WASTEWATER SLUDGE MANAGEMENT OPTIONS FOR HONDURAS

BY

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ABSTRACT

Sludge management is a fundamental area of concern across wastewater treatment systems in Honduras. The lack of timely sludge removal has led to declining plant performance in many facilities throughout the country. In addition to maintaining treatment efficiency, proper sludge management is important for mitigating pathogen levels and providing opportunities for safe beneficial reuse of biosolids.

Based on analyses of data collected at waste stabilization ponds in the municipalities of Puerto Cortes and La Lima, sludge was characterized with respect to quantities generated (accumulation rates) and quality (helminths and heavy metals content). A review was conducted of appropriate sludge treatment technologies including sludge drying beds, alkaline stabilization, acid stabilization, anaerobic digestion, and composting. These options were evaluated based on a set of selected criteria. Anaerobic digestion, alkaline stabilization, and composting were all found to be suitable methods of sludge treatment. Alkaline stabilization and composting are well suited to facilities with sufficient land. Anaerobic digestion was recommended for areas with land constraints.

Treated biosolids can be beneficially used within the community and/or at a regional scale. Potential regional end-uses include soil amendment in agriculture and forestry, or for land reclamation of mined lands. Public participation and acceptance is essential for the success of a biosolids reuse program. Potential strategies for engaging the community and addressing public concerns regarding biosolids were identified.

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1.0 INTRODUCTION

1.1 Project Background and Objective

During the academic year of 2008-2009, three Masters of Engineering students from the Department of Civil and Environmental Engineering at the Massachusetts Institute of Technology (MIT) conducted a study of wastewater treatment systems in Honduras. The purpose of the study was to assess the state of centralized wastewater treatment facilities, focusing on Imhoff tank and wastewater stabilization pond systems with a cursory look at other forms of treatment implemented in the country. This project included travel to Honduras in January 2009 for a field survey of these systems (Bhattacharya et al, 2009). A summary of this investigation is presented in Chapter 2.

In addition to this assessment, each member of the research team focused on a particular aspect of wastewater treatment specific to Honduras. This study addresses the management of wastewater sludge generated from treatment facilities.

Sludge management is a fundamental area of concern across wastewater treatment systems in Honduras. Previous studies of different wastewater treatment systems in Honduras, including Imhoff tanks (Herrera, 2006; Hodge, 2008) and waste stabilization ponds (Oakley et al., 2000), have indicated the need for regular sludge removal in order to maintain treatment efficiencies. Sludge management is gaining growing importance in Honduras as an increasing number of wastewater treatment systems become critically overdue with respect to desludging. This is largely due to the lack of initial funding allocation and planning for sludge management during the design of treatment facilities.

Sludge, the concentrated solids waste stream generated from wastewater treatment, has important public health implications. Due to the high pathogen levels, proper solids treatment and disposal should be considered as part of the overall sludge management plan (Oakley, 2005).

This study provides an overview of current sludge management practices in Honduras, as observed during field visits. Based on analyses of data collected at selected treatment facilities, sludge was characterized with respect to quantities generated and quality. A review of appropriate sludge treatment technologies was carried out; these were assessed based on a set of selected evaluation criteria leading to recommendations for the most suitable stabilization methods. Some preliminary design estimations for selected technologies have been provided for municipalities where field measurements were taken. End-use scenarios for treated biosolids, both at a regional and community scale, were also discussed.

Ultimately, this study aims to provide suggestions for viable and beneficial wastewater sludge management strategies for municipalities in Honduras.

1.2 Honduras: General Background

The Republic of Honduras is the second largest country in Central America, covering a total area of 112,000 square kilometers. The total population is about 7.7 million, with 43% representing urban dwellers and 57% residing in rural areas.

Honduras is a Spanish-speaking nation comprised of 18 departments or political territories, which are further divided into a total of 298 municipalities. The nation is democratic, with universal mandatory voting by all citizens over the age of 18 years (U.S. CIA, 2008). The country's capital of Tegucigalpa is also its largest city, where 12% of the population resides. Figure 1.1 provides an overview map of Honduras showing its geographic location and major cities.

Figure 1.1 Overview Map of Honduras (Encyclopedia Britannica, 2009).

Honduras has one of the highest levels of poverty in the Central American region, with 65% of the population living on less than two dollars a day (Water for People, 2006) and a nominal per capita GDP of $1,635 (FCO, 2008). The literacy rate in the nation was reported to be about 80% on the 2001 census. The median age in the country is 20 years, with a life expectancy at birth of 69 years (U.S. CIA, 2008).

Agriculture contributes to a large portion of the economy, with banana, coffee, tobacco, and sugarcane being some of the country's main exports. Forestry, livestock, aquaculture, manufacturing and mining represent other important sectors of the economy. The economy has generally been geographically divided, with subsistence farming, livestock raising, and mining commonly practiced in higher mountainous terrain, and intensive plantation farming dominating in the flatter lowlands.

1.3 Honduras: Water and Sanitation

Poverty reduction, through the provision of essential services such as adequate water and sanitation, has been a primary development initiative in Honduras (Mikelonis, 2008). However, poverty levels have also been a factor in the historical lack of sewerage fee collection, with current service providers facing cultural and economic challenges in levying rates on sanitation services. As a result, sanitation is largely inadequate throughout the country; in urban areas, 41% of all residences lacked sanitation services as of 2001, while rural sanitation connection rates were reportedly below 20% (WHO, 2001). Similar investigative work performed by the organization Water for People five years later found improvement in these numbers, as indicated in Table 1.1; however, services are still lacking across both urban and rural populations.

Table 1.1 Sanitation Coverage in Rural and Urban Areas of Honduras (Water For People, 2006).

Sanitation Coverage in Honduras 2001 Groups of Population	2001 Population	Population with Sewerage Service	Population with Latrines	Total Population Served	Coverage %
Rural	3,113,304	-	1,541,085	1,541,085	49.5
Urban	2,895,776	1,538,440	1,006,947	2,545,387	87.9
Global	6,009,080	1,538,440	2,548,032	4,086,472	68.0

Inadequate sanitation has severe consequences for the population of Honduras with regards to water-related diseases. The country has a high infant mortality rate of 42 out of 1000 births, the leading cause of which is reported to be intestinal infectious diseases. For children under the age of 5, the second leading cause of death is diarrheal diseases. Major water-related diseases include waterborne (e.g. bacterial diarrhea, hepatitis A, typhoid fever) as well as vector-borne illnesses (e.g. malaria and dengue fever), whose transmission is exacerbated by unsanitary conditions. Cholera, a waterborne illness previously eradicated from Honduras, re-emerged with an outbreak in 2001. Proper sanitation is therefore critical to raising the standards of public health in the nation (WHO, 2001).

2.0 SURVEY OF WASTEWATER TREATMENT SYSTEMS IN HONDURAS

During the academic year 2008-2009, MIT Masters of Engineering students, Lisa Kullen, Mahua Bhattacharya, and Robert McLean, jointly carried out a study of centralized wastewater treatment systems in Honduras. The purpose of the study was to assess the state of these treatment facilties, including Imhoff tanks, waste stabilization ponds, constructed wetlands, and package activated sludge systems. This was done through field visitations of ten different facilities, based on which observed trends and recommendations for system improvements were developed. This section provides a brief summary of this study, with a focus on sludge management practices. For further details on this project, the reader is referred to the joint team report *Evaluating Wastewater Treatment Options for Honduras* (Bhattacharya et al., 2009).

2.1 Sites Visited

The research team visited ten different wastewater treatment facilties in Honduras during January of 2009. These included facilities at the municipalities of Guaimaca, Talanga, Villa Linda Miller, Amarateca, Teupasenti, Las Vegas, Puerto Cortés, Choloma, La Lima, and Tela. An effort was made to select systems that are representative of those found throughout the country. Thus the ten facilities included Imhoff tanks, waste stabilization ponds, constructed wetlands, anaerobic treatment and aerated package plants.

The characteristics of the systems were found to vary considerably. Some have received regular attention with regards to operation and maintenance while others have been maintained minimally or abandoned. Other variables represented in the facility roster were urban versus rural, inland versus coastal, newer versus older, and larger versus smaller. In particular, two systems studied were over 15 years old while four were less than 4 years old, and the populations served ranged from 1,700 to 50,000 people. A listing of these facilities is presented in Table 2.1 below.

Table 2.1 Summary of Facilities Visited.

Location	Date Visited	Treatment Type
Guaimaca	10-Jan-09	Imhoff Tank and Constructed Wetland
Talanga	10-Jan-09	Waste Stabilization Ponds
Villa Linda Miller	10-Jan-09	Imhoff Tank and Anaerobic Filter
Amarateca	11-Jan-09	Package Plants
Teupasenti	11-Jan-09	Anaerobic Treatment and Constructed Wetland
Las Vegas	7-Jan-09	Imhoff Tank
Puerto Cortés	20-Jan-09	Waste Stabilization Ponds
Choloma	19-Jan-09	Waste Stabilization Ponds
La Lima	17-Jan-09	Waste Stabilization Ponds
Tela	18-Jan-09	Waste Stabilization Ponds

2.2 Sludge Management Practices

Of the wastewater treatment systems visited, only three had reportedly been desludged at least once. Most facilities that had not performed desludging did not have any explicit sludge management strategy in place at the time of the survey.

A number of the facilities were recently brought into operation and have not yet needed to carry out desludging. Facilities such as those in La Lima and Puerto Cortés have been monitoring sludge depth and are reportedly in the process of developing a sludge management plan. Puerto Cortés anticipates desludging its anaerobic ponds later this year.

The systems at Tela, Teupasenti, and Las Vegas reportedly have been desludged although not necessarily on a routine basis. Sludge levels at Tela had reached critical levels, surfacing through the water level at the primary facultative lagoon. In 2007, solids were dried and buried onsite in order to minimize transportation costs and risks associated with environmental contamination and public health (EWB, 2006). At Las Vegas, sludge was both discharged to Raices Creek and buried onsite. This was also carried out in 2007, which was reportedly the first time since the tank came into operation in 1992; the system currently shows signs of requiring desludging once again. Drying beds were used for sludge management at Teupasenti; it is unclear how frequently sludge was removed at this facility. None of the facilities surveyed has been successful in implementing or marketing sludge for beneficial reuse.

Based on the survey, there appears to be a general lack of planning and maintenance with respect to sludge management. Of the three facilities known to have carried out desludging, two (Las Vegas and Tela) had been done after sludge depths had reached critical levels.

3.0 SLUDGE MANAGEMENT

Sludge management is a critical, yet often neglected, aspect of wastewater treatment. Timely sludge removal from treatment systems plays an important role in preventing loss of effective treatment capacity and maintaining design hydraulic retention times. Because raw wastewater sludge contains concentrated levels of pathogens, safe handling and disposal (or reuse) of this material is essential from a public health standpoint. Sludge also contains high amounts of organic matter and nutrients, which can be beneficially reused. Therefore, proper sludge management is not only important with regards to wastewater treatment efficiency and public health, it can also allow the wider community to utilize the resource value of sludge which would otherwise go to waste.

3.1 The Importance of Sustainable Sludge Management

Lack of adequate sanitation is a major contributor to waterborne diseases in the developing world. Incidences of diarrheal and parasitic diseases are largely due to unsanitary conditions, which are often a result of the interaction between wastewater and drinking water. This highlights the importance of appropriate wastewater and drinking water treatment in reducing such diseases.

Though less emphasized, sludge management is also critical for controlling the spread of pathogens. Sludge, the solids waste stream generated from wastewater treatment processes, contains concentrated levels of pathogens and organic matter. The incidences of some diseases, such as helminthiasis, are closely linked to sludge and wastewater effluent management practices (USEPA, 1991). The land application of inadequately treated sludge can significantly contribute to the spread of helminths. In Honduras, the prevalence of helminth infections is about 60% in endemic regions (Oakley et al., 2000).

As the need for wastewater treatment in the developing world grows, devising appropriate management strategies to address the resulting increment in sludge generation will become imperative.

3.1.1 Economic Considerations

Sludge management is an aspect that is often not considered when planning financial budgets for wastewater treatment systems in developing countries. For instance, the Nicaraguan Institute of Water Supply and Sewerage (INAA), which is responsible for wastewater effluent monitoring, operation and maintenance, did not budget for costs associated with sludge handling and removal from municipal wastewater stabilization ponds within their financial plans. As a result, ponds in operation for over 10 years had not been desludged (Oakley et al., 2000). This oversight, which is common in many other countries, is particularly significant when one considers that sludge management can represent up to 50% of the total cost of a wastewater treatment plant (Jimenez et al., 2004).

There are a number of long-term economic benefits that could be realized through proper sludge treatment and reuse. These include potential savings in public health resources (particularly regarding treatment of waterborne diseases), decrease in use of chemical fertilizers, and reduction in land degradation. In many developing countries, intensive agriculture depletes the organic content of soils. Because crop residues are often used as fuel or fodder, soil is inadequately replenished with organic matter. A study by the FAO (2003) based on 15 different developing regions found land degradation contributed to 1-12% loss of agricultural GDP (AGDP). In Mexico, losses up to 12.3% of AGDP were estimated in severely eroded regions. The controlled application of treated biosolids can recycle nutrients and change soil conditions by improving structure, organic matter content, and water retention capacity (Jimenez et al., 2004). It can also reduce costs associated with the use of commercial fertilizers.

3.1.2 Sludge Quality Considerations

While sludge reuse alternatives can provide significant value, it is vital to assess the quality of sludge prior to reuse in order to mitigate negative impacts on public and ecological health. Based on the sludge quality characterization, suitable treatment methods can be identified to lower pathogen content and to address issues related to odor and vector attraction.

As mentioned earlier, land application of raw sludge with high pathogen content can contribute to bacterial and parasitic infections. In Honduras, high sludge concentrations of helminth eggs are of particular concern. Because these are very resistant and can survive in the environment for long periods of time, conventional treatment methods are not very effective in producing biosolids that are safe for reuse. Sludge quality in Honduras is discussed in further detail in Chapter 4. Based on this, Chapter 5 provides a discussion and assessment of various suitable treatment technologies.

3.2 Biosolids Reuse Guidelines

In order to determine whether treated biosolids are safe for reuse, some criteria must be established to guide sludge handling and treatment efforts. At present, there are no set sludge treatment guidelines in Honduras. In this section, sludge regulation from the US EPA, Mexico, and the World Health Organization (WHO) are considered.

3.2.1 USEPA Regulations on Biosolids Reuse

The USEPA's regulations on biosolids reuse are detailed in 40 Code of Federal Regulations (CFR) Part 503. The regulations specify two different quality levels for biosolids: Class A and Class B. Class A biosolids are of the highest quality and can be applied for "unrestricted use". This implies that a Class A product, which has very low levels of pathogens, can be used in the same manner as commercial fertilizers. For helminth eggs in particular, Class A standards require that there are less than 1 viable egg per 4 grams of TS (0.25 eggs/g TS).

In order to attain Class B standards, sludge must also undergo some form of treatment process to significantly reduce pathogen content. Class B biosolids can be applied to agricultural land with certain restrictions regarding public access and management of crops. There are no specific limitations for helminth eggs under Class B requirements (USEPA, 2001).

The Class A and Class B standards with respect to pathogens are summarized in Table 3.1.

3.2.2 Mexican Standards for Biosolids Reuse

The Mexican standards for biosolids are detailed in the Mexican Official Standard NOM-004-ECOL and are structurally modeled after the USEPA's regulations. As shown in Table 3.1, Mexican Class A and Class B standards require the same limits for heavy metals, fecal coliforms and *Salmonella* as USEPA regulations. With respect to helminth eggs, however, Mexican standards have higher limits and stipulate restrictions for both Class A and Class B biosolids. This adjustment is likely due to higher helminth egg concentrations in raw sludge compared to situations in the US. In addition, while the USEPA monitors viable eggs only, the Mexican regulations include both viable and non-viable eggs (Jimenez et al., 2004).

3.2.3 WHO Guidelines

The WHO guidelines (2006) for fecal matter or fecal sewage suggest treatment to reduce helminth egg concentrations to below 1 egg/gTS. The guidelines do not distinguish between viable and non-viable helminth eggs.

Table 3.1 Summary of USEPA, Mexican, and WHO pathogen guidelines for biosolids reuse.

	Fecal Coliform Bacteria (MPN/g TS)	Helminth Eggs (eggs/g TS)
USEPA		
Class A	1×10^3	0.25**
Class B	2×10^6	No limit
Mexico		
Class A	1×10^3	10
Class B	2×10^6	35
WHO	<1000*	<1

*E.Coli only
**Viable eggs only

For the purposes of this study, the Mexican standards for biosolids reuse will be used for evaluating the various sludge treatment technologies examined in later sections of this report.

4.0 SLUDGE CHARACTERIZATION

As discussed in Chapter 3, sludge characterization is one of the key components that form the basis of sound biosolids management strategies. Appropriate treatment and reuse options are significantly dependent on sludge characteristics such as total volume, solids content, and pathogen levels. In this chapter, sludge is characterized both with respect to quantity and quality parameters. Some of these, including estimates for sludge volume, are based on field data whereas other aspects have been developed from a review of available literature.

Based on the sludge volume estimates and quality analysis, some preliminary design calculations will be made in later sections of this report for treating sludges produced in waste stabilization ponds at the municipalities of La Lima and Puerto Cortes, where most of the fieldwork for this study was carried out. Although no sludge measurements were carried out for Imhoff tanks or other systems, final recommendations for sludge stabilization technologies and end-use options will consider solids produced at different types of facilities Honduras.

4.1 Sludge Quantity

The quantity of sludge generated determines the size of treatment system required, as well as the magnitude of costs associated with solids handling and disposal. Sludge volumes were estimated for Puerto Cortes and La Lima based on gathered field data. This section discusses the applied methodology and results for this analysis, and how they compare to results obtained in other studies.

4.1.1 Field Data Collection

During field visits in January of 2009, sludge depth measurements were taken from two different waste stabilization pond systems. Data was collected from two anaerobic ponds and two facultative ponds at Puerto Cortes and La Lima, respectively.

Sludge depth measurements were carried out at specific intervals along the pond dimensions using either the “white towel” method or a hatched PVC pipe. For the white towel method, white absorbent cloth was wrapped and attached around the end of a long wooden pole and submerged vertically into the pond until it reached the pond bottom. It was then gradually withdrawn and the sludge level was measured using a measuring tape. The level was clearly visible as solids particles became entrapped in the cloth, roughly demarcating the thickness of the sludge bed.

A hatched PVC pipe can also be similarly used for measuring sludge depths. Sludge blanket levels can be approximated visibly as some of the solids particles got entrapped into the hatched sections.

Depth readings were taken along a grid across the pond, with grid units ranging from approximately 7 to 10 m in width and length. Boats, which were provided onsite by the facility operators, were used to access the various measurement locations in the pond. A sludge profile was developed for each pond based on these measurements from which total volumes were estimated.

Puerto Cortes: Anaerobic Waste Stabilization Ponds

The facility at Puerto Cortes consists of two parallel circuits, each consisting of an anaerobic pond and a facultative pond in series. Downstream of the facultative ponds, both circuits are joined and flow through two maturation ponds in series as shown in Figure 4.1. Planned future expansions include one additional anaerobic, facultative, and maturation pond each. The facility currently services approximately 50,000 people and has been in operation for about 2.5 years. The final effluent is discharged to the Alvarado Lagoon, off the Caribbean Sea.

