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Assessment of Sediment Handling Strategies in the Regulation Pond of *El Canadá* Hydropower Plant, Guatemala

Processing and analyzing sediment information collected *in situ*

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Abstract

El Canadá HPP is a 47 MW run-of-river hydropower plant located in Guatemala. The power plant is highly affected by sediments, especially its off-stream regulation pond. Some sediment handling strategies have been implemented at the power plant, including the installation and operation of one conventional dredge and one hydrosuction dredge. The present study aims to analyze and assess the sediment challenges in the power plant and the adopted sediment handling strategies.

The required information for the assessment was collected during a field trip to the power plant. A back-calculation method to estimate sediment yield in the catchment was successfully developed using the collected information. Finally, operation data of the power plant and the two dredges was used to estimate the annual costs related to sediment problems in the power plant.

The back-calculation method showed an average sediment yield in the catchment of 578,000 ton/year, or 703 ton/year/km^2. From that sediment load, an average of 117,000 tons of sediments are deposited in the regulation pond every year, representing nearly 107,000 m^3, which is approximately 50% of the total volume of the pond.

Sediment samples taken in the pond showed that the sediment deposits are mainly composed of silt and have a cohesion of 12 kPa. Sediment removal capacity of the two dredges was measured, giving values of 33.2 m^3/h for the hydrosuction dredge and 17.1 m^3/h for the conventional dredge. Despite the values are lower than reference values given by the manufacturers, the removal capacity is still enough to deal with the annual sediment income. Estimated unit cost of hydrosuction dredging is US$1.5/m^3, while for the conventional dredge is US$2.8/m^3.

Cost analysis using actual energy prices for every year and a fixed average energy price of the period showed that the sediment-related costs have been reduced after the implementation of the hydrosuction dredge in 2011. Using the fixed average energy price, the net benefit of introducing the hydrosuction dredge was US$607,600 per year on average. The analysis proves that the cost of implementing sediment handling strategies is considerably lower than the cost of the sediment impacts.

Preface

The present thesis document is submitted to fulfill the requirements for a Master's Degree in Hydropower Development at the Department of Civil and Environmental Engineering, Norwegian University of Science and Technology (NTNU). It contains the work done from January to June 2018, under the supervision of Associate Professor Nils Rüther (NTNU) and co-supervisor Tom Jacobsen (SediCon AS).

The study is an assessment of the sediment handling strategies at El Canadá Hydro Power Plant, located in Guatemala. The information required to assess the strategies and study the sediment challenges in the catchment was obtained thanks to a close communication with El Canadá HPP owners and SediCon AS, suppliers of sediment solutions for the power plant. A field trip was also organized in collaboration with the hydropower plant owner.

The thesis was possible thanks to the cooperation of several persons from the different institutions and companies involved. Special gratitude to Nils Rüther and Tom Jacobsen, for all the guidance that made possible this project; to Mr. Paulo Anleu for the willingness to facilitate the required information to make the thesis possible; to the power plant workers, Mr. Luis Baldetti and Nelson Sontay for all the help with the fieldwork; and to Alberto Jiménez, for his guidance and help as a connection between SediCon and the El Canadá HPP.

Last but not the least, I would like to thank my friends and classmates who supported me not only through the process of the thesis but through the whole Master program.

Javier Zamora

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Abbreviations

AMM - Administrator of Wholesale Market by its initials in Spanish

CIR - Capacity Inflow Ratio

CSR - Capacity Sediment-inflow Ratio

HPP – Hydro Power Plant

ICH - International Centre for Hydropower

ICOLD - International Commission on Large Dams

INDE – National Institute of Electricity of Guatemala by its initials in Spanish

INSIVUMEH – National Institute of Seismology, Volcanology, Meteorology, and Hydrology by its initials in Spanish

MUSLE - Modified Universal Soil Loss Equation

NTNU - Norwegian University of Science and Technology

PSD – Particle Size Distribution

RUSLE – Revised Universal Soil Loss Equation

SDR - Sediment Delivery Ratio

SSIM - Sediment Simulation in Intakes with Multiblock option

USLE – Universal Soil Loss Equation

WEPP - Water Erosion Prediction Project

1. Introduction

1.1. General

Countries under development require energy supply to maintain economic growth. Many of these countries have been developing small hydro, which has become a strong component in their energy matrix. Nevertheless, this development is raising in regions highly affected by sediments.

Hence, understanding the challenges related to high sediment load in medium-small hydropower plants and finding proper sediment handling strategies becomes crucial to ensure the energy supply in many countries.

Awareness of sediment-related problems in hydropower plants has been increasing during the last years. Important organizations as the International Commission on Large Dams (ICOLD), the International Centre for Hydropower (ICH) and the World Bank are studying the impact and possible solutions for hydropower plants facing sediment challenges. These challenges are especially complex in regions like Southern Asia, East Africa, and Latin America. Figure 1.1 shows a world distribution of suspended sediment load.

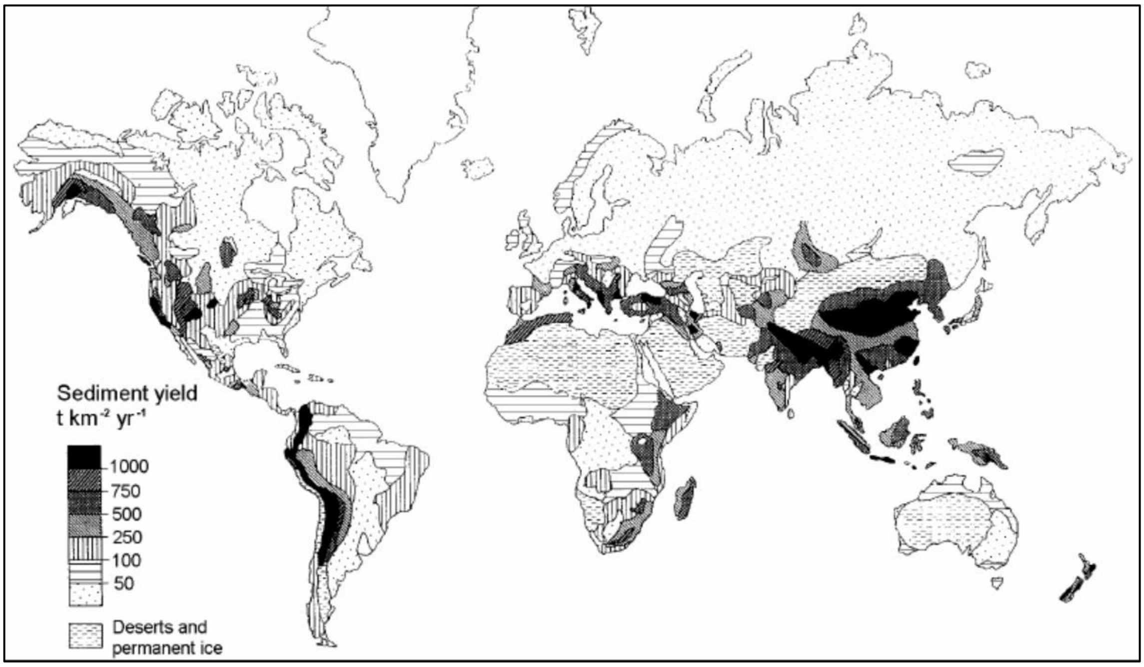

Figure 1.1 Map of annual suspended sediment load. **(Walling & Webb, 1996)**

1.2. Background

Samalá river is located in Retalhuleu, Guatemala, on the Pacific side of Central America. The river has a large amount of sediment, affecting the hydropower plants that use its water. In this catchment, among other hydropower plants, one can find El Canadá HPP. Figure 1.2 shows the overview of the study area.

Figure 1.2 Overview of the study area

Until the intake of El Canadá HPP, the Samalá catchment has an area of 822 km^2. The catchment presents a high sediment yield as it has four volcanoes, with one of them active; an uncontrolled large human activity, including agriculture as a main use of land; and high precipitation, with very intense extremes during large storms. El Canadá HPP is a 47 MW run-of-river hydropower plant with an off-stream peaking pond of 200,000 m^3, which has large amounts of sediments depositing every year.

During the last years, the sediment income in the pond has been handled by continuous dredging. Two different dredges are currently being used: A conventional diesel dredge and a hydrosuction dredge. The information of the daily dredging has been recollected since 2012, which gives important data to analyze the efficiency of dredging as a sediment handling strategy.

1.2.1. Samalá catchment

The Samalá catchment is located in the southwest of Guatemala and drains to the Pacific Ocean. It has a total area of 1,510 km^2 and a total length of 145 km. The highest point of the catchment is at 2,800 m a.s.l., leading to a considerable climate difference between the upper lands and lower lands within the catchment. The location and catchment area are shown in Figure 1.2.

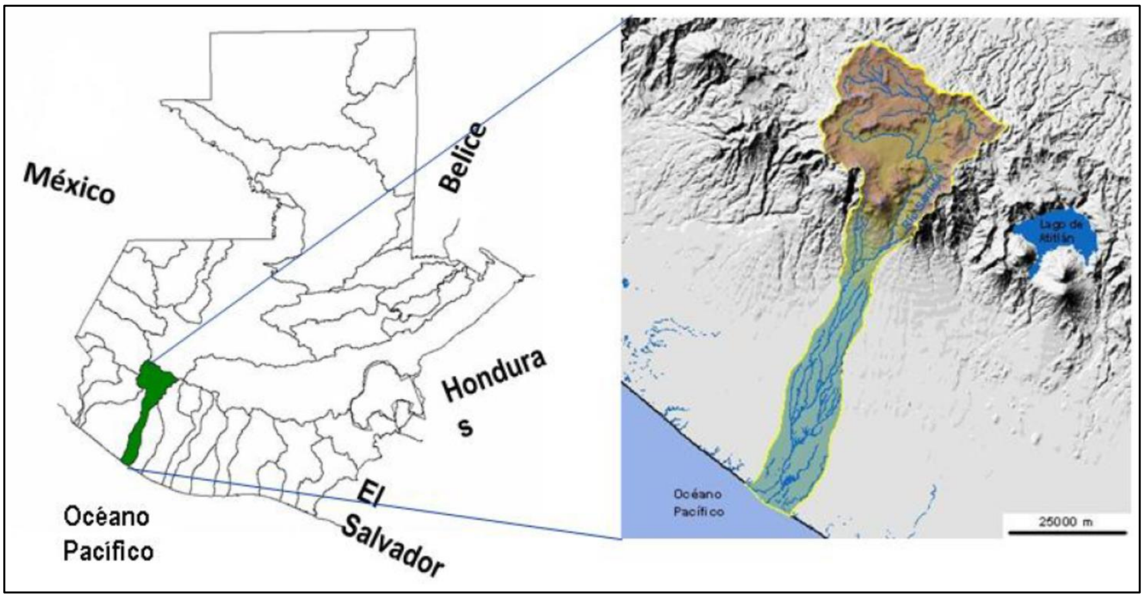

Figure 1.3 Location of Samalá catchment. **(Cedepem; ALDES, 2008)**

The study area in the present research is the upper part of the catchment, defined by the intake of El Canadá HPP. This sub-catchment has an area of 822 km^2. As it is shown in Figure 1.3, the catchment includes some of the main cities in the area, including Quetzaltenango, the second largest city in Guatemala. Within the catchment area, there is a population of approximately 500,000 people. Within and surrounding the catchment one can find a volcanic chain with 4 volcanos, one of them currently active, *Santiaguito* volcano.

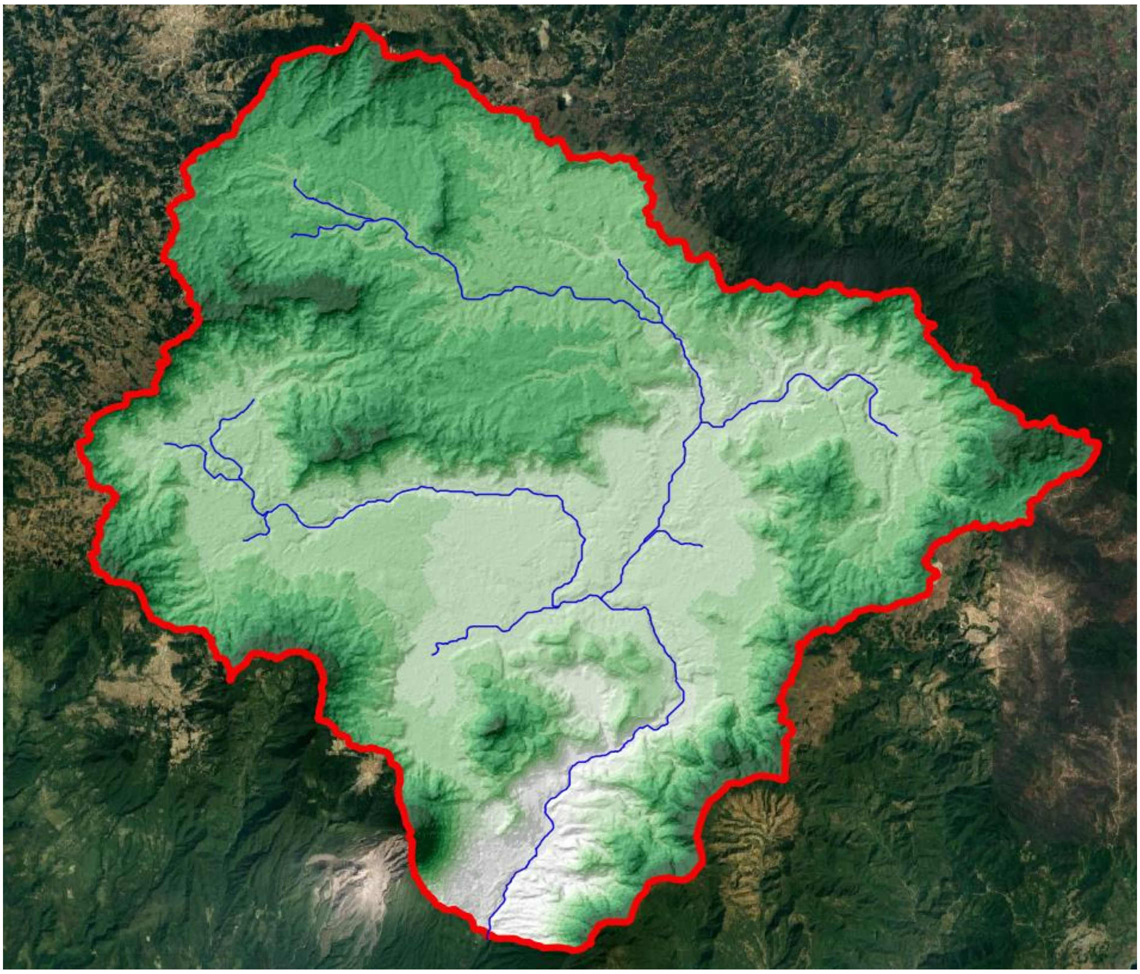

Figure 1.4 El Canadá HPP Catchment, Upper Samalá.

The average annual temperature in the catchment is highly variable depending on the elevation. In the upper part of the catchment, at 2,200 m a.s.l., the annual average temperature is 14°C, while at sea level the annual average is 26 °C. The annual precipitation in the upper Samalá catchment is between 850 and 2,000 mm, having the maximum values in June and September, and in average 89% of the rain comes during the wet season, between May and October.

The extreme events have a large influence on the sediment transport situation in the catchment. The region is commonly affected by tropical storms, producing large floods. Tropical storms can produce rain over 250 mm in 24 hours. In October 2005, there was 868 mm of rain in 10 days due to Stan storm, with a maximum of 297 mm in only 24 hours. (Cedepem; ALDES, 2008)

With the tropical weather, the main driver generating discharge is rain. Thus, the highest discharges in the river come together with the largest rain events during the wet season, as it can be seen in Figure 1.4. The measured average annual discharge at in the station *El Túnel*, located a few kilometers upstream El Canadá HPP, is 5.56 m^3/s.

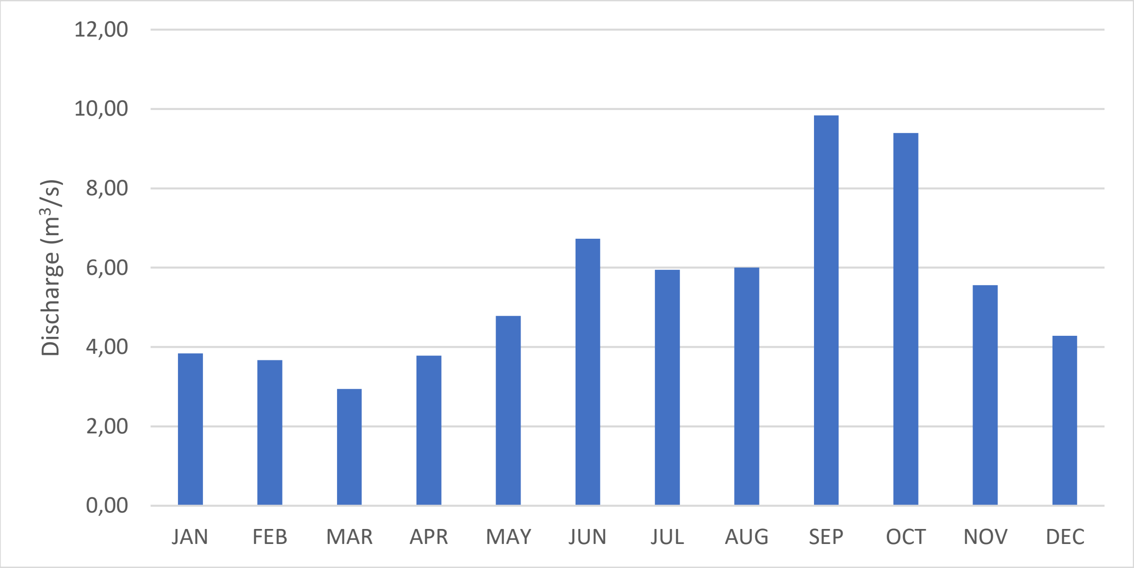

Figure 1.5 Average annual discharge in *El Túnel* Station.

The land use in the catchment is mainly agricultural, with a 68%. Urbanized areas cover 2.1% of the catchment, 23% is different types of forest and the rest is covered by natural pasture. The extensive agricultural use has little or none regulations, which, together with the high population density, poverty and lack of education, produces a large contamination in the river.

1.2.2. El Canadá Hydropower Plant

As it was pointed in the previous section, and shown in Figure 1.3, El Canadá HPP takes water from the upper Samalá river, immediately after the powerhouse of Santa María HPP, at an elevation of 1,420 m a.s.l. The power plant has an installed capacity of 47 MW and produces, on average, 178 GWh annually. The power is generated using a design discharge of 15 m^3/s and a net head of 365 m.

The power plant derives the water from the river with a rubber dam with a total height of 8 meters. The water is taken towards a 105 meters-long and 12.2 meters-wide desander, passing through a trash rack and filter systems to retain large particles and garbage. A 1.2 km tunnel takes the water to the off-stream regulation pond of 200,000 m^3. The high-pressure tunnel has a length of 2.4 km, reaching the power plant equipped with 2 vertical Pelton turbines. The overview of the power plant is shown in Figure 1.5 and the main technical characteristics of the power plant are summarized in Table 1.1.

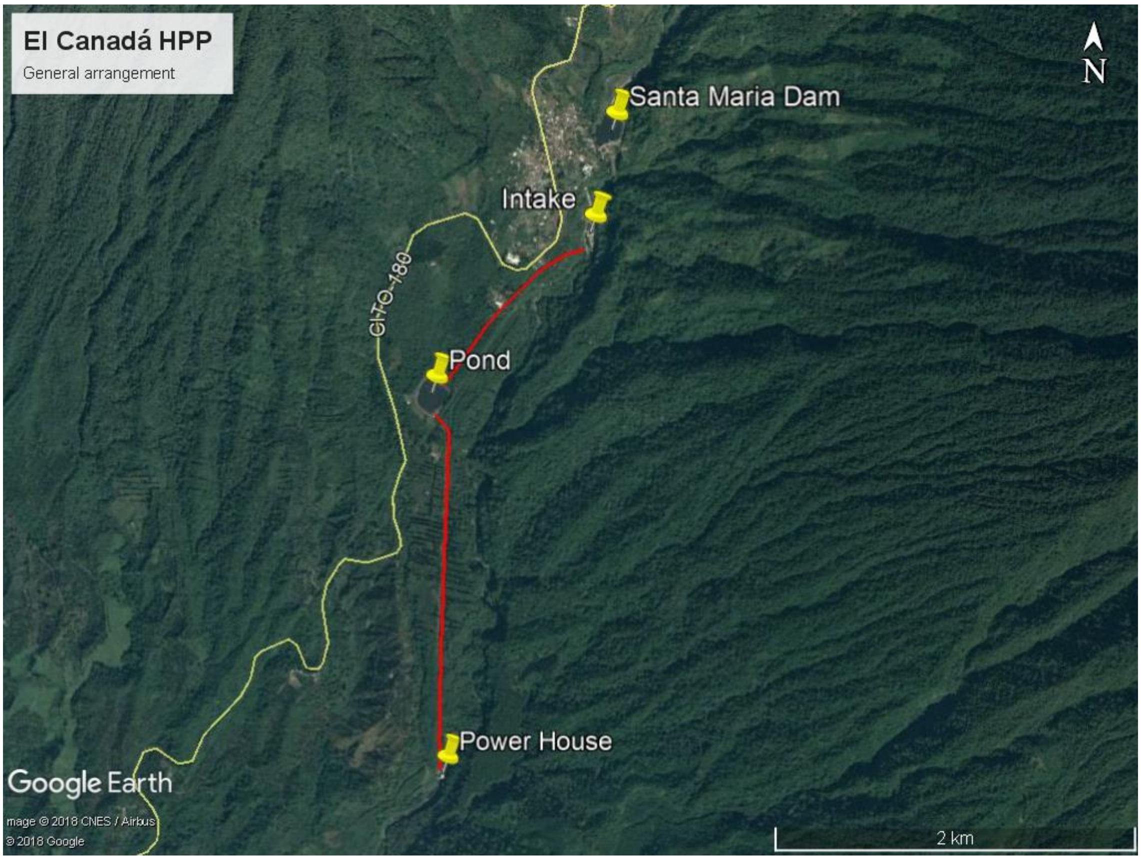

Figure 1.6 El Canadá HPP, general arrangement.

