Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

Medhin Shiferaw Assaminew

# Sediment Yield Assessment and Management Strategy for Paso Ancho Hydropower Plant

Master's thesis in Hydropower Development
Supervisor: Nils Rüther
June 2019

NTNU
Kunnskap for en bedre verden

Medhin Shiferaw Assaminew

# Sediment Yield Assessment and Management Strategy for Paso Ancho Hydropower Plant

Master's thesis in Hydropower Development
Supervisor: Nils Rüther
June 2019

Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

NTNU
Norwegian University of
Science and Technology

Abstract

Paso Ancho is run off river hydropower plant with an install capacity of 6.4MW and located in south west region of panama. The catchment area of the powerplant is highly exposed for erosion. Therefore, sedimentation is the main problem for the powerplant. Due to this several method of sediment management strategies has been applied. Such as mechanical removal, conventional dredging as well as currently installed SediCon dredging. The objective of this thesis is to estimate the sediment yield from the catchment area to the river by using RUSLE model, to evaluate sediment management strategy which is installed in the peaking pond by using RESCON 2 model. In addition, to measure and calculate the actual capacity of sediment management strategy from the field. And finally, the model results were proved to reasonably match the field data.

The required information's and input data for this study were taken both from online sources and actual data taken during the field visit to the project area. The sediment yield estimation was done by using the RUSLE model with ArcGIS, and the result was satisfactory. The RESCON 2 model was used to evaluate the HSRS. The sediment yield to the river annually estimated around 0.089Mill.ton $yr^{-1}$, which is 37,547$m^3$ $yr^{-1}$. The amount of sediment removed by HSRS from RESCON2 result is 33,771$m^3$ $yr^{-1}$ with sediment concentration through pipe of 7.78E+03ppm.

Sample taken from off-stream peaking pond shows that the sediment deposition is a mix of silt and sand. The capacity of SediCon dredging on sediment removal for 5 months shows that, 17,000 $m^3$ of sediment removed for 382 hours with sediment concentration through pipe of 159E+03 ppm.

There is a large amount of sediment yield to the river and if 50% of it get transported to the off-stream peaking pond, then it will have significant impact on reduction of storage capacity. But the SediCon dredging which is installed in off-stream peaking pond used to remove the sediment per month is efficient and proved to perform better than the model result.

# Preface

This thesis is submitted to fulfill the requirements for Master's Degree in Hydropower Development at the Department of Civil & Environmental Engineering, Norwegian University of Science and Technology (NTNU). It discusses the work done from mid-January to mid-June 2019 under supervision of Associate Professor Nils Rüther (NTNU) and co-supervisor of Tom Jacobsen (SediCon AS).

The objective of this thesis is to estimate the sediment yield to the river in Paso Ancho hydropower project by RUSLE mode, to evaluate the current installed sediment management strategy by using RESCON 2 model and access the sustainability and efficiency of SediCon dredging. RUSLE and RESCON2 models were prepared in this study to estimate sediment yield and evaluate sediment management strategy respectively are the 1$^{st}$ experience of the author. It has been a great experience to gain learn about a model used for estimation of sediment yield and evaluating sediment strategy.

The information required for the study regarding the powerplant and the sediment challenge in the project is obtained from the owner of powerplant and SediCon AS, suppliers of SediCon dredging for the powerplant. Site visitation also organized by SediCon AS in collaboration with the powerplant owner.

This thesis work was possible due to kind co-operation of different persons from different institute and companies involved. Special gratitude to my main supervisor Nils Rüther and co-supervisor Tom Jacobsen for all your guidance and providing required information. I would like to thank Simone Bizzi and Lucia Maletti for giving information on RUSLE model as well as to Nikolaos Efthymiou from world bank, for your detail explanation on RESCON 2 model. I would like to thank Alberto Jiménez and Javier Zamora for the guidance and helps related to SediCon dredging and the project. To Marcos A. Dominguez for your willingness to facilitate the required information as well as for all your kind help during field work. And to all kind powerplant workers.

I would like to thank my family specially my brother for your support, comment and suggestion. And lastly, I would like to thank to all my friends and my classmates for your encouragement and support.

Medhin Shiferaw

Trondheim, June 2019

# Table of Contents

# LIST OF FIGURES

# LIST OF TABLES

# Abbreviation

RUSLE: Revised Universal Soil Loss Equation

RESCON: Reservoir Conservation

SDR: Sediment Delivery Ratio

DEM: Digital Elevation Model

USLE: Universal Soil Loss Equation

MAP: Mean Annual Precipitation

SY: Sediment Yield

HSRS: Hydrosuction Sediment Removal System

HPP: Hydro Power Project

SPSS: Slotted Pipe Sediment Sluicer

SSS: Saxophone Sediment Sluicer

GUI: Graphical User Interface

ROR: Run off River

NPV: Net Present Value

NTNU - Norwegian University of Science and Technology

USDA- United State Department of Agriculture

# 1 Introduction

## 1.1 General

Electricity is an essential part of modern life and important to the world economy. The use of electricity is for cooking, heating, lighting, refrigeration, electronics, machinery and public transportation systems in residential, commercial and industrial sectors. To fulfil the demand for electricity in the world there are several sources of energy. From those sources, renewable energy source is the one which generate electricity continuously with no risk of depletion. From the Renewable 2018 Global Status Report, the cost competitive source and mainstream of renewable energy have been stablished for long term. The sources of energy covered in the report are hydropower, bioenergy, Solar PV, wind energy and geothermal power and heats. Therefore, Figure 1-1 shown that, the global renewable power capacity growth has continued year to year [1].

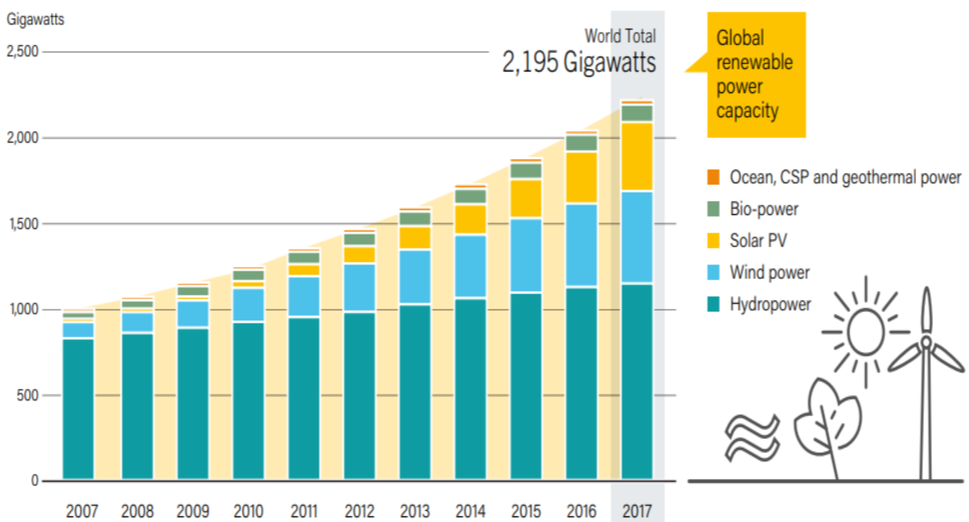



*Figure 1-1 Global renewable power capacity growth from 2007-2017* *Source:[1]*

Hydropower is one of the environmentally friend and renewable sources of energy. The main source of energy production for hydropower project is water and the power plant need to be located near to the water source [2]. This water source must be clean as much as possible and the incoming sediment need to be handled. This is because sediment transportation has several impacts on hydro powerplant. Therefore, the amount of sediment yield from the catchment area to the river also need to be known to be prevented from sedimentation.

The hydropower generation is also affected by climate change and variability. The impact of climate change on hydropower generation through temperature and rainfall pattern in hydrological cycle is complex [3] .

## 1.2 Background

Hydropower is generated from plentifully available water source in the world. As a result, it is a highly interesting market area for the private and governmental investors. But nowadays several hydropower projects are facing problems due to high sediment transportation to the river. Damming of river for hydropower project will also alter the sediment balance in the river.

Due to sedimentation problem on hydropower plant, world bank developed a model called reservoir conservation (RESCON 2) for greenfield or for existing project to select economically and technically feasible sediment management strategy.

As panama is in tropical region and the specific project area of this thesis has rock type called volcanic rock, it has high sediment yield in the river and to the peaking pond too. This sedimentation creates several problems on the power plant.

## 1.3 Objective of the study

The main objective of this study is to estimate the sediment yield from catchment of Paso Ancho to the Chiriquí Viejo river by using RUSLE model and SDR as well as to evaluate the sustainability of current sediment management strategies by using RESCON 2 and finally compare the result of sediment management strategy from actual field measured with the RESCON 2 model result.

The specific objectives are listed as: -

- ✓ To understand RUSLE model with ArcGIS and how the process will work.
- ✓ Preparing all necessary data of the Paso Ancho catchment area for the RUSLE model to estimate soil loss.
- ✓ Understand RESCON 2 model and mandatory input data.
- ✓ Prepare the data for Paso Ancho peaking pond in RESCON 2.

- ✓ Actual field measurement and data gathering of current sediment management strategy.

## 1.4 Methodology

To estimate the sediment yield to the Chiriquí Viejo river and evaluate the sustainability of sediment management strategy on Paso Ancho hydropower project, getting the necessary model input data was mandatory. Getting data for Panama were not easy. For RUSLE model calculation, hydrological data were found from online source (metrological station in panama web map), soil data from world soil map, land use coverage from world land cover (land viewer) and DEM from Global data explorer. The shape file of the catchment area was also created by processing the DEM file in ArcGIS. For RESCON 2 model all the necessary input data were collected from SediCon AS and from the owner of the powerplant. The steps of the method of the work are presented as:

Step 1

- ✓ Study about the project area
- ✓ Collecting the necessary data for running the RUSLE model
- ✓ Estimate the sediment yield by using RUSLE in ArcGIS and SDR
- ✓ Output result of soil loss and sediment yield

Step 2

- ✓ Collect the mandatory input data for the RESON 2 model
- ✓ Evaluate the efficiency of sediment management strategy by using RESON 2
- ✓ Output result about the sediment removal method

Step 3

- ✓ Actual field measurement of sediment management strategy
- ✓ Result from field work

Step 4

- ✓ Compare the results
- ✓ Evaluate the efficiency of the current management strategy.

## 1.5 Structure of the thesis

This thesis consists of seven chapters and each chapter is focused on discussing its topic as presented below.

Chapter 1: covers about the general overview of energy sources and some facts about renewable energy sources. I also discuss on how the needs for energy in the world has changed from year to year and the impact of sediment on hydropower project. In addition, the motivation for this thesis with the objective of the study and methodology is also discussed.

Chapter 2: Present theoretical background of sources and properties of sediments. It explains the sediment yield estimation, RUSLE model and Impact of sedimentation on hydropower projects. Moreover, the sediment management strategy including structure of RESCON 2 is also covered.

Chapter 3: Covers about Paso Ancho hydropower project, sediment yield estimation from the catchment area on Chiriquí Viejo river by using RUSLE model and SDR. However, In the end results of soil loss and sediment yield to the river are also presented.

Chapter 4: Discussed on evaluating the sustainability of current sediment management strategy by using RESCON 2. In addition, the result from the model is also presented.

Chapter 5: Dealt with field work data gathering of currently used sediment management strategy and actual measurement. It also discusses and presents the capacity as well as the efficiency of this sediment management strategy.

Chapter 6: Covers the comparison of the result from field measurement as well as from RESCON 2 output.

Chapter 7: Contains conclusion and recommendations.

# 2 Theoretical background

## 2.1 Sources and property of sediment

The primary source of soil material is chemical and mechanical destruction of rock. The mechanical destructions are due to cracking of rocks by temperature change, abrasion, wetting and drying as well as freezing and movement of living organisms and plants roots. Whereas the chemical destruction is due to water with the processes of hydrolysis, hydration, oxidation, reduction and carbonation [4]. Therefore, the main source of sediments is soil erosion. The decomposed rocks are transported by different agent such as wind, gravity and water stream.

Classification of sediments based on their property are presented below such as based on: -

- ✓ Particle size: median diameter of clay, silt, sand, granular, pebble, cobble and boulder within the particle size of (4 µm -256mm)
- ✓ Type of material: like gravel, sand, clay, silt
- ✓ Frequency of particle size distribution is by degree of sorting like well sorting as well as poorly sorting.
- ✓ Cohesiveness: cohesive and non-cohesive. The cohesive sediment is mixture of silt and clay with particle size of $d_{50}$ less than 4µm whereas non-cohesive sediments are those with particle size of $d_{50}$ greater than 64µm which are silt, sand and large particle. silt is the hardest sediment for studying because of weakly cohesive property. The transportation system of mud and sand in the river is in suspension in the water column and along the bottom of the river respectively. The sedimentation and erosion of mud and sand transport have impact on bathymetry [5].

## 2.2 Sediment yield estimation

Estimation of sediment yield to the river as well as to the reservoir are mandatory. This is used to evaluate how the sedimentation has impacted the reservoir storage in hydropower project and other purpose of project. In addition, it is also used to evaluate the sediment management strategy.

Sediment yield is the amount of eroded material that gets transported from the origin of detached soil and delivered to the outlet of the watershed. This sediment yield in the watershed includes the sum of erosion from slopes, channel and wasting mass minus the sediment which is deposited before it reaches to the point of interest [6]. Sedimentation has different mode of transportation in a river such as wash load, suspended load and bed load. Wash loads are very fine particle like clay or silt which easily get suspended and remain in suspension or do not touch the bed of the river even if there is very low sediment transport capacity. Suspended load is fine particle which easily get suspended with turbulent flow but, if the sediment transport capacity decreases with decreasing turbulence of the water then some of the suspended sediment return to riverbed. Bed load is coarse particle of sediment transported by rolling, sliding and saltating to the river bed [7]. Now a days Sedimentation in reservoir is the main concern. Almost 100% of the bedload is trapped by reservoir as well as the deposition of suspended load in the reservoir depends on hydraulic characteristics of the flow through the reservoir and particle size of suspended sediment. So that, to estimate the sediment yield in the reservoir the amount of suspended sediment and wash load are needed.

The specific sediment yield in the world varies from 50-100 ton. $Km^{-2}$ $Yr^{-1}$ as shown in Figure 2-1.This variation in sediment yield depends on different reason such as climate, lithology, topography, human influenced soil erosion, forest fires, catchment area, river discharge, temperature and trap efficiency of upstream of the reservoir [7].

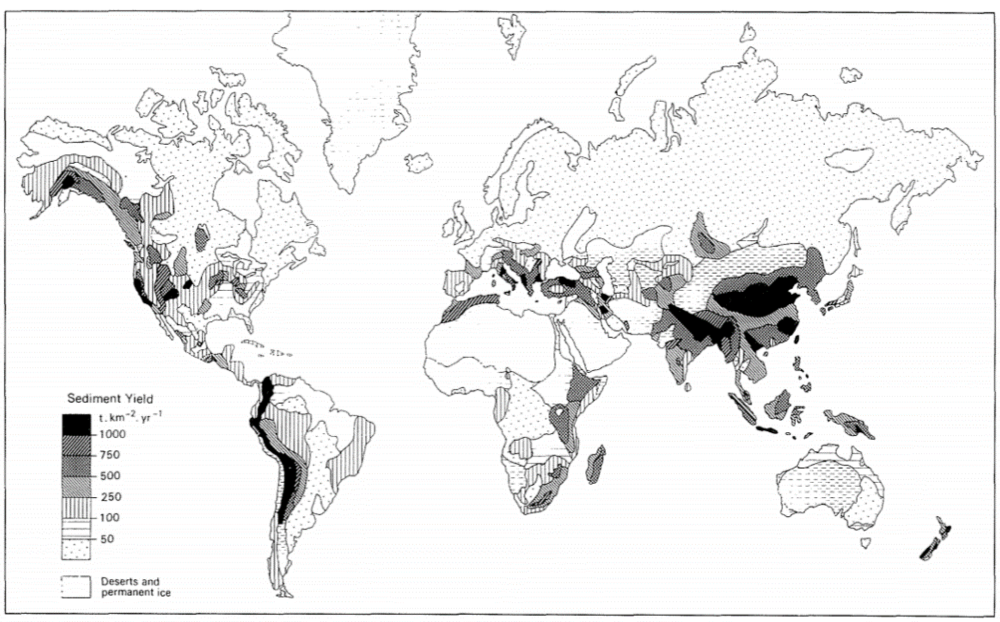



*Figure 2-1 Global Suspended sediment yield, source [8]*

Sediment yield is not found by direct measurement, but it is estimated by using sediment delivery ratio and gross erosion in the entire area. In sedimentation process, soil erosion is the primary process. It consists of erosion, transportation and deposition of the sediment, whereas sediment delivery ratio (SDR) is the percentage of gross soil erosion which is delivered to a specific point in the drainage system by watersheds [9]. Estimation of soil erosion rate requires several field data which makes it a complex process. Therefore, there are empirical formulae used for estimation of soil erosion rate which is developed using the collected data from specific graphical data and it is generally limited to those area which is represented in the base data [10]. These empirical formulas are USLE and later RUSLE has developed. There are different factors that affect for the formation of erosion and this are expressed in the equation below:

$$E=F(C, S, T, SS, M) \qquad (Eq.\ 1)$$

*Where E (Soil erosion), is a function of Climate, soil property, topography, soil surface condition and human activity[6].*

The main purpose of the soil loss equation is to guide the methodological decision making in conservation planning and enable the planner for each alternative management method. It control the practice of site to predict average rate of soil erosion rate[11].

Universal soil loss equation (USLE) is developed in 1960 and updated in 1978 by Wischmeier and Smith of the united states department of agriculture. It is used for long term annual average rate of erosion prediction on the field caused by rainfall and associated overland flow. It is one of the field scale models[12]. In 1985 there was workshop in West Lafayette, Indiana between scientist and engineers from USDA-ARS and USDA soil conservation service and affiliated academics with expertise in soil erosion. One of the important decisions from this workshop was to computerize and update the USLE of 1978 version to improved model which is called revised universal soil loss RUSLE[13]. It is the improved and the revised version of universal soil loss equation used for prediction of annual soil loss. RUSLE is also based on extensive review of USLE. Data for RUSLE model is usually available from institutional database with less expense[14].

Now a days a lot of computer-based application and regional models have been developed based on RUSLE for the estimation of sediment yield. But by considering the availability of the data and to make it simple for this thesis on Paso Ancho hydropower catchment area, RUSLE model with GIS application is selected. Therefore, the soil loss equation of RUSLE model is given as shown in equation 2 as well as the data needed for this calculation are rainfall data, soil data, topographic map and land use map for the given catchment area as shown in the Figure 2-2.

$$E = R * K * L * S * C * P \qquad (Eq.\ 2)$$

Where $E$ is Annual soil loss in ton. $ha^{-1}$ $Yr^{-1}$, $R$ is Rainfall erosivity factor (MJ mm $ha^{-1}$ $h^{-1}$ $yr^{-1}$), $K$ is Soil erodibility factor (ton. h. $MJ^{-1}$ $mm^{-1}$), $LS$ is Slope length and steepness factor (dimensionless), $C$ is Cover management factor (dimensionless) and $P$ is Support particle factor (dimensionless).