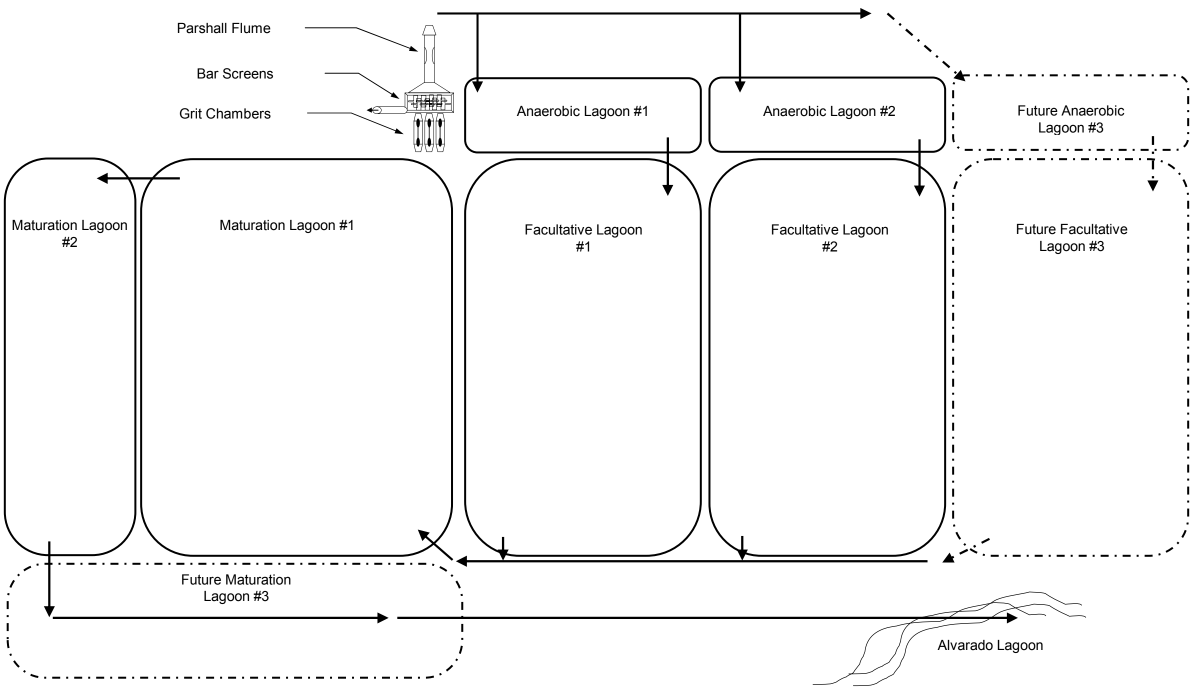

Figure 4.1 Schematic of the waste stabilization pond system at Puerto Cortes (Bhattacharya et al, 2009).

Sludge depth measurements were taken in the anaerobic ponds only; it was assumed that the bulk of sludge deposition within the system occurs in these ponds. This appeared to be reasonable given that, according to the facility manager, previous sludge depth measurements had shown levels in facultative ponds to be significantly lower than those in the anaerobic ponds.

Sludge depth readings were taken at 27 different locations across each pond and are shown in Tables 4.1 and 4.2. Sludge readings were found to be highest in Anaerobic Lagoon 2. At Puerto Cortes, the hatched PVC pipe method was used for measuring sludge depths. This approach had been previously used by the operations staff and was also adopted for this study. Certain readings taken in Anaerobic Lagoon 1 were at the maximum recordable level (0.64 m) due to limited number of hatches on the PVC pipe suggesting that actual levels may be higher.

Additional hatches were made on the pipe prior to taking readings at Anaerobic Lagoon 2. Highest levels in Lagoon 2 (1 m) exceeded those in Lagoon 1, likely due to the increased measurement capacity. However, in this case also the maximum recordable level was reached. This suggests certain sludge levels in both lagoons may be higher than recorded.

Table 4.1 Sludge depth readings in Anaerobic Lagoon 1 at Puerto Cortes.

	DISTANCE ACROSS POND WIDTH* (m)		
	14	21	28
14	0.58	0.6	0.35
24	0.64	0.64	0.46
34	0.63	0.51	0.42
44	0.29	0.48	0.32
54	0.21	0.18	0.23
64	0.13	0.15	0.23
74	0.11	0.21	0.23
84	0.18	0.26	0.18
94	0.21	0.18	0.18

*Starting from left to right facing upstream
**Starting in upstream direction

Table 4.2 Sludge depth readings in Anaerobic Lagoon 2 at Puerto Cortes.

	DISTANCE ACROSS POND WIDTH* (m)		
	14	21	28
14	1	1	0.96
24	1	1	1
34	0.98	1	0.91
44	0.98	0.94	0.76
54	0.26	0.49	0.35
64	0.03	0.23	0.42
74	0.03	0.23	0.26
84	0.03	0.06	0.03
94	0.03	0.03	0.1

*Starting from left to right facing upstream
**Starting in upstream direction

La Lima: Facultative Ponds

La Lima's waste stabilization pond system has been in operation for about 3.5 years. Although the facility currently services a population of approximately 3500, the total design capacity is for 10,000 people. The system consists of two parallel flow circuits, each flowing through a facultative pond and a maturation pond in series (Figure 4.2). The final effluent is discharged to the Rio Chamelecon.

Sludge measurements at this facility were taken at the facultative ponds only, as these generally tend to accumulate the bulk of sludge depositions (Mara, 2003). Measurements in both ponds were taken using the white towel method described earlier. Tables 4.3 and 4.4 show the sludge depth readings obtained for Facultative Lagoons 1 and 2.

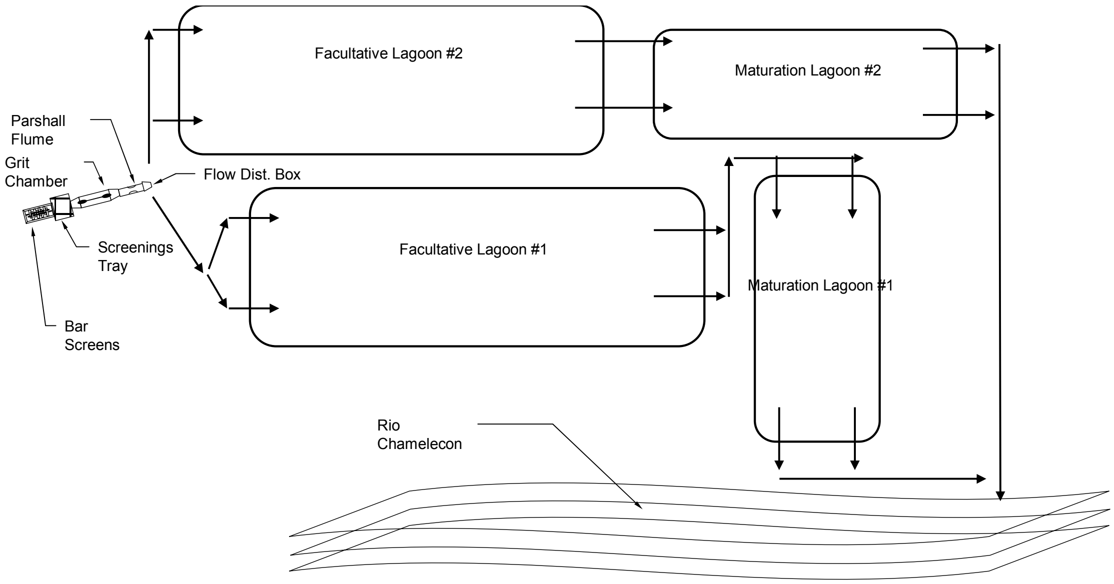

Figure 4.2 Schematic of the waste stabilization pond system at La Lima (Bhattacharya et al, 2009).

Table 4.3 Sludge depth readings in Facultative Pond 1 at La Lima.

		DISTANCE ACROSS POND WIDTH* (m)			
		10	20	30	40
	11.5	11	13	64	5
	21.0	16	13	19	11
	30.5	9	10	9	7
	40.0	13	7	7	12
	49.5	8	6	9	6
	59.0	8	12	3	8
	68.5	10	13	10	5
	78.0	13	18	12	5

* Starting from left to right facing upstream
** Starting in upstream direction
No reading (off pond)

Table 4.4 Sludge depth readings in Facultative Pond 2 at La Lima.

		DISTANCE ACROSS POND WIDTH* (m)				
		2	11	20	29	38
	2.0		0.16	0.23	0.27	
	11.5	0.11	0.13	0.14	0.28	0.16
	21.0	0.08	0.11	0.13	0.29	0.15
	30.5	0.06	0.09	0.11	0.26	0.18
	40.0	0.13	0.09	0.12	0.13	0.13
	49.5	0.12	0.09	0.12	0.16	0.13
	59.0	0.11	0.15	0.12	0.17	0.1
	68.5	0.05	0.13	0.15	0.14	0.1
	78.0	0	0.16	0.15	0.14	

* Starting from left to right facing upstream
** Starting in upstream direction
No reading (off pond)

In all the ponds studied, the majority of sludge deposition occurred mainly over the initial one-third of the total pond length, with especially high peaks observed in front of the inlet pipes. This distribution pattern is similar to that expected in an ideal plug flow reactor. If the physical solids settling process is modeled as first-order decay, then solids concentration profiles vary with distance as shown in Figure 4.3 (assuming a constant velocity, v). It can be seen that the solids concentration (C) would decrease at a higher rate (i.e. higher rate of removal) over the initial length (d) of the reactor. This corresponds to a higher solids deposition, or sludge levels, at lower values of d.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

(d)

Figure 4.3 Concentration profile for first-order decay in an ideal plug flow reactor (von Sperling, 2007).

4.1.2 Estimation of Sludge Volume and Accumulation Rates

Sludge depth profiles developed from field data were used for estimating sludge volumes and accumulation rates. The total sludge volume was determined by integrating sludge depths over the pond length and width. This was done numerically on a spreadsheet. Each pond was divided into a triangulated irregular network (TIN), with measured data points as triangle nodes. The volume of sludge contained within each triangular “prism” was estimated from the area of each triangle and the average sludge depth (average of sludge depths measured at each node of the triangle).

The sides of all ponds were sloped at a 3:1 ratio. This is illustrated in Figure 4.4, a sectional schematic diagram of one of the anaerobic lagoons at Puerto Cortes. Sludge depth measurements were taken along the flat bed of the pond. It is unknown how sludge levels vary up to and along the pond slope. As indicated by the red line segments in Figure 4.4, sludge levels were assumed to be constant when extrapolating from the outermost measurement location to the sloped walls. The TINs and volume estimations for each pond are contained in Appendix A.

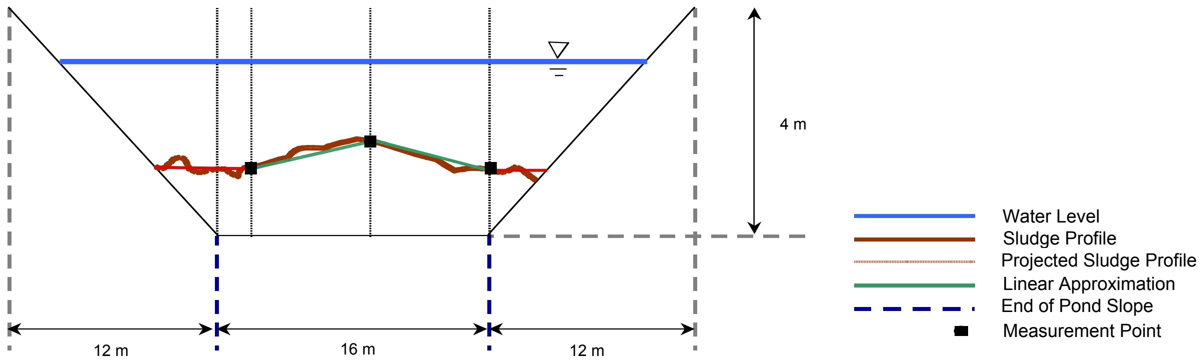

Figure 4.4 Sectional schematic of one of the anaerobic lagoons at Puerto Cortes.

Sludge accumulation rates fall in the overall range of 0.03 – 0.1 m^3/capita•year; however, in warmer climates, values are typically lower and have been observed to be in the range of 0.02 – 0.04 m^3/capita•year (Nelson et al., 2004). Values in the order of 0.01 m^3/capita•year have also been observed in waste stabilization pond systems in Brazil (Mara, 2003). A study by Oakley et al. (2000) involving 6 waste stabilization ponds in Nicaragua found an average sludge accumulation rate of 0.15 m^3/capita•year.

In the present study, the sludge accumulation rate (volume/capita/year) for each waste stabilization pond system was estimated by dividing the total sludge volume by the population served and the number of years in operation. The total estimated sludge volumes and accumulation rates for each facility are shown in Table 4.5.

Table 4.5 Estimated sludge volumes and accumulation rates at La Lima and Puerto Cortes.

Sludge Volume (m^3)			
La Lima		Puerto Cortes	
Facultative Lagoon 1	309	Anaerobic Lagoon 1	483
Facultative Lagoon 2	347	Anaerobic Lagoon 2	838
TOTAL	**656**	**TOTAL**	**1321**
Sludge Accumulation Rate (m^3/capita year)			
La Lima	0.054	Puerto Cortes	0.011

The sludge accumulation rate at La Lima was higher than the expected typical range. One possible reason for this may be the presence of illegal connections to the municipal wastewater system, resulting in the plant servicing a greater population than is currently recorded.

In contrast, the sludge accumulation rate at Puerto Cortes was found to be slightly lower than the expected typical range. It is likely that the sludge volume in Anaerobic Lagoon 1 is similar to that in Lagoon 2 since no significant discrepancy was observed in flow distribution. As discussed earlier, the overall sludge levels in both anaerobic ponds may have been underestimated due to limitations in the measurement capacity of the PVC pole used. In addition, sludge levels in the facultative ponds at Puerto Cortes were not measured. Although these are expected to be relatively low, given the vast areas of these ponds (about 26,400 m^2 each), the total accumulated volumes could be significant.

4.2 Sludge Quality

An assessment of sludge quality is important for selecting appropriate technologies that provide adequate levels of treatment for safe disposal or reuse. In this section, sludge quality is considered with respect to two general parameters: pathogens, specifically helminth eggs, and heavy metals content. While the latter is not necessarily relevant as criteria for selecting stabilization methods (since it cannot be addressed through conventional treatment), it is important for identifying reuse options. Biosolids with high heavy metals contents are not suitable for unrestricted agricultural use given public health concerns associated with crop uptake.

Sludge samples were taken from facultative lagoons at La Lima and Choloma for heavy metals analysis. Samples were not tested for helminth eggs; these levels were assessed based on a review of available literature on previous studies done in other waste stabilization pond systems in Honduras.

4.2.1 Heavy Metals Analysis

Sludge samples from facultative lagoons at La Lima and Choloma were tested for selected heavy metals at the laboratory of the Honduran Agricultural Research Foundation (FHIA). Samples were analyzed with respect to lead, mercury, cadmium, copper, and zinc levels. EPA Method 3050 was used for the analysis of cadmium, lead, copper, and zinc; mercury levels were determined using EPA Method 241.1. A general analysis was also done to determine pH, nitrogen, phosphorus, and potassium levels. The laboratory analysis results are contained in Appendix B.

The purpose of the heavy metals analysis was to assess the suitability of the sludge for land application.

As indicated previously, due to the absence of biosolids regulations in Honduras, the Mexican guidelines will be used for evaluation purposes. The limits for heavy metals concentrations for biosolids land application under the Mexican guidelines are the same as those set by US EPA. The results of the sludge analysis for both municipalities, alongside the levels required by the regulations, are shown in Table 4.6.

Table 4.6 Sludge heavy metals contents at facultative lagoons in La Lima and Choloma in relation to limits set by the EPA and Mexican guidelines (EPA, 2001).

	La Lima (mg/kg)*	Choloma (mg/kg)*	EPA/Mexico Guidelines (mg/kg)*
Cadmium	2.64	1.18	39
Copper	58	47	1500
Lead	37.52	19.23	300
Mercury	0.376	0.186	17
Zinc	260	117	2800

*Dry weight basis

Levels for all heavy metals tested in the sludge samples were found to be very low compared to concentration limits set by the guidelines. This indicates that these sludges are considered safe for agricultural land application with respect to heavy metals loadings.

These results are reasonable given that the waste stabilization pond systems studied treat primarily domestic wastewater, which is typically not a significant source of heavy metals. Municipal wastewater treatment facilities elsewhere in Honduras are likely to have heavy metals contents within a similar range, unless there is a substantial industrial contribution to the influent sewage. In considering reuse options for sludge produced Puerto Cortes, it is assumed that its heavy metals content is similar in range to those found in La Lima and Choloma.

4.2.2 Helminth Eggs

Due to the limited testing capacity of the accessible laboratories during our study, sludge samples were not tested for helminth eggs content. However, a similar study was conducted by Oakley (2006) on sludges from 10 different waste stabilization pond systems in Honduras. The helminth egg levels found at the various sites are summarized in Table 4.7. All sampled ponds were facultative with the exception of those at Danli and Villaneuva, which were anaerobic.

Table 4.7 Average helminth egg concentrations in wastewater pond sludges in Honduras (Oakley, 2006).

	Average Helminth Egg Concentration (eggs/gram dry weight)	
	Dry Season	Wet Season
Catacamas E.	53	308
Catacamas W.	303	674
Danli	-	467
Juticalpa	-	35
Moroceli	189	-
Pajuiles	4473	-
El Progreso	-	62
Tela	1	50
Trinidad	-	15
Villanueva	738	-

Helminth egg concentrations were found to vary significantly across the waste stabilization ponds sampled, with 1 egg/gram dry sludge at Tela and 4473 eggs/gram dry sludge at Pajuiles during dry season flows. Given the wide range of helminth egg concentrations, required levels of sludge treatment will vary from site to site. For sludge at Pajuiles, 2 log removal of helminth eggs is required to achieve treated levels in the vicinity of Mexican Class B standards (35 eggs/gram dry weight). At other ponds with lower concentrations, less removal is sufficient to meet minimum reuse standards. In some cases, such as Tela and Trinidad, no sludge treatment appears to be required; this is likely due to an effective degree of anaerobic digestion within the waste stabilization pond.

In Section 5.3 of this report, some preliminary design calculations, including required land area, will be made for treating sludges produced at Puerto Cortes and La Lima. Because specific data on sludge pathogen concentrations are not available for these sites, design estimations will consider target alternatives of 1 to 2-log removal of helminth eggs.

5.0 SLUDGE TREATMENT ALTERNATIVES

In order to plan ecologically and socially responsible sludge disposal or end-use options, it is first necessary to address sludge quality issues as discussed in Chapter 3. Unrestricted reuse of raw sludge with high pathogen or metals content can have significant environmental and health impacts. A treatment or stabilization process should be implemented in order to lower pathogen content and mitigate odors prior to safe disposal or reuse. Such stabilization processes can vary in their treatment efficiencies.

As discussed in Chapter 3, municipal sludge in Honduras typically contains high levels of helminth eggs. Because these are the most difficult to inactivate relative to other pathogens of concern, the reduction of viable helminth eggs will be considered the primary evaluative criteria with respect to treatment efficiency. Other selected criteria for evaluating the appropriateness of various treatment alternatives will also be discussed in further detail in this chapter.

Having designed an appropriate set of evaluation criteria, the different treatment alternatives will be assessed in order to identify preferred sludge treatment solutions for municipalities in Honduras.

5.1. Sludge Stabilization Technology Alternatives

The five sludge stabilization methods that were considered include sludge drying, alkaline stabilization, acid stabilization, anaerobic digestion and composting. Aerobic digestion was not considered due to high energy demands associated with aeration.

5.1.1. Sludge Drying Beds

A sludge drying beds consists of an open area where sludge is distributed and dried. This is the most commonly used method for sludge drying in the United States due to a number of advantages (Metcalf & Eddy, 2003). Sludge drying beds are economical and require very low maintenance. The dried product usually has a high solids content, making it easy to handle and reducing transportation costs to final disposal or end-use location.

There are five main types of drying beds, namely: conventional sand; paved; artificial media; vacuum-assisted; and solar. Only conventional sand drying beds will be considered for the purposes of this evaluation.

Figure 5.1 shows plan and sectional views of a typical conventional sand drying bed. Sludge spread over a sand and gravel bed ranging from 400-600 mm in thickness. The sludge layer is usually 200-300 mm thick. Drained moisture from the sludge layer percolates through the sand and gravel layer and is collected through an underdrainage system. This consists of a network of perforated pipes supported and covered by coarse gravel. Sludge drying beds may be covered particularly in areas where sludge must be dried on a continuous basis regardless of weather or where there are odor concerns.

Sludge drying time can vary depending on ambient conditions. Under favorable conditions, a Total Solids (TS) content of up to 40% could be achieved within 10 to 15 days. Dried sludge can then be removed manually or mechanically and transported for final disposal or reuse.

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Figure 5.1 (a) Plan and (b) sectional view of a typical conventional sand drying bed. Top right image shows sludge drying beds containing sludges of different degrees of dryness (Metcalf & Eddy, 2003).

Because of their substantial area requirements, drying beds are typically used for small and medium-sized communities (i.e. up to 20,000 people) only. Other major disadvantages of sludge drying beds include: potential odors, the influence of weather on drying times, and vector attraction.

While sludge drying beds can be an inexpensive sludge management alternative, they have minimal impact on helminth eggs. A study by Cofie et al. (2006) in Ghana investigating solid-liquid separation of fecal sludge using sludge drying beds found 100% retention of helminth eggs in the solid phase with no observed inactivation through the drying cycle. Unless temperatures are maintained about 40 ^{o}C or moisture content below 5% (TS > 95%), helminth inactivation is typically not achieved (Jimenez et al., 2007; Cofie et al., 2006). Therefore prior to agricultural reuse, dried sludge should undergo an additional treatment process for pathogen removal.