Table 1.1 El Canadá HPP main characteristics.

El Canadá HPP			
Structure	***Characteristic***	***Value/Description***	***Unit***
Dam	Type	Rubber	-
	Length	25	m
	Height (Concrete + rubber)	8	m
Desander	Length	105	m
	Depth	13	m
Derivation Tunnel	Length	1 215	m
	Diameter	3.15	m
Regulation Pond	Type	Off-stream, lined, peaking	-
	HRWL	1417.5	m a.s.l.
	LRWL	1409.0	m a.s.l.
	Total storage (at HRWL)	200 000	m^3
	Live storage	184 000	m^3
Pressurized Tunnel	Length	2 400	m
	Diameter	1.8-2.15	m
Power House	Units	2 Vertical Pelton	-
	Discharge	15	m^3/h
	Installed capacity	47	MW
	Annual generation	178	GWh

The power plant was commissioned in 2003. Since then, the project has been affected by the large sediment transport in the river. Large amounts of debris and garbage must be handled at the intake, while an average of around 100,000 m^3 of fine sediments are depositing in the regulation pond annually. The sediments are highly cohesive, making removal by flushing impossible. The regulation pond was designed to generated electricity during 4 hours at maximum capacity, but the large amount of deposited sediments has been reducing the plant factor.

Due to sedimentation problems, and especially after the Tropical Storm Stan in 2005, the power plant owners have been taking measurements to reduce the sedimentation. Currently, the main strategies are focused on stopping the water supply when the sediment concentration in the river is high and dredging the deposited sediments in the regulation pond with one diesel dredge and one hydrosuction dredge.

1.3. Scope of the work

The present study tries to approach the challenge of hydropower facing sediments by analyzing the sediment handling strategies at El Canadá hydropower plant. Knowing that the power plant owner has been gathering information about the sediment income and the sediment handling strategies, the study is aiming to answer two questions: Are the current sediment handling strategies in the power plant financially worth it? And, how can the practical information be used to improve the understanding of the sedimentation problem?

Within the context of a complex sediment situation in the catchment and the information available about the sediment handling strategies in the power plant, the main objective of the present study has been defined as:

- Assess the sediment handling strategies in the regulation pond of El Canada HPP.

To achieve the main objective, secondary objectives have been defined as follow:

- Estimate the sediment yield of the Samalá River.
- Recollect information about the sediment handling strategies, including power plant operation, dredging equipment, removal rates and current situation.
- Assess the convenience of the current strategies.

1.4. Structure of the thesis

The chapters of the present study have been organized aiming to explain the challenge of hydropower projects facing large amounts of sediment, and for the case of El Canadá HPP, the sediment handling strategies implemented and the data processing to fulfill the objectives of the thesis.

Chapter one gives a general overview of the worldwide sediment challenge, describes the questions that the study aims to answer, the objectives and the structure of the document. Besides, it describes the study area, including its specific challenges.

Chapter two gives the theoretical background of the sediment phenomena and its interaction with the development of hydropower plants. It includes an overview of the sediment characteristics, the impacts they have in hydropower projects and sediment handling strategies.

Chapter three describes the followed methodology, summarized in field work to collect practical data, methods for estimating sediment yield, and the description of the cost analysis to assess the financial convenience of the sediment handling strategies.

Chapter four presents the details of the sediment properties and the associated challenges in the catchment and the hydropower plant. It develops an estimation of the sediment yield using the sediment balance in the pond and compares the result with earlier estimations.

Chapter five describes and study the sediment handling strategies that are currently implemented in the power plant. It shows the results of efficiency tests performed on site and studies the capacity and cost of two dredging systems: diesel and hydrosuction.

Chapter six provides a cost analysis to assess the financial convenience of the sediment handling strategies by studying the annual costs related with sediments over 9 years.

Chapter seven and eight, finally, summarize the obtained results and the conclusions of the study.

2. Theoretical background

To understand the problems surrounding hydropower plants in catchments with high sediment yield, this chapter provides an overview of the sediment phenomena and its relationship with hydropower generation. First, it is needed to understand the origin of the sediments, its properties, and the transport mechanisms. Then, there is an explanation of the sediment yield concept, including its characteristics and the current state of estimation methods. Once the behavior of the sediments in the catchment is explained, the next step is to research the effects of sediments in hydropower plants and what methods can be used to reduce or control such effects.

2.1. Origin of sediments and sediment properties

Sediments are particles produced by the decomposition of rock and transport by natural processes like gravity, wind and water streams. The main source of sediments is soil erosion, but they can come also from other sources such as landslides, glacial melting, and human activity.

Several factors affect the erosion rates in a catchment, such as the catchment morphology (slope, area, shape, elevation distribution), climate (temperature, precipitation, wind), soil characteristics and condition (soil type, compaction, moisture content), land cover (vegetation, urban areas) and land use (agriculture, industry).

To understand the sediment behavior in a catchment, one must understand the factors producing sediments and the transport mechanisms. According to Hicking, E. (1995), the amount and type of sediments in a river basin are determined by what he calls Competence, Capacity and Sediment Supply. The first two factors are related to the hydraulic characteristics: Competence is the largest diameter that the river can transport while Capacity is the maximum bedload concentration possible. On the other hand, Sediment Supply refers to the sediment available in the basin.

Incipient motion models are used to determine the erosion and deposition patterns in the river basin, depending on the hydraulic capacity and the sediment characteristics. The most widely used method to approach incipient motion is the standard or modified version of the critical Shields parameter (Buffinghton & Montgomery, 1997). Regarding the sediment supply, soil loss equations are commonly used, especially the Universal Soil Loss Equation (USLE) or any of its variations. More details about these equations are given in the next section.

Knowing the characteristics of the sediments allows a better estimation of the sediment transport in the river basin and a better understanding of the possible consequences that sediments might have in the hydropower development in the river. In the context of the present study, the key sediment properties are:

- Particle size distribution: Percentage distribution of sizes of a sediment sample. The percent finer than a certain size is denoted by *d*, followed by the percent as a sub-index. The most common one is the d_{50}, which divides in equal weights the finer and coarser particles.
- Density: Ratio between mass and volume of the sediments. A sediment density widely used in practice is 2,650 kg/m^3.
- Fall velocity: Rate of falling for a specific particle due to gravity. Fall velocity is affected mainly by the particle's submerged weight and its shape, among other parameters.
- Cohesivity: Interparticle forces affecting fine particles, normally below 20 μm.
- Porosity: Ratio between the fraction of voids and the total volume of sediment deposits.
- Organic content: Percentage of organic material present in a sediment sample. When the organic content is more than 30 percent, the sediments are considered "organic". (Lysne, Glover, Støle, & Tesaker, 2003)

Sediment load in rivers is transported in different ways depending on the particle size and the hydraulic capacity of the river. A commonly used categorization of the transport modes is the one described by Hicking, E. (1995): (1) Dissolved load, (2) Suspended load, (3) Intermittent suspension or saltation load, (4) Wash load, and (5) Bedload.

The dissolved load and the wash load can be considered as part of the suspended load. The intermittent suspension is very related with the river discharge, moving from bed load to suspended load, so for practical reasons, the transport modes can be categorized in two modes:

1. Suspended load.
2. Bed load.

The differentiation between these two transport modes can be done through the Rouse number (Z). Rouse number is a non-dimensional number that determines how sediment will be transported in a flowing fluid. It is expressed as the ratio between the fall velocity and the product of the Von Karman constant (κ) and the shear velocity. If the Rouse number is larger than 5, the transport mode is bed load. For values between 3 and 5 the transport mode is considered as transition, and for values between 0.1 and 3 it is considered as suspended load.

The percentage of total load occupied by bed load is nearly impossible to find due to the large variation of its nature. From experience, bed load can be assumed to be in the lower 5% of the flow depth (Lysne, Glover, Støle, & Tesaker, 2003). Other measurements have shown that the bed load is often between 1% and 10% of the suspended load (Hickin, 1995). Values of bed load between 5% and 20% are commonly used.

The particle size distribution in rivers is highly variable, varying from mainly fine sediments during low flow periods to gavel, rocks and large boulders during floods. Figure 2.1 shows the result of several measurements in different rivers (Chao & Ahmed, 1985). Comparing the d_{50} value of both curves, one can see that the amount of coarse material increases when the river flow is larger, reaching a d_{50} of 0.075 mm (sieve #200), which means that half of the sediment being transported is course material and the other half is fine material.

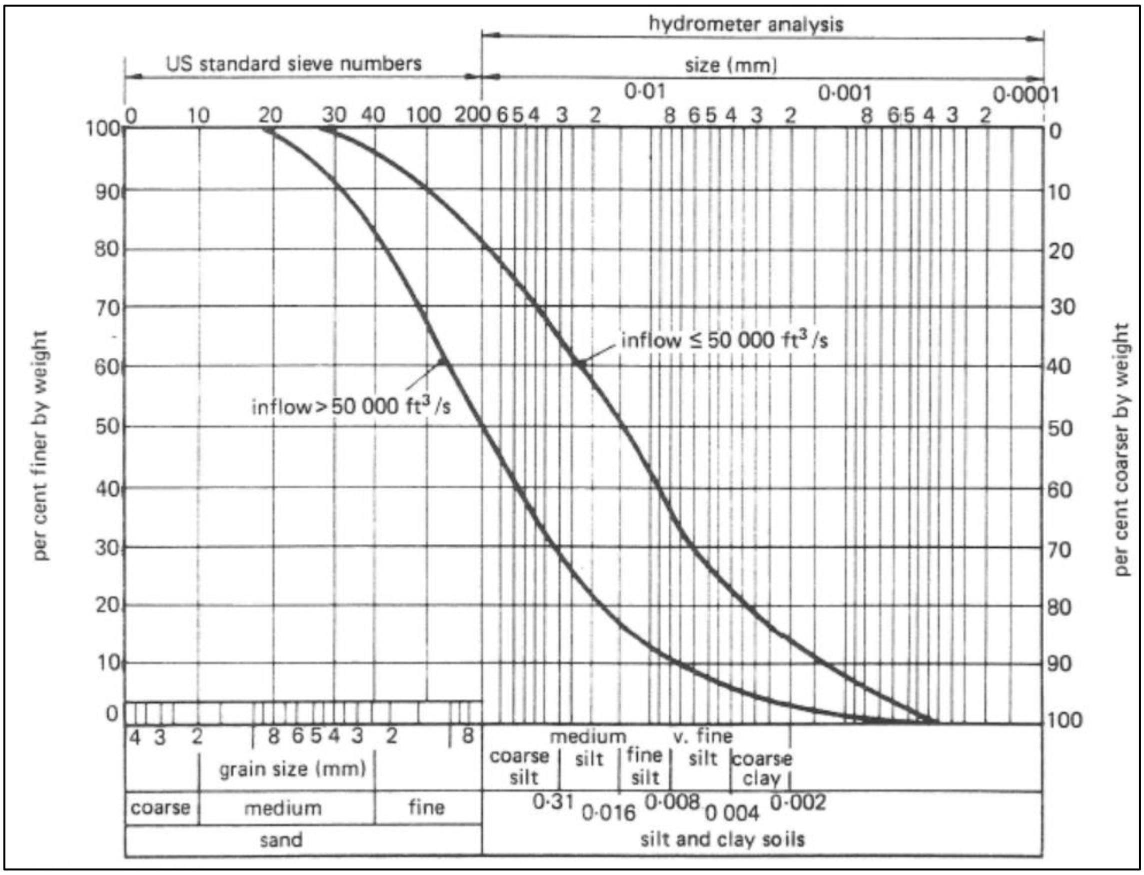

Figure 2.1 Particle size distribution of suspended load. **(Chao & Ahmed, 1985)**

2.2. Sediment yield

Sediment yield is defined as the annual amount of sediments transport by a watercourse at an specific point defining a cathcment area. Sediment yield is commonly expressed in tons per year or tons per square kilometer per year (Lysne, Glover, Støle, & Tesaker, 2003). Sediment yield estimations give an overview of the sediment situation in a catchment, but it must be used carefully, as sediment transport is variable and most of it happens during extreme events.

There are several models and methods to estimate the sediment supply in a catchment. The most commonly used is the Universal Soil Loss Equation (USLE). USLE is an empirical method to estimate the long-term erosion rates (Morris & Fan, 1998). A revised version of the universal soil loss equation (RUSLE) was developed to include algorithms for computing individual factors.

USLE is based on a regression equation that includes the factors influencing soil loss: the inherent erodibility of the soil (K), erosive rainfall forces (R), gravitational forces affecting runoff are given by the hillside length-slope factor (LS), and cover factors modifying erosive forces (C and P). Finally, the equation gives the annual long-term rate of soil loss (A). (Morris & Fan, 1998)

The main limitation of USLE model is that it does not simulate physical processes, so it cannot be used to estimate short-term variations in sediment yield. In other words, it cannot model sediment yield for specific events, when most of the sediment transport occurs. Other methods as Water Erosion Prediction Project (WEPP) or the Modified Universal Soil Loss Equation (MUSLE) allow modeling specific events instead of only annual averages.

Furthermore, the described models estimate the erosion potential in the catchment, but not the actual sediment income in the studied point. Several factors limit the movement of the sediment particles, such as decreasing in slope, the presence of vegetation acting as a natural filter, reduction in runoff, infiltration, and ponding.

Therefore, to determine the actual sediment income to the hydropower plant, the estimated erosion potential must be multiplied by the Sediment Delivery Ratio (SDR). The sediment delivery ratio is the fraction of the eroded material that actually reaches the point of interest in the catchment.

The sediment delivery ratio value depends on six factors: Erosion process, proximity to the catchment outlet, drainage efficiency, soil and cover characteristics, depositional features and watershed size and slope.

It is not possible to perform a direct measurement of the SDR. Nevertheless, many researchers have developed empirical equations to estimate the SDR. Several models use the area of the catchment as the main parameter. For instance, in 1972 Renfro developed an equation by studying 14 watersheds in Texas. Three years after, Vanoni did the same but using 300 watersheds around the world, resulting in a model by a power function. Other relations to estimate SDR were developed by USDA in 1972 and Boyce in 1975. (Demetris & Panagoulia, 2011)

Finally, the sediment yield can be estimated by combining a soil loss erosion model with a sediment delivery ratio equation. The accuracy of the estimation will depend on the chosen models and the quality of the available data.

Even when it is possible to estimate the sediment yield, one must be careful when using such estimations, because it has large temporal and spatial variations. Sediment transport is related to climatic and hydrological variations, increasing exponentially during floods and extreme events. Besides, local events in a small area of the catchment may increase the sediment yield of the river. Such local events and extreme flood conditions are often out of the registers used for sediment yield estimations.

2.3. Sediments and hydropower

Hydropower development aims to seize the energy from natural water courses to produce electricity, but natural water courses contain sediments. Such sediments will inevitably have an impact in the hydropower plant. Such impacts depend on the type and amount of sediments, and the hydropower plant design. The present study analyzes a hydropower plant with a mixed scheme of run-of-the-river headworks design with a small off-stream reservoir for daily regulation, thus, sediment challenges in both structures must be described.

2.3.1. Headworks

A run-of-river power plant has not water storage capacity, it simply derives the available water in the river to produce electricity. In this scheme, the sediments are handled in the headworks structures, where the sediments entrance is avoided. A typical arrangement of a run-of-river scheme includes a diversion weir equipped with sluicing gates and low height spillway to allow the flow of bed load, a trash rack to stop garbage and debris, and a settling basing to retain sand and even silt. This typical arrangement is illustrated in Figure 2.2.

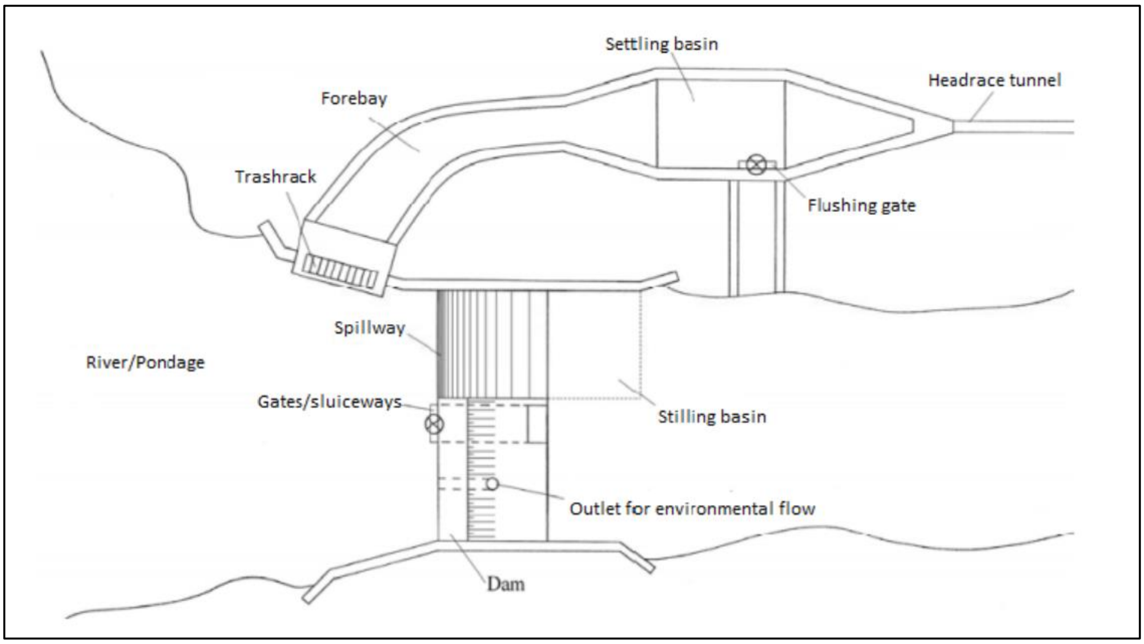

Figure 2.2 Typical headworks arrangement of a run-of-river hydropower plant. **(Jennsen, Tesaker, Steinar, & Huber, 2006)**

A good performance of a run-of-river project relies on the proper design of the headworks structures to ensure the highest possible regularity of power production, a predictable operation and acceptable costs of the headworks itself, waterways and hydraulic machinery. (Lysne, Glover, Støle, & Tesaker, 2003)

Even with a proper headworks design, projects with small reservoirs, such as El Canadá HPP, face complex sediment challenges. Headworks can avoid the entrance of coarse material to the power plant, but it cannot retain the fine suspended sediments, which will deposit in the reservoir where the water velocity is lower. Besides, due to the annual variation in sediment yield, even one single flood may be enough to fill up the reservoir. (Lysne, Glover, Støle, & Tesaker, 2003)

2.3.2. Reservoir

Hydropower plants with reservoirs are exposed to reservoir sedimentation. Sedimentation problem in reservoirs is mainly related to the loss of storage capacity, reducing the water supply and the flood control capacity. Other problems produced by sedimentation in reservoirs are blockage of low-level outlets, erosion of hydropower turbine runners by entrained sediment, impairment of both commercial and recreational navigation and reduction in water quality. Reservoirs also affect the natural balance in the river system, producing overall impacts like increase of erosion downstream of the dam, and bed aggradation due to delta deposition upstream of the reservoir. (Morris & Fan, 1998)

An especially useful approach to foresee the impact that sediments might have in a reservoir is the Capacity Inflow Ratio (CIR). CIR is the ratio between the volume of the reservoir and the volume of annual inflow:

$$CIR = \frac{Reservoir\ Volume}{Volume\ of\ Annual\ Inflow} \qquad \textit{Equation 2.1}$$

Jacobsen (1997) describes the different categories of a reservoir depending on the CIR value:

- CIR > 0.3: Large reservoirs able to store the incoming sediment loads before the end of its economic life.
- 0.03 < CIR < 0.3: Reservoirs that can be affected by sedimentation within their economic lifetime, but still too large to have efficient sediment handling.
- CIR < 0.03 Sediment inflow is large compared to reservoir size, but the removal of sediment deposits is usually possible.

Another valuable parameter that can be used to quantify the sediment impact in a reservoir is the Capacity Sediment-inflow Ratio (CSR), which is the ratio of the volume of the reservoir over the volume of annual sediment inflow:

$$CSR = \frac{Reservoir\ Volume}{Volume\ of\ Annual\ Sediment\ Inflow} \qquad \textit{Equation 2.2}$$

2.4. Sediment handling strategies

Several references like Basson and Rooseboom (1996), Morris and Fan (1996) and Jacobsen (1997) categorize the sediment handling strategies for reservoir sedimentation. On the other hand, Lysne et al. (2003) describe the main sediment handling concerns to consider in headworks structures. A comprehensive summary of the sediment handling strategies including both reservoirs and headworks is described next:

- Reduction of sediment inflow.
    - Soil conservation.
    - Slope protection.
    - Sediment traps.

- Minimize deposition in the reservoir/headworks.
    - Bypassing large sediment loads.
    - Bed control at the intake.
    - Operation of settling basin.
    - Density current venting.
- Removal of accumulated sediment deposits.
    - Flushing during floods or in the high flow season. Flushing is most efficient for reservoirs with CIR < 0.05. (Basson & Rooseboom, 1996)
    - Mechanical excavation.
    - Conventional hydraulic dredging.
    - Hydrosuction dredging (hydraulic dredging by use of gravity).
- Accepting sediment deposition.
    - Recover storage capacity by raising the dam.
    - Build a new reservoir.
    - Import water from other reservoir or water source.

