Pratik Bijukchhe

3D Numerical Modelling of Sediment Fluxes at Paso Ancho Hydropower Project

Master's thesis in Hydropower Development
Supervisor: Nils Ruther
July 2019

Master's thesis

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Preface

This report title "3D Numerical Modelling of Sediment Fluxes at Paso Ancho Hydropower Project" is a master thesis for the Master of Science in Hydropower Development and submitted to the Department of Civil and Environmental Engineering, Norwegian University of Science and Technology. The topic of this master's thesis was made with an agreement between NTNU and SediCon AS with focus on the sediment problem at the Paso Ancho Hydropower Project at Panama.

The work on the thesis started on January 15, 2019 and finished on July 14, 2019. Before going to the site for data collection, full time was spent on getting to know the measurement and survey techniques of Acoustic Doppler Current Profiler, using the River Surveyor Live software and post processing a collected data. The project site at Volcan, Panama was visited from February 19, 2019 to March 18, 2019 to collect necessary data for the numerical model and thesis report. The three-dimensional numerical model is setup for the peaking pond and simulation results are compared with the field data and is discussed.

I would like to express my sincere gratitude to my supervisor, Professor Nils Ruther for his assistance, guidance, suggestions, encouragement and sharing his wide knowledge and expertise.

I would like to thank my co-supervisor Diwash Lal Maskey, Ph.D. candidate at Department of Civil and Environment Engineering at NTNU, for the suggestions and guidance on using the SSIIM throughout the semester.

I would like to express my gratitude to my co-supervisor Tom Jacobsen, Technical Director at SediCon AS for his cooperation to formulate the topic of this thesis, suggestions on the thesis report and his support and guidance during the site visit.

I would also like to thank Alberto Jimenez Cordero, Regional Director of SediCon AS, Costa Rica for the organizing things in Panama and his support and guidance throughout the time in site.

I would like to thank Marcos A. Domínguez Aguirre, Plant Manager at Paso Ancho Hydropower Project and rest of the staff of the project for supporting me to carry out field measurements at site and providing all the necessary data of the project.

I would like to extend the thank to Slaven Conevski, Ph.D. Candidate at Department of Civil and Environmental Engineering, NTNU for the guidance on the working of the ADCP and River Live Software and supporting me for the postprocessing of the data in MATLAB.

Abstract

The purpose of this thesis was to setup a three-dimensional numerical model on SSIIM 2 for the peaking pond of the Paso Ancho Hydropower Project. Not limited to numerical model, failure reasons for the desander is also studied. The main aim of the numerical model is to obtain the distribution of bed sediment in the pond and compare with the data from the field.

The peaking pond has severe sediment problem due to the poor efficiency of the desander located at the headworks. All the sediments entering through the intake passes through the desander and enter in to the pond. This has led to loss of capacity of the pond and extra financial cost for implementation of different sediment removal methods. At present, 200mm dredge installed by SediCon is removing the sediments from the pond. It was installed in August 2018 and by January 2018 had removed around 14458m^3 volume of sediments. The total capacity of pond is 70000m^3.

A survey was done by Acoustic Doppler Current Profiler (ADCP) to obtain the bathymetry and velocity profile of the peaking pond. Sediment samples from the bed of the pond was analyzed in the lab to obtain the grain size distribution of the samples. The discharge in river was measured to obtain the inflow in the pond. These field data are compared with the results from the SSIIM model.

A three-dimensional numerical model has been setup to perform hydraulic and sediment transport simulation. A first model is setup with the measured discharge and surveyed geodata to perform a water flow simulation. The obtained velocity magnitude is compared with the surveyed velocity profile data. The hindrance most encountered was in shaping the inflow structure for the peaking pond to imitate the same flow pattern as actual in the site. The model showing similar pattern of flow is chosen and two additional cases of water flow simulation are performed which later is used for sediment transport simulation. Second model is run with the higher discharge corresponding to the discharge of wet season at which the pond receives high sediment inflow. And third model is run again on the higher discharge but the geodata of original geometry of the pond is used, which has no sediment deposition. The second and third cases of water flow simulation are used to the run the sediment transport simulation. From the sediment simulation, the bed grain size distribution is obtained and compared with the sediment samples taken from the pond.

Number of changes to the geometry and location of the inflow were done and different algorithms and parameters were used simultaneously to produce a likely result. The result showed similar flow patterns but different bed sediment distribution when comparing with the field data. There are still uncertainties concerning the input data, geometry of inflow and outflow. The sediment deposition and distribution pattern in pond is affected by the daily fluctuation of water level in the pond. There is a daily lowering down of water level to the lowest possible operation level since this is a daily peaking type project and has different inflow and outflow discharge. The numerical model is run in the scenario assumed that in the wet season, when discharge is high in the river, the level of water at the pond is maintained at constant normal water level throughout the day and has an equal inflow and outflow discharge.

To conclude, the model requires more calibration and validation from the field data and further work on the geometry of model is also recommended to use the model for the prediction of sediment distribution.

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1. Introduction

1.1. Objective of the study

In this modern world, the energy demand is increasing more and more at fast pace. Energy demand worldwide grew by 2.3% in 2018, which is the fastest in the last decade and renewable energy sources were major contributor for fulfilling this energy demand. (IEA, 2019). Among the renewable's energy source, the hydropower is one of the established and oldest sources of energy for producing mechanical and electrical energy and still has great interest form the market players and developers. It has been estimated that if all the available resources are to be harnessed, extra 10,000 TWh/year can be produced. According to the 2018 Hydropower Status report, 4,185 TWh in electricity was generated by the hydropower last year.

However, having a such big potential and being a sustainable source of energy, many projects faces a technical challenge, sediments being one of them. Sediments are the naturally occurring fragments of rock and minerals originating from catchment area or within the river bed and is broken down by processes of weathering and erosion and subsequently transported by the help of wind, water, ice or by the force of the gravity. Sediment transport in the river is a natural phenomenon and a natural river with no artificial or natural obstruction will often have a balanced sediment inflow and outflow.

The hydropower projects obstruct the natural flow of the river. In case of storage projects, sediment starts to accumulate in front of the dam and without proper sediment handling, there is a loss of storage capacity in the reservoirs. But in the run of the river type project, where there is no storage in front of the dam, sediment can enter in the intake. So, sediments should be trapped and flushed well before the water reaches to turbines. Sediment flow in the turbine can cause erosion of the turbine which lead to loss in efficiency and in worst cases breakdown of the turbine components. Run on the river project doesn't alter the sediment balance in the river dramatically but the hydropower project itself faces the challenge in trapping the sediment entering through the intake. So, a sediment trapping system is required. A desander is a common structure in the run of river project to trap and remove the suspended sediment particles that enters through the intake. The performance of desander is dependent on its ability to trap and remove suspended particles and will also influence the power generation. So, a wrong design of the settling basin creates a lot of problems.

In this study, the desander and peaking pond of Paso Ancho Hydropower Project located at Volcan, Panama is investigated. The settling basin is operating with a poor efficiency which leads to the continuous filling of peaking pond with the sediments.

The site was visited from February 19, 2019 to March 22, 2019 to collect data and carry out field measurements.

2. Theory

This chapter aims to give a theoretical description of sedimentation process relevant in this study, survey methods and modelling of sediment transport.

2.1. Sediment sizes

Sediment can be originated from the catchment area or within the river bed and are mainly created by weathering and erosion of the surface. Their occurrence depends on many factors like river morphology, soil properties, land utilization, and others. Sediment properties can be classified into two: cohesive and granular sediments. Silt and Clay has cohesive properties which cause the sediment to bind together and other than silt and clay, there are granular sediments. Figure below show the different types of sediment and their classification based on the particle size;

ISO 14688-1			
Name			Size range
Very coarse soil		Large boulder, LBo	>630 mm
		Boulder, Bo	200 – 630 mm
		Cobble, Co	63 – 200 mm
Coarse soil	Gravel	Coarse gravel, CGr	20 – 63 mm
		Medium gravel, MGr	6.3 – 20 mm
		Fine gravel, FGr	2.0 - 6.3 mm
	Sand	Coarse sand, CSa	0.63 - 2.0 mm
		Medium sand, MSa	0.2 - 0.63 mm
		Fine sand, FSa	0.063 - 0.2 mm
Fine soil	Silt	Coarse silt, CSi	0.02 - 0.063 mm
		Medium silt, MSi	0.0063 - 0.02 mm
		Fine silt, FSi	0.002 - 0.0063 mm
	Clay, Cl		≤0.002 mm

Figure 2-1 Sediment properties

2.2. Sediment Transport

The forces acting on sediment particles are normally split into two categories, i.e. the stabilizing forces and the destabilizing forces. Sediment have a higher density than water, and if there is no movement of the water, the sediments will remain stable at the bottom. Gravity in addition to cohesive forces between fine sediment particles, may in general represent the stabilizing forces, which resist movement. The flow velocity or the turbulence level in the fluid may likewise represent the destabilizing forces, which lifts and drags the sediments, that are in suspension or as bed load.