5.1.2. Alkaline Stabilization

Alkaline stabilization is a form of chemical treatment where an alkali, typically lime (CaO), is added to sludge. The process raises the pH of the sludge mixture creating an unfavorable environment for microbial growth. In addition to inactivation of pathogens, this also mitigates odors and vector attraction.

Lime chemically reacts with various components in the sludge; simplified forms of some these reactions are shown below (WEF, 2003):

Carbon Dioxide: $CaO + CO_2 \rightarrow CaCO_3$
Organic Acids: $CaO + RCOOH \rightarrow RCOOCaOH$
Fats: CaO + Fats → Fatty Acids

Lime can be added to and mixed with raw sludge either manually or through a mechanical mixer, such as a pugmill, paddle mixer or screw conveyor. Typically lime is added to dewatered or dried sludge; however, it can also be used to stabilize liquid raw sludge especially for direct land application or as a conditioner prior to dewatering. Figure 5.2 shows a schematic diagram of a typical dry liming system applied to dewatered sludge.

Depending on the process, alkaline stabilization of sludge can meet the USEPA's Class A or Class B requirements for biosolids reuse (see Chapter 3). Compliance with Class A standards can be achieved when the pH of the sludge and lime mixture is maintained above 12 for at least 72 hours, with a temperature of 52^{o}C for at least 12 hours. Class A standards can also be met if the temperature is raised to 70^{o}C or higher for at least 30 minutes, while maintaining the pH requirement of 12 (EPA, 2000). As discussed in Chapter 3, the Class A requirement for helminth eggs is 0.25 helminth eggs/g TS. Even with the treatment efforts recommended above, this can be an impractical treatment objective in Honduras where there are typically high helminth egg concentrations in raw sludge. Class B requirements are generally met when the sludge and lime mixture is maintained at a pH of 12 for at least 2 hours; Class B stipulates no explicit requirement for helminth egg concentrations.

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Figure 5.2 Schematic of dry lime stabilization process

The addition of lime can be an effective means of reducing viable helminth eggs in sludge. At lime doses of 20-40% w/w and where pH is maintained at ≥ 12 for a minimum of 2 hours, about 0.5 – 2 log inactivation of helminth eggs can be achieved (Jimenez et al., 2007). This estimation is based on studies performed on sludge obtained from an advanced primary treatment process in Mexico. It can be expected that raw sludge from waste stabilization ponds (or any secondary treatment process) would have lower pathogen concentrations due to some degree of anaerobic digestion.

When lime is added to sludge, it reacts with water to form hydrated sludge. Because this is an exothermic reaction, heat is generated as a result (approximately 64 kJ/g·mol) raising the overall temperature of the mixture. This can increase the sludge treatment efficiency. For instance, if the process is carried out in an insulated reactor, higher temperatures can be maintained resulting in lower sludge residence times and lime dosage requirements for the same level of treatment (Metcalf & Eddy, 2003).

Another benefit of closed alkaline stabilization systems is the containment of ammonia. The advantages of such systems are two-fold. Firstly, this mitigates odorous ammonia emissions, which constitute one of the major concerns with respect to alkaline stabilization. In addition, ammonia has disinfectant properties, which can also enhance the sludge treatment efficiency. A study from Mexico by Mendez et al. (2002) found that at low lime doses (≤ 20% w/w), the efficiency of viable helminth egg inactivation could be improved by upto 10% in closed systems compared to open systems. Figures 4.3 and 4.4 summarize the findings of the study with respect to inactivation of fecal coliforms and viable helminth eggs.

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Figure 5.3 Inactivation of fecal coliforms in open and closed alkaline stabilization systems for various lime doses (Mendez et al., 2002).

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Figure 5.4 Inactivation of viable helminth ova (HO) in open and closed alkaline stabilization systems for various lime doses (Mendez et al., 2002).

Although lime, in the form of quicklime, is the most commonly used, other forms of alkaline substances can also be applied for treating sludge. Cement kiln dust (CKD) has also been used both as an additive and as a lime substitute. CKD is a by-product of the cement manufacturing process and is emitted with cement kiln exhaust gases. CKD is highly alkaline since it is essentially unreacted raw material, typically rich in lime content. Because unused CKD is a waste product, it can provide an attractive lower cost alternative to quicklime for alkaline stabilization. Depending on the lime content of the CKD, dosage rates may vary compared to quicklime. Some patented systems such as the N-Viro™ process use CKD as a supplement alkaline stabilization agent (N-Viro International, 2008).

In addition to odorous ammonia emissions, the main disadvantage of alkaline stabilization processes is a net increase in the amount of solids for final disposal or reuse. Therefore, although alkaline stabilization systems can be economical options due to low materials costs and maintenance requirements, they may have higher costs associated with solids handling and transportation.

5.1.3. Acid Stabilization

Another form of chemical stabilization, albeit less common than liming, is acid treatment. Acid treatment also dramatically alters the pH of sludge in order to induce unfavorable conditions for microbial growth. While a variety of acids has been used for wastewater and sludge disinfection, organic acids, such as acetic and peracetic acid (PAA), are found to be most effective (Jimenez et al., 2007). This is likely due to their ability to access and interfere with cellular activities.

PAA is formed as a product of acetic acid and hydrogen peroxide, as shown in the chemical equation below:

$$CH_3CO_2H + H_2O_2 \rightarrow CH_3CO_3H + H_2O$$

It has been widely used as a sterilizer in hospitals, and has been more recently applied to wastewater disinfection (Metcalf & Eddy, 2003). According to the USEPA (1999), it is one of the disinfectants that can be used for treating combined sewer overflows and is considered advantageous due to the absence of persistent residuals and byproducts, short contact time, and not being affected by pH. PAA has been shown to be a suitable alternative to chlorine oxide in terms of abatement of microorganisms (Stampi et al., 2002). A study by Koivunen and Heinonen-Tanski (2005) found the application of PAA to primary, secondary and tertiary effluents to achieve 3-4 log reductions in total coliforms and enterococci after 27 min of contact time. The PAA doses used in the study ranged from 2-15 mg/L, with primary effluent requiring higher dosages because of higher microbial, organic matter, and suspended solids concentrations.

With respect to sludge stabilization, both PAA and acetic acid treatment were effective in reducing fecal coliforms and helminth eggs in primary sludge obtained from an advanced primary treatment plant in Mexico. The stabilization process, using a PAA strength of 20,000 mg/L, reduced helminth eggs concentration from 120 to 2 helminth eggs/gTS (Jimenez-Cisneros, 2001). The treated biosolids met Type A standards as defined by the sludge reuse guidelines in Mexico (see Chapter 3). In contrast to lime stabilization, the use of PAA does not increase the amount of solids in the treated sludge.

Despite its substantial benefits, PAA is relatively high in cost since it is not frequently produced in bulk quantities. This may change as demand and use of the chemical increases (Kitis, 2003). Because the addition of PAA increases the organic content of the sludge, there is also some concern regarding microbial re-growth.

5.1.4. Anaerobic Digestion

Anaerobic digestion is one of the oldest known processes used for sludge stabilization (Metcalf & Eddy, 2003). In this process, anaerobic bacteria break down organic matter in the absence of oxygen. As illustrated in Figure 5.5, anaerobic decomposition occurs in three basic stages: hydrolysis, fermentation, and methanogenesis.

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Figure 5.5 Schematic diagram showing the main stages in anaerobic digestion (Metcalf & Eddy, 2003).

During hydrolysis, the first step of anaerobic digestion, large compounds are hydrolyzed to form simple monomers and soluble compounds, which can then be easily utilized by bacteria as substrate for the fermentation process. In the fermentation stage, organic substrates including amino acids, sugars, and fatty acids are degraded to form acetic acid, hydrogen, and carbon dioxide. Because of the formation of acetic acid, the fermentation step is also known as acidogenesis. The final step of anaerobic digestion, methanogenesis, is carried out by a group of obligate anaerobes called methanogens. In this process, either acetic acid or hydrogen is used to produce methane and carbon dioxide.

The biomass yield of anaerobic processes is much lower (by a factor of 6 to 8 times) compared to other forms of digestion, resulting in significantly reduced sludge production and associated handling costs. Another major advantage of anaerobic treatment systems is the production of methane, which can be recovered as an energy source.

Anaerobic digestion can be carried out under mesophilic (30-38^{o}C) or thermophilic (50-57^{o}C) conditions. Temperature-phased anaerobic digestion (TPAD) takes place within a two-staged system that uses a combination of both mesophilic and thermophilic bacteria. Thermophilic systems offer the advantages of increased solids and bacterial destruction; however, they have higher costs associated with heating.

Anaerobic digestion can be an effective stabilization process for reducing pathogen content in sludge. A study by Rojas-Oropeza et al. (2001) compared the removal efficiency of fecal coliforms and helminth eggs from sludge in Mexico through anaerobic mesophilic digestion to anaerobic thermophilic digestion. Thermophilic digestion was found to be the more effective treatment alternative, achieving 70% removal of viable helminth eggs for a sludge retention time of 16-20 days. In comparison, the removal efficiency of mesophilic digestion was approximately half (35%) for a similar retention time.

Improved helminth egg inactivation efficiencies in thermophilic digesters were confirmed in a follow-up study by the same team (Cabirol et al., 2002). The quality of final treated biosolids was very close to meeting the USEPA's Class A standards (0.25 viable helminth eggs/gTS). Mesophilic digestion reduced the concentration of helminth eggs to about 3 viable helminth eggs/gTS.

A pilot plant in France applying TPAD process achieved 5.5 and 2.6 log reductions of fecal coliforms and viable helminth eggs, respectively (Huyard et al., 2000). In the system, the acidogenic and methanogenic phases of digestion are physically separated and carried out in two separate tanks. The first tank is maintained under mesophilic conditions to preferentially encourage the growth of acidogenic bacteria; similarly, the second tank operates in thermophilic temperature ranges to favor methanogens. Although this process can effectively reduce pathogen content in sludge while maximizing biogas production, it requires careful process control in order to maintain the required operating conditions.

One of the main disadvantages of thermophilic anaerobic digestion is the energy requirement associated with heat supply. This can often be overcome by using recovered biogas for heating purposes. There are also concerns related to the production of hydrogen sulfide, which is odorous and corrosive. Anaerobic digesters can be very sensitive to toxic substances, which can cause a process upset and require the system to be restarted. Because of its low biomass yield, the startup time for an anaerobic reactor (i.e. to accumulate the necessary biomass stock) can also be much longer compared to other processes.

5.1.5. Composting

Composting involves the biological degradation of organic material to produce a stable humus-like end product. During this process, organic compounds including proteins, lipids and fats are microbially broken down to produce humic acid, carbon dioxide and water. The biological reactions release thermal energy, increasing the overall temperature of the compost to the thermophilic range (40-70^{o}C). This stage, called the high-rate composting phase, is when the maximum degradation and stabilization of organic material occurs. Following the thermophilic stage, the compost undergoes the curing phase during which it cools to the mesophilic range (30-40^{o}C) as microbial activity declines. As the compost cures, it releases moisture through further evaporation and pH levels are stabilized as humic acid production is completed. Figure 5.6 illustrates the stages of the biological composting process as a function of temperature and microbial activity (represented as carbon dioxide respiration).

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Figure 5.6 Phases of the composting process with respect to carbon dioxide respiration and temperature (Metcalf and Eddy, 2003).

The addition of a carbon source is required to sustain microbial activity during composting. For this purpose, a bulking agent, such as wood chips or yard waste, is initially mixed with dewatered or dried sludge. After the stabilization process, the compost is screened and a portion of the recovered bulking agent is typically recycled and mixed with new bulking agent.

Co-composting of wastewater sludge with municipal solid waste is a commonly practiced form of integrated waste management. The organic fraction of municipal solid waste can be used as a bulking agent in this case. Co-composting does not require sludge to be dewatered or dried, and can be particularly beneficial where sludge heavy metals content are of concern as it dilutes the concentration in the final compost.

A study by Kone et al (2007) examined the inactivation efficiency of helminth eggs during a co-composting process piloted in Ghana. Fecal sludge from toilets and septic tanks was mixed with municipal solid waste at a 1:2 volume ratio. Helminth eggs concentrations were reduced from an initial sludge load ranging from 25-83 eggs/g TS to <1 egg/g TS, complying with the WHO guidelines for reuse.

Vermicomposting, a process that utilizes worms for biodegradation, of sewage sludge was investigated in a pilot study in Mexico (Vigueros and Camperos, 2002). In this case, water hyacinths, an invasive aquatic plant species, were used as bulking agents. The optimum worm survival and treatment performance were found to be with a mixture of 70% sewage sludge and 30% water hyacinths. The process produced a Mexican Class A compost. All helminth eggs were removed, although concentrations in the raw mixture were relatively low. The concentration of fecal coliforms was reduced from 10,000 MPN/g in the raw mixture to 400 MPN/g in the final product (96% removal efficiency).
One of the main advantages of composting is that it produces a highly stable end product that is marketable for reuse. If the process is executed properly, most pathogens are inactivated in the compost. Approximately 20-30% of the volatile solids in the raw material are converted to carbon dioxide, reducing the final sludge volume significantly.

There are some public health concerns related to composting; if the process is incomplete and pathogen levels are not sufficiently mitigated, there are potential risks of exposure to workers. Composting processes can be odorous and must be sited accordingly to prevent public complaints.

5.2. Evaluation of Technology Alternatives

A number of selected criteria were used to evaluate the sludge stabilization technologies in consideration. These were: required level of maintenance, end-use diversity, social acceptance, and efficacy of treatment. Little information is available regarding acid stabilization. It is assumed that with respect to most factors except for cost, it will have similar characteristics to lime stabilization.

5.2.1. Required Level of Maintenance

As previously mentioned, all the technologies considered have relatively low maintenance requirements compared to other sludge stabilization processes. However, all of the options require some degree of periodic attention. Sludge drying beds likely require the least level of maintenance. Liming and composting both require manual mixing, approximately once in 3-4 days in the case of composting (EPA, 2003). Anaerobic digestion, however, may require closer process monitoring to ensure the reaction proceeds to completion as expected.

5.2.2. Social Acceptance

Public perception is an important aspect of any successful biosolids reuse program. Biosolids can be applied to their maximum potential value if the wider community is willing to accept and use them as a resource, rather than a waste. Lime stabilized biosolids are typically odorous to some degree due to the release of ammonia; this may cause negative public perception. Anaerobically digested and composted biosolids have an earthy odor and soil-like consistency, which are generally agreeable to the public. The anaerobic digestion process, however, can be odorous if off-gases are not properly managed. Dried sludge is likely to have high pathogen content and associated health risks; therefore public acceptance for reuse is expected to be low.

5.2.3. Required Land Area

Honduras has a significant proportion of hilly terrain, being one of the most mountainous countries in the region. As a result, the availability of useable land area can be a constraint in many communities. Sludge drying and composting are particularly land-intensive processes. Lime and acid stabilization may also require significant land area in order to achieve effective manual mixing. In addition, these processes should be preferably carried out with dried sludge (downstream of a sludge drying bed), which would increase land requirements accordingly. The inclusion of a drying process would facilitate sludge handling and mixing, as well as reduce lime costs; higher lime dosages are required for raising the pH of wet sludge compared to dried sludge. In contrast, anaerobic digesters require less land. Also, digesters can be placed below grade allowing multiple uses for a given land area.

5.2.4. Efficacy of Treatment

Lime stabilization, acid stabilization, composting, and anaerobic digestion have all been shown to effectively reduce concentrations of helminth eggs in sludge. Sludge drying beds, however, are typically not effective in inactivating significant levels of helminth eggs unless the moisture level is reduced to ≤ 5% (95% solids); typical solids content of dried sludge is approximately 40%. Sludge that receives effective treatment can be safely reused as a benefical resource in a variety of applications, rather than disposed of as a waste material.

5.2.5. Total Cost

The technologies described were selected for consideration on the basis of their relatively low capital and operation & maintenance costs compared to other stabilization processes. A detailed comparative cost analysis is beyond the scope of this study; however, some consideration of relative costs is important for carrying out a complete evaluation of these technologies. Sludge management can contribute to a significant fraction of total plant operation costs. Kroiss (2004) estimated that sludge treatment and handling costs approximately 49-53% of a treatment plant's total operating cost, based on studies carried out in Austria.

A life cycle inventory of 9 different sludge treatment scenarios was carried out for the city of Chengdu in Sichuan, China (Murray et al, 2008). Treatment processes considered included mechanical dewatering, lime stabilization, anaerobic digestion, aerobic digestion, heat drying (using natural gas), composting and incineration (using fluidized bed combustion). The various scenarios involved different combinations of these processes. The life cycle cost analysis included two independent components: sludge treatment and sludge end use. The factors considered in the study were economic costs and benefits, key air emissions, and energy consumption and production. The estimated economic costs of each technology are summarized in Table 5.1. The total cost was adjusted to include "external" environmental costs associated with 6 different air pollutants, CO ($0.52/kg), CO_2 ($0.014/kg), NO_x ($1/kg), PM ($2.80/kg), SO_2 ($1.80/kg) and volatile organic carbons (VOCs) ($1.40/kg).

The absolute cost figures are not necessarily relevant to the alternatives being considered for Honduras in this study. For instance, the cost associated with mechanical dewatering is included in these scenarios. Other additions, such as the construction of a building enclosure and provision of mechanical (rather than manual) mixing, may also have been included. Nonetheless these estimates do provide value for comparing the relative costs of the different technology alternatives.

Table 5.1 Total costs associated with various sludge treatment technologies (Murray et al, 2008).

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Lime stabilization and anaerobic digestion (without the addition of lime for pH adjustment) were found to have the lowest overall costs. When considering direct costs only, lime stabilization was estimated to be cheaper than anaerobic digestion. However, when taking into account savings with respect to environmental costs, anaerobic digestion became less expensive than lime stabilization. Although dewatering is shown to be the lowest cost option, it was not considered as a stand-alone sludge management option in the study as it does not provide any sludge treatment per se.

Composting was found to be more expensive given a slightly higher operation & maintenance requirement. This cost is offset in the case of anaerobic digestion due to recovery and application of biogas. Information on acid stabilization is limited; however, the operating cost is expected to be greater given the high cost of peracetic acid.

5.2.6. Summary

Table 5.2 shows the evaluation matrix used for assessing the various treatment alternatives. A relative scoring range of 1-5 was used, 1 being the poorest and 5 being the best. The criteria for this evaluation were equally weighed; all were treated to have the same degree of importance.

Table 5.2 Evaluation matrix for assessment of sludge treatment alternatives.

	Required Level of Maintenance	Social Acceptance	Required Land Area	Efficacy of Treatment	Total Cost	**Total Score**
Lime Stabilization	4	4	1	5	4	18
Acid Stabilization	4	4	1	5	2	16
Drying	5	1	1	1	5	13
Composting	3	5	1	5	3	17
Anaerobic Digestion	1	5	5	5	4	20

Anaerobic digestion achieved the highest overall score, followed by lime stabilization and composting. Anaerobic digestion can be a particularly attractive alternative for facilities such as Puerto Cortes and La Lima, where the provision of maintenance is less problematic due to well-trained staff. Compared to lime stabilization, it presents the advantages of energy recovery and reduced final sludge volume. Due to its lower land requirement, anaerobic digestion is also a viable alternative for municipalities such as Las Vegas, which are situated in mountainous regions. As mentioned previously, anaerobic digesters can be placed below grade (such as at the wastewater treatment facility in Teupasenti) allowing versatility in land use.

Treatment facilities with no land constraints and limited availability of trained staff can install lime stabilization processes, either as stand-alone options, treating liquid sludge, or downstream of a drying bed. The major benefit of including a drying process is the reduced lime requirement and associated costs. Treatment of liquid sludge would have costs associated with a holding tank and mechanical mixing. Transportation costs of liquid sludge would be significantly higher due to increased volumes and the requirement for a tanker truck. With the exception of direct land application, reuse or disposal options for liquid sludge are also limited. For municipalities that are in a position to invest in higher capital costs, enclosed lime stabilization systems may be considered for taking advantage of the disinfectant properties of the ammonia released and for reducing overall lime requirements.