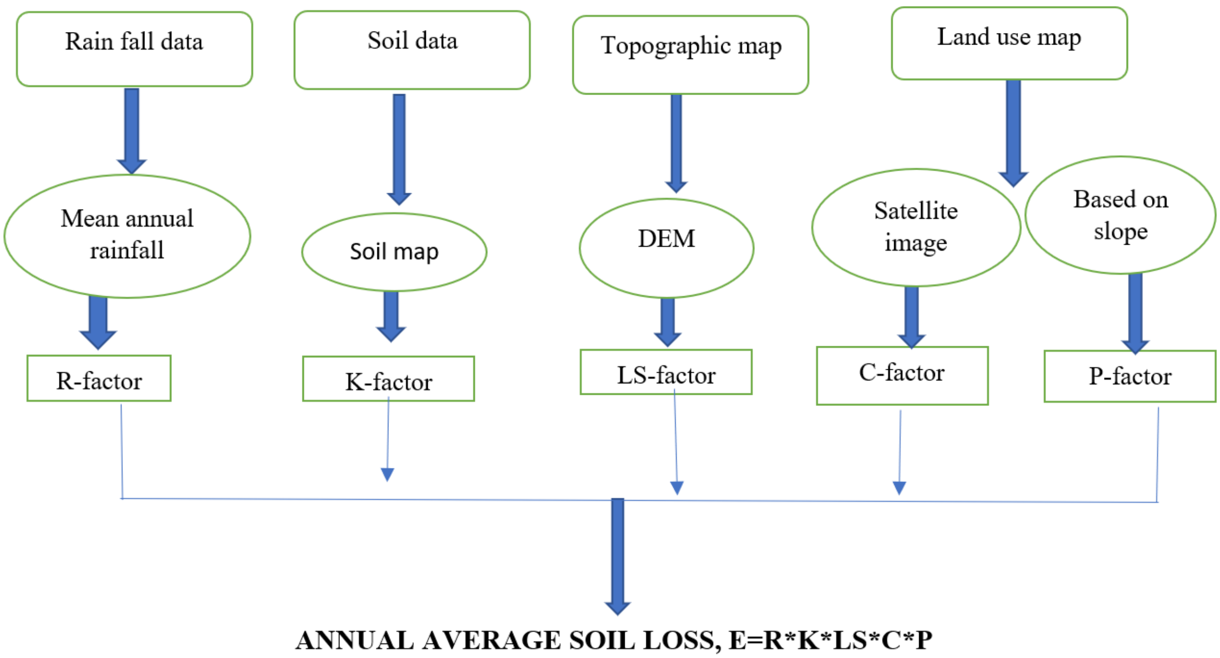



*Figure 2-2 Methodology and computation of RUSLE factors in ArcGIS*

### 2.2.1 Rainfall Erosivity (R-factor)

Rainfall is the most important natural factor which is highly affecting erosion in tropical and subtropical region. Rainfall erosivity is a measurement for erosive force of specific rainfall and the energy input which drives several erosion processes. There is linear relationship between soil loss and rainfall and this shows, individual storm values are directly additive and the sum of it in that period is erosive potential of rainfall [11]. The greater intensity and duration of rainstorm makes the higher erosion potential. As the rainfall erosion is the sum of individual storm erosion, the continues measurement of gauging station in the catchment area is necessary [6]. And these intensity and storm energy are maximum intensity in 30 minutes ($I_{30}$) and total kinetic storm energy (E), but it is not common to get this data in standard meteorological station. Because of this several studies have been done to calculate the R factor by using the available data. As a result, there are different equation for different region to calculate rainfall erosivity factor.

Unfortunately, there is no standard equation for panama to calculate rainfall erosivity. Therefore, the option is to find equation from neighboring country or a country of similar climatic condition as panama. For this study equation from Costa Rica and other tropical country has used as reference and for calculation of R factor. The equation from Costa Rica for calculating rainfall erosivity needs maximum annual rainfall event of 6-hour duration and 2-year return period ($MAR_{2.6}$) [15]. The equation below is used in Costa Rica. Even if finding rainfall event of 6hr duration and 2-year return period for panama is not possible.

$$R = 0.00245 * (MAR)^{2.17} \quad \textit{(Eq. 3)}$$

Rainfall erosivity are highly related with MAP but the way of estimation is different among different authors. Some of the author suggest linear relationship between the mean annual precipitation and rainfall erosivity factor as shown in equation below[15].

$$R = a * P^{b} \quad \textit{(Eq. 4)}$$

Where a and b are the coefficient that describes for local condition. And as a reference the Indonesian journal of geospatial has used the coefficient of a = 0.41 and b =1.09 for estimation of R factor [16].

### 2.2.2 Soil Erodibility (K-factor)

The resistance of erosion is naturally different for different soil type depending on the soil property such as grain size, organic content, drainage potential, structural integrity and cohesiveness of the soil [14]. Soil Erodibility (K) is the soil responsiveness to the detachment. The field survey is not applicable for estimation of K factor and it is expensive. So, instead of field survey, data from global soil map as well as regional soil map has taken and then by using the equation below the soil erodibility factor can be estimated.

Equation for calculating soil erodibility is based on the soil property in the catchment area which used for this study is shown in the equation 5 and 6 below [17].

$$K = \left(0.2 + 0.3exp\left(0.0256SAN\left(1 - \frac{SIL}{100}\right)\right)\right) * \left(\frac{SIL}{CLA+SIL}\right)^{0.3} * \left(1 - \frac{0.25C}{c+exp(3.72-2.95C)}\right) * \left(1 - \frac{0.7SN_1}{SN_1+exp(-5.51+2.95SN_1)}\right) \quad \textit{(Eq. 5)}$$

$$SN1 = 1 - SAN/100 \quad \textit{(Eq. 6)}$$

Where *SAN*, *SIL*, *CLA* and *C* are sand, silt, clay and organic carbon fraction respectively as well as all represented to topsoil of watershed because of it is directly affected by raindrop energy.

### 2.2.3 Slope Length and Steepness Factors (LS)

Slope length and steepness represent the topographic effect on erosion, and it has direct relationship with slope length. So, both slope length and steepness considerably affect sheet and rill erosion estimated by RUSLE. LS is not absolute value, but it has referenced at 22.13m and 9% of slope length and steepness respectively for value of 1. So, LS is the ratio of soil loss on a given slope length and steepness to slope that has length of 22.13m and steepness of 9% by keeping other condition constant.

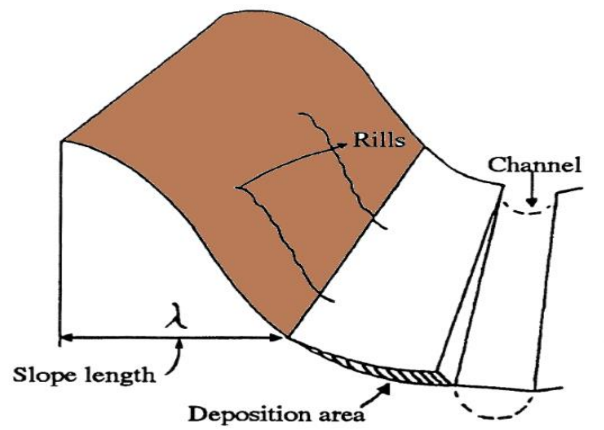



*Figure 2-3 schematic presentation of rill erosion and slope length up to where deposition area occur [6].*

There is high soil loss due to slope steepness than slope length. The slope steepness, slope length and LS calculated by using the equation as shown below [17], [6] and [18] .

$$L = \left(\frac{\lambda}{22.13}\right)^{\beta} \qquad (Eq. 7)$$

$$\beta = \frac{(\sin\theta/0.0896)\Big/\left[3*(\sin\theta)^{0.8}+0.56\right]}{1+(\sin\theta/0.0896)\Big/\left[3*(\sin\theta)^{0.8}+0.56\right]} \qquad (Eq. 8)$$

$$\lambda = flow\ accumulation * cellsize\ resolution \qquad (Eq. 9)$$

$$S = \begin{Bmatrix} 10.8\times\sin(\theta)+0.03\, for S<9\% \\ 16.8\times\sin(\theta)-0.5\, for S\geq 9\% \end{Bmatrix} \qquad (Eq. 10)$$

$$LS = power(Flow\ accumulation\ layer * cell\ size/22.1, 0.4) * power(sin(slop * 0.01745)/0.089, 1.4) * 1.4 \qquad (Eq.\ 11)$$

### 2.2.4 Cropping Management Factor (C)

It is the soil loss from the specified catchment area cover and management. Erosion rate is also affected by cropping and management practice which is represented by C factor. The cropping management factor is used to indicate how the average annual soil loss will be affected by conservation plan and how this soil loss during the timing of construction activity, crop rotation or other management activity will distribute. When there is no vegetation and high risk of erosion then C factor become 1. When there is high vegetation or the soil is covered by vegetation as well as for water cover, the C value become 0. Therefore, 1 and 0 shows the maximum and minimum value of C factor respectively [6].

### 2.2.5 Support Particle Factor (P)

The support practice factor is the ratio of soil loss with specific support practice and corresponding loss with up and down slope culture. The effective way of reducing erosion are practice of tillage and farming on the contour. As shown in the Table 2-1 below several studies found contouring factor depending on the land slope therefore, it is possible to find the P factor by using this table [19].

*Table 2-1 support practice factor [11]*

| Land slope (%) | contour factor | Strip crop factor |
|---|---|---|
| 1 – 2 | 0.6 | 0.3 |
| 3 – 8 | 0.5 | 0.25 |
| 9 – 12 | 0.6 | 0.3 |
| 13 – 16 | 0.7 | 0.35 |
| 17 – 20 | 0.8 | 0.4 |
| 21 – 25 | 0.9 | 0.45 |

### 2.2.6 Sediment delivery ratio (SDR)

Sediment delivery ratio (SDR) is defined as the amount of soil erosion which is transported from a given catchment area within a given time interval. It is also a measurement of the amount of sediment transported from the catchment area to stream cross-section [20]. Mathematically expressed as the ratio of sediment yield in the stream cross-section and soil erosion from the catchment area as shown below.

$$SDR = \frac{SY}{E} \qquad (Eq.12)$$

Where *SY* is the average annual sediment yield in a given area, *E* is average annual soil erosion in the same area and *SDR* is sediment delivery ratio from the catchment area to the specific point (stream cross-section). In large catchment area compare to small area, most of the sediment eroded will deposit within the catchment and only some fraction of sediment eroded from hillslope will get transported to the stream network [21].

There are different factors that affect sediment delivery ratio, such as hydrological input especially rainfall, landscape property such as (vegetation, topography and soil property) and their complex interaction are common. The most widely used method to estimate sediment delivery ratio are through SDR as area power function as shown below.

$$SDR = \partial A^{\beta} \qquad (Eq. 13)$$

Where $\alpha$ and $\beta$ are empirical parameters, which different authors give their own explanation as well as values and those equation will be presented below. Sediment delivery ratio and catchment area has inverse relationship as shown in equation 13. The steepness area of the catchment is the main sediment formation zone, but this slope decreases with increasing catchment area and the sediment production with in that area also decreases, because it will deposit before it reaches the specific point or stream network [21].

Equation of SDR from different authors has presented below. Such as equation developed by (Boyce (1975) Eq14, Renfro (1975) Eq15 as well as Vanoni (1975) Eq16). The equation shows sediment delivery ratio decrease by increasing the catchment area.

$$SDR = 0.566A^{-0.11} \qquad (Eq. 14)$$

$$SDR = 0.472A^{-0.125} \qquad (Eq. 15)$$

$$SDR = 0.375A^{-0.2382} \qquad (Eq. 16)$$

Therefore, sediment yield (*Y* in ton. $Yr^{-1}$) is obtained by multiplying the soil loss (*E*) which is estimated from RUSLE in ton. $Yr^{-1}$, *a* is the cell size in the GIS and sediment delivery ratio SDR which is the percent of soil erosion that is delivered by water as shown in equation 17 [22].

$$Y = SDR * E * a \qquad (Eq. 17)$$

## 2.3 Impact of sediment on HPP

The sediment carried by the river flow will deposit in the reservoir due to the decrease in flow velocity, this consume the storage capacity of the reservoir which was originally considered for storing water. The deposition of sediment in reservoir decrease the amount of sediment release in downstream and it leads for change in river morphology, degradation of river channel, aquatic habitat and reduce fish's food. Therefore, sedimentation has an impact on reservoir storage, upstream and downstream of the dam [7].

### 2.3.1 Sedimentation impact on upstream of the dam

The total storage in the reservoir is the sum of dead storage and live storage. Dead storage is storage of the reservoir below the lowest water level whereas live storage is the storage that contain water which is released for power production or other purpose as shown in Figure 2-4 below. Sedimentation in the reservoir has impact on power production by reducing the active storage and due to turbine down time because of sediment related maintenance [7].

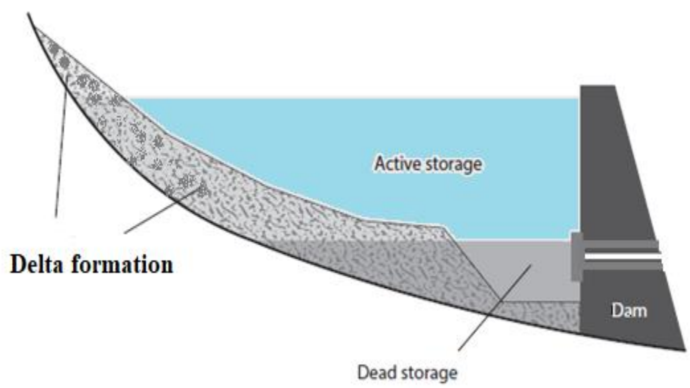



*Figure 2-4 Sedimentation impact in the upstream of the dam ( source [7])*

### 2.3.2 Sedimentation impact on downstream of the dam

Sedimentation in downstream of the dam has impact on morphology, aquatic ecosystem and costal impact. Damming and reservoir in the river will disturb the normal flow of the river and decreases amount of sediment which get released to the downstream. The water flow to the downstream have high tendency to take additional sediment (or becomes sediment hungry water) as a result the riverbed will erode and degrade. Sources of beach sand along the costal line is the sediment which get discharged to the ocean by the river, but the sedimentation in the reservoir will reduce the amount of sediment transport to the ocean which is known as the costal impact [7].

## 2.4 Sediment management strategy

Management strategy to the reservoir sedimentation is crucial for restoring storage and reducing long term maintenance cost of turbine as well as damaging turbine and hydraulic structures. Sediment management activity in the reservoir is classified to four categories such as [7].

- ✓ Methods used to reduce sediment yield from upstream of the reservoir by taking two alternatives
  - i. The first is controlling soil and canal erosion,
  - ii. The other is providing trap for the eroded soil upstream of the reservoir.
- ✓ Method used to reduce trapping of sediment by passing sediment through or around the reservoir by providing sediment bypass or sediment pass through.
- ✓ Method used to redistribute or removing of sediment by mechanical excavation (dry excavation or dredging) and modify operating rule (pressure flushing or empty flushing).
- ✓ Methods to adapt sedimentation by reallocate storage, modify intakes, hydro turbine, raising dam height to increase the volume and so on.

Figure 2-5 below shows the applicability of sediment management technique based on hydrological capacity and sediment loading. The hydraulic retention time in the X-axis of the graph defined as the ratio of reservoir capacity to mean annual runoff as well as the reservoir life span in the Y-axis of the graph defined as the ratio of reservoir capacity to mean annual sediment inflow.

On the sediment removal method, hydrosuction dredging is included. To see the applicability of sediment management technique based on hydrological capacity and sediment loading for Paso Ancho peaking pond, with storage capacity of 100,000$m^3$, mean annual runoff 143.8 Mill $m^3$ as well as mean annual sediment inflow of 37,547.8 $m^3$, Figure 2-5 below is used. The value of Y-axis is the ratio of reservoir capacity to mean annual sediment flow and become 2.66 and the value of X-axis is the ratio of reservoir capacity to mean annual runoff and become 0.000695. Therefore, from the result the applicable sediment management technique is known by using Figure 2-5 below and such as flushing, sluicing and hydrosuction dredging.

As a result, for this study, on Paso Ancho HPP peaking pond, the sediment removal method has focused on hydrosuction and the detail will be discussed below.

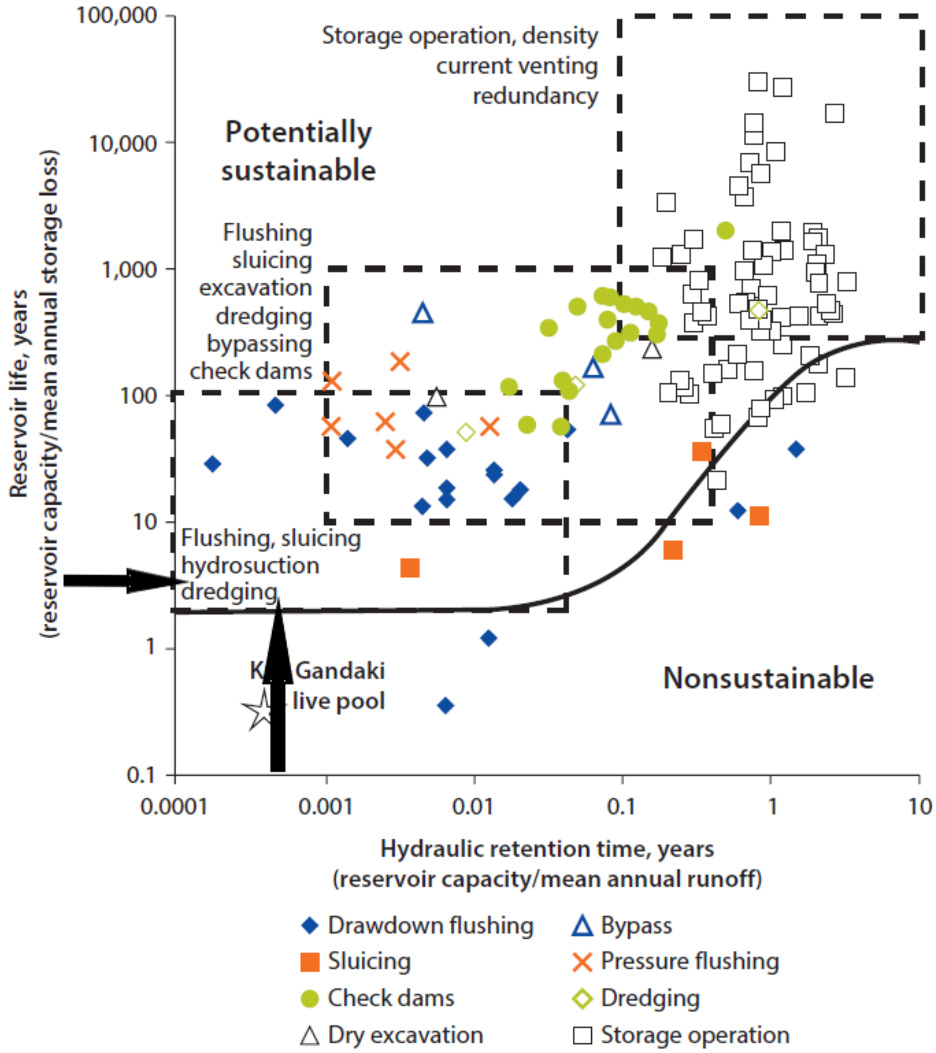



*Figure 2-5* Applicability of sediment management technique (source [7])

### 2.4.1 Hydrosuction dredging

Hydrosuction dredging is one of the sediment removal method which uses hydraulic head difference between the water surface of the reservoir and outlet of pipeline. The first hydrosuction dredging performed in Djidiouia Reservoir, Algeria from 1892 to 1894. People of republic of china is the most experienced country on hydrosuction dredging until now. From 1975 in 10 different reservoirs, two type of hydrosuction sediment removal (HSRS) method has been used by them such as bottom outlet and siphon [23]. In recent year almost, all hydropower projects of hydrosuction sediment removal method has been done by SediCon.