2.2.1. Particle fall velocity

The fall velocity is an important parameter for sediment behavior in a motion. A sediment particle can be transported in the suspension only if its settling velocity is less than the vertical component of hydraulic turbulence. Settling basin design is guided by the fall velocity of the sediment particle which shall be trapped and removed. The fall velocity depends on the characteristics such as size, shape and density, and on fluid characteristics such as temperature, salinity, and sediment concentration which affects the fluid viscosity and density. There are different charts, formulae and expression that determines the fall velocity. A simplified equation for fall velocity is developed by Rubey in 1931 to estimate terminal fall velocity over the full range of particle diameters, which is expressed in the following form:

$$\omega = \frac{[1636(\rho_s - \rho)d^3 + 9\mu^2]^{0.5} - 3\mu}{500d} \qquad 1$$

where ω = terminal fall velocity, m/s; ρ_s and ρ= density of sediment and water respectively, kg/m^3; μ= viscosity or dynamic viscosity, (N.s)/m^2 and d = particle diameter, m.

2.2.2.Drag, lift and gravity

The water exerts forces on the particle often referred to as drag and lift. The drag works in the main direction of flow and lift transversally to the flow direction. The general formula for drag and lift are:

$$F_D = C_D.A.\rho.\frac{u^2}{2}, \text{ and } F_L = C_L.A.\rho.\frac{u^2}{2} \qquad 2$$

where, C_D and C_L = coefficient and drag and lift, u = water velocity at river bed.

As stated earlier, 2.2.1., gravity forces are stabilizing force, which in suspended transport is balanced by the forces of the turbulent current and in bed load motion also causes resistance due to friction against the stationary bed.

2.2.3. Bed shear stress and shear velocity

The transport theory of sediments particularly for bed load is based on the shear stress and turbulence as determining factor. The shear stress is average force per unit bed area exerted by the water on the bed which arises due to friction and depends on the roughness, water depth and slope of the bed. Shear stress is the result of turbulence, transferring momentum to the bed.

Direct measurement of turbulence is impossible in practical case. But turbulent to the velocity distribution near the bed can be known if the average velocity of two points near the bed is known. It is possible to assess the effect of turbulence and calculate the bed shear stress using the following formulae:

$$u_* = \frac{0.17(u_1 - u_2)}{\log(z_1 - z_2)} \qquad 3$$

$$\tau_\circ = u_*^2.\rho_w \qquad 4$$

Where, u_* is the shear velocity and u_1 and u_2 are the two measured bed velocities, z_1 and z_2 are the corresponding distances from the bed, $\tau_\circ$ is bed shear stress and ρ_w is the density of water.

In uniform flow, when bed and water surface are parallel, the bed shear stresses are found directly by combining slope, S fluid density and hydraulic radius, R

$$\tau_\circ = g.\rho_w.R.S \qquad 5$$

2.2.4.Incipient motion

Shields combined expression for the destabilizing forces drag and lift, against weight or friction as the stabilizing force into general formula for the equilibrium of particles;

$$F_r = \frac{\tau_0}{(\rho_s - \rho_w).g.d} \qquad 6$$

The Shields diagram is shown below which relates the F_r to a particle Reynolds' Number Re= u*. d/v, where u_* is the shear velocity, d is the gran size and v is the kinematic viscosity of water.

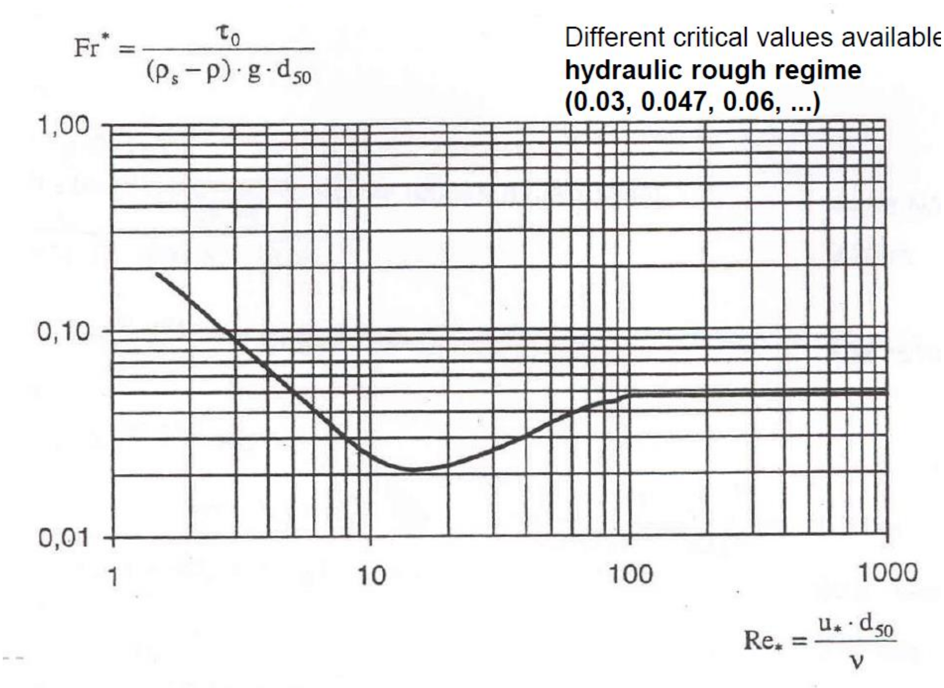


Figure 2-2 Shields diagram for start of motion

Value of F_r below the curve indicate the stability against motion. Values on the curve indicate start of the motion and are labelled critical Shields number, F_r. The corresponding shear stress is the critical shear stress.

2.2.5.Hjulstrøms diagram

Hjulstrøm's curve is a simpler method to determine whether a river will erode, transport or deposit sediments. The velocity is assumed to be the average velocity of the cross section. The diagram was developed with relatively constant water depth and with grains of similar sizes. (Fergus 2010)

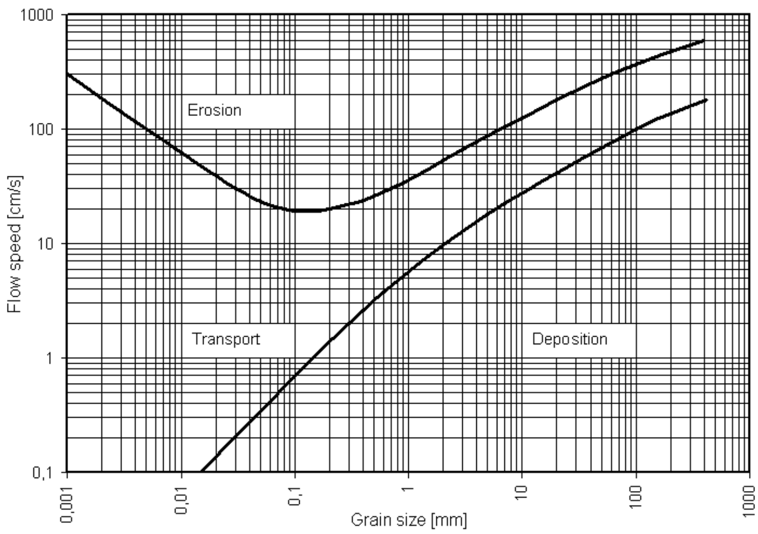


Figure 2-3 Hjulstrøms Curve

2.3. Survey Methods

The deposition and distribution pattern of sediment in reservoir can be obtained from the repeated bathymetric surveys. Accurate bathymetric survey is important and is an appropriate means for monitoring the accumulation of sediments overtime in reservoir. Repetitive surveys are important to find out the total volume, sediment pattern and the shift in the stage area and stage-storage curves of the reservoir. Surveys can be classified as range surveys or contour and among them, contour surveys are the most accurate technique for determining volume to obtain the complete information on sediment distribution. The photogrammetric technique or airborne laser can also be applied, if the reservoir is emptied or significantly drawn down (*Morris and Fan, 1997).*

Range method has traditionally been the most widely used method to measure reservoir sedimentation. It provides the means to efficiently track sediments accumulation with a minimum field data. When sediment thickness is known along the range lines, the range methods can also be used to compute sediment volume.

Contour surveys use more complete topographic or bathymetric information to prepare a contour map. They are the most accurate technique for determining volume and provide the most complete information on sediment distribution. Advanced automated hydrographic equipment can define the absolute x, y, z coordinates of the reservoir bottom during traverses. The networks of traverses should be much denser that in the traditional range survey method. All position and depth data are continuously recorded into the file which can subsequently be post processed to plot survey results and automate tedious volume computation. The hydrographic survey should be performed when the reservoir is at the high level. Area above water must be surveyed by either traditional or photogrammetric methods and merged with the hydrographic data. (*Morris and Fan, 1997).* In addition to position and depth data, there are equipment which can also obtain velocity profile of the surveyed cross-section.

For the small and medium sized reservoirs, the range line method can be used as a survey method. However, features that are critical for accurate volume calculation are often missed with several hundred metres interval. (D. P. Sangroula, 2005).

With the long-term multiple survey data and sediment data, sediment deposition and distribution pattern can be assessed which helps in proper sediment management and handling.

2.4. Modelling of sediment transport and deposition

Numerical sediment transport models are available to simulate flow in one, two- and three-dimensional models. There are different aspects to each of them and each have their positive and negative sides. The most important are the time consumptions and accuracy where generally two- and three-dimensional models require more extensive amount of computer time and calibration data and may not be desirable for solving engineering problems with limited data and resources when the problem can be analysed within the context of a one-dimensional model. However one-dimensional models are not appropriate for complex geometries. And, two- and three-dimensional models can produce enhanced visual results with tools such as contour mapping, animation, and particle-tracing. (*Morris and Fan, 1997).*

The program used in this thesis is SSIIM, a three-dimensional CFD model designed to simulate sediment transport in rivers and reservoirs. The program is described in the next section.