Composting can also be a viable option for communities with sufficient land area and reliable maintenance staff. Unlike anaerobic digestion, composting does not require technically trained operators; however regular maintenance is needed for mixing compost piles once ever 3-4 days. Co-composting with municipal solid waste can be a particularly appealing integrated waste management solution given that open dumping of solid waste appears to be a common problem in Honduras. Regional composting sites may be considered where a common facility would receive and treat municipal solid waste and sewage sludge from neighboring communities. Such a facility would be economically advantageous since the costs would be shared amongst a number of municipalities. There are also potential cost recovery opportunities if the final product could be marketed for sale. Because both waste sources would be managed in a combined system under this scenario, this solution may result in reduced household fees levied for garbage and sewage.

5.3. Preliminary Design Estimations for Puerto Cortes and La Lima

Preliminary design calculations were carried out for treating sludges produced at the waste stabilization pond systems of Puerto Cortes and La Lima. As discussed, both composting and alkaline stabilization processes, downstream of sludge drying beds, could be viable options for Puerto Cortes given the availability of ample land. It is unclear how much land is available at La Lima for sludge treatment. The facility is located within a compound consisting of some currently unused land; it is assumed that, as a minimum measure, sufficient land can be acquired for accommodating sludge drying beds.

Land requirements for sludge drying beds and composting were calculated for both facilities. It is assumed that lime can be added and mixed to dried sludge directly on drying beds; no additional land requirement was considered for this purpose. Land area estimates for composting were based on windrow configurations. It should be noted that although this is the most economical form of composting, it is also the most land-intensive. In-vessel composting may be considered as a lower footprint alternative, with a higher capital cost.

Approximate cost estimates were developed for lime requirements. Two scenarios were considered in this regard. Estimates were made for using quicklime only, as well as for a second scenario where the quicklime is used in conjunction with cement kiln dust (CKD). Depending on its availability, the use of CKD as a supplemental treatment agent reduces overall lime requirements and associated material costs.

5.3.1. Puerto Cortes

The municipality of Puerto Cortes anticipates desludging its anaerobic lagoons by the end of the year. The total sludge volume in the anaerobic lagoons was estimated to be 1321 m^3. As discussed in Chapter 4, this is likely an underestimation, particularly for volumes in Anaerobic Lagoon 1, due to the limited measurement capacity of the pole used for estimating sludge depth. To take this into account, it is assumed that the sludge volume in Anaerobic Lagoon 1 was the same as Lagoon 2 (838 m^3), amounting to approximately 1700 m^3 of sludge in total.

The total area required for a sludge drying bed at Puerto Cortes is shown in Table 5.3. A sludge depth of 200-300 mm is typically recommended (Metcalf & Eddy, 2003); for this estimation a depth of 250 mm was selected.

Table 5.3 Required area for sludge drying bed at Puerto Cortes.

Total Volume (m^3)	1700
Sludge Layer Thickness (mm)	250
Drying Bed Area (m^2)	6800

The amount of land currently available at Puerto Cortes for future expansion is significant greater than the estimated area required for accommodating a sludge drying bed. Therefore, with respect to land, there appears to be no constraints for drying and alkaline treatment at this site.

Table 5.4 shows the chemical requirements for alkaline stabilization. A lime dosage level of 40% on a wet weight (w/w) basis was assumed, based on the range of 20-40% w/w recommended by Jimenez et al (2001) for achieving 0.5 to 2-log removal of helminth eggs. For the scenario applying CKD in addition to quicklime, dosages of 40% and 6% w/w were considered for CKD and lime, respectively, for maintaining a pH of 12 for at least 2 hours (Lue-Hing, 1998).

Table 5.4 Chemical requirements for alkaline stabilization at Puerto Cortes

Sludge Weight	
Dried Sludge Solids Content (%)	40
Wet Weight (tons)	143
Dry Weight (tons)	86
Lime Addition*	
Lime (tons)	57
Lime Addition with Cement Kiln Dust**	
Lime (tons)	9
CKD (tons)	57

*Based on lime dosage of 40% w/w
**Based on lime dosage of 6% w/w and CKD dosage of 40% w/w

Chemical costs were estimated based on the requirements shown in Table 5.4. A lime cost of $60/ton was assumed, based on average U.S. prices in 2001 (USGS, 2002), although this may differ from the local cost of lime in Honduras. CKD was assumed to be free, as it is a waste by-product of cement manufacturing; however there may be some costs associated with transportation, which were not taken into account. The total estimated costs and the annual cost per capita are shown in Table 5.5.

Table 5.5 Chemical costs for alkaline stabilization at Puerto Cortes

Facility and Cost Assumptions	
Cost of Quicklime ($/ton)	60
Cost of CKD ($/ton)	0
Number of Residents Serviced	50000
Desludging Frequency (years)	3
Lime Addition	
Total Cost (USD)	$3,434
Cost/cap·yr (USD)	$0.02
Lime Addition with Cement Kiln Dust	
Total Cost	$515
Cost/cap·yr (USD)	$0.003

The total chemical costs for alkaline stabilization were found to be low, especially when considered on an annual per capita basis. Cost is minimal where cement kiln dust is used (approximately 0.3 cents or 0.06 lempiras annually per capita, based on an exchange rate of 20 lempiras to 1 USD). From an operational cost standpoint, this appears to be a viable alternative for sludge treatment.

Land area for windrow composting of dried sludge was estimated and is shown in Table 5.6. Windrows are typically 2-4.5 m wide at the base, 1-2 m high (with a triangular cross section), and can range up to 100 m in length depending on site constraints (Metcalf & Eddy, 2003). For a preliminary layout, a width of 3 m, height of 1 m and length of 30 m was chosen. A windrow height of 1 m was chosen for easier access for operators when mixing the compost. A spacing of 1.5 m was also added between windrows to allow enough space for operators to walk through. A total of 2 windrows would be required to treat the sludges produced in the anaerobic lagoons at Puerto Cortes. A schematic diagram of the preliminary layout is shown in Figure 5.7.

As indicated in Table 5.6, area requirement for composting is quite small, particularly given the extent of land availability onsite. Also, compared to the area of a sludge drying bed, the additional space needed for composting is relatively low.

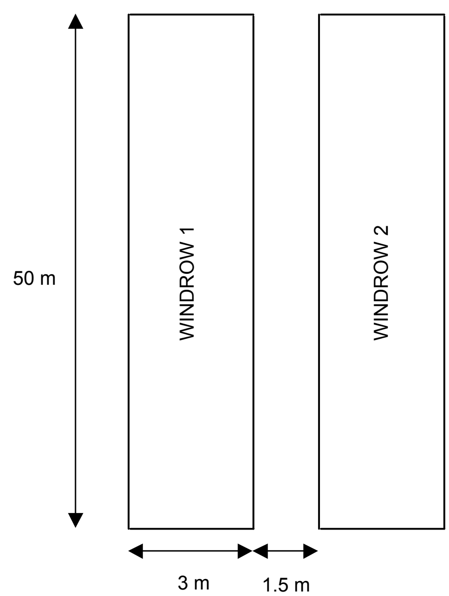

Figure 5.7 Preliminary layout of windrows for composting sludge at Puerto Cortes.

Table 5.6 Required land area for windrow composting at Puerto Cortes.

Total Dried Sludge Volume (m^3)	183
Windrow Dimensions	
Windrow Base (m)	3
Windrow Height (m)	1
Windrow Length(m)	50
Windrow Spacing (m)	1.5
Number of Windrows	2
Total Area (m^2)	**375**

In summary, the either alkaline stabilization or composting could be applied downstream of drying beds for treating sludge. For drying followed by alkaline stabilization, a total land area of approximately 6800 m^2 is required. If composting is carried out downstream of drying, an additional 375 m^2 would be needed, amounting to a total land requirement of about 7200 m^2.

5.3.2. La Lima

The total volume of sludge generated from the facultative ponds of La Lima is approximately 700 m^3. The land area required for drying the sludge in drying beds is shown in Table 5.7. As in the case of Puerto Cortes, a sludge layer depth of 250 mm was assumed for this estimate.

Table 5.7 Required land area for sludge drying bed at La Lima.

Total Volume (m^3)	700
Sludge Layer Thickness (mm)	250
Drying Bed Area (m^2)	2800

As mentioned previously, it is unclear how much land is available at La Lima for the purposes of sludge management. However, it is assumed that the municipality will at least be able to acquire enough land to accommodate a sludge drying bed. In this case, this would require an area of about 2800 m^2, which is similar in range to the area of one of the facultative ponds (3200 m^2).

Chemical requirements and cost estimates for alkaline stabilization were made on the same basis as for Puerto Cortes. A quicklime dosage rate of 40% w/w was assumed. Where CKD is used as a supplemental alkaline agent, dosage rates of 40% and 6% w/w of CKD and quicklime were assumed, respectively. The estimated chemical requirements and costs are summarized in Tables 5.8 and 5.9.

Table 5.8 Chemical requirements for alkaline stabilization at La Lima

Sludge Weight	
Dried Sludge Solids Content (%)	40
Wet Weight (tons)	59
Dry Weight (tons)	35
Lime Addition*	
Lime (tons)	24
Lime Addition with Cement Kiln Dust**	
Lime (tons)	4
CKD (tons)	24

*Based on lime dosage of 40% w/w
**Based on lime dosage of 6% w/w and CKD dosage of 40% w/w

Table 5.9 Chemical costs for alkaline stabilization at La Lima

Facility and Cost Assumptions	
Cost of Quicklime ($/ton)	60
Cost of CKD ($/ton)	0
Number of Residents Serviced	3500
Desludging Frequency (years)	5
Lime Addition	
Total Cost (USD)	$1,414
Cost/cap·yr (USD)	$0.08
Lime Addition with Cement Kiln Dust	
Total Cost	$212
Cost/cap·yr (USD)	$0.01

Chemical costs for alkaline stabilization were found to be low for both scenarios considered. In addition, the plant is currently operating below its design capacity; as a larger population is connected to the wastewater treatment system, these costs are expected to further decrease.

If sufficient land is available, composting may also be considered in lieu of alkaline stabilization. In this case, only a single windrow is required with dimensions of 3 m at the base, 1 m in height, and 35 m in length. The total land requirement, as shown in Table 5.10, is relatively low.

Table 5.10 Total land requirement for windrow composting sludge at La Lima.

Total Dried Sludge Volume (m^3)	76
Windrow Dimensions	
Windrow Base (m)	3
Windrow Height (m)	1
Windrow Length(m)	35
Number of Windrows	1
Total Area (m^2)	**105**

Both composting and alkaline stabilization, downstream of sludge drying, are suitable options for sludge treatment at La Lima given that sufficient land is available. A total area of 2800 m^2 is required for sludge drying followed by alkaline treatment. If composting is carried out instead, an additional 105 m^2 of space is needed resulting in a total area requirement of about 2900 m^2. The space required for both cases is similar in range to the area of one facultative pond at the facility.

6.0 BIOSOLIDS END-USE SCENARIOS

Treated biosolids may be beneficially utilized in a number of applications that make use of the resource value they offer. Potential markets for large-scale or regional biosolids end-use will be discussed in this section, based on a study of Honduran land use data. These will mainly include considerations for agricultural application and rehabilitation of mined lands. Community-scale end-use scenarios will also be considered including municipal and household uses.

Social acceptance is vital for the success of any biosolids reuse program, whether it is large-scale or at the community level. Most reuse options cannot be carried out without the public willingness to view and utilize biosolids as a resource, rather than a waste. In this regard, some possible strategies will be identified for improving public perception and gaining necessary support for a successful biosolids management program.

6.1. End-Use Scenarios

6.1.1. Regional End-Use Scenarios

Based on Honduran land use data, three major sectors were identified as potential markets for regional biosolids beneficial reuse. These include agriculture, forestry and mining; the specific advantages of biosolids application within each of these areas is discussed in further detail below.

Agriculture

The agricultural reuse of biosolids can play an important role in nutrient cycling and maintenance of soil fertility. They may be used as an alternative or supplement to chemical fertilizers for soil amendment and conditioning. Biosolids can also be applied for restoring nutrient levels in soils that have undergone significant nutrient losses due to intensive agriculture or erosion. Lands consisting of degraded soils are typically abandoned or left fallow for a period of time to allow for natural restoration of nutrients. This process can be facilitated through the application of biosolids as a nutrient source.

A significant portion of the Honduran economy is based on agriculture, with key national exports including coffee, bananas, tobacco and sugarcane (Encyclopedia Britannica, 2009). GIS data was obtained from SANAA on overall land use in Honduras; Figure 6.1 shows a map illustrating this information. As shown, permanent intensive agriculture (depicted in black, orange, dark green, light pink) is typically carried out in the lowlands of Honduras, such as near the coastal areas. The areas shown in black and light pink, in particular, are where the cultivation of cash crops such as coffee and bananas are carried out.

The presence of these agricultural zones presents opportunities for municipalities located in the lowlands, such as in the vicinity of San Pedro Sula and Choluteca, to send (or potentially sell) their treated biosolids to nearby farmers. Biosolids can be marketed to large-scale farmers as a means to reduce costs associated with chemical fertilizers. Depending on the type of crop, biosolids can provide the entirety or a significant portion of required nutrients at appropriate loading rates. For instance, economically optimum sugarcane yields have been observed at a fertilizer Nitrogen-Phosphorus-Potassium (NPK) ratio of 90-50-40 kg/ha, with 50% of the nitrogen added initially and the remaining added in equal doses over a number of weeks (Wayagari et al., 2001). A NPK ratio of approximately 40-15-40 can be obtained from sludges produced at Puerto Cortes and La Lima, based on nutrient analysis results (see Appendix B). This can provide the initial required levels of nitrogen and potassium, with additional supplemental applications of nitrogen and phosphorus at later stages to obtain high yields. Overall, the reduction in fertilizer demand can result in significant cost savings.

Similarly, biosolids can also be beneficially applied in banana plantations, which typically require a NPK ratio of 200-100-200 kg/ha (AP Horticulture, 2009). Sludges produced at La Lima and Puerto Cortes, at higher loading rates, can provide an NPK ratio of approximately 200-50-200 kg/ha. Supplemental addition of phosphorus may be needed to obtain optimum yields. Nonetheless, considerable cost savings may be realized through an overall reduction in fertilizer use.

Although lab analysis of sludge samples from La Lima and Puerto Cortes have shown low heavy metals contents, these should be closely monitored at municipalities where biosolids is used for agricultural land application.

Some coastal areas near Choluteca, particularly around the western side of the southernmost tip of Honduras, are currently left fallow for restoration of nutrients (shown in light peach). Such soils could potentially be reclaimed more effectively through the application of biosolids.

As shown in Figure 6.1 cultivation by rotation is practiced more heavily in mountainous inland areas, often for subsistence farming. In addition to providing value as fertilizer, biosolids addition can potentially reduce the time required between cultivation rotations through nutrient recycling.

Forestry

Two-fifths of the total land in Honduras consists of forested areas. Forestry is a major industry in the country, with forest products providing a substantial source of national income. Biosolids can be beneficially reused in areas where soils have undergone nutrient loss through evaporation and erosion. Biosolids applications in forestry may also be easier to coordinate and implement as much of land is under state ownership (Encyclopedia Britannica, 2009).

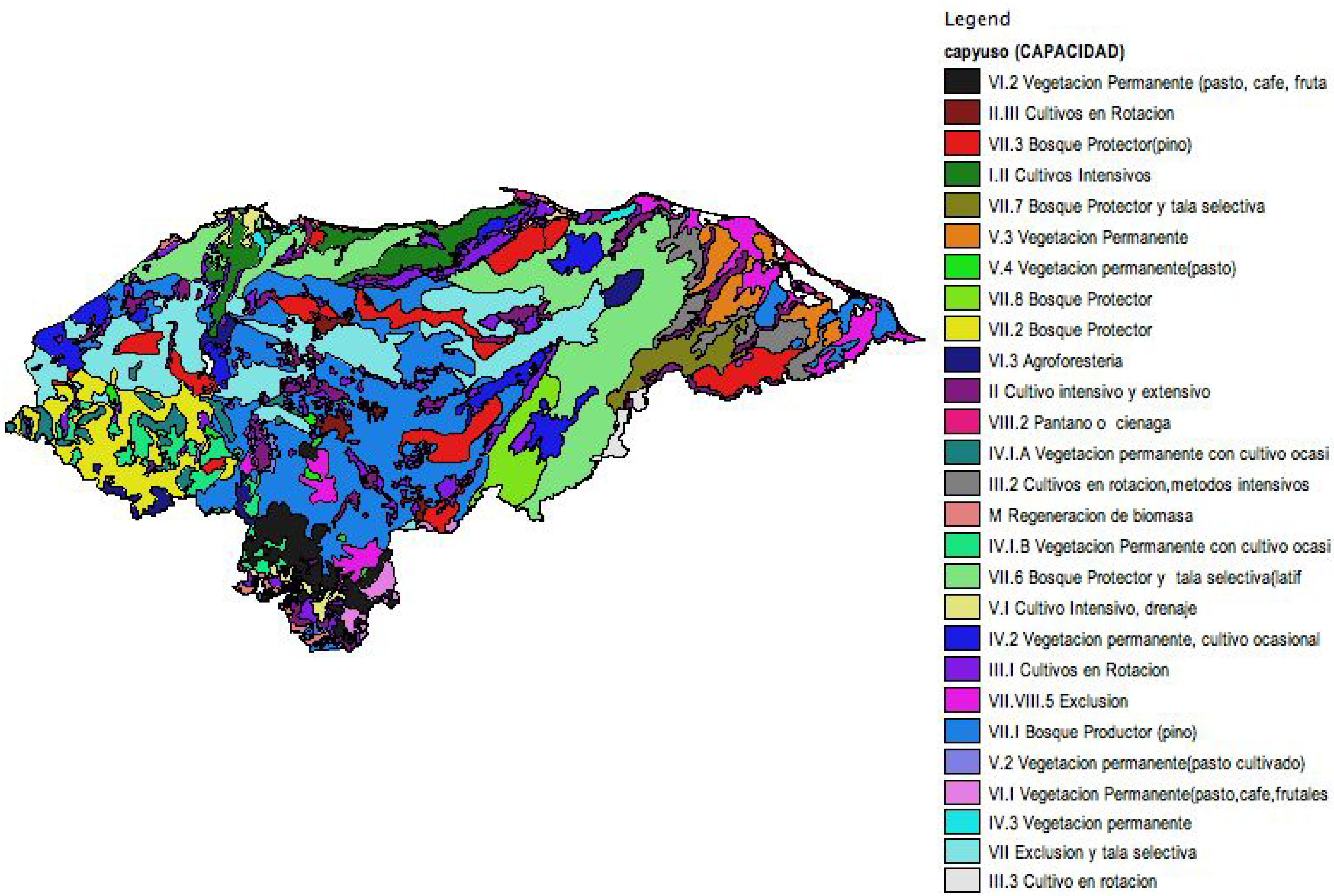

Figure 6.1 Map of land use in Honduras.

Mining

There are a number of mining operations in Honduras, mainly for silver, gold, lead and zinc. The El Mochito mine, located near Las Vegas, was previously the largest mine in Central America. This and other major mining operations throughout Honduras are displayed in Figure 6.2.