It is difficult to cover all the possible sediment handling strategies at the headworks, as the design criteria and final arrangement are site-specific (Lysne, Glover, Støle, & Tesaker, 2003). For this matter, a throughout description of the sediment handling strategies at El Canadá HPP's headworks is given in Chapter 5 of this document.

When it comes to sediment handling strategies at the off-stream regulation pond, El Canadá HPP has been focused on hydraulic dredging, using both conventional and hydrosuction equipment. Then, a more detailed description of these strategies is given next.

2.4.1. Hydraulic dredging, general considerations

Hydraulic dredging consists in the movement of a mix of water and sediments through a pipeline system. The sediments can be removed from the reservoir or relocated to a place where their impact is reduced. Either way, the primary mechanism behind the hydraulic dredging is the slurry flow (sediment-water mixture) in a pipeline. Slurry flow is a complex hydraulic phenomenon and this study does not aim to explain it in detail, but some concepts are explained for a better understanding of the hydraulic dredging.

Morris and Fan (1998) describe the three regimes of slurry flow in a pipeline: (1) Pseudo-homogeneous, (2) Heterogeneous and (3) Stationary bed. Slurry flow regimes are illustrated in

Figure 2.3. These regimes are determined by the flow velocity and the sediments particle size. Fine sediments will be transported in a homogeneous way, while coarser sediments will flow in a heterogeneous flow for high velocities and as a stationary bed for lower velocities.

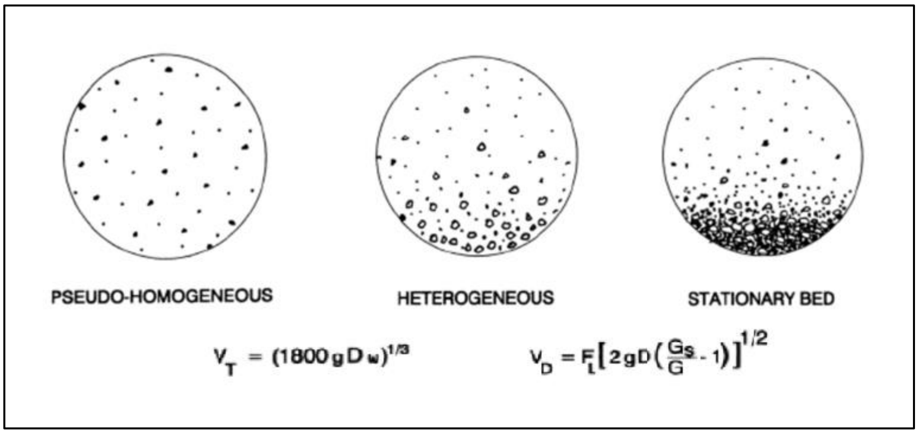

Figure 2.3 Regimes of slurry flow. **(Morris & Fan, 1998)**

Headloss in the pipeline is also affected by the sediment-water mixture flow. The headloss increases with the sediment concentration. Figure 2.4 shows the variation of headloss depending on the flow velocity and the sediment concentration in the slurry flow.

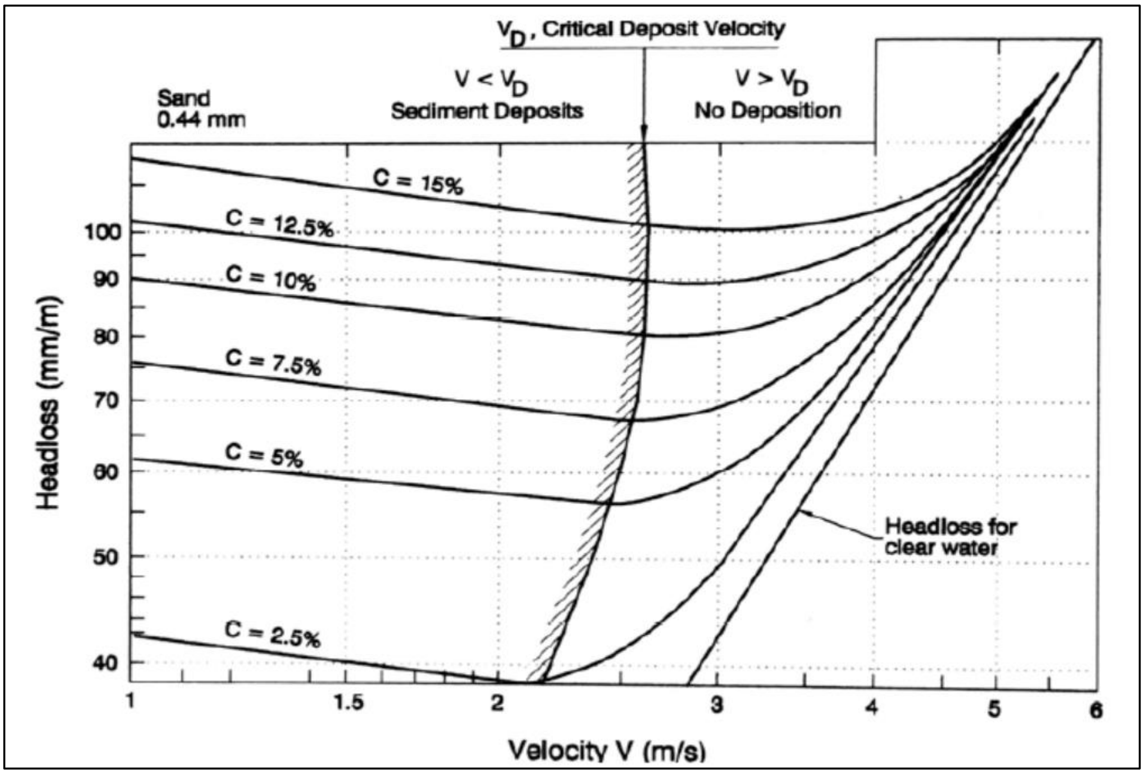

Figure 2.4 Headloss variation with velocity and sediment concentration. **(Morris & Fan, 1998)**

The optimum hydraulic dredge design can be found where the transport of the particles is ensured with the minimum head loss. In other words, the most economical operating point is when heterogeneous flow regime happens, which means that the particles are transported with the lowest velocity.

2.4.2. Conventional hydraulic dredging

Conventional hydraulic dredging is understood as the type of dredging that uses pumps to generate the flow inside the pipeline, and thus, transport the sediments. The market offers a wide variety of dredges for different applications and with different sediment removal capacities.

The size of hydraulic dredges is linked to the diameter of the suction pipeline. The capacity of a hydraulic dredge is related to the diameter of the pipeline and the pumping capacity, which together give the discharge and sediment concentration. The pumping system can be either a centrifugal pump onboard or a submerged slurry pump.

Conventional dredges can handle material from fine sediments to coarse sand. When fine materials are compacted and/or cohesive, a cutting system is implemented in the dredge. A commonly use cutter-head consists of a series of blades rotating on a variable speed.

Main advantages of conventional dredging are the low unit cost (cost per cubic meter of sediment removed) and the possibility to remove the sediments without interfering with normal operation of the reservoir. Some disadvantages are the required energy input (fossil fuels or electricity), limitations on the depth of dredging and limitation in the particle size that it can manage, being sand the coarser material possible to remove.

Conventional dredging has been widely used for removing sediments in reservoirs, therefore, there is a broad experience and information available. Just to mention some examples, Lake Springfield (Illinois, USA) performed a two-stage dredging, first with a conventional cutter-head dredge and the second phase with a single barge-mounted diesel booster pump. Bai-Ho Reservoir (Taiwan) removed the sediment deposits with a combination of hydraulic dredging and dry excavation. The unit costs of each case were \$3.02/m^3 and 5.24 US\$/m^3 respectively. (Morris & Fan, 1998)

2.4.3. Hydrosuction dredging

The key difference between conventional dredging and hydrosuction dredging is that hydrosuction does not use pumps to power the slurry flow. Instead of pumps, the flow is driven by gravity, using the differential head between the water surface upstream of the dam and the discharge point located downstream of the dam, at the lowest possible point. Therefore, no external energy is required to transport the sediments. (Hotchkiss & Huang, 1995)

The components of a hydrosuction dredge are the intake or suction head, pipeline, outlet valve, and practical accessories, such as an operating system for the suction head and a system to break the cohesivity of the sediments. In the same way as the conventional dredges, the size of hydrosuction dredges is linked to the pipeline diameter, but its capacity depends on the available water column. According to Hotchkiss and Huang (1995), there are two variations of hydrosuction dredging: (1) Bottom discharge and (2) siphon dredging. Both variations are shown in Figure 2.5.

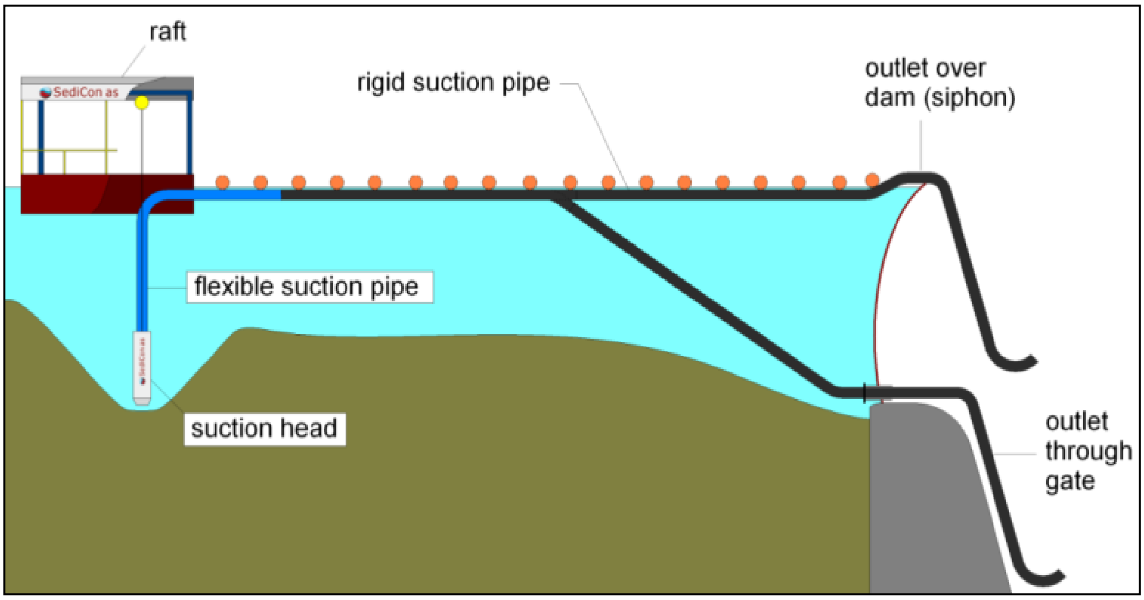

Figure 2.5 Hydrosuction dredging variations: Bottom discharge and siphon. **(SediCon AS, 2018)**

Hydrosuction dredge do not use pumps, therefore, the pipeline system is free of any obstruction, making possible to transport particles up to the size of the internal pipeline diameter. Hydrosuction dredges removing particles up to 240 mm has been tested (Jimenez, 2012). On the other extreme, auxiliary water jetting system can be included in case of fine cohesive sediments.

Hydrosuction dredging has the same advantages as conventional dredging, i.e. low cost and non-interruptive operation; and other advantages, like not requiring external energy supply, virtually no limit on the dredging depth and a broader range of sediments size capable to remove. Besides, considering that hydrosuction dredging is still developing, its cost is likely to drop further due to improvement in technology, reduction in manufacturing cost and alternative commercial models for supplying the dredges. The main disadvantages are related with its hydraulic limitation: the capacity depends on the available head, normally limiting the length of the pipeline to a maximum of 2 km, and as a lower discharge point is required, the sediments have to be discharged back in the river, which is forbidden by environmental authorities in some countries.

There are not many experiences with hydrosuction dredging. Hotchkiss and Huang (1995) describe the first recorded hydrosuction dredging on Djidiouia Reservoir, in Algeria, 1892 and the experience of Geolidro, S.p.A., who has used hydrosuction dredging in alpine reservoirs in Italy. Morris and Fan (1998) describe the case of Valdesia Reservoir, Dominican Republic, the largest siphon dredge ever employed in a reservoir with a diameter of 700 mm.

More recent experiences on a smaller scale have been carried on by SediCon AS, Norway. Dredges from 200 mm to 350 mm has been successfully used in Malana HPP, India, 2005; La Garita HPP, Costa Rica, 2010; El Canadá HPP, Guatemala, 2011; Doña Julia HPP, Costa Rica, 2012; and El General HPP, Costa Rica, 2014 (SediCon AS, 2018).

3. Methodology

As it was stated in the first chapter, the objectives of the present study are based on three main topics: (1) Data collection about the sediment challenges and current sediment handling strategies, (2) estimation of sediment yield, and (3) cost assessment of the sediment handling strategies. The followed methodology for each objective is described next.

3.1. Data collection

All the required information for the thesis was collected through a field trip to the power plant and through direct communication with the owners of El Canadá HPP and the manufacturer of the hydrosuction dredge, SediCon AS.

The field trip was done between the 9th and 20th of January 2018. The field trip was planned to collect different type of information, from checking the hydropower plant libraries to take direct measurements of the sediments and the sediment handling strategies. The defined objectives of the field trip were:

1. Collect available information from El Canada libraries such as hydropower plant characteristics, relevant drawings, hydrology studies, sediment studies.
2. Visual evaluation of the catchment. Visit key areas of the catchment such as steep mountains, volcanic areas, river reaches, downstream of the power plants.
3. Study sediment challenge and sediment handling strategies in the regulation pond.
4. Study the sediment monitoring activities.
5. Collect operational register and related costs of the strategies.
6. Measure efficiency of the sediment handling strategies at the regulation pond.
7. Take sediment samples and measure shear strength.
8. Verify and document actual dimensions of the dredges.
9. Evaluate other structures: Santa Maria Reservoir and El Canada Headworks.

The collected information has been used to describe the catchment, the hydropower plant, the sediment handling strategies, and to perform the required calculations of sediment yield and cost analysis.

Two main limitations arose during the field trip. Due to safety reasons and lack of proper equipment, it was only possible to take sediment samples in the regulation pond, but not in any other structure. Santa María HPP is located upstream of El Canadá and it has a large influence on the sediment behavior, nevertheless, the project is owned and operated by a different company (INDE), so it was not possible to take samples or get information from it.

3.2. Sediment yield estimation

A method to estimate sediment yield using the sediment balance in the regulation pond was developed. The method consists in a back-calculation from the real-data of bathymetries and sediment removed by dredging that has been registered in the pond of El Canadá HPP.

The percentage of the total sediment in the river that is annually deposited in the pond can be found using the particle size distribution of the sediment deposited, the hydrology of the river and the operation of the power plant. Such calculation is based on the methodology proposed by Verstraeten and Poesen (2002):

$$SY = \frac{SV * dBD}{TE} \qquad \textit{Equation 3.2}$$

where SY is the sediment yield in tons per year, SV is the measured sediment deposition rate in cubic meters per year, dBD is the dry bulk density of the sediment deposits in tones per cubic meter and TE is the sediment trapping efficiency of the pond in percentage (Verstraeten & Poesen, 2002).

The Equation 3.2 was deconstructed to be applied at El Canadá HPP. Bathymetric surveys and estimation of removal capacity of the dredges were used to find the Sediment Volume. The density of the sediments was divided into two conditions: (1) density of sediments deposited in the pond, and (2) density of sediment at the discharge of the dredges. The trapping efficiency was calculated not only for the pond but also for the desander, to understand the sediment distribution from the intake to the pond.

The trapping efficiency of the desander and the regulation pond were calculated using the Sed-Trap model. Sed-Trap is a 2D numerical model that calculates the particles fall velocity using a log-law distribution. Sed-Trap is simplified version of SSIM (Sediment Simulation in Intakes with Multiblock option), an open software developed by Nils Reidar Olsen for the Norwegian University of Science and Technology (NTNU).

Sed-Trap lays on the calculation of fall velocity, w_s, using Equation 3.3.

$$w_s = \sqrt{\frac{4gD(S_s - 1)}{3C_D}} \qquad \textit{Equation 3.3}$$

where g is the gravitational acceleration, D is the particle diameter, S_s is the specific weight of the sediment and C_D is the drag coefficient of the particle. C_D is calculated from an empirical equation based on the Archimedes number.

The developed method to estimate sediment yield can be summarized in the following steps:

1. Collection of bathymetric surveys, operation log of dredging and sediment removal rates of the dredges.
2. Estimation of the annual sediment deposition in the pond.
3. Estimation of the sediment distribution through the power plant.
4. Estimation of the total load in the river.

3.3. Cost analysis

Operation data of the power plant and the two dredges was collected during the field trip. This information allowed to estimate all the annual costs related to sediment problems in the power plant from 2009 to 2017.

The considered costs in the analysis were: (1) Cost of energy lost, (2) maintenance cost, (3) cost of replacing worn out equipment, (4) cost of regulation or peaking capacity lost, (5) operation cost of trash rack and filters, (6) cost of conventional dredging and (7) cost of hydrosuction dredging.

Once the annual costs were obtained, the annual costs before and after the implementation of the hydrosuction dredge were compared. The comparison was done under two scenarios: assuming a fixed energy price during the whole period and using real energy prices. The second scenario was included because the energy prices in Guatemala has been dramatically dropping since 2012.

4. Sediment challenges

The present chapter describes the sediment challenges in the catchment of Samalá River and how they affect El Canadá HPP. Further, a sediment yield calculation was performed, using sediment measurements in the power plant's regulation pond. Finally, climate change considerations and recommendations are given to assess the problem in the future.

4.1. Sediments in El Canadá HPP

El Canadá HPP intake is located in Samalá river, which transports a large amount of sediments. The origin of the sediments is both natural and induced by human activities. Main factors producing the sediments are the steep slopes, volcanic activity, heavy rain, agriculture and extraction of material from the riverbed (Vargas, 2009). Figure 4.1 shows an example of sediment produced by a landslide due to the steep slopes. The landslide is next to the sand trap of El Canadá HPP.

Figure 4.1 Landslide throwing sediments to El Canadá HPP Headworks.

The headworks structures of the power plant were designed to avoid the income of bed load, garbage, debris and retain suspended sand particles, while fine suspended particles are deposited in the regulation pond. Then, the sediment-related challenges can be divided in three:

1. Garbage and debris: Quetzaltenango, the city located upstream of El Canadá HPP, has 500,000 inhabitants and an extensive agricultural activity, with no water treatment facilities. Large amounts of plastic and organic waste reach the intake every day. Figure 4.2 shows the garbage collected in the trash rack.
2. Suspended sand: Part of the coarse material is transported as a suspended load, especially during floods. This material enters the waterway, but it is efficiently trapped in the sand trap as it is illustrated in Figure 4.3.
3. Fine particles: The sand trap was not designed to allow the deposition of particles smaller than 0.2 mm. These particles continue through the waterway until the pond, where they are deposited. If the sediments are not removed from the pond, the particles can be transported through the penstock and the powerhouse, producing wear in the units. For several years there was an extreme sediment deposition in the pond, which is illustrated in Figure 4.4.

Figure 4.2 Garbage collected at El Canadá HPP headworks.

Figure 4.3 Flushing of sediments in the sand trap. (Source: El Canadá HPP)

Figure 4.4 Sediment deposition in the pond, 2009. (Source: El Canadá HPP)

4.1.1. Consequences of sediments

Presence of sediments has been affecting the power plant operation since it started production in 2003. Sediments affect directly the power plant operation and maintenance activities, increasing the costs and reducing the benefits. In the case of El Canadá HPP, the consequences related to sediments are a reduction in capacity factor, increase in operation costs, increase in time and frequency of maintenance activities, reduction of peaking capacity and equipment wear.

Capacity factor is defined as the ratio between the actual energy produced in a year and the maximum possible energy output over that time. Every time the power plant is not producing or producing at partial capacity, the capacity factor is reduced. El Canadá HPP interrupts the water income when the sediment concentration in the river is higher than 2% (Anleu, 2018). Therefore, every time there is a flood or Santa María reservoir is flushing, the energy production at El Canadá HPP is affected, reducing the capacity factor and, with it, the financial benefit.

An increase in operation costs happens because sediments must be handled continuously. Everyday activities performed to handle the sediments in El Canadá HPP include measurement of sediment concentration in the river, trash rack and filters cleaning and operation of conventional and hydrosuction dredges.

When sediments are transported in the waterways, its abrasion produces wear in the equipment, forcing the power plant operator to perform more frequent maintenance and even unexpected corrective maintenance. Other specific events have produced forced corrective maintenance activities. In 2008, the trash rack at the penstock entrance was clogged with sediments, increasing the water pressure up to the breaking point. The power plant had to be shut down to replace the trash rack.

Figure 4.5 Damaged trash rack due to sediment clogging. (Source: El Canadá HPP)

The main function of the pond is to store water for daily peaking capacity. Being able to produce during peaking hours, when the energy price is higher, allows a larger income for the power plant. However, sediment deposition started to reduce the peaking capacity, reaching critical levels on 2006, when the pond had lost nearly 50% of its storage capacity due to sediments (Jimenez & Figueroa, 2015).

Sediments are abrasive, which means that the power plant equipment is subjected to wear when there is sediment in the waterways. The most sensitive equipment to abrasion are the turbines. The factors affecting turbine wear are the head, type of turbine, sediment size and sediment composition. El Canadá HPP has two Pelton turbines working with a 365 m net head, making them overly sensitive to sediment abrasion. Figure 4.6 shows the abrasion damage in one of the nozzles of the turbine.