There are Several studies on hydrosuction until now and from them Jacobsen, during his PHD study develop Slotted Pipe Sediment Sluicer (SPSS) and Saxophone Sediment Sluicer (SSS). For both case the driving force to remove the sediment is natural head difference between the water surface in the reservoir and the outlet of the pipe. The sediment water mixture which is removed from the reservoir through the pipeline must be with in optimum concentration because, too much concertation will result in reduction of velocity as well as blocking of pipe. The 1$^{st}$ laboratory model of Slotted Pipe Sediment Sluicer (SPSS) and Saxophone Sediment Sluicer has been tested in July and September 1993 respectively [24].

The system operation of HSRS is limited to the available head difference to transport deposited material to downstream. In designing stage to decide a pipe diameter, sediment size is the main parameter. Sediment size is the main factor that determine the feasibility of HSRS. It is more effective for fine and non-cohesive. A particle coarser than sand may be transported but there will be additional head loss and require high head. The effect of increased turbidity level to downstream changes in water chemistry and impact of it must be considered for environmental impact. Therefore it may not be feasible if there is requirement with low turbidity in receiving water [25].

Type of hydrosuction sediment removal system are: -

- Hydrosuction dredging (where the deposited sediment is dredged and transported to downstream or treatment basin) and
- Hydrosuction bypassing (where the sediment is transported without deposition).

There are two methods of hydrosuction dredging sediment removal: -

The first one is conventional method of hydraulic dredging; it uses mechanical pump to give the driving power for removing of deposited sediment. Whereas, the second one is hydrosuction dredging and uses hydraulic head difference between the upstream and downstream of water level without external energy to remove the sediment unless for pumping water. It needs pipeline that starts from the bottom of the reservoir where deposited sediments are accessible to the discharged point of the downstream. This sediment removing will continue until the water that flows to the turbine become clear or of less sediment content [25].

In addition, two type of hydrosuction dredging has been used such as bottom dredging and siphon dredging. In siphon dredging the discharged pipe is passed over the top of the dam whereas in the bottom dredging the pipe passes through low level outlet at the dam. But both methods use floating barge which is used to move the pipeline to access large area of the reservoir. Siphon dredging is applied for the existing project, whereas bottom dredging is used for Greenfield project.

## 2.5 RESCON2 Model

Reservoir conservation (RESCON2) model is a computer program developed by world bank, which is used to rank the technical and economic performance of the sediment management strategy for the Greenfield as well as for existing project. The data input and reading of result performed through graphical user interface (GUI) and the calculation of the model is performed in excel by considering the following management strategy. Such as sediment removal, catchment management and combining methods.

All in all, the model is used to select sediment management strategy, which is economically and technically feasible by maximizing the benefit of reservoir operation [26].

### 2.5.1 Analysis steps in RESCON 2

Analysis step in the model involves: [26]

- ✓ Data collection
- ✓ Model setup
- ✓ Calibration and
- ✓ Sensitivity analysis

### 2.5.2 Input data of RESCON 2

In RESCON2 model the main steps involved are: -

- ✓ Input data regarding reservoir geometry, hydrological data, sedimentation data and economical parameter regarding valuation of revenue and costs related reservoir operation,
- ✓ Input data for each sediment management technique and parameters which define the efficiency,
- ✓ Evaluating technical feasibility of the management strategy by considering user specified constraint. For the method which is feasible the temporal and spatial development of reservoir storage and economic return are computed. Based on these the reservoir will be determined as either sustainable or non- sustainable and lastly economic performance of the reservoir is calculated throughout the life time [26].

Reservoir geometry data inputs that RESCON 2 allows are specification of two different pools, such as initial active storage and inactive storage. The user defined parameters are: -

- ✓ Elevation of normal operating water level (ELowl)
- ✓ Elevation of minimum operating water level (ELmwl)
- ✓ Active storage of the reservoirs (St_a_res)
- ✓ Inactive storage of reservoir (St_d_res)
- ✓ Length of reservoir (L_res)
- ✓ Elevation of minimum riverbed level (elevation of riverbed at the dam site) (ELbim)

The hydrological and sediment data inputs are water characteristics and sediment characteristics such as:

- ✓ Mean annual reservoir water inflow
- ✓ Mean annual total sediment inflow (suspended and bed load) mass
- ✓ Temperature of the reservoir
- ✓ Interannual sediment and water inflow
- ✓ Catchment area characteristics and others

### 2.5.3 Sediment handling Method presented in RESCON 2 model

RESCON performed an evaluation method of sediment deposition removal. This sediment removal management techniques includes flushing, dredging, hydrosuction sediment removal and trucking. Whereas the modified RESCON 2 is not limited to perform removing deposited sediment but also has additional option involving reduction of sediment inflow as well as reduction of sediment deposition by using the following method: -

- ✓ Catchment management
- ✓ Sediment sluicing
- ✓ Sediment by-pass
- ✓ Density current vent

All in all, Sediment management alternatives of RESCON 2 model which is presented in the user manual are summarized below [26]: -

- ✓ No action: - where there is no management plan is implemented. The solution for this case is decommissioning of the facility or use it as run-off river scheme.

- ✓ Catchment management: - where this is a method used to reduce sediment inflow in the reservoir and it comprise the following techniques:
    - o Watershed management used to reduce surface soil erosion and achieved by implementing improved agricultural practice, reforestation and de-intensification of land use practices.
    - o Implementation of check structure on mountainous streams upstream of the reservoir.
- ✓ Deposition removal: - such as flushing, hydrosuction sediment removal system, dredging, and trucking.
- ✓ Sediment routing: - includes sluicing, density current venting and by-pass.

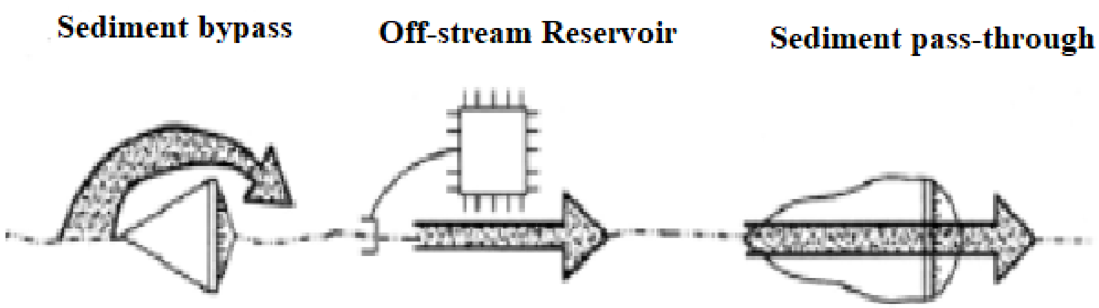



*Figure 2-6 schematic presentation of sediment routing strategy (source[26])*

Figure 2-7 below represent the summarized program structure of RESCON 2 from the user input to economic appraisal. The aim of this thesis is to focus on HSRS and what will be the result or output from the RESCON2. The necessary data to run the model for HSRS is presented below in detail.

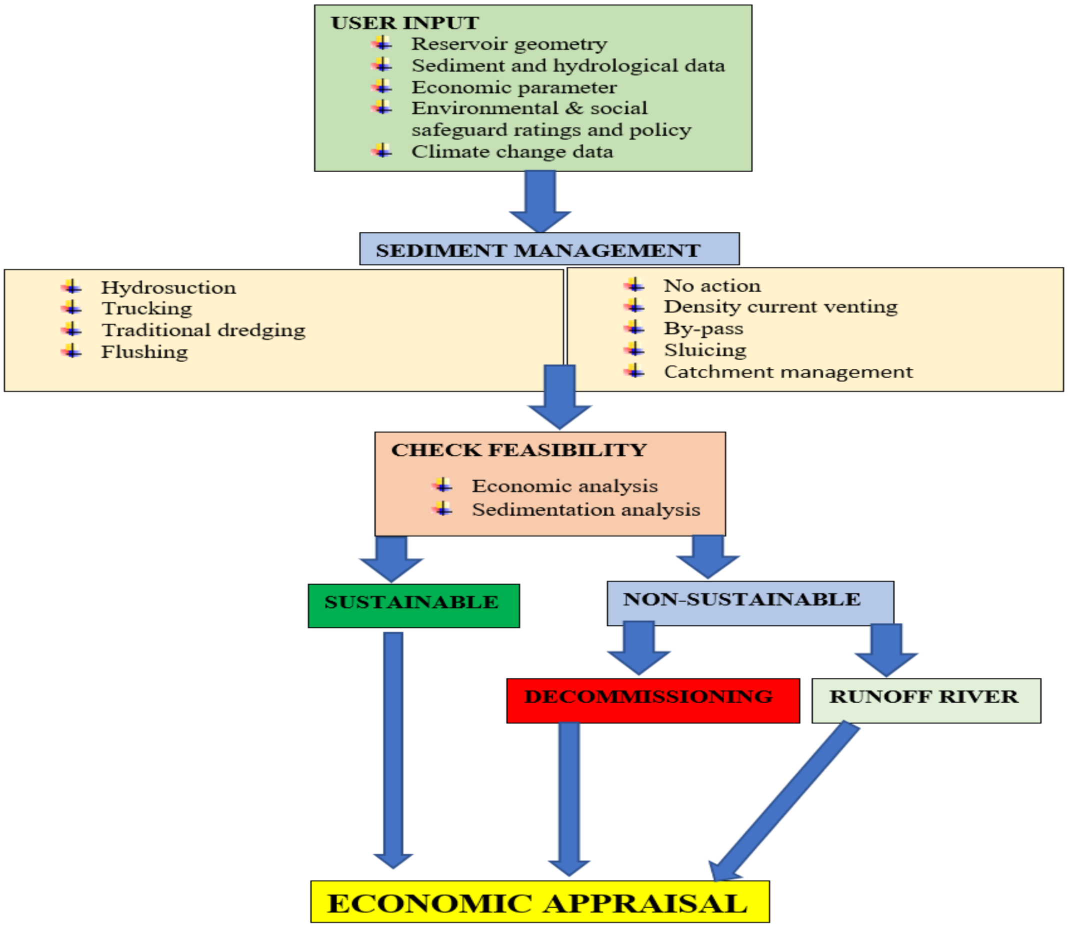



*Figure 2-7 Structure of RESCON2*

### 2.5.4 Hydrosuction removal system in RESCON 2

Hydrosuction removal method requires input of reservoir length, energy head at the dam, deposited sediment data and trial pipe diameter of hydrosuction. The input parameter for HSRS is presented in the Table 2-2 below.  From experience hydrosuction sediment removal is appropriate for small reservoir. The technical feasibility of HSRS for implementation depends on length of the pipe. During implementation for safety, the length of the pipe is taken as equal to the reservoir length. When the length of the pipe increases, the efficiency of hydrosuction removal decreases due to high hydraulic loss. As result for reservoir length greater than 5000 m, HSRS will not be feasible. The sustainability of HSRS method has been evaluated and taken as feasible, when the removal capacity of it greater than maximum annual deposition of sediment in the reservoir. Otherwise HSRS is considered as non-sustainable strategy.

*Table 2-2 parameter applied for assessment of reservoir when HSRS is selected*

| Parameter for determining HSRS efficiency | | |
|---|---|---|
| Type | 1 or 2 | Sediment type category to be removed by Hydrosuction Sediment Removal System (HSRS), (1 is for medium sand and smaller, 2 is for gravel) |
| D | [m] | Assume a trial pipe diameter for HSRS (0.3 to 1.2m) |
| NP | 1, 2, or 3 | Number of pipes for HSRS |
| YA | [%] | Maximum fraction of total yield that can be used in HSRS operations |
| CLH | [%] | Maximum percent of capacity loss that is allowable at any time in reservoir for HSRS |
| Water losses and cost for implementation of HSRS | | |
| PH | [$/m3] | Unit value of water released downstream of dam in river by HSRS operations |
| HI | [US$] | Cost of capital investment to install HSRS |
| DU | [Years] | The expected life of HSRS |
| Shall the implementation strategy of HSRS be determined through economic optimization? | | |
| Year HSRS start | [Years] | Timing of HSRS installation |
| HSRS limit | [m] | Length limit for implementation of HSRS |

# 3 Sediment yield estimation in Paso Ancho HPP

## 3.1 About Paso Ancho hydro power project

### 3.1.1 Geographical location and hydrological data

Panama is in Central America, bordering both the Caribbean Sea and the Pacific Ocean, between Colombia and Costa Rica. With coordinate of latitudes 8° to 9°N, and longitudes 80° and 82°W. The location of Paso Ancho hydropower project as shown in the Figure 3-1 below, it is in south west region of Panama near to the border of Costa Rica in between Volcan and Paso Ancho in the place called Nueva California.

The total catchment area of Paso Ancho hydropower project is 108km$^2$ with the highest elevation of 3291a.m.s.l and lowest elevation of 1532a.m.s.l as shown in Figure 3-1. The main river which flows in the catchment is Chiriquí Viejo.

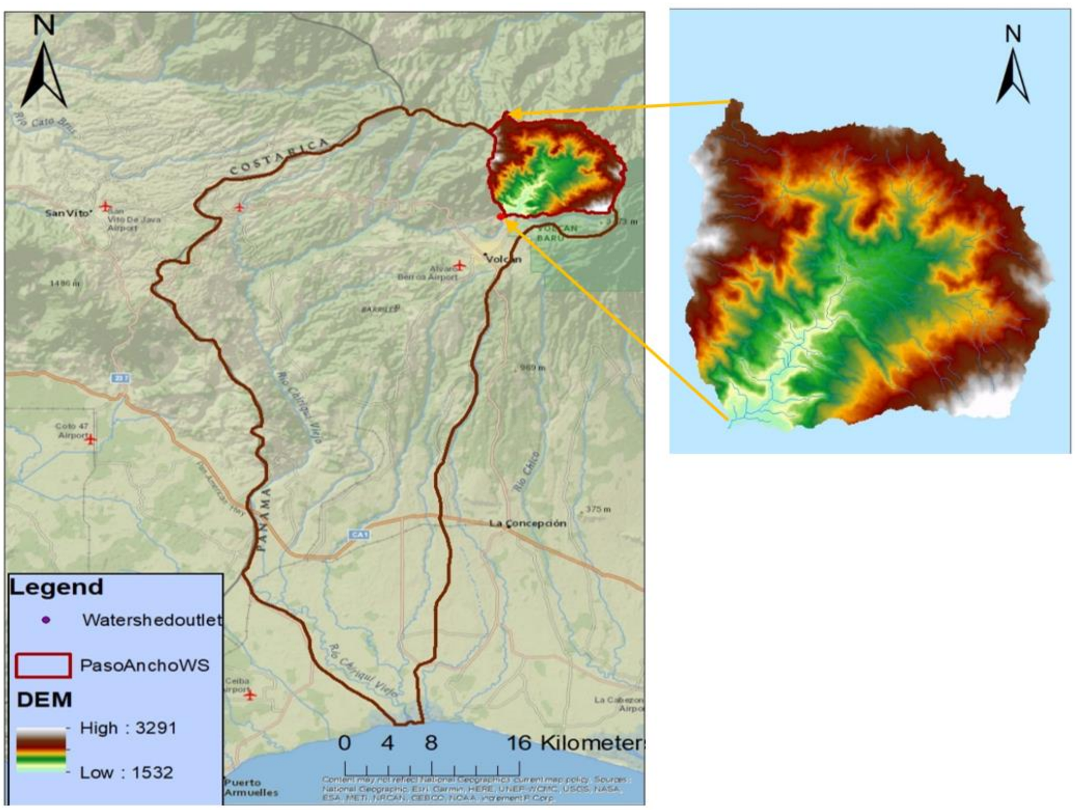



*Figure 3-1 Location and DEM of the Paso Ancho catchment area with river network*

There are two seasons in Panama such as the dry season and rainy season. During the rainy season from May to December the average flow to the Chiriquí Viejo river is 7.48 m$^3$/s and during dry season from January to April it is 5.14 $m^3/s$. As a result, the average annual flow in this river is 6.5$m^3/s$ from prefeasibility study report of Paso Ancho HPP. Mean monthly temperature of panama from meteorological data as shown in Appendix A is in the range of 13 to 15.5 °C as well as mean monthly precipitation from gauging station varies throughout the year from 50mm to 470mm.

Paso Ancho hydropower project utilizes Chiriquí Viejo river. The diverted flow from river to the power plant will vary throughout the year as the flow depends on the seasons. Therefore, the monthly flow for production is also different as shown in the Figure 3-2. The flow ranges with the maximum of 5.82$m^3/s$ in rainy season and minimum of 2.9$m^3/s$ in dry season as a result the average monthly flow for production is 4.6$m^3/s$ with environmental flow of 0.7$m^3/s$. The Figure 3-2 below shows flow variation in a year for power production.

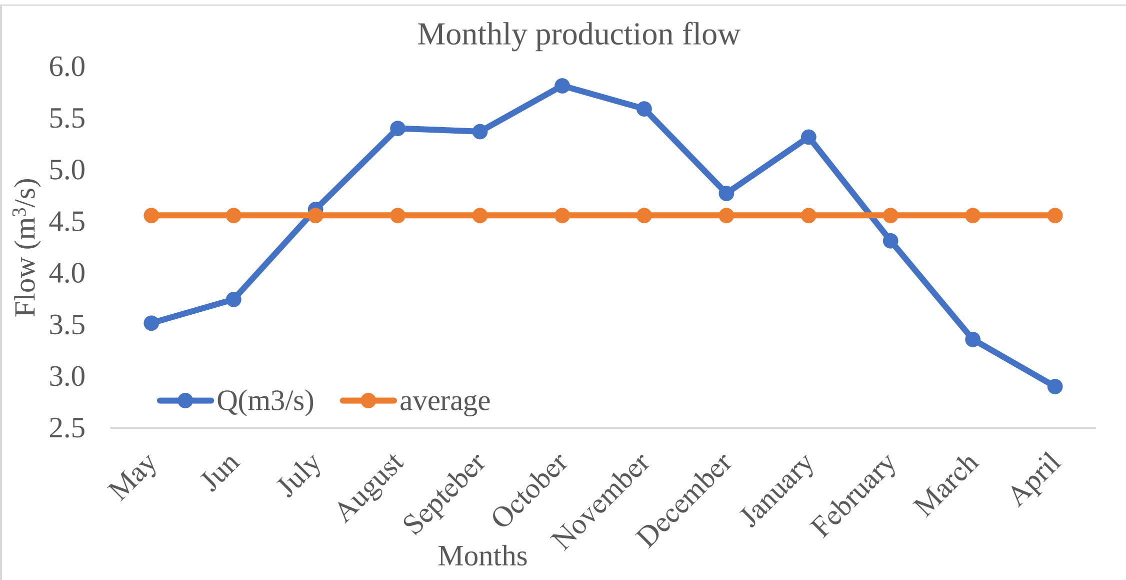



*Figure 3-2 Monthly flow of production in Paso Ancho HPP*

The project is ROR scheme with daily regulated peaking pond by utilizing Chiriquí Viejo river. The flow of water has diverted from river to off-stream peaking pond through headwork structure. The project has installed capacity of 6.4 MW with two Francis turbines, and each unit generate with equal capacity. The catchment area is 108 $Km^2$ with gross head of 80m. The power production schedule done depending on the daily flow to the peaking pond. In rainy season the powerplant will produce with two turbines up to full capacity of production whereas in dry season the production will go down up to around 25% of the total production. As a result, in dry season, mostly the production has been done with one turbine. Therefore, the power production in the powerplant varies depending on the daily flow in the river.

The soil type in the catchment area of Paso Ancho hydropower project is fertilized volcanic rock, which is good for plantation, but it can easily erode by rain and becomes the main problem for hydropower project. The Chiriquí Viejo river is highly exposed for sediment and the main source of sediment is riverbank erosion during heavy rain fall.