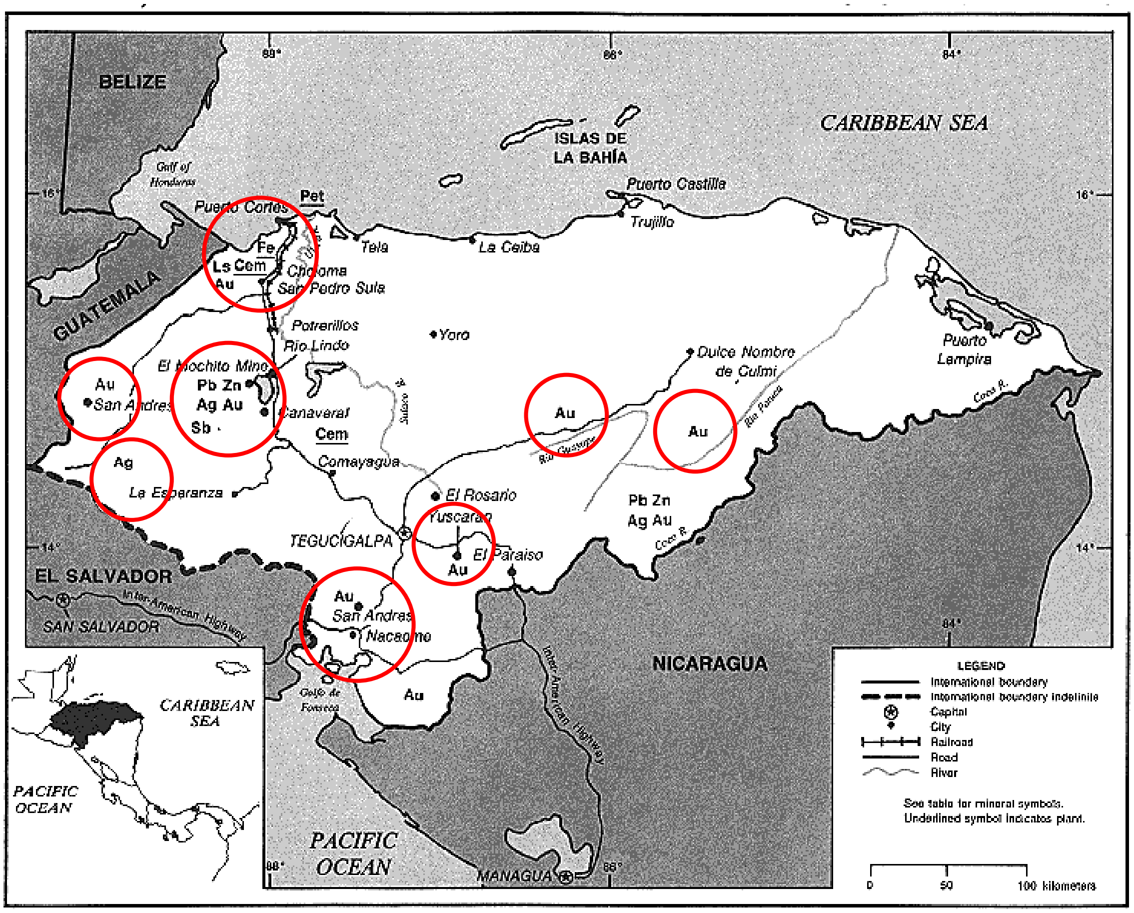

Figure 6.2 Major Mining Operations in Honduras (USGS, 2009).

Mining can cause extensive land degradation from soil disturbance, nutrient leaching due to erosion, and overburden contamination in the case of surface mining. During mining operations, reduced sulfur compounds within deeper soil layers are oxidized to sulfuric acid as a result of oxygen exposure. Because of this mined soils are typically acidic in nature, and can cause severe water pollution through acid mine drainage.

Biosolids have been successfully applied in land remediation of previously mined areas, including a number of US Superfund metals mining sites. One such example is the case of the Palmerton Zinc Superfund site in Pennsylvania (EPA, 2007). Previous mining activities had resulted in a 2000 acre defoliated area, with 33 million tons of material containing leachable metals. Biosolids were applied for increasing the nutrient and total organic carbon content of the soils, thereby accelerating revegetation of the land. Plant growth has increased ecosystem function, reduced erosion, and improved water quality by decreasing the overall concentration of soluble metals.

Biosolids that have been treated through alkaline stabilization can further improve land reclamation efforts by increasing the pH of acidic mine soils.

Land reclamation through biosolids applications provide potential markets for municipalities located near mines, such as Las Vegas, Comayagua, and Choloma. The viability of this option would be increased if mining operations were required by law to have a plan for land remediation upon closure, if this is not already the case. Due to its proximity to the El Mochito mine, Las Vegas in particular may have some opportunities for reusing its biosolids for current or future land remediation efforts.

6.1.2. Community Scale End-Use Scenarios

Biosolids reuse may be promoted within the community for both domestic and municipal applications. Domestic end-use options include household gardening and small-scale agricultural applications. Municipal applications can include landscaping of common green spaces, and use for landfill cover.

If heavy metals contents are low, biosolids may be commercially marketed as a soil amendment alternative to chemical fertilizers. They can also be sold to local businesses, involved in the production of soil amendment products, for mixing with compost or fertilizer products and enhancing the overall nutrient composition.

6.2 Social Acceptance

Negative public perception of biosolids is a challenge faced by municipalities in the developed and developing world alike. Public concerns are generally with respect to the presence of pathogens, heavy metals, and odors in wastewater sludge.

Considerable efforts have been taken in some countries, including the US, to address these issues. Regulatory bodies have developed biosolids quality guidelines such as those described in Section 3.2. Treated solids are often subjected to rigorous testing measures to ensure that quality standards are met for safe biosolids reuse programs. However, the communication of these progresses to the public has not always been commensurate, resulting in common misconceptions regarding the safety of biosolids reuse. Therefore, while it is important to invest in sound sludge treatment to mitigate related health concerns, the promotion of public involvement and awareness is also essential.

Community forums can provide opportunities to discuss the municipality's sludge management plan, the extent of risk reduction related to public health, and the potential benefits of biosolids reuse. Such forums can also identify the full nature of public concerns, allowing planners to address these specifically. It is crucial for representatives from the municipality as well as from federal regulatory bodies, such as SANAA, to play an active role in these initiatives. In addition to providing technical and regulatory guidance to municipal planners, government participation introduces a certain degree of accountability from the public's perception. Sludge management practices that are developed with support from the government are likely to find greater acceptance within the community. Active non-governmental organizations (NGOs), such as Water For People and Engineers Without Borders, can also play an important role in working with municipal and governmental representatives. Because these NGOs have prior experience working in grassroots level projects, their expertise in community organization can be beneficial in facilitating participation efforts.

Demonstration projects can be another valuable tool for educating the public regarding the advantages of biosolids reuse. Such projects can include those carried out in nearby communities, or they may also pilot programs undertaken by the municipality. For instance, if biosolids can be successfully applied to rehabilitate abandoned lands or for landscaping common spaces, this can encourage the wider community to use the material for domestic or commercial purposes.

Municipalities can form partnerships with local farming groups in order to supply biosolids for soil amendment, either at a reduced rate or free of charge. A similar approach has been adopted in the Guateng Province of South Africa. Wastewater treatment plants are involved in efforts to promote biosolids application on agricultural land. One of the measures taken was the negotiation of a supply contract with a local farming association; under this plan, biosolids are delivered to participating farmers for application to over 3000 hectares of agricultural land cultivating maize and soybean (Du Preez et al., 2000).

Encouraging community involvement through multi-sector involvement and developing partnerships are some of the measures that can be taken for promoting public awareness on issues related to biosolids reuse. These efforts can also bring to light the nature of public concerns, which can then be specifically addressed in the overall sludge management plan.

7.0 SUMMARY AND RECOMMENDATIONS

Sludge management is a vital component of wastewater treatment and must be addressed appropriately in order to maintain treatment efficiency, as well as mitigate public health risks associated with unsafe disposal. This issue is particularly important in Honduras where an increasingly large portion of treatment facilities critically requires desludging. As efforts are increased to improve access to sanitation, developing adequate management strategies will become more important in order to address the resulting increment in sludge generated.

Proper sludge treatment can generate biosolids that are considered safe for reuse in a variety of applications. Sludge treatment and biosolids reuse can provide a number of social and economic benefits. In the long-term, significant savings in public health resources could be realized, given that waterborne illnesses contribute to a large fraction of diseases in the country. Costs associated with commercial fertilizers can also be reduced. Biosolids application has also been beneficial for reclamation of degraded lands. These benefits are particularly advantageous for rural communities of Honduras, where access to resources can be limited financially.

In this study, sludge was characterized with respect to quantity and quality parameters. Based on field data and a review of available literature, volumetric accumulation rates, heavy metals contents and helminth egg concentrations were assessed. Volumetric accumulation rates were estimated to be 0.01 and 0.05 m^3/capita·day at La Lima and Puerto Cortes, respectively; these are close to the expected ranges for tropical climates. Heavy metals concentrations in the sludges analyzed were found to be very low with respect to the USEPA and Mexican biosolids reuse guidelines. Helminth egg concentrations are generally very high in waste stabilization pond sludges. A 1 to 2-log removal is typically required for treated sludge to meet the Class B standard set by the Mexican guideline.

Based on a review and evaluation of five different sludge stabilization methods, recommendations for most suitable technologies were made. These are summarized below:

- Anaerobic digestion is favorable for facilities that have technically trained staff for adequate operation and maintenance of the system. It is also recommended for areas that have land constraints as it has a relatively small footprint compared to other treatment methods and can be located below grade to allow greater versatility in land use.
- Sludge drying followed by composting is recommended for facilities that have no land constraints and have reliable staff available. Although composting does not require technically involved attention, regular maintenance is required to mix the compost piles. Co-composting with municipal solid waste can be a particular attractive option for municipalities in Honduras, addressing two waste streams with one integrative method.
- For municipalities with no land constraints and limited access to trained reliable staff, sludge drying followed by alkaline stabilization is recommended. This option is relatively simple to maintain and effectively reduces pathogen concentrations

in sludge. The main caveat of this method is the increase in the final amount of treated sludge.

Regional and community scale biosolids end-use scenarios were developed based on a study of Honduran land use data. Regional end-use options include biosolids application to agricultural lands, forested areas, as well as for remediation of mined lands. Alkaline biosolids can be particularly effective for the treatment of acidic mine soils. Community scale biosolids end-use applications primarily include household gardening, small-scale agriculture, landscaping of common green spaces, and landfill cover.

Public acceptance is critical to the success of a biosolids reuse program. Strategies for community participation can be beneficial for identifying and addressing public concerns with regard to biosolids reuse. Governmental involvement and visibility in biosolids reuse planning is important for presenting an accountable front to communities. Demonstrative projects and partnerships with local farming cooperatives can also be useful tools for improving public perception.

Necessary funding allocation and planning for sludge management should be carried out during the design of wastewater treatment facilities. This can be ensured by setting these measures as required criteria for obtaining regulatory approvals.

An important initial measure to allow for sustainable sludge management is the development of a regulatory framework for biosolids reuse. Standards with quantifiable parameters should be set to guide sludge management efforts. Tiered quality guidelines (e.g. Class A, Class B, etc) with identified appropriate end-uses can aid municipalities in selecting and planning for the most suitable sludge management scheme for their communities.

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APPENDIX A

TRIANGULATED IRREGULAR NETWORKS (TINS) AND SLUDGE VOLUME ESTIMATIONS

La Lima Facultative Lagoons: TIN

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

La Lima Facultative Lagoon 1: Node Coordinates

Node	x	y	z
1	**3.27**	**3.27**	**0.11**
2	**3.27**	**3.6**	**0.11**
3	**3.27**	**11.5**	**0.11**
4	**3.12**	**21**	**0.16**
5	**3.33**	**30.5**	**0.09**
6	**3.21**	**40**	**0.13**
7	**3.36**	**49.5**	**0.08**
8	**3.36**	**59**	**0.08**
9	**3.3**	**68.5**	**0.1**
10	**3.21**	**76.4**	**0.13**
11	**3.21**	**76.73**	**0.13**
12	**3.6**	**3.27**	**0.11**
13	3.6	3.6	0.11
14	3.6	11.5	0.11
15	3.6	21	0.16
16	3.6	30.5	0.09
17	3.6	40	0.13
18	3.6	49.5	0.08
19	3.6	59	0.08
20	3.6	68.5	0.1
21	3.6	76.4	0.13
22	3.6	76.73	0.13
23	**11**	3.27	**0.11**
24	11	3.6	0.11
25	11	11.5	0.11
26	11	21	0.16
27	11	30.5	0.09
28	11	40	0.13
29	11	49.5	0.08
30	11	59	0.08
31	11	68.5	0.1
32	11	76.4	0.13
33	11	76.79	0.13
34	**20**	**3.21**	**0.13**
35	20	3.6	0.13
36	20	11.5	0.13
37	20	21	0.13
38	20	30.5	0.1
39	20	40	0.07
40	20	49.5	0.06
41	20	59	0.12
42	20	68.5	0.13
43	20	76.4	0.18
44	20	76.94	0.18
45	**29**	**1.68**	**0.64**

Node	x	y	z
46	29	3.6	0.64
47	29	11.5	0.64
48	29	21	0.19
49	29	30.5	0.09
50	29	40	0.07
51	29	49.5	0.09
52	29	59	0.03
53	29	68.5	0.1
54	29	76.4	0.12
55	29	76.76	0.12
56	**36.4**	**3.45**	**0.05**
57	36.4	3.6	0.05
58	36.4	11.5	0.05
59	36.4	21	0.11
60	36.4	30.5	0.07
61	36.4	40	0.12
62	36.4	49.5	0.06
63	36.4	59	0.08
64	36.4	68.5	0.05
65	36.4	76.4	0.05
66	36.4	76.55	0.05
67	36.55	3.45	0.05
68	36.55	3.6	0.05
69	36.55	11.5	0.05
70	36.73	21	0.11
71	36.61	30.5	0.07
72	36.76	40	0.12
73	36.58	49.5	0.06
74	36.64	59	0.08
75	36.55	68.5	0.05
76	36.55	76.4	0.05
77	36.55	76.55	0.05

Sludge on flat area
Sludge "wedge"
Sludge "pyramid"
Measured readings

La Lima Facultative Lagoon 1: Sludge Volume Estimation

Triangle	Node 1	Node 2	Node 3	X_1	X_2	X_3	Y_1	Y_2	Y_3	Z_1	Z_2	Z_3	Area (m^2)	Average Z (m)	Volume (m^3)
A	1	12	2	3.27	3.6	3.27	3.27	3.27	3.6	0.11	0.11	0.11	0.05445	0.11	0.0019965
B	12	2	13	3.6	3.27	3.6	3.27	3.6	3.6	0.11	0.11	0.11	0.05445	0.11	0.0019965
C	2	13	3	3.27	3.6	3.27	3.6	3.6	11.5	0.11	0.11	0.11	1.3035	0.11	0.0716925
D	13	3	14	3.6	3.27	3.6	3.6	11.5	11.5	0.11	0.11	0.11	1.3035	0.11	0.0716925
E	3	14	4	3.27	3.6	3.12	11.5	11.5	21	0.11	0.11	0.16	1.5675	0.126666667	0.099275
F	14	4	15	3.6	3.12	3.6	11.5	21	21	0.11	0.16	0.16	2.28	0.143333333	0.1634
G	4	15	5	3.12	3.6	3.33	21	21	30.5	0.16	0.16	0.09	2.28	0.136666667	0.1558
H	15	5	16	3.6	3.33	3.6	21	30.5	30.5	0.16	0.09	0.09	1.2825	0.113333333	0.072675
I	5	16	6	3.33	3.6	3.21	30.5	30.5	40	0.09	0.09	0.13	1.2825	0.103333333	0.0662625
J	16	6	17	3.6	3.21	3.6	30.5	40	40	0.09	0.13	0.13	1.8525	0.116666667	0.1080625
K	6	17	7	3.21	3.6	3.36	40	40	49.5	0.13	0.13	0.08	1.8525	0.113333333	0.104975
L	17	7	18	3.6	3.36	3.6	40	49.5	49.5	0.13	0.08	0.08	1.14	0.096666667	0.0551
M	7	18	8	3.36	3.6	3.36	49.5	49.5	59	0.08	0.08	0.08	1.14	0.08	0.0456
N	18	8	19	3.6	3.36	3.6	49.5	59	59	0.08	0.08	0.08	1.14	0.08	0.0456
O	8	19	9	3.36	3.6	3.3	59	59	68.5	0.08	0.08	0.1	1.14	0.086666667	0.0494
P	19	9	20	3.6	3.3	3.6	59	68.5	68.5	0.08	0.1	0.1	1.425	0.093333333	0.0665
Q	9	20	10	3.3	3.6	3.21	68.5	68.5	76.4	0.1	0.1	0.13	1.185	0.11	0.065175
R	20	10	21	3.6	3.21	3.6	68.5	76.4	76.4	0.1	0.13	0.13	1.5405	0.12	0.09243
S	10	21	11	3.21	3.6	3.21	76.4	76.4	76.73	0.13	0.13	0.13	0.06435	0.13	0.0027885
T	21	11	22	3.6	3.21	3.6	76.4	76.73	76.73	0.13	0.13	0.13	0.06435	0.13	0.0027885
U	12	23	13	3.6	11	3.6	3.27	3.27	3.6	0.11	0.11	0.11	1.221	0.11	0.067155
V	23	13	24	11	3.6	11	3.27	3.6	3.6	0.11	0.11	0.11	1.221	0.11	0.067155
W	13	24	14	3.6	11	3.6	3.6	3.6	11.5	0.11	0.11	0.11	29.23	0.11	3.2153
X	24	14	25	11	3.6	11	3.6	11.5	11.5	0.11	0.11	0.11	29.23	0.11	3.2153
Y	14	25	15	3.6	11	3.6	11.5	11.5	21	0.11	0.11	0.16	35.15	0.126666667	4.4523333
Z	25	15	26	11	3.6	11	11.5	21	21	0.11	0.16	0.16	35.15	0.143333333	5.0381667
AA	15	26	16	3.6	11	3.6	21	21	30.5	0.16	0.16	0.09	35.15	0.136666667	4.8038333
AB	26	16	27	11	3.6	11	21	30.5	30.5	0.16	0.09	0.09	35.15	0.113333333	3.9836667
AC	16	27	17	3.6	11	3.6	30.5	30.5	40	0.09	0.09	0.13	35.15	0.103333333	3.6321667
AD	27	17	28	11	3.6	11	30.5	40	40	0.09	0.13	0.13	35.15	0.116666667	4.1008333

Triangle	Node 1	Node 2	Node 3	X1	X2	X3	Y1	Y2	Y3	Z1	Z2	Z3	Area (m2)	Average Z (m)	Volume (m3)
AE	17	28	18	3.6	11	3.6	40	40	49.5	0.13	0.13	0.08	35.15	0.113333333	3.9836667
AF	28	18	29	11	3.6	11	40	49.5	49.5	0.13	0.08	0.08	35.15	0.096666667	3.3978333
AG	18	29	19	3.6	11	3.6	49.5	49.5	59	0.08	0.08	0.08	35.15	0.08	2.812
AH	29	19	30	11	3.6	11	49.5	59	59	0.08	0.08	0.08	35.15	0.08	2.812
AI	19	30	20	3.6	11	3.6	59	59	68.5	0.08	0.08	0.1	35.15	0.086666667	3.0463333
AJ	30	20	31	11	3.6	11	59	68.5	68.5	0.08	0.1	0.1	35.15	0.093333333	3.2806667
AK	20	31	21	3.6	11	3.6	68.5	68.5	76.4	0.1	0.1	0.13	29.23	0.11	3.2153
AL	31	21	32	11	3.6	11	68.5	76.4	76.4	0.1	0.13	0.13	29.23	0.12	3.5076
AM	21	32	22	3.6	11	3.6	76.4	76.4	76.73	0.13	0.13	0.13	1.221	0.13	0.079365
AN	32	22	33	11	3.6	11	76.4	76.73	76.79	0.13	0.13	0.13	1.443	0.13	0.093795
AO	23	34	24	11	20	11	3.27	3.21	3.6	0.11	0.13	0.11	1.485	0.116666667	0.086625
AP	34	24	35	20	11	20	3.21	3.6	3.6	0.13	0.11	0.13	1.755	0.123333333	0.108225
AQ	24	35	25	11	20	11	3.6	3.6	11.5	0.11	0.13	0.11	35.55	0.116666667	4.1475
AR	35	25	36	20	11	20	3.6	11.5	11.5	0.13	0.11	0.13	35.55	0.123333333	4.3845
AS	25	36	26	11	20	11	11.5	11.5	21	0.11	0.13	0.16	42.75	0.133333333	5.7
AT	36	26	37	20	11	20	11.5	21	21	0.13	0.16	0.13	42.75	0.14	5.985
AU	26	37	27	11	20	11	21	21	30.5	0.16	0.13	0.09	42.75	0.126666667	5.415
AV	37	27	38	20	11	20	21	30.5	30.5	0.13	0.09	0.1	42.75	0.106666667	4.56
AW	27	38	28	11	20	11	30.5	30.5	40	0.09	0.1	0.13	42.75	0.106666667	4.56
AX	38	28	39	20	11	20	30.5	40	40	0.1	0.13	0.07	42.75	0.1	4.275
AY	28	39	29	11	20	11	40	40	49.5	0.13	0.07	0.08	42.75	0.093333333	3.99
AZ	39	29	40	20	11	20	40	49.5	49.5	0.07	0.08	0.06	42.75	0.07	2.9925
BA	29	40	30	11	20	11	49.5	49.5	59	0.08	0.06	0.08	42.75	0.073333333	3.135
BB	40	30	41	20	11	20	49.5	59	59	0.06	0.08	0.12	42.75	0.086666667	3.705
BC	30	41	31	11	20	11	59	59	68.5	0.08	0.12	0.1	42.75	0.1	4.275
BD	41	31	42	20	11	20	59	68.5	68.5	0.12	0.1	0.13	42.75	0.116666667	4.9875
BE	31	42	32	11	20	11	68.5	68.5	76.4	0.1	0.13	0.13	35.55	0.12	4.266
BF	42	32	43	20	11	20	68.5	76.4	76.4	0.13	0.13	0.18	35.55	0.146666667	5.214
BG	32	43	33	11	20	11	76.4	76.4	76.79	0.13	0.18	0.13	1.755	0.146666667	0.1287
BH	43	33	44	20	11	20	76.4	76.79	76.94	0.18	0.13	0.18	2.43	0.163333333	0.19845
BI	34	45	35	20	29	20	3.21	1.68	3.6	0.13	0.64	0.13	1.755	0.3	0.26325
BJ	45	35	46	29	20	29	1.68	3.6	3.6	0.64	0.13	0.64	8.64	0.47	2.0304
BK	35	46	36	20	29	20	3.6	3.6	11.5	0.13	0.64	0.13	35.55	0.3	10.665
BL	46	36	47	29	20	29	3.6	11.5	11.5	0.64	0.13	0.64	35.55	0.47	16.7085
BM	36	47	37	20	29	20	11.5	11.5	21	0.13	0.64	0.13	42.75	0.3	12.825
BN	47	37	48	29	20	29	11.5	21	21	0.64	0.13	0.19	42.75	0.32	13.68