2.4.1. SSIIM

2.4.1.1. General Introduction

SSIIM is an acronym for Sediment Simulation in Intakes with Multiblock option. This program was developed as Sediment Simulation in Intake (SSII) in 1990-91 at the Division of Hydraulic Engineering at the Norwegian Institute of Technology by Dr. Ing. Nils Reidar B. Olsen during his dr. Ing. Degree. Since then, many improvements have been done and is still ongoing which leading up to today has two version of software: SSIIM 1 and SSIIM 2 which has their own advantages and disadvantages according to the needs of analysis. This program is made for the teaching and research purposes and used in River/Environmental/Hydraulic/Sedimentation Engineering with the primary focus to model sediment transport in rivers, reservoirs and around hydraulic structures (Olsen 2018).

2.4.1.2. Theoretical basis

The program computes the water velocities and sediment transport in river, channels and reservoirs. SSIIM model solves the Navier-Equations using the control-volume approach with the SIMPLE (Semi-Implicit Method for Pressure linked Equation) algorithm and the k-epsilon turbulence model to obtain the water velocity and to calculate the turbulent shear stress. The velocities are used when solving the convection-diffusion equations for different sediment sizes which gives trap efficiency and sediment deposition pattern.

The Navier Stokes equation for turbulence flow is

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = \frac{1}{\rho} \frac{\partial}{\partial x_j}\left(-P\delta_{ij} + \rho \bar{u}_i \bar{u}_j\right) \qquad 7$$

where,

P is the pressure

U is the velocity

δ_{ij} is the Kronecker's delta

ρ is the water density

t is the time

x is a space coordinate

The first term on the left side of the equation is transient term, which means it is time dependent and so it is an acceleration term. The next term is a convection term, which also is an acceleration term. The third term on the right side is the pressure term and forth is the Reynolds stress term or the turbulence term without which the equation would have been for the laminar flow.

Th transient term is neglected by default in the SSIIM but can be included in the computation where water level and discharge may change. The discretization of convective term is solved using power-law scheme or the second-order upwind scheme. It is both used in water flow simulation as well as sediment flow computation. The pressure term is modelled using the SIMPLE and SIMPLEC methods. SIMPLE method is based on the principle to use the water continuity as an indicator to check the pressure value.

2.4.1.3. The k-ε turbulence model

To model Reynolds stress term, the eddy-viscosity concept is used with the Boussineq approximation;

$$-\rho \bar{u}_i \bar{u}_j = v_T \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_i}{\partial x_j} \right) + \frac{2}{3} k \delta_{ij} \qquad 8$$

where,

V_T is the eddy viscosity

K is kinetic turbulent energy

The eddy viscosity describes the effect of eddies in turbulent flow by representing the energy dissipated in the eddies. It is modelled by the following equation;

$$v_T = c_\mu \frac{k^2}{\varepsilon} \qquad 9$$

where,

c_μ is a constant

k is the kinetic turbulence which equals $\frac{1}{2} \bar{u}_i \bar{u}_j$

2.4.1.4. Wall laws

An empirical formula for rough walls (Schlichting, 1979) is used as a default wall law in SSIIM is given below;

$$\frac{U(z)}{U_*} = \frac{1}{\kappa} ln \left(\frac{30y}{k_s} \right) \qquad 10$$

where,

κ is a constant equal to 0.4

$k_s$is equivalne to diameter of particles on the bed

$U_*$is the shear velocity

2.4.1.5. Sediment Transport Calculation

SSIIM calculates sediment transport by size fractions. Sediment transport calculation can categorize into calculation of suspended material and bed load. The total load is the combination of both.

The suspended load is calculated with the convection-diffusion equation for the sediment concentration, c

$$\frac{\partial c}{\partial t} + U_j \frac{\partial c}{\partial x_j} + w \frac{\partial c}{\partial z} = \frac{\partial}{\partial x_j} \Gamma \left(\frac{\partial c}{\partial x_j} \right) \qquad 11$$

Here, 'w' denotes the fall velocity of sediment particles. The diffusion coefficient, Γ, is computed from the eddy-viscosity from the k-ε turbulence model.

$$\Gamma = \frac{v_T}{S_c} \qquad 12$$

where,

S_c is the Scmidth number set to 1.0 as default in model

The well-known bed load formula is Van Rijn formula, which is as follows;

$$\frac{q_b}{D_{50}^{1.5}\sqrt{\frac{(\rho_s-\rho_w)g}{\rho_w}}} = 0.053\frac{\left[\frac{\tau-\tau_c}{\tau_c}\right]^{2.1}}{D_{50}^{0.3}\left[\left(\frac{(\rho_s-\rho_w)g}{\rho_w v^2}\right)\right]^{0.1}} \qquad 13$$

where,

q_b is the sediment transport in in kg/s

D_{50} is the sediment particle diameter

τ is the bed shear stress

τ_c is the critical bed stress for movement of sediment particles

ρ_s is the density of sediment

ρ_w is the density of water

v is the viscosity of water

g is the acceleration due to gravity

a is the reference level set equal to the roughness height

Another well known bed load formula is given by Meyer-Peter and Mullers formula;

$$q_s = \frac{1}{g}\left[\frac{\rho_w grS - 0.047(\rho_s-\rho_w)d_{50}}{0.25\rho_w^{\frac{1}{3}}\left(\frac{\rho_s-\rho_w}{\rho_s}\right)^{\frac{2}{3}}}\right]^{\frac{3}{2}} \qquad 14$$

where,

q_s is the sediment transport in in kg/s

r is the hydraulic radius of the river

2.4.2. Version

SSIIM is available in two versions: SSIIM 1 and SSIIM 2. The main difference between both is that SSIIM 1 uses a structured 3D grid whereas SSIIM 2 uses unstructured grid. Difference also lies in the speed of computation, where often it will be better for structured grid as faster solver are available.

There are algorithms which models water quality and sediment transport that are not in SSIIM 1. But the main advantage of unstructured grid is its ability to model complex structures for wetting/drying conditions. Olsen 2018 suggests using SSIIM 1 and to only use SSIIM 2 if there is very complex geometry and/or wetting/drying processes. For this thesis, SSIIM 2 has been used due to complex geometry of the peaking pond.

2.4.2.1. Input File

Various input files are required in SSIIM in before simulation is started. The procedure in SSIIM 2 follows grid generation, hydraulic computation and sediment flow computation. Following are the brief description of input files used in this thesis.

2.4.2.1.1. The control File

The control file gives most of the parameter the simulation requires. Few examples are the water discharge data, grid size, time step, number of iterations, Manning-Strickler's friction factor, etc. There are certain rules that needs to be followed when writing the parameters. A data sets starts with a letter and a floating number depending on the type of data set. SSIIM checks the datasets and if error is found, a message is written in a *boogie* file.

```
control - Notepad
File  Edit  Format  View  Help
T Paso Ancho Hydropower Project, Peaking Pond
F 2 URIS                                        read unstruct
F 6 0.015 1.5 0.3                               coeff of bed conc. var
F 37 1                                          transient sediment com
F 64 2                                          will not recomoute hyd
F 84 2                                          bed load and suspended
F 65 10000000 10000000 10000000 100000 10000    to allocate the arrays
F 64 11                                         non horizontal grid, F
F 112 1                                         regenerates grid aFter
F 102 1                                         invoKe an algorithm to
F 113 7                                         avoid unphysical veolo
F 159 1 9 0 1 0                                 disconnecting cells in
F 168 8                                         multi blocK solver
F 92 0.1 0.3                                    invoKes new cells
F 94 0.1 0.1                                    minimum cell corner he
F 235 10                                        triangular cell dampin
F 33 250 200
```

Figure 2-4 Control file sample

2.4.2.1.2. The geodata file

The grid generated in the SSIIM 2 is with the help of the geodata file, which consists of point coordinates for the topography. Each point is given in one line in the file and consists of three floating numbers x, y and z which represent easting, northing and altitude and a capital E needs to be at start of each line which is used for counting the number of points.

```
geodata - Notepad
File  Edit  Format  View  Help
E 319847.902900 973231.467500 1459.839000
E 319847.997200 973232.057000 1459.661000
E 319848.146700 973232.701500 1459.434000
E 319848.259300 973233.290900 1459.253000
E 319848.427100 973233.916900 1459.048000
E 319848.594600 973234.487600 1458.818000
E 319848.689000 973235.113900 1458.706000
E 319848.838300 973235.703200 1458.615000
E 319849.006600 973236.458200 1458.558000
E 319849.119500 973237.102900 1458.452000
E 319849.250700 973237.765900 1458.312000
E 319849.437200 973238.484000 1458.193000
E 319849.586200 973238.999500 1458.087000
```