The layout of the power plant as shown in Figure 3-3 below, the flow diverted by Tyrolean intake into the collection chamber then flows towards the settling basin. As the peaking pond is off-stream and it is around 240m far from the outlet of settling basin, underground waterway tunnel has provided. As well as the waterway from the outlet of the peaking pond to powerhouse has underground tunnel and surface penstock. At the end from powerhouse after production the water flows through outlet channel towards the Chiriquí Viejo river.

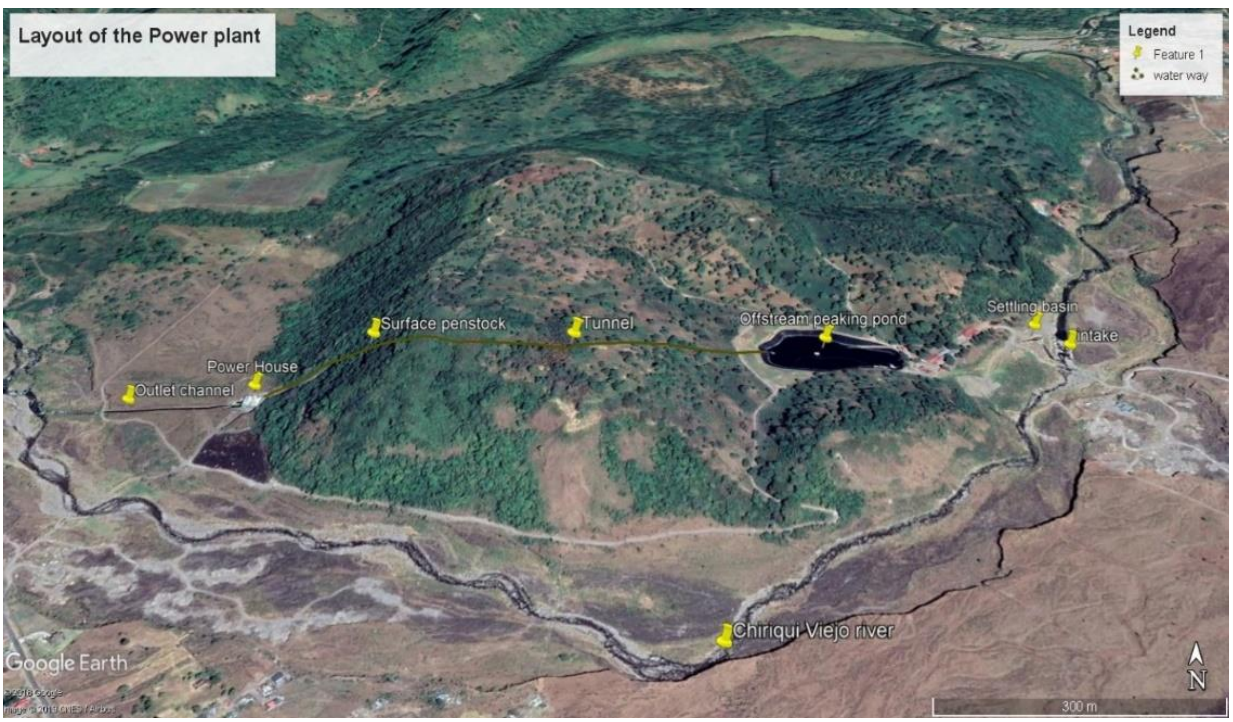



*Figure 3-3 Layout of the Paso Ancho hydro power plant (source Google earth map 2019)*

The overall summery of Paso Ancho powerplant is presented in the Table 3-1 below. Which includes the installed capacity and annual average production, but the current energy production which is taken from the powerplant owner is annually with an average of around 30 GWh. Such different in production is due to variation of flow throughout the year.

*Table 3-1 Summary about Paso Ancho power plant including the sediment type in the peaking pond*

| Project: | Paso Ancho HPP, Panamá |
|---|---|
| River: | Chiriquí Viejo |
| Operation: | Since 2011 |
| Catchment area | 108 km2 |
| Design discharge | 9 m3/s (4.5 m3/s for each turbine) |
| Installed capacity | 6.4 MW |
| Average annual production: | 43 GWh |
| Gross head | 80 m |
| Original storage volume of peaking pond | 100,000 $m^3$ |
| HRWL | 1462.2 |
| LRWL | 1455.6 |
| Deposited Sediment volume: | 30,000 $m^3$ |
| Aviable head (for Dredge): | 6.6 m |
| Dredging maximum distance: | 185 m |

### 3.1.2 Sediment property in the peaking pond

To know the sediment property in the peaking pond, seven samples has been taken and analyzed in the laboratory. For the selected samples, granulometry analysis has been done with ASTM D-6913 method. The sieve size analysis of the test uses a sieve size No. 4 up to No. 200 as shown in Appendix E. From the laboratory result the graph of grain size distribution versus percent pass plotted as shown in the Figure 3-4 below and from the graph of grain size analysis, $d_{50}$ of all samples are read and presented in the Table 3-2 below. But if $d_{50}$ value is taken by interpolation the value will be higher than this.

From the result of sieve size distribution, the type of sediment in the peaking pond is a mixture of silt and sand. Which means larger size of particles from 0.21mm up to 0.82mm are transported to the off-stream peaking pond. These means the settling basin in headwork structure has not performing well. Some sample pictures of sediment from the peaking pond are also presented below in Figure 3-5. This shows how the sediment looks in the peaking pond.

*Table 3-2 $d_{50}$ value of all sample and distance from the inlet of the pond to the sample taken*

| $d_{50}$ | *S1* | *S2* | *S3* | *S4* | *S5* | *S6* | *S7* |
|---|---|---|---|---|---|---|---|
| Mm | 0.39 | 0.72 | 0.48 | 0.29 | 0.26 | 0.82 | 0.21 |
| Distance from inlet of pond to sample location (m) | 30 | 33 | 35 | 75 | 120 | 90 | 160 |

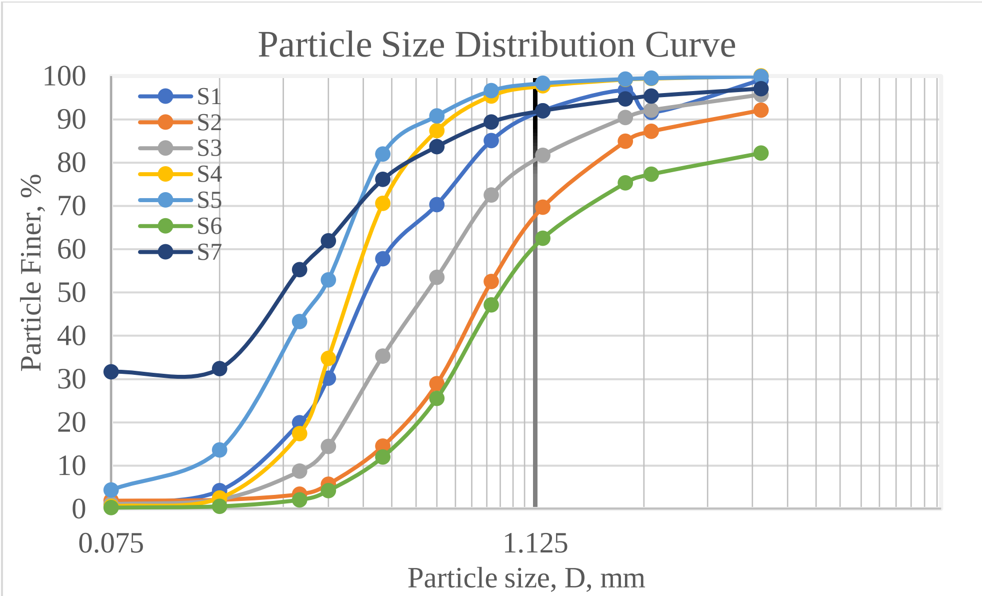



*Figure 3-4 Grain size distribution of seven samples from peaking pond of Paso Ancho HPP*

*Figure 3-5 Sample picture of soil type in Paso Ancho peaking pond*

## 3.2 Estimation of sediment yield in Chiriquí Viejo river

### 3.2.1 RUSLE Model and SDR

RUSLE model and SDR is used to estimate the annual average soil loss and sediment yield from Paso Ancho catchment area to the river. As the catchment area of the Paso Ancho is highly exposed for soil erosion as shown in the Figure 3-6 below sedimentation is the main problem for the powerplant. The equation of RUSLE model and SDR is presented in the section 2.2 above and the detail output result of each factors are presented below.

*Figure 3-6 Photo taken from highly exposed area for erosion near to intake location.*

## 3.3 Result from RUSLE model

### 3.3.1 Rainfall erosivity factor

For the calculation of Rainfall erosivity factor long term rainfall data is mandatory. In Paso Ancho catchment area, there are 3 gauging stations. The mean annual precipitation for each gauging station is taken from metrological Stations in Panama Web map. Average monthly rainfall throughout the year in each gauging station is shown Figure 3-7 below.

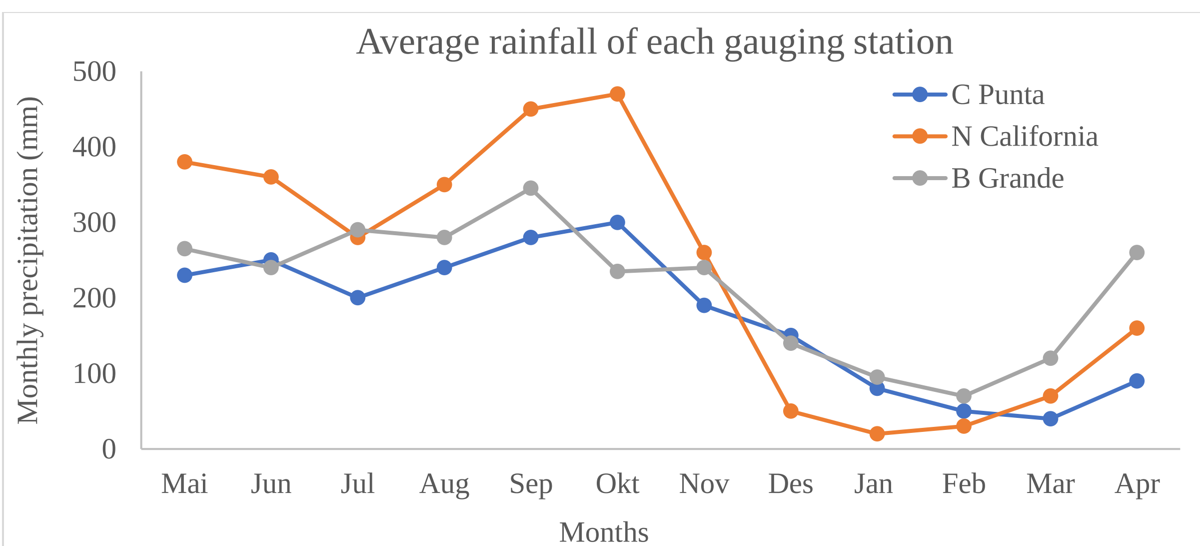



*Figure 3-7* Average monthly rainfall in three gauging stations

The mean annual precipitation which is shown in the Table 3-3 below is used for interpolation through the catchment area by following spatial interpolation tool in ArcGIS. The resolution of the data was 45m*45m and resampled to 30m*30m. As it is explained on the section 2.2.1 the equation for panama region is not known as a result related equation which has been developed for other country is used. Therefore, there will be uncertainty on the result of rainfall erosivity factor.

Table 3-3 Mean annual precipitation for gauging station

| Gauging station | latitude (N) | longitude (W) | MAP (mm) |
|---|---|---|---|
| C Punta | 8.85 | 82.58 | 2100 |
| N California | 8.85 | 82.68 | 2880 |
| B Grande | 8.85 | 82.61 | 2580 |

In ArcGIS by using raster calculator tool, the R factor has been computed and the result is presented in the Figure 3-8 below. From the result output the value of R factor is in the range of 1645.44 to 2183.99. Therefore, the average rainfall erosivity factor is taken as around 1935.

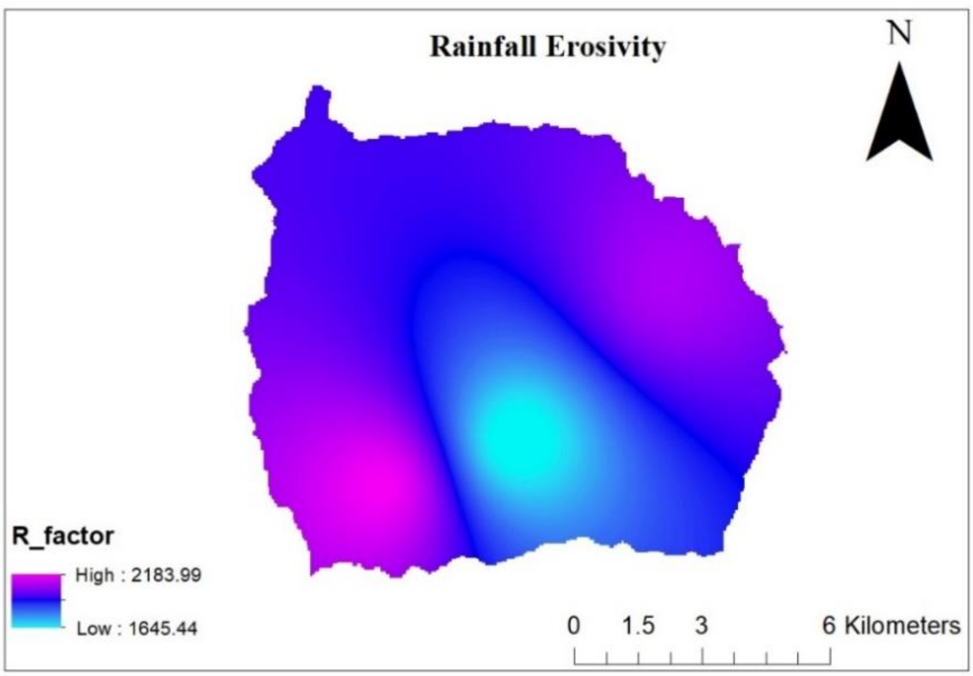



*Figure 3-8 Rainfall erosivity map of Paso Ancho catchment area*

### 3.3.2 K factor

As the field measurement to get soil data is difficult, world soil map has solution to find the soil type of a given catchment area. Therefore, to get this data the process must be involved in ArcGIS by adding the shape file of the given catchment area into the world soil map.

The most important soil layer which leads for erosion is topsoil. As a result, for K factor calculation, percent of topsoil layer is used from world soil map data. The data taken for Paso Ancho catchment area from world soil map after processed in ArcGIS is presented in the Table 3-4 below. The resolution of the data after taken from world soil map was 46m*46m so, needed to be resampled into 30m*30m. Then the soil erodibility factor is calculated in ArcGIS using equations 5 and 6 as presented above through raster calculator tool. The result shows the catchment area has two soil type with the K factor value of 0.144 and 0.176 as shown in Figure *3-9* below. In addition, the highest erodibility factor is near to the intake location.

*Table 3-4 Generalized Soil Unit Information of Paso Ancho catchment area*

| Soil unit symbol | sand % topsoil | silt % topsoil | clay % topsoil | OC % topsoil |
|---|---|---|---|---|
| AH | 31.3 | 24.8 | 43.8 | 3.34 |
| BD | 32.7 | 30.3 | 37.1 | 3.28 |

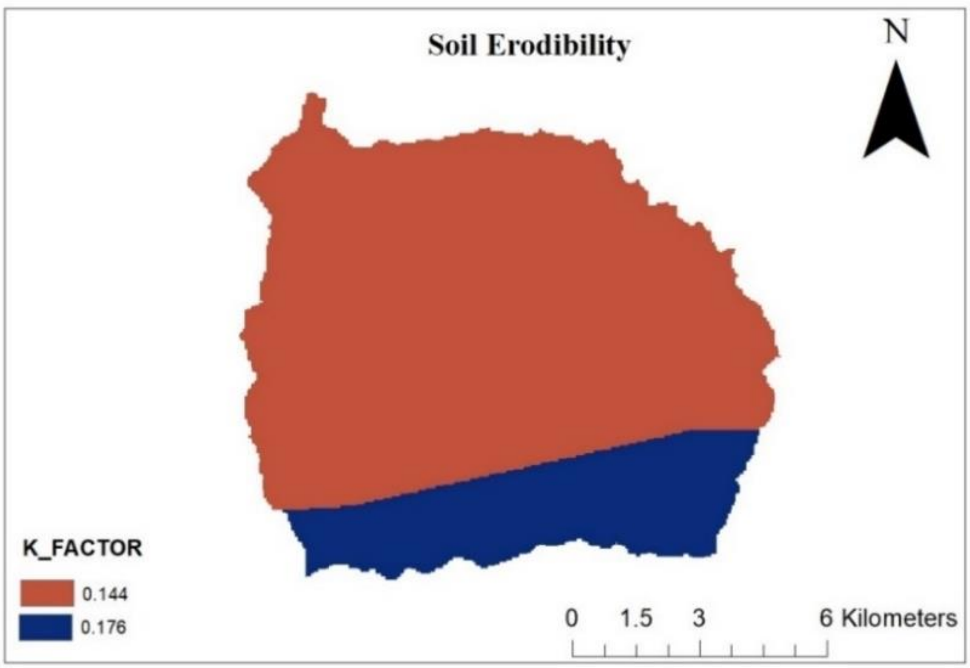



Figure 3-9 Soil erodibility factor map of Paso Ancho catchment area

### 3.3.3 LS factor

The Soil erosion and velocity increase when slope length and steepness increases. Slope length and steepness has been estimated by involvement of digital elevation model (DEM) in ArcGIS. The resolution of DEM was 30m*30m. L and S are calculated separately in raster calculator and multiply both values to get LS factor. All the formulas which are used for calculation of LS factor are presented in the section 2.2.3 above. From the output result the highest LS factor is 16.7 as shown in Figure 3-10 below and around 90% of the catchment area is less than 1.57 LS factor.

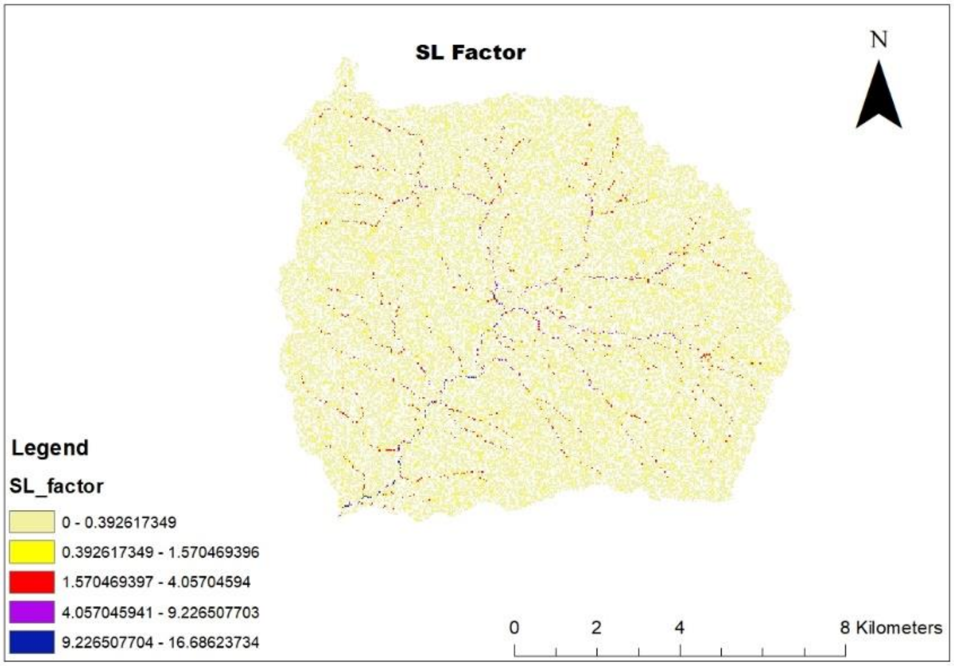



*Figure 3-10 Slope length and steepness map of Paso Ancho catchment area*

### 3.3.4 C factor

Vegetation cover on the catchment area has large impact on erosion. For example, if it is highly covered with vegetation then, the vegetation will reduce rainfall energy, increases infiltration and increases interception (by holding the water on the leaf). Therefore, there will be reduction of runoff on the catchment area as well as erosion. The raster data for land cover is found from land use map or satellite map. For Paso Ancho case the data found from online data base called land viewer map with a resolution of 307m*307m. The resolution needs to be resampled to 30m*30m cell size. The land use class of the Paso Ancho catchment area is shown in the Table 3-5 below.