Triangle	Node 1	Node 2	Node 3	X1	X2	X3	Y1	Y2	Y3	Z1	Z2	Z3	Area (m2)	Average Z (m)	Volume (m3)
BO	37	48	38	20	29	20	21	21	30.5	0.13	0.19	0.1	42.75	0.14	5.985
BP	48	38	49	29	20	29	21	30.5	30.5	0.19	0.1	0.09	42.75	0.126666667	5.415
BQ	38	49	39	20	29	20	30.5	30.5	40	0.1	0.09	0.07	42.75	0.086666667	3.705
BR	49	39	50	29	20	29	30.5	40	40	0.09	0.07	0.07	42.75	0.076666667	3.2775
BS	39	50	40	20	29	20	40	40	49.5	0.07	0.07	0.06	42.75	0.066666667	2.85
BT	50	40	51	29	20	29	40	49.5	49.5	0.07	0.06	0.09	42.75	0.073333333	3.135
BU	40	51	41	20	29	20	49.5	49.5	59	0.06	0.09	0.12	42.75	0.09	3.8475
BV	51	41	52	29	20	29	49.5	59	59	0.09	0.12	0.03	42.75	0.08	3.42
BW	41	52	42	20	29	20	59	59	68.5	0.12	0.03	0.13	42.75	0.093333333	3.99
BX	52	42	53	29	20	29	59	68.5	68.5	0.03	0.13	0.1	42.75	0.086666667	3.705
BY	42	53	43	20	29	20	68.5	68.5	76.4	0.13	0.1	0.18	35.55	0.136666667	4.8585
BZ	53	43	54	29	20	29	68.5	76.4	76.4	0.1	0.18	0.12	35.55	0.133333333	4.74
CA	43	54	44	20	29	20	76.4	76.4	76.94	0.18	0.12	0.18	2.43	0.16	0.1944
CB	54	44	55	29	20	29	76.4	76.94	76.76	0.12	0.18	0.12	1.62	0.14	0.1134
CC	45	56	46	29	36.4	29	1.68	3.45	3.6	0.64	0.05	0.64	7.104	0.443333333	1.57472
CD	56	46	57	36.4	29	36.4	3.45	3.6	3.6	0.05	0.64	0.05	0.555	0.246666667	0.06845
CE	46	57	47	29	36.4	29	3.6	3.6	11.5	0.64	0.05	0.64	29.23	0.443333333	12.958633
CF	57	47	58	36.4	29	36.4	3.6	11.5	11.5	0.05	0.64	0.05	29.23	0.246666667	7.2100667
CG	47	58	48	29	36.4	29	11.5	11.5	21	0.64	0.05	0.19	35.15	0.293333333	10.310667
CH	58	48	59	36.4	29	36.4	11.5	21	21	0.05	0.19	0.11	35.15	0.116666667	4.1008333
CI	48	59	49	29	36.4	29	21	21	30.5	0.19	0.11	0.09	35.15	0.13	4.5695
CJ	59	49	60	36.4	29	36.4	21	30.5	30.5	0.11	0.09	0.07	35.15	0.09	3.1635
CK	49	60	50	29	36.4	29	30.5	30.5	40	0.09	0.07	0.07	35.15	0.076666667	2.6948333
CL	60	50	61	36.4	29	36.4	30.5	40	40	0.07	0.07	0.12	35.15	0.086666667	3.0463333
CM	50	61	51	29	36.4	29	40	40	49.5	0.07	0.12	0.09	35.15	0.093333333	3.2806667
CN	61	51	62	36.4	29	36.4	40	49.5	49.5	0.12	0.09	0.06	35.15	0.09	3.1635
CO	51	62	52	29	36.4	29	49.5	49.5	59	0.09	0.06	0.03	35.15	0.06	2.109
CP	62	52	63	36.4	29	36.4	49.5	59	59	0.06	0.03	0.08	35.15	0.056666667	1.9918333
CQ	52	63	53	29	36.4	29	59	59	68.5	0.03	0.08	0.1	35.15	0.07	2.4605
CR	63	53	64	36.4	29	36.4	59	68.5	68.5	0.08	0.1	0.05	35.15	0.076666667	2.6948333
CS	53	64	54	29	36.4	29	68.5	68.5	76.4	0.1	0.05	0.12	29.23	0.09	2.6307
CT	64	54	65	36.4	29	36.4	68.5	76.4	76.4	0.05	0.12	0.05	29.23	0.073333333	2.1435333
CU	54	65	55	29	36.4	29	76.4	76.4	76.76	0.12	0.05	0.12	1.332	0.096666667	0.06438
CV	65	55	66	36.4	29	36.4	76.4	76.76	76.55	0.05	0.12	0.05	0.555	0.073333333	0.02035
CW	56	67	57	36.4	36.55	36.4	3.45	3.45	3.6	0.05	0.05	0.05	0.01125	0.05	0.0001875
CX	67	57	68	36.55	36.4	36.55	3.45	3.6	3.6	0.05	0.05	0.05	0.01125	0.05	0.0001875

Triangle	Node 1	Node 2	Node 3	X1	X2	X3	Y1	Y2	Y3	Z1	Z2	Z3	Area (m2)	Average Z (m)	Volume (m3)
CY	57	68	58	36.4	36.55	36.4	3.6	3.6	11.5	0.05	0.05	0.05	0.5925	0.05	0.0148125
CZ	68	58	69	36.55	36.4	36.55	3.6	11.5	11.5	0.05	0.05	0.05	0.5925	0.05	0.0148125
DA	58	69	59	36.4	36.55	36.4	11.5	11.5	21	0.05	0.05	0.11	0.7125	0.07	0.0249375
DB	69	59	70	36.55	36.4	36.73	11.5	21	21	0.05	0.11	0.11	1.5675	0.09	0.0705375
DC	59	70	60	36.4	36.73	36.4	21	21	30.5	0.11	0.11	0.07	1.5675	0.096666667	0.0757625
DD	70	60	71	36.73	36.4	36.61	21	30.5	30.5	0.11	0.07	0.07	0.9975	0.083333333	0.0415625
DE	60	71	61	36.4	36.61	36.4	30.5	30.5	40	0.07	0.07	0.12	0.9975	0.086666667	0.043225
DF	71	61	72	36.61	36.4	36.76	30.5	40	40	0.07	0.12	0.12	1.71	0.103333333	0.08835
DG	61	72	62	36.4	36.76	36.4	40	40	49.5	0.12	0.12	0.06	1.71	0.1	0.0855
DH	72	62	73	36.76	36.4	36.58	40	49.5	49.5	0.12	0.06	0.06	0.855	0.08	0.0342
DI	62	73	63	36.4	36.58	36.4	49.5	49.5	59	0.06	0.06	0.08	0.855	0.066666667	0.0285
DJ	73	63	74	36.58	36.4	36.64	49.5	59	59	0.06	0.08	0.08	1.14	0.073333333	0.0418
DK	63	74	64	36.4	36.64	36.4	59	59	68.5	0.08	0.08	0.05	1.14	0.07	0.0399
DL	74	64	75	36.64	36.4	36.55	59	68.5	68.5	0.08	0.05	0.05	0.7125	0.06	0.021375
DM	64	75	65	36.4	36.55	36.4	68.5	68.5	76.4	0.05	0.05	0.05	0.5925	0.05	0.0148125
DN	75	65	76	36.55	36.4	36.55	68.5	76.4	76.4	0.05	0.05	0.05	0.5925	0.05	0.0148125
DO	65	76	66	36.4	36.55	36.4	76.4	76.4	76.55	0.05	0.05	0.05	0.01125	0.05	0.0001875
DP	76	66	77	36.55	36.4	36.55	76.4	76.55	76.55	0.05	0.05	0.05	0.01125	0.05	0.0001875

TOTAL VOL **308.5826** m3

La Lima Facultative Lagoon 2: Node Coordinates

Node	x	y	z
1	**3.27**	**3.27**	**0.11**
2	**3.27**	**3.6**	**0.11**
3	**3.27**	**11.5**	**0.11**
4	**3.36**	**21**	**0.08**
5	**3.42**	**30.5**	**0.06**
6	**3.21**	**40**	**0.13**
7	**3.24**	**49.5**	**0.12**
8	**3.27**	**59**	**0.11**
9	**3.45**	**68.5**	**0.05**
10	**3.45**	**76.4**	**0.05**
11	**3.45**	**76.88**	**0.05**
12	**3.6**	**3.27**	**0.11**
13	3.6	3.6	0.11
14	3.6	11.5	0.11
15	3.6	21	0.08
16	3.6	30.5	0.06
17	3.6	40	0.13
18	3.6	49.5	0.12
19	3.6	59	0.11
20	3.6	68.5	0.05
21	3.6	76.4	0.05
22	3.6	76.88	0.05
23	**11**	3.27	**0.16**
24	11	3.6	0.16
25	11	11.5	0.13
26	11	21	0.11
27	11	30.5	0.09
28	11	40	0.09
29	11	49.5	0.09
30	11	59	0.15
31	11	68.5	0.13
32	11	76.4	0.16
33	11	76.88	0.16
34	**20**	**2.91**	**0.23**
35	20	3.6	0.23
36	20	11.5	0.14
37	20	21	0.13
38	20	30.5	0.11
39	20	40	0.12
40	20	49.5	0.12
41	20	59	0.12
42	20	68.5	0.15
43	20	76.4	0.15
44	20	76.85	0.15
45	**29**	**2.79**	**0.27**

Node	x	y	z
46	29	3.6	0.27
47	29	11.5	0.28
48	29	21	0.29
49	29	30.5	0.26
50	29	40	0.13
51	29	49.5	0.16
52	29	59	0.17
53	29	68.5	0.14
54	29	76.4	0.14
55	29	76.82	0.14
56	**36.4**	**3.12**	**0.16**
57	36.4	3.6	0.16
58	36.4	11.5	0.16
59	36.4	21	0.15
60	36.4	30.5	0.18
61	36.4	40	0.13
62	36.4	49.5	0.13
63	36.4	59	0.1
64	36.4	68.5	0.1
65	36.4	76.4	0.1
66	36.4	76.7	0.1
67	36.88	3.12	0.16
68	36.88	3.6	0.16
69	36.88	11.5	0.16
70	36.85	21	0.15
71	36.94	30.5	0.18
72	36.79	40	0.13
73	36.79	49.5	0.13
74	36.7	59	0.1
75	36.7	68.5	0.1
76	36.7	76.4	0.1
77	36.7	76.7	0.1

Sludge on flat area
Sludge "wedge"
Measured readings
Sludge "pyramid"

La Lima Facultative Lagoon 2: Sludge Volume Estimation

Triangle	Node 1	Node 2	Node 3	X_1	X_2	X_3	Y_1	Y_2	Y_3	Z_1	Z_2	Z_3	Area (m^2)	Average Z (m)	Volume (m^3)
A	1	12	2	3.27	3.6	3.27	3.27	3.27	3.6	0.11	0.11	0.11	0.05445	0.11	0.0019965
B	12	2	13	3.6	3.27	3.6	3.27	3.6	3.6	0.11	0.11	0.11	0.05445	0.11	0.0019965
C	2	13	3	3.27	3.6	3.27	3.6	3.6	11.5	0.11	0.11	0.11	1.3035	0.11	0.0716925
D	13	3	14	3.6	3.27	3.6	3.6	11.5	11.5	0.11	0.11	0.11	1.3035	0.11	0.0716925
E	3	14	4	3.27	3.6	3.36	11.5	11.5	21	0.11	0.11	0.08	1.5675	0.1	0.078375
F	14	4	15	3.6	3.36	3.6	11.5	21	21	0.11	0.08	0.08	1.14	0.09	0.0513
G	4	15	5	3.36	3.6	3.42	21	21	30.5	0.08	0.08	0.06	1.14	0.073333333	0.0418
H	15	5	16	3.6	3.42	3.6	21	30.5	30.5	0.08	0.06	0.06	0.855	0.066666667	0.0285
I	5	16	6	3.42	3.6	3.21	30.5	30.5	40	0.06	0.06	0.13	0.855	0.083333333	0.035625
J	16	6	17	3.6	3.21	3.6	30.5	40	40	0.06	0.13	0.13	1.8525	0.106666667	0.0988
K	6	17	7	3.21	3.6	3.24	40	40	49.5	0.13	0.13	0.12	1.8525	0.126666667	0.117325
L	17	7	18	3.6	3.24	3.6	40	49.5	49.5	0.13	0.12	0.12	1.71	0.123333333	0.10545
M	7	18	8	3.24	3.6	3.27	49.5	49.5	59	0.12	0.12	0.11	1.71	0.116666667	0.09975
N	18	8	19	3.6	3.27	3.6	49.5	59	59	0.12	0.11	0.11	1.5675	0.113333333	0.088825
O	8	19	9	3.27	3.6	3.45	59	59	68.5	0.11	0.11	0.05	1.5675	0.09	0.0705375
P	19	9	20	3.6	3.45	3.6	59	68.5	68.5	0.11	0.05	0.05	0.7125	0.07	0.0249375
Q	9	20	10	3.45	3.6	3.45	68.5	68.5	76.4	0.05	0.05	0.05	0.5925	0.05	0.0148125
R	20	10	21	3.6	3.45	3.6	68.5	76.4	76.4	0.05	0.05	0.05	0.5925	0.05	0.0148125
S	10	21	11	3.45	3.6	3.45	76.4	76.4	76.88	0.05	0.05	0.05	0.036	0.05	0.0006
T	21	11	22	3.6	3.45	3.6	76.4	76.88	76.88	0.05	0.05	0.05	0.036	0.05	0.0006
U	12	23	13	3.6	11	3.6	3.27	3.27	3.6	0.11	0.16	0.11	1.221	0.126666667	0.07733
V	23	13	24	11	3.6	11	3.27	3.6	3.6	0.16	0.11	0.16	1.221	0.143333333	0.087505
W	13	24	14	3.6	11	3.6	3.6	3.6	11.5	0.11	0.16	0.11	29.23	0.126666667	3.70246667
X	24	14	25	11	3.6	11	3.6	11.5	11.5	0.16	0.11	0.13	29.23	0.133333333	3.89733333
Y	14	25	15	3.6	11	3.6	11.5	11.5	21	0.11	0.13	0.08	35.15	0.106666667	3.74933333
Z	25	15	26	11	3.6	11	11.5	21	21	0.13	0.08	0.11	35.15	0.106666667	3.74933333
AA	15	26	16	3.6	11	3.6	21	21	30.5	0.08	0.11	0.06	35.15	0.083333333	2.92916667
AB	26	16	27	11	3.6	11	21	30.5	30.5	0.11	0.06	0.09	35.15	0.086666667	3.04633333
AC	16	27	17	3.6	11	3.6	30.5	30.5	40	0.06	0.09	0.13	35.15	0.093333333	3.28066667
AD	27	17	28	11	3.6	11	30.5	40	40	0.09	0.13	0.09	35.15	0.103333333	3.63216667

Triangle	Node 1	Node 2	Node 3	X1	X2	X3	Y1	Y2	Y3	Z1	Z2	Z3	Area (m2)	Average Z (m)	Volume (m3)
AE	17	28	18	3.6	11	3.6	40	40	49.5	0.13	0.09	0.12	35.15	0.113333333	3.9836667
AF	28	18	29	11	3.6	11	40	49.5	49.5	0.09	0.12	0.09	35.15	0.1	3.515
AG	18	29	19	3.6	11	3.6	49.5	49.5	59	0.12	0.09	0.11	35.15	0.106666667	3.7493333
AH	29	19	30	11	3.6	11	49.5	59	59	0.09	0.11	0.15	35.15	0.116666667	4.1008333
AI	19	30	20	3.6	11	3.6	59	59	68.5	0.11	0.15	0.05	35.15	0.103333333	3.6321667
AJ	30	20	31	11	3.6	11	59	68.5	68.5	0.15	0.05	0.13	35.15	0.11	3.8665
AK	20	31	21	3.6	11	3.6	68.5	68.5	76.4	0.05	0.13	0.05	29.23	0.076666667	2.2409667
AL	31	21	32	11	3.6	11	68.5	76.4	76.4	0.13	0.05	0.16	29.23	0.113333333	3.3127333
AM	21	32	22	3.6	11	3.6	76.4	76.4	76.88	0.05	0.16	0.05	1.776	0.086666667	0.07696
AN	32	22	33	11	3.6	11	76.4	76.88	76.88	0.16	0.05	0.16	1.776	0.123333333	0.10952
AO	23	34	24	11	20	11	3.27	2.91	3.6	0.16	0.23	0.16	1.485	0.183333333	0.136125
AP	34	24	35	20	11	20	2.91	3.6	3.6	0.23	0.16	0.23	3.105	0.206666667	0.32085
AQ	24	35	25	11	20	11	3.6	3.6	11.5	0.16	0.23	0.13	35.55	0.173333333	6.162
AR	35	25	36	20	11	20	3.6	11.5	11.5	0.23	0.13	0.14	35.55	0.166666667	5.925
AS	25	36	26	11	20	11	11.5	11.5	21	0.13	0.14	0.11	42.75	0.126666667	5.415
AT	36	26	37	20	11	20	11.5	21	21	0.14	0.11	0.13	42.75	0.126666667	5.415
AU	26	37	27	11	20	11	21	21	30.5	0.11	0.13	0.09	42.75	0.11	4.7025
AV	37	27	38	20	11	20	21	30.5	30.5	0.13	0.09	0.11	42.75	0.11	4.7025
AW	27	38	28	11	20	11	30.5	30.5	40	0.09	0.11	0.09	42.75	0.096666667	4.1325
AX	38	28	39	20	11	20	30.5	40	40	0.11	0.09	0.12	42.75	0.106666667	4.56
AY	28	39	29	11	20	11	40	40	49.5	0.09	0.12	0.09	42.75	0.1	4.275
AZ	39	29	40	20	11	20	40	49.5	49.5	0.12	0.09	0.12	42.75	0.11	4.7025
BA	29	40	30	11	20	11	49.5	49.5	59	0.09	0.12	0.15	42.75	0.12	5.13
BB	40	30	41	20	11	20	49.5	59	59	0.12	0.15	0.12	42.75	0.13	5.5575
BC	30	41	31	11	20	11	59	59	68.5	0.15	0.12	0.13	42.75	0.133333333	5.7
BD	41	31	42	20	11	20	59	68.5	68.5	0.12	0.13	0.15	42.75	0.133333333	5.7
BE	31	42	32	11	20	11	68.5	68.5	76.4	0.13	0.15	0.16	35.55	0.146666667	5.214
BF	42	32	43	20	11	20	68.5	76.4	76.4	0.15	0.16	0.15	35.55	0.153333333	5.451
BG	32	43	33	11	20	11	76.4	76.4	76.88	0.16	0.15	0.16	2.16	0.156666667	0.1692
BH	43	33	44	20	11	20	76.4	76.88	76.85	0.15	0.16	0.15	2.025	0.153333333	0.15525
BI	34	45	35	20	29	20	2.91	2.79	3.6	0.23	0.27	0.23	3.105	0.243333333	0.377775
BJ	45	35	46	29	20	29	2.79	3.6	3.6	0.27	0.23	0.27	3.645	0.256666667	0.467775
BK	35	46	36	20	29	20	3.6	3.6	11.5	0.23	0.27	0.14	35.55	0.213333333	7.584
BL	46	36	47	29	20	29	3.6	11.5	11.5	0.27	0.14	0.28	35.55	0.23	8.1765
BM	36	47	37	20	29	20	11.5	11.5	21	0.14	0.28	0.13	42.75	0.183333333	7.8375
BN	47	37	48	29	20	29	11.5	21	21	0.28	0.13	0.29	42.75	0.233333333	9.975