Figure 4.6 Nozzle wear due to sediments. (Source: El Canadá HPP)

4.1.2. Sediment sampling

Sediment sampling is required to understand the characteristics of sediments in the power plant. It was intended to do sediment sampling at the headworks, regulation pond and powerhouse discharge. Nevertheless, due to safety regulations and lack of proper equipment, it was only possible to perform the sampling in the regulation pond.

The two parameters of interest are the particle size distribution and the shear strength of the sediment deposits. Two samples were taken and analyzed using laser diffraction to find the particle size distribution. The shear strength was measured directly on site using a shear vane. The shear strength quantifies the cohesive and compaction forces in the deposit.

Shear strength measurements were performed in four points of the regulation pond and sediment samples were taken from two of those points. The measured points are shown in Figure 4.7. Sediment samples were taken in the points number 2 and 4.

Figure 4.7 Shear strength measurements and sediment sampling location points.

Both shear strength measurements and sediment samples were taken from a boat on the pond. Sediment deposits were located between 50 cm to 2 m below the water surface. Shear strength measurements were performed using a shear vane with a rod extension and sediment samples were taken with a drop-on sampler. The equipment used for sampling and measurement is shown in Figure 4.8.

(a) Sediment sampler (b) Shear vane

Figure 4.8 Equipment used for sediment sampling (a) and shear strength measurements (b).

Three measurements of shear strength were performed in each point. The measurements and averages results are shown in Table 4.1

Table 4.1 Results of shear strength measurements in the regulation pond.

Sediment shear strength		
Point	***Measurement (kPa)***	***Average (kPa)***
#1	9	9,67
	8	
	12	
#2	10.5	11,00
	11	
	11	
#3	9	11,33
	14	
	11	
#4	15	16,00
	17	
	16	
Average	12,0 kPa	

The average shear strength of 12 kPa demonstrates that there are important cohesion forces in the sediment deposits. Measurements were taken approximately 50 cm depth, in areas where sediments have been deposited for relatively short time. Shear strength of sediments may be higher at deeper locations and after consolidation. Shear strength must be taken into consideration when choosing removal strategies.

The samples taken in the points #2 and #4 were analyzed in a Laboratory, using a laser diffraction particle size analyzer. The laser diffraction particle size analyzers measure particle size using Fraunhofer and Mie theories of light scattering. The equipment used is the model LS230, produced by Beckman Coulter. LS230 analyzer provides size distribution in volume, number and surface area in one measurement, with a sizing range from 0.04 to 2000 µm. The output values from the LS230 are indicated in Annex II.

The results show a d_{50} value of 21.05 µm for the sample #2 and 16.67 µm for the sample #4, proving that the sediments that reach the pond are fine particles mainly composed by clay and silt. There is a very low percentage of particles larger than 0.2 mm, around 10%, which means that the sand trap is working according to the design. The particle size distribution of the samples is shown in Figure 4.9.

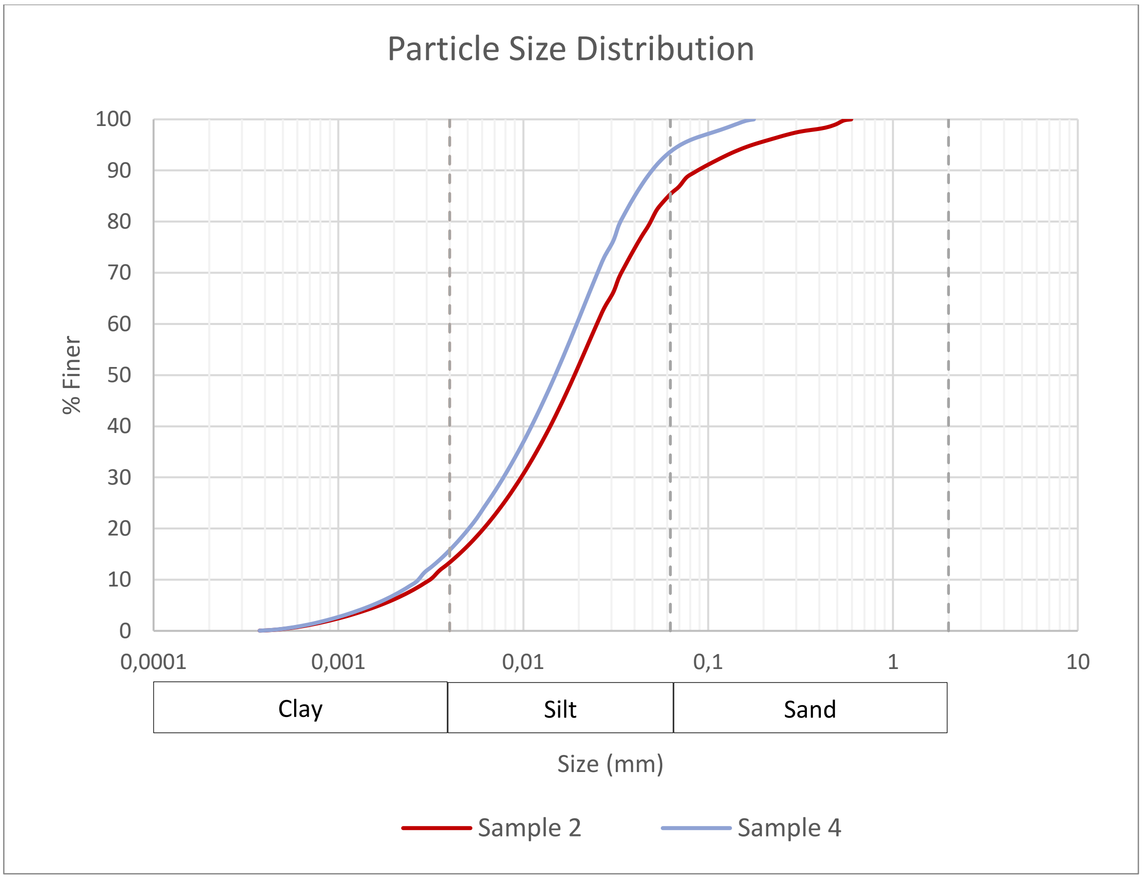

Figure 4.9 Particle size distribution of the two samples taken from the regulation pond.

4.2. Sediment yield

There is still not an exact method to estimate sediment yield. A common approach is using the empirical Universal Soil Loss Equation (USLE) together with the Sediment Delivery Ratio (SDR). Sediment yield can be also estimated by measuring sediment concentration in the river. However, the results of these approaches may lead to underestimation of the sediment yield due to the variable nature of sediment transport.

The present chapter presents different sources and estimations of sediment yield in the upper Samalá catchment. Earlier studies and references that have estimated sediment yield were gathered and a back calculation was done using the sediment balance in the regulation pond of El Canadá HPP.

4.2.1. Earlier estimations

Since 1960, worldwide suspended sediments runoff maps have been developed, including rough estimations for Central America. More specific studies have been performed by the National Institute of Electricity of Guatemala (INDE by its initials in Spanish) and El Canadá HPP. Such studies consist of direct measurements of sediment concentration in the river in several stations along the river.

The first suspended load runoff maps were developed by Fournier in 1960. Since then, an updated version of the maps has been presented by Strakhov (1967), and UNESCO (1974), but such maps used little information, making them inaccurate (Jacobsen, 1997). Later, Walling and Webb (1996) developed a map based on data from nearly 2000 river stations. From Walling and Webb map (See Figure 1.1 in chapter 1), a suspended sediment yield between 250 and 500 t/km^2-year can be expected in Samalá catchment, which translates to a range between 205,500 and 411,000 ton/year for El Canadá HPP catchment.

The sediment yield from suspended sediment runoff maps must be used carefully, as the estimation does not consider bedload. Bedload is an important component of the sediment transport in the river. Besides, the input data does not show the sediment concentration during large events, despite extreme floods carry large parts of the total sediment load.

In 2008, a study of the Upper Samalá catchment summarized the sediment measurements and estimations performed by INDE (Cedepem; ALDES, 2008). The estimations were done by measuring sediment concentration in stations *Cantel*, *Candelaria* and *El Túnel*, located upstream of the Intake of El Canadá HPP, and by measuring bedload in Santa María reservoir.

In 2009, El Canadá HPP estimated the sediment yield using sediment concentration measurements from *El Túnel* station (Vargas, 2009). The sediment yield estimations are summarized in Table 4.2.

Table 4.2 Sediment yield estimations previously done by INDE and El Canadá HPP

Sediment yield measurements			
Source	***Sediment yield (ton/year)***	***Period of measurements***	***Description***
INDE	542,000.0	1964-1978	Suspended load, Cantel Station
INDE	270,000.0	1962-1978	Suspended load, Candelaria Station
INDE	306,000.0	1980-1988	Suspended load, El Túnel Station
INDE	126,000.0	1992	Bed load, Santa María reservoir
El Canadá HPP	211,482.0	Not specified	Suspended load, El Túnel Station

As one can see, the measured suspended load varies from 211,482 to 542,000 ton/year, similar values to the ones from the suspended sediment runoff maps. In average, the measured suspended load is 332,370.5 ton/year. The only measurement of bedload shows a value of 126,000 ton/year. Therefore, using the average measured values, the total sediment load is **458,370.5 ton/year**, of which 27% is bed load.

It is crucial to clarify the limitations related to the measurements used for the sediment yield estimation. The measurements are mainly for suspended load only, and for relatively short periods. Besides, the only bedload measurement was done in Santa María reservoir, and the data is only from one year. Thus, hydrological variations may not be represented in the measurements. Moreover, the measurements were done a long time ago, when the land use and economic activity of Quetzaltenango were different than today, factors that affect the sediment yield.

4.2.2. Back-calculation

The amount of sediments depositing at the pond of El Canadá HPP during the last ten years can be estimated from the power plant operational records. Knowing the amount of sediment deposition in the pond, a back-calculation of the sediment yield can be performed. For this to be done, the next steps were followed:

1. Collection of bathymetric surveys, operation log of dredging and sediment removal rates of the dredges.
2. Estimation of the annual sediment deposition in the pond.

3. Estimation of the sediment distribution through the power plant: Overflow, bedload percentage, trapping efficiency in the desander and in the pond.
4. Estimation of the total load in the river.

Two main assumptions were done to proceed with the calculation: (1) Santa María reservoir is assumed to be in balance, which means that it has no relevant effect on the sediment transport in the river, and (2) the particle size distribution in the river is assumed similar to the distribution found by Chao and Ahmed (1985), presented in Figure 2.1.

In 2007, when the sediment problems in the pond of El Canadá HPP became clear, the owner decided to purchase conventional dredges. Together with the dredging, a monitoring strategy of the sediment volume in the pond was set up. Therefore, bathymetric surveys of the pond have been performed at least once per year since 2008. Besides, the operations hours of both dredges have been also registered from 2012, when the hydrosuction dredge was commissioned. The operation hours from the dredges are shown in Table 4.3.

Table 4.3 Operation hours registered for the dredges at El Canadá HPP's pond.

Operation hours		
Year	***Hydrosuction***	***Diesel***
2012	3,587.0	661.0
2013	4,359.5	1,528.5
2014	3,606.0	1,367.5
2015	4,175.0	18.5
2016	4,191.0	602.0
2017	2,427.0	392.0

The annual sediment volume in the pond was estimated using the operation hours together with the removal rates. The discharge of the hydrosuction dredge is 1,000 m^3/s and the annual average sediment concentration varies from 7.2% to 10%, while the conventional diesel dredge has a discharge of 450 m^3/s and an average concentration of 6%. The measured sediment volume from bathymetries and the sediment volumes removed with each dredge are shown in Table 4.4.

Table 4.4 Annual sediment volumes from bathymetries and dredging removal rates.

Sediment volumes (m^3)			
Year	*Bathymetry*	*Hydrosuction*	*Diesel*
2011	80 038.3	-	59 886.0
2012	87 201.8	293 966.6	17 847.0
2013	60 102.5	248 446.5	41 269.5
2014	53 928.3	208 507.2	36 922.5
2015	33 372.2	264 415.2	499.5
2016	33 034.7	256 470.6	16 254.0
2017	47 456.4	157 937.8	10 584.0

The annual sediment income in the pond can be estimated by adding up the sediment deposit measured with the bathymetric surveys and the sediment removed with the dredging. However, one must be careful when comparing the volume measured with the bathymetries and the volume calculated with the sediment removal rates, because both measurements are done at different sediment compaction condition. The sediment in the pond has been deposited for several months and it has been subjected to frequent drawdowns, while the sediment concentration measured at the discharge of the dredges is taken only after 24 hours of deposition.

To compare both measurements, the sediment volume must be transformed to weight, using the dry bulk density for the respective situation. It was not possible to measure the density in-situ during the field trip, so the density in the pond must be estimated using an empirical approach. The dry bulk density of the dredging discharge measurements was obtained by simulating the sampling procedure in a laboratory.

The dry bulk density of the sediment deposited in the pond was estimated using the equation developed by Lara and Pemberton (1963):

$$\gamma = W_c p_c + W_m p_m + W_s p_s \qquad \textit{Equation 4.1}$$

where γ is the density in lb/ft^3, W is a coefficient depending on the type of reservoir, p is the percentage of particle size, and the sub-indexes c, m, and s are clay, silt, and sand respectively.

The pond of El Canadá HPP is defined as Type II reservoir: normally moderate to considerable reservoir drawdown, giving values of 35 for W_c, 71 for W_m and 97 for W_s (Lara & Pemberton, 1963). The percentages of clay, silt, and sand are given in the particle size distribution of the samples taken from the pond (See previous Figure 4.8) and are 15% of clay, 75% of silt and 10% of sand. The dry bulk density of the sediment deposits in the pond is then **1.09 t/m^3**.

The sediments measured at the discharge of the dredges are affected by bulking, showing a lower density than the deposits in the pond. The dry bulk density of the sediments at the discharge of the dredges was estimated by simulating the sampling procedure in a laboratory, where it was possible to measure the volume and the weight of dry sediments. The laboratory test showed that the dry bulk density of the sediments after 24 hours of repose is **0.48 t/m^3**, which corresponds to the density of the measurements taken at the discharge of the dredges. Details of the test are summarized in Annex II.

Now, the total sediment income in the pond can be estimated by calculating the sediment balance. The total sediment income during that year is the measurement from the bathymetric survey plus the sediment that was removed with the dredging. The measured sediments in weight units (tons) and the estimated total sediment income are shown in Table 4.5.

Table 4.5 Sediment balance at the regulation pond to estimate the annual sediment income.

Annual sediment income at the pond (ton/year)				
Year	***Bathymetry***	***Hydrosuction***	***Diesel***	***Total income***
2011	87 446.92	-	-	-
2012	95 273.49	139 634.15	8 477.33	155 938.05
2013	65 665.83	118 012.11	19 603.01	108 007.46
2014	58 920.12	99 040.90	17 538.19	109 833.38
2015	36 461.26	125 597.24	237.26	103 375.65
2016	36 092.51	121 823.54	7 720.65	129 175.44
2017	51 849.10	75 020.46	5 027.40	95 804.44
			Average	**117 022**

As it can be seen, an average of 117,022 tons of sediments are depositing in the pond every year. Calculating back with the dry bulk density estimated for the pond, the annual average of sediment deposition in the regulation pond is 107,108 m^3, which is approximately 50% of the total volume of the pond.

The next step is to understand the sediment transport behavior in the power plant. The sediment income was measured at the pond, so it is needed to estimate the sediment percentages that are not trapped, or “lost”, between the river and the pond. The sediments that are not trapped at the pond for the run-of-river scheme of El Canadá HPP are:

- Bedload: Run-of-river power plants are designed to let all bedload pass through the intake.
- Sediment transported by overflow: The hydropower plant has a limited discharge capacity, every time there is a river flow larger than the design discharge, including floods, the sediment transported by the overflow is not entering the power plant.
- Sediment trapped in the desander: The desander retains particles larger than 0.2 mm. The trapped sediments are flushed back to the river often.
- Sediment not trapped in the pond: The pond has also an established trapping efficiency, trapping only part of the sediments and letting pass the rest.

Figure 4.10 shows the division of the sediments at the intake and the pond of El Canadá HPP.

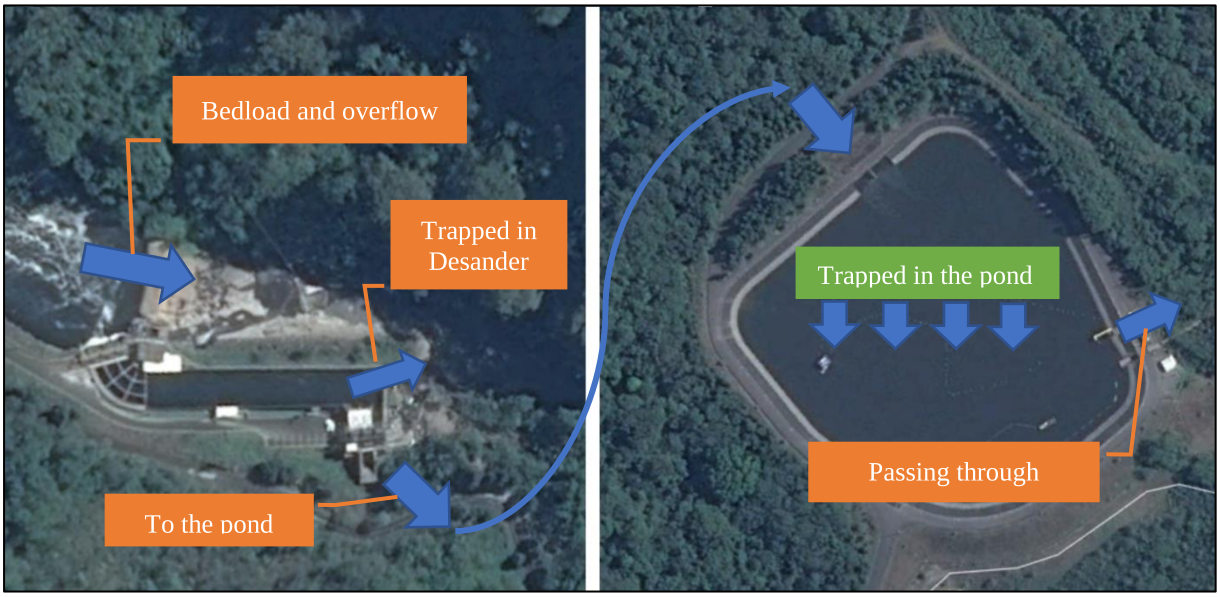

Figure 4.10 Distribution of sediment load at the intake (left) and the pond (right) of El Canadá HPP.

Considering the sediment distribution, Equation 3.2 (Verstraeten & Poesen, 2002), can be modified to be used in a pond of a run-of-river scheme as:

$$SY = \frac{SD}{TF} \qquad \textit{Equation 4.2}$$

where *SY* is the sediment yield in tons per year, *SD* is the amount of sediment depositing at the pond, and *TF* is the Trapped Factor, defined as the percentage of sediments from the total load that deposits in the pond. The Trapped Factor for a run-of-river scheme can be calculated as:

$$TF = (1 - BL) * (1 - 2 * OF) * (1 - TE_D) * TE_P \qquad \textit{Equation 4.3}$$

where *BL* is the bedload percentage of the total load, *OF* is the overflow volume as a percentage of the total water volume, TE_D is the trapping efficiency of the desander and TE_P is the trapping efficiency of the pond.

The fact that most of the sediment transport happens during floods is included in Equation 4.3 by using a factor of 2 for the Overflow parameter.

Information about bedload is limited in the catchment. The earlier measurements presented in the previous section shows that the bedload is 27% of the total load, but it was measured in one year only. References from literature present a range between 1% to 20%. Most of sediment transport occurs during floods, when large amounts of bedload are also transported. Therefore, a value of 20% is chosen for the calculation.

The overflow percentage was obtained from the duration curve and the design discharge of El Canadá HPP. The duration curve gives a total water volume of 243.95 Mm^3. For the design discharge of 15 m^3/s, the overflow volume is 47.83 Mm^3. Therefore, the percentage of overflow is 19.6%. The duration curve is shown in Figure 4.11.

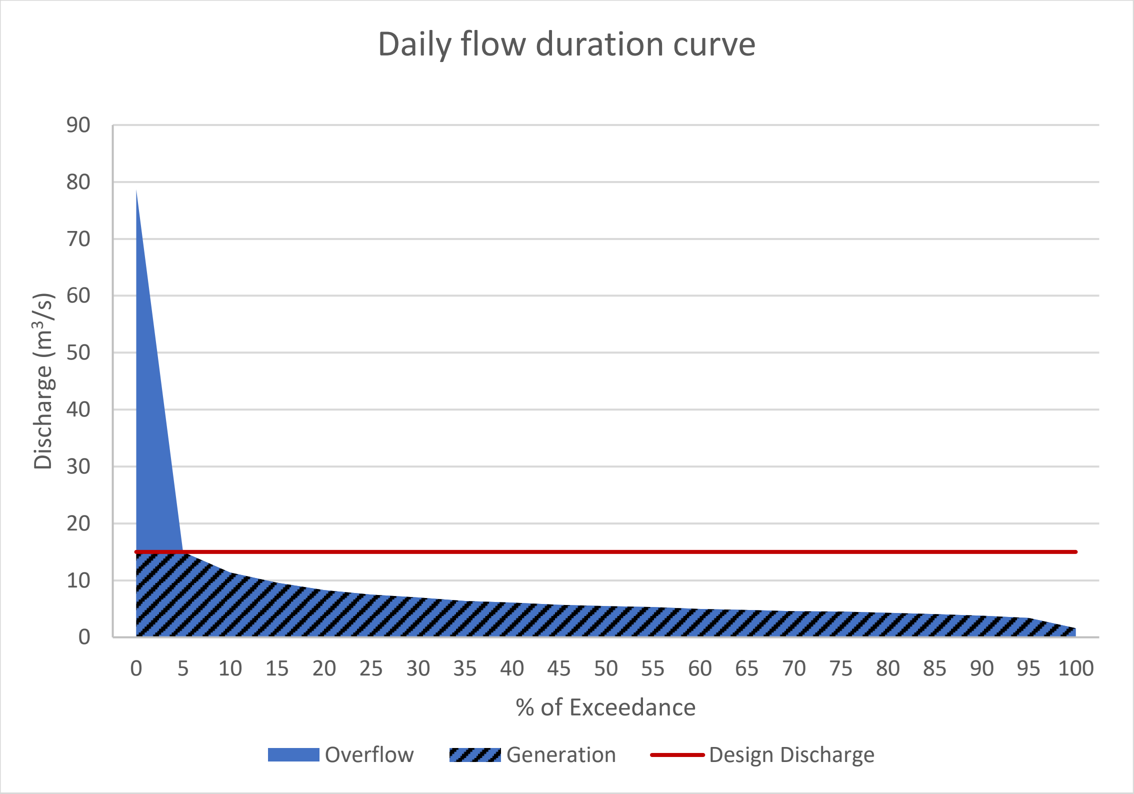

Figure 4.11 Daily duration curve of El Canadá HPP.