Figure 2-5 Geodata file sample

2.4.2.1.3. The koordina file

The data on the koordina file defines a surface, which describes the bed of the geometry and water surface level. Each line in the file has two integers and four floats.

```
koordina - Notepad
File  Edit  Format  View  Help
1 1 320068.020685 973231.974120 1470.000000 1461.790000
1 2 320067.489184 973231.650073 1470.000000 1461.790000
1 3 320066.957683 973231.326027 1470.000000 1461.790000
1 4 320066.426182 973231.001981 1470.000000 1461.790000
1 5 320065.894681 973230.677935 1470.000000 1461.790000
1 6 320065.363179 973230.353889 1470.000000 1461.790000
1 7 320064.831678 973230.029843 1470.000000 1461.790000
1 8 320064.300177 973229.705797 1470.000000 1461.790000
1 9 320063.768676 973229.381751 1470.000000 1461.790000
1 10 320063.237175 973229.057705 1470.000000 1461.790000
```

Figure 2-6 koordina file sample

2.4.2.1.4. The koomin file

The koomin file is same as the koordina file but without the water surface. This file is created when the koordina file is written. This koomin file can used by removing the extension. The surface level in koomin file is used as minimum elevation surface for bed changes. So, the bed will not be lowered under this surface. This is necessary incase when erosion is not required in the simulation.

```
koomin - Notepad
File  Edit  Format  View  Help
1 1 320068.020685 973231.974120 1470.000000
1 2 320067.489184 973231.650073 1470.000000
1 3 320066.957683 973231.326027 1470.000000
1 4 320066.426182 973231.001981 1470.000000
1 5 320065.894681 973230.677935 1470.000000
1 6 320065.363179 973230.353889 1470.000000
1 7 320064.831678 973230.029843 1470.000000
1 8 320064.300177 973229.705797 1470.000000
1 9 320063.768676 973229.381751 1470.000000
1 10 320063.237175 973229.057705 1470.000000
```

Figure 2-7 Koomin file sample

2.4.2.1.5. The timei file

The *timei* file is for the time series data of discharge, water level, sediment concentration and control for output. Each row contains time step, upstream and downstream discharge and water level, sediment concentration value for each sediment size that is used in defined in the *control* file.

```
timei - Notepad
File  Edit  Format  View  Help
I 0 3.24 3.24 1461.79 1461.79 0.00005 0.00005 0.00005 0.00005 0.00005 0.00005 0.00005 0.00005 0.00005 0.00005
I 200 3.24 3.24 1461.79 1461.79 0.00005 0.00005 0.00005 0.00005 0.00005 0.00005 0.00005 0.00005 0.00005 0.00005
```

Figure 2-8 Timei file sample

2.4.2.1.6. The unstruc file

The unstruc file contains the data of geometry and grid of the model. It also contains information about inflow/outflow of water. This file is only possible to generate using the SSIIM 2.

```
unstruc - Notepad
File Edit Format View Help
3 859272 2646723 1 0 0 0 929627
320061.729120 973241.387001 1470.000000
320061.194991 973241.929421 1470.000000
320061.729120 973241.387001 1470.200000
320061.194991 973241.929421 1470.200000
320060.700563 973241.557567 1470.000000
320060.700563 973241.557567 1470.200000
320061.232421 973241.016897 1470.000000
320061.232421 973241.016897 1470.200000
```

Figure 2-9 Unstruc file sample

2.4.2.2. Output files

The output file is data file provided by the SSIIM 2. For example, after hydraulic computation, the output is stored in the result file and after sediment computation, the output result is stored in the bedres and con2res file. Below is the brief description of some of the output files used in this thesis.

2.4.2.2.1. The result file

This file contains the results from the hydraulic and sediment computation. The result includes residuals, roughness, grid size and data, water flow calculation with velocities, pressure and turbulence. It can be written automatically after the computation completes by help of control file or can be created manually by the SSIIM 2 user interface.

```
result - Notepad
File Edit Format View Help
1200.000000 seconds
Results, iter = 6
Residuals: 0.000099 0.000083 0.000020 7.722820 0.000000 0.000000
Roughness : 0.011160
U 195473 162607 519698 1 0 0
 i     u     v     w     k    e     p
C 1 5.20363682e-002 -2.14940157e-002 1.81317501e-003 1.46539249e-004 5.48953628e-005 1.08177616e+002
C 2 5.20560294e-002 9.60222368e-003 1.61404926e-003 1.11870939e-004 2.34541635e-005 1.07188223e+002
C 3 3.06303346e-002 -2.27660871e-002 -2.40001577e-004 3.90351370e-005 4.62895345e-006 1.42953361e+002
C 4 6.78511006e-002 -2.00186962e-002 6.72447103e-004 9.40743307e-005 5.14788804e-006 1.44401097e+002
C 5 4.76957492e-002 6.41083446e-003 1.06026281e-003 9.27858547e-005 9.48866591e-006 1.47319552e+002
C 6 2.62310877e-002 -1.27880923e-002 -2.35270230e-004 3.82694662e-005 5.52047805e-006 1.47894705e+002
C 7 -1.59651793e-002 -2.60180847e-004 1.48079890e-003 4.04836453e-005 1.97165492e-006 1.48048500e+002
C 8 -1.94260665e-002 -1.71146337e-003 3.80142683e-003 1.91434098e-005 7.74535344e-007 1.48115289e+002
```

Figure 2-10 Result file sample

2.4.2.2.2. The boogie File

This is a file that shows a printout of immediate results from the calculations. It also shows the parameters as average water velocity, shear stress and water depth in the initialization. If an error occurs, an explanation is also often written to this file before the program stops. (SSIIM User Manual, Olsen 2018)

```
boogie - Notepad
File  Edit  Format  View  Help
SSIIM 2 2016 output file.
In kread

TurbulenceModel = 0 (F 24)
Number of threads: 0 (F 206)
Have allocated        21.93 Mbytes structured arrays
Have not used inflow file
Have allocated     13127.61 Mbytes unstructured arrays

G 6/62 2D reference indexes: 0 0 0 0
In ReadUnstructure:
Group 1, surfaces 1897, xyno 269, discharge 3240.000000 l/s Dirichle
In ReadUnstructure:
Group 2, surfaces 2827, xyno 260, discharge 3240.000000 l/s Dirichle
Generating grid with F 64 11 algorithm
Have not used 'bedres' file
 In readres
```

Figure 2-11 Boogie file sample

2.4.2.2.3. The con2res file

The con2res file contains the sediment concentration values in the grid. These files are written after the sediment computation is finished.

```
con2res.new - Notepad
File  Edit  Format  View  Help
162607 10
2.745129e-008 9.628871e-028 6.846240e-019 1.857333e-016 3.081360e-015 1.793609e-014
9.487999e-008 3.725358e-026 1.329495e-017 2.789643e-015 3.989317e-014 2.086587e-013
7.263726e-007 8.041793e-021 4.972198e-014 2.101141e-012 1.210218e-011 3.990187e-011
2.296822e-006 1.126125e-019 6.094830e-013 2.212336e-011 1.143503e-010 3.475713e-010
9.486399e-006 3.873200e-018 1.253557e-011 3.661401e-010 1.654260e-009 4.551310e-009
3.707166e-007 3.233900e-020 1.507601e-013 4.774624e-012 2.292992e-011 6.623355e-011
3.729756e-006 6.518017e-019 3.170627e-012 9.699965e-011 4.561858e-010 1.287177e-009
9.478250e-007 2.263028e-020 1.877097e-013 7.027422e-012 3.742594e-011 1.157374e-010
1.223949e-006 8.843896e-021 1.260888e-013 5.073211e-012 2.871395e-011 9.428177e-011
3.802924e-006 9.094429e-020 1.159835e-012 4.257964e-011 2.259156e-010 7.042351e-010
9.045811e-007 3.622658e-021 7.472598e-014 3.321528e-012 1.970917e-011 6.652356e-011
2.498946e-007 1.461105e-022 4.960849e-015 2.665572e-013 1.772809e-012 6.696685e-012
2.950833e-006 2.487926e-021 9.963045e-014 5.248091e-012 9.162235e-011 6.651655e-010
3.470565e-006 1.539604e-020 4.633161e-013 2.147311e-011 3.367158e-010 2.236981e-009
```

Figure 2-12 Con2res file sample

2.4.2.2.4. The bedres file

The bedres file contains information regarding the bed sediments, including the grain size distribution, bed form height and bed roughness. The file is automatically created when the result file is written in SSIIM 2 during or after the sediment transport simulation.

```
bedres.t - Notepad
File  Edit  Format  View  Help
Results from SSIIM 2.0, iter = 6
K 300 300 11 10 49551   13.609999999999990000 162607
1 1    0.0  1470.00000000000000  1461.79000000000000 1460.000000 0.000000
1 2    0.0  1470.00000000000000  1461.79000000000000 1460.000000 0.000000
1 3    0.0  1470.00000000000000  1461.79000000000000 1460.000000 0.000000
1 4    0.0  1470.00000000000000  1461.79000000000000 1460.000000 0.000000
1 5    0.0  1470.00000000000000  1461.79000000000000 1460.000000 0.000000
1 6    0.0  1470.00000000000000  1461.79000000000000 1460.000000 0.000000
```

Figure 2-13 Bedres file sample

2.4.2.2.5. Paraview files

Paraview is the program which can read 2D and 3D version graphic files created by SSIIM. The SSIIM can create multiple files for a time dependent computation to create an animation. The file can be written with multiple user specified variables like horizontal velocity, pressure, sediment concentration, etc. The variable can be found in the G 24 data set in the SSIIM User Manual.