*Table 3-5 Land use class in Paso Ancho catchmnet area*

| Value | Land use class |
|---|---|
| 14 | Rainfed croplands |
| 20 | Mosaic cropland (50-70%) / vegetation (grassland/shrubland/forest) (20-50%) |
| 30 | Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%) |
| 40 | Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m) |
| 110 | Mosaic forest or shrubland (50-70%) / grassland (20-50%) |

| | |
|---|---|
| 120 | Mosaic grassland (50-70%) / forest or shrubland (20-50%) |
| 140 | Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses) |

As it is shown from the output result map in Figure 3-11, 90% of the catchment area has the crop management factor of less than 0.2.

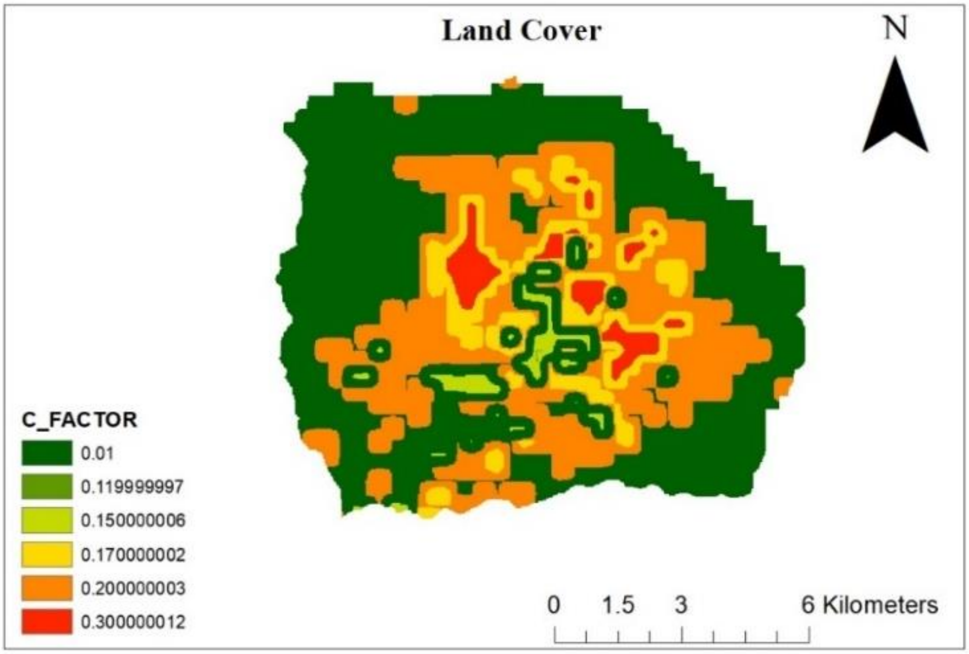



*Figure 3-11 Crop management map of Paso Ancho catchment area*

### 3.3.5 P factor

In Paso Ancho there are coffee farm and other farming activity. Therefore, support practice factor needs to be estimated. Support practice factor is estimated based on slope or land use map. For this study P factor is calculated based on slope and the slope is estimated in ArcGIS by using spatial tool analysis of DEM. Then reclassifying the slope based on the table presented in Table 2-1 above and add the values from the table. The resolution of the DEM data was 45m*45m then resampled to 30m*30m. Then the result for P factor is shown below, and from the result 80% of the area has P factor of above 0.6. Therefore, average support practice factor in Paso Ancho catchment area as shown in Figure 3-12 below is around 0.75.

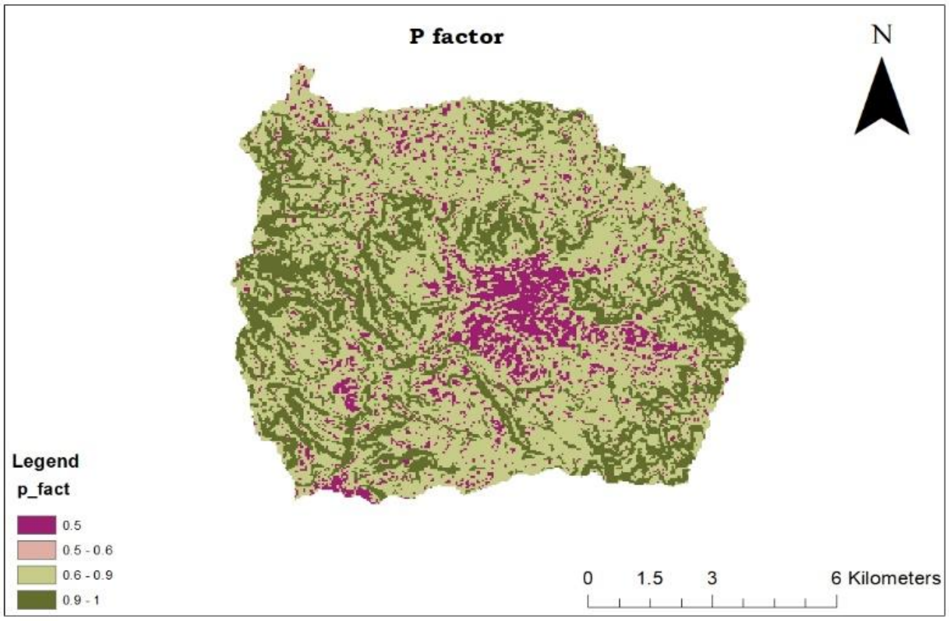



*Figure 3-12 Support practice map of Paso Ancho catchment area*

### 3.3.6 Annual Soil loss

All the factors were not on the same resolution and to solve the problem while multiplying individual raster, resample in one cell size was necessary. Then each factor become on the same resolution with the cell size of 30m*30m after resampling. The annual soil loss can be calculated in ArcGIS by adding all the factors and using raster calculator.

There are uncertainties while calculating all the factors in RUSLE model due to unavailable data and limitation of equation for the project. Therefore, the only solution for this study was to take equation which is derived for other country and use available data to run the model. As a result, the output of soil erosion estimation which is shown in Figure 3-13 below is uncertain and may be higher or lower than the given values.

*Table 3-6 Category of soil loss (Source [27])*

| Erosion category | Slight | Moderate | High | Very high | Extremely high |
|---|---|---|---|---|---|
| Soil loss (Ton. $ha^{-2}$. $Yr^{-1}$.) | 0-12 | 12 – 25 | 25-60 | 60-150 | >150 |

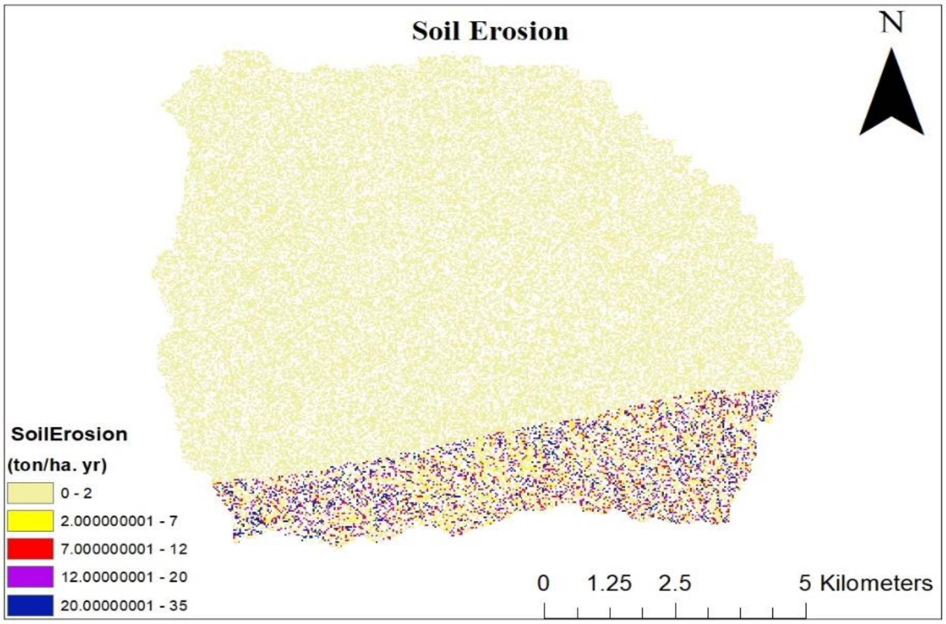



*Figure 3-13 Annual Soil erosion result from RUSLE model*

The Table 3-6 also show the category of soil loss range from a scenario where there is small erosion to extremely high erosion. Therefore, the average soil erosion in Paso Ancho catchment area is in average 34 Ton ha$^{-1}$ Yr$^{-1}$ as shown in Table 3-7 as well as from soil loss category it is in the range of 25 to 60 Ton ha$^{-1}$ Yr$^{-1}$. Therefore, the result of average soil erosion for Paso Ancho catchment area is in high soil erosion soil loss category.

*Table 3-7 Average annual soil loss calculation from the RUSLE model output*

| Average value from the result | | |
|---|---|---|
| R | 1935.82 | |
| K | 0.15 | |
| SL | 1.5 | |
| C | 0.1 | |
| P | 0.75 | |
| Average annual soil loss | 34.3 | Ton. ha$^{-1}$. Yr$^{-1}$. |

After soil erosion result from RUSLE model as shown in Table 3-7, SDR need to be calculated by using different equations which has discussed in the section 2.2.6 above and use average of them. Therefore, sediment yield is estimated by multiplying the soil loss which is estimated by RUSLE model with average SDR which is calculated based on equation as shown in Table 3-8 below. Table 3-8 shows calculation of SDR by three different equation to use the average value of it and Table 3-9 below shows sediment yield in the river.

*Table 3-8 Sediment delivery ratio calculation*

| SDR | | | | |
|---|---|---|---|---|
| Area ($km^2$) | Boyce | Renfro | Vanoni | SDR avg |
| 108 | 0.34 | 0.26 | 0.12 | 0.24 |

*Table 3-9 Soil loss result from RUSLE model and sediment yield calculation*

| Area ($km^2$) | Average annual soil loss ton. $ha^{-2}$. $Yr^{-1}$ | Soil.loss. (Mill. Ton. $Yr^{-1}$) | $SDR_{avg}$ | SY. Mill. ton. $Yr^{-1}$ | SY. ($m^3$. $Yr^{-1}$) |
|---|---|---|---|---|---|
| **108** | 34.3 | 0.37 | 0.24 | 0.089 | 37,547.67 |

Annual soil loss from the Paso Ancho catchment area to the Chiriquí Viejo river as presented in Table 3-9 above is 0.37 Mill. ton $Yr^{-1}$. The annual sediment yield and specific sediment yield to the river is 0.089 Mill. ton $Yr^{-1}$ and 827.8 ton. $km^{-2}$ $Yr^{-1}$ respectively. All the sediment yield from Paso Ancho catchment area to the river are not draining to the peaking pond. But it is possible to say in average 50% of the total specific sediment yields drain to peaking pond which is 413.9 ton. $km^{-2}$ $Yr^{-1}$. In average around 1564.8 $m^3$ per month of sediment can transport to peaking pond. But in rainy season, during high flood more than this value of sediment will transport to the peaking pond.

## 3.4 Sedimentation problem and consequence in Paso Ancho hydropower

Sedimentation in the reservoir has created several problems such as storage capacity reduction, production loss, abrasion of turbine and hydraulic structure. The main source of sediment in the river is erosion due to high rainfall, agricultural activity, human activity and other modes of transportation. Sedimentation is the main challenge in this hydropower project by decreasing the storage capacity of peaking pond and damaging the machine as well as production loss due to turbine down time for sediment related maintenance. In rainy season there are a lot of sediment and debris transportation in the river. As a result, large amount of sediment load can also transport to the peaking pond, this yields for large sedimentation. Due to high sediment transportation, there are different ways of sediment handling method used from headwork structure to the peaking pond. On the next section, sedimentation problem on the powerplant is discussed.

### 3.4.1 Sedimentation in settling basin and off-stream daily regulated pond

The original storage capacity of the off-stream peaking pond in Paso Ancho Hydropower project has 100,000 $m^3$. However, due to high sediment inflow the existing storage of the peaking pond is 70,000$m^3$ with 30,000$m^3$ of sediment deposit. The valuation of storage shows, how the sedimentation reduced the storage capacity. In addition to storage loss, sedimentation has direct influence on production loss. In the rainy season sediment deposition in the off-stream peaking pond becomes in the range of 30,000$m^3$ to 50,000$m^3$. Which means in some months the storage capacity loss becomes more than half of the original storage capacity. This shows that in Paso Ancho hydropower project, high sedimentation flow occurs in rainy season, as a result there should be some mechanism to reduce the problem.

Figure 3-14 (a) below shows removing of sediments during high sedimentation in the reservoir and it was almost half of the reservoir capacity. Figure 3-14 (b) shows sediment accumulated in settling basin during heavy rain. This happens after the gate has closed due to high sediment entering intake structure. During that time in order to remove the sediment from peaking pond, the water from the storage needs to be drained out and use mechanical removing system. In the settling basin there has been a flushing gate, but it has not enough to flush all sediments as shown in the figure below where deposition occurs.

*(a) Sedimentation in peaking pond (b) sediment deposited in settling basin during heavy rain*

*Figure 3-14 Mechanically removal of sediment from peaking pond due to high sedimentation*

The other problem due to sedimentation on this project are damaging machines and hydraulic structure as well as production losses. These production losses were due to storage capacity loss and stopping of production for maintenance reasons. All in all, the Paso Ancho powerplant has several problems due to sedimentation therefore, evaluation of best sediment management strategy for the project is vital.

# 4 Evaluating the sustainability of Paso Ancho HPP using RESCON 2 Model

## 4.1 Input data

Input data for modeling RESCON 2 needs to be good quality to get reasonable result. The purpose of using this model for Paso Ancho hydropower project is, to evaluate the currently installed sediment management strategy whether it is feasible or not. In addition, it is also used to evaluate the capacity of these method on removing sediments. So, the input parameter for sediment management strategy in Paso Ancho HPP is already known and it has been in use. The other input parameters are calculated, measured and taken from online source. Moreover, there are some input parameters for which the default value has been used. The sources of input data are the owner of the powerplant and SediCon AS. Therefore, each of the input data will be presented below.

### 4.1.1 Reservoir geometry

Reservoir geometry is an important parameter for the RESCON 2 model to allocate the deposition of active storage and inactive storage. The needed input data including value and sources are presented in the Table 4-1.

*Table 4-1 Reservoir geometry input data*

| Reservoir geometry input | Value | Source |
|---|---|---|
| Original gross storage capacity of reservoir | 100,000 | Owner of the powerplant |
| Original active storage capacity of reservoir | 100,000 | Owner of the powerplant |
| Original dead storage capacity of reservoir | 0 | Owner of the powerplant |
| Existing gross storage capacity of reservoir | 70,000 | Owner of the powerplant |
| Existing active storage capacity of reservoir | 70,000 | Owner of the powerplant |
| Existing dead storage capacity of reservoir | 0 | Owner of the powerplant |
| Representative riverbed width at the dam location[m] | 30 | Measure |
| Maximum pool elevation of reservoir [m.a.s.l] | 1,462.2 | Owner of the powerplant |
| Minimum operation water level [m.a.s.l] | 1,455.6 | Owner of the powerplant |
| Minimum reservoir bed elevation at dam Site [m.a.s.l] | 1,455.6 | Owner of the powerplant |
| Reservoir length[m] | 185 | Owner of the powerplant |
| Number of reservoir compartments | 2 | Assumed |

### 4.1.2 Hydrological data

For the hydrological input data of this study, it is not mandatory to add interannual variation of water and sediment inflow as well as other related information. Because the sediment yield has already been estimated by using RUSLE model. If sediment yield estimation is not known, the model by itself can estimate it and for that case it is necessary to add all hydrological input data. The necessary input data for this case is presented in the Table 4-2 below. Mean annual reservoir water inflow has been calculated from average discharge to the off-stream peaking pond. The water temperature in the peaking pond has been measured by using ADCP during bathymetry survey.

*Table 4-2 Hydrological data input*

| Hydrological data | Value | Source |
|---|---|---|
| Mean annual reservoir water inflow (mill. m3/yr.) | 143.8 | Owner of the company |
| Coefficient of variation of annual runoff volume | 0.2 | Assumed |
| Representative water temperature in the reservoir | 19 | Measured (ADCP) |

### 4.1.3 Sediment characteristics

The sediment characteristic needs the total sediment load, such as suspended and bedload. The total sediment yield to the Paso Ancho peaking pond has been calculated by using RUSLE model. But it is not easy to divide the percent of bed load from total sediment inflow. As it is shown in Table 4-4 below the duration and percentage of bed load transport need to be assumed for this case. For computation of specific weight of in-situ reservoir sediment (bulk density), the equation below has been used. And the factor of equation is based on the operation type of the reservoir which is presented in the Table 4-3 below [28].

$$\gamma_i = W_c * P_c + W_m * P_m + W_s * P_s \qquad \textit{(Eq. 18)}$$

Where $\gamma_i$ is initial specific weight, $W_c$, $W_m$, $W_s$ are coefficient of compaction for clay, silt and sand respectively as well as $P_c$, $P_m$, $P_s$ are percentage of clay, silt and sand deposition in the reservoir respectively.

There has been sieve size analysis result which has done in laboratory for 7 different samples that taken from the peaking pond. The average fraction of sediment deposition in the peaking pond from sieve size analysis report are 4.8% of gravel, 89.3% of sand and 5.9% of fine (silt). The reservoir type used for this calculation to get coefficient of compaction is little to medium reservoir depletion. Therefore, the specific weight calculation is done by using equation 18 and the result is 1.45 ton/m$^3$.

*Table 4-3 Coefficient of compaction for clay, silt and sand of different reservoir operation [28]*

| Reservoir operation | Clay | Silt | Sand |
|---|---|---|---|
| | Wc | Wm | Ws |
| Continuously submerged | 0.416 | 1.121 | 1.554 |
| little to medium reservoir depletion | 0.561 | 1.137 | 1.554 |
| Reservoir reporting significant level variations | 0.641 | 1.153 | 1.554 |
| Reservoir usually empty | 0.961 | 1.169 | 1.554 |

The input parameter for sediment characteristics has taken from the RUSLE model output as well as from calculation, as presented in Table 4-4.

*Table 4-4 Sediment characteristics*

| Sediment characteristics | Value | Source |
|---|---|---|
| Specific weight of in-situ reservoir sediment (bulk density) ton/m3 | 1.47 | Calculated |
| Mean annual total sediment inflow mass (mill. ton/yr.) | 0.089 | RUSLE |
| % bed load transport | 10 % | Assumed |
| Duration of bed load transport (%) | 5 % | Assumed |

### 4.1.4 Sediment management parameter

Under sediment management parameter, sediment removal method has been chosen and from that hydrosuction sediment removal method is the focus of this thesis. For Paso Ancho hydropower peaking pond, sediment management strategy has already been installed. Therefore, the input data for the model is taken from SediCon AS and the rest is by assumption as shown in the

Table 4-5 below. The model has limitation to add input data for pipe diameter as well as for installation timing of HSRS. Such as minimum pipe diameters of 0.3m and minimum installation time of 1year. Therefore, for Paso Ancho case to see what the result will be, the minimum value must be taken for installation time. However, for pipe diameter 0.45m has taken which is the model accepted HSRS to be feasible. But it is not the actual installation time and pipe diameter which is needed to be checked.