The trapping efficiency of the desander and the pond were calculated using the Sed-Trap model. The main required input for the model is the discharge, the specific weight of the sediments, the geometry of the basin, Manning's number and the grain size. Most of the parameters are already define or measured, but the grain size distribution of the sediments in the river is not known.

As it was stated before, the particle size distribution in the river is assumed similar to the distribution found by Chao and Ahmed (1985). The grain size passing each ten percent was used to construct the particle size distribution (d_{10}, d_{20}, …, d_{100}). Then, the Sed-Trap model was set up for the desander, using the entire particle size distribution. This calculation also allows estimating the particle size distribution of the sediment passing the desander, which is the one reaching the pond. The particle size distributions entering and passing the desander are shown in Figure 4.12.

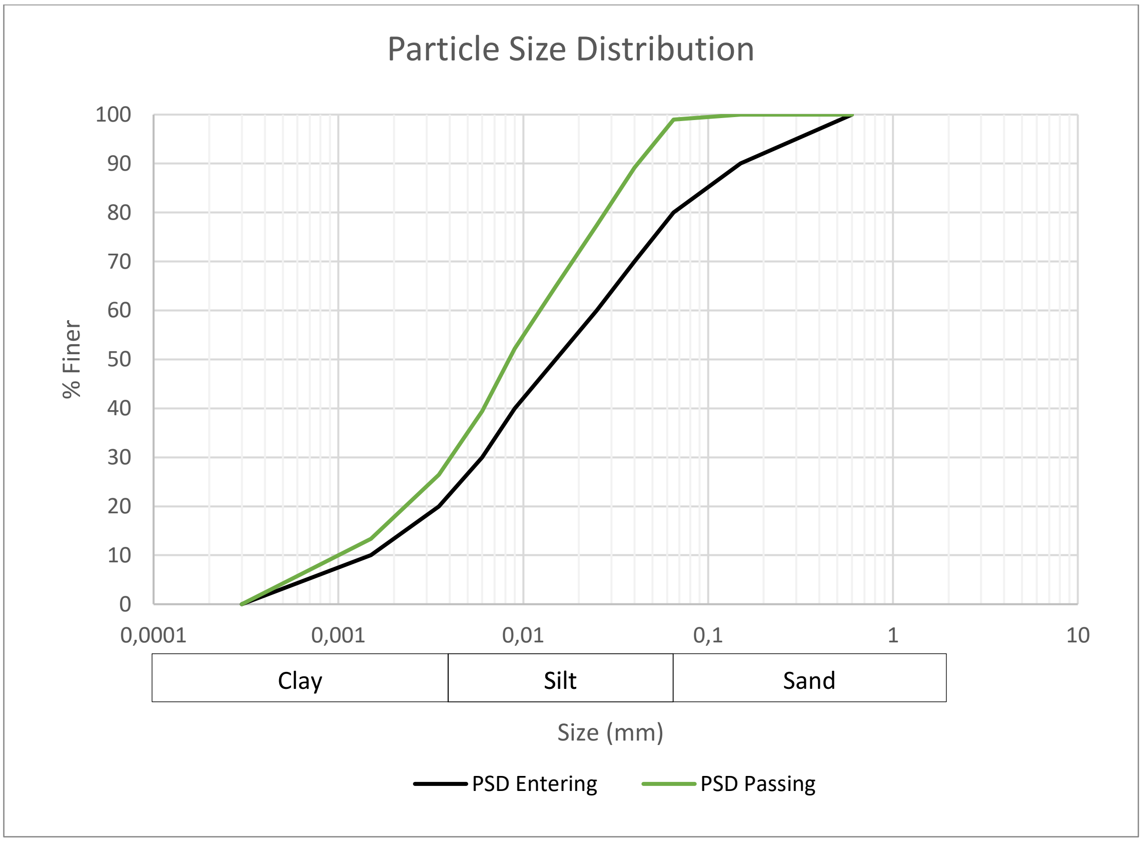

Figure 4.12 Particle size distribution entering and passing the desander.

Most of the parameters defining the geometry of the structures are fixed, except the depth of the pond, which varies depending on the sediment deposits and with the operation of the power plant. From 2009 to 2017, the average depth at high regulation water level was 5,8 m. Besides, the pond is daily drawdown to the level of sediment deposits. So, the net depth was defined as half of the average water depth, i.e. 2,9 m. The net length of the desander is considered as the 80% of the total length.

The parameters used in the Sed-Trap model for the desander and the pond are indicated in Table 4.6

Table 4.6 Parameters for trapping efficiency calculation using Sed-Trap model.

Trapping efficiency calculation		
Parameter	***Desander***	***Pond***
Discharge (m^3/s)	15	15
Specific weight (kg/m^3)	2650	2650
Net Depth (m)	6.3	2.9
Width (m)	12.2	200
Net Length (m)	85	180
Manning's number, M	60	60

Trapping efficiency is then calculated for each grain size in the particle size distribution. The overall trapping efficiency is found by adding the portion trapped of each grain size. The resulting trapping efficiency for the desander is 25,0% and for the pond is 55.5%. The results for the desander and the regulation pond are shown in Tables 4.7 and 4.8 respectively.

Table 4.7 Trapping efficiency of the desander.

PSD Entering		**Trapping efficiency**	
% finer (d_x)	***Size (mm)***	***Total Trapped (%)***	***Portion Trapped (%)***
0	0.0003	0.0	0.00
10	0.0015	0.0	0.00
20	0.0035	1.7	0.17
30	0.006	3.0	0.30
40	0.009	3.7	0.37
50	0.015	4.8	0.48
60	0.025	6.6	0.66
70	0.04	11.4	1.14
80	0.065	26.6	2.66
90	0.15	92.4	9.24
100	0.6	100.0	10.00
Trapping efficiency			**25.0**

Table 4.8 Trapping efficiency of the regulation pond.

PSD Entering		Trapping efficiency	
% finer (d_x)	*Size (mm)*	*Total Trapped (%)*	*Portion Trapped (%)*
0	0.0003	26.7	0.00
10	0.001	27.3	2.73
20	0.0021	27.7	2.77
30	0.004	28.9	2.89
40	0.006	31.1	3.11
50	0.0085	35.3	3.53
60	0.012	44.0	4.40
70	0.018	65.7	6.57
80	0.028	95.3	9.53
90	0.045	100.0	10.00
100	0.12	100.0	10.00
Trapping efficiency			**55.5**

For validation, the resulting particle size distribution trapped in the pond was compared with the particle size distribution of the samples taken in the pond. As it can be seen in Figure 4.13, the calculated particle size distribution trapped in the pond is remarkably similar to the samples. Therefore, the estimated trapping efficiencies can be trusted.

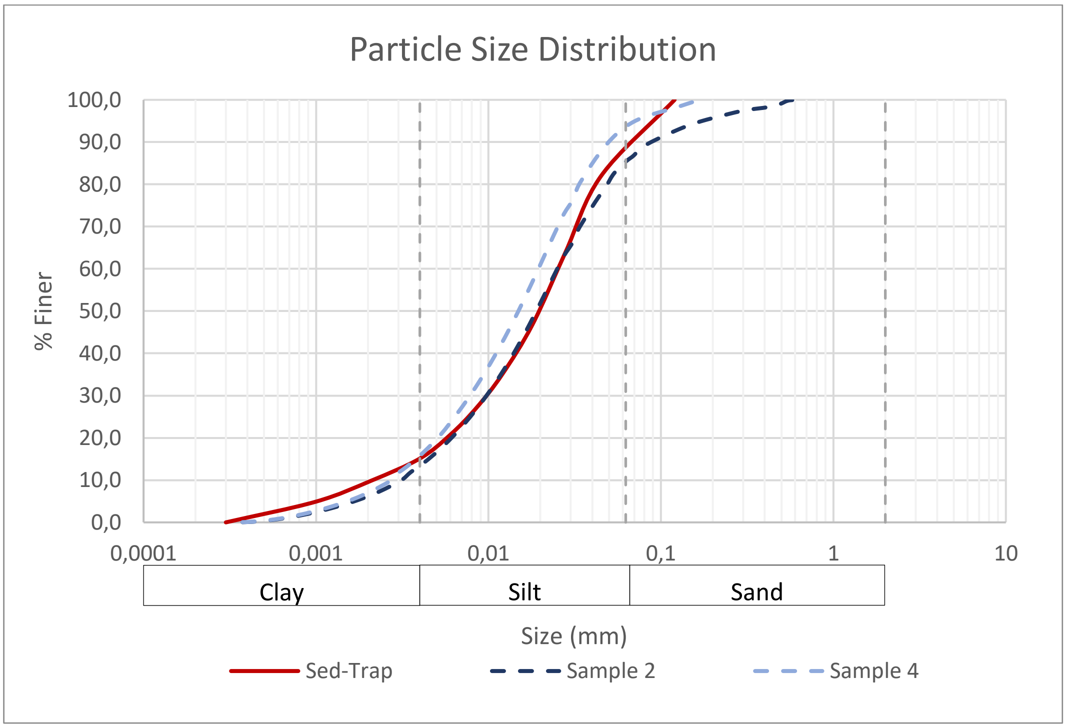

Figure 4.13 Comparison of particle size distribution estimated with Sed-Trap and the samples taken at El Canadá HPP.

Now that all the values of the sediment distribution along the power plant are defined, the Trapping Factor in the pond can be calculated from Equation 4.3:

$$TF = (1 - 20\%) * (1 - 2 * 19.6\%) * (1 - 25.0\%) * 55.5\% = 20.2\%$$

Finally, the sediment yield can be estimated for every year, using Equation 4.2. The results are shown in Table 4.9.

Table 4.9 Results of sediment yield back-calculation.

Sediment yield estimation		
Year	***Sediment deposited (ton/year)***	***Sediment Yield (ton/year)***
2012	155 938.05	770 201.4
2013	108 007.46	533 465.0
2014	109 833.38	542 483.5
2015	103 375.65	510 587.8
2016	129 175.44	638 016.8
2017	95 804.44	473 192.5
Average		**577 991**

The average sediment yield is approximately 578,000 ton/year, ranging from 473,192 ton/year (2017) to 770,201 ton/year (2012). Knowing that the catchment has an area of 822 km^2, the sediment yield can be expressed as 703 ton/km^2-year. The calculated sediment yield is larger than the values estimated in earlier studies, which suggests that measuring the concentration of suspended sediments may lead to an underestimation of the sediment yield.

4.3. Remarks on future scenarios

Sediment yield estimations performed in the previous sections are based on actual measurements, therefore, they represent the current situation only. Sediment yield is highly affected by climate and land use, two factors that might change considerably in the near future. According to the power plant manager (Anleu, 2018), the main challenges regarding sediment yield are:

- Land use, mainly the extensive deforestation and agriculture.
- Microclimates generating intense rainfall in the focused parts of the catchment.
- Hurricanes.

Land use is an economic and political issue. If Quetzaltenango continues developing agriculture as the main economic activity and it does not control deforestation, the soil erodibility will grow, increasing the sediment yield.

Climate change will have a strong effect on the rainfall patterns. Even though the climate change scenarios show a general decrease in rainfall for Guatemala (INSIVUMEH, 2018), there is a generalized trend to increase the intensity of extreme events. This effect will intensify the localized rainfall and the strength and frequency of hurricanes, which will lead to larger floods, and therefore, a larger sediment yield.

Further work is recommended to estimate the potential increase of sediment yield considering climate change and land use scenarios. A model based on USLE may be developed and calibrated using the sediment yield estimation of the present study. The calibrated model would allow foreseeing the sediment yield in the mid and long-term, helping to make decisions on land use and hydropower operation.

5. Sediment handling strategies

El Canadá HPP has been affected by sediments since it was commissioned in 2003. Nevertheless, it was not until 2005, when hurricane Stan generated large floods bringing with it a large amount of sediments, that the power plant owners decided to implement active sediment handling strategies.

As it was described in Chapter 4, the main challenges faced by the power plant are the large amount of garbage and debris, and the suspended sediment load that gets into the power plant and deposits in the regulation pond.

The actions taken by the power plant owner were focused on the three main areas of the power plant: headworks, pond, and powerhouse. At the headworks, the trash rack was improved by installing an automatic garbage collector and secondary filters. Besides, a new operational strategy was set at the intake to reduce the sediment income. For the pond, two conventional dredges were purchased in 2007, and later, in 2011, one of them was replaced by a hydrosuction dredge with a higher capacity. Finally, the runners of the units were reinforced with tungsten to reduce wear (Anleu, 2018).

The strategies have given positive results for the power plant operation. The peaking capacity of the pond has been partially restored and the sediment deposits have been continuously reduced. Before, the runners and nozzles had to be changed every 2-3 years, but now they last around 5 years (Anleu, 2018).

Details of the sediment handling strategies at the headworks and at the pond are described in the following sections.

5.1. Headworks

The headworks of El Canadá consist in a rubber weir to divert the water, a bottom flush gate, an intake with trash racks, a 105 m long desander, and a garbage filter before the water enters the tunnel towards the regulation pond. The project was designed to let the bedload pass over the weir and through the bottom flush gate. The desander efficiently traps and return to the river the particles larger than 0.2 mm. Figure 5.1 shows the headworks site.

Figure 5.1 El Canadá HPP headworks.

5.1.1. Intake operation

After the hurricane Stan, it was clear that a large amount of suspended sediments is affecting the operation of the power plant. The two main reasons to have a high sediment concentration in the river are floods and flushing from Santa María dam.

In order to reduce the amount of suspended sediment entering the power plant, a new operational strategy was set at the intake. The new strategy dictates that the bottom gate of the intake must be opened when there is a high sediment transport in the river, to stop the water supply into the power plant. The sediment concentration threshold in the river was set in 2%, which was obtained through trial and error (Anleu, 2018).

The amount of energy lost due to shut down when there is a high sediment concentration in the river is in average 3,150 MWh/year. Nevertheless, the economic losses related to the energy loss are compensated by the reduction of the sediment consequences, such as loss of peaking capacity and turbine wear.

A throughout cost analysis is described in Chapter 6, comparing the cost of the sediment handling strategies with their benefit.

5.1.2. Trash rack and garbage filters

Samalá river is highly contaminated from all the waste produced in the cities and towns upstream. Despite the headworks are handling the coarse material properly, a large amount of garbage and debris are carried out as floating material, affecting the intake operation.

To keep the intake free of garbage and debris, a secondary filter system was installed, together with an automatic collector system. Thereby, most of the floating load is retained in the two barriers and then it is automatically transported to a disposal area, where the material is dried out, separated and packed for further treatment. The collector system is activated automatically every 2 hours.

The following Figures illustrate the installed system. Figure 5.2 shows the three filters that were installed right before the headrace tunnel. Figure 5.3 illustrates the path through where the garbage and debris are taken out from the trash rack. Figure 5.4 shows the disposal area. Finally, Figure 5.5 illustrates the area where the waste is separated and packed to be sent either for recycling or disposal.

Figure 5.2 Garbage filters installed after the desander in El Canadá HPP’s intake.

Figure 5.3 Trash rack with automatic collecting system in El Canadá HPP. The arrows show the path of the collection system.

Figure 5.4 Disposal area for collecting garbage and debris.

Figure 5.5 Separation and packing of the disposed material for further treatment.

5.2. Regulation pond

An average of approximately 100,000 m^3 of sediments are depositing in the pond every year. Such sediments must be removed to maintain the daily regulation capacity of the 200,000 m^3 pond and to avoid equipment wear.

Despite there is a bottom valve for emptying the pond, it has not enough capacity to be used for sediment removal by flushing. Besides, the pond has a polyethylene lining, impeding the use of machinery for mechanical removal. Thus, the only available possibility for removing sediments is dredging.

Dredging activities started on 2007 when the power plant owner purchased two conventional dredges, an electrical one, and a diesel one. The removal capacities of the dredges were 3.4 m^3 of sediment per hour for the electrical dredge (Jimenez & Figueroa, 2015), and 27 m^3 of sediment per hour for the diesel dredge, accordingly to the theoretical values of discharge and concentration for the dredge.

The combined capacity of the two conventional dredges was not enough to face the sediment income. Then, in 2011, the electrical dredge was replaced by a hydrosuction dredge with a theoretical capacity of 50 m^3 of sediment per hour. Diesel and hydrosuction dredges have been working since 2012 until today. A detailed description of this equipment is given next.

5.2.1. Conventional diesel dredge

The diesel dredge in the regulation pond of El Canadá HPP is a conventional hydraulic dredge of 8” (app. 200 mm) diameter, brand PIT HOG, model 727, manufactured by Liquid Waste Technology, LLC (U.S.A.). The dredge’s motor has a power of 225 HP (167.8 kW), with a consumption of around ten gallons of diesel per hour (37 l/h). The dredging is powered with a submersible pump with a total capacity of 2,000 gal/min (450 m^3/h). The dredge is also equipped with an auger cutter to break the cohesivity of the sediments, increasing the sediment concentration. The auger cutter is powered by a hydraulic system with pumping capacity of 5.5 m^3/h. Figure 5.6 shows the diesel dredge.

Figure 5.6 Conventional diesel dredge at El Canadá HPP.

The diesel dredge is mobilized along a steel cable from side to side of the pond. As it is shown in Figure 5.7, the pipeline is discharging the slurry flow over the spillway. Due to the depth limit of the dredge arm, the operation is performed when the water level allows sediment removal, which happens on average 6 hours per day.

Figure 5.7 Diesel dredge arrangement and discharge.

The main advantage of the dredges is that the sediments are removed without interfering with the power plant production. The average cost of running the diesel dredge is US$75 per hour (Vargas, 2009). Despite the cost is higher compared with the hydrosuction dredge, the diesel dredge is still used to face the large sediment income. The main two disadvantages of the diesel dredge are the limitation on the dredging depth, which restricts the amount of time the dredge can be used, and the risk of water contamination by diesel or oil spill.

5.2.2. Hydrosuction dredge

The hydrosuction dredge in the regulation pond of El Canadá HPP has a combined pipe diameter of 10”-12” (app. 250 mm – 300 mm). It is a tailormade dredge for the regulation pond of El Canadá HPP, manufactured by SediCon AS (Norway). The slurry flow in the pipeline is driven by gravity, so the dredge has no motor and no energy consumption for the dredging. Nevertheless, the dredge requires electricity as it is equipped with a water jetting system, an electric winch for operation, and sockets for small tools and light. The water jetting system has the larger electricity consumption as it is powered with a pump of 100 HP (75 kW). Figure 5.8 shows the hydrosuction dredge.

Figure 5.8 Hydrosuction dredge at El Canadá HPP.

The distinguishing characteristic of the SediCon hydrosuction dredge is the design of the suction head, which ensures an ideal concentration in the pipeline and avoids blocking in the flow. Even when hydrosuction dredging principle is not covered by any patent, the design of the SediCon suction head is patented. The suction head is operated with a chain winch from a light raft. The winch allows the operation of the system without depth restriction. At the same time, the raft is mobilized with ropes attached to the pond periphery.

The pipeline is subjected to negative pressure because the system works with hydrosuction. Therefore, the pipeline is made with a combination of HDPE and flexible suction hose, both materials capable of handling the negative pressure. The pipeline is connected to a bypass in the bottom flushing valve, taking the slurry flow through the dam and back in the river. The available head for hydrosuction varies from 8 m to 14 m depending on the water level in the pond. The pipeline length is 175 m. The general arrangement of the hydrosuction dredge is shown in Figure 5.9, while the bypass connection is shown in Figure 5.10, which was taken during the installation of the dredge in 2011.