Triangle	Node 1	Node 2	Node 3	X1	X2	X3	Y1	Y2	Y3	Z1	Z2	Z3	Area (m2)	Average Z (m)	Volume (m3)
BO	37	48	38	20	29	20	21	21	30.5	0.13	0.29	0.11	42.75	0.176666667	7.5525
BP	48	38	49	29	20	29	21	30.5	30.5	0.29	0.11	0.26	42.75	0.22	9.405
BQ	38	49	39	20	29	20	30.5	30.5	40	0.11	0.26	0.12	42.75	0.163333333	6.9825
BR	49	39	50	29	20	29	30.5	40	40	0.26	0.12	0.13	42.75	0.17	7.2675
BS	39	50	40	20	29	20	40	40	49.5	0.12	0.13	0.12	42.75	0.123333333	5.2725
BT	50	40	51	29	20	29	40	49.5	49.5	0.13	0.12	0.16	42.75	0.136666667	5.8425
BU	40	51	41	20	29	20	49.5	49.5	59	0.12	0.16	0.12	42.75	0.133333333	5.7
BV	51	41	52	29	20	29	49.5	59	59	0.16	0.12	0.17	42.75	0.15	6.4125
BW	41	52	42	20	29	20	59	59	68.5	0.12	0.17	0.15	42.75	0.146666667	6.27
BX	52	42	53	29	20	29	59	68.5	68.5	0.17	0.15	0.14	42.75	0.153333333	6.555
BY	42	53	43	20	29	20	68.5	68.5	76.4	0.15	0.14	0.15	35.55	0.146666667	5.214
BZ	53	43	54	29	20	29	68.5	76.4	76.4	0.14	0.15	0.14	35.55	0.143333333	5.0955
CA	43	54	44	20	29	20	76.4	76.4	76.85	0.15	0.14	0.15	2.025	0.146666667	0.1485
CB	54	44	55	29	20	29	76.4	76.85	76.82	0.14	0.15	0.14	1.89	0.143333333	0.13545
CC	45	56	46	29	36.4	29	2.79	3.12	3.6	0.27	0.16	0.27	2.997	0.233333333	0.34965
CD	56	46	57	36.4	29	36.4	3.12	3.6	3.6	0.16	0.27	0.16	1.776	0.196666667	0.17464
CE	46	57	47	29	36.4	29	3.6	3.6	11.5	0.27	0.16	0.28	29.23	0.236666667	6.9177667
CF	57	47	58	36.4	29	36.4	3.6	11.5	11.5	0.16	0.28	0.16	29.23	0.2	5.846
CG	47	58	48	29	36.4	29	11.5	11.5	21	0.28	0.16	0.29	35.15	0.243333333	8.5531667
CH	58	48	59	36.4	29	36.4	11.5	21	21	0.16	0.29	0.15	35.15	0.2	7.03
CI	48	59	49	29	36.4	29	21	21	30.5	0.29	0.15	0.26	35.15	0.233333333	8.2016667
CJ	59	49	60	36.4	29	36.4	21	30.5	30.5	0.15	0.26	0.18	35.15	0.196666667	6.9128333
CK	49	60	50	29	36.4	29	30.5	30.5	40	0.26	0.18	0.13	35.15	0.19	6.6785
CL	60	50	61	36.4	29	36.4	30.5	40	40	0.18	0.13	0.13	35.15	0.146666667	5.1553333
CM	50	61	51	29	36.4	29	40	40	49.5	0.13	0.13	0.16	35.15	0.14	4.921
CN	61	51	62	36.4	29	36.4	40	49.5	49.5	0.13	0.16	0.13	35.15	0.14	4.921
CO	51	62	52	29	36.4	29	49.5	49.5	59	0.16	0.13	0.17	35.15	0.153333333	5.3896667
CP	62	52	63	36.4	29	36.4	49.5	59	59	0.13	0.17	0.1	35.15	0.133333333	4.6866667
CQ	52	63	53	29	36.4	29	59	59	68.5	0.17	0.1	0.14	35.15	0.136666667	4.8038333
CR	63	53	64	36.4	29	36.4	59	68.5	68.5	0.1	0.14	0.1	35.15	0.113333333	3.9836667
CS	53	64	54	29	36.4	29	68.5	68.5	76.4	0.14	0.1	0.14	29.23	0.126666667	3.7024667
CT	64	54	65	36.4	29	36.4	68.5	76.4	76.4	0.1	0.14	0.1	29.23	0.113333333	3.3127333
CU	54	65	55	29	36.4	29	76.4	76.4	76.82	0.14	0.1	0.14	1.554	0.126666667	0.09842
CV	65	55	66	36.4	29	36.4	76.4	76.82	76.7	0.1	0.14	0.1	1.11	0.113333333	0.0629
CW	56	67	57	36.4	36.88	36.4	3.12	3.12	3.6	0.16	0.16	0.16	0.1152	0.16	0.006144
CX	67	57	68	36.88	36.4	36.88	3.12	3.6	3.6	0.16	0.16	0.16	0.1152	0.16	0.006144

CY	57	68	58	36.4	36.88	36.4	3.6	3.6	11.5	0.16	0.16	0.16	1.896	0.16	0.15168
CZ	68	58	69	36.88	36.4	36.88	3.6	11.5	11.5	0.16	0.16	0.16	1.896	0.16	0.15168
DA	58	69	59	36.4	36.88	36.4	11.5	11.5	21	0.16	0.16	0.15	2.28	0.156666667	0.1786
DB	69	59	70	36.88	36.4	36.85	11.5	21	21	0.16	0.15	0.15	2.1375	0.153333333	0.163875
DC	59	70	60	36.4	36.85	36.4	21	21	30.5	0.15	0.15	0.18	2.1375	0.16	0.171
DD	70	60	71	36.85	36.4	36.94	21	30.5	30.5	0.15	0.18	0.18	2.565	0.17	0.218025
DE	60	71	61	36.4	36.94	36.4	30.5	30.5	40	0.18	0.18	0.13	2.565	0.163333333	0.209475
DF	71	61	72	36.94	36.4	36.79	30.5	40	40	0.18	0.13	0.13	1.8525	0.146666667	0.13585
DG	61	72	62	36.4	36.79	36.4	40	40	49.5	0.13	0.13	0.13	1.8525	0.13	0.1204125
DH	72	62	73	36.79	36.4	36.79	40	49.5	49.5	0.13	0.13	0.13	1.8525	0.13	0.1204125
DI	62	73	63	36.4	36.79	36.4	49.5	49.5	59	0.13	0.13	0.1	1.8525	0.12	0.11115
DJ	73	63	74	36.79	36.4	36.7	49.5	59	59	0.13	0.1	0.1	1.425	0.11	0.078375
DK	63	74	64	36.4	36.7	36.4	59	59	68.5	0.1	0.1	0.1	1.425	0.1	0.07125
DL	74	64	75	36.7	36.4	36.7	59	68.5	68.5	0.1	0.1	0.1	1.425	0.1	0.07125
DM	64	75	65	36.4	36.7	36.4	68.5	68.5	76.4	0.1	0.1	0.1	1.185	0.1	0.05925
DN	75	65	76	36.7	36.4	36.7	68.5	76.4	76.4	0.1	0.1	0.1	1.185	0.1	0.05925
DO	65	76	66	36.4	36.7	36.4	76.4	76.4	76.7	0.1	0.1	0.1	0.045	0.1	0.0015
DP	76	66	77	36.7	36.4	36.7	76.4	76.7	76.7	0.1	0.1	0.1	0.045	0.1	0.0015

TOTAL VOL **347.3454** m3

Puerto Cortes Anaerobic Lagoons: TIN

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Puerto Cortes Anaerobic Lagoon 1: Node Coordinates

Node	x	y	z
1	**10.26**	**12**	**0.58**
2	**10.26**	**14**	**0.58**
3	**10.08**	**24**	**0.64**
4	**10.11**	**34**	**0.63**
5	**11.13**	**44**	**0.29**
6	**11.37**	**54**	**0.21**
7	**11.61**	**64**	**0.13**
8	**11.67**	**74**	**0.11**
9	**11.46**	**84**	**0.18**
10	**11.37**	**94**	**0.21**
11	**11.37**	**96**	**0.21**
12	**12**	**12**	**0.58**
13	12	14	0.58
14	12	24	0.64
15	12	34	0.63
16	12	44	0.29
17	12	54	0.21
18	12	64	0.13
19	12	74	0.11
20	12	84	0.18
21	12	94	0.21
22	12	96	0.21
23	**14**	**12**	**0.58**
24	14	14	0.58
25	14	24	0.64
26	14	34	0.63
27	14	44	0.29
28	14	54	0.21
29	14	64	0.13
30	14	74	0.11
31	14	84	0.18
32	14	94	0.21
33	14	96	0.21
34	**21**	**12**	**0.6**
35	21	14	0.6
36	21	24	0.64
37	21	34	0.51
38	21	44	0.48
39	21	54	0.18
40	21	64	0.15
41	21	74	0.21
42	21	84	0.26
43	21	94	0.18
44	21	96	0.18
45	**28**	**12**	**0.35**

Node	x	y	z
46	28	14	0.35
47	28	24	0.46
48	28	34	0.42
49	28	44	0.32
50	28	54	0.23
51	28	64	0.23
52	28	74	0.23
53	28	84	0.18
54	28	94	0.18
55	28	96	0.18
56	**29.05**	**12**	**0.35**
57	29.05	14	0.35
58	29.38	24	0.46
59	29.26	34	0.42
60	28.96	44	0.32
61	28.69	54	0.23
62	28.69	64	0.23
63	28.69	74	0.23
64	28.54	84	0.18
65	28.54	94	0.18
66	28.54	96	0.18
67	11.37	96.63	0.21
68	12	96.63	0.21
69	14	96.63	0.21
70	21	96.54	0.18
71	28	96.54	0.18
72	28.54	96.54	0.18
73	10.26	10.26	0.58
74	12	10.26	0.58
75	14	10.26	0.58
76	21	10.2	0.6
77	28	10.95	0.35
78	29.05	10.95	0.35

Sludge on flat area
Sludge "wedge"
Measured readings
Sludge "pyramid"

Puerto Cortes Anaerobic Lagoon 1: Sludge Volume Estimation

Triangle	Node 1	Node 2	Node 3	X_1	X_2	X_3	Y_1	Y_2	Y_3	Z_1	Z_2	Z_3	Area (m^2)	Average Z (m)	Volume (m^3)
A	1	12	2	10.26	12	10.26	12	12	14	0.58	0.58	0.58	1.74	0.58	0.5046
B	12	2	13	12	10.26	12	12	14	14	0.58	0.58	0.58	1.74	0.58	0.5046
C	2	13	3	10.26	12	10.08	14	14	24	0.58	0.58	0.64	8.7	0.6	2.61
D	13	3	14	12	10.08	12	14	24	24	0.58	0.64	0.64	9.6	0.62	2.976
E	3	14	4	10.08	12	10.11	24	24	34	0.64	0.64	0.63	9.6	0.636666667	3.056
F	14	4	15	12	10.11	12	24	34	34	0.64	0.63	0.63	9.45	0.633333333	2.9925
G	4	15	5	10.11	12	11.13	34	34	44	0.63	0.63	0.29	9.45	0.516666667	2.44125
H	15	5	16	12	11.13	12	34	44	44	0.63	0.29	0.29	4.35	0.403333333	0.87725
I	5	16	6	11.13	12	11.37	44	44	54	0.29	0.29	0.21	4.35	0.263333333	0.57275
J	16	6	17	12	11.37	12	44	54	54	0.29	0.21	0.21	3.15	0.236666667	0.37275
K	6	17	7	11.37	12	11.61	54	54	64	0.21	0.21	0.13	3.15	0.183333333	0.28875
L	17	7	18	12	11.61	12	54	64	64	0.21	0.13	0.13	1.95	0.156666667	0.15275
M	7	18	8	11.61	12	11.67	64	64	74	0.13	0.13	0.11	1.95	0.123333333	0.12025
N	18	8	19	12	11.67	12	64	74	74	0.13	0.11	0.11	1.65	0.116666667	0.09625
O	8	19	9	11.67	12	11.46	74	74	84	0.11	0.11	0.18	1.65	0.133333333	0.11
P	19	9	20	12	11.46	12	74	84	84	0.11	0.18	0.18	2.7	0.156666667	0.2115
Q	9	20	10	11.46	12	11.37	84	84	94	0.18	0.18	0.21	2.7	0.19	0.2565
R	20	10	21	12	11.37	12	84	94	94	0.18	0.21	0.21	3.15	0.2	0.315
S	10	21	11	11.37	12	11.37	94	94	96	0.21	0.21	0.21	0.63	0.21	0.06615
T	21	11	22	12	11.37	12	94	96	96	0.21	0.21	0.21	0.63	0.21	0.06615
U	12	23	13	12	14	12	12	12	14	0.58	0.58	0.58	2	0.58	1.16
V	23	13	24	14	12	14	12	14	14	0.58	0.58	0.58	2	0.58	1.16
W	13	24	14	12	14	12	14	14	24	0.58	0.58	0.64	10	0.6	6
X	24	14	25	14	12	14	14	24	24	0.58	0.64	0.64	10	0.62	6.2
Y	14	25	15	12	14	12	24	24	34	0.64	0.64	0.63	10	0.636666667	6.3666667
Z	25	15	26	14	12	14	24	34	34	0.64	0.63	0.63	10	0.633333333	6.3333333
AA	15	26	16	12	14	12	34	34	44	0.63	0.63	0.29	10	0.516666667	5.1666667
AB	26	16	27	14	12	14	34	44	44	0.63	0.29	0.29	10	0.403333333	4.0333333
AC	16	27	17	12	14	12	44	44	54	0.29	0.29	0.21	10	0.263333333	2.6333333
AD	27	17	28	14	12	14	44	54	54	0.29	0.21	0.21	10	0.236666667	2.3666667
AE	17	28	18	12	14	12	54	54	64	0.21	0.21	0.13	10	0.183333333	1.8333333

AF	28	18	29	14	12	14	54	64	64	0.21	0.13	0.13	10	0.156666667	1.5666667
AG	18	29	19	12	14	12	64	64	74	0.13	0.13	0.11	10	0.123333333	1.2333333
AH	29	19	30	14	12	14	64	74	74	0.13	0.11	0.11	10	0.116666667	1.1666667
AI	19	30	20	12	14	12	74	74	84	0.11	0.11	0.18	10	0.133333333	1.3333333
AJ	30	20	31	14	12	14	74	84	84	0.11	0.18	0.18	10	0.156666667	1.5666667
AK	20	31	21	12	14	12	84	84	94	0.18	0.18	0.21	10	0.19	1.9
AL	31	21	32	14	12	14	84	94	94	0.18	0.21	0.21	10	0.2	2
AM	21	32	22	12	14	12	94	94	96	0.21	0.21	0.21	2	0.21	0.42
AN	32	22	33	14	12	14	94	96	96	0.21	0.21	0.21	2	0.21	0.42
AO	23	34	24	14	21	14	12	12	14	0.58	0.6	0.58	7	0.586666667	4.1066667
AP	34	24	35	21	14	21	12	14	14	0.6	0.58	0.6	7	0.593333333	4.1533333
AQ	24	35	25	14	21	14	14	14	24	0.58	0.6	0.64	35	0.606666667	21.233333
AR	35	25	36	21	14	21	14	24	24	0.6	0.64	0.64	35	0.626666667	21.933333
AS	25	36	26	14	21	14	24	24	34	0.64	0.64	0.63	35	0.636666667	22.283333
AT	36	26	37	21	14	21	24	34	34	0.64	0.63	0.51	35	0.593333333	20.766667
AU	26	37	27	14	21	14	34	34	44	0.63	0.51	0.29	35	0.476666667	16.683333
AV	37	27	38	21	14	21	34	44	44	0.51	0.29	0.48	35	0.426666667	14.933333
AW	27	38	28	14	21	14	44	44	54	0.29	0.48	0.21	35	0.326666667	11.433333
AX	38	28	39	21	14	21	44	54	54	0.48	0.21	0.18	35	0.29	10.15
AY	28	39	29	14	21	14	54	54	64	0.21	0.18	0.13	35	0.173333333	6.0666667
AZ	39	29	40	21	14	21	54	64	64	0.18	0.13	0.15	35	0.153333333	5.3666667
BA	29	40	30	14	21	14	64	64	74	0.13	0.15	0.11	35	0.13	4.55
BB	40	30	41	21	14	21	64	74	74	0.15	0.11	0.21	35	0.156666667	5.4833333
BC	30	41	31	14	21	14	74	74	84	0.11	0.21	0.18	35	0.166666667	5.8333333
BD	41	31	42	21	14	21	74	84	84	0.21	0.18	0.26	35	0.216666667	7.5833333
BE	31	42	32	14	21	14	84	84	94	0.18	0.26	0.21	35	0.216666667	7.5833333
BF	42	32	43	21	14	21	84	94	94	0.26	0.21	0.18	35	0.216666667	7.5833333
BG	32	43	33	14	21	14	94	94	96	0.21	0.18	0.21	7	0.2	1.4
BH	43	33	44	21	14	21	94	96	96	0.18	0.21	0.18	7	0.19	1.33
BI	34	45	35	21	28	21	12	12	14	0.6	0.35	0.6	7	0.516666667	3.6166667
BJ	45	35	46	28	21	28	12	14	14	0.35	0.6	0.35	7	0.433333333	3.0333333
BK	35	46	36	21	28	21	14	14	24	0.6	0.35	0.64	35	0.53	18.55
BL	46	36	47	28	21	28	14	24	24	0.35	0.64	0.46	35	0.483333333	16.916667
BM	36	47	37	21	28	21	24	24	34	0.64	0.46	0.51	35	0.536666667	18.783333
BN	47	37	48	28	21	28	24	34	34	0.46	0.51	0.42	35	0.463333333	16.216667
BO	37	48	38	21	28	21	34	34	44	0.51	0.42	0.48	35	0.47	16.45
BP	48	38	49	28	21	28	34	44	44	0.42	0.48	0.32	35	0.406666667	14.233333

BQ	38	49	39	21	28	21	44	44	54	0.48	0.32	0.18	35	0.326666667	11.433333
BR	49	39	50	28	21	28	44	54	54	0.32	0.18	0.23	35	0.243333333	8.5166667
BS	39	50	40	21	28	21	54	54	64	0.18	0.23	0.15	35	0.186666667	6.5333333
BT	50	40	51	28	21	28	54	64	64	0.23	0.15	0.23	35	0.203333333	7.1166667
BU	40	51	41	21	28	21	64	64	74	0.15	0.23	0.21	35	0.196666667	6.8833333
BV	51	41	52	28	21	28	64	74	74	0.23	0.21	0.23	35	0.223333333	7.8166667
BW	41	52	42	21	28	21	74	74	84	0.21	0.23	0.26	35	0.233333333	8.1666667
BX	52	42	53	28	21	28	74	84	84	0.23	0.26	0.18	35	0.223333333	7.8166667
BY	42	53	43	21	28	21	84	84	94	0.26	0.18	0.18	35	0.206666667	7.2333333
BZ	53	43	54	28	21	28	84	94	94	0.18	0.18	0.18	35	0.18	6.3
CA	43	54	44	21	28	21	94	94	96	0.18	0.18	0.18	7	0.18	1.26
CB	54	44	55	28	21	28	94	96	96	0.18	0.18	0.18	7	0.18	1.26
CC	45	56	46	28	29.05	28	12	12	14	0.35	0.35	0.35	1.05	0.35	0.18375
CD	56	46	57	29.05	28	29.05	12	14	14	0.35	0.35	0.35	1.05	0.35	0.18375
CE	46	57	47	28	29.05	28	14	14	24	0.35	0.35	0.46	5.25	0.386666667	1.015
CF	57	47	58	29.05	28	29.38	14	24	24	0.35	0.46	0.46	6.9	0.423333333	1.4605
CG	47	58	48	28	29.38	28	24	24	34	0.46	0.46	0.42	6.9	0.446666667	1.541
CH	58	48	59	29.38	28	29.26	24	34	34	0.46	0.42	0.42	6.3	0.433333333	1.365
CI	48	59	49	28	29.26	28	34	34	44	0.42	0.42	0.32	6.3	0.386666667	1.218
CJ	59	49	60	29.26	28	28.96	34	44	44	0.42	0.32	0.32	4.8	0.353333333	0.848
CK	49	60	50	28	28.96	28	44	44	54	0.32	0.32	0.23	4.8	0.29	0.696
CL	60	50	61	28.96	28	28.69	44	54	54	0.32	0.23	0.23	3.45	0.26	0.4485
CM	50	61	51	28	28.69	28	54	54	64	0.23	0.23	0.23	3.45	0.23	0.39675
CN	61	51	62	28.69	28	28.69	54	64	64	0.23	0.23	0.23	3.45	0.23	0.39675
CO	51	62	52	28	28.69	28	64	64	74	0.23	0.23	0.23	3.45	0.23	0.39675
CP	62	52	63	28.69	28	28.69	64	74	74	0.23	0.23	0.23	3.45	0.23	0.39675
CQ	52	63	53	28	28.69	28	74	74	84	0.23	0.23	0.18	3.45	0.213333333	0.368
CR	63	53	64	28.69	28	28.54	74	84	84	0.23	0.18	0.18	2.7	0.196666667	0.2655
CS	53	64	54	28	28.54	28	84	84	94	0.18	0.18	0.18	2.7	0.18	0.243
CT	64	54	65	28.54	28	28.54	84	94	94	0.18	0.18	0.18	2.7	0.18	0.243
CU	54	65	55	28	28.54	28	94	94	96	0.18	0.18	0.18	0.54	0.18	0.0486
CV	65	55	66	28.54	28	28.54	94	96	96	0.18	0.18	0.18	0.54	0.18	0.0486
CW	11	22	67	11.37	12	11.37	96	96	96.63	0.21	0.21	0.21	0.19845	0.21	0.0138915
CX	22	67	68	12	11.37	12	96	96.63	96.63	0.21	0.21	0.21	0.19845	0.21	0.0138915