There are two parameters in the model input section which is shown in the

Table 4-5 below. For Paso Ancho peaking pond case both have no influence on the result when the value for YA is greater than or equal to 10% and for CLH value greater than or equal to 50%. As a result, the minimum value has been taken.

*Table 4-5 HSRS input data*

| HSRS | Value | Source |
|---|---|---|
| Sediment type category to be removed by Hydrosuction Sediment Removal System (HSRS) | 1 | SediCon |
| Assume a trial pipe diameter for HSRS in (m) | 0.45 | Model accepted |
| Number of pipes for HSRS | 1 | SediCon |
| Maximum fraction of total yield that can be used in HSRS operations (YA) [%] | 10 | Assumed |
| Maximum percent of capacity loss that is allowable at any time in reservoir for HSRS (CLH) [%] | 50 | Assumed |
| Unit value of water released downstream of dam in river by HSRS operations | 0 | Assumed |
| Cost of capital investment to install HSRS in (US$) | 300,000 | SediCon |
| The expected life of HSRS in (year) | 30 | SediCon |
| Shall the implementation strategy of HSRS be determined through economic optimization? | No | |
| Timing of HSRS installation in (year) | 1 | Minimum |
| Length limit for implementation of HSRS in (m) | 185 | SediCon |

### 4.1.5 Economic parameter

Economic analysis is used for comparison of different management strategy and the one with highest net present value is selected. But for Paso Ancho case the method has already been selected and no need for comparison. As a result, the discount rate is taken from the user manual default value and for market interest rate of annual retirement also assumed with greater value of discount rate. The total cost of reservoir impoundment is also not actual but from the information gathered at the project site by interview has taken. In RESCON 2 model the discounting can be performed in two way one is accepting declining discount rate the other one is without accepting declining discount rate. To consider renewable nature of natural resource of the storage, the user strongly recommended to use declining discount rate. For this study the declining discount rate has been used as shown in the Table 4-6 below. And the economic parameter input of Paso Ancho powerplant is presented in the

Table 4-7 below.

*Table 4-6 Declining discount rate of Paso Ancho peaking pond*

| Year | 0-30 | 31-75 | 76-125 | 126-200 | 201-300 | >300 |
|---|---|---|---|---|---|---|
| Rate% | 3.00 % | 2.57 % | 2.14 % | 1.71 % | 1.29 % | 0.86 % |

*Table 4-7 Economic parameter input data*

| **Economic parameter** | | |
|---|---|---|
| Unit cost of construction per m3 or reservoir capacity | 600 | Calculated |
| Total cost of reservoir impoundment | 60E+06 | Assumed |
| Discount rate | 3.0 % | From user manual |
| Market interest rate of annual retirement | 6.0 % | Assumed |
| Decommissioning cost | 0 | |
| Capacity loss for characterization of a reservoir as non-sustainable | 95 % | Assumed |
| Total annual operation & maintenance costs [$/year] | 1.2 E+06 | Calculated (2%) |

## 4.2 Result from RESCON2 model

Hydrosuction sediment removal system for Paso Ancho hydropower project peaking pond is technically feasible. The result from RESCON 2 showed that HSRS method can sustain the peaking pond life for more than 300 years. The economic performance of the peaking pond for the first 300 years operation will have aggregate NPV of around 339 million US$ as shown in the

Table 4-8 below. The physical performance of the peaking pond storage after 300 years of operation will be around 36,229 $m^3$.

*Table 4-8 Result from RESCON 2 for HSRS*

| Reservoir Sustainability | Sustainable | Non-sustainable | |
|---|---|---|---|
| | | Decommissioning | Run-of-river |
| Technique yielding the highest Aggregate Net Benefit: | HSRS | No Action | No Action |
| Aggregate Net Benefit [US$] | 338,919,490 | 0 | 0 |

From the result of RESCON 2 model about the operation and capacity of HSRS, the total amount of sediment removed from the peaking pond annually is 33,771$m^3$ as well as the sediment concentration which will removed by hydrosuction through the pipe is 7.78E+03 ppm. The detail result from the RESCON 2 model is presented in Appendix H.

Hydropower projects are highly sensitive due to different factors as a result, the sensitivity analyses are necessary to check whether the project with a given factors are highly sensitive or not.

### 4.2.1 Sensitivity analysis

The sensitivity analysis for HSRS method performed by varying the sediment inflow, installation cost of sediment management strategy, discounting scheme as well as annual operation and maintenance cost. For the Paso Ancho case, the sensitivity analysis has been presented below by increasing and decreasing 50% of the average annual sediment inflow to the river. But the rest factors are not that much influential for this project.

*Table 4-9 Sensitivity analysis of sediment inflow*

| | **add 50%** | **Mean value** | **Subtract 50%** |
|---|---|---|---|
| mean annual sediment flow (ton/ha. yr.) | 51.5 | 34.3 | 17.2 |
| sediment removed annually | 50,846 | 33,771 | 17,075 |
| Feasibility | Yes | Yes | Yes |
| aggregate net present value | 323,441,700 | 338,919,490 | 354,053,329 |
| reservoir storage capacity after 300yr | 19,154 | 36,229 | 52,925 |

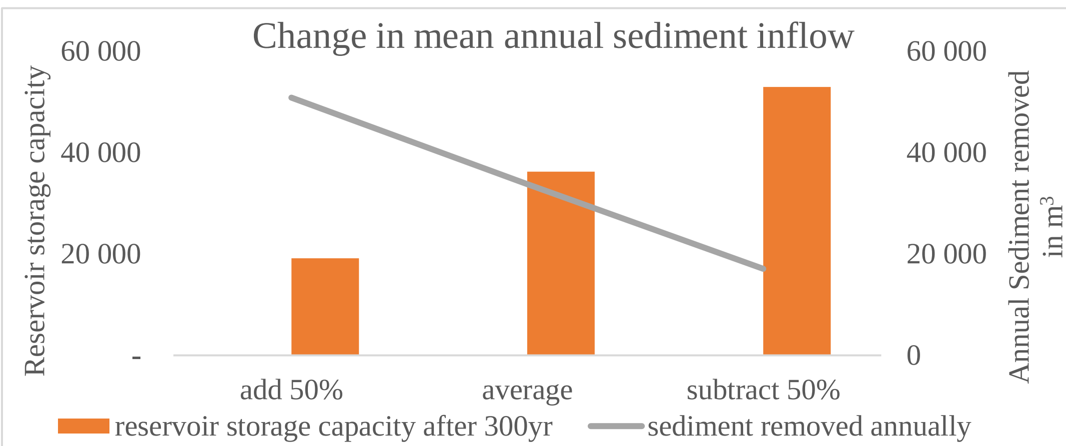



*Figure 4-1 Result for HSRS and how sensitive it is for sediment inflow*

The Paso Ancho hydropower project is highly sensitive for mean annual sediment inflow change. When the sediment inflow to the pond is increased by half then the reservoir storage capacity will decrease almost by half even if the sediment removed from the pond is increased from around 33,770m$^3$ to 51,000m$^3$.

All in all, the mean annual sediment inflow to the river will always vary and the estimation of mean annual sediment yield to the river has several uncertainties. As a result, it is necessary to check the sensitivity analysis of sediment inflow with the condition of when there is high sediment inflow as well as low sediment inflow to the peaking pond.

# 5 Result from sampling

## 5.1 Sediment handling strategy

As it is discussed in previous section about the source of sediment, amount of sediment yield in the river and when will be high sediment concentration transported to the off-stream peaking pond, then sedimentation is the main problem for this project. In addition, the incoming sediment inflow in the river always vary depending on the season. Such as in rainy season due to high tropical rain, it has large amount of sediment transportation into the headwork structure and into waterway. As a result, there has different method of sediment handling used in headwork structure and in off-stream daily regulated pond. From them, Tyrolean intake with inclined trash rack, settling basin with flashing gate and off-stream reservoir. In the off-stream peaking pond there is also flushing gate and SediCon dredging, but before installing SediCon dredging different sediment removal mechanism has tried. Such as mechanical removal and conventional dredging which uses diesel. The previous owner sells the power plant to the current owner due to high sedimentation problems in the powerplant and this occurs due to lack of information on how to prevent the incoming sediment as well as how to manage the sediment problem. During the previous owner own the power plant in rainy season, the gate in the settling basin has not operated properly so, the peaking pond has almost filled with sediment as result there was loss of storage capacity as well as energy production. Even if, the project has different sediment handling methods in headwork structure as well as in off-stream peaking pond, there has been sedimentation due to high sediment flow in the river and into headwork structure as a result it had several problems.

### 5.1.1 In headwork structure and settling basin

The intake structure is Tyrolean with proper inclination of trash rack. It has self-cleaning characteristics and adequate for coarse bed load sediment transport as well as for debris. But those lower than the spacing can pass through the intake structure and transported into the settling basin through collection chamber. Almost all the sediment which has transported into settling basin cannot settle due to unproper design of settling basin.

Infront of the settling basin there is gate which must be operated manually by closing when the sediment concentration of the incoming flow is in the range of 1% to 2%. This is done by taking continuous sample in the settling basin. There is also the 2$^{nd}$ trash rack in front of the water way tunnel in the settling basin. The purpose of trash rack is to retain debris and large stone, which is bigger than the spacing, whereas the settling basin is designed to reduce velocity of the inflow and settle the sediment. But for the Paso Ancho hydropower project the flow velocity in settling basin is not getting reduced as shown in the Figure 5-1. As a result, the sediment can be easily transported into the off-stream daily peaking pond through the tunnel.

*Figure 5-1 Shows the flow in Settling basin during rainy season.*

### 5.1.2 In off-stream daily regulated pond

When the storage of hydropower plant has built on the river, then the river will loss sediment transporting capacity and it will deposit on the reservoir. Due to this the daily peaking pond for Paso Ancho hydropower project built as off-stream.  The off-stream regulation pond is used to reduce sediment inflow but, in this case, due to design problem of the settling basin, which is not performing properly, large amount of sediment has transported into the off-stream peaking pond. Therefore, even if the peaking pond is off stream, sedimentation is the main problem. To manage the incoming sediment in the off-stream peaking pond several sediment handling mechanisms has applied. From them flushing gate is the one which located near to the inlet of the pond adjacent to spillway, but it was not enough to restore the storage of the peaking pond. Even if there are sediment handling methods in headwork structure and in the peaking pond. So, in order to remove the sediment, different sediment removal strategy has applied during the previous and the current owners own the power plant. Such as mechanical removal, conventional dredging and SediCon dredging from September 2017 until now separately.  The detail of each sediment handling method which is applied on the peaking pond will present below.

#### *5.1.2.1 Conventional dredging*

The previous owner used conventional dredge for continues management strategy due to continues sediment inflow incoming into the regulated pond. After the previous owner sell the power plant, the current owner also tried to use the it for 3 days, but it was not efficient, not comfortable for the operator due to heating and disturbing sound with high cost of operation and high consumption of diesel. So, it was necessary to find other method to solve the sediment problem.

#### *5.1.2.2 Mechanical removal*

The other option of the previous owner was decided to use mechanical removal method and to operate this method, the reservoir needs to drain down and totally stope the production. And this was happened in September 2017 and start removing with the cost of around 100,000US$. This cost is mechanical equipment rent per hour and rough estimation of removed sediment was around 13,000$m^3$ and estimation of energy production loss within this period was around 200,000US$. The other cost due to mechanical removal for this project is damaging the plastic membrane of the artificial peaking pond and which is not counted in cost. And the current owner also uses mechanical removal method with cost of 6000US$ for machine rent per hour to remove 3400$m^3$ of sediment, but this cost doesn’t include energy production loss.

Lastly the owner decides to find long lasting method to reduce the incoming sediment or to manage the sedimentation in the off-stream peaking pond with less cost. The alternative solution which the owner has found was to install dredging machine or build properly designed settling basin. To select one of them the cost benefit analysis has been done. And finally, SediCon dredging has found as the best management strategy.

#### *5.1.2.3 SediCon dredging*

SediCon dredging is a hydrosuction system which uses the available head between the reservoir and outlet of the pipe to pump out or remove deposited sediment. The outlet system of the pipe may also be either siphon or bottom outlet. The SediCon dredging can handle wide range of sediment property such as cohesive clay, organic material, sand and stones. The benefit of this sediment management strategy is the power production can continue during the operation of removing sediment, without affecting the water quality and water level. Now a days SediCon dredging is found as environmentally friend sediment management strategy as well as it has used widely. The operation of SediCon dredging uses electric power to pump water for jetting purpose only. The components of SediCon dredging are raft for operation, suction head, jetting system, flexible suction pipe and rigid suction pipe. The schematic presentation of SediCon dredging for bottom outlet and siphon outlet including all the components are shown in the Figure 5-2 below.

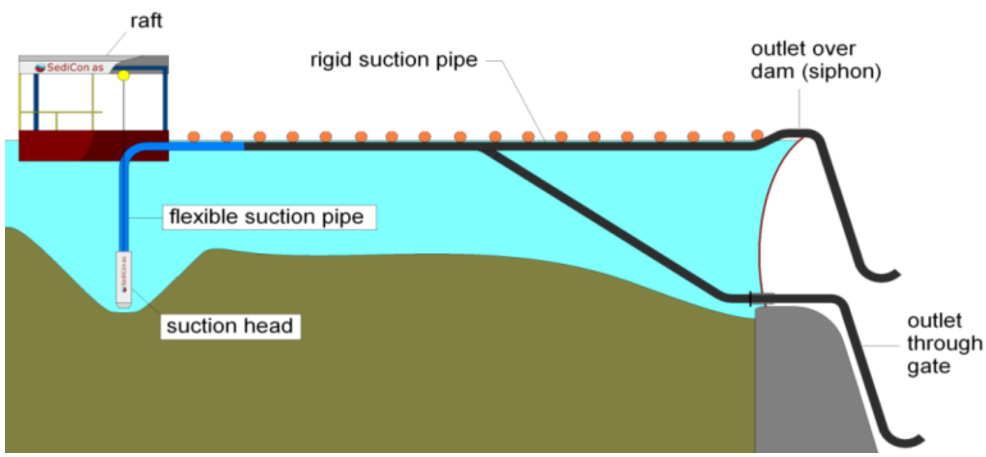



*Figure 5-2 schematic presentation of SediCon dredging (source SediCon AS)*

Sediment removal system operation in SediCon dredging is: - Before starting to remove the sediment in siphon type of SediCon dredging, the air needs to be removed from the system through the air release valve. The check valve stopped the water flow towards the inlet after the pipe is successfully filled with water. Then Water need to be pumped from the pond to the pipe in order to disperse the consolidated sediment before suction is started. lastly the outlet valve will open to discharge the sediment and suction developed to transport sediment mix. In case of bottom dredging no need for the air release but the rest operation is the same as siphon type.

If the pipe is blocked by sediment, it is cleaned by injecting the water into the pipe, but the operation could be difficult. Therefore, during suction, clear water need to be supplied to reduce clogging of pipes.

#### *5.1.2.4 SediCon dredging in Paso Ancho peaking pond*

As the large amount of sediment receive in the peaking pond, the sediment must continuously be removed without drawdown of the reservoir and stopping of production. Therefore, SediCon dredging taken as the best solution and especially designed for this project. It has installed and commissioned at the end of August 2018. The sediment removal of SediCon dredging is driven by gravity whereas for water jetting system which is used for disintegrating the sediment requires power. The hydrosuction system uses available water head between the peaking pond and outlet discharging pipe for pumping out sediment and it is 6.6m. The siphon outlet pipe is over the spillway crust. SediCon dredging is designed to remove all type of sediment in a wide range from cohesive clay and organic material to gravel and stone as shown in the Figure 5-3 below which is taken as a sample from the discharged sediment in the project area. SediCon dredging is used for frequent removal of sedimentation. Due to large amount of sediment incoming during heavy rain and flood, the owner enforced to remove gravel material, debris and other sediments in the river in front of the intake. And this has performed for 2 or 3 days in a year with mechanical removal method and it costs around 2500 US$. The installation cost of SediCon dredging was 300,000US$ and installed within two weeks. The performance has measured by taking sample every day during operation and around 17,000 $m^3$ of sediment has been removed in average for 5 months from September 2018 to January 2019.

*Figure 5-3 Stones and gravel found while removing sediment from peaking pond by SediCon dredging*

## 5.2 Sediment sampling

### 5.2.1 Sampling of incoming sediment

The incoming sediment inflow concentration in Paso Ancho HPP is estimated by taking continuous sample in the settling basin. The instrument used to measure the concentration is called Imhoff cone. From the sample, which is taken in settling basin, the sediment concentration is calculated with respect to the volume which has taken. Therefore, the result of sediment concentration is presented in graph as shown in Figure 5-4 below. And sediment concentration has also converted in to flow of sediment in the settling basin but there is uncertain while doing this. So, for this study the sample which is measured in settling basin has used to show how the variation of sediment concentration was in one year. The maximum concentration of sediment inflow in settling basin is around 6.8% in October 2018.

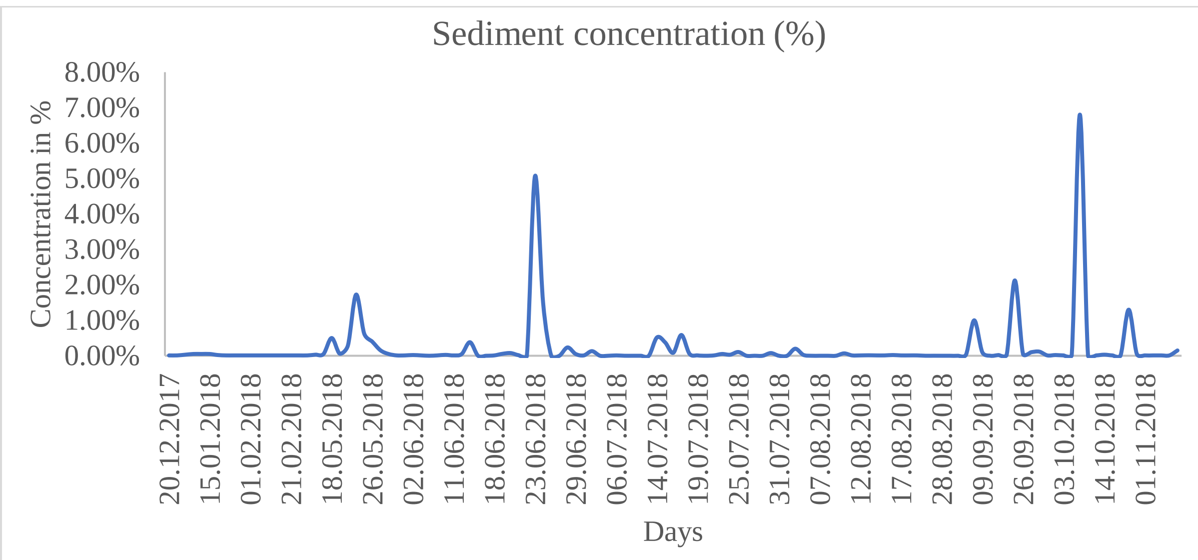



*Figure 5-4 Inflow of sediment concentration in settling basin from December 2017 to November 2018*

### 5.2.2 Sampling of discharged sediment from SediCon dredging

The two major parameters used to calculate the sediment removal capacity are, concentration and discharge. The concentration is measured by taking sample whereas the discharge is given by the pump for hydrosuction dredging. Sampling of discharged sediment from the SediCon dredging has taken to see how the concentration of sediment removed by SediCon dredging. The sampling is performed during the operation of dredging and it is taken continuously. So, the daily concentration of discharged sediment is taken by making an average of collected sample. The instrument used to measure sediment concentration is called Imhoff cone and it is a graduated cone with 1litter size as shown in the Figure 5-5 below. The figure shows dredging location of the sediment removed, how the siphon outlet pipe system looks, discharged sediment at the outlet as well as sample taken from discharged sediment and then added to Imhoff cone for concentration measurement.

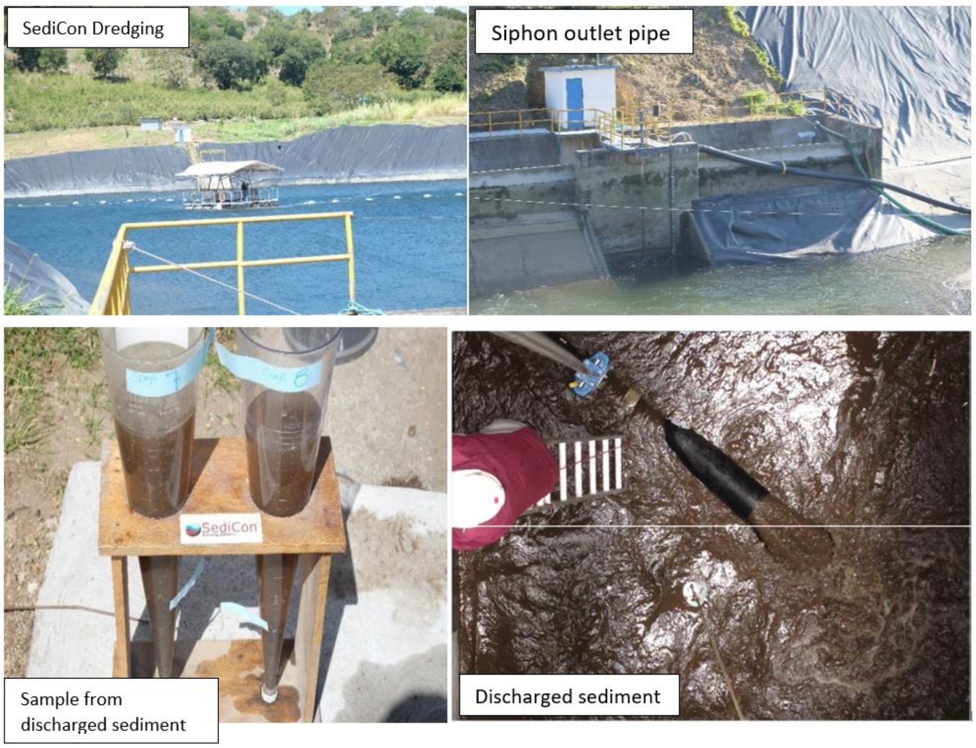



*Figure 5-5 Measurement of sediment concentration and location of discharged sediment in the pond*

An average of continuous sediment concentration data measurement is taken from September 2018 to January 2019. From the actual measurement taken on site, the sediment removed by SediCon dredging in Paso Ancho hydropower project is 44.5m$^3$/hr. And the total sediment removed within these months were 17,000 m$^3$ for 382 hr. with an average concentration of 11%. Figure 5-6 below shows the sediment removed in each month with respect to the operation hour, whereas the Table 5-1 shows the average sediment concentration in each month from the outlet discharged sediment.

*Table 5-1 The average sediment concentration in each month*

| **Months** | Sep.2018 | Oct. 2018 | Nov.2018 | Dec. 2018 | Jan.2019 | Average |
|---|---|---|---|---|---|---|
| **Concentration** | 5 % | 15 % | 15 % | 10 % | 10 % | **11 %** |

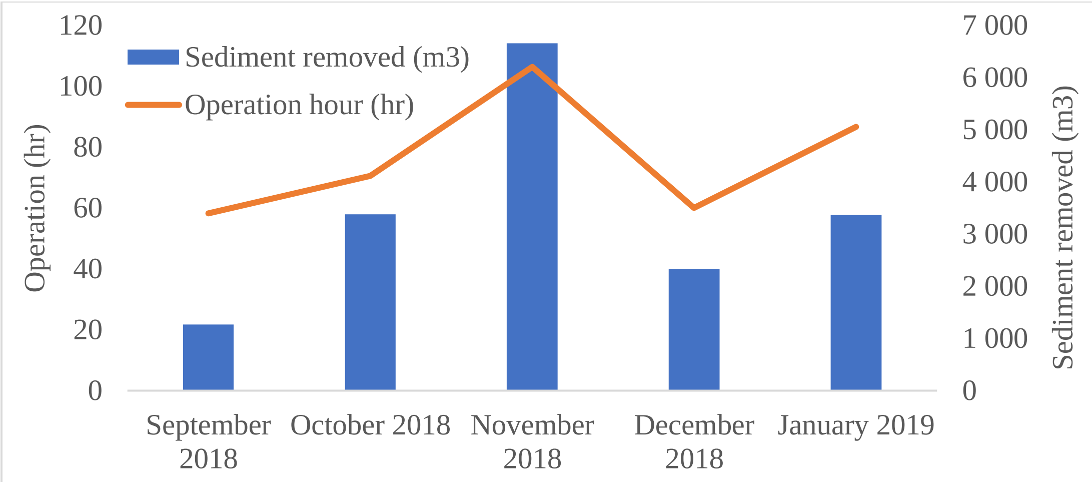



*Figure 5-6 sediment removed and operation hour of SediCon dredging in each month*

From this graph the large amount of sediment has been removed in November for around 106 hour per month which is in average 3.5 hour per day. This shows when the working hour of SediCon dredging increases, the amount of sediment removed will also increase. However, this will be dependent on the operation schedule of removing the sediment.

# 6 Result and Discussion

The manual of RESCON 2 says the model was programed based on empirical formula, which is not intended to replace detail studies. Therefore, good engineering judgment is necessary to interpret the result. But the aim of this thesis is to check the model with the known input data. Such as the sediment yield into the river as well as the selected sediment management strategy and others as presented in chapter 4. Therefore, if the input data is known rather than calculated based on empirical formula then the output can be compared with the actual result of sediment management method.

With the given input data, the result of RESCON 2 model shows that hydrosuction sediment removal is feasible for Paso Ancho peaking pond with pipe diameter of 0.45m. The amount of sediment which is removed from the peaking pond with this method is around 33,771m$^3$ annually which is in average of 2814 m$^3$ per month. But this result is by assuming 100% of the sediment yield to the river flows to the peaking pond. However, this is not possible. So, if the sediment which is transported to the peaking pond is assumed to be 50% of the total sediment yield then the result of sediment removed annually by this method from the model will go down and becomes half of the above quantity. The concentration of sediment removed through the pipe is also 7.78E+03 ppm. From this model it is not specified for how long this method will work or working hour of the machine.

From the actual filed data, SediCon dredging is designed for this project with pipe diameter of two sizes as shown in Figure 5-2 above. The one in blue color is for diameter of 0.2 m and the one in black is for diameter of 0.26 m. The amount of sediment removed for 5 months were around 17,000m$^3$ which means with an average of around 3400m$^3$ per month. As the average sediment concentration of SediCon dredging is 11% then it will be around 159.5E+03 ppm. The working hour of SediCon dredging to remove this much sediment for 5 months was 382 hr., in average of 2.5 hr. Per day. As a result, if the working hour increased specially during rainy season then the amount of sediment removed will also increase.

The other parameter that determines the sediment removal efficiency is the pipe diameter. As the pipe diameter increases the velocity of the flow will increase and this result for head losses. The head loss will have direct influence on the amount of sediment removed because the hydrosuction needs head as it works with gravity.

The actual installation time of SediCon dredging was only two weeks but the model has minimum installation time of 1 year. This is a short coming of the RESCON 2 model, and it is advices to consider implementing a shorter installation time in the model.

# 7 Conclusion and Recommendation

## 7.1 Conclusion

There is no sediment yield estimation which has been done before for Paso Ancho catchment area. Therefore, the sediment yield estimated on this study is comparable to the world map result for panama as well as from prefeasibility study of downstream powerplant project.

From world map, the annual specific sediment yield in panama is in the range of 100-250 ton. $km^{-2}$. $Yr^{-1}$. From downstream project the annual specific sediment yield estimation with a catchment area of 788 $km^2$ is 250 ton.$km^{-2}$. $Yr^{-1}$. This study shows that sediment yield estimation from Paso Ancho catchment area by using RUSLE model and Sediment delivery ratio, is 827.8 ton. $km^{-2}$. $Yr^{-1}$. These implies, the Chiriquí Viejo river carry high sediment load as a result a large amount of sediment will also be transported to the peaking pond.

The capacity of installed sediment management strategy in the peaking pond is also comparable with the result from RESCON 2. HSRS result from RESCON 2 model with pipe diameter 0.45m is, 33,771$m^3$ of sediment annually can be removed (2814$m^3$ per month). The sediment concentration that pass through the pipe is also 7.78E+03 ppm. Whereas, the result from the actual measured capacity of SediCon dredging with pipe diameter of 0.26m and 0.2m are, 17,000 $m^3$ of sediment is removed with in five months (3400$m^3$ per month) for 382 working hours. The sediment concentration that pass through the pipe is 11% which is 159E+03 ppm. Therefore, this comparison shows SediCon dredging designed for the Paso Ancho peaking pond properly remove the sediments and helps to minimize the production loss. In other words, in a high sediment carrying river, a sustainable powerplant with a daily regulation pond as well as a minimum turbine wear is achieved. This is because of SediCon dredging sediment management strategy.

All in all, SediCon dredging which was designed for Paso Ancho hydropower project is highly efficient with respect to the amount of sediment removed.

## 7.2 Recommendation

Result from RUSLE model as well as from RESCON 2 for this study is satisfactory. But there are uncertainties related to the model input data and the empirical formulas. Therefore, for the future a detail study is advised.

To the extent of the work, there was shortage of time and luck of important data.  Some factors are taken from global map which could highly influence the result. In addition, most of the time was spent on data collection. Therefore, to get a better result on RUSLE model and validate the result, which is in this thesis, there should be detail study with more time and resources at the project site in Panama.

With respect to the comparison of RESCON 2 model result of HSRS and the actual installed SediCon dredging, both uses different design method and equation. Due to this the pipe diameter of SediCon dredging will give negative head loss gradient in the RESCON 2 model, and it becomes positive when the pipe diameter is 0.45m. But due to shortage of time this was not covered in this study. Therefore, for further work it is recommended to investigate the effect of those two method and equations.

In the project area it is advised to have a continuous sediment measurement method. It will help for a better powerplant operation.

## Reference


[1] "17-8652_GSR2018_FullReport_web_-1.pdf." .

[2] "Hydropower - Energy Explained, Your Guide To Understanding Energy - Energy Information Administration." [Online]. Available: https://www.eia.gov/energyexplained/index.php?page=hydropower_home. [Accessed: 01-Feb-2019].

[3] G. P. Harrison and H. W. Whittington, "Impact of climatic change on hydropower investment," p. 6.

[4] P. Négrel *et al.*, "Soil–Sediment–River Connections: Catchment Processes Delivering Pressures to River Catchments," in *Risk-Informed Management of European River Basins*, vol. 29, J. Brils, W. Brack, D. Müller-Grabherr, P. Négrel, and J. E. Vermaat, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2014, pp. 21–52.

[5] E. Wolanski and M. Elliott, "Estuarine sediment dynamics," in *Estuarine Ecohydrology*, Elsevier, 2016, pp. 77–125.

[6] K. G. Renard, G. R. Foster, G. A. Weesies, D. K. McCool, and D. C. Yoder, "Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE).," *Agric. Handb. Wash.*, no. No. 703, 1997.

[7] G. W. Annandale, G. L. Morris, and P. Karki, "Extending the Life of Reservoirs," p. 191.

[8] D. E. Walling and B. Webb, *Erosion and Sediment Yield: Global and Regional Perspectives : Proceedings of an International Symposium Held at Exeter, UK, from 15 to 19 July 1996*. IAHS, 1996.

[9] I. of W. R. Da Ouyang, Jon Bartholic Michigan State University, East Lansing, MI, "PREDICTING SEDIMENT DELIVERY RATIO IN SAGINAW BAY WATERSHED," 19-May-1997. [Online]. Available: http://www.iwr.msu.edu/rusle/sdr/sag-sdr.htm. [Accessed: 07-Feb-2019].

[10] D P C Laknath, Jeewanthi Sirisena, "(PDF) Sediment Yield Estimation on a Reservoir in Severely Eroding River Basin," *ResearchGate*, Aug-2017. [Online]. Available: https://www.researchgate.net/publication/319238661_Sediment_Yield_Estimation_on_a_Reservoir_in_Severely_Eroding_River_Basin. [Accessed: 03-Feb-2019].

[11] M. L. Wischmeier, W. H., and Smith, D.D., "1 PREDICTING - RAINFALL EROSION LOSSES f A GUIDE TO CONSERVATION PLANNING," vol. U.S. Department of Agriculture, p. Agriculture Handbook No. 537.-, 1978.

[12] "Revised Universal Soil Loss Equation for Application in Canada Handbook." [Online]. Available: http://sis.agr.gc.ca/cansis/publications/manuals/2002-92/index.html. [Accessed: 04-Feb-2019].

[13] K. G. Renard, D. C. Yoder, D. T. Lightle, and S. M. Dabney, "Universal Soil Loss Equation and Revised Universal Soil Loss Equation," in *Handbook of Erosion Modelling*, R. P. C. Morgan and M. A. Nearing, Eds. Chichester, UK: John Wiley & Sons, Ltd, 2011, pp. 135–167.

[14] V. Prasannakumar, H. Vijith, S. Abinod, and N. Geetha, "Estimation of soil erosion risk within a small mountainous sub-watershed in Kerala, India, using Revised Universal Soil

Loss Equation (RUSLE) and geo-information technology," *Geosci. Front.*, vol. 3, no. 2, pp. 209–215, Mar. 2012.

[15] J. C. Calvo-Alvarado, C. D. Jiménez-Rodríguez, and V. Jiménez-Salazar, "Determining Rainfall Erosivity in Costa Rica: A Practical Approach," *Mt. Res. Dev.*, vol. 34, no. 1, pp. 48–55, Feb. 2014.

[16] A. E. Jazouli, A. Barakat, R. Khellouk, J. Rais, and M. E. Baghdadi, "Remote sensing and GIS techniques for prediction of land use land cover change effects on soil erosion in the high basin of the Oum Er Rbia River (Morocco)," *Remote Sens. Appl. Soc. Environ.*, vol. 13, pp. 361–374, Jan. 2019.

[17] L. Xu, X. Xu, and X. Meng, "Risk assessment of soil erosion in different rainfall scenarios by RUSLE model coupled with Information Diffusion Model: A case study of Bohai Rim, China," *CATENA*, vol. 100, pp. 74–82, Jan. 2013.

[18] A. S. M. Habtamu Sewnet Gelagay, "Soil loss estimation using GIS and Remote sensing techniques: A case of Koga watershed, Northwestern Ethiopia," *Int. Soil Water Conserv. Res.*, vol. 4, no. 2, pp. 126–136, Jun. 2016.

[19] K. K. K. Kuok, D. Y. S. Mah, and P. C. Chiu, "Evaluation of C and P Factors in Universal Soil Loss Equation on Trapping Sediment: Case Study of Santubong River," *J. Water Resour. Prot.*, vol. 05, no. 12, pp. 1149–1154, 2013.

[20] H. Lu, C. J. Moran, I. P. Prosser, M. R. Raupach, J. Olley, and C. Petheram, "Sheet and Rill Erosion and Sediment Delivery to Streams: A Basin Wide Estimation at hillslope to Medium Catchment Scale," *Tech. Rep.*, p. 56, 2003.

[21] M. Ramdhan Olii, B. Agus Kironoto, B. Yulistiyanto, and Sunjoto, "DETERMINING SEDIMENT DELIVERY RATIO OF CATCHMENT Of RESERVOIR IN JAVA," 2017.

[22] D. Buhr, M. Camplair, and E. Hamilton, "Modeling Post-Fire Sediment Yields and Reservoir Capacity in the Upper Mad River Basin, California," p. 24.

[23] H. S. Shrestha, "Application of Hydrosuction Sediment Removal System (HSRS) on Peaking Ponds," *Hydro Nepal J. Water Energy Environ.*, vol. 11, pp. 43–48, Jul. 2012.

[24] T. Jacobsen, "SEDIMENT PROBLEMS IN RESERVOIRS, control of sediment deposits. PHD dissertation, Norwegian University of Science and Technology, Trondheim.," p. 183, Nov. 1997.

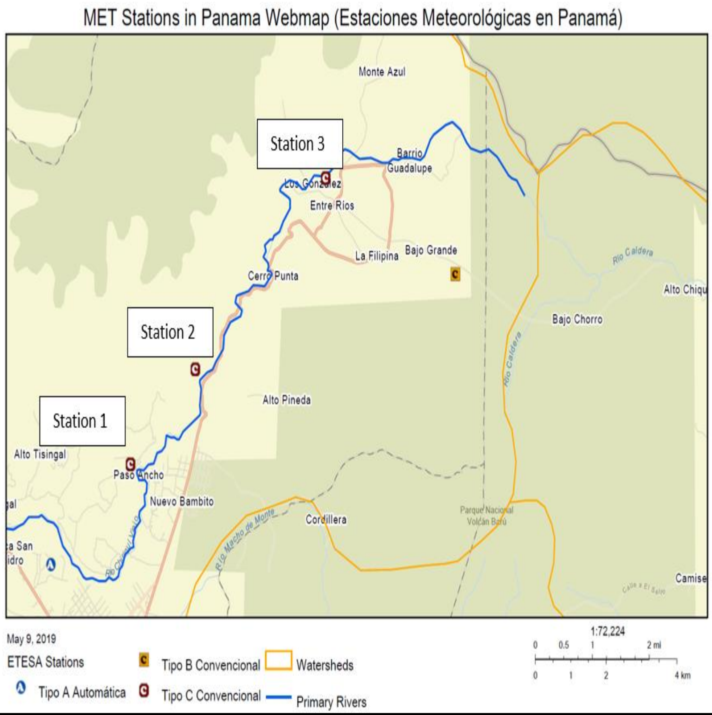
[25] R. H. Hotchkiss and X. Huang, "Hydrosuction Sediment-Removal Systems (HSRS): Principles and Field Test," *J. Hydraul. Eng.*, vol. 121, no. 6, pp. 479–489, Jun. 1995.

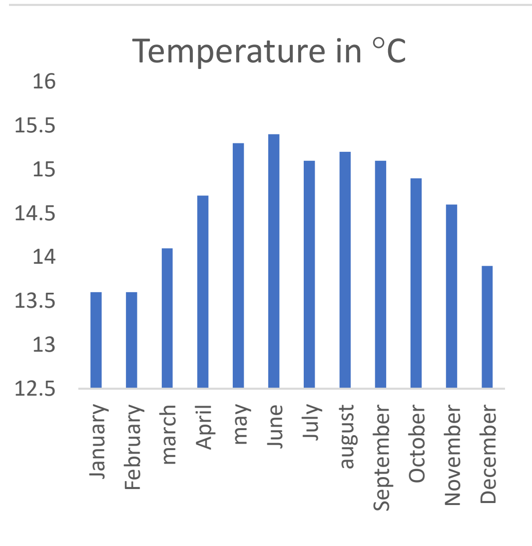
[26] A. Palmieri, F. Shah, G. W. Annandale, and A. Dinar, "Nikolaos Efthymiou, Sebastian Palt, George W. Annandale, Pravin Karki," p. 218.