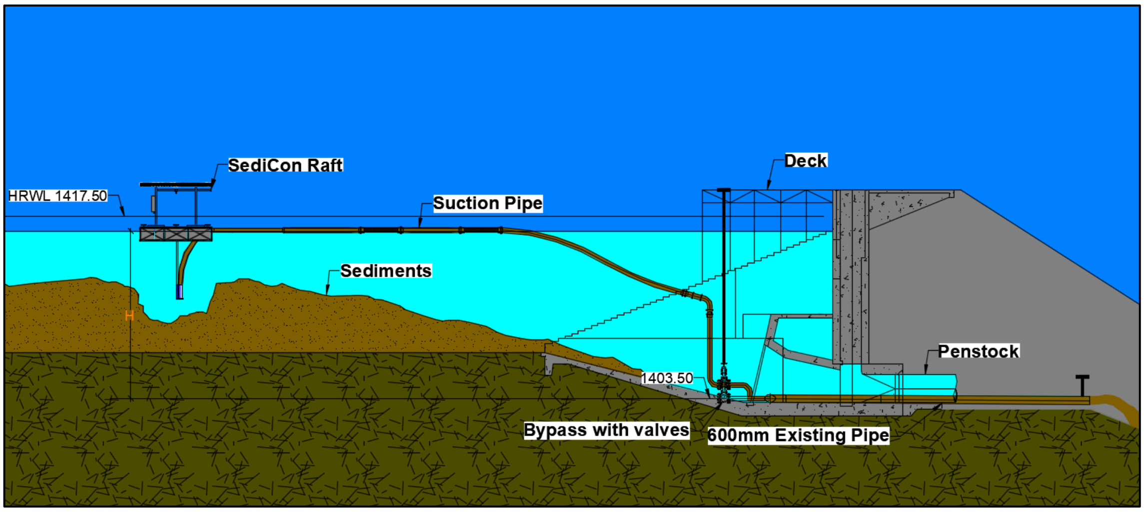

Figure 5.9 Arrangement of hydrosuction dredge in El Canadá HPP **(Jimenez & Figueroa, 2015)**.

Figure 5.10 Bypass installation in the flushing pipe for connection of hydrosuction dredge **(Jimenez & Figueroa, 2015)**.

The main advantage of the hydrosuction dredge is the lower cost and higher capacity, giving a lower cost per cubic meter of sediment removed. Other advantages are the removal without interrupting the power plant operation, low energy supply requirements, unrestricted depth of dredging, the possibility of removing all size of particles including garbage and debris, a water jetting system that does not harm the polyethylene lining, and the zero risk of water contamination with oils or fuels.

The disadvantages related with hydrosuction dredging, like the hydraulic limitation and environmental restrictions of sediment disposal, do not apply for El Canadá HPP. Thus, considering the regulation pond characteristics and the sediment income situation, the hydrosuction dredge is the most convenient solution.

5.2.3. Comparison

The technical information of the dredges was collected from the manufacturers. The main technical information of both dredges is summarized and compared in Table 5.1.

Table 5.1 Comparison of hydrosuction and diesel dredges characteristics at El Canadá HPP.

Dredges technical information		
Data	***Hydrosuction***	***Diesel***
Pipeline diameter	10" / 12"	8"
Sediment cutting system	Water Jetting	Mechanical cutter
Discharge	1000 m^3/h	450 m^3/h
Maximum dredging depth	No limit	4.6 m
Theoretical concentration	7%	6%
Theoretical capacity	50 m^3/h	27 m^3/h
Operation Cost	US$12.5 /h	US$75 /h
Rental Cost	US$50 /h	-
Total Cost	US$62.5 /h	US$75 /h

The main difference between both dredges is that the hydrosuction dredge has a much higher capacity with a lower cost. Other advantages of the hydrosuction dredge over the diesel dredge are the possibility to dredge at any depth no matter the water level, a larger range of particle size that can be removed, low risk of damaging the polyethylene lining, and low risk of water contamination.

5.2.4. Capacity measurement

Concentrations and capacities shown in Table 5.1 are reference values given by the manufacturers. The actual removal capacity of both dredges was measured on site to confirm or correct the reference values. There are two main parameters to measure the removal capacity: discharge and sediment concentration. The discharge is given by the pump for the conventional dredge and by the water column and pipeline length for the hydrosuction dredge, while the sediment concentration must be measured.

Sediment concentration was measured at the dredges discharge using Imhoff cones. The Imhoff cone is a graduated cone with capacity for 1 liter. When the sediment is deposited in the bottom, low concentration can be easily read thanks to the conical shape. To capture the variability of sediment concentration during the dredging operation, the measurements were taken every ten minutes for one hour. Figure 5.11 shows the samples taken at the discharge of the conventional dredge.

Figure 5.11 Measurement of sediment concentration at the discharge of the conventional dredge.

Then, the concentration used for estimating the sediment removal capacity is the average sediment concentration during one hour of dredging. The results of sediment concentration are presented in Table 5.2.

Table 5.2 Result of sediment concentration measurements at the discharge of the dredges.

Sediment concentration measurement		
Time	***Hydrosuction***	***Diesel***
10	4,0%	13,0%
20	6,2%	4,0%
30	13,0%	12,0%
40	4,0%	8,0%
50	11,0%	7,0%
60	6.5%	8,5%
Average	7,64%	8,75%

Sediment concentrations values were taken after 24 hours of repose. Hence, the density of the measurements is lower than the sediment deposits in the pond, that have been subjected to long a consolidation process. To compare the measured concentration with the actual sediment density in the pond, a bulking factor must be used. The bulking factor shows the ratio between densities for different consolidation conditions. In Chapter 4, the density in the pond was estimated as 1.09 ton/m^3, while the density at the discharge, after 24 hours, was found to be 0.48 ton/m^3, giving a bulking factor of 2.3. Then, the sediment removal capacity can be estimated as:

$$SRC = Q * C * BF \qquad \text{Equation 5.1}$$

where SCR is the sediment removal capacity in cubic meters of sediment per hour, Q is the discharge in cubic meters per hour, C is the concentration in percentage and BF is the dimensionless bulking factor.

The results of the measured sediment removal capacity for both dredges are presented in Table 5.3

Table 5.3 Results of sediment removal capacity measurements.

Measured sediment removal capacity		
Data	***Hydrosuction***	***Diesel***
Discharge	1000 m^3/h	450 m^3/h
Measured efficiency	7.64%	8.75%
Bulking Factor	2.3	2.3
Measured capacity	33.2 m^3/h	17.1 m^3/h
Average daily operation	13.5 hours	6 hours
Daily Sediment removal rate	448 m^3/day	103 m^3/day

The results show that the theoretical sediment removal capacity of both dredges is higher than the actual removal capacity. Even though, if the dredges are operated continuously (365 days per year), the capacity of the hydrosuction dredge allows an annual removal of 163,520 m^3, while the conventional dredge can remove 37,595 m^3, for a total removal capacity of 201,115 cubic meters of sediment per year, a higher value than the average sediment income.

5.3. Monitoring

Monitoring of sediment transport in the river and the power plant is a relevant tool for hydropower plants affected by sediments. Measuring and recording sediment transport patterns can improve the operation of the power plant in short and long-term. Immediate decisions like when to shut down to avoid sediment related damages or long-term decisions like what sediment handling solutions are cost-efficient can be taken if the monitoring is carried out correctly.

Comparatively with most of hydropower plants, where few or no monitoring is performed, El Canadá HPP has good monitoring activities. Nevertheless, the monitoring strategies at El Canadá HPP are still limited and mainly focused on the operation of the regulation pond. According to Anleu (2018), the monitoring strategies conducted at El Canadá HPP are:

- Sediment concentration measurements at the intake with the Imhoff cone, registered in the headworks logbook.
- A complete bathymetric survey in the pond twice per year. Partial manual survey every month.
- Dredging capacity measurement of the hydrosuction dredge by measuring the sediment concentration and discharge in the outlet, registered in the dredging logbook.

The sediment concentration measurements taken at the intake are used for daily operation. If the sediment concentration in the river is above 2%, the flushing gates at the headworks are opened, reducing the water and sediment income to the power plant.

Bathymetric surveys and daily sediment concentration measurements at the discharge of the hydrosuction dredge are used to monitor the performance of the dredge. By the time this study was carried out, the hydrosuction dredge had a rental contract, where the manufacturer ensures a defined sediment removal capacity. Thus, the monitoring is carried out to prove that the capacity defined in the contract is being achieved.

Considering the complex sediment problem at El Canadá HPP and the uncertain situation in the catchment regarding land use and climate change, it is recommended to improve the monitoring procedure at the headworks. Continuous measurements of sediment concentration can be used not only for the daily operation of the power plant but also for understanding the sediment transport behavior of the river and detecting long-term variations in the sediment load, which could affect the power plant in the future.

6. Cost analysis of strategies

The current sediment strategies being carried out at El Canadá HPP successfully control the sediment challenges in the power plant from a technical perspective. However, no detailed financial analysis has been performed to understand the impact of such strategies in the power plant economy.

An annual cost analysis can be developed using the power plant fail log and the operation log of the two dredges. The power plant fail log registers every time the power plant had to shut down and the reason behind. The operation log of the dredges collects the number of hours of daily operation and daily sediment removal capacity measurements. The information is available from 2009 to 2017, and it can be used to estimate the following annual costs:

1. Cost of energy losses due to sediments.
2. Maintenance cost due to sediments.
3. Cost of peaking capacity lost.
4. Cost of conventional dredging.
5. Cost of hydrosuction dredging.
6. Other costs.

Following sections explain how these costs were calculated to finally analyze the sediment handling strategies from a financial point of view.

6.1. Energy losses

El Canadá HPP's fail log register every shutting down event that has affected the power plant operation. Fails are registered and categorized depending on the cause and include the amount of time that the power plant was shut down and the related energy lost.

Among the fail categories, three of them are directly related to sediment challenges: (1) Floods, which includes shutting doing during exceptional high discharge in the river and sediment concentration above the established threshold of 2%; (2) Maintenance due to sediment problems, such as corrective maintenance of worn out and damage equipment, sediment removal activities like flushing of the desander, among others; and (3) Flushing of Santa María reservoir, located upstream the intake, which implies a non-hydrological increase in sediment concentration of the river.

The fail log was then processed to gather the energy losses related to sediment problems. Results are shown in Table 6.1.

Table 6.1 Annual energy losses in El Canadá HPP due to sediments related causes.

Energy losses due to sediments (MWh)				
Year	***Flood***	***Maintenance***	***Santa María flushing***	***Total***
2009	0.00	3,519.55	669.72	4,189.27
2010	3,573.28	4,029.12	2,640.89	10,243.29
2011	1,063.10	3,120.26	1,586.59	5,769.95
2012	2,690.14	2,034.23	2,553.31	7,277.68
2013	860.95	750.55	2,429.21	4,040.71
2014	3,611.81	1,715.22	2,185.40	7,512.43
2015	70.80	2,279.00	2,035.67	4,385.47
2016	799.60	1,974.00	1,536.46	4,310.06
2017	938.52	1,789.30	1,087.07	3,814.89
Total	13,608.20	21,211.23	16,724.32	51,543.75
Average	1,512.02	2,356.80	1,858.26	5,727.08

The average energy loss due to sediments between 2009 and 2017 was 51.5 GWh. Knowing that the annual generation of the power plant is 178 GWh, the sediments represent a loss of 29% of the annual generation. Figure 6.1 shows the energy losses during the period together with the time during which the power plant was shut down for the same causes.

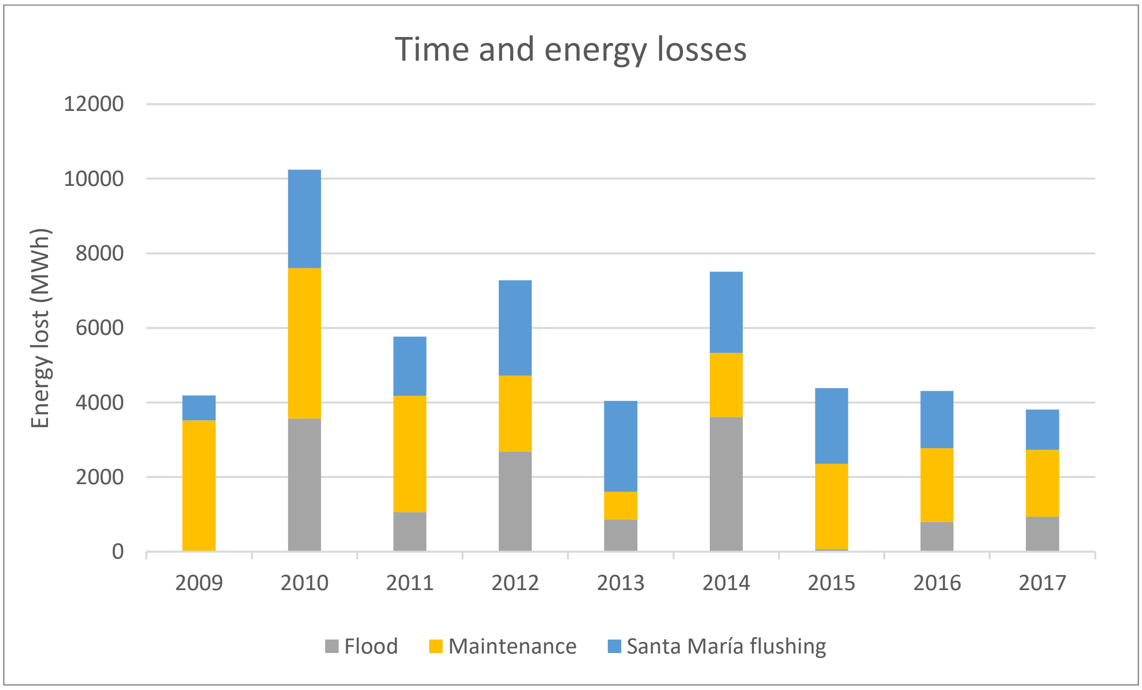

Figure 6.1 Annual energy losses due to sediments.

A wide variation in the values can be seen in Figure 6.1. For example, 2009 did not have any shut down due to floods, while 2010 was highly affected by floods. This variation is related to the natural hydrological variation and the flushing operation of Santa María reservoir, two factors that cannot be controlled or influenced by the owner of El Canadá HPP.

From the three factors mentioned, the sediment handling strategies can only reduce the energy losses related to maintenance. Figure 6.2 shows the energy losses of only sediment-related maintenance.

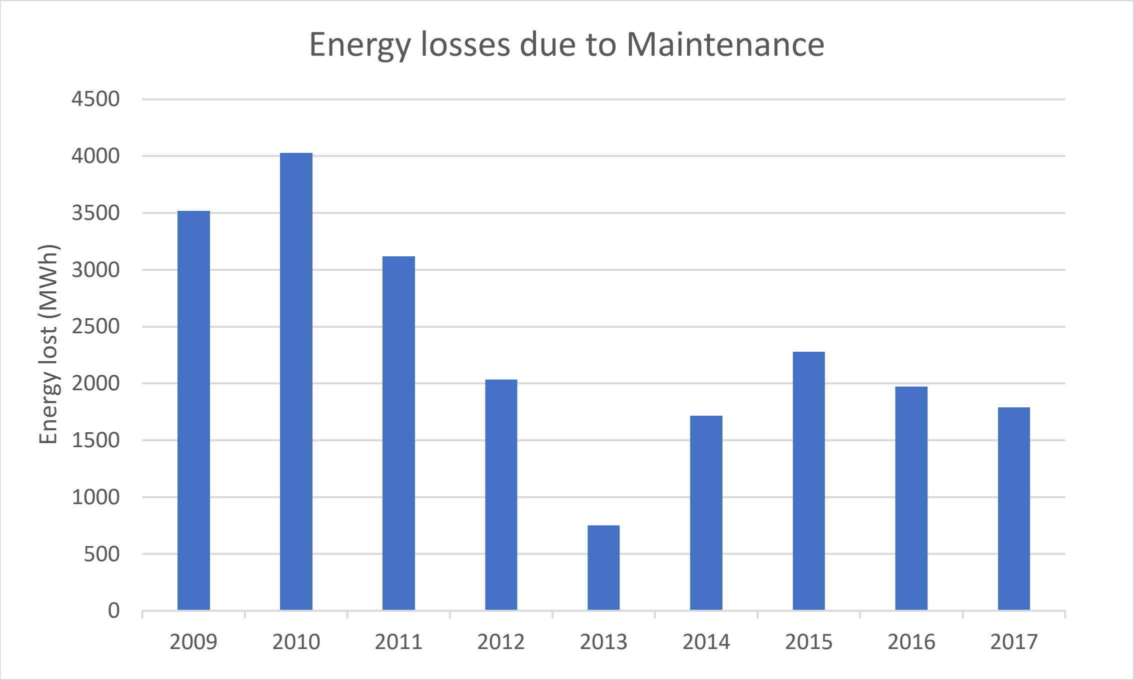

Figure 6.2 Annual energy losses due to sediment related maintenance.

Figure 6.2 shows clearly a reduction in the energy losses due to maintenance after 2012, when the hydrosuction dredge started operation. The energy price of the market is needed to quantify the financial impact of the reduction of energy losses. Energy prices in Guatemala are published by the Administrator of Wholesale Market (AMM by its initials in Spanish). Base, peak and average energy prices are shown in Figure 6.3.

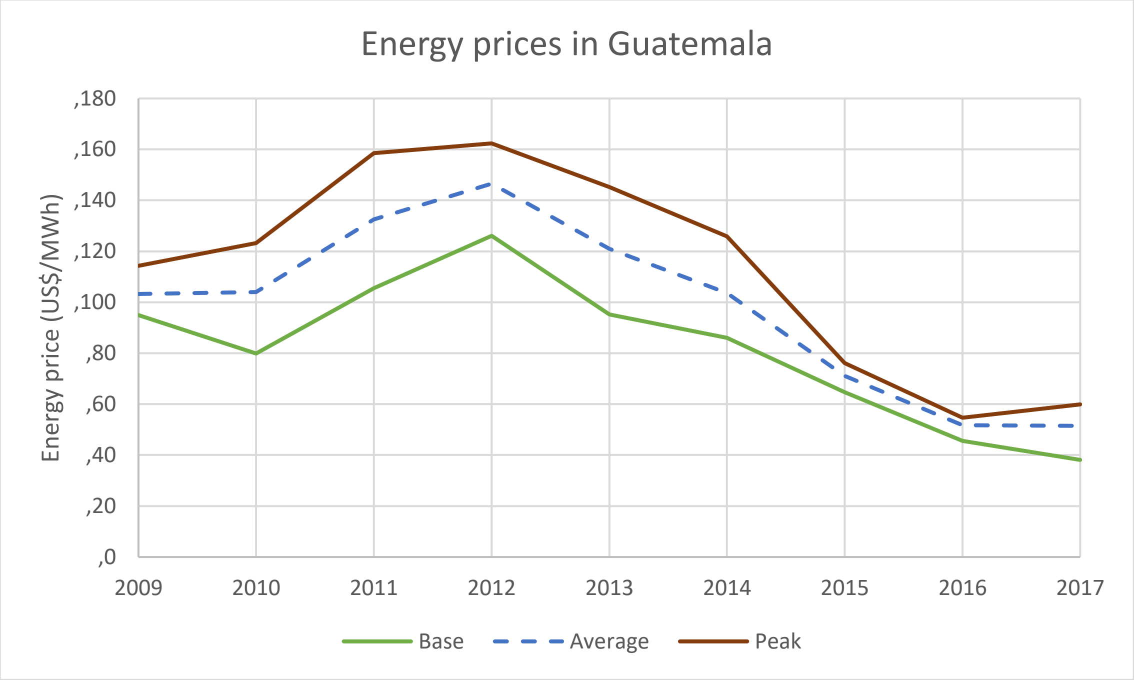

Figure 6.3 Energy prices in Guatemala **(AMM, 2018)**.

Using the average energy price value for each year is possible to estimate the income that was not received from the energy that could not be produced due to sediments. This income that was not received is defined as the cost of energy lost. The results are shown in Table 6.2.

Table 6.2 Annual cost of energy lost due to sediment related maintenance.

Year	***Cost of Energy lost during maintenance***
2009	$363,358
2010	$418,908
2011	$413,590
2012	$298,116
2013	$90,787
2014	$177,714
2015	$161,991
2016	$102,036
2017	$92,113
Total	$2,118,614
Average	$235,402

The average income that was lost in the period due to shutdowns of the power plant for sediment-related maintenance is US$235,402.

6.2. Sediment-related maintenance cost

Besides the cost of energy lost during maintenance, there is a cost related to the maintenance activities themselves. The annual maintenance cost is normally around 1% of the construction cost. For El Canadá HPP, the 1% of the construction cost is approximately US$400,000. In average, the maintenance activities due to any cause, not only sediments, take around 600 hours. Using these values, the cost of maintenance can be assumed as US$615 per hour. Then, the cost of sediment-related maintenance can be estimated knowing the hours used every year. Results are shown in Table 6.3.

Table 6.3 Annual cost of sediment-related maintenance.

Year	*Time lost (hours)*	*Maintenance cost*
2009	539.73	$331,934
2010	511.52	$314,585
2011	762.87	$469,165
2012	519.18	$319,296
2013	71.37	$43,890
2014	199.17	$122,490
2015	74.60	$45,879
2016	214.10	$131,672
2017	247.38	$152,139
Total	3,139.92	$1,931,049
Average	348.88	$214,561

The average annual cost for sediment-related maintenance is US$214,561.

6.3. Reduction of peaking capacity

El Canadá HPP’s regulation pond was designed to give daily peaking capacity to the power plant. This peaking capacity allows producing energy during hours of high energy demand, when the price is higher. However, the sedimentation in the pond have been reducing the storage capacity of the regulation pond, and, therefore, its peaking capacity.

The power plant owner has been performing bathymetric surveys, which gives a good perspective of the variation of storage capacity over the years. Figure 6.4 shows the sediment volume deposited at the regulation pond between 2009 and 2017.