CY	22	33	68	12	14	12	96	96	96.63	0.21	0.21	0.21	0.63	0.21	0.06615
CZ	33	68	69	14	12	14	96	96.63	96.63	0.21	0.21	0.21	0.63	0.21	0.06615
DA	33	44	69	14	21	14	96	96	96.63	0.21	0.18	0.21	2.205	0.2	0.2205
DB	44	69	70	21	14	21	96	96.63	96.54	0.18	0.21	0.18	1.89	0.19	0.17955
DC	44	55	70	21	28	21	96	96	96.54	0.18	0.18	0.18	1.89	0.18	0.1701
DD	55	70	71	28	21	28	96	96.54	96.54	0.18	0.18	0.18	1.89	0.18	0.1701
DE	55	66	71	28	28.54	28	96	96	96.54	0.18	0.18	0.18	0.1458	0.18	0.008748
DF	66	71	72	28.54	28	28.54	96	96.54	96.54	0.18	0.18	0.18	0.1458	0.18	0.008748
DG	73	74	1	10.26	12	10.26	10.26	10.26	12	0.58	0.58	0.58	1.5138	0.58	0.292668
DH	74	1	12	12	10.26	12	10.26	12	12	0.58	0.58	0.58	1.5138	0.58	0.292668
DI	74	75	12	12	14	12	10.26	10.26	12	0.58	0.58	0.58	1.74	0.58	0.5046
DJ	75	12	23	14	12	14	10.26	12	12	0.58	0.58	0.58	1.74	0.58	0.5046
DK	75	76	23	14	21	14	10.26	10.2	12	0.58	0.6	0.58	6.09	0.586666667	1.7864
DL	76	23	34	21	14	21	10.2	12	12	0.6	0.58	0.6	6.3	0.593333333	1.869
DM	76	77	34	21	28	21	10.2	10.95	12	0.6	0.35	0.6	6.3	0.516666667	1.6275
DN	77	34	45	28	21	28	10.95	12	12	0.35	0.6	0.35	3.675	0.433333333	0.79625
DO	77	78	45	28	29.05	28	10.95	10.95	12	0.35	0.35	0.35	0.55125	0.35	0.0643125
DP	78	45	56	29.05	28	29.05	10.95	12	12	0.35	0.35	0.35	0.55125	0.35	0.0643125

TOTAL VOL **482.5277** m^3

La Lima: Total Estimated Sludge Volumes in Facultative Ponds

	Sludge Volume (m^3)
Facultative Pond 1	309
Facultative Pond 2	347
Total	656

Puerto Cortes Anaerobic Lagoon 2: Node Coordinates

Node	x	y	z
1	**9**	**12**	**1**
2	**9**	**14**	**1**
3	**9**	**24**	**1**
4	**9.06**	**34**	**0.98**
5	**9.06**	**44**	**0.98**
6	**11.22**	**54**	**0.26**
7	**11.91**	**64**	**0.03**
8	**11.91**	**74**	**0.03**
9	**11.91**	**84**	**0.03**
10	**11.91**	**94**	**0.03**
11	**11.91**	**96**	**0.03**
12	**12**	**12**	**1**
13	12	14	1
14	12	24	1
15	12	34	0.98
16	12	44	0.98
17	12	54	0.26
18	12	64	0.03
19	12	74	0.03
20	12	84	0.03
21	12	94	0.03
22	12	96	0.03
23	**14**	**12**	**1**
24	14	14	1
25	14	24	1
26	14	34	0.98
27	14	44	0.98
28	14	54	0.26
29	14	64	0.03
30	14	74	0.03
31	14	84	0.03
32	14	94	0.03
33	14	96	0.03
34	**21**	**12**	**1**
35	21	14	1
36	21	24	1
37	21	34	1
38	21	44	0.94
39	21	54	0.49
40	21	64	0.23
41	21	74	0.23
42	21	84	0.06
43	21	94	0.03
44	21	96	0.03
45	**28**	**12**	**0.96**

Node	x	y	z
46	28	14	0.96
47	28	24	1
48	28	34	0.91
49	28	44	0.76
50	28	54	0.35
51	28	64	0.42
52	28	74	0.26
53	28	84	0.03
54	28	94	0.1
55	28	96	0.1
56	**30.88**	**12**	**0.96**
57	30.88	14	0.96
58	31	24	1
59	30.73	34	0.91
60	30.28	44	0.76
61	29.05	54	0.35
62	29.26	64	0.42
63	28.78	74	0.26
64	28.09	84	0.03
65	28.3	94	0.1
66	28.3	96	0.1
67	11.91	96.09	0.03
68	12	96.09	0.03
69	14	96.09	0.03
70	21	96.09	0.03
71	28	96.3	0.1
72	28.3	96.3	0.1
73	9	9	1
74	12	9	1
75	14	9	1
76	21	9	1
77	28	9.12	0.96
78	30.88	9.12	0.96

Sludge on flat area
Sludge "wedge"
Measured readings
Sludge "pyramid"

Puerto Cortes Anaerobic Lagoon 2: Sludge Volume Estimation

Triangle	Node 1	Node 2	Node 3	X_1	X_2	X_3	Y_1	Y_2	Y_3	Z_1	Z_2	Z_3	Area (m^2)	Average Z (m)	Volume (m^3)
A	1	12	2	9	12	9	12	12	14	1	1	1	3	1	1.5
B	12	2	13	12	9	12	12	14	14	1	1	1	3	1	1.5
C	2	13	3	9	12	9	14	14	24	1	1	1	15	1	7.5
D	13	3	14	12	9	12	14	24	24	1	1	1	15	1	7.5
E	3	14	4	9	12	9.06	24	24	34	1	1	0.98	15	0.993333333	7.45
F	14	4	15	12	9.06	12	24	34	34	1	0.98	0.98	14.7	0.986666667	7.252
G	4	15	5	9.06	12	9.06	34	34	44	0.98	0.98	0.98	14.7	0.98	7.203
H	15	5	16	12	9.06	12	34	44	44	0.98	0.98	0.98	14.7	0.98	7.203
I	5	16	6	9.06	12	11.22	44	44	54	0.98	0.98	0.26	14.7	0.74	5.439
J	16	6	17	12	11.22	12	44	54	54	0.98	0.26	0.26	3.9	0.5	0.975
K	6	17	7	11.22	12	11.91	54	54	64	0.26	0.26	0.03	3.9	0.183333333	0.3575
L	17	7	18	12	11.91	12	54	64	64	0.26	0.03	0.03	0.45	0.106666667	0.024
M	7	18	8	11.91	12	11.91	64	64	74	0.03	0.03	0.03	0.45	0.03	0.00675
N	18	8	19	12	11.91	12	64	74	74	0.03	0.03	0.03	0.45	0.03	0.00675
O	8	19	9	11.91	12	11.91	74	74	84	0.03	0.03	0.03	0.45	0.03	0.00675
P	19	9	20	12	11.91	12	74	84	84	0.03	0.03	0.03	0.45	0.03	0.00675
Q	9	20	10	11.91	12	11.91	84	84	94	0.03	0.03	0.03	0.45	0.03	0.00675
R	20	10	21	12	11.91	12	84	94	94	0.03	0.03	0.03	0.45	0.03	0.00675
S	10	21	11	11.91	12	11.91	94	94	96	0.03	0.03	0.03	0.09	0.03	0.00135
T	21	11	22	12	11.91	12	94	96	96	0.03	0.03	0.03	0.09	0.03	0.00135
U	12	23	13	12	14	12	12	12	14	1	1	1	2	1	2
V	23	13	24	14	12	14	12	14	14	1	1	1	2	1	2
W	13	24	14	12	14	12	14	14	24	1	1	1	10	1	10
X	24	14	25	14	12	14	14	24	24	1	1	1	10	1	10
Y	14	25	15	12	14	12	24	24	34	1	1	0.98	10	0.993333333	9.9333333
Z	25	15	26	14	12	14	24	34	34	1	0.98	0.98	10	0.986666667	9.8666667
AA	15	26	16	12	14	12	34	34	44	0.98	0.98	0.98	10	0.98	9.8
AB	26	16	27	14	12	14	34	44	44	0.98	0.98	0.98	10	0.98	9.8
AC	16	27	17	12	14	12	44	44	54	0.98	0.98	0.26	10	0.74	7.4
AD	27	17	28	14	12	14	44	54	54	0.98	0.26	0.26	10	0.5	5
AE	17	28	18	12	14	12	54	54	64	0.26	0.26	0.03	10	0.183333333	1.8333333
AF	28	18	29	14	12	14	54	64	64	0.26	0.03	0.03	10	0.106666667	1.0666667

AG	18	29	19	12	14	12	64	64	74	0.03	0.03	0.03	10	0.03	0.3
AH	29	19	30	14	12	14	64	74	74	0.03	0.03	0.03	10	0.03	0.3
AI	19	30	20	12	14	12	74	74	84	0.03	0.03	0.03	10	0.03	0.3
AJ	30	20	31	14	12	14	74	84	84	0.03	0.03	0.03	10	0.03	0.3
AK	20	31	21	12	14	12	84	84	94	0.03	0.03	0.03	10	0.03	0.3
AL	31	21	32	14	12	14	84	94	94	0.03	0.03	0.03	10	0.03	0.3
AM	21	32	22	12	14	12	94	94	96	0.03	0.03	0.03	2	0.03	0.06
AN	32	22	33	14	12	14	94	96	96	0.03	0.03	0.03	2	0.03	0.06
AO	23	34	24	14	21	14	12	12	14	1	1	1	7	1	7
AP	34	24	35	21	14	21	12	14	14	1	1	1	7	1	7
AQ	24	35	25	14	21	14	14	14	24	1	1	1	35	1	35
AR	35	25	36	21	14	21	14	24	24	1	1	1	35	1	35
AS	25	36	26	14	21	14	24	24	34	1	1	0.98	35	0.993333333	34.766667
AT	36	26	37	21	14	21	24	34	34	1	0.98	1	35	0.993333333	34.766667
AU	26	37	27	14	21	14	34	34	44	0.98	1	0.98	35	0.986666667	34.533333
AV	37	27	38	21	14	21	34	44	44	1	0.98	0.94	35	0.973333333	34.066667
AW	27	38	28	14	21	14	44	44	54	0.98	0.94	0.26	35	0.726666667	25.433333
AX	38	28	39	21	14	21	44	54	54	0.94	0.26	0.49	35	0.563333333	19.716667
AY	28	39	29	14	21	14	54	54	64	0.26	0.49	0.03	35	0.26	9.1
AZ	39	29	40	21	14	21	54	64	64	0.49	0.03	0.23	35	0.25	8.75
BA	29	40	30	14	21	14	64	64	74	0.03	0.23	0.03	35	0.096666667	3.3833333
BB	40	30	41	21	14	21	64	74	74	0.23	0.03	0.23	35	0.163333333	5.7166667
BC	30	41	31	14	21	14	74	74	84	0.03	0.23	0.03	35	0.096666667	3.3833333
BD	41	31	42	21	14	21	74	84	84	0.23	0.03	0.06	35	0.106666667	3.7333333
BE	31	42	32	14	21	14	84	84	94	0.03	0.06	0.03	35	0.04	1.4
BF	42	32	43	21	14	21	84	94	94	0.06	0.03	0.03	35	0.04	1.4
BG	32	43	33	14	21	14	94	94	96	0.03	0.03	0.03	7	0.03	0.21
BH	43	33	44	21	14	21	94	96	96	0.03	0.03	0.03	7	0.03	0.21
BI	34	45	35	21	28	21	12	12	14	1	0.96	1	7	0.986666667	6.9066667
BJ	45	35	46	28	21	28	12	14	14	0.96	1	0.96	7	0.973333333	6.8133333
BK	35	46	36	21	28	21	14	14	24	1	0.96	1	35	0.986666667	34.533333
BL	46	36	47	28	21	28	14	24	24	0.96	1	1	35	0.986666667	34.533333
BM	36	47	37	21	28	21	24	24	34	1	1	1	35	1	35
BN	47	37	48	28	21	28	24	34	34	1	1	0.91	35	0.97	33.95
BO	37	48	38	21	28	21	34	34	44	1	0.91	0.94	35	0.95	33.25
BP	48	38	49	28	21	28	34	44	44	0.91	0.94	0.76	35	0.87	30.45

BQ	38	49	39	21	28	21	44	44	54	0.94	0.76	0.49	35	0.73	25.55
BR	49	39	50	28	21	28	44	54	54	0.76	0.49	0.35	35	0.533333333	18.666667
BS	39	50	40	21	28	21	54	54	64	0.49	0.35	0.23	35	0.356666667	12.483333
BT	50	40	51	28	21	28	54	64	64	0.35	0.23	0.42	35	0.333333333	11.666667
BU	40	51	41	21	28	21	64	64	74	0.23	0.42	0.23	35	0.293333333	10.266667
BV	51	41	52	28	21	28	64	74	74	0.42	0.23	0.26	35	0.303333333	10.616667
BW	41	52	42	21	28	21	74	74	84	0.23	0.26	0.06	35	0.183333333	6.4166667
BX	52	42	53	28	21	28	74	84	84	0.26	0.06	0.03	35	0.116666667	4.0833333
BY	42	53	43	21	28	21	84	84	94	0.06	0.03	0.03	35	0.04	1.4
BZ	53	43	54	28	21	28	84	94	94	0.03	0.03	0.1	35	0.053333333	1.8666667
CA	43	54	44	21	28	21	94	94	96	0.03	0.1	0.03	7	0.053333333	0.3733333
CB	54	44	55	28	21	28	94	96	96	0.1	0.03	0.1	7	0.076666667	0.5366667
CC	45	56	46	28	30.88	28	12	12	14	0.96	0.96	0.96	2.88	0.96	1.3824
CD	56	46	57	30.88	28	30.88	12	14	14	0.96	0.96	0.96	2.88	0.96	1.3824
CE	46	57	47	28	30.88	28	14	14	24	0.96	0.96	1	14.4	0.973333333	7.008
CF	57	47	58	30.88	28	31	14	24	24	0.96	1	1	15	0.986666667	7.4
CG	47	58	48	28	31	28	24	24	34	1	1	0.91	15	0.97	7.275
CH	58	48	59	31	28	30.73	24	34	34	1	0.91	0.91	13.65	0.94	6.4155
CI	48	59	49	28	30.73	28	34	34	44	0.91	0.91	0.76	13.65	0.86	5.8695
CJ	59	49	60	30.73	28	30.28	34	44	44	0.91	0.76	0.76	11.4	0.81	4.617
CK	49	60	50	28	30.28	28	44	44	54	0.76	0.76	0.35	11.4	0.623333333	3.553
CL	60	50	61	30.28	28	29.05	44	54	54	0.76	0.35	0.35	5.25	0.486666667	1.2775
CM	50	61	51	28	29.05	28	54	54	64	0.35	0.35	0.42	5.25	0.373333333	0.98
CN	61	51	62	29.05	28	29.26	54	64	64	0.35	0.42	0.42	6.3	0.396666667	1.2495
CO	51	62	52	28	29.26	28	64	64	74	0.42	0.42	0.26	6.3	0.366666667	1.155
CP	62	52	63	29.26	28	28.78	64	74	74	0.42	0.26	0.26	3.9	0.313333333	0.611
CQ	52	63	53	28	28.78	28	74	74	84	0.26	0.26	0.03	3.9	0.183333333	0.3575
CR	63	53	64	28.78	28	28.09	74	84	84	0.26	0.03	0.03	0.45	0.106666667	0.024
CS	53	64	54	28	28.09	28	84	84	94	0.03	0.03	0.1	0.45	0.053333333	0.012
CT	64	54	65	28.09	28	28.3	84	94	94	0.03	0.1	0.1	1.5	0.076666667	0.0575
CU	54	65	55	28	28.3	28	94	94	96	0.1	0.1	0.1	0.3	0.1	0.015
CV	65	55	66	28.3	28	28.3	94	96	96	0.1	0.1	0.1	0.3	0.1	0.015
CW	11	22	67	11.91	12	11.91	96	96	96.09	0.03	0.03	0.03	0.00405	0.03	4.05E-05
CX	22	67	68	12	11.91	12	96	96.09	96.09	0.03	0.03	0.03	0.00405	0.03	4.05E-05

CY	22	33	68	12	14	12	96	96	96.09	0.03	0.03	0.03	0.09	0.03	0.00135
CZ	33	68	69	14	12	14	96	96.09	96.09	0.03	0.03	0.03	0.09	0.03	0.00135
DA	33	44	69	14	21	14	96	96	96.09	0.03	0.03	0.03	0.315	0.03	0.004725
DB	44	69	70	21	14	21	96	96.09	96.09	0.03	0.03	0.03	0.315	0.03	0.004725
DC	44	55	70	21	28	21	96	96	96.09	0.03	0.1	0.03	0.315	0.053333333	0.0084
DD	55	70	71	28	21	28	96	96.09	96.3	0.1	0.03	0.1	1.05	0.076666667	0.04025
DE	55	66	71	28	28.3	28	96	96	96.3	0.1	0.1	0.1	0.045	0.1	0.0015
DF	66	71	72	28.3	28	28.3	96	96.3	96.3	0.1	0.1	0.1	0.045	0.1	0.0015
DG	73	74	1	9	12	9	9	9	12	1	1	1	4.5	1	1.5
DH	74	1	12	12	9	12	9	12	12	1	1	1	4.5	1	1.5
DI	74	75	12	12	14	12	9	9	12	1	1	1	3	1	1.5
DJ	75	12	23	14	12	14	9	12	12	1	1	1	3	1	1.5
DK	75	76	23	14	21	14	9	9	12	1	1	1	10.5	1	5.25
DL	76	23	34	21	14	21	9	12	12	1	1	1	10.5	1	5.25
DM	76	77	34	21	28	21	9	9.12	12	1	0.96	1	10.5	0.986666667	5.18
DN	77	34	45	28	21	28	9.12	12	12	0.96	1	0.96	10.08	0.973333333	4.9056
DO	77	78	45	28	30.88	28	9.12	9.12	12	0.96	0.96	0.96	4.1472	0.96	1.327104
DP	78	45	56	30.88	28	30.88	9.12	12	12	0.96	0.96	0.96	4.1472	0.96	1.327104

TOTAL VOL **838.4605** m^3

Puerto Cortes: Total Estimated Sludge Volumes in Anaerobic Ponds

	Sludge Volume (m^3)
Anaerobic Pond 1	483
Anaerobic Pond 2	838
Total	1321

APPENDIX B

SLUDGE HEAVY METALS ANALYSIS

Choloma Sludge Analysis Results (Dry Weight Basis)

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

La Lima Sludge Analysis Results (Dry Weight Basis)

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.