3. Paso Ancho Hydropower Project

3.1. Project Background

The Paso Ancho Hydropower Project is located along the Chiriquí Viejo River in the District of the Bugaba of the Chiriquí Province in the south west region of Panama near the border of Costa Rica. The project is located between the following UTM coordinates 318750 – 320400 E, 973000 – 973400 N. The project site can be reached by the Panama International Airport, Tocumen in Panama City. The closest local airport is E. Malek in David City, which is approximately two-hour from the project site.

Figure 3-1: Location of Paso Ancho Hydropower Project

The project utilizes daily peaking run of river hydropower technology that uses water from the Chiriquí Viejo River, with an annual average flow of 6.17m^3/s and design discharge of 9m^3/s. A diversion dam is constructed from concrete and is 4.5 metres high. Water is conveyed to the peaking pond through a 25m long culvert and a 350m long circular tunnel. A desander of 6.5m long and 8m wide is placed after the culvert to trap and flush the incoming sediments back to the river. A penstock with diameter of 2m and net head of 76.9m carries water to the superficial powerhouse which is equipped with 2 Francis type turbines and 2 generators with 3.06MW installed capacity each. On an average year, the project is expected to produce 42,889 MWh of energy. On 2018, according to the energy production data from the powerplant, 28,790 MWh energy was produced even though the project has been on continuous operation in that year, expect 4 days where it was stopped for the turbine maintenance. The part of energy loss is helped by the lower than required average monthly flow (Figure 3-4) and capacity loss of peaking pond due to large incoming sediments being deposited in the pond every year. The project was commissioned in 2010 and is on operation since 2011 with project life of 50 years.

3.2. Climatic and physical characterization of the river basin Chiriquí Viejo

The Chiriquí river basin is in the western part of Chiriquí province. The total drainage area of the basin up to the sea is 1376km^2. The average elevation of the basin is 1100 meters above the sea level and the highest point is on the Volcan Baru, located in the northeast part of the basin, with an elevation of 3474 metres above sea level. The basin records an average annual rainfall of 3341mm. Precipitation is categorized into two parts in this basin. The first with low rainfall, is in the north-eastern part of the basin and records average annual rainfall between 2200mm and 2400mm. The second with high precipitation, where average annual precipitates are recorded between 4000mm and 4800mm, located in the middle part of the basin. 90% of the rainfall occurs between the months of May to November and the remaining 10% falls between the months of December to April. In the northern part of the basin, where there is less rainfall, the rainfall distribution is more homogenous with 15% of the rainfall in the dry period. *(Feasibility Study Report, SETECOOP, 2004)*

3.3. Hydrology

The hydrology for the project was analysed using three rainfall station 102-001 Cerro Punta, 102-002 Nueva California and 102-009 Bajo Grande. For the water flow analysis, the water level gauging station 102-01-01, Volcan was used which is located at the proximity of the intake point of project. This station is located at elevation 1520 metres above sea level and has an information since March 1957. The catchment area of the project is 108km^2 as represented below.

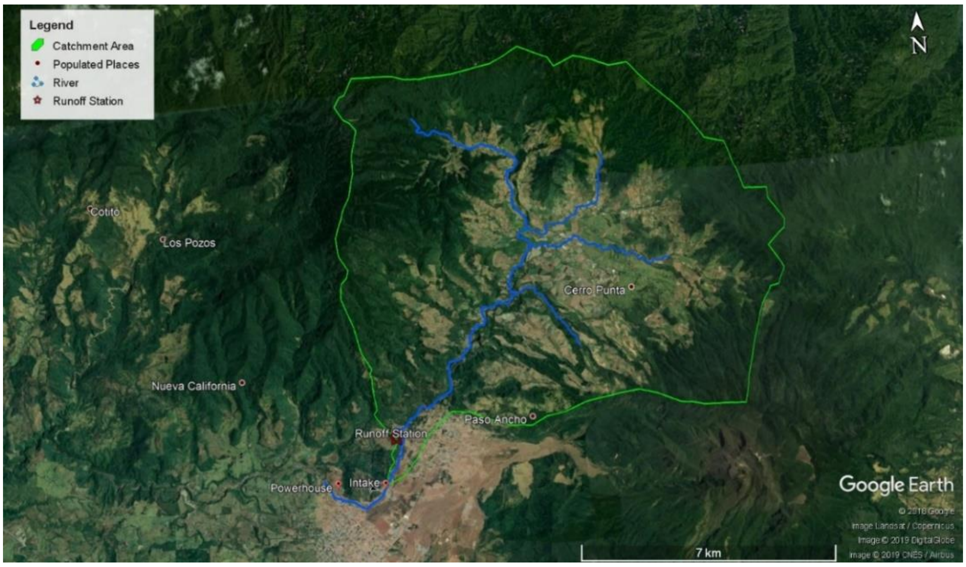


Figure 3-2 Catchment Area

Figure below shows the relationship between the average rainfall recorded in the each of rainfall stations and runoff recorded in the gauging station.

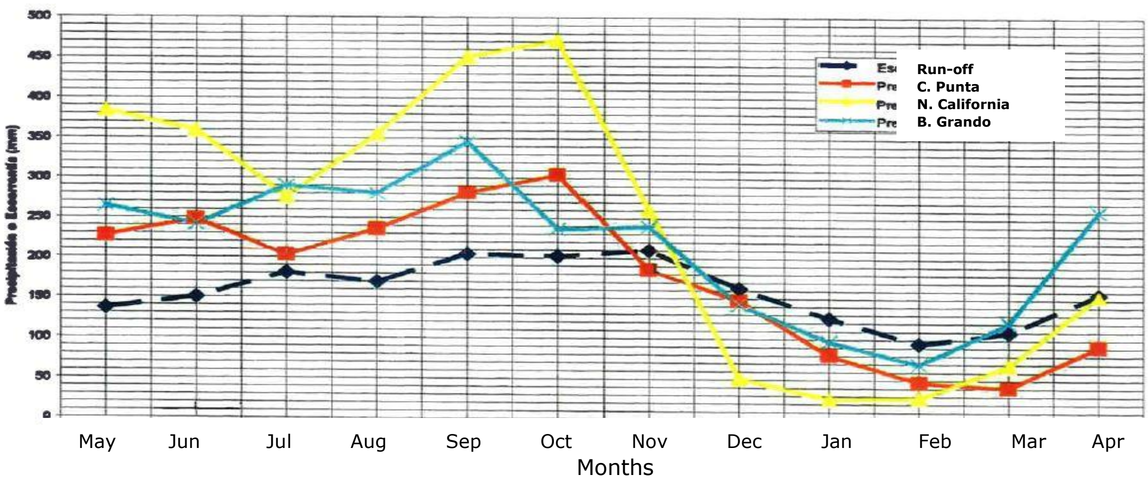


Figure 3-3 Graphical Representation of runoff and rainfall stations (Feasibility Study Report, SETECOOP, 2004)

From Figure 3-3, you can see that there is wet season between the months of July to October, where the highest rainfall is recorded and the dry season where rainfall and runoff tends to fall is between November to March. Between the months of March and July, there is transition between dry and wet period. The variation between of the flow between the runoff station and precipitation in practical terms is significant and is much higher in wet seasons. The maximum recorded runoff is 206.63mm in the month of November and minimum is 96.66mm in the month of February.

The station 102-01-01, Volcan gives the values of water flow between levels of 0m and 3m in the river. So, different empirical equations were used to calculate the maximum flow in the river which ranges from 280m^3/s to 3169m^3/s. The minimum flow in river is in table below. *(Feasibility Study Report, SETECOOP, 2004)*

Return Period (Years)	Flow (m^3/s)	Return Period (Years)	Flow (m^3/s)
5	2.15	25	1.47
10	1.85	50	1.19
15	1.68	100	0.90

Table 3-1 Minimum Flow with different return period for the station 102-01-01, Volcan

The station 102-01-01, Volcan provides the historic average monthly flows. Discharge data is also provided of the powerplant for the year of 2018 which can be computed to the average monthly flow. Comparison between two data set is presented in the Figure 3-4.