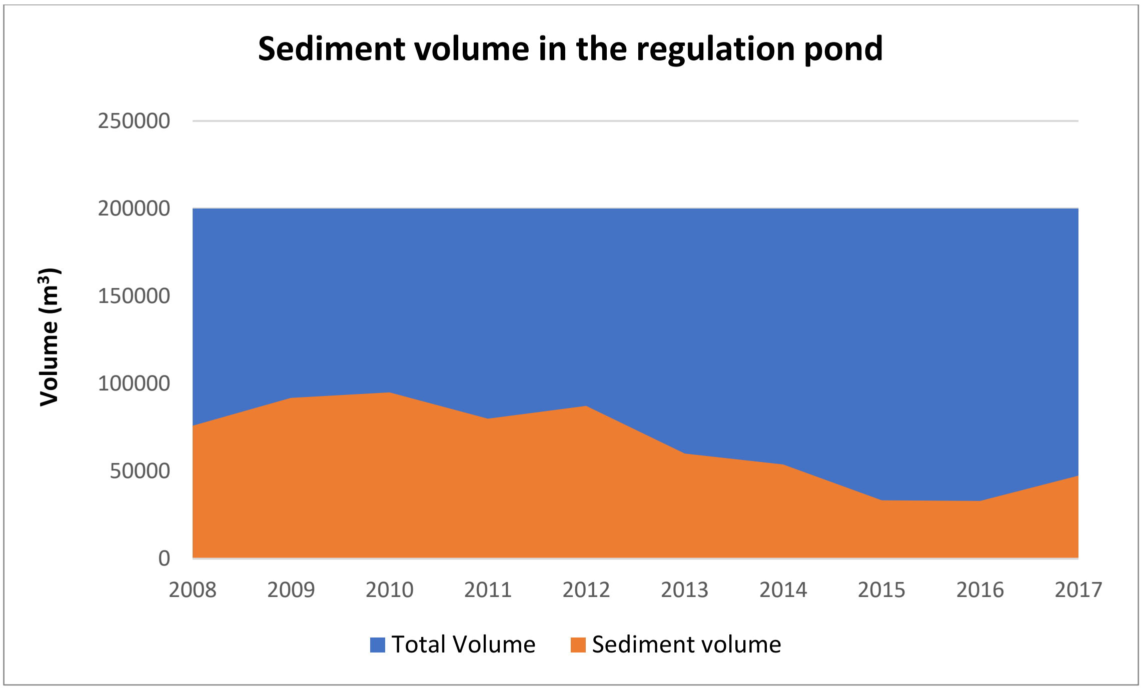

Figure 6.4 Sediment volume deposited at the regulation pond over the years.

The highest regulation water level (HRWL) of the regulation pond is 1,417.5 m a.s.l., and original lowest regulation water level (LRWL) is 1,419.0 m a.s.l., giving a total height of 8.5 m of oscillation. The 8.5 m height difference gives 4 hours of daily continuous production, that represents one-sixth of the total generation (29.7 GWh of 178 GWh). The actual lowest water regulation level is affected by the amount of sediments, and it can be found using the stage-volume curve of the pond, shown in Figure 6.5.

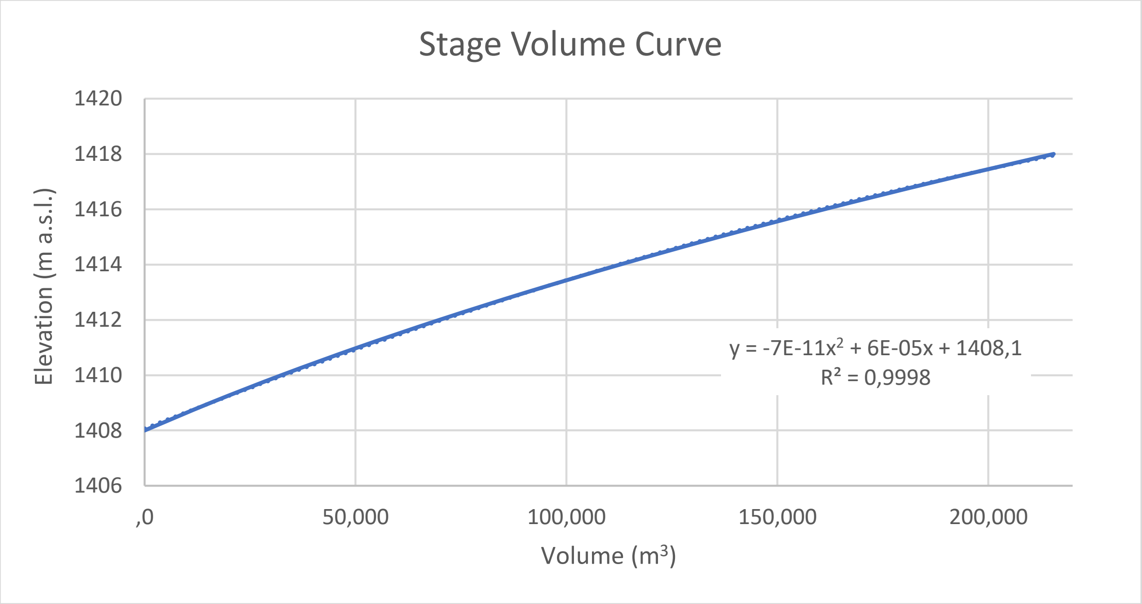

Figure 6.5 Stage-volume curve for El Canadá HPP's regulation pond.

Knowing the sediments level is possible to estimate the actual regulation capacity for every year, and therefore, the remaining peaking capacity of the regulation pond. Results are shown in Table 6.4.

Table 6.4 Remaining regulation capacity of the pond and lost peaking production due to sediment deposition.

Year	*Sediment volume (m^3)*	*Sediment level (m a.s.l.)*	*Regulation capacity (m)*	*Peaking capacity (hours)*	*Lost peaking production (GWh)*
2009	91,920.0	1,413.02	4.48	2.1	14.04
2010	95,000.0	1,413.17	4.33	2.0	14.55
2011	80,038.3	1,412.45	5.05	2.4	12.05
2012	87,201.8	1,412.80	4.70	2.2	13.26
2013	60,102.5	1,411.45	6.05	2.8	8.56
2014	53,928.3	1,411.13	6.37	3.0	7.44
2015	33,372.2	1,410.02	7.48	3.5	3.58
2016	33,034.7	1,410.01	7.49	3.5	3.51
2017	47,456.4	1,410.79	6.71	3.2	6.25

The results show how the peaking capacity was highly affected due to sedimentation in 2009 and 2010, but it has been slowly recovered over the years. Again, the energy price on high demand must be established to quantify the cost of peaking capacity losses. When there is no peaking capacity, the power plant would be able to produce at base price, therefore, the financial loss is the difference between the peak price and the base price (values showed in Figure 6.3). The resulting cost due to the peaking energy that could not be produced is shown in Table 6.5.

Table 6.5 Annual cost of peaking energy that could not be produced.

Year	*Cost of peaking capacity lost*
2009	$270,762
2010	$630,656
2011	$639,139
2012	$481,149
2013	$428,893
2014	$296,619
2015	$41,080
2016	$31,801
2017	$136,049
Total	$2,956,148
Average	$328,461

The average cost due to peaking energy not produced is US$328,461, being the highest cost due to sediments in El Canadá HPP.

6.4. Conventional dredging cost

The cost of dredging for the conventional dredge is determined by the number of hours of operation per year and the cost of operation per hour. The cost of operation per hour is US$75 (Vargas, 2009). Operation hours and annual cost are given in Table 6.6.

Table 6.6 Annual operation hours and cost of dredging with the conventional diesel dredge.

Year	*Operation hours*	*Cost of Conventional dredging*
2009	2416.8	$181,256
2010	1452.0	$108,900
2011	2218.0	$166,350
2012	661.0	$49,575
2013	1528.5	$114,638
2014	1367.5	$102,563
2015	18.5	$1,388
2016	602.0	$45,150
2017	392.0	$29,400
Total	10656.3	$799,219
Average	1184.0	$88,802

The average cost of dredging with the conventional dredge is US$88,802. The average annual removal rate for this dredge is 31,670 m^3 of sediment, which gives a total unit cost of **US$2.8 per cubic meter of sediment removed**.

6.5. Hydrosuction dredging cost

Since the hydrosuction dredge was commissioned in 2011 until 2017, the contract scheme has been a rental. Therefore, the cost of the hydrosuction dredge is divided into two components: rental cost and operation cost. The annual rental cost is US$143,360, expect from the first year (2011), when installation costs were included, giving a total of US$255,360 for that year.

The operation cost of the hydrosuction dredge was estimated based on the electricity consumption and the operators' salary. Electricity consumption is mainly for the water jetting pump and the electric winch, which gives a consumption of 75 kW at a cost of US$0.1 / kWh. Operation of the hydrosuction dredge requires two operators, each one's salary was assumed as US$20 per hour (Qz. 150), in accordance with Guatemalan regulations. Both together give an operation cost of US$12.5 per hour. Operation hours and the resulting annual costs of the hydrosuction dredge are given in Table 6.7.

Table 6.7 Annual operation hours and cost of dredging with the hydrosuction dredge.

Year	*Operation hours*	*Cost of Hydrosuction dredging*
2009	0.0	$0
2010	0.0	$0
2011	0.0	$255,360
2012	3587.0	$188,287
2013	4359.5	$197,963
2014	3606.0	$188,525
2015	4175.0	$195,652
2016	4191.0	$195,852
2017	2427.0	$173,758
Total	22345.5	$1,395,397
Average	2482.8	$155,044

The average cost of dredging with the hydrosuction dredge is US$155,044. The average annual removal rate for this dredge, using the actual concentrations, operation hours and considering the bulking factor, is 103.605 m^3 of sediment, which gives a total unit cost of **US$1.5 per cubic meter of sediment removed**. The unit cost of the hydrosuction dredge is almost half of the unit cost of the conventional dredge.

6.6. Other costs

The other costs included in the analysis are the operation cost of trash rack and filters and the cost of repairing worn out equipment. Estimation of trash racks and filters operation cost was based on its electricity consumption. The cost of repairing worn out equipment was based on the number of times that the equipment was replaced according to the power plant fail log and reference prices of repairing runners in Latin America.

Trash rack and filters cleaning system is automatically operated every 2 hours, during approximately half an hour, giving a total of 6 hours of operation per day of operation. Each of the three filters has a 45 A motor, hence, the consumption is around 30 kWh each. The trash rack cleaner has a consumption of approximately 10 kWh. Using an electricity cost of US$0.1/kWh, the cost of operation is US$10 per day.

Costs related to worn out equipment was based on repairing the runners. The cost of repairing a 23.5 MW Pelton runner in Latin America is around US$30,000-US$40,000. The cost used in the estimation is the higher range, US$40,000, assuming that it includes other related costs such as transport of the runner and required manpower. Runners had to be replaced several times during 2009 and 2010. The last registered change of runner was on 2017.

The annual cost of repairing worn out equipment and operation of the trash rack cleaning and filters system is indicated in Table 6.8.

Table 6.8 Other annual costs related to sediment problems.

Year	***Runners repairing cost***	***Trash rack cleaning and filters***
2009	$160,000	$3,650
2010	$40,000	$3,650
2011	$0	$3,650
2012	$0	$3,650
2013	$0	$3,650
2014	$0	$3,650
2015	$0	$3,650
2016	$0	$3,650
2017	$40,000	$3,650
Total	$240,000	$32,850
Average	$26,667	$3,650

The estimated average annual cost due to repairing worn out equipment is US$26,667, while for the operation of the trash rack cleaning and filters system is only US$3,650.

6.7. Annual cost analysis

So far, the annual cost of sediment consequences and the annual cost of sediment handling strategies has been estimated. Now, gathering all these sediment-related annual costs gives a broad perspective of the situation and allows to identify the benefit of the sediment handling strategies. Figure 6.6 gathers the annual costs of the sediment handling strategies, while Figure 6.7 shows the annual costs of the consequences of sediments.

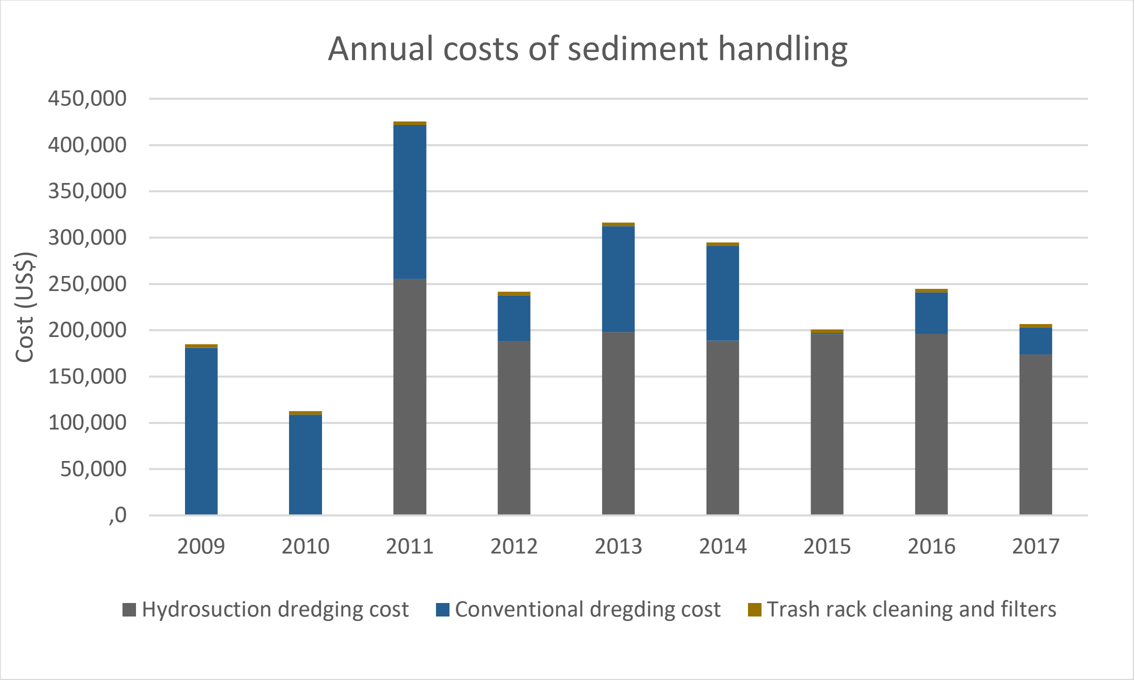

Figure 6.6 Annual costs of sediment handling strategies at El Canadá HPP.

Figure 6.6 shows that the cost of sediment handling strategies increased significantly in 2011, when the hydrosuction dredge was commissioned. Nevertheless, over the years, the hydrosuction dredge has been reducing the need for operating the conventional diesel dredge, which has a higher operational cost. From 2015 onwards, the cost of the strategies is only slightly higher than 2009, when only the conventional dredge was used, and therefore, a lower sediment removal capacity. This means that the power plant owner was able to introduce a solution with higher capacity at a similar cost.

Besides, it can be seen that the cost percentage of the trash rack cleaning and filters operation is very low compared with the costs of dredging, even though, such systems have an extraordinary performance maintaining the power plant free of floating sediments, especially garbage.

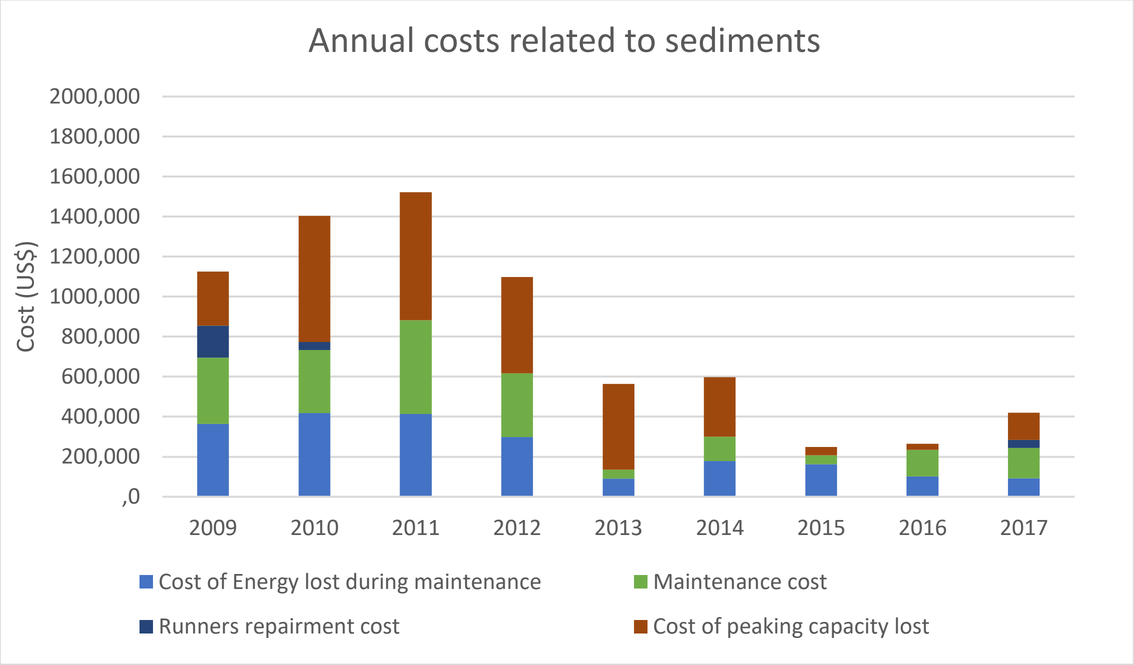

Figure 6.7 Annual cost of sediment consequences at El Canadá HPP.

Figure 6.7, on the other hand, illustrates the cost related to the sediment consequences. It becomes clear that the cost related to sediment problems has been reduced after the implementation of the hydrosuction dredge in 2011. The same behavior is shown when all the costs are illustrated together, despite the increase of the sediment handling strategies cost. Figure 6.8 shows the overall annual costs related to sediments, including the consequences and the cost of the sediment strategies. The energy prices in the market are also shown.

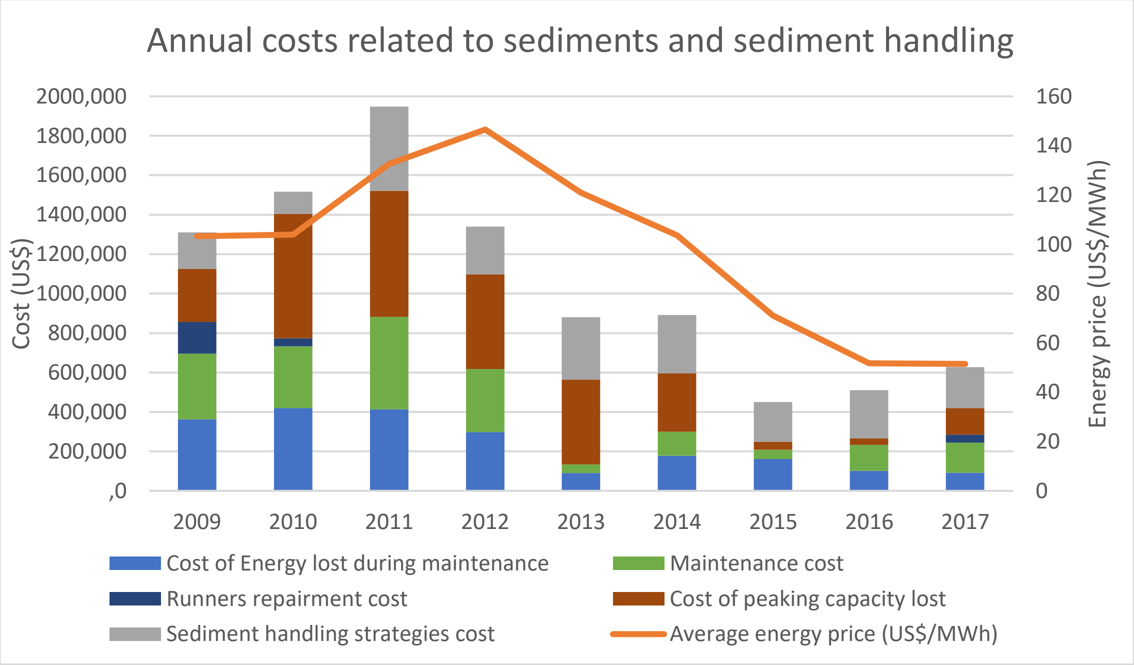

Figure 6.8 Overall annual cost of sediment-related problems at El Canadá HPP.

Generally, there is a decrease in the costs after 2011. However, the market energy prices have been also decreasing from 2012 onwards, which directly affects the magnitude of the energy lost during maintenance and the peaking capacity lost. To differentiate the effect of the hydrosuction dredging from the drop of energy prices, the cost analysis was done assuming a fixed energy price during the whole period. The fixed energy price used for the analysis is the average price in the period 2009-2017. Results are shown in Figure 6.9.

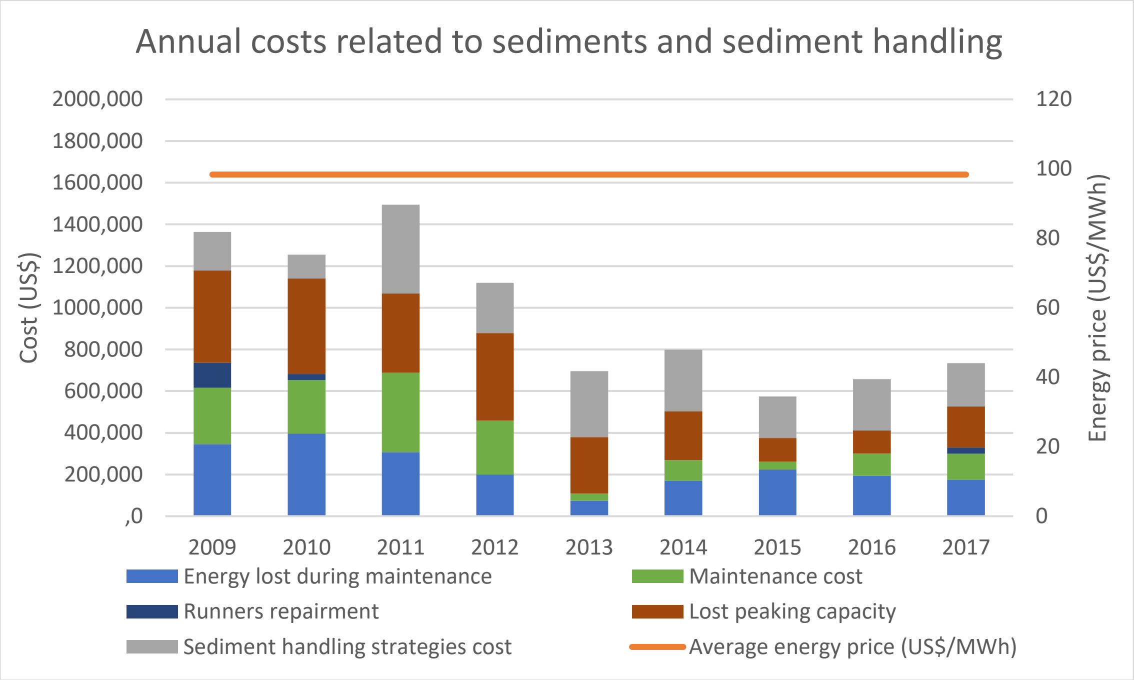

Figure 6.9 Overall annual cost of sediment-related problems at El Canadá HPP, using the average energy prices of the period.