[27] Y. Farhan and S. Nawaiseh, "Spatial assessment of soil erosion risk using RUSLE and GIS techniques," *Environ. Earth Sci.*, vol. 74, Sep. 2015.

[28] N. de O. Carvalho and N. P. F. Júnior, "RESERVOIR SEDIMENTATION ASSESSMENT GUIDELINE," p. 101.

# Appendix A: Precipitation and temperature data




| Gauging station | N California (station 1) | C Punta (station 2) | B Grande (station 3) |
|---|---|---|---|
| May | 380 | 230 | 265 |
| June | 360 | 250 | 240 |
| July | 280 | 200 | 290 |
| August | 350 | 240 | 280 |
| September | 450 | 280 | 345 |
| October | 470 | 300 | 235 |
| November | 260 | 190 | 240 |
| December | 50 | 150 | 140 |
| January | 20 | 80 | 95 |
| February | 30 | 50 | 70 |
| March | 70 | 40 | 120 |
| April | 160 | 90 | 260 |
| **MAP (mm)** | **2880** | **2100** | **2580** |

# Appendix B: Picture taken from the catchment area

Pictures of near to the intake

**Pictures of around 100m upstream of the dam**

**Pictures of around 2km upstream of the dam**



**Picture of farming area up stream of intake**

# Appendix C: Sedimentation problem on the powerplant

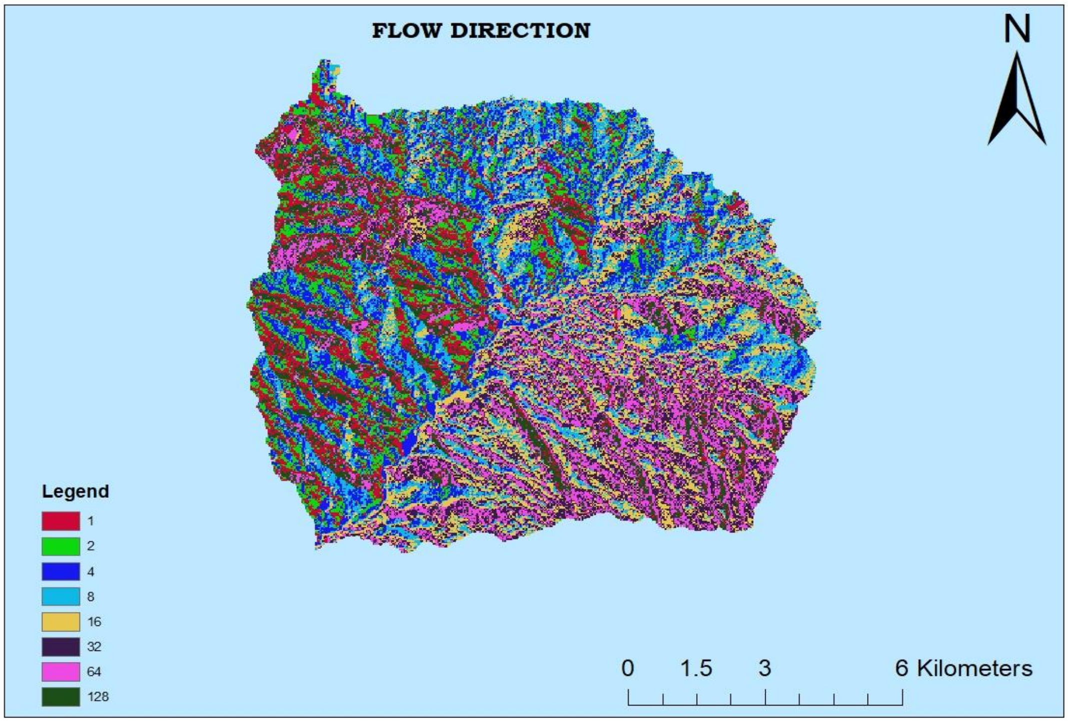
# Appendix D: Daily peaking pond variation

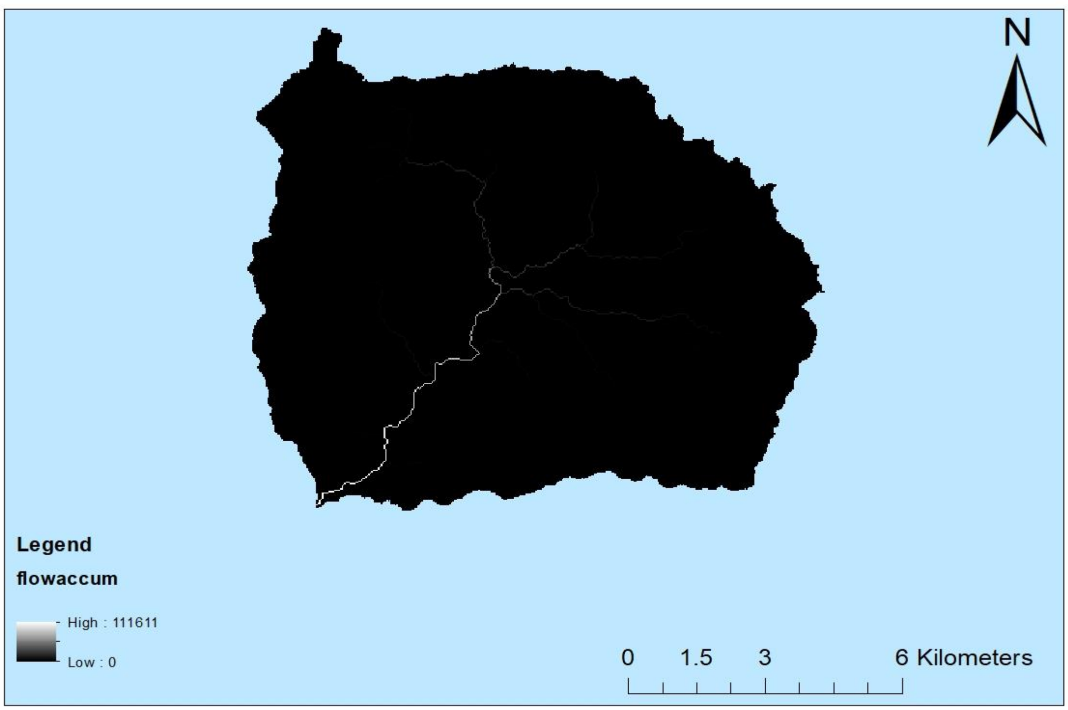
| In the morning at full level with spilling |
| --- |
|  |
| around 18:00 the peaking pond become |
|  |

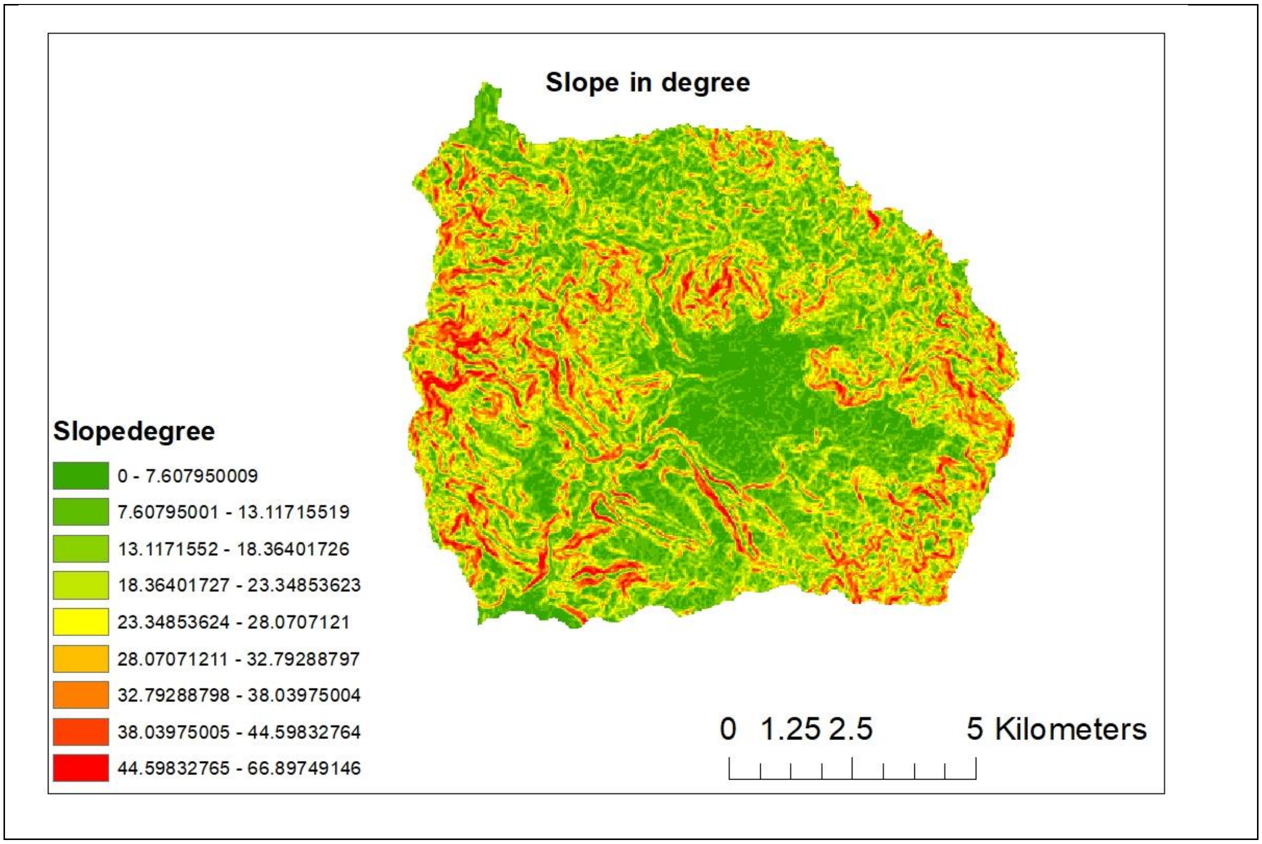
# Appendix E: Sieve analysis of 7 different sample location and result

| | | % pass | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Sieve No | Grain size | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 | Sample 6 | Sample 7 |
| No 4 | 4.75mm | 99.1 | 92.1 | 95.7 | 100 | 99.9 | 82.2 | 97.1 |
| No 8 | 2.36mm | 91.6 | 87.2 | 92.1 | 99.4 | 99.5 | 77.3 | 95.4 |
| No 10 | 2mm | 96.7 | 84.9 | 90.4 | 99.2 | 99.3 | 75.3 | 94.7 |
| No 16 | 1.18mm | 92 | 69.7 | 81.7 | 97.7 | 98.3 | 62.5 | 92 |
| No 20 | 850µm | 85.1 | 52.5 | 72.5 | 95.4 | 96.6 | 47.1 | 89.4 |
| No 30 | 600µm | 70.3 | 28.9 | 53.5 | 87.4 | 90.8 | 25.5 | 83.7 |
| No 40 | 425µm | 57.8 | 14.5 | 35.3 | 70.6 | 82 | 12 | 76.1 |
| No 50 | 300µm | 30.2 | 5.7 | 14.4 | 34.8 | 52.9 | 4.2 | 61.9 |
| No 60 | 250µm | 19.9 | 3.4 | 8.7 | 17.4 | 43.3 | 2.1 | 55.3 |
| No 100 | 150µm | 4.2 | 2.1 | 2.2 | 2.5 | 13.6 | 0.6 | 32.4 |
| No 200 | 75µm | 1.1 | 1.9 | 1.1 | 0.6 | 4.4 | 0.3 | 31.7 |

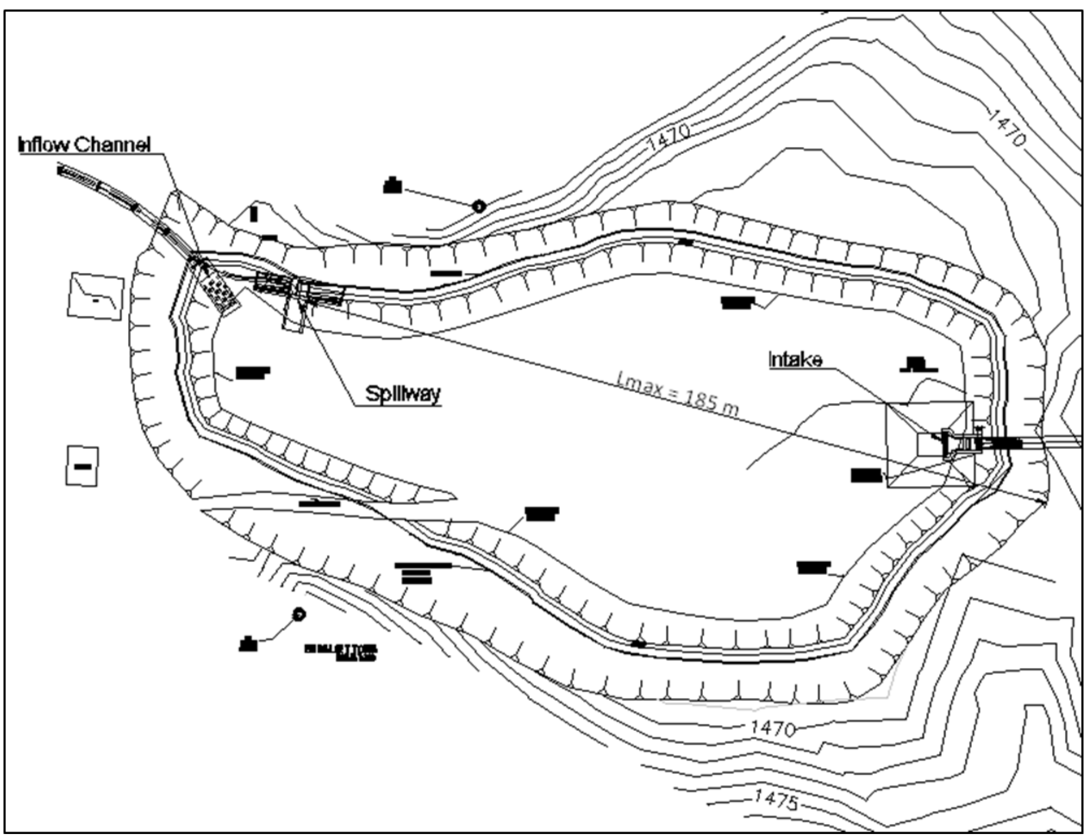
## Appendix F: Flow direction, accumulation and slope map




Slope in degree
Slopedegree
0 - 7.607950009
7.60795001 - 13.11715519
13.1171552 - 18.36401726
18.36401727 - 23.34853623
23.34853624 - 28.0707121
28.07071211 - 32.79288797
32.79288798 - 38.03975004
38.03975005 - 44.59832764
44.59832765 - 66.89749146
0 1.25 2.5 5 Kilometers

# Appendix G: RESCON 2 user interface and reservoir geometry

# Appendix H: Result from RESCON 2 model for HSRS

| Technique | Hydrosuction Sediment Removal System (HSRS) | |
|---|---|---|
| **Extend of removal of annual deposits** | No removal of deposits until year 0. Total deposit removal after that. | |
| **Conclusion on technical feasibility** | Technically feasible. | |
| **Physical performance of reservoir** | | |
| **Reservoir Sustainability** | **Sustainable** | |
| **Reservoir lifetime** | > 300 | [years] |
| **Reservoir storage capacity after 300 years of operation** | 36 229 | [m3] |
| **# of years until reservoir is sustained at long term capacity (LTC) for sustainable HSRS** | 0 | [years] |
| **Economic performance of reservoir** | | |
| **Aggregate Net Present Value (first 300 years of operation)** | 338 919 490 | [US$] |
| **Annual Retirement Fund for sustainable reservoir operation** | N/A | [US$/a] |
| **Description of HSRS operation** | | |
| **Installation year of HSRS system** | 1 | [Year] |
| **Frequency of HSRS operation** | Annual operation | [Years] |
| **Sediment removed annually by HSRS** | 33 771 | [m³] |
| **Average expected concentration of sediment to water:** | | [ppm] |
| **Implicit unit cost of HSRS expressed as $/m3 of sediment removed** | 0.14 | [US$/m³] |
| **Definition of Hydrosuction Sediment Removal System (HSRS)** | | |
| **Tolerance Check** | OK | |
| **Sediment Transport Rate, Qs** | 2.52E-03 | [m³/s] |
| | 320 | [metric tons/d] |
| | 107 092 | [metric tons/a] |
| **Reservoir Volume restored** | 218 | [m³/d] |
| | 72 852 | [m³/a] |
| **Mixture Velocity, Vm** | 3.0 | [m/s] |
| **Mixture Flowrate, Qm** | 0.5 | [m³/s] |
| **Sediment Concentration through Hydrosuction Pipe, C** | 7.78E+03 | [ppm] |
| **Sediment to Water HSRS Ratio** | 5.28E-03 | [m³ sed / m³ water] |

# Appendix I Master thesis task description

Title: Sediment yield assessment and sediment management strategy for Paso Ancho HPP

**1. Background**

Solar energy, Wind energy, Thermal energy, Biomass and Hydropower energy are examples of major renewable energy sources in the present century. Among these, the hydropower is of a great interest among the market players and developers. The reasons behind it are the generation of energy from abundantly available water resource, highest energy payback ratio and ability to respond quickly during peak demands. Consequently, hydropower has taken a remarkable position in the energy market being a sustainable source of energy. However, many hydropower plants (HPP) are facing technical challenges, among one of them are sediments. Hydropower dams are altering the sediment balance of a river reach significantly and have consequently to cope with the consequences. These consequences are e.g. lifetime reduction due to sedimentation processes, risk of destruction of the headwork due to extreme flood events or high operation and maintenance costs due to abrasion of turbines and hydraulic structures.

With this background, the HPP Paso Ancho will be investigated. The candidate will model the sediment yield compare that to the volume of sediment deposited in the peaking pond. Knowing the sediment yield in addition to other input data, the candidate will then apply the RESCON II model to get a recommendation for a sediment handling operation. This recommendation will then be compared to the sediment handling operation installed at the HPP. This includes efficiency measurement of the installed hydro suction system.

Learning outcomes:

- Understanding sediment management strategies
- Understanding sediment yield modelling including the collection of the input data.
- Understanding operation of HPP Paso Ancho as it is today including their operation schedule (and what is going wrong).
- Understanding the installed hydro suction systems
- Understanding and conducting efficiency measurements of hydro suction systems
- Understanding RESCON II model

Thesis outcomes:

- Sediment yield estimation for the catchment of the HPP Paso Ancho
- Evaluating of the hydro suction efficiency
- Theoretical sediment management strategy for HPP Paso Ancho
- Suggestion for different management strategy including on the one hand operation changes and on the other hand constructional changes based on local experiences.

**2. Work description**

The thesis shall cover, though not necessarily be limited to the main tasks listed below. Based on the available documentation the following shall be carried out:

1. Literature review on sediment handling in general and on hydro suction
2. Short literature overview of the use of RUSLE & RESCON II modeling including a list of input data needed for both models.
3. Traveling to the HPP for field measurements
4. Setting up and sediment yield model (RUSLE) for Paso Ancho catchment.
5. Setting up and running RESCON II model HPP Paso Ancho with focus on hydrosuction
6. Presentation of the results.
7. Discussion of the results
8. Conclusions
9. Proposals for future work
10. Presentation

**3. Supervision**

Associate Prof. Nils Rüther will be the main supervisor. Dr. Tom Jacobsen from SediCon AS is appointed as co-supervisors.

Trondheim, 14. January 2019

____________________________

Nils Rüther

Associate Professor

Department of Civil and Environmental Engineering

NTNU

NTNU

Kunnskap for en bedre verden