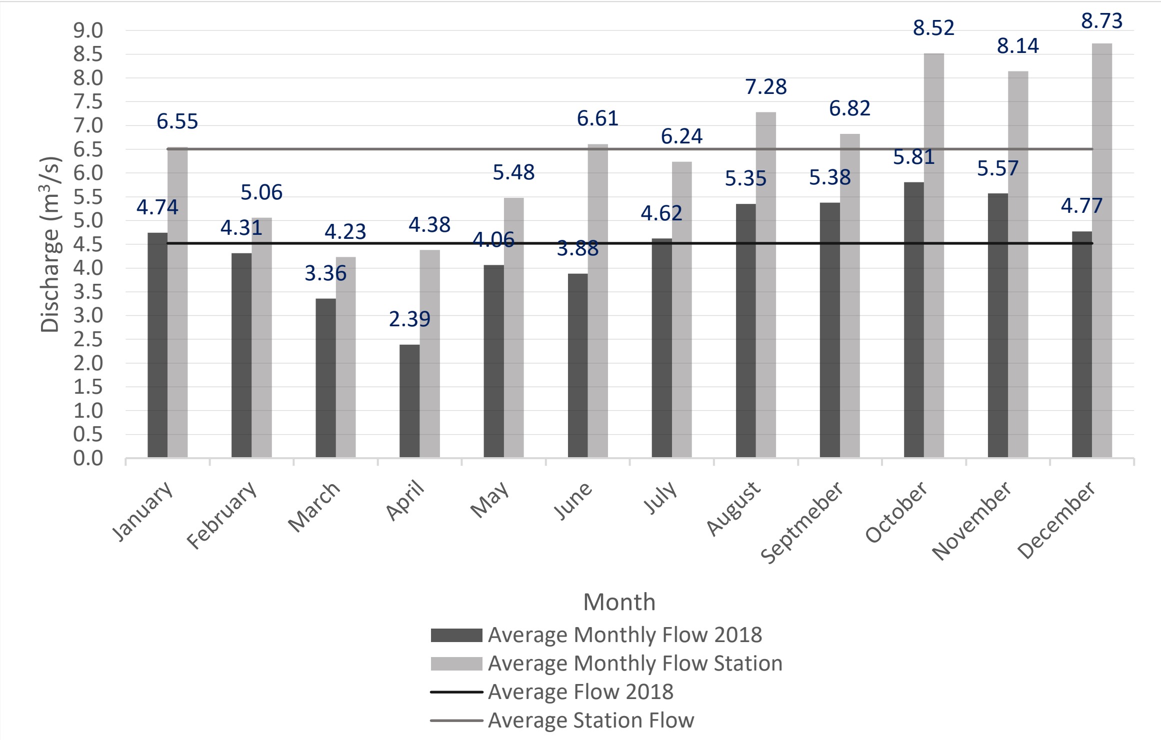


Figure 3-4 Average Monthly Flows from the station 102-01-01 Volcan and Average monthly flow of year 2018

We can see that the average discharge for the year 2018 is 4.52m^3/s which is less than the required average annual flow of 6.5m^3/s. The design discharge of the project is 9m^3/s and the size of all hydraulic structures and hydromechanical equipment is constructed based on this discharge.

The duration curve is represented by Figure 3-5. The flow rate of $4m^3/s$ is maintained for 100% of the time and 50% of the time equals or exceeds the flow of $6.5m^3/s$.

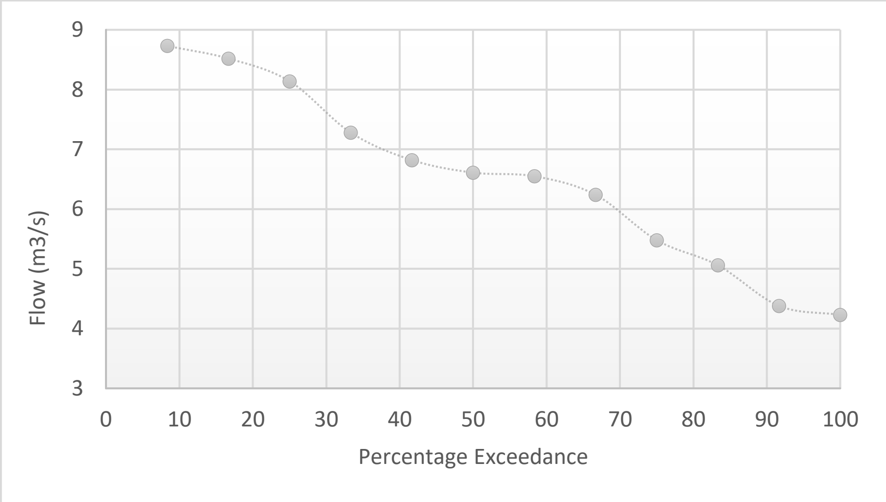


Figure 3-5 Duration Curve (Feasibility Study Report, SETECOOP, 2004)

The upper part of the duration curve where the flow that equals or below 60% exceedance of the time has the smooth curve which indicates that during the month of high flow variations are small whereas the slope of the curve is strong for the flow that exceeds 60% of the time indicating the rapid variation of flow during the months of low precipitation.

3.4. Peaking Pond

The peaking pond at the Paso Ancho Hydropower Project is an off-stream artificial man-made reservoir from which the powerplant is operated on daily hourly peaking. The plant is operated at maximum possible load during the day to keep being operated throughout the day and at night, the load on the plant is lowered down to recover the level of reservoir. There is daily fluctuation of water level with highest water level at morning to lowest possible water level at evening. However, when there is a high discharge in the river in the wet seasons, the pond is maintained at NRWL during operation. Water is conveyed to the pond through a 2.5 m diameter circular tunnel with invert level of 1461.46 amsl at inflow. The combine spillway and flushing structure is placed near the inflow and two 1.2 m diameter pipe at bottom take away the debris and excess water from the structure back to the river. Flushing system contain a hydraulic motorized gate of size 1 m X 1 m. The bed and slope of the pond is lined with the synthetic impermeable geomembrane which maintains clean soil and prevents water seepage into the ground. This also helps in loss of water capacity and protect the stability of side slope and structures nearby. The general geometry of pond is as follows.

Capacity	$700000m^3$
Maximum Length	220m
Maximum Width	117m
Highest regulated water level	1462.39 amsl
Normal regulated water level	1461.79 amsl
Minimum Level of operation	1456.10 amsl
Bed Level at inflow	1455.20 amsl
Bed level at outflow	1454.70 amsl

Average normal water depth	7 metres
Side Slope	1V:0.73H

Table 3-1: General geometry of the pond

The pond faces a hard challenge maintaining to its full capacity because it receives large amount of sand and fine sediment every year. From the data collected during the site visit on March 2019, there is around 37000m^3 volume of sediments deposited in the pond, calculated by the bathymetry survey.

The large incoming sediment to the pond is due to the poor efficiency of desander in the headworks. Below are the pictures of desander taken during the site visit.

Figure 3-6 Aerial view of desander (Left) and Inlet of the desander (Right)

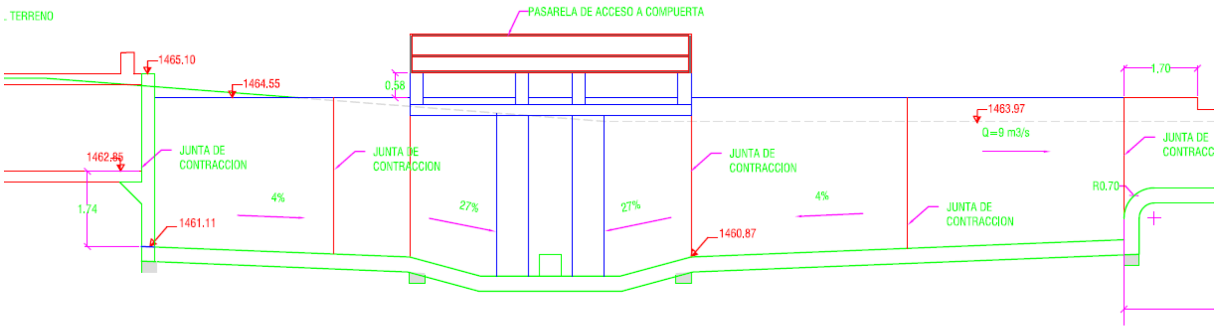
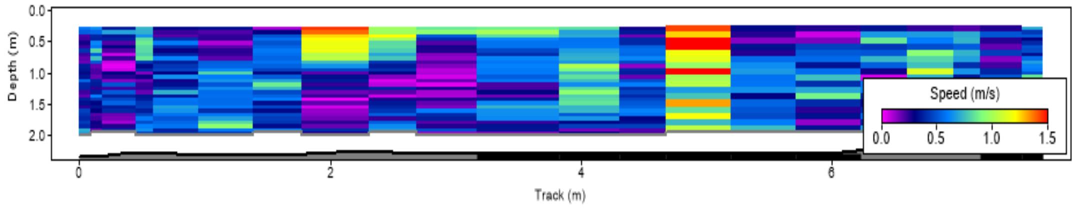


Figure 3-7 Longitudinal profile drawing of the desander

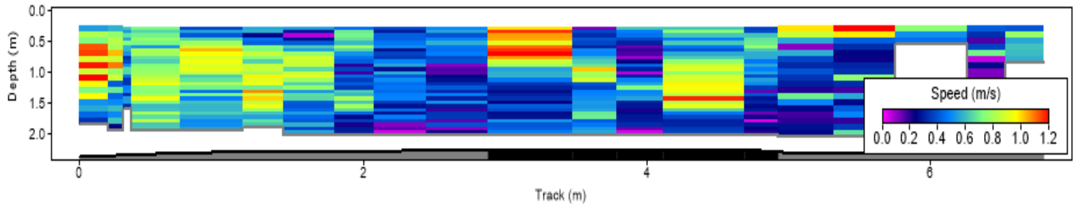
This is a single basin desander with a settling zone of 6.5 m length, 8 m width and 3.68 m depth. A flushing gate of size 0.15 m is installed at the bottom center. The observation made on the structure are as follows;

- The structure does not represent a typical settling basin. There is no inlet transition for the approach flow and vertical drop of 1.74 m can be seen at inlet in Figure 3-7.
- The approach canal is not straight before expansion. (Dagfinn Lysne et al., 2003) states that the approach canal should preferably be straight for a length of ten times the width of the canal upstream of the start of the expansion to avoid the effect of second currents or rotational flow set up by a bend.
- There is a significant turbulence observed in the water flow. This is in dry season when the pictures of Figure 3-6 are taken. In the wet seasons, the conditions as said by the plant manager is very bad. The high turbulence level in the water will create the sediment flux upwards and towards the outlet rather downwards towards the flushing.