Results of the cost analysis using a fixed price also shows a decrease in the sediment-related costs after the commissioning of the hydrosuction dredge, which proves that the current sediment handling strategies, especially the hydrosuction dredging, have a positive financial impact in the power plant. Further, under this scenario, the average total sediment-related cost before the hydrosuction dredging (2009-2011) is US$1,370,900, and after the hydrosuction dredge was commissioned, the average total sediment-related cost is US$763,260. Therefore, the net benefit of introducing the hydrosuction dredge is, in average, US$607,600 per year.

Anyhow, energy lost and peaking capacity losses are highly affected by energy prices, thus, if the energy prices continue dropping, it might be more convenient to reduce the sediment handling and run the power plant entirely as run-of-river. A further financial analysis must be done by the power plant owner in case energy prices continue dropping.

7. Results

The main objective of the present study was to assess the sediment handling strategies at El Canadá hydropower plant, located in Guatemala. It was proven that the current sediment handling strategies in the power plant are technically and financially worth it. Besides, the in-situ collected information was used to estimate sediment yield, improving the understanding of the sedimentation problem.

The study results can be then categorized into three topics, (1) Sediment challenges and sediment handling strategies, (2) estimation of sediment yield, and (3) cost assessment of the sediment.

7.1. Sediment challenges and sediment yield

During the field trip, the sediment challenges in El Canadá HPP were identified, being the main problems the floating load (garbage and debris), suspended sand, which is efficiently trapped in the desander, and the fine particles depositing in the off-stream regulation pond. The consequences of such sediment challenges are a reduction in capacity factor, increase in operation costs, increase in time and frequency of maintenance activities, reduction of peaking capacity and equipment wear.

Sediment samples and shear strength measurements were taken in the regulation pond. Shear measurements showed an average shear strength of 12 kPa, which proves that there are important cohesion forces in the sediment deposits.

The results of the particle size distribution analysis of two of the samples showed a d_{50} value of 21.05 μm for the sample #2 and 16.67 μm for the sample #4, which means that the sediments that reach the pond are fine particles mainly composed by silt. The percentage of particles larger than 0.2 mm was around 10%, proving that the sand trap is working according to the design.

A sediment balance in the regulation pond was calculated using the bathymetric surveys and removal rates of the dredges. Dry bulk density in the pond was estimated as 1.09 ton/m^3 using empirical equations, while the dry bulk density at the discharge of the dredges was found in the laboratory, giving a result of 0.48 ton/m^3. It was found that an average of 117.022 tons of sediments are depositing in the pond every year, representing 107,108 m^3, which is approximately 50% of the total volume of the pond.

A back-calculation was successfully developed to estimate sediment yield in the catchment, using the sediment balance in the regulation pond and the estimated trapping efficiency of the desander and the regulation pond. The calculated average sediment yield was 578,000 ton/year, or 703 ton/year/km^2, ranging from 473,200 ton/year to 770,200 ton/year.

Earlier estimations of sediment yield showed an average of 332,370 ton/year of suspended load. The only measurement of bedload shows a value of 126,000 ton/year. Therefore, the average total sediment load accordingly to earlier measurements is 458,370 ton/year. The calculated sediment yield using the back-calculation method is larger than the values estimated in earlier studies, which suggests that measuring concentration of suspended sediments may lead to a sub estimation of the sediment yield.

7.2. Sediment handling strategies

According to personal interviews with the power plant manager, the active sediment handling actions taken at El Canadá HPP were installing secondary filters and an automatic garbage collector at the intake, a new operational strategy to reduce the sediment income and the installation and operation of a conventional dredge and a hydrosuction dredge.

A visual evaluation of the power plant showed that the strategies have given positive results for the power plant operation. The peaking capacity of the pond has been partially restored and the sediment deposits in the regulation pond have been continuously removed.

A comparison between the two dredges in the regulation pond was done. The theoretical sediment removal capacity of the hydrosuction dredge is 50 m^3/h, while for the conventional dredge is 27 m^3/h. Operation costs of the dredges are US$62.5/h for the hydrosuction dredge and US$75/h for the conventional dredge.

Unit costs of dredging were estimated for both dredges. The unit cost of hydrosuction dredging is US$1.5/m^3 of sediment removed, while for the conventional dredge is US$2.8/m^3. The unit cost of the hydrosuction dredge is almost half of the unit cost of the conventional dredge.

Therefore, the main difference between both dredges is that the hydrosuction dredge has a higher capacity with a lower cost. Other advantages found about the hydrosuction dredge over the diesel dredge are the possibility to dredge at any depth no matter the water level, a larger range of particle size that can be removed, low risk of damaging the polyethylene lining, and low risk of water contamination.

Sediment removal capacity measurements were performed at site. The results show that the theoretical sediment removal capacity of both dredges is higher than the removal capacity measured at site, with values of 33.2 m^3/h for the hydrosuction dredge and 17.1 m^3/h for the conventional dredge. Even though, using the measured capacities and assuming a daily operation during the whole year, the capacity of the hydrosuction dredge allows an annual removal of 163,520 m^3, while the conventional dredge can remove 37,595 m^3, for a total removal capacity of 201,115 cubic meters of sediment per year.

7.3. Cost analysis

A cost analysis approach to assess the financial convenience of the sediment handling strategies was done by studying the annual sediment-related costs between 2009 and 2017. The analysis was done using the real energy prices in Guatemala for every year, and an average fixed price for the period, in order to understand the sediment-related costs without the variation of energy prices.

Using the real energy prices, the analysis shows that the cost of sediment handling strategies increased after 2011, due to the implementation of the hydrosuction dredge. On the other hand, the costs related to the sediment consequences were reduced after the implementation of the hydrosuction dredge in 2011. The same behavior was found when all the costs are considered together, meaning that the sediment-related costs have been reduced despite the cost increase of the sediment handling strategies.

Results of the cost analysis using a fixed price also shows a decrease in the sediment-related costs after the commissioning of the hydrosuction dredge, which proves that the current sediment handling strategies, especially the hydrosuction dredging, have a positive financial impact in the power plant. Further, it was found that the net benefit of introducing the hydrosuction dredge is, in average, US$607,600 per year.

8. Conclusions

From the obtained results of the study, the following points can be concluded:

- Sediment behavior in Samalá River is complex due to the topographical, geological and hydrological conditions of the upper part of the catchment, together with the land use and unregulated human activity.
- Despite sediments were included in the original design of the power plant, unexpected large amount of garbage, debris, and fine particles have a large impact in the power plant operation and, therefore, in the power plant economy.
- Sediment yield can be estimated using a back-calculation from the sediment balance in the off-stream regulation pond of El Canadá HPP. The same method can be used in other catchments where the sediment balance of a pond or a settling basing is known.
- Measurement of sediment removal rates of the dredges must be corrected due the bulking of water-sediment from the regulation pond at the discharge of the dredges, where the removal rate is measured.
- The sediment handling strategies in El Canadá successfully reduce the impact of sediments. The cost analysis proves that the cost of implementing sediment handling strategies is considerably lower than the cost of the sediment impacts if they are not handled.
- Hydrosuction dredging has several benefits over conventional dredging, including operational qualities, higher capacity and a lower cost per removed cubic meter of sediment.

9. Recommendations

Finally, some recommendations for a best sediment handling plan in the hydropower plant are:

- To foresee future scenarios considering climate change and human activity, it is recommended to develop a model based on the Universal Soil Loss Equation. The model can be validated with the sediment yield estimation using the back-calculation method developed in this study.
- Improve sediment monitoring in the river, using a method that allows continuous sediment concentration measurement, which will improve the power plant operation and the estimations of sediment yield.
- If the energy prices continue dropping, a further financial analysis is needed to ensure that the sediment handling strategies are cost-efficient.
- The experience of El Canadá HPP has shown that the use, development and improvement of sediment handling strategies increases the power plant efficiency and reduce costs. This case encourages other power plants and research institutions to explore and develop new alternatives for sediment handling.

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Annex I. Photography records of the catchment

Totonicapán

San Francisco El Alto

San Francisco El Alto

Salcajá

San Juan Ostuncalco

San Juan Ostuncalco

Almolonga

Almolonga

Zunil

El Canadá HPP Intake

Annex II. Laboratory tests

LS230 Particle size distribution output

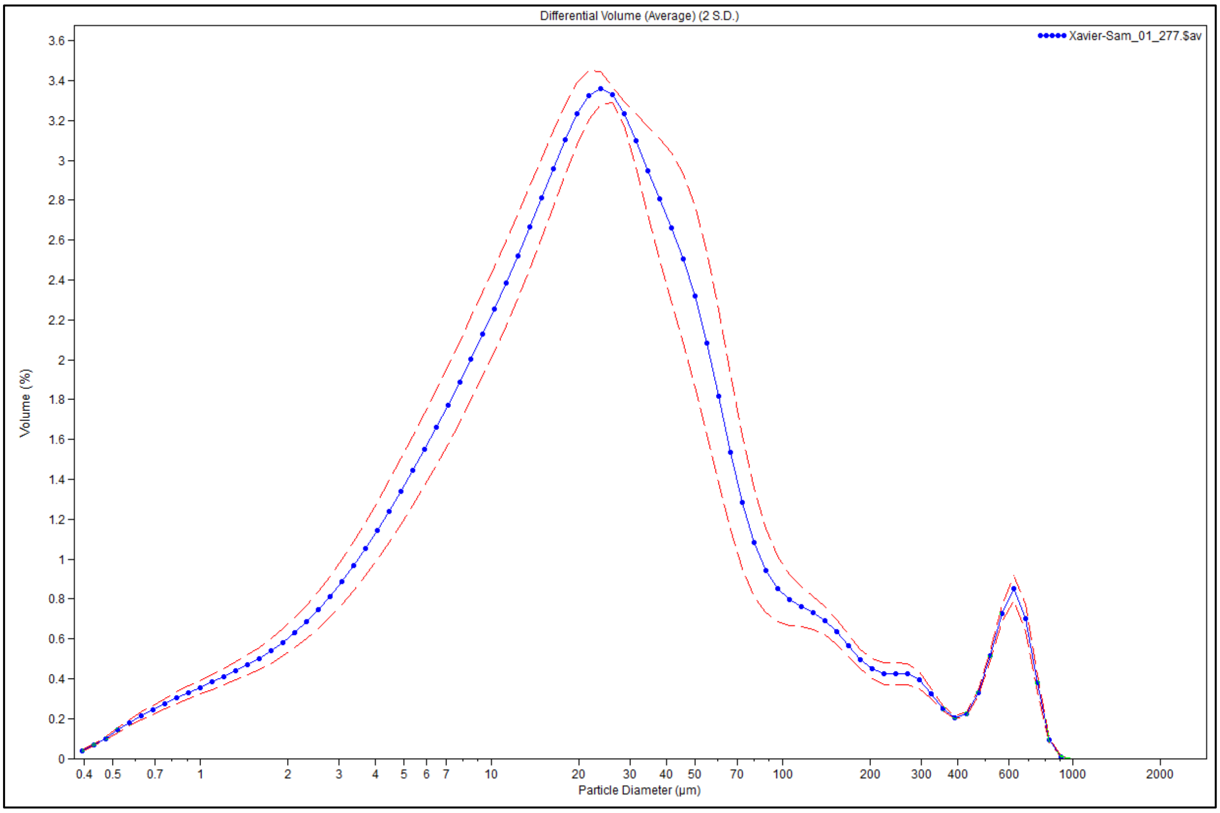
Sample #2:

Channel Number	Channel Diameter (Lower) um	Diff. Volume %
1	0.375	0.04
2	0.412	0.07
3	0.452	0.10
4	0.496	0.14
5	0.545	0.18
6	0.598	0.21
7	0.656	0.24
8	0.721	0.28
9	0.791	0.30
10	0.868	0.33
11	0.953	0.36
12	1.047	0.38
13	1.149	0.41
14	1.261	0.44
15	1.384	0.47
16	1.52	0.50
17	1.668	0.54
18	1.832	0.58
19	2.011	0.63
20	2.207	0.68
21	2.423	0.74
22	2.66	0.81
23	2.92	0.89
24	3.205	0.97
25	3.519	1.50
26	3.863	1.14
27	4.24	1.24
28	4.655	1.34
29	5.11	1.44
30	5.61	1.55
31	6.158	1.66
32	6.76	1.77
33	7.421	1.89
34	8.147	2.00
35	8.943	2.13
36	9.818	2.25
37	10.78	2.38
38	11.83	2.52
39	12.99	2.66
40	14.26	2.81
41	15.65	2.96
42	17.18	3.10
43	18.86	3.23
44	20.71	3.33
45	22.73	3.36
46	24.95	3.33
47	27.39	3.21
48	30.7	3.10
49	33.01	2.95
50	36.24	2.80
51	39.78	2.66
52	43.67	2.51
53	47.94	2.32
54	52.62	2.80
55	57.77	1.82
56	63.41	1.54
57	69.61	1.26
58	76.42	1.80
59	83.89	0.94
60	92.09	0.85
61	101.1	0.79
62	111	0.76
63	121.8	0.73
64	133.7	0.69
65	146.8	0.63
66	161.2	0.57
67	176.9	0.5
68	194.2	0.45
69	213.2	0.43
70	234	0.42
71	256.9	0.42
72	282.1	0.39
73	309.6	0.33
74	339.9	0.25
75	373.1	0.2
76	409.6	0.22
77	449.7	0.33
78	493.6	0.51
79	541.9	0.72
80	594.8	0.85
81	653	0.7
82	716.8	0.38
83	786.9	0.09
84	863.9	0.0091
85	948.3	0.00
86	1041	0.00
87	1143	0.00
88	1255	0.00
89	1377	0.00
90	1512	0.00
91	1660	0.00
92	1822	0.00

Volume:	100%		
Mean:	58.61 µm	S.D.:	122.2 µm
Median:	21.05 µm	Variance:	14937 µm^2
D(3,2):	7.830 µm	Skewness:	3.882 Right skewed
Mode:	23.81 µm	Kurtosis:	15.46 Leptokurtic

d_{10}: 3.424 µm d_{50}: 21.05 µm d_{90}: 119.4 µm

<1 µm	<10 µm	<100 µm	<1000 µm
2.07%	27.9%	88.5%	100%



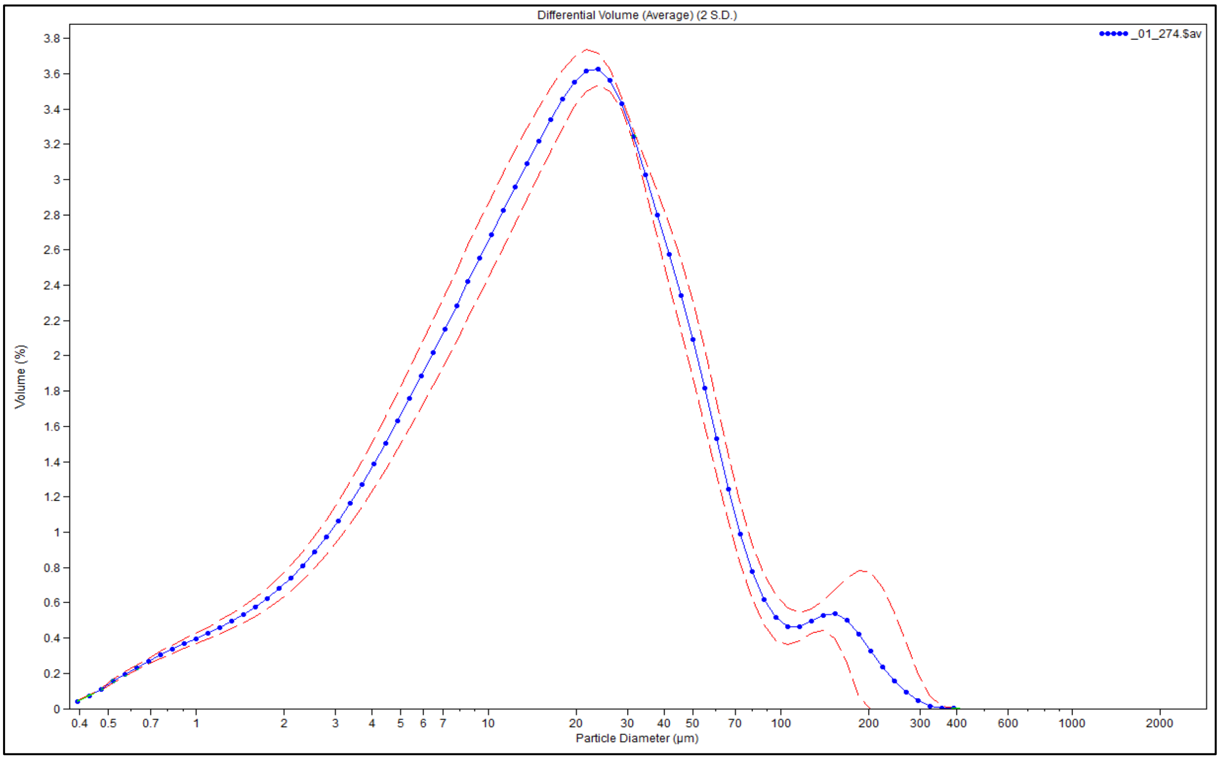
Sample #4:

Channel Number	Channel Diameter (Lower) um	Diff. Volume %
1	0.375	0.042
2	0.412	0.074
3	0.452	0.11
4	0.496	0.16
5	0.545	0.2
6	0.598	0.23
7	0.656	0.27
8	0.721	0.3
9	0.791	0.34
10	0.868	0.37
11	0.953	0.4
12	1.047	0.43
13	1.149	0.46
14	1.261	0.5
15	1.384	0.53
16	1.52	0.58
17	1.668	0.62
18	1.832	0.68
19	2.011	0.74
20	2.207	0.81
21	2.423	0.89
22	2.66	0.97
23	2.92	1.7
24	3.205	1.17
25	3.519	1.27
26	3.863	1.39
27	4.24	1.51
28	4.655	1.63
29	5.11	1.76
30	5.61	1.89
31	6.158	2.2
32	6.76	2.15
33	7.421	2.29
34	8.147	2.42
35	8.943	2.55
36	9.818	2.69
37	oct-78	2.82
38	nov-83	2.96
39	dic-99	3.1
40	14.26	3.22
41	15.65	3.34
42	17.18	3.45
43	18.86	3.55
44	20.71	3.62
45	22.73	3.63
46	24.95	3.56
47	27.39	3.43
48	30-jul	3.24
49	33.01	3.2
50	36.24	2.8
51	39.78	2.57
52	43.67	2.34
53	47.94	2.1
54	52.62	1.82
55	57.77	1.53
56	63.41	1.24
57	69.61	0.99
58	76.42	0.78
59	83.89	0.62
60	92.09	0.51
61	101.1	0.47
62	111	0.47
63	121.8	0.49
64	133.7	0.53
65	146.8	0.54
66	161.2	0.5
67	176.9	0.42
68	194.2	0.33
69	213.2	0.23
70	234	0.16
71	256.9	0.094
72	282.1	0.045
73	309.6	0.016
74	339.9	0.0028
75	373.1	0.0002
76	409.6	0
77	449.7	0
78	493.6	0
79	541.9	0
80	594.8	0
81	653	0
82	716.8	0
83	786.9	0
84	863.9	0
85	948.3	0
86	1041	0
87	1143	0
88	1255	0
89	1377	0
90	1512	0
91	1660	0
92	1822	0

```
Volume:          100%
Mean:            27.24 µm       S.D.:            35.00 µm
Median:          16.77 µm       Variance:        1225 µm²
D(3,2):          6.858 µm       Skewness:    3.314 Right skewed
Mode:            23.81 µm       Kurtosis:    14.10 Leptokurtic

d10:   3.004 µm          d50:   16.77 µm          d90:   57.66 µm

<1 µm          <10 µm          <100 µm          <1000 µm
2.28%          33.3%           95.6%            100%
```



Dry bulk density estimation

Graduated Cylinder			
	Total volume	250	ml
	Weight cylinder	238.35	g
	Weight cylinder + mix	499.73	g
	Weight of mix	261.38	g
	Mix density	1.05	g/ml
Dried out sediments			
	Weight of Tray	266.84	g
	Weight of Tray + dry sediments	296.29	g
	Dry weight of sediments	29.45	g
After 10 min			
	Sediment volume	110	ml
	Concentration	44%	
	Dry bulk density	0.27	g/ml
After 1 hour			
	Sediment volume	70	ml
	Concentration	28%	
	Dry bulk density	0.42	g/ml
At 24 hours			
	Sediment volume	62	ml
	Concentration	25%	
	Dry bulk density	0.48	g/ml