrate and the left cylinder of 3M NaOH. The blue clamps straps the hoses when necessary to stop the flow. The gasbag is located in the right picture.

The experiment was located in an office with an air temperature altering between 28-32°C, which is similar to outside air conditions. The residence time for the batch process was 30 days. No mixing or stirring of the substrate was done since it was assumed that villagers would not mix the substrate in reality.

5.3 Full-scale anaerobic digestion

Parallel to the lab-scale gas production tests, full-scale biodigesters were tested for gas production and pathogen reduction by LLEEC at RUA. Measurements of produced biogas volumes were daily taken by students at the university since these biodigesters were continuous reactors. Samples from the input and output of the digesters were sent to lab for *E. coli* and total coliforms analysis. Four soft plastic biodigesters and three hard plastic biodigesters were tested with different feeds. Some of the biodigesters had a larger volume than 500 L to also test what effect the retention time had on the production.

The biodigesters were continuously fed with fresh substrate on a daily basis which forced a similar amount (slightly lower) of the digestate out. This was different from the lab-scale testing that were batch processes. For comparison between the lab-scale and the full-scale testing, two of the lab-scale containers had the same fractions of pig manure, human waste and water as one biodigester (no. 7) in the full-scale experiments. The results from that biodigester are used to confirm if the lab-scale results were reasonable.

Figure 22. Experimental setup of the biodigesters at Royal University of Agriculture in Phnom Penh.

5.4 Total solids and volatile solids

Total solids and volatile solids are parameters representing the dry content of the total substrate weight. It is more accurate to compare energy potential in different substrates per TS/VS substrate than per volume substrate. The reason is that the water content in the substrates cannot be combusted and do not contribute with energy to the process. In addition, the measurement technique is pretty simple. In this study, TS and VS were determined for each specific pure substrate, namely water hyacinth, pig manure and human waste. A thorough methodology is presented in Appendix A.

The TS and VS measurements were performed in collaboration with the Royal University of Phnom Penh (RUPP). Pure substrates were handed to them and then students at the university performed the measurements.

5.5 Water quality of Tonlé Sap

The methodology for the water quality assessment was based on collection of already measured data. Initially, own measurements were proposed to be performed around Phat Sanday but due to practical complications this was not possible.

Instead data was gathered from relevant authorities and organisations. LLEEC had access to water quality data that proved useful. In addition, Mekong River Commission (MRC) which is a large transboundary organisation in Mekong River, had useful data for this study. Raw data from these sources were analysed and their relevance for Phat Sanday were evaluated.

5.6 Components in pig manure and human waste

The components of the waste must be determined to fully establish waste addition from Phat Sanday. Important parameters for the scope of this study are ammonia, ammonium, nitrate, total phosphorous, phosphate, *E. coli* and total coliforms. Ideally, total nitrogen would be measured but no lab facility in Cambodia had any equipment for that analysis. Therefore, total nitrogen is simplified to nitrate, ammonia and ammonium. Organically bound nitrogen is lacking so in reality the total nitrogen concentrations are most likely higher. The above mentioned parameters were tested for both human waste as well as pig manure.

Collaboration with the Resource Development Institute Cambodia (RDI) was made to perform this assessment. RDI staff are well educated in raw water quality testing for numerous parameters. It was therefore considered more advantageous to use their knowledge to make sure that the testing was as accurate as possible.

E. coli and total coliforms were measured through the collaboration with Royal University of Phnom Penh (RUPP) as well. Pure substrates of pig manure and human waste were handed to RUPP and they performed the analysis.

5.7 Global Warming Potential

Global Warming Potential (GWP) is a term used to present how different sources of pollution contribute to the global warming. Pollution will be presented in carbon dioxide equivalents ($CO_{2,eq}$) per day to simplify all greenhouse gases (GHG). Different GHG molecules have different impact on the global warming in terms of how well they absorb and emit radiation. It is therefore important to recalculate them with the accurate GHG emission factors to see what the impact will be in terms of $CO_{2,eq}$. The GHG present in the biogas system are presented in Table 3 with their GHG emission factors compared to CO_2.

Table 3. GWP for different greenhouse gases. NO_x represents many different nitrogenoxides, where N_2O is one. N_2O is the dominant nitrogen compound from combustion and its GHG emission factor is used to simplify the calculations (Börjesson, Thufvesson and Lantz, 2010). The GHG emission factors are based on the global warming effect for a 100-year timeperiod.

GHG	Chemical formula	GHG emission factor
Carbon dioxide	CO_2	1
Methane	CH_4	23
Dinitriousoxide	N_2O	296
Nitrogenoxides	NO_x	296

It is a complicated matter to calculate the GWP from different activities. It needs to be included in the calculations that other activities can be replaced which also will have an effect on GWP. With bioenergy systems there have to be concerns whether the fuel is renewable or not and how this will affect the calculations. A more thorough explanation on this way of thinking is given in Appendix C.

6 Results

The results from this study consist of two parts. Firstly, measurements from lab results are presented. These values are then combined with the earlier collected data to make up the scenario analysis.

6.1 Lab results

Results related to the measurements taken in Cambodia are presented in this section. Originally, it was desired to measure the gas production for three different substrates. However, problems with leakages arose in the gas collection bags and therefore the results for test 2 (human waste and water hyacinth) and test 3 (human waste, pig manure, water hyacinth) was not considered to be reliable. Total gas production was therefore only determined for the fraction in test 1 (pig manure and human waste).

6.1.1 Determination of components in waste

Four samples were handed in to RDI for analysis of nutrient and pathogens in the substrates. Two of the samples contained human waste and two contained pig manure. The analysed pig manure samples were diluted with 100 g water/g pig manure before handed in to RDI. In the human waste sample, around 80 % is water that was used when flushing the toilet (manually with a scoop). The result is corrected to contain only waste since the villagers of Phat Sanday defecate and urinate directly into the lake.

6.1.1.1 Nutrients

Human waste and pig manure production in Phat Sanday has previously been determined in section 5.3.1. Total daily load is calculated using the manure and waste production[1].

Table 4. Daily load of nutrient compounds in pig manure and human waste.

	Pig manure (g/pig & day)			Human waste (g/person & day)		
ID	1	2	**Mean**	1	2	**Mean**
Ammonia (NH_3-N)	4.37	3.62	**4.00**	0.53	0.05[2]	**0.53**
Ammonium (NH_4^+-N)	6.72	7.91	**7.32**	0.91	0.85	**0.88**
Nitrate (NO_3^--N)	0.36	0.45	**0.40**	0.00	0.00	**0.00**
Phosphate (PO_4^{2-}-P)	5.14	4.68	**4.91**	0.07	0.06	**0.07**
Total phosphorous (Tot-P)	20.4	15.1	**17.8**	0.12	0.21	**0.17**

Total daily nitrogen load from pig manure is 11.5 g per pig. Correspondingly, the daily nitrogen load from a human is 1.4 g. Daily phosphorous load is 17.8 g/pig and 0.17 g/person. Once again, it should not be forgotten that the total nitrogen in this study excludes organic nitrogen and is therefore, to an unknown extent, higher in reality. Compositions of waste and manure do also change with the diet making comparison between different tests harder.

[1] Detailed calculations are given in Appendix B

[2] Probably measurement error, not further used

As previously mentioned, a household that own pigs in average consists of five humans and two pigs. The total daily load from a pig owning household is presented in Table 5.

Table 5. Nutrient load from an average household in Phat Sanday.

	Pig manure (g/day)	Human waste (g/day)
Daily nitrogen load	23	7.1
Daily phosphorous load	36	0.75

If all households in the Phat Sanday community would be pig owners in the future, then the total daily load from the entire community is roughly as in Table 6. For households data see Table 1, section 1.2.

Table 6. Nutrient loads from all households in Phat Sanday.

	Pig manure (PW) (kg/day)	Human waste (HW) (kg/day)
Daily nitrogen load	23	9.8
Daily phosphorous load	34.8	1.2

Clearly, the pig manure contributes the larger loads of nutrients into the water. Implementation of anaerobic digesters together with a feasible usage of the digestate can remove this daily addition of nutrients.

6.1.1.2 Pathogens

Concentrations for *E. coli* and total coliforms were measured for similar samples at both RUPP and RDI. Problems with the measurement occurred at RDI and the measured data were therefore not considered to be reliable[3]. The results from RUPP were more credible and are presented in Table 7.

Table 7. Concentration of *E. coli* and total coliforms in human waste and pig manure.

	Pig manure (CFU/ 100 mL)[4]			Human waste (CFU/ 100 mL)[5]		
ID	**1**	**2**	**Mean**	**1**	**2**	**Mean**
E. coli	$50 \cdot 10^6$	$28.8 \cdot 10^6$	$\mathbf{39.4 \cdot 10^6}$	$8.90 \cdot 10^6$	$9.85 \cdot 10^6$	$\mathbf{9.38 \cdot 10^6}$
Total coliforms	$73 \cdot 10^6$	$46.6 \cdot 10^6$	$\mathbf{59.8 \cdot 10^6}$	$27.7 \cdot 10^6$	$25.3 \cdot 10^6$	$\mathbf{26.5 \cdot 10^6}$

[3] Data are given in Appendix B
[4] Been compensated for the dilution of 100 g water/g sample
[5] Been compensated for the 80 % water used when flushing

The daily loads of pathogens can be determined by multiplying the mean results of *E. coli* and total coliforms from Table 7, with the daily produced volumes by one pig and one human.

Table 8. Daily pathogen load from pig manure and human waste.

	Pig manure (CFU/pig & day)			Human waste (CFU/person & day)		
ID	1	2	**Mean**	1	2	**Mean**
E. coli	$9.83 \cdot 10^{8}$	$5.66 \cdot 10^{8}$	**$7.74 \cdot 10^{8}$**	$0.23 \cdot 10^{8}$	$0.26 \cdot 10^{8}$	**$24.5 \cdot 10^{6}$**
Total coliforms	$14.3 \cdot 10^{8}$	$9.16 \cdot 10^{8}$	**$11.8 \cdot 10^{8}$**	$0.72 \cdot 10^{8}$	$0.66 \cdot 10^{8}$	**$69.0 \cdot 10^{6}$**

One average pig owning household with 5 members and 2 pigs will daily produce 1.3 kg of human waste and 5.5 kg of pig manure. This is equal to 1.3 L of human waste and 3.93 L of pig manure (pig manure density is 1.4 kg/L (LLEEC, 2012)). The total daily load from this household is presented in Table 9.

Table 9. Daily household load of *E. coli* and total coliforms.

	Pig manure (CFU/day)	Human waste (CFU/day)	Total (CFU/day)
***E. coli* load**	$15.5 \cdot 10^{8}$	$1.23 \cdot 10^{8}$	**$16.7 \cdot 10^{8}$**
Total coliforms load	$23.5 \cdot 10^{8}$	$3.45 \cdot 10^{8}$	**$27.0 \cdot 10^{8}$**

If all households in the community would own pigs the total daily load from the community would be as in table 10. Village data are collected from section 1.2.

Table 10. Daily community load of E. coli and total coliforms.

	Pig manure (PW) (CFU/day)	Human waste (HW) (CFU/day)	Total (CFU/day)
***E. coli* load**	$1.52 \cdot 10^{12}$	$1.21 \cdot 10^{11}$	**$1.64 \cdot 10^{12}$**
Total coliforms load	$2.3 \cdot 10^{12}$	$3.38 \cdot 10^{11}$	**$2.64 \cdot 10^{12}$**

Clearly, the pig manure contributes to the larger pathogen load into the water.

6.1.2 Determination of potential gas production

6.1.2.1 Lab-scale anaerobic digestion

The lab-scale testing simulates a batch process with no input or output to the process during the retention time of 30 days. The lab-scale results are scaled up with a factor Y (see Equation I) to represent results for reality size batch biodigesters (500 L).

Each day one average household with pigs produces 5.5 kg of pig manure and 1.3kg of human waste. However it is estimated that only 0.5 kg of human waste will be accessible to the biodigester. During 30 days this will be 165 kg of pig manure and 15 kg of human waste. It is assumed for the sake of the experiment that this amount will be fed into the biodigester at once to establish a batch process. In reality this is not the case since the biodigesters are fed daily.

The factor Y is calculated by equation I:

$$Y = \frac{Full\ scale\ amount\ of\ waste(kg)}{lab\ scale\ amount\ of\ \ waste\ (kg)} = \frac{165+15}{0.467+0.041} = 354.3 \qquad \text{(I)}$$

Table 11. Original results from the lab-scale biodigester test.

Lab-scale biodigester	1	1*	Average
Pig manure (kg)	0.467	0.467	**0.467**
Human waste (kg)	0.041	0.041	**0.041**
Water (L)	0.6	0.6	**0.6**
Inoculum (L)	0.05	0.05	**0.05**
Tolerance space (L)	1.5	1.5	**1.5**
Produced methane (L/30 days)	7.16	7.17	**7.165**
Calculated biogas production (L/30 days)	11.93	11.95	**11.94**

Results in Table 11 can be multiplied with Y=354.3 to establish the results in Table 12. The tolerance space will be smaller for the full-scale biodigesters than the lab-scale biodigesters.

Table 12. Potential results from a full-scale biodigester when scaled up from a lab-scale biodigester.

Full-scale biodigester	
Pig manure (kg)	165
Human waste (kg)	15
Water (L)	213
Inoculum (L)	18
Tolerance space (L)	138
Produced methane (L/30 days)	**2539**
Calculated biogas production (L/30 days)	**4230**

To estimate the daily amount of gas that is accessed, the results in Table 12 is simply divided with 30.

Table 13. Assumed biogas production and amount of produced methane from scaling up the lab-scale experiment to a full-scale biodigester.

Produced methane (L/day)	**84.6**
Calculated biogas production (L/day)	**141**

6.1.2.2 Full-scale anaerobic digestion

The full-scale anaerobic digestion was performed by LLEEC and students at RUA. The 500 L biodigester was, on a daily basis, fed with 5.5 kg pig manure, 0.5 kg human waste and 7 L of water. A retention time of 30 days for the substrate was expected.

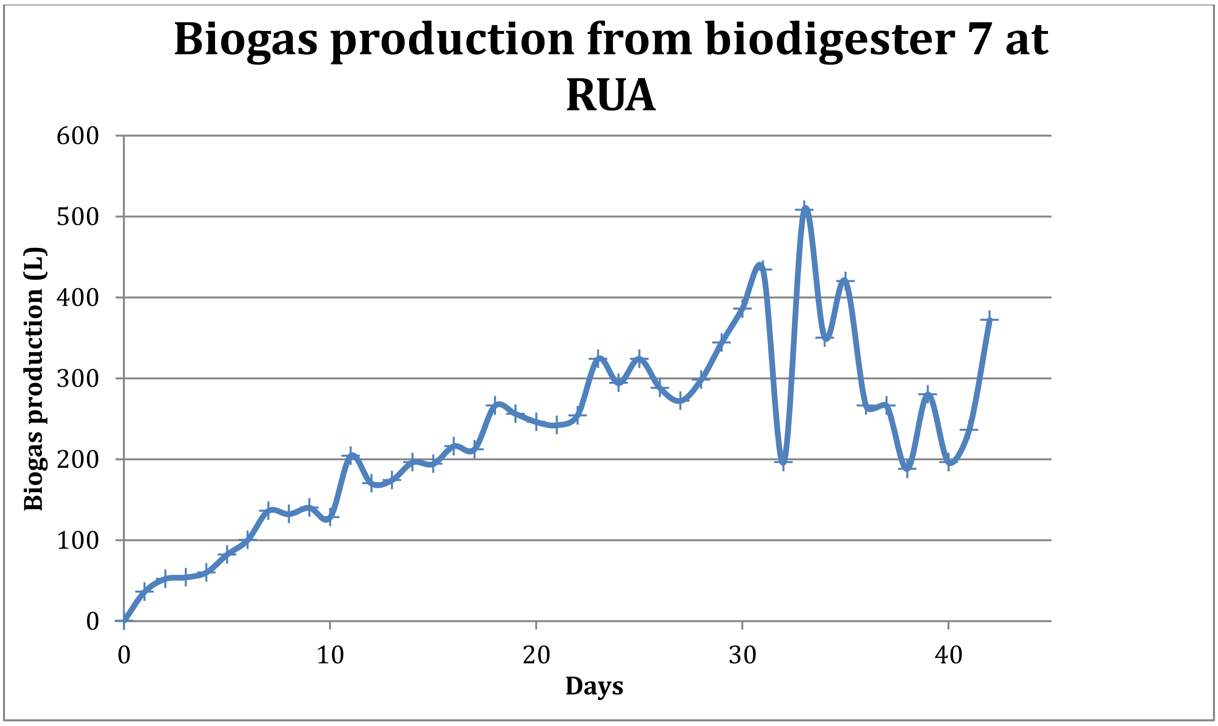

Figure 23. Biogas production from the continuous biodigester 7 at RUA that daily was fed with 5.5 kg pig manure and 0.5 kg human waste.

The first 30 days was considered to be a start up time until the biodigester was completely filled. The system seems to reach an approximate production of 300 L/day after the start up time.

6.1.3 Determination of Total solids and volatile solids

Three samples containing pure substrate of water hyacinth, pig manure and human waste was handed in to RUPP for VS/TS analysis and the results are given in Table 14.

Table 14. TS and VS for water hyacinth, human waste and pig manure.[6]

	TS (%)	VS (%)
Human waste	0.27	29.3
Pig manure	15.2	56
Water hyacinth	5	73.5

TS is presented as percentage of the total weight of the sample while VS is presented as percentage of TS. Fractions between the substrates are the same as in Table 2 (section 2.2) and then the amounts are scaled up to the daily addition of waste to the biodigester, namely 5.5 kg pig manure and 0.5 kg human waste. The methane yield is in section 5.2.6.2 presented as 275-400 L CH_4 /kg VS for pig manure (an average of 350 is used). It is assumed that the methane yield for pig manure is representative for test 1 since 90 % is pig manure. The yield for the other tests could not be established since methane yield was not found for human waste.

Table 15. TS and VS in the substrates from the lab-scale experiment, where amounts have been scaled up to real substrate feeds. Expected production is included as well to show the potential biogas production.

Lab-Scale Setup	Input (g)	TS (%)	TS (g)	VS (%)	VS (g)	Methane yield (L CH_4/kg VS)	Methane production (L)	Biogas production (L)
Test 1	6000	14.0	837	56.0	469	350	164	273
Test 2	6000	3.6	59.9	72.5	43.4		-	-
Test 3	6000	11.2	973	58.4	569		-	-

Samples from the continuous biodigester at RUA were also sent for TS and VS analysis. Both the incoming substrate and the effluent were tested. The effluent was collected after 30 days when the start up time for the biodigester was finished. TS and VS are based on the raw substrates meaning that additional water fed to the biodigester is not included[7].

Table 16. TS and VS for the influent and effluent from the biodigester at RUA.

Full-scale setup	TS (%)	VS (%)
Substrate (in)	7.2	72.0
Effluent (out)	10.0	72.8

[6] Complete lab results are presented in Appendix B
[7] Raw data and conversion calculations are given in Appendix B

The TS/VS analysis for this particular sample from RUA is probably not correct. The TS is larger in the effluent which would imply that no breakdown has occurred and that the amount of solids has increased. These results were therefore not further analysed.

6.2 Scenario analysis

To illustrate the environmental consequences an implementation of biodigesters can have on the community, three future scenarios are presented (repeated from section 5) where it is assumed that all households on average own two pigs.

1. What will be the status of the human health and environment if no biodigesters are implemented? This means that no sanitary systems are introduced. The scenario is a baseline for the pollution.
2. What will be the status of the human health and environment if biodigesters are introduced in all households of the village with limitations for waste management that reflect the current situation?
3. What potential does the full implementation of biodigesters in Phat Sanday have on the human health and the environment? For this scenario, waste management are functioning optimally and there is a usage of the digestate.

The scenarios are presented in the schematic description in Figure 24 as well.

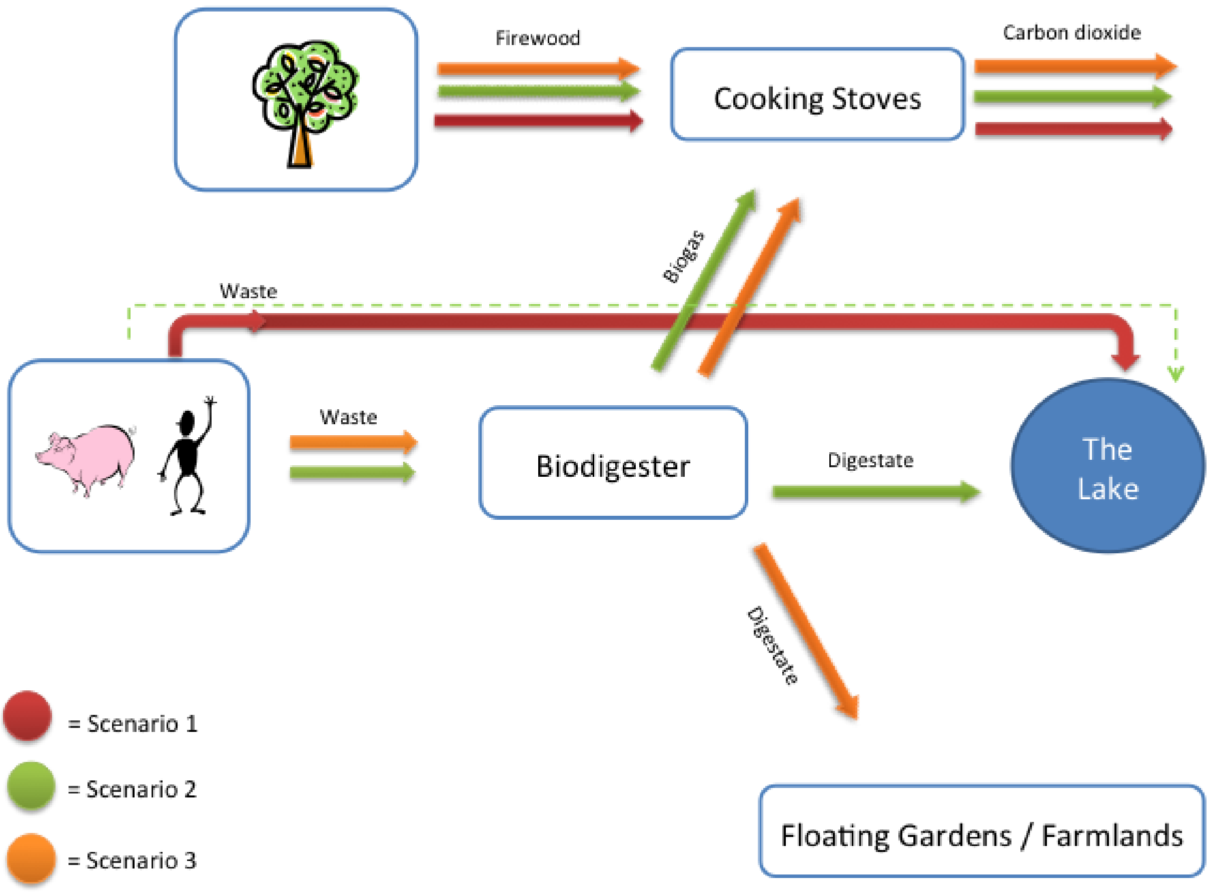

Figure 24. Schematic description of flows in the three scenarios.

The three scenarios are the benchmark for analysis of all different parts within this study. For simplicity, all scenarios are analysed for conditions applying during the dry season. However, this simplification is relevant because the dilution of pathogens and nutrients is then at its lowest state. Hence, concentrations are largest in the lake during low water level season.

The following parameters are used for the calculations within the scenario analysis:

- PW_x – Daily community load of a specified parameter from pig manure in Phat Sanday
- HW_x – Daily community load of a specified parameter from human waste in Phat Sanday
- F_x – Breakdown of pathogens in the biodigester

6.2.1 Nutrients

Each scenario is discussed on the basis of nutrient additions from the community in Phat Sanday. An accurate assessment on how much impact the load of nutrients has on the quality of the water is difficult to perform. A lake is a complex system with many processes that alter the chemical composition of the water. It would require a lot of effort to quantitatively assess the effect of the nutrient addition. This discussion is rather an analysis of potential problems related to increased nutrient concentrations.

6.2.1.1 Scenario 1

The first scenario where no biodigesters are implemented creates a daily addition of waste to the lake. No breakdown of the nutrient occurs before entering the water, that is F=0. It is assumed that 20 % of the human waste is excreted in the open water when fishermen work during the day. Still, the fishermen´s excretion is considered as pollution from villagers in Phat Sanday. Community loads are calculated from daily nutrient additions presented in Table 5.

$$Nitrogen\ load\ in\ scenario\ 1:$$

$$PW_N + HW_N = 33\ kgN/day \tag{II}$$

$$Phosphorous\ load\ in\ scenario\ 1:$$

$$PW_P + HW_P = 36\ kgP/day \tag{III}$$

Villagers in Phat Sanday together release 33 kg nitrogen and 36 kg phosphorous each day.

6.2.1.2 Scenario 2

Currently LLEEC focuses on making the biodigesters function properly for all households. Afterwards they will try to establish solutions on a large scale for the end use of the digestate from anaerobic digestion. The digestate is currently dumped directly to the water after it has been digested. Anaerobic digestion mainly utilises the organic material in the substrate while nutrients remain undigested. Thus, the breakdown factor F for nutrients is 0. Consequently, nutrient load to the water are not decreased and the situation is similar to the one described in the first scenario.

$$Nitrogen\ load\ in\ scenario\ 2:$$

$$PW_N + HW_N = 33\ kgN/day \tag{IV}$$

$$Phosphorous\ load\ in\ scenario\ 2:$$

$$PW_P + HW_P = 36\ kgP/day \tag{V}$$

6.2.1.3 Scenario 3

Finally, the third scenario represents the environmental potential of a biodigester implementation when collection of waste and digestate are working optimally so that the digestate can be used as fertilizer on future floating gardens or adjacent fields. It is assumed that there is no leakage to the water from the floating gardens or the adjacent farmlands. The only contamination source is the 20% of total waste that fishermen dump into the water during their working hours.

$$\textit{Nitrogen load in scenario } 3:$$

$$0.2 \cdot HW_N = 2\ kgN/day \qquad \text{(VI)}$$

$$\textit{Phosphorous load in scenario } 3:$$

$$0.2 \cdot HW_P = 0.250\ kgP/day \qquad \text{(VII)}$$

By assuming this scenario, the human impact on the lake from waste is negligible. Addition of nutrients to Tonlé Sap will cease totally. The community becomes, on a nutrient basis, environmentally sustainable especially since nutrients are recycled from the waste to farmlands.

6.2.1.4 Summary

Effects from scenario 1 and 2 are the same, independently on whether the waste passes the biodigester or not. Waste is dumped into the water contaminating the lake with additional nutrients. In scenario 3, the digestate is considered and taken care of. Loads for the three scenarios are presented in Figure 25.

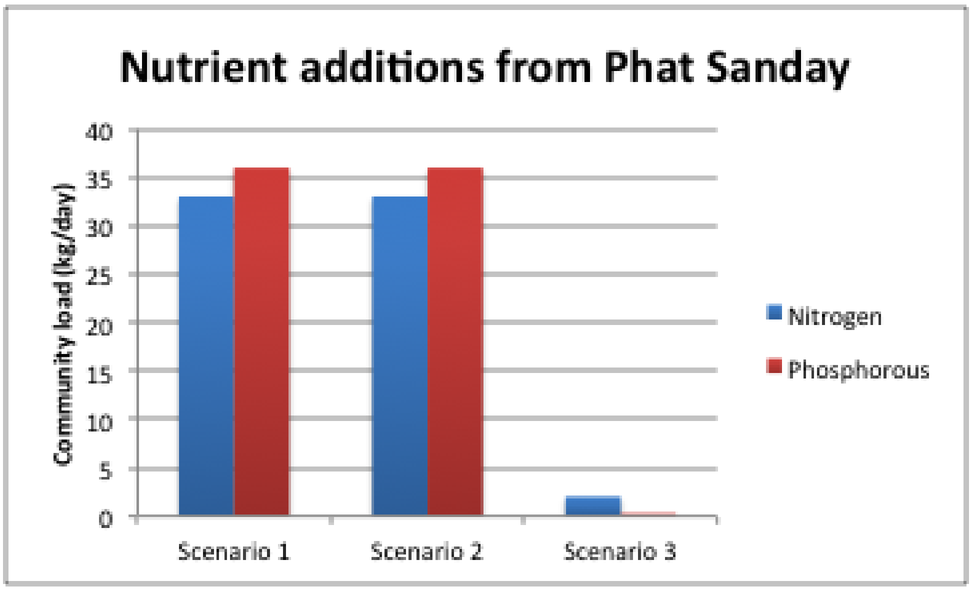

Figure 25. Daily nutrient loads in form of nitrogen and phosphorous from Phat Sanday

6.2.1.5 Impact quantification

It is very difficult to estimate the direct impact the nutrients have on the water quality. In the lake, an enormous amount of processes are affecting the final water quality impact from the waste. A huge effort and knowledge is required to model the waste decomposition and spreading in the lake. For this particular study, a simple analysis was performed to in some way quantify the effect from the waste addition. The expected outcome from this analysis is to establish if the addition contributes to a change in lake nutrient concentration or if it is a negligible amount. That is, does the waste have the potential to on a local scale, change the concentration with 50% or 0.0005%? The result gives a guideline if the removal of waste input has a considerable effect or not.

The area of Phat Sanday has previously not been determined in a precise way. It is especially difficult to delimit since the village is floating and houses are moving back and forth. A rough generalization is though performed to estimate the area of Phat Sanday. It is based on the location of most houses that are situated along the main trench. The village becomes more widespread during wet season but during dry season the village is located in the trench. The delimitation of Phat Sanday is presented in Figure 26.

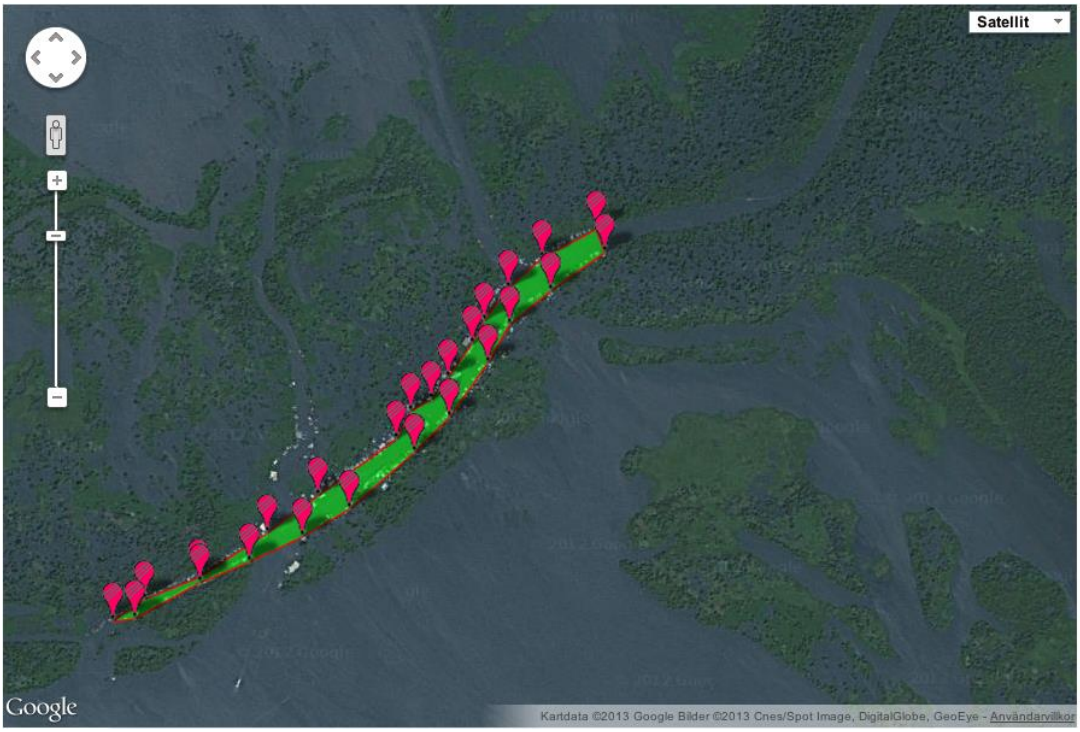

Figure 26. The delimited area of Phat Sanday (Google, 2013b).

Total area for this delimitation is approximately 200 000 m^2. During the dry season, average water level ranges between 1 and 3 meter as previously seen in Figure 6. This is applicable for the period February to May. Given these circumstances, and approximating the average depth to 2 meters, a generalised volume of 400 000 m^3 is estimated. This approximation should not be considered as an exact determination of the volume of Phat Sanday, it is only a guidance value.

The average time a water particle spends in the delimited area is required for the analysis. It is simply calculated as the residence time, namely the delimited volume divided by the flow. Flow is annually reversible but here based on the dry season flow in the channel. From the flow in Stung Sen river measured at Kampong Thom station, where the average flow is 800 000 m^3/day, a residence time of 0.5 days is acquired (Puy, 2011).

About 800 000 m^3 are passing through Phat Sanday every day and to this water volume, 31 kg N/day and 36 kg P/day are added from the community. About 2 kg of nitrogen is as previously mentioned excreted by fishermen outside this delimited area and not included in this calculation. The daily concentration addition from Phat Sanday is thereby 0.04 mg/L nitrogen and 0.05 mg/L phosphorous.

Assuming that the incoming concentration from Stung Sen River to Phat Sanday resemble concentrations from Kampong Luong, one finds that phosphorous concentration varies between 0.05-0.4 mg/l (Figure 8, section 3.1.2.1). This means that the above calculated concentration addition potentially would represent an increase of 13-100% in local phosphorous concentration. Similar assumptions and calculations for nitrogen would show an incoming concentration of around 0.1-0.6 mg/l (Figure 9, section 3.1.2.2) and thus a local nitrogen increase of 7-40%. Moreover, organically bound nitrogen could not be measured for the pure wastes meaning that the nitrogen addition might be even higher.

Once again it should be stressed that these values are based on simplified calculations. However, the results still show that the effect of the waste addition from the community should not be neglected on a local scale.

6.2.2 Pathogens

6.2.2.1 Scenario 1

The majority of the total coliforms load (which includes *E. coli* bacteria) would directly pollute the local water if no biodigesters would be installed in Phat Sanday. The local *E. coli* concentrations in the water will then be even higher than the current concentrations of approximately 1000-1300 CFU in low water season since not all households currently have pigs (Brown, 2010). Swedish bathing waters are regulated by the *EU directive 2006/7/EC of bathing water* which states that a excellent bathing water should have *E. coli* concentrations of less than 100 CFU/100mL and that waters higher E. coli concentrations should not be used for bathing.

$$E.coli\ pollution\ in\ scenario\ 1:$$

$$HW_{e.coli} + PW_{e.coli} = 1.64 \cdot 10^{12}\ CFU \qquad \text{(VIII)}$$

$$Total\ coliform\ pollution\ in\ scenario\ 1:$$

$$HW_{tot.col} + PW_{tot.col} = 2.64 \cdot 10^{12}\ CFU \qquad \text{(IX)}$$

6.2.2.2 Scenario 2

In scenario 2 there are limitations to the capacity of degrading the *E. coli* pollution, mainly because not all of the pig manure is put into the biodigesters. Also, since many of the villagers are occupied with fishing on the open water body of the lake during the day, they do their needs directly from the boat (previously estimated to 20 %). This may not contribute to local *E. coli* concentrations around the village but should still be considered as a pollution to the lake. All of the pig owners will use pig manure to feed their digester. Unfortunately not all pig manure can be collected since the pigsties usually are very low which mean that parts of it will be flushed out by the water. An estimation is that 60 % is accessible.

Figure 27. A pigsty in Phat Sanday. Note that water is leaking into the sty.

Both the amounts of pig manure and human waste fed to the biodigester will be treated for pathogens through the competition from the anaerobic bacteria. The degradation factor F is determined from the test results of *E. coli* and total coliforms in the outputs and inputs to the biodigester at RUA[8]. The degradation factor is 96 % for *E. coli* and 99 % for total coliforms. In the current situation the treated digestate flows through the output pipe directly into the water thus polluting it with the remaining pathogens.

$$E.coli\ pollution\ in\ scenario\ 2:$$

$$(0.4 \cdot PW_{e.coli}) + (0.6 \cdot PW_{e.coli} \cdot (1 - F)) + (0.8 \cdot HW_{e.coli} \cdot (1 - F)) + (0.2 \cdot HW_{e.coli})$$

$$= 6.73 \cdot 10^{11}\ CFU \qquad \text{(X)}$$

$$Total\ coliform\ pollution\ in\ scenario\ 2:$$

$$(0.4 \cdot PW_{tot.col}) + (0.6 \cdot PW_{tot.col} \cdot (1 - F)) + (0.8 \cdot HW_{tot.col} \cdot (1 - F)) + (0.2 \cdot HW_{tot.col})$$

$$= 1 \cdot 10^{12}\ CFU \qquad \text{(XI)}$$

[8] See Appendix B

6.2.2.3 Scenario 3

In this scenario all produced pig manure are used in the biodigesters. This could be solved by introducing some sort of plastic carpet in the pigsties with high edges preventing the waste from being flushed out. All produced human waste will be fed to the digesters except the 20 % that the fishermen will dump while fishing on the open waters. This represent the full potential of biodigester implementations.

It will also be assumed that the degradation factor for pathogens in the biodigesters is the same as in scenario 2.

After being processed in the digester, the effluent will be collected and used as fertilizer in either floating gardens or fields on land. Even though some will be flushed out from the gardens or fields by rainwater, it can still be expected that the majority of pathogens left in the digestate will be assimilated by the soil or crops. All pathogens are assumed to be removed from the system and will not pollute the water.

$$E.coli\ pollution\ in\ scenario\ 3:$$

$$0.2 \cdot HW_{e.coli} = 2.42 \cdot 10^{10}\ CFU \qquad \text{(XII)}$$

$$Total\ coliform\ pollution\ in\ scenario\ 3:$$

$$0.2 \cdot HW_{tot.col} = 6.76 \cdot 10^{10}\ CFU \qquad \text{(XIII)}$$

6.2.2.4 Summary

The pathogen additions for all scenarios are presented in Figure 28.

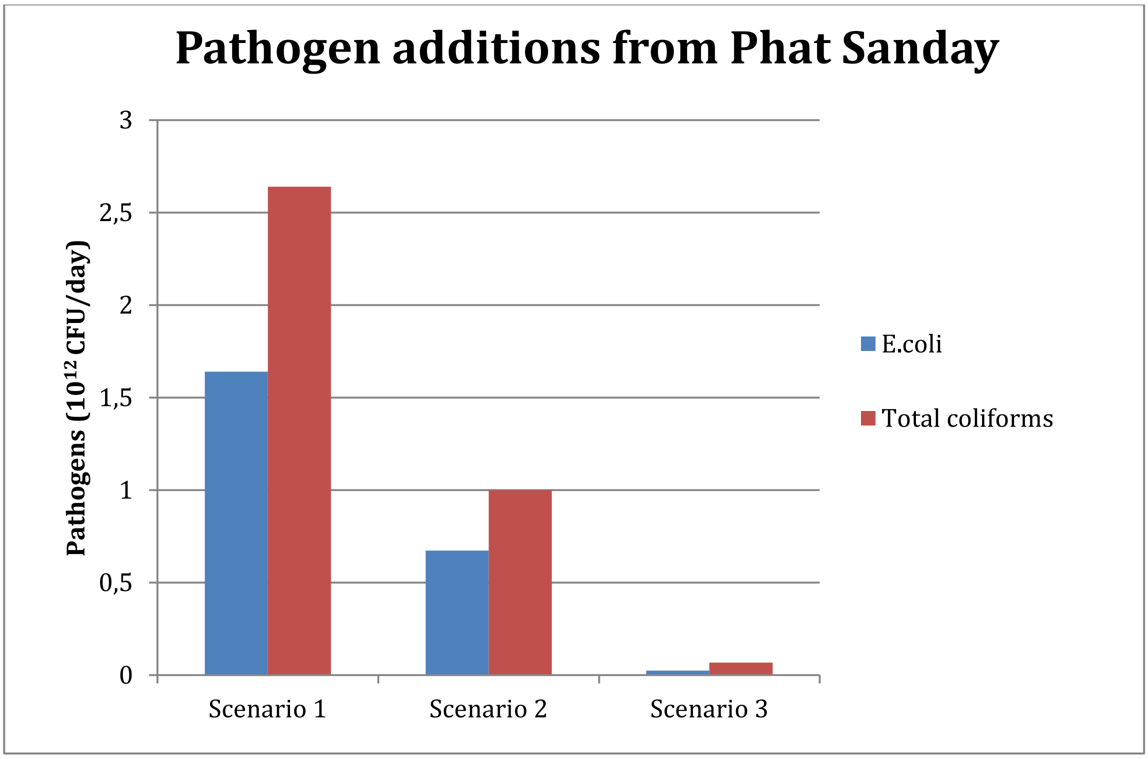

Figure 28. Pathogen pollution for the three different scenarios.

The *E.coli* concentration in scenario 3 is only 0.6 % of the concentration in scenario 1. The concentration of total coliforms is in scenario 3, 1.1 % of the concentration in scenario 1. Even if the waste management system in scenario 2 is not fully implemented it still reduces the *E. coli* pollution to 41 % and the total coliforms pollution to 37% which should be seen as a good improvement.

6.2.3 Greenhouse gas emissions

6.2.3.1 Energy need

Calculations below describe how many kWh of heat that can be expected for an average household when cooking with a typical biogas stove.

$\eta_b = Efficiency\ of\ biogas\ stove = 49\ \%$ (Shrestha, 2004)

$C_b = Calorific\ value\ of\ biogas = 6\ kWh/m^3\ (Kossman, Pönitz\ and\ Habermal, 2011)$

$V_b = Daily\ produced\ volume\ of\ biogas\ per\ average\ household = 0.3\ m^3$

$E_b = Heat\ available\ for\ cooking\ per\ day\ from\ biogas$

$$E_b = C_b \cdot V_b \cdot \eta_b = 0.882\ kWh \qquad \text{(XIV)}$$

To estimate the needed energy for cooking, data are used from GERES that have made research on floating villages in other parts of Tonlé Sap. In the current situation Traditional Lao Stoves are used to burn fuelwood for cooking. It is assumed that all fuelwood are used for cooking (GERES 2013, GERES 2012).

$\eta_w = Efficiency\ of\ Traditional\ Lao\ Stove = 25\ \%$

$C_w = Calorific\ value\ of\ fuelwood = 15.6\ Gj/ton = 4.33\ kWh/kg$

$m_w = Daily\ mass\ need\ of\ fuelwood\ per\ average\ household = 3.4\ kg$

$E_w = Heat\ available\ for\ cooking\ per\ day\ from\ fuelwood$

$$E_w = C_w \cdot m_w \cdot \eta_w = 3.68\ kWh \qquad \text{(XV)}$$

This means that the daily energy need for cooking is 3.68 kWh heat.

6.2.3.2 Scenario 1

Since no biodigesters will be installed the villagers will only use firewood for their cooking. Table 17, presents what the exhaust gases contain when combusting 1 kg firewood in a Traditional Lao Stove.

Table 17. Emissions when combusting firewood in g CO2-equivalents. Data collected from GERES (Van Mansvelt and Buysman, 2006).

Element	CO_2 (g)	CH_4 (g)	N_2O (g)	Sum (g)
When combusting 1 kg of firewood	1 560	8	0.04	1 568
Carbon emission factors	1	23	296	-
CO_2-eq (g/kg firewood)	1 560	184	12	1 756
CO_2-eq (g/daily use of firewood per household)[9]	5 304	626	40	5 970

It should be noticed that other sources for pollution not directly associated with biogas have not been considered, like transport or recharging of batteries. Including these sources would probably imply an even larger reduction of greenhouse gas emissions from implementing the biodigesters. The total emissions of greenhouse gases are presented in Table 18.

Table 18. Total GHG emissions for scenario 1.

	Combustion of firewood (kg CO_2-eq /day)	Waste management (kg CO_2-eq/day)	Total (kg CO_2-eq/day)
One household	5.97	-	5.97
Total for Phat Sanday	5 850	-	5 850

6.2.3.3 Scenario 2

As previously stated the second scenario will have losses of pig manure from the pigsty of 40 %. Pig manure is the dominant substrate based on mass and a reduction of 40 % will approximately lead to a 40 % reduction of gas production which is equivalent to 40 % less energy.

$$E = n \cdot E_b = 0.6 \cdot 0.882\ kWh = \ 0.530\ kWh \qquad \text{(XVI)}$$

The total energy need is 3.68 kWh which means that the produced biogas will fulfil the need with:

$$\frac{E}{E_w} = 0.144 = 14.4\ \% \qquad \text{(XVII)}$$

The remaining firewood will be combusted which will result in:

$$CO_{2,eq/day} \cdot (1 - 0.144) = 5.97 \cdot (1 - 0.144) = 5.11\ \ kg\ CO_2\ eq/day \quad \text{(XVIII)}$$

As stated in section 6.2.2.2 not all of the waste will added to the biodigester. 40 % of the pig manure and 20 % of the human waste will be dumped in the water.

[9] One household use 3.4 kg firewood per day

Table 19. Total GHG emissions from scenario 2.

	Combustion of firewood ($kg\ CO_2$-eq /day)	Waste management ($kg\ CO_2$-eq/day)	Total ($kg\ CO_2$-eq/day)
One household	5.11	-	5.11
Total for Phat Sanday	5008	-	5008

6.2.3.4 Scenario 3

In this scenario it is assumed that all of the daily produced substrate will be used in the biodigester and produce the theoretically possible volume of biogas. Pig manure potentially produce 50 L biogas/kg and it is assumed to represent the substrate well (SNV, 2009b). The approximation is:

$$V_b = biogas\ production \cdot substrate\ production = 50\ L/kg \cdot 6kg = 300\ L \quad \text{(XIX)}$$

$$300\ L\ of\ biogas = 0.882\ kWh\ heat\ (\ see\ section\ 6.2.3.1)$$

$$\frac{E_b}{E_w} = 0.240 = 24\ \% \quad \text{(XX)}$$

The remaining firewood will be combusted which will result in:

$$CO_{2,eq/day} \cdot (1 - 0.240) = 5.97 \cdot (1 - 0.240) = 4.54\ \ kg\ CO_2\ eq/day \quad \text{(XXI)}$$

Table 20. Total GHG emissions from scenario 3.

	Combustion of firewood ($kg\ CO_2$-eq/day)	Waste management ($kg\ CO_2$-eq/day)	Total ($kg\ CO_2$-eq/day)
One household	4.54	-	4.54
Total for Phat Sanday	4 446	-	4 446

6.2.3.5 Summary

The emissions of GHG from an average household for the different scenarios are presented in Figure 29.

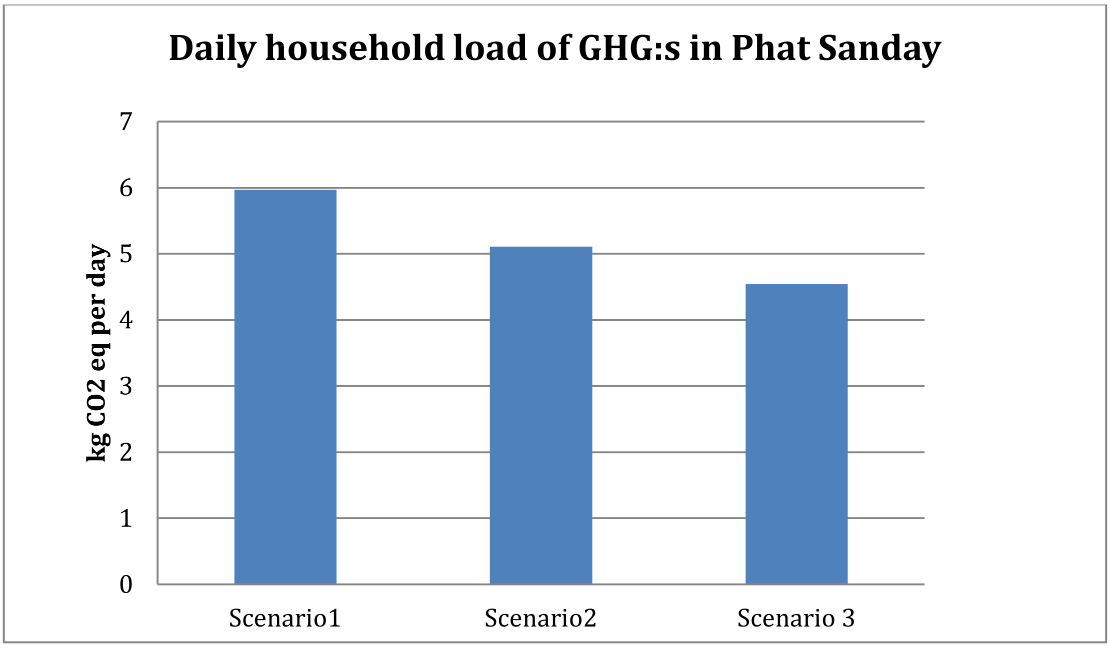

Figure 29. Total GHG emissions in kg CO2-equivalents per household and day for scenario 1, 2 and 3.

Similarly, the GHG emissions from the whole community is for each scenario presented in Figure 30.

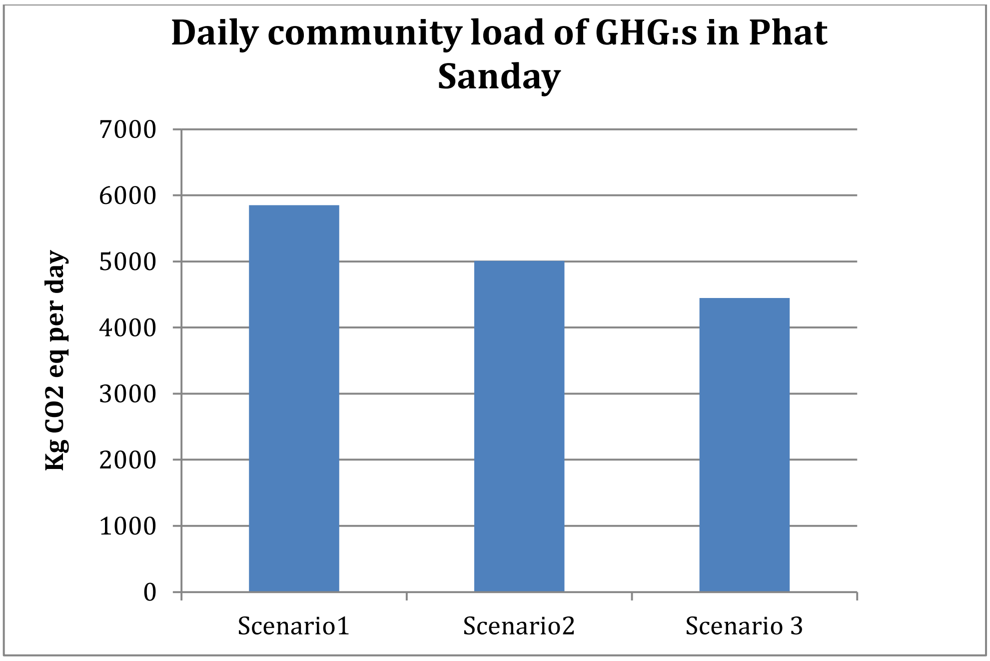

Figure 30. Community daily GHG emissions in kg CO2-eq. for scenario 1, 2 and 3.

6.2.3.6 Including indirect effects from waste management in Global Warming Potential from the biogas system

In Sweden biogas production from manure has strong reductions of GHG if indirect effects from changed manure management are included. The first effect is that ordinary storage of pig manure in open silos causes high leakages of methane, something that will cease completely if all manure is used for the digester. The second effect is that digestate from the biodigester will replace chemical fertilizers which means that GHG are reduced when less chemical fertilizers are produced. The third effect is that the farmland usually takes up carbon easier from digestate than from chemical fertilizers (Börjesson, Thufvesson and Lantz, 2010). These indirect effects are mainly the reason why biogas from manure is considered such an environmental success as a biofuel in Sweden. It is therefore important to estimate these effects on the biodigester system in Cambodia where conditions are completely different.

A national survey on energy use and farming in Cambodia showed that 92 % of the land-based biodigester owners use their digestate as an addition to chemical fertilizers to improve the yield from their fields (Van Mansfelt and Buysman, 2006). There is therefore nothing suggesting that any chemical fertilizers will be replaced on land-based farming. In the floating villages, no chemical fertilizers are used and it is not probable that any chemical fertilizers will be introduced there either.

The Global Warming Potential depends on whether the waste will be aerobically or anaerobically digested. To what extent each process will occur is difficult to determine and thereby the magnitude of this natural pollution is hard to estimate. Aerobic digestion has no effect on the Global Warming Potential since only one carbon dioxide molecule is released for each carbon molecule digested (see Appendix C for further clarification). This molecule is the same molecule that has been taken up by plants from the atmosphere. In a life cycle perspective, the same molecule that is taken up by the plants is released back to the atmosphere during aerobic digestion (after being transported through the gut of the animal and released to the water) and should not be considered as a contribution to global warming. However, with anaerobic digestion, a methane molecule is released instead of a carbon dioxide molecule. A methane molecule is a much stronger greenhouse gas than carbon dioxide (23 times) and must be considered to contribute to global warming. Therefore, in the case of anaerobic digestion a carbon dioxide molecule is taken up by the plants and then converted to a methane molecule, thus increasing the Global Warming Potential. It is recommended to establish the fraction between aerobic and anaerobic digestion to be able to perform a more exhaustive analysis.

Determination of the fraction between aerobic digestion and anaerobic digestion is problematic to establish. As seen in Figure 6, Tonlé Sap is during dry season very shallow (≈2 m) and during wet season also by definition shallow (max 10 m). Conditions are also well mixed at wet season since the high flow from Mekong River creates a lot of turbulence in the water. The shallowness of Tonlé Sap would therefore imply well-mixed oxygen conditions throughout the lake favouring aerobic digestion. On the other hand, the waste added to the lake will sink to the bottom and becomes trapped to the sediment. Digestion of the waste at the bottom will consume oxygen thus depleting it from the bottom. Consequently, anaerobic zones are created at the sediment where the majority of the waste is.

The effluent from the biodigester process will be directly dumped to the lake in scenario 2. However, it is assumed that all biogas potential in the material has been used in the process and no that no natural anaerobic digestion degrades the digestate further. This also means that no chemical fertilizer will be replaced and that no GHG can be reduced from the production of these.

To exemplify the effect that methane leakage will have on the results, calculations have been made on the GWP when 0, 50 and 100 % of the waste are digested anaerobically[10]. This has then been applied on the three scenarios, see Figure 31.

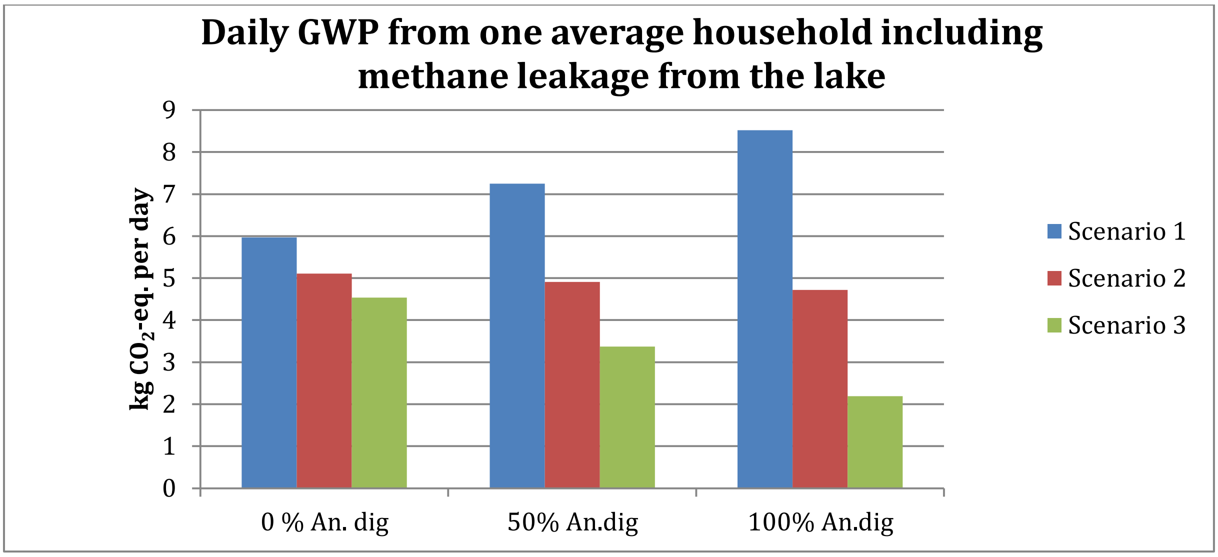

Figure 31. GWP for the three scenarios with the uncertainty of anaerobic digestion in the lake.

[10] Thorough calculations are given in Appendix C

7 Sensitivity analysis

This section presents a discussion of the validity for assumptions made within this study. The assumptions are divided into major and minor considerations due to their potential impact on the results.

7.1 Major considerations

7.1.1 Amount of pig owners

It has in the scenarios been assumed that all households will have an average of 2 pigs. Currently, only a few households own pigs, perhaps 2-5 % (Hughes, 2013). The average amount of pigs in the village is therefore considerably smaller in the current situation than when all households have 2 pigs. If all households have an average of 2 pigs there will be 1960 pigs in the community. In reality where approximately 5 % of the households have pigs, there will be 98 pigs in the community.

The assumption that all households will buy pigs in the future is realistic but not certain. To predict the potential outcome from this uncertainty, the pollution of pathogens and nutrients was calculated when 5, 50 and 100 % of the household would own pigs in the future. In these diagrams the pollution are estimated from scenario 1 (no biodigesters installed). Thorough calculations for this section are given in appendix E.

7.1.1.1 Nutrients

Figure 32 presents how the community load differs depending on how many households that own pigs in the community.

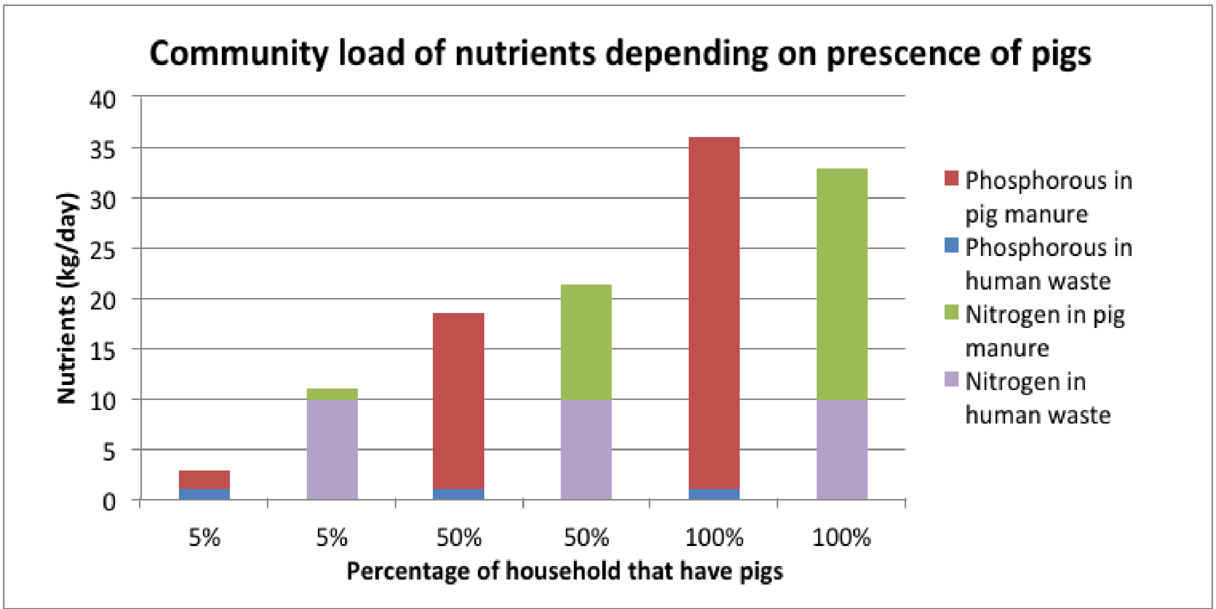

Figure 32. Load of phosphorous and nitrogen depending on how many that own pigs in the community.

Figure 32 shows that pig manure becomes the main pollutant when introducing more pigs to the community. Especially, phosphorous addition will increase significantly with more pigs. The main reason for larger pollutant is that pig manure is produced in a larger quantity (2.75 kg for pigs compared to 0.26 kg for humans). Adding more pigs to the community will therefore create a larger pollution of nutrients to the lake, unless a biodigester system with digestate handling is introduced.

7.1.1.2 Pathogens

Figure 33 shows the pollution of pathogens, represented by total coliforms, from the community depending on how many households that own pigs.

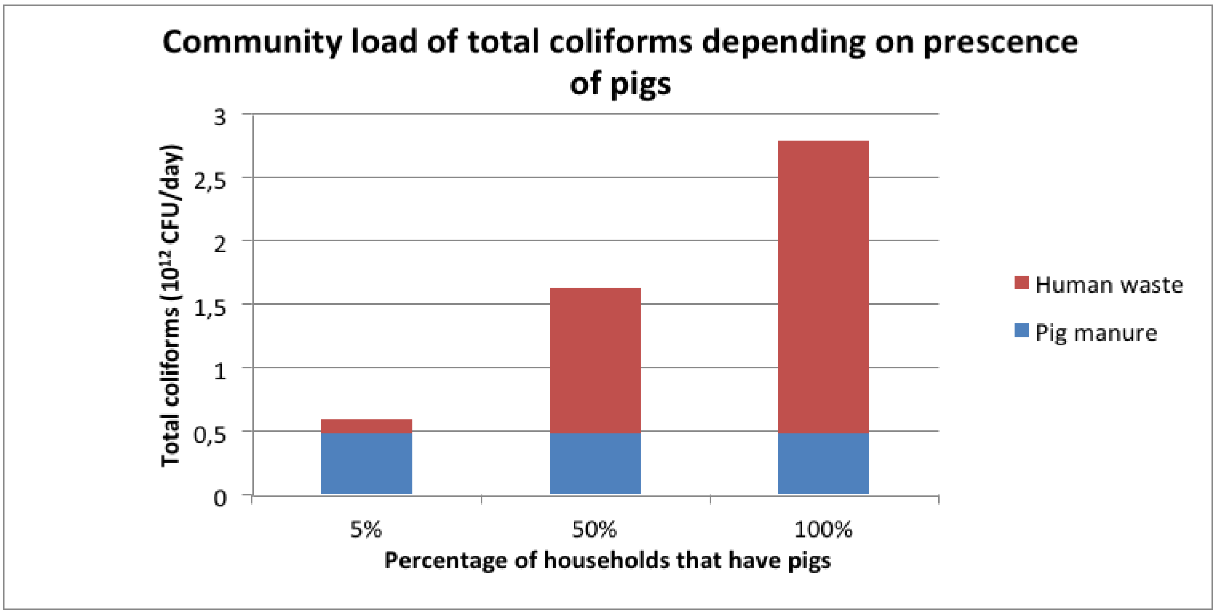

Figure 33. Community load of total coliforms depending on how many households that own pigs.

The results from Figure 33 show that by increasing the pig owners in the community from 5 % to 100 %, total coliforms addition increases with 444 % assuming that no biodigesters are installed.

Pig manure has more than twice the amount of total coliforms per 100 mL of waste than human waste (see Table 7). This partly explains why pig manure are the dominant pollutant source. The other reason is that larger quantities of pig manure are produced. It should be noted that the pollution are not linear with increasing pigs since human waste contributes to the majority of the pathogen pollution with only 5 % pig owners. However, pig manure are contributing most when all households are pig owners.

It is interesting to see how the pathogen pollution varies with the amount of pig owners and the implementation of biodigesters. In Figure 34, the presence of pigs has been included in the three scenarios presented within this study.

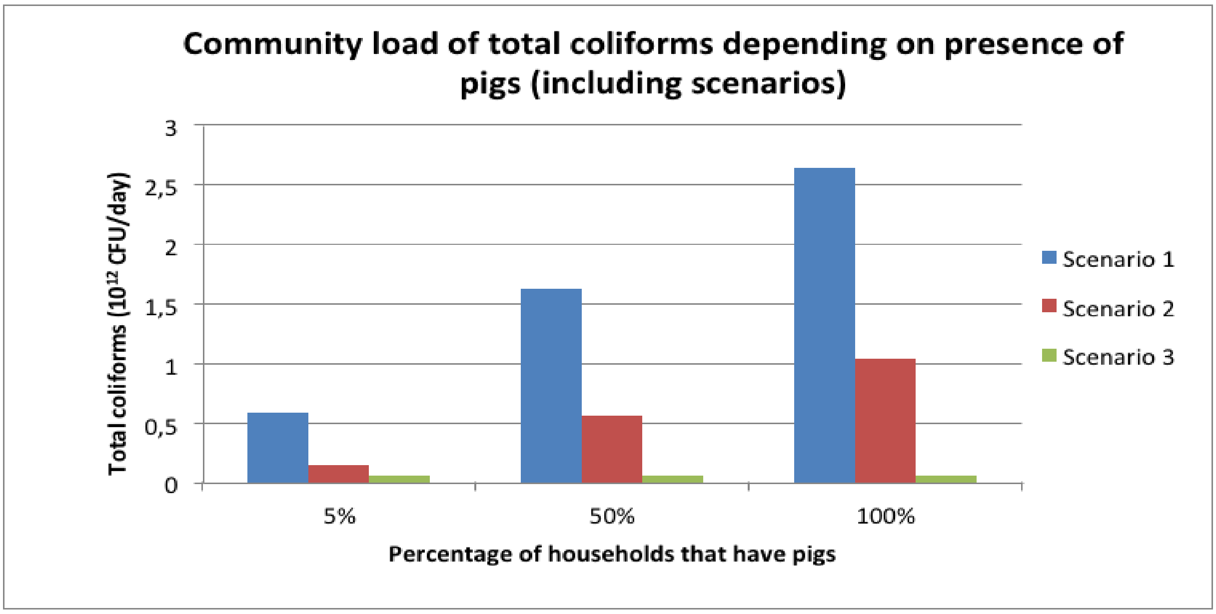

Figure 34. Load of total coliforms in the three scenarios depending on how many households that own pigs.

Figure 34 clearly shows that the pathogen pollution is increasing when more households are pig owners. The differences between pathogen additions are larger in scenario 1 than scenario 2, simply because 60 % is, in scenario 2, put into a biodigester where pathogens are degraded. Scenario 3 pollutes with the same amount of pathogens independently of how many pigs that are present in the community. The reason is that the pollution only consists of the 20 % of human waste excreted by fishermen. The pathogen concentrations are in the biodigester degraded substantially and no pollution will occur since it is assumed that the digestate is used as fertilizer. There are therefore no limitations for introducing more pigs assuming that no pig manure is lost from the pigsties and that there is a decent handling system of the digestate.

7.1.2 Lost pig manure

It was assumed that 40 % of the pig manure are lost from low built pigsties. The number is based on a personal estimation at the site. An exact amount of this fraction is very difficult to define and therefore the real percentage could be both lower and higher. However, a considerable amount is known to be lost so the reality is probably well mirrored by assuming 40%.

7.1.3 Energy need

The daily energy need for cooking (1250 L) is based on the current firewood consumption of 3.4 kg firewood/day. Depending on cooking habits and firewood use this can differ a lot between households. The heat can be better regulated with a gas stove than a wood stove and enable slow cooking which would reduce the energy need. However, there seem to be problems for some pig farmers to prepare pig food on biogas stoves since that require larger pots. More heat is demanded with a larger pot and this was easier to get with a firewood stove.

The literature gives different estimations on energy need for cooking. Kossman, Pönitz and Haberman (2011) have determined that 200 L of biogas replace 1 kg of wood which would result in a daily biogas demand for the households of 680 L instead of 1250 L. On the other hand the same authors estimate the energy consumption for cooking to 150-300 L of biogas per person and meal that would give a biogas demand higher than 1250 L/day for a household with

5 people. San, et al. (2012) have made a study on energy consumption in another province in Cambodia. Their estimation is that 2 m^3 biogas replaces 5.2 kg firewood for cooking per day and household (3.4 kg firewood = 1300 L biogas). With this in mind, 1250 L of biogas per day for cooking seems reasonable.

7.1.4 Methane leakage

As described in section 6.2.3.6, the methane leakage from the lake is depending on how much anaerobic digestion that occurs in the lake. The complexity of the ecological system in the lake makes this value very difficult to estimate. Results have been presented for 0, 50 and 100 % anaerobic digestion but these percentages could in reality be any other value between 0-100 %. Figure 31 shows that this have strong impact on the result.

7.1.5 Organic nitrogen

As described in section 5.6, organic nitrogen was not included in the results for total nitrogen in the waste. Organic nitrogen content can vary considerably and this will have different positive effects on the results (Seitzinger and Sanders, 1997; Hansson, 2013). No considerations have been taken to how organic nitrogen reacts in the water.

7.2 Minor considerations

7.2.1 Lost human waste

Daily, one or two fishermen from each household travel to the open water of Tonlé Sap to fish. Normally, they leave early morning and return in the afternoon. Personal needs are done directly to the water during the fishing trips. This is waste produced by the community that not will go through the biodigester. For one or two people being away around half the day, 20 % of the household human waste is assumed to represent direct excretion from fishermen. For individual households, the percentage might vary depending on how many that go fishing. However, 20 % seems to be a feasible loss for the entire community based on the personal perception made during the field site visit. It is hard to establish this part explicitly and small variations might occur but the order of magnitude is in this assumption probably reasonable.

7.2.2 Ideal gases

In the calculations of GWP from reduced methane leakage, both methane and carbon dioxide are assumed to behave as ideal gases. This simplification is made to be able to convert volume to mole by the ideal gas law. No calculations have been made to verify this, but according to Boles and Cengel (2006), most gases are probable to behave as ideal at atmospheric pressure and a temperature of 30 °C.

7.3 Lab results - Biodigester

Some difficulties were experienced during the lab-scale experiment. A couple of systems were exposed to leakage due to problems with the sealing. Silicone was used for tightening around the inlet to the gasbag. Apparently, the tightness of the silicone decreased with time and some leakage occasionally occurred. The problem was adjusted as soon as possible and the bag was emptied. The lost biogas was not compensated and therefore the total biogas production should have been slightly higher. Many of the leakages were discovered the first days of the experiment. This is extra problematic for the accuracy of the lab-scale results since batch processes usually produce most biogas in the first week, especially for easily degradable substrates (Nges, 2013).

Another problem was the large air space in the tank containing NaOH-solution. Ideally, a smaller Erlenmeyer flask was desired (having less air space) but it was not possible to access in Cambodia. In addition, more hoses were required which further would decrease the biogas pressure. Probably a shorter system with a smaller NaOH-tank would force more gas to flow to the gasbag.

In fact, it would in many situations be enough to just measure the biogas production instead of using NaOH to receive the methane production. In most literature a methane concentration of 60 % are used and it is common to use calorific values for biogas instead of methane. It is however not uncommon that the methane content can vary between 50-70 % (SNV, 2009a). If it does in this study, it will affect the estimated calorific value and thereby the final results. To diminish this problem it would be preferred to measure the methane content once in a gas chromatograph.

The lab-scale setup was carried out as a batch process for practical reasons. It was not possible to feed the lab reactors every day. The biodigesters set up in Phat Sanday are continuous reactors. Performance between batch and continuous are different and the relation between them is not easy to establish. Normally, maintained continuous reactors perform better than batch reactors implying a slightly higher biogas production if continuous reactors were used in the lab instead. However, lab-scale setups often perform better than real size setups. To what extent they perform better is unknown. Possibly the two above described causes even each other out so the lab-scale results can be scaled up to mirror results from larger reactors well.

8 Discussion

8.1 Nutrients

Scenario 1 and 2 do not differ in terms of nutrient additions since the effluent currently are discharged into the water. Bacteria in anaerobic digestion do not reduce the mass of nutrients, instead they only mineralise the waste from organic to inorganic forms. Biodigesters are therefore, without proper management of the digestate, not useful in terms of nutrients reduction. Scenario 3 shows the prospective improvements, in terms of reduced waste addition, when an end use for the effluent is introduced.

The primary source of nutrients originates from pig manure. Table 6 in section 6.1.1.1 shows that 70 % of the nitrogen and 97 % of the phosphorous added from Phat Sanday are pig manure. The estimated manure loss (40 %) from badly constructed pigsties has consequently major implications on the nutrient load from the community, even with biodigesters implemented. A crucial part is therefore to improve the construction of the pigsties to omit manure losses to the water.

Quantification of the results shows that the waste added to the village in scenario 1 and 2 potentially contributes to a concentration increase in the lake ranging between 10 and 100 % for both phosphorous and 7-40 % for nitrogen during dry season conditions. Wet season conditions have not been evaluated since Phat Sanday become a part of the major water body thus changing the dilution conditions completely. It should be stressed that this quantification is simplified and has excluded all natural processes within the lake. Several processes (oxidations, sediment attraction, decomposition, etc.) occur in the lake affecting the nutrients and their composition. Exact determination of the new concentrations is difficult and for accurate quantification, more data sampling and modelling are recommended. In this study, the analysis was solely done to assess the order of magnitude of the waste addition.

Simplifications were performed for flow, area and depth but the errors of these parameters are within the same magnitude. Error range for area is estimated to not deviate more than 10% while depth variations are ±1 m. The flow is probably reasonable since river conditions (width, depth) in Phat Sanday resemble conditions further upstream in Kampong Thom where the point of measurement is located. With these possible errors included, the potential concentration increase is large enough to not be negligible. Clearly, the waste addition from Phat Sanday has a significant effect during dry season and it is important to implement a waste management system, for example biodigesters.

The Tonlé Sap is known to have a high resistance to elevated nutrient levels, primarily because large concentrations of suspended solids attract and bind phosphorous. This is also reflected by the low phosphate/total phosphorous ratio of about 0.3. Lately, there has been a slight increase in phosphorous concentration in nearby locations of Tonlé Sap implying a potentially increasing problem (Figure 8). Trends for nitrogen components are however stable and have not changed significantly. It is not known if Tonlé Sap is nitrogen or phosphorous limited and it is therefore difficult to say if the phosphorous increase is a potential problem or not. The N:P ratio in the waste addition was not determined since total nitrogen was simplified to ammonia, ammonium and nitrate. However, it can be established that without sanitation facilities, the nutrient additions can lead to elevated lake concentrations and plausibly local eutrophication, especially since Phat Sanday is located in a trench. Here, the dilution might be less efficient than in the open water and the risk for accumulation of nutrients is larger.

The uncertainty regarding the flow in Phat Sanday also affects the potential for local eutrophication. A high upstream flow would partly flush the waste out from Phat Sanday and dilute the waste in the open water body. However, most waste will probably sink to the bottom of the lake and accumulate in the sediment. Nutrients are consequently retained in Phat Sanday and the potential for enhanced algal blooms increases. In addition, breakdown of the waste will consume oxygen causing lower oxygen concentrations as well as anaerobic zones close to the sediment. It could also be expected that methane leakage would increase from the lake because of the above mentioned effects with eutrophication.

Looking on human health aspects, on a nutrient basis, the waste load to the water does not primarily affect them. For drinking, bathing and washing purposes, the guidelines for nutrients are high and a nutrient concentration increase in Tonlé Sap is not harmful for the human body. However, the secondary consequences of elevated nutrient levels can lead to environmental problems for humans in the community. Firstly, altered nutrient concentrations can change the habitat for species and invading organisms might become problematic. One example is a water hyacinth invasion potentially covering the entire trench of Phat Sanday. Currently, the water hyacinth growth is a minor nuisance but modified nutrient levels can alter this. Overgrown lakes will affect the villagers by a reduced availability for fishermen to travel to the open water. In general, all forms of transportation can be problematic. Secondly, modified nutrient concentrations can cause local eutrophication leading to toxic conditions. An example is the previously mentioned problems with large populations of cyanobacteria producing cyanotoxins. These toxins are very harmful and humans are exposed while bathing or drinking the water. The final and possibly worst problem that could arise with severe eutrophication in Tonlé Sap is widely spread fish kill due to low oxygen conditions. The majority of people in Phat Sanday fish as their main livelihood (95 %) and a heavy reduction of fish population will have serious effects on the human poverty in floating villages.

Complete management of the waste in Phat Sanday must involve a safe and secure handling of the effluent from the biodigester. In Sweden, digestate is spread on adjacent farmlands as fertilizer after it has been hygienised to reduce pathogens. The potential for similar actions in Phat Sanday is probably small since there is a scarcity of nearby located farmlands, especially during wet season. Transportation is thus required and the possibility of introducing cooperation with villagers and farmers could be difficult. Spreading on temporary farm fields during dry season might also be an option but problems could occur during flooding when some nutrients, not taken up by the crops, are transported back to the water. Consequently, nutrient concentrations in the water will still be affected by waste added from Phat Sanday. Hughes (2013) reports that some interviews with farmers suggest that the temporary lands during dry season already are high in nutrients and that there is no need of fertilizer.

Another alternative is to use the fertilizer to feed caged fish farms. These are not very common in Phat Sanday but could possibly exist more in the future. However, the negative aspects with direct contamination from adding the effluent to the water, negates the positive aspect with supplying caged fish with more food. This alternative is therefore not recommended. The final and probably most promising option is to spread the effluent on floating gardens. The idea is that floating gardens are connected to each household where they can grow vegetables and fertilize it with digestate from their biodigester. The effluent is thereby used as a resource and the inhabitants will profit since they increase their food supply. In addition, a proper design of the floating gardens preventing the effluent from being flushed out will cease nutrient additions to the lake originating from human waste and pig manure. This option is therefore recommended since it both improves lake quality and the villager's food supply.

Tonlé Sap is currently not exposed to any severe eutrophication problems. However, increasing populations living on or in the vicinity of the lake are contributing larger nutrient additions through their waste. Prevention of waste contamination is therefore crucial, not only in Phat Sanday but throughout the whole lake. LLEEC are actively working to establish linkages with fertilizer demand and markets in upland areas, as well as developing low-cost floating gardens to encourage greater food production and potential for beneficial reuse of nutrient-rich treated wastes. This work is crucial and it is recommended that it is being scaled up in the future to include all floating villages in the lake which have similar issues as Phat Sanday. Currently, Hughes (2012) estimates that there are 1.5 million people living in floating communities.

8.2 Pathogens

A reduced pathogen concentration in the waters of Phat Sanday will most likely improve the human health in the community. With the use of biodigesters, scenario 3 showed a substantial decrease in *E. coli* and total coliforms concentrations. *E. coli* and total coliforms concentrations were only 0.6 and 1.1 %, respectively, compared to the concentrations without biodigesters as reflected by scenario 1. Scenario 2 showed an *E. coli* concentration that was 41 % of the concentration in scenario 1. It should be noted that the efficiency of the degradation of pathogens is the same as in scenario 3. The only reason for the substantial difference between scenario 2 and 3 is that 40 % of the pig manure pollutes the lake in scenario 2. It would be beneficial to improve the designs for the pigsties with more suitable floors and collection systems so that all pig manure can be used.

The direct concentration decrease of *E. coli* and total coliforms in the lake is hard to estimate. Current concentrations of 5000-7000 CFU/100 mL will likely decrease since the pathogen addition with biodigesters is 100 times lower than without biodigesters. Incoming concentration to the community measured by LLEEC was 1380 CFU/100 mL for total coliforms and 195 CFU/100 mL for *E. coli*. Ceasing the waste addition from Phat Sanday will probably maximally decrease the pathogen concentration to the concentration in the incoming water from Stung Sen. Concentration of *E. coli* would then, according to the *EU directive 76/160/EEC of bathing water* be classified as excellent for bathing water. However, villagers use the water for drinking as well and Cambodian standards (2004) for drinking water, which are set to 0 for *E. coli* and total coliforms, will definitely not be met. The implementation of biodigesters is still beneficial due to the 100 times lowered pathogen addition.

Even with treated digestate from biodigesters there is a risk for *E. coli* contamination if it is used as fertilizer when growing vegetables on floating gardens. To reduce this problem, further research should be conducted to ensure better pathogen removal in the biodigesters. There have not been conclusive studies on the microbiology of the biodigesters to draw any direct conclusions on how pathogen reduction can be improved. If the temperature in the reactor could be raised to thermophilic conditions, then the pathogen reduction would improve substantially (see section 4.2.3). Whether solutions like solar collectors or black painted biodigesters could meet this challenge need to be further studied. During the hot season period, outside temperature can reach over 40^{0}C which should improve the chances of better pathogen reduction. However, the water temperature fluctuates less than the air temperature (Figure 12). In case the temperature just rises from 30^{0}C to 35-37^{0}C, previous studies indicates that the pathogen reduction can improve since the methanogens populations thrive in this environment. The effect on *E. coli* is still uncertain since most pathogens also thrive well at these temperatures (section 4.2.3).

LLEEC is also testing how well a longer retention time for the substrate in the biodigesters and different design options can improve the pathogen reduction for the systems. The results from this testing will tell if an improved pathogen reduction compromises the gas production over a certain time period. Parallel to the biodigester project LLEEC are also trying to reduce pathogen risks in other parts of the chain, such as secondary treatment of waste, application methods for suitable selected crops, safe handling measures and hygiene etc.

The biodigesters will not completely degrade the pathogen concentration which emphasizes that there always will be a need for other complementary solutions to achieve good drinking water (e.g. ceramic water filters) and if the incoming concentration from Stung Sen is reached, a decent bathing water is established. Perhaps decent bathing water is a realistic and reasonable goal for the pathogen reduction in the biodigesters. This would leave more time and space to instead focus on improving the gas production. Many inhabitants in Phat Sanday suffer from diseases related to water-borne pathogens meaning that it is still important to continue testing and studying this matter.

8.3 Global Warming

Scenario 2 illustrates that the current biogas production will decrease the firewood consumption by 14.4 % and consequently a reduction of 0.73 kg CO_2-equivalents per day for each household. This is equivalent to 260 ton CO_2 per year from the whole of Phat Sanday. If the indirect effect of 50 % methane leakage from anaerobic digestion of waste is included, there is a reduction of 30 % of the GHG pollution equivalent to 791 ton CO_2 per year from Phat Sanday. If this is scaled up to all floating communities (a population of 1.5 million), the reduced emissions will be 170 600 ton CO_2-equivalents per year. According to Gapminder (2013), Cambodia emitted approximately 4.6 million tons CO_2-equivalents in 2009. A rough estimation therefore is that the floating villages can reduce 3.7 % of Cambodia's GHG emissions if all households have biodigesters according to the above scenario. The results depend on how much energy a family needs for cooking (discussed in 7.1.3).

Since substrate is scarce in the village, it should be of extra importance to collect all of the pig manure and not lose approximately 40 %. This is not only due to poor design of pigsties making the collection of manure difficult, but partly also due to lack of motivation to collect all the manure from the biogas owners. The villagers need a better knowledge of the benefits of using all of the pig manure, and not only parts of it.

In case all pig manure is used in scenario 3 the daily gas production might reach 300 L per biodigester and reduce the GHG emissions with 24 % excluding indirect effects. When the indirect effect of 50 % reduced methane leakage of waste in the lake is included, the reduction of GHG emissions becomes 56 % which is equal to 1 445 ton CO_2 per year from the village. This is a significant reduction of firewood and should be considered as a realistic goal to reach. It is almost the double amount of the case in scenario 2 which would mean that approximately 7.5 %

of Cambodia's GHG emissions can be reduced if scenario 3 is scaled up to all floating communities on Tonlé Sap.

Optimization of the biogas process by changing microbiological or physical parameters could reduce the GHG emissions further and should be studied. The anaerobic digestion could be expected to be more efficient during the summer because of higher surrounding temperatures. There are also possibilities to raise the temperature in the reactor by adding a solar collector around the digester or simply paint the digester black.

Since both human waste and pig manure show high concentrations of ammonia and ammonium there can be risks of ammonia inhibition which causes too high pH for the methanogens in the biogas process. Results from RUA do not indicate any ammonia inhibitions since the gas production are close to the theoretic production of 300 L/day and digester (see Figure 23). However, this could be tested with a pH meter.

It is not recommended to have too much variation of the feed to the digesters even if substrate is scarce in the village. The bacteria in the digesters adapt to specific substrate and irregular input of other material could cause insufficient degradation which in turn results in clogging and ammonia inhibition. It is therefore important for the biodigester owners to plan ahead if different substrates will be used. Fish waste and water hyacinth are for example two alternative substrates that could complement pig manure and human waste. If so, it should be fed daily and not just now and then. Results from RUA indicates that a biodigester replacing human waste and 1 kg of pig manure with water hyacinth still produces the same amount of biogas (see biodigester 4, Figure 38, appendix B). The test was originally performed with larger fraction of water hyacinth but that caused unfortunately clogging in the inlet.

Too little research has been done on the microbiology in the current anaerobic digestion process to draw any more direct conclusions, as of publication in March 2013.

8.3.1.1 Introducing scenario 4

The ultimate goal with the installed biodigesters could be to replace all firewood. To do so 3.68 kWh are needed which is equal to 1 250 L of biogas. It will only be possible to produce this high volume by adding more waste into the biodigesters. It should be noticed that many of the community members in reality either have zero or several pigs. There are therefore good chances for the pig owners to reach the need of 1 250 L per day and thereby completely reduce their carbon emissions from firewood combustion. On the other hand it is very difficult for households without pigs to access enough substrate to replace their firewood consumption. In case no pig- or cow manure is purchased it should not be considered a realistic alternative for these households to solely use biogas for cooking.

In case all firewood will be replaced and the indirect effects from changed waste management are included, the GWP from an average household will approximately appear as scenario 4, see Figure 35.

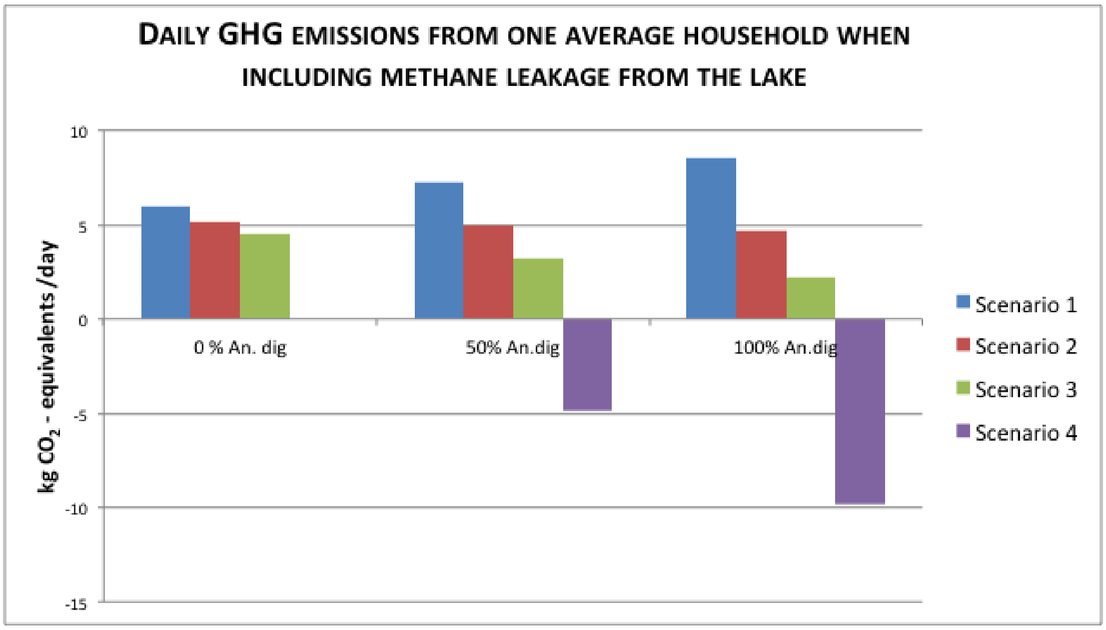

Figure 35. GWP for the four scenarios when there is anaerobic digestion to different extents

When the indirect effect of 50 % reduced methane leakage of waste in the lake is included, the reduction of GHG emissions becomes 167 % equivalent to 4 325 ton CO_2 from the village per year or 0.88 ton CO_2 per capita and year. The village is then no longer a net emitter of GHG:s but an absorber.

Considering that the average Cambodian have a carbon footprint below 1 ton CO_2 per year a reduction of 0.88 ton is extremely high. Since GHG:s are global, the reduction will not have any larger impact on the global warming and unfortunately not prevail the climate effects presented in section 3.3.1. To put the emissions in perspective the carbon footprint from citizens in China, Sweden, Vietnam and the US are presented in Figure 36.

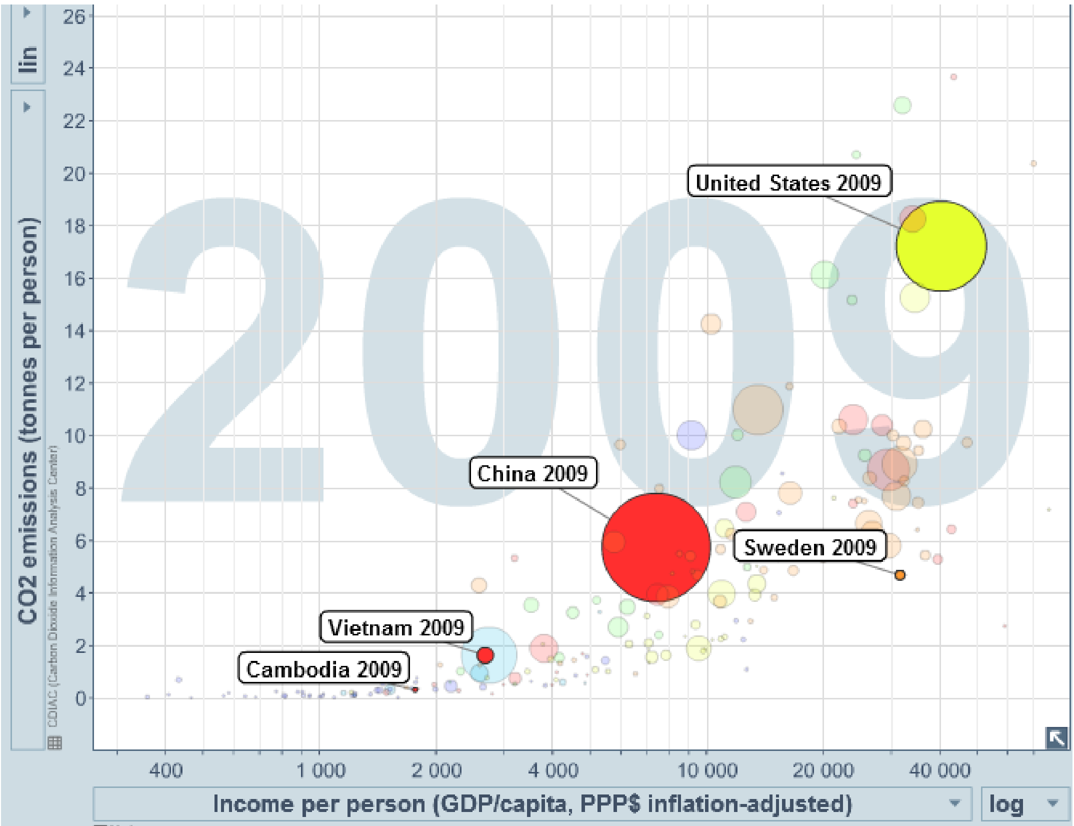

Figure 36. GWP/Capita related to the GDP/capita for Cambodia as well as Vietnam, China, Sweden and the US (Gapminder, 2013).

Cambodia has obviously less responsibility to reduce their carbon emission compared to many other countries in the world. Their primary motivation for implementing biodigesters should instead be to reduce energy costs and improve water quality and health. The reduction of carbon emissions should be seen as a secondary benefit to the village. However, it should be noted that reduction of GHG:s can be financed through carbon credit systems which would reduce the installation costs for the village. According to SNV (2012b), National Biodigester Programmes in Cambodia and Vietnam have been working towards carbon financing and they were proved successful in Vietnam.

9 Conclusions

Introducing biodigesters in floating communities is a sustainable environmental measure since it addresses several environmental problems simultaneously by reducing excremental waste pollution and greenhouse gas emissions whilst also potentially reducing deforestation and allowing safer nutrient reuse. Implementation of other renewable energy solutions like solar panels does not improve sanitation issues, and implementation of other sanitary solutions generally do not produce renewable energy. Live and Learn Environmental Education Cambodia has progressed far in development and installation of the biodigesters but there are still many technical, economical, and practical problems to overcome. The villager's acceptance and cooperation in the project are also crucial to make the biodigesters a success in reality.

This study show that the most important effect from installing biodigesters in Phat Sanday is the reduction of pathogens in the water, which results in improved health for the villagers. Greenhouse gas emissions and nutrient pollutions can be reduced significantly by installing well functioning biodigesters and implementing a solution for reusing the effluent. This implementation will not have a substantial effect on global warming and eutrophication because of other pollution sources outside the community. Pig manure is a key source to both energy production as well as reduction of local pollution of pathogens, nutrients and greenhouse gases.

9.1 Primary recommendations

- Prioritise biogas systems for all pig owners before installing systems at households with no pigs will result in more environmental and health benefits for the whole community. A key factor is to design and develop the pigsties and collection systems so that all manure can be gathered and added to the biodigesters in a simple way, for example with some sort of plastic carpet. Other necessary actions are repairing and improving stoves, gas reservoirs, ability to prepare pig feed and the biodigesters floating capacity.
- Emphasise the biodigesters ability of pathogen reduction to improve bathing water. This should be done parallel with more focus on other solutions for drinking water treatment (i.e. ceramic water filters).
- Improve the knowledge of the benefits from sanitary solutions such as biodigesters through dissemination of more information and marketing. Since substrate is scarce and pathogen concentrations are high in the village, it is of importance to educate and motivate people even more to gather pig manure and to use the ecosan toilets for their own needs. One alternative is to develop a fun, comfortable and important toilet culture among children in schools where they get the motivation to affect their parents.

9.2 Secondary recommendations

- Continue to develop solutions for using the digestate as fertilizer or to find another secondary treatment option. Promoting food availability with farming on floating gardens and relate it to increased yields with digestate as fertilizer will indirectly have very strong reductive effects on nutrient pollution. There is no need to stress or demand a reduction of nutrient pollution from the villagers, the reduction will occur indirectly through focus on other actions.

- Further research and testing should be done on biogas production without pig manure to establish good solutions for villagers also without pigs. It would for example be worthwhile to establish what fractions of human waste, water hyacinth, and fish waste that would have the highest potential for biogas production. It is of environmental importance that human waste always is included in all the alternatives. There should also be more research on the possibility of importing substrates from land such as cow manure, straw and rice husks to increase the feed to the biodigesters.
- The current gas production with pig manure could be optimized by further testing which would be beneficial to improve energy production and reduce deforestation.

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Appendix A - Lab method and theory

Lab-scale anaerobic digestion

Six lab-scale biodigesters were put up with three different substrate fractions. Duplicate tests were conducted for each substrate fraction for safety reasons to make sure that data for all tests could be gathered. 3000 mL substrate tanks were used in the lab-scale setup. Inoculum was added to each biodigester to help the microorganisms to grow faster. The fractions of each substrate used are presented in Table 21.

Table 21. Substrate fractions used in the lab-scale anaerobic digestion.

	Wet weight (g)			Water to substrate	Water (mL)	Inoculum (mL)	Air space (mL)
Setup	Pig manure	Human waste	Water hyacinth				
1	467	41.5	-	6/7	600	50	1500
2	-	83	192	6/14	640	50	2000
3	467	41.5	231	6/9	1130	50	1000
1*	467	41.5	-	6/7	600	50	1500
2*	-	83	192	6/14	640	50	2000
3*	467	41.5	231	6/9	1130	50	1000

The substrate tank was connected through gas tight hoses to a cylinder containing 1250 mL 3M liquid sodium hydroxide (NaOH) solution. Biogas consists of methane and carbon dioxide where only the first one is possible to combust. The sodium hydroxide was used to scrub the carbon dioxide to make sure that the remaining biogas consists of pure methane with only negligible amounts of other gases. A large concentration of sodium hydroxide was used to make sure that carbon dioxide was absorbed by the solution. A large volume was necessary to prevent the solution from being saturated, thus no longer being able to remove the CO_2.

Finally, the remaining gas was directed to a gas collection bag consisting of Transofoil material making the bag completely gas tight. The volume of the bag was limited making it necessary to empty the bag regularly. A glass syringe that can suck gas into its measuring cylinder was used for emptying. Clamps were connected to the hoses to block the pathways for the gas to escape when the bag was emptied. Hence, leakage during emptying was negligible. The total setup is presented in Figure 37.

Figure 37. Setup of the lab scale anaerobic digestion. The right cylinder in the left picture consists of the substrate and the left cylinder of 3M NaOH. The blue clamps closes the hoses when necessary to stop the flow. The gasbag is located in the right picture.

The experiment was located in an office with an air temperature altering between 28-32°C, similar to outside air conditions. Hence, the temperature within the setup was stable and did not affect the microorganisms in the substrate container.

The residence time for the batch process was 30 days. No mixing or stirring of the substrate was undertaken due to practical reasons. Firstly, mixing requires an additional hole or inlet of the tank which potentially could cause gas leakages. An external stirring source could theoretically be used, but it was not feasible to find in Cambodia.

CO_2 Scrubbing theory

The breakdown by microorganisms of substrates in anaerobic digestion results in a biogas mainly containing methane (CH_4) and carbon dioxide (CO_2). The latter is not possible to combust and considered as an undesired by-product in anaerobic digestion. Therefore, to determine the total energy content of the biogas, one has to use a method for separation of carbon dioxide and methane or use advanced equipment that can determine the composition of the biogas such as a gas chromatograph.

Scrubbing with Sodium Hydroxide

A method for separation of methane and carbon dioxide is scrubbing with sodium hydroxide (NaOH). Sodium hydroxide is a strong base and consequently fully dissolves in an aqueous solution (Chang, 2008).

$$NaOH(s) + H_2O(l) \rightarrow Na^+(aq) + OH^-(aq) + H_2O(l) \qquad \text{(A-I)}$$

Carbon dioxide then reacts with hydroxide ions in the solution (Tippayawong and Thanompongchart, 2010)

$$CO_2(g) + OH^-(aq) \rightarrow CO_3^{2-}(aq) + H_2O \qquad \text{(A-II)}$$

Carbon dioxide can also react with the formed carbonate ion (Tippayawong and Thanompongchart, 2010)

$$CO_2(g) + CO_3^{2-}(aq) + H_2O \rightarrow HCO_3^-(aq) \qquad \text{(A-II)}$$

The incoming gas does not have to be bubbled through the solution since the absorbent (NaOH) is strong enough to attract the carbon (Nges, 2013).

The pH continuously decreases in the NaOH-solution because hydroxide ions are consumed in reaction A-II. With time, the solution becomes saturated when there are no hydroxide ions left in the system. The capability of absorbing carbon dioxide is thus removed.

Method for total solids and volatile solids measurements

First, the pure substrate (sample) is weighed. It is then dried in an oven at 105°C for around 24 hours. The sample is taken out and weighed after 22 hours and compared to the weight after 24 hours to make sure that no water is left in the sample. If the weight is equal, the sample has been completely dried. If not, the procedure is repeated until the sample weight equals two successive hours. TS is calculated by equation A-IV.

$$TS\ (\%) = \frac{D-W}{O-W} \cdot 100 \qquad \text{(A-IV)}$$

where

D is the dried weight + the dish weight

W is the dish weight

O is the original weight of sample + the dish weight.

TS is expressed as percentage of the original weight. To calculate VS, the dried sample is put into a furnace and burned at 550°C degrees for 2 hours. VS which is expressed as percent of TS is calculated by equation A-V.

$$VS\ (\%) = \frac{D-B}{D-W} \cdot 100 \qquad \text{(A-V)}$$

where

D is the dried weight + the dish weight

W is the dish weight

B is the burned weight + the dish weight.

Appendix B – Lab Raw Data

Waste component conversion from raw data

Raw data from RDI for two human waste samples and two pig manure samples are presented in Table 22.

Table 22. Concentration of different compounds in human waste and pig manure.

	Pig manure (g/L)[11]			Human waste (g/L)[12]		
ID	**1**	**2**	**Mean**	**1**	**2**	**Mean**
Ammonia (NH_3)	2.70	1.60	**2.15**	2.48	(0.25)[13]	**2.48**
Ammonium (NH_4^+)	4.40	3.70	**4.05**	4.51	4.21	**4.36**
Nitrate (NO_3^-)	0.81	0.72	**0.77**	0.08	0.08	**0.08**
Phosphate (PO_4^{2-})	8.02	5.21	**6.61**	0.86	0.71	**0.78**
Total phosphorous (Tot-P)	10.40	5.50	**7.95**	0.47	0.81	**0.64**

It is more comparable to measure the weight of nutrient in the waste components. Hence the concentration is recalculated into NH_3-N, NH_4^+-N, NO_3^- -N and PO_4^{2-}-P. The molar masses of the compounds and the elements are required for conversion.

Table 23. Molar masses for specific compounds.

Compounds	Molar mass (g/mole)
Nitrogen	14.0
Phosphorous	31.0
Ammonia (NH_3)	17.0
Ammonium (NH_4^+)	18.0
Nitrate (NO_3^-)	62
Phosphate (PO_4^{2-})	95

Conversion from the molecular concentration to elemental concentration in the compound is done by multiplying the concentration of the compound with the ratio between molar mass for the element and molar mass for the compounds.

11 This sample has been compensated for the dilution of 100 g water/g sample
12 This sample has been compensated for the 80 % water used when flushing
13 Outlier, probably a measurement error. Not used for further calculation

$$Compound\ element\ concentration = compound\ concentration \frac{molar\ mass\ element}{molar\ mass\ compound} \quad \text{(B-I)}$$

Table 24. Concentration of different compounds recalculated as element concentration

	Pig manure (g/L)			Human waste (g/L)		
ID	**1**	**2**	**Mean**	**1**	**2**	**Mean**
Ammonia (NH_3-N)	2.22	1.32	**1.77**	2.04	-	**2.04**
Ammonium (NH_4^+-N)	3.42	2.88	**3.15**	3.50	3.27	**3.39**
Nitrate (NO_3^--N)	0.18	0.16	**0.17**	0.02	0.02	**0.02**
Phosphate (PO_4^{2-}-P)	2.62	1.70	**2.16**	0.28	0.23	**0.26**
Total phosphorous (Tot-P)	10.40	5.50	**7.95**	0.47	0.81	**0.64**

The values in Table 24 are multiplied with the daily waste production by pigs (1.97 L/day) and daily human waste production (0.26 L/day). The results are given in Table 25.

Table 25. Daily load of pig manure and human waste.

	Pig manure (g/pig & day)			Human waste (g/person & day)		
ID	1	2	**Mean**	1	2	**Mean**
Ammonia (NH_3-N)	4.37	3.62	4.00	0.53	-	0.53
Ammonium (NH_4^+-N)	6.72	7.91	7.32	0.91	0.85	0.88
Nitrate (NO_3^--N)	0.36	0.45	0.40	0.00	0.00	0.00
Phosphate (PO_4^{2-}-P)	5.14	4.68	4.91	0.07	0.06	0.07
Total phosphorous (Tot-P)	20.4	15.1	17.8	0.12	0.21	0.17

Total addition of nutrients could be calculated using Table 25 and this is performed in section 6.1.1.1.

Raw data from TS/VS analysis

Table 26. Raw data sent from RUPP for TS and VS analysis

Label	Dish weight (g)	Sample weight (g)	Weight of sample after 105° C (g)	Weight of empty dish (For SW) (g)	Sample+ Dish weight before 550°C (g)	Weight of sample after 550°C (g)	TS (%)	VS (%)
Human waste	51.1	25	0.07	-	-	0.05	0.27	29.3
Pig manure	423.2	500	152.0	50.7	52.7	51.6	15,2	56
Water hyacinth	432.5	500	50.0	52.9	54.9	53.4	5	73.5
RUA (in) test 7	52.9	25	0.8	-	-	0.2	3.3	72
RUA (out) test 7	54.7	25	1.1	-	-	0.3	4.6	72.8

Samples from RUA are representing the total input and output from the biodigester, including the water addition. RUA results are in this study converted to pure substrates for better comparison with the lab-scale results.

$Water\ to\ substrate\ ratio = 7\ kg\ \ water/6\ kg\ substrate$

Mass of pure substrate in samples:

$$Substrate_{in}\ (g) = Substrate_{out}\ (g) = 25 \cdot \frac{6}{13} = 11.54 \qquad \text{(B-II)}$$

Total solids (g) in sample with water included:

$$Substrate_{in}\ (g) = 25 \cdot 0.033 = 0.83\ g \qquad \text{(B-III)}$$

$$Substrate_{out}\ (g) = 25 \cdot 0.046 = 1.15\ g \qquad \text{(B-IV)}$$

TS in pure samples:

$$TS_{in}\ (\%) = \frac{0.83}{11.54} = 7.2\ \% \qquad \text{(B-V)}$$

$$TS_{out}\ (\%) = \frac{1.15}{11.54} = 10\ \% \qquad \text{(B-VI)}$$

VS are expressed as percentage of TS and do therefore remain the same undependable of the dilution.

Raw data from pathogens analysis at RDI

Substrates were sent for analysis at RDI but their method seemed to contain some errors. Many samples showed 0 in *E. coli* and total coliforms and that is not likely for pure waste. In addition, some samples showed too numerous to count (TNTC) and no results were given.

Table 27. Raw data from RDI's lab analysis. TNTC is an acronym for too numerous to count.

	Pig manure				Human waste			
Test number	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
E. coli	0	0	$1 \cdot 10^6$	0	0	0	0	0
Total coliforms	$4 \cdot 10^6$	0	$9 \cdot 10^6$	0	TNTC	$4 \cdot 10^9$	TNTC	$7 \cdot 10^9$

Raw data from biodigester test at RUA

Production from biodigesters at RUA are presented in Figure 38.

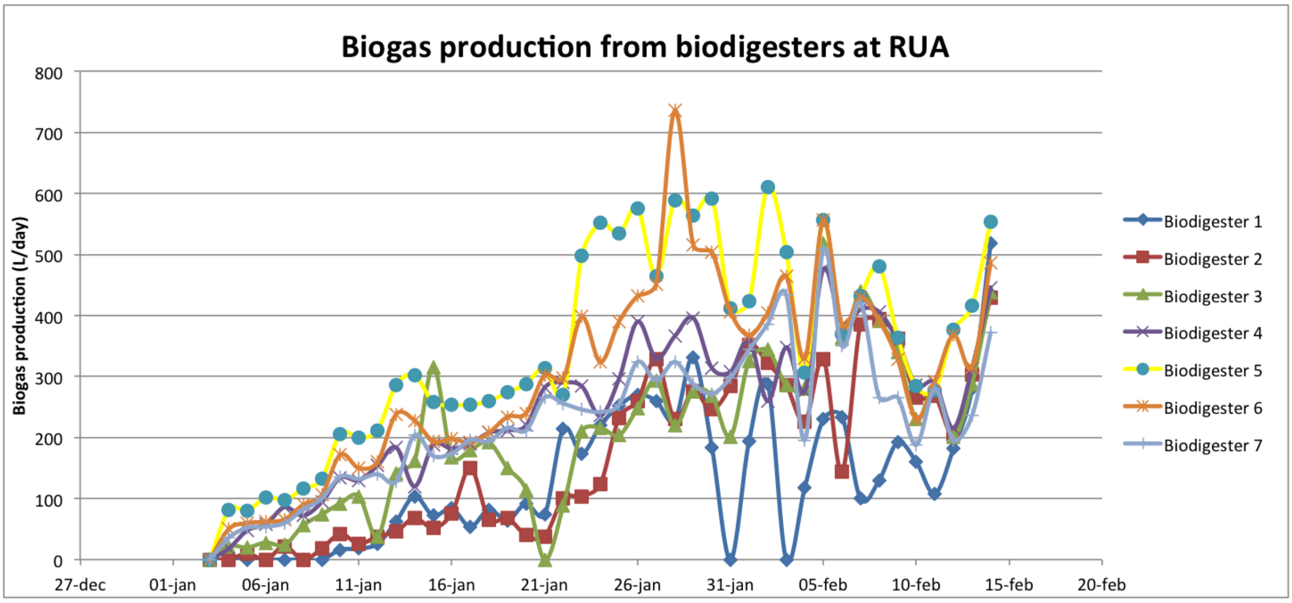

Figure 38. Biogas production for the seven biodigesters at RUA.

The information for the biodigesters at RUA are given in Table 28.

Table 28. Information for the biodigesters at RUA.

	Size (L)	Feed
Biodigester 1	400	6 kg pig manure
Biodigester 2	400	3 kg pig manure and 3 kg water hyacinth
Biodigester 3	500	6 kg pig manure
Biodigester 4	500	3 kg pig manure and 3 kg water hyacinth
Biodigester 5	900	6 kg pig manure
Biodigester 6	1400	6 kg pig manure
Biodigester 7	500	5.5 kg pig manure and 0.5 kg human waste

Pathogen testing on Biodigester 7

Pathogen concentrations in the input and output of biodigester 7 are presented in Table 29.

Table 29. Results from *E. coli* concentration in the input and output to biodigester 7.

	E. coli (CFU/100 mL)	Total coliforms (CFU/100 mL)
BD7 – In	$41 \cdot 10^6$	$192 \cdot 10^6$
BD7 - Out	$16 \cdot 10^5$	$22 \cdot 10^5$

$$Degradation\ factor\ E.coli = 1 - \frac{BD7-OUT}{BD7-IN} = 1 - \frac{16 \cdot 10^5}{41 \cdot 10^6} = 0.961 \qquad \text{(B-VII)}$$

$$Degradation\ factor\ total\ coliforms = 1 - \frac{BD7-OUT}{BD7-IN} = 1 - \frac{22 \cdot 10^5}{192 \cdot 10^6} = 0.989 \ \text{(B-VIII)}$$

Appendix C – Global Warming Potential calculations

The carbon cycle

It is important to clarify the way of thinking when considering which emissions that should be included in the calculations for Global Warming Potential.

In the natural carbon cycle, the CO_2 molecules assimilated by plants are degraded naturally by either pigs, humans or other animals and bacteria. If it is done aerobically, the CO_2 molecule is once again emitted back into the atmosphere as a by-product in the degradation. The molecules emitted were originally taken up from the atmosphere and they do not raise the concentration of molecules in the atmosphere. If new plants grow up, it is a natural cycle and thereby not increasing the global warming. The same reasoning applies for combustion of renewable bio-fuels like biogas from waste or crops. Since trees have a longer life cycle it is of importance to plant a new tree if you cut one down for combustion. If not, there is a net addition of greenhouse gases to the atmosphere since there will be no new tree to absorb carbon dioxide.

Methane is a stronger greenhouse gas than carbon dioxide. A net addition to the atmosphere is created when the assimilated carbon dioxide in the plants photosynthesis are broken down by anaerobic digestion and emitted as methane. When waste is digested anaerobically in Tonlé Sap, it is considered as a natural emission, but it still contributes to the global warming. If this methane leakage is stopped by introducing biodigesters, then all of the methane that otherwise would be emitted can be considered as a reduction of greenhouse gases. In the end, this value have to be corrected since another emission is created when the biogas are combusted to receive energy. The methane reduction becomes the difference between the carbon emission factors that methane and carbon dioxide have as greenhouse gases. The upper part of Figure 39 shows the situation with no waste management while the lower part shows the situation with waste management

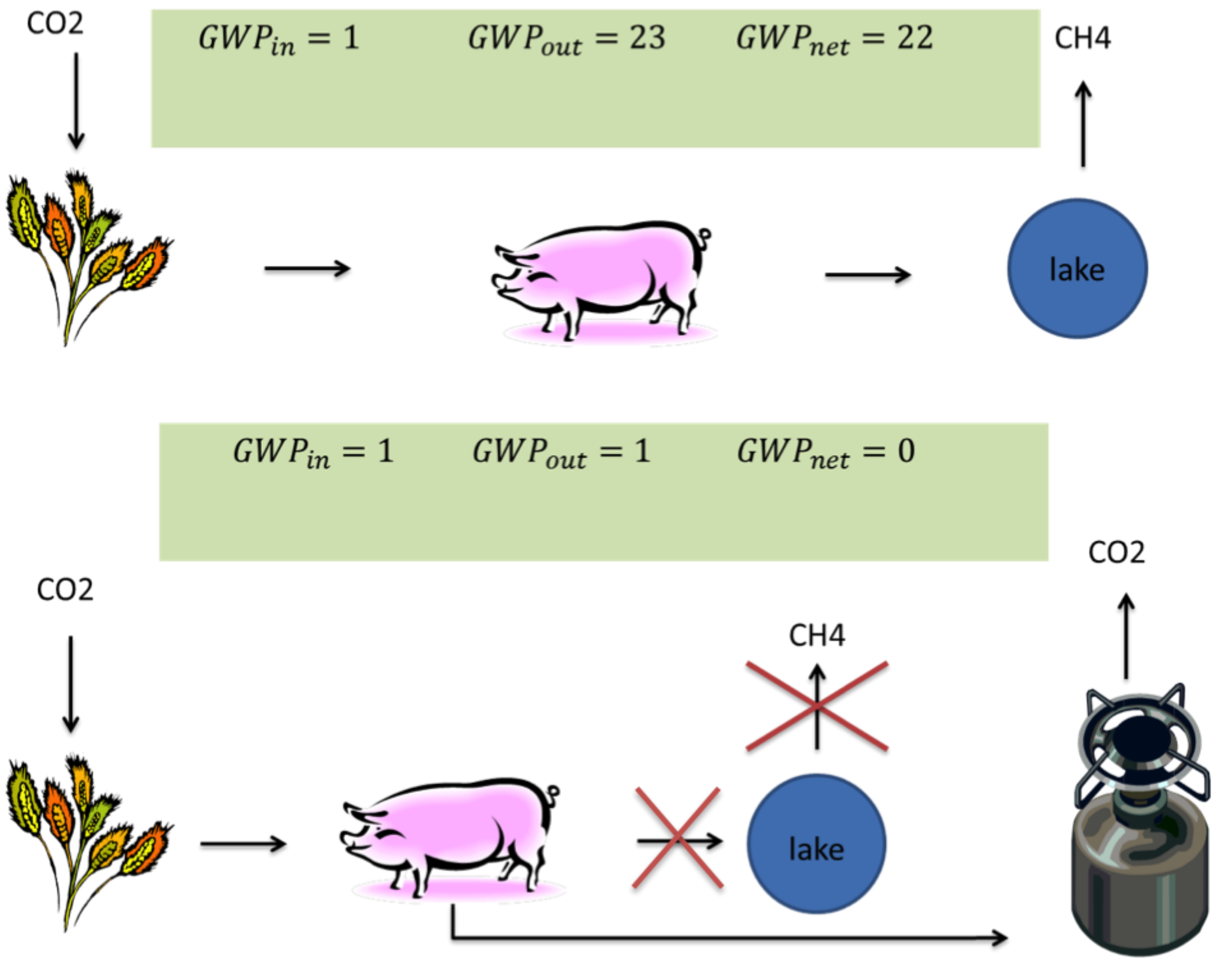

Figure 39. The cycle for one unit carbon dioxide without biodigesters above and with biodigesters below.

Calculations of changes in GWP, for the four scenarios when the indirect effects of methane leakage from the lake are included, are presented in this section. Since it is difficult to determine to what extent anaerobic digestion will take place in the lake two alternatives are presented, one alternative with 50 % anaerobic digestion and one alternative with 100 % anaerobic digestion. Calculations are in all scenarios shown for 100 % anaerobic digestion. Results from 50 % anaerobic digestion is only presented in the tables.

Scenario 1

In case no waste is used in the biodigesters, everything will be dumped in the water and potentially lead to methane leakage depending on how dominating anaerobic digestion is in the lake. The added waste has a potential biogas production of 300 L where 60 % is methane.

$V_l = Daily\ methane\ production\ in\ the\ lake = 180\ L$

$P = Pressure\ (assumed\ atmospheric) = 101\ 325\ Pa$

$R = 8.314\ kj\ /(mol \cdot K)$

$T = Temperature\ (assumed\ average\ air\ temperature) = 30^0 C = 303.15\ K$

$$n(CH_4) = \frac{P \cdot V_l}{R \cdot T} = \frac{101\ 325 \cdot 0.180}{8.314 \cdot 303.15} = 7.24\ mol \qquad \text{(C-I)}$$

$M_{CH_4} = 16.0\ g/mol$

$$m_{CH_4} = n(CH_4) \cdot M_{CH_4} = 115.8\ g \qquad \text{(C-II)}$$

Methane is a 23 times stronger greenhouse gas than carbon dioxide. However, when the methane is produced through anaerobic digestion, it replaces the CO_2-molecule that otherwise would be produced with aerobic digestion. The difference in GWP is therefore 22 $CO_{2,eq}$. The increased emission in $CO_{2,eq}$, by anaerobic digestion is therefore calculated by multiplying the mass of CH_4 with the difference in GWP.

$$115.8\ g\ CH_4 \cdot 22 = 2547\ g\ CO_{2,eq} \qquad \text{(C-III)}$$

Summary of scenario 1

The total emissions including firewood combustion is presented in Table 30.

Table 30. Methane leakage from waste in the lake water.

	50 % Anaerobic digestion	100 % Anaerobic digestion
Combustion of firewood (kg $CO_{2,eq}$/day)	5.97	5.97
Waste management (kg $CO_{2,eq}$ /day)	1.28	2.55
Total (kg $CO_{2,eq}$/day)	7.25	8.52

Scenario 2

Reduced methane leakage from biogas production

In scenario 2, 40 of the pig waste is lost meaning that 180 L of biogas will be produced in each biodigester (see section 6.2.3.3).

$V_b = Daily\ household\ biogas\ production = 180\ L$

The ideal gas law is used to calculate the number of moles in each gas and then the mass can be calculated. The biogas is assumed to have methane content of 60 % (SNV, 2009a)

$$V_{CH_4} = 180 \cdot 0.6 = 108\ L\ CH_4 \qquad \text{(C-IV)}$$

$P = Pressure\ (assumed\ atmospheric) = 101\ 325\ Pa$

$R = 8.314\ kj\ /(mol\ \cdot K)$

$T = Temperature\ (assumed\ average\ air\ temperature) = 30^0 C = 303.15\ K$

$$n(CH_4) = \frac{P \cdot V_{CH_4}}{R \cdot T} = \frac{101\ 325 \cdot 0.108}{8.314 \cdot 303.15} = 4.34\ mole \qquad \text{(C-V)}$$

$M_{CH_4} = 16.0\ g/mol$

$$m_{CH_4} = n(CH_4) \cdot M_{CH_4} = 69.47\ g \qquad \text{(C-VI)}$$

$$69.47\ g\ of\ CH_4 \rightarrow 69.47 \cdot 23 = 1598\ g\ CO_{2,eq} \qquad \text{(C-VII)}$$

Biogas combustion

The biogas that leaks from the lake is also containing 40 % CO_2. However, since plants previously have assimilated these molecules they are a part of the natural carbon cycle and should not be included in the system.

An important consideration is that when the biogas will be combusted, all of the CO_2 in the gas will be directly exhausted to the air and the CH_4 will be oxidized to CO_2. Gas stoves are usually very efficient and the assumption is that all methane is oxidized. If there is incomplete combustion there will also be some methane in the exhaust gases. The CO_2 emissions must be considered as an output from the biogas system since we are assuming all of the methane leakage to be an input to the system. Normally, combustion of gas from renewable sources like pig manure are not considered as an addition to the global warming. The CO_2 that flows through the gas stove will not be combusted and is considered inert. It is still presented in the formula below.

$$CH_4 + CO_2 + 2O_2 \rightarrow CO_2 + CO_2 + 2H_2O \qquad \text{(C-VIII)}$$

$n(CH_4) = 4.34\ mole$ (from equation C-V)

An element balance for the carbon atom gives the moles of CO_2 in the products.

$$n_1(CH_4) + n_2(CO_2) = n_1(CO_2) + n_2(CO_2) \qquad \text{(C-IX)}$$

Equation C-IX is simplified to equation C-X.

$$4.34\ mole = n_1(CO_2) \qquad \text{(C-X)}$$

$$m_{CO_2} = n(CO_2) \cdot M_{CO_2} = 4.34\ mole \cdot 44.0\ g/mol = 191\ g \qquad \text{(C-XI)}$$

GWP from methane leakage

With the same argument as above, 40 % of the pig manure that will not be put in the biodigester will be degraded in the lake and produce approximately:

$$V_b = biogas\ production\ from\ lost\ substrate = potential\ biogas\ production - actual\ biogas\ production = 300\ L/day - 180\ L/day = 120\ L/day \qquad \text{(C-XII)}$$

$$V_{CH_4} = 120 \cdot 0.6 = 72\ L/day \qquad \text{(C-XIII)}$$

The same calculations as before are performed to determine how many g $CO_{2,eq}$ that is released.

$$46.31\ g\ CH_4 \cdot 22 = 1018.88\ g\ CO_{2,eq} \qquad \text{(C-XIV)}$$

Notice that a carbon emission factor of 22 is used instead of 23 since it should be assumed that on CO_2 molecule is a part of the natural carbon cycle.

Summary of scenario 2

GHG emissions from the waste management are presented in Table 31.

Table 31. GHG emissions from indirect effects (Waste management) in scenario 2.

	50 % Anaerobic digestion	100 % Anaerobic digestion
Methane leakage from lake (kg $CO_{2,eq}$ /day)	0.51	1.02
Reduced methane leakage from lake (kg $CO_{2,eq}$ /day)	-0.80	-1.60
Combustion of biogas (kg $CO_{2,eq}$/day)	0.1	0.19
Total (kg $CO_{2,eq}$ /day)	-0.20	-0.39

Table 32 shows the total emission by also including emissions from combusting firewood.

Table 32. Total GHG emission in scenario 2 when indirect effects are included.

	50 % Anaerobic digestion	100 % Anaerobic digestion
Combustion of firewood (kg $CO_{2,eq}$ /day)	5.11	5.11
Waste management (kg $CO_{2,eq}$ /day)	-0.20	-0.39
Total (kg $CO_{2,eq}$ /day)	4.91	4.72

Scenario 3

Reduced methane leakage from biogas production

Since the biodigester will produce 300 L of biogas that volume will also be reduced as natural leakage. Similar calculations as for scenario 1 are used to estimate GHG reduction.

$V_b = Daily\ household\ biogas\ production = 300\ L$

The same calculations as for scenario 2 are performed to establish how much g CO_2-equivalents that are reduced.

The ideal gas law is used to calculate the number of moles in each gas and then the mass can be calculated. The biogas is assumed to have methane content of 60 %

$$V_{CH_4} = 300 \cdot 0.6 = 180\ L\ \ CH_4 \qquad \text{(C-XV)}$$

$P = Pressure\ (assumed\ atmospheric) = 101\ 325\ Pa$

$R = 8.314\ kj/(mol \cdot K)$

$T = Temperature\ (assumed\ average\ air\ temperature) = 30^0C = 303.15\ K$

$$n(CH_4) = \frac{P \cdot V_{CH_4}}{R \cdot T} = \frac{101\ 325 \cdot 0.180}{8.314 \cdot 303.15} = 7.24\ mol \qquad \text{(C-XVI)}$$

$M_{CH_4} = 16.0\ g/mol$

$$m_{CH_4} = n(CH_4) \cdot M_{CH_4} = 115.8\ g \qquad \text{(C-XVII)}$$

$$115.8\ g\ of\ CH_4 \rightarrow 115.8 \cdot 23 = 2\ 663\ g\ CO_{2,eq} \qquad \text{(C-XVIII)}$$

Scenario 3 reduces the methane leakage by 2 663 g $CO_{2,eq}$.

Biogas combustion

Carbon molecules are emitted back to the atmosphere through the biogas production

A similar element balance for the carbon atom (C-VIII) gives the moles of CO_2 in the products.

$$n_1(CH_4) + n_2(CO_2) = n_1(CO_2) + n_2(CO_2) \qquad \text{(C-XIX)}$$

Equation C-XIX is simplified to equation C-XX.

$$7.24\ mole = n_1(CO_2) \qquad \text{(C-XX)}$$

$$m_{CO_2} = n(CO_2) \cdot M_{CO_2} = 7.24\ mole \cdot 44.0\ g/mol = 318\ g \qquad \text{(C-XXI)}$$

Summary of scenario 3

GHG emissions from the waste management are presented in Table 33.

Table 33. GHG emissions from methane leakage in scenario 3.

	50 % Anaerobic digestion in lake	100 % Anaerobic digestion in lake
Methane leakage from lake (kg $CO_{2,eq}$/day)	0	0
Reduced methane leakage from lake (kg $CO_{2,eq}$/day)	-1.33	-2.663
Combustion of biogas (kg $CO_{2,eq}$/day)	0.16	0.318
Total (kg $CO_{2,eq}$/day)	-1.17	-2.345

Table 34 shows the total emission by also including emissions from combusting firewood.

Table 34. Total GHG emissions from scenario 3 when indirect effects are included.

	50 % Anaerobic digestion in lake	100 % Anaerobic digestion in lake
Combustion of firewood (kg $CO_{2,eq}$/day)	4.54	4.54
Waste management (kg $CO_{2,eq}$/day)	-1.17	-2.35
Total (kg $CO_{2,eq}$/day)	3.37	2.19

Scenario 4

It is assumed in this scenario that the biogas production is optimized to produce enough gas to fulfil the daily energy need for cooking. From section 6.2.3.1 the estimated daily energy need is 3.68 kWH corresponding to 1250 L biogas.

All energy is received from the biogas, thus no combustion of firewood will take place. In reality, it might be difficult to completely replace firewood since many of the fishermen smoke their fish. This is most likely more difficult with biogas stoves.

Realistically the accessible waste is not enough to produce 1250 L of biogas even if the process is optimised (SNV, 2009a). It needs to be complemented with more pig manure, water hyacinth or cow manure. To simplify this calculation, it is assumed that more manure is accessed from for instance farmers from land.

Reduction methane leakage from biogas production

Since the biodigester will produce 1250 L of biogas that volume will also be reduced as natural leakage.

$V_b = Daily\ household\ biogas\ prodution = 1250\ L$

The ideal gas law is used to calculate the number of moles in each gas and then the mass can be calculated. The biogas is assumed to have methane content of 60 %.

$$V_{CH_4} = 1250 \cdot 0.6 = 750\ L\ \ CH_4 \quad \text{(C-XXIII)}$$

$P = Pressure\ (assumed\ atmospheric) = 101\ 325\ Pa$

$R = 8.314 kj/(mol \cdot K)$

$T = Temperature\ (assumed\ average\ air\ temperature) = 30^0 C = 303.15\ 30^0 K$

$$n(CH_4) = \frac{P \cdot V_{CH_4}}{R \cdot T} = \frac{101\ 325 \cdot 0.75}{8.314 \cdot 303.15} = 30.15\ mol \quad \text{(C-XXIV)}$$

$M_{CH_4} = 16.0\ g/mol$

$$m_{CH_4} = 482.4\ g = 11\ 095\ \text{g}\ CO_{2,eq} \quad \text{(C-XXV)}$$

Biogas combustion

A similar element balance for the carbon atom (C-VIII) gives the moles of CO_2 in the products.

$$n_1(CH_4) + n_2(CO_2) = n_1(CO_2) + n_2(CO_2) \quad \text{(C-XXVI)}$$

Equation C-XXVI is simplified to equation C-XXVII.

$$30.15\ mole = n(CO_2) \quad \text{(C-XXVII)}$$

$$m_{CO_2} = n(CO_2) \cdot M_{CO_2} = 30.15\ mole \cdot 44.0\ g/mol = 1327\ g \quad \text{(C-XXVIII)}$$

Summary of scenario 4

GHG emissions from the waste management are presented in Table 35.

Table 35. GHG emissions from indirect effects when all firewood is replaced.

	50 % Anaerobic digestion in lake	100 % Anaerobic digestion in lake
Methane leakage from lake (kg $CO_{2,eq}$/day)	0	0
Reduced methane leakage from lake (kg $CO_{2,eq}$/day)	-5.5	-11.1
Combustion of biogas (kg $CO_{2,eq}$/day)	0.66	1.32
Total (kg $CO_{2,eq}$/day)	-4.84	-9.78

Table 36 shows the total emission by also including emissions from combusting firewood.

Table 36. Total GHG emissions from scenario 4 when indirect effects are included.

	50 % Anaerobic digestion in lake	100 % Anaerobic digestion in lake
Combustion of firewood (kg $CO_{2,eq}$/day)	0	0
Waste management (kg $CO_{2,eq}$/day)	-4.84	-9.78
Total (kg $CO_{2,eq}$/day)	-4.84	-9.78

Appendix D – Equations

Complete calculations for the equations given in the report are presented in this section.

I. $$Y = \frac{Full\ scale\ amount\ of\ waste(kg)}{lab\ scale\ amount\ of\ \ waste\ (kg)} = \frac{165+15}{0.467+0.041} = 354.3$$

II. $$PW_N + HW_N = 23 + 9.8 = 33kgN/day$$

III. $$PW_P + HW_P = 34.8 + 1.2 = 36\ kgP/day$$

IV. $$PW_N + HW_N = 23 + 9.8 = 33\ kgN/day$$

V. $$PW_P + HW_P = 34.8 + 1.2 = 36\ kgP/day$$

VI. $$0.2 \cdot HW_N = 0.2 \cdot 9.8 = 2\ kgN/day$$

VII. $$0.2 \cdot HW_P = 0.2 \cdot 1.2 = 0.250\ kgP/day$$

VIII. $$HW_{e.coli} +\ PW_{e.coli} = 1.21 \cdot 10^{11} + 1.52 \cdot 10^{12} = 1.64 \cdot 10^{12}\ CFU$$

IX. $$HW_{tot.col} +\ PW_{tot.col} = 3.38 \cdot 10^{11} + 0.3 \cdot 10^{12} = 2.64 \cdot 10^{12}\ CFU$$

X. $$(0.4 \cdot PW_{e.coli}) + \left(0.6 \cdot PW_{e.coli} \cdot (1-F)\right) + \left(0.8 \cdot HW_{e.coli} \cdot (1-F)\right) + (0.2 \cdot HW_{e.coli}) = (0.4 \cdot 1.52 \cdot 10^{12}) + \left(0.6 \cdot 1.52 \cdot 10^{12} \cdot (1-0.96)\right) + \left(0.8 \cdot 1.21 \cdot 10^{11} \cdot (1-0.96)\right) + (0.2 \cdot 1.21 \cdot 10^{11}) = 6.73 \cdot 10^{11}\ CFU$$

XI. $$(0.4 \cdot PW_{tot.col}) + \left(0.6 \cdot PW_{tot.col} \cdot (1-F)\right) + \left(0.8 \cdot HW_{tot\ col} \cdot (1-F)\right) + (0.2 \cdot HW_{tot.col}) = (0.4 \cdot 2.3 \cdot 10^{12}) + \left(0.6 \cdot 2.3 \cdot 10^{12} \cdot (1-0.989)\right) + \left(0.8 \cdot 3.38 \cdot 10^{11} \cdot (1-0.989)\right) + (0.2 \cdot 3.38 \cdot 10^{11}) = 1 \cdot 10^{12}\ CFU$$

XII. $$0.2 \cdot HW_{e.coli} = 0.2 \cdot 1.21 \cdot 10^{11} = \ 2.42 \cdot 10^{10}\ CFU$$

XIII. $$0.2 \cdot HW_{tot.col} = 0.2 \cdot 3.38 \cdot 10^{11} = 6.76 \cdot 10^{10}\ CFU$$

XIV. $$E_b = C_b \cdot V_b \cdot \eta_b = 6 \cdot 0.3 \cdot 0.49 = 0.882\ kWh$$

XV. $$E_w = C_w \cdot m_w \cdot \eta_w = 4.33 \cdot 3.4 \cdot 0.25 = 3.68\ kWh$$

XVI. $$E = n \cdot E_b = 0.6 \cdot 0.882 = 0.530\ kWh$$

XVII. $$\frac{E}{E_w} = \frac{0.530\ kWh}{3.68\ kWh} = 0.144 = 14.4\ \%$$

XVIII. $$CO_{2,eq/day} \cdot (1 - 0.144) = 5.97 \cdot (1 - 0.144) = 5.11\ \ kg\ CO_2\ eq/day$$

XIX. $$V_b = biogas\ production \cdot substrate\ production = 50\ L/kg \cdot 6kg = 300\ L$$

XX. $$\frac{E_b}{E_w} = \frac{0.882\ kWh}{3.68\ kWh} = 0.240 = 24\ \%$$

XXI. $$CO_{2,eq/day} \cdot (1 - 0.240) = 5.97 \cdot (1 - 0.240) = 4.54\ \ kg\ CO_2\ eq/day$$

Appendix E – Calculations for amount of pigs in Phat Sanday

Calculations from the sensitivity analysis regarding the amount of pigs are presented in this section. The results show how much the load of nutrients from the community varies when amount of pig owners where either 5, 50 or 100 % of all households in the community.

$$Number\ of\ households = 980$$

$$Citizens\ in\ the\ community = 6\,954$$

$$Average\ number\ of\ pigs = 2$$

$$100\ \%\ pig\ owners \rightarrow 2 \cdot 980 = 1\,960\ pigs\ in\ the\ community$$

$$50\ \%\ pig\ owners \rightarrow 2 \cdot 980 \cdot 0.5 = 980\ pigs\ in\ the\ community$$

$$5\ \%\ pig\ owners \rightarrow 2 \cdot 980\ \cdot 0.05 = 98\ pigs\ in\ the\ community$$

Data from Table 4 presenting daily load of nutrients in gram of total phosphorous and nitrogen per pig and human where used and multiplied with number of pigs and number of humans in the community. The results are shown in Table 37.

Table 37. Daily community load of nutrients depending on number of pigs.

	5%	5%	50%	50%	100%	100%
Pig manure	1.74	1.15	17.42	11.49	34.84	23.00
Human waste	1.15	9.84	1.15	9.84	1.15	9.84
	Tot-P	Tot-N	Tot-P	Tot-N	Tot-P	Tot-N

Same procedure was used to estimate the community's daily pathogen addition but data of total coliforms per pig and human where collected from Table 8. Results are presented in Table 38.

Table 38. Daily community load of total coliforms depending on number of pigs.

Percentage pig owners in community	5 %	50 %	100 %
Pig manure (10^{12} CFU total coliforms)	0.12	1.16	2.31
Human waste (10^{12} CFU total coliforms)	0.48	0.48	0.48
Total (10^{12} CFU total coliforms)	**0.60**	**1.64**	**2.79**

To calculate the daily community additions of pathogens when biodigesters were implemented according to scenario 2 and 3, the equations XI and XIII were used and the percentage of pig owners where included in the parts of the equations that concerned pig manure, see Table 39.

Table 39. Daily community load of total coliforms for the three scenarios, depending on presence of pigs.

Percentage pig owners in community	5 %	50 %	100 %
Tot. load of coliforms for scenario 1 (10^{12} CFU)	0.60	1.64	2.64
Tot. load of coliforms for scenario 2 (10^{12} CFU)	0.15	0.57	1.04
Tot. load of coliforms for scenario 3 (10^{12} CFU)	0.067	0.067	0.067