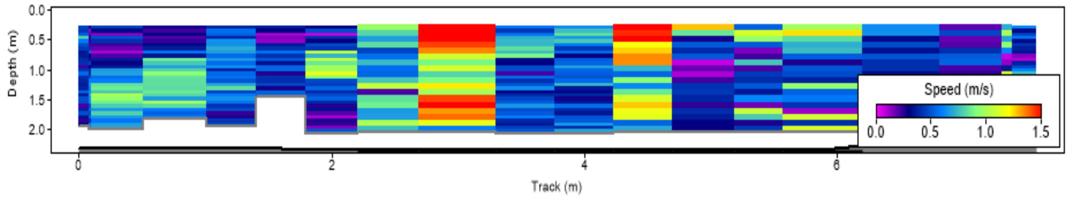
- Below are velocity measurements profile data in the settling zone using the ADCP;



i. Starting of settling zone



ii. Middle of settling zone



iii. End of the settling zone

Figure 3-8 Velocity measurement in the different sections of settling zone

The velocity range has an upper limit of 1.5m/s, which is a high velocity for a desander. An uneven flow distribution can be seen which can reduce the trap efficiency drastically. The velocity in the desander should normally be in the range of 0.1m/s to 0.4m/s depending on the design criteria and to the area available for structure. A velocity of 0.2m/s is adopted during an early stage of planning a desander. (Dagfinn Lysne, et al. 2003)

According to T.R Camp, the critical velocity for the diameter of particle can be determined by following;

$$V = a\sqrt{d} \qquad 15$$

where,

V= flow through velocity m/s

d= diameter of particle up to which sediment load is desired to be removed.

a= constant which is 0.36 for d>1mm, 0.44 for 1mm>d>0.1mm and 0.51 for 0.1mm>d.

From Table 4-1, the maximum D90 sediment size is 12mm among the samples taken. So, according to T. R Camp, the flow velocity is 1.24m/s.

Also looking at Figure 2-3 Hjulstrøms Curve, the curve indicates the transport of 12mm sediment size for the velocity of 1.5m/s.

- The opening angle of expansion zone is 53° and there are no guide walls to minimize the flow separation. An angle of 10-12 degree is suggested to prevent flow separation and if not possible, a guide wall in the inlet transition can applied to minimize flow separation. (Dagfinn Lysne et al., 2003)

- The single basin does not allow for inspection and maintenance without affecting the operation of the plant.

Numerical modelling has not been setup for the desander. However, the observation of the desander shows firstly that the structure has not been built with proper design criteria. High surface velocity and turbulence exists in the desander. The length of settling zone is very small and flow velocity is high enough to transport all the suspended particles to the pond.

The volume of sediment in the pond has been measured by the owner of the project from time to time with detail bathymetry survey to general approximation. A bathymetry survey was done in 2014 and the volume was found to be 29091m^3. In September of 2018, there was an approximate 30000m^3 of sediments in the pond which increased to 50000m^3 by October 2018. The capacity of the pond reduced to 29%.

Many methods of sediment removal have been used till date in the pond. On September 2017, mechanical dry excavation was done to remove around 30000m^3 of sediment and there was full production in the wet season. Diesel power dredging has also been used until October 2018.

The SediCon Dredge was installed and commissioned by the end of August 2018. The equipment was especially designed for this pond and by January 2018, around 15000m^3 of sediment had been removed. This equipment can remove sediments without disturbing the normal power production and has a removal capacity of approximately 40m^3/h. (*Project Brochure, SediCon AS*)

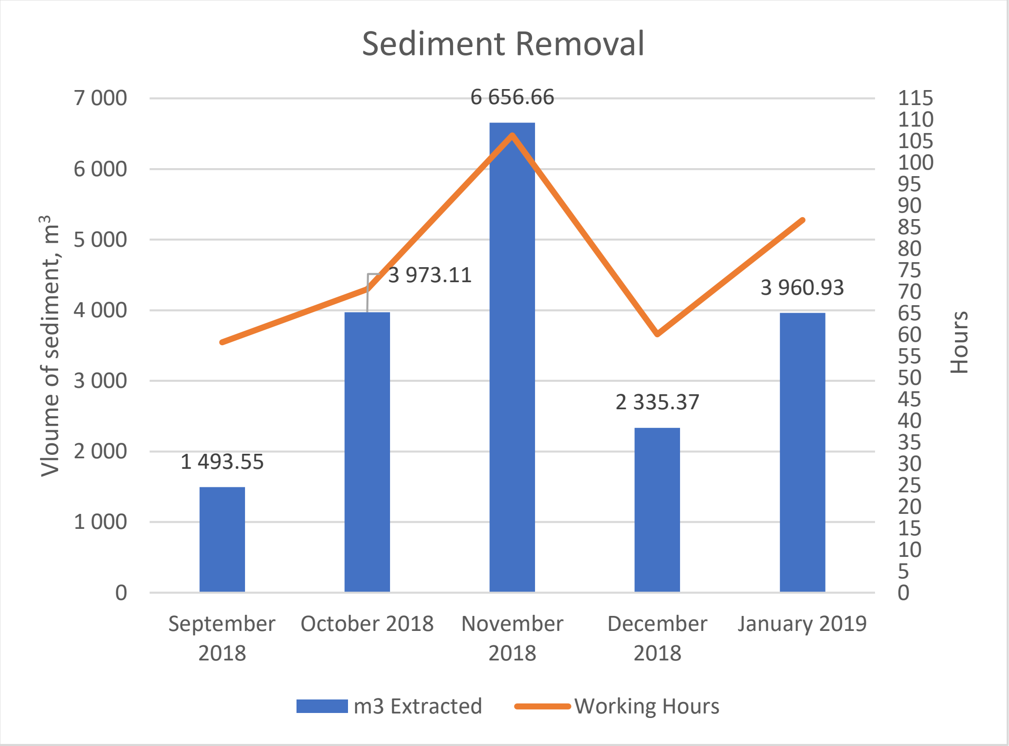


Figure 3-9 Monthly data of removed sediment by the SediCon Dredge.

Figure 3-9 shows the volume of sediment removed from the pond and number of hours worked per month by the SediCon Dredge. 6656.66m^3 volume of sediment has been removed in November 2018 when working for 105 hours. If the dredge works in full capacity for 8hrs every day, it can remove almost double the volume. And this is without affecting the powerplant operation.

Figure 3-10 Aerial picture of the pond. Picture taken by the drone during the evening when the water level is at the lowest. SediCon Dredge can be seen in the picture and area of removed sediments is highlighted.

The sediment deposition and distribution pattern in the pond has been the object of study for this thesis. Bathymetric survey, velocity and discharge measurement and sediment sampling were done during the site visit which is explained in the next chapter.

4. Data Collection

4.1. Introduction

Technique of both contour and range survey is applied for the bathymetric survey in this thesis. The survey is carried out in the peaking pond of the Paso Ancho Hydropower Project to prepare the bathymetric map. River Surveyor M9 from SonTek, a xylem brand equipment is used for the survey. The equipment configuration setup consists of a Hydroboard, M9 Acoustic Doppler Profiler (ADP) and integrated power/communication module (PCM) and global positioning systems (GPS). This system measure river discharge,3-Dimensional water currents, depths and bathymetry from a moving or stationary vessel.

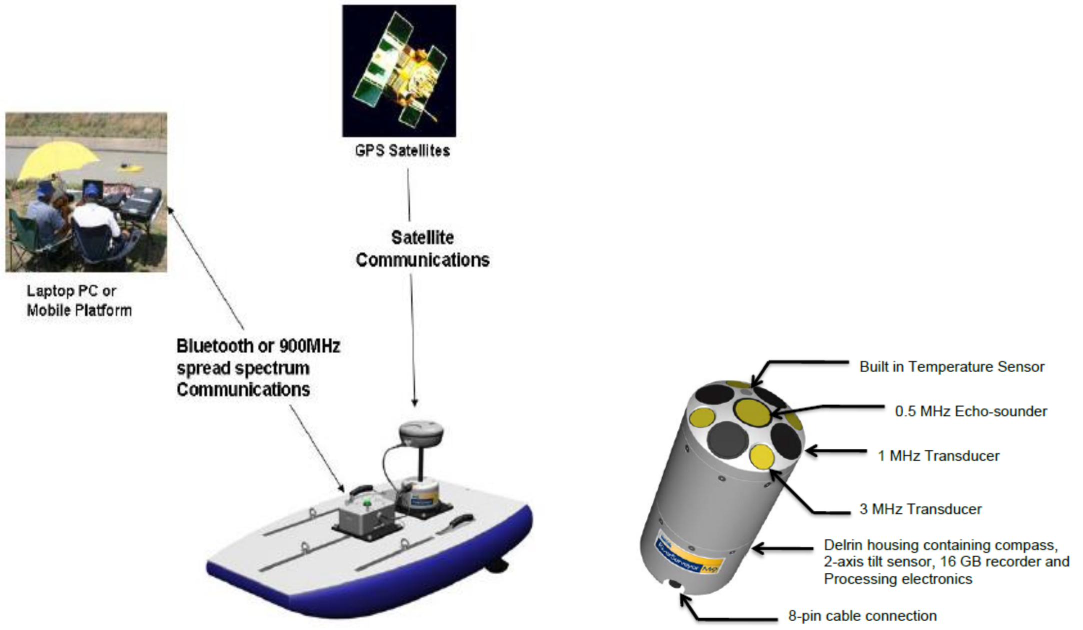


Figure 4-1 Equipment Setup (left) and M9 ADP (right) (River Surveyor S5/M9 System Manual, Firmware Version 3.96)

The M9 ADP consists two sets of four profiling beams and one vertical beam. It has a velocity profiling range of up to 40m and a discharge measurement range of 80m (when referencing GPS and the vertical beam). The PCM connects directly to the M9 and GPS and provides the power to the ADP using the rechargeable battery pack. The Bluetooth on the PCM provides the remote communication between ADP and personal computer, tablet or mobile device. The Hydroboard is a light weight floating board designed to be used with a M9 ADP system. It has easy to use, drop in installation mounts for the ADP and the PCM. The directions for mounting the hardware is followed as per the River Surveyor S5/M9 manual. To read the data on PC while surveying, the River Surveyor Live software is used. This software has a discharge measurement interface for the River Surveyor S5/M9 systems. The software includes everything needed to make real-time discharge measurement and post-process the data. *(River Surveyor S5/M9 Manual, Firmware Version 3.96)*

4.2. Survey Methodology

A survey plan was decided in such a way that a measurement was done for a number of cross sections throughout the length of the pond. An approximate interval between the consecutive cross section was decided based on the average depth of the reservoir and vertical angle of profiling beam from the ADP. A typical representation is shown below;

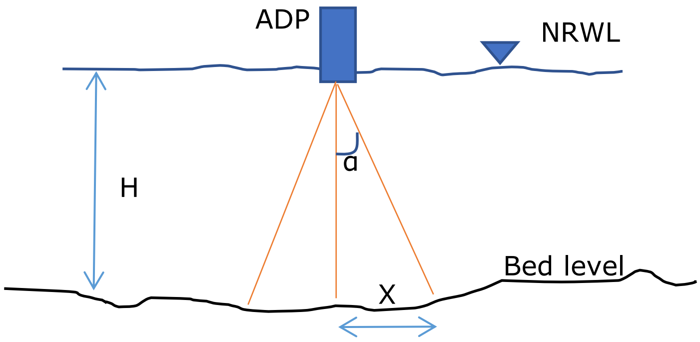


Figure 4-2 Interval between two measurements

Average depth of reservoir from NRWL(H)= 2.79m

Angle of profiling beam(α)= 20-30 degree ~25 degree

Distance between two cross-sections (2 times X) = 2*H*tan(α)= 2.6m

Required interval was maintained as much as possible and total of 76 cross sections were measured across the length of the pond.

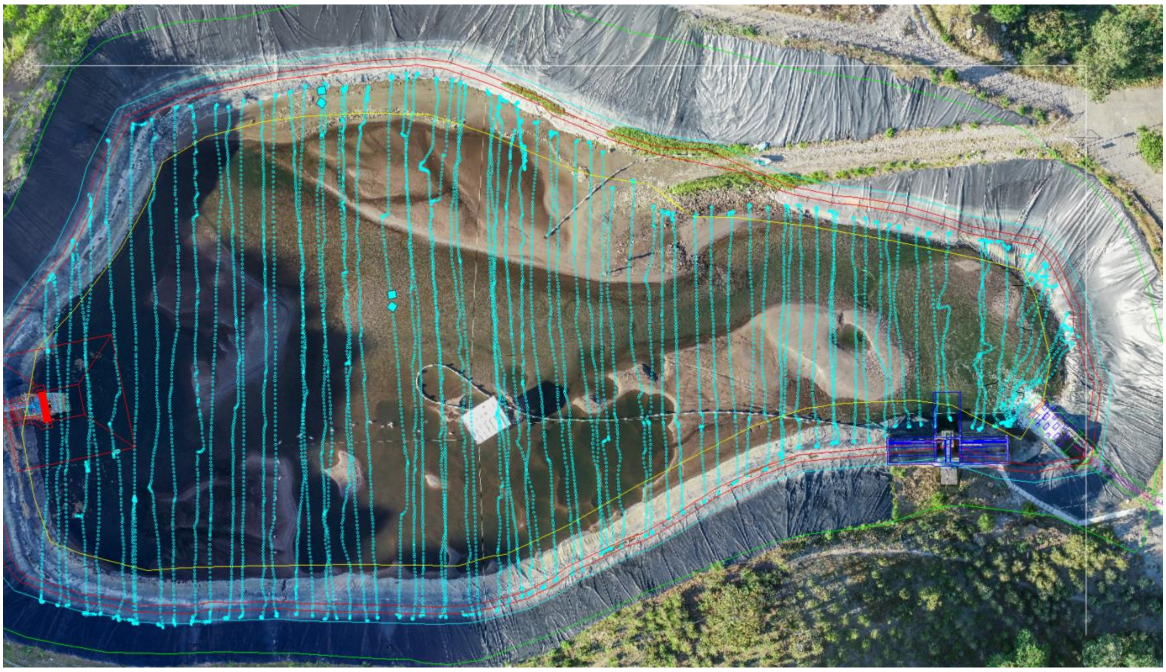


Figure 4-3 Measured cross section track lines across the pond

Pre-measurement includes checking all the cables and connections, communication between the PCM and PC, running system test which verifies battery voltage, system compass, memory card and temperature sensor, compass calibration and check on internal storage of the system. These checks should be done prior to each measurement to ensure the functionality of the River Surveyor hardware for proper data collection. Also, before measurement, input data like site information, transducer depth, screening distance, salinity of water, magnetic declination, track reference, depth reference, edge settings and coordinate system should be provided to the software. These can also be changed during the post processing of the measured data.

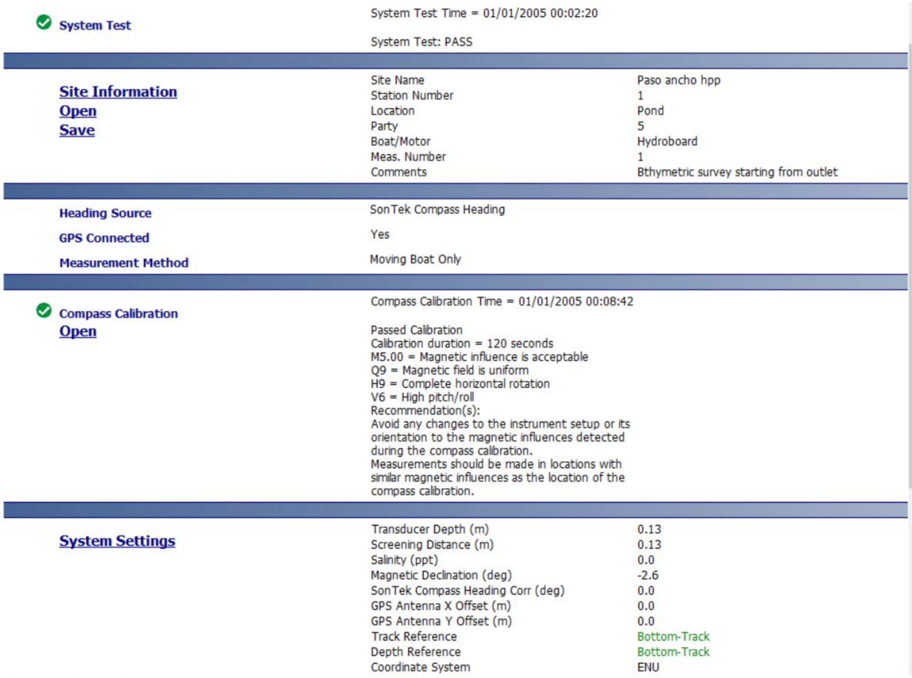


Figure 4-4 Smart page tab on the software which shows the pre-measurement checks and input data

After the premeasurement tests and initial site information data are complete, the equipment is ready to measure. An overview of how the measurement is done needs to be understood. The total discharge is computed from the mean flow velocity and cross-sectional area of the measured cross section.

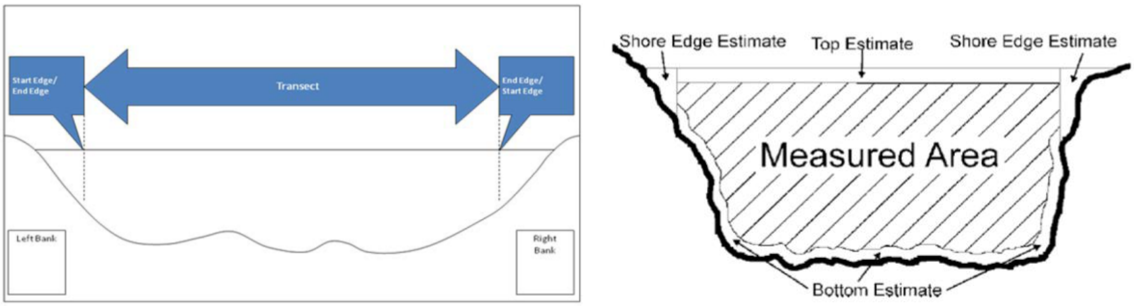


Figure 4-5 Measurement Section (Left) and Cross-sectional areas not measured by the ADP (Right) (River Surveyor S5/M9 System Manual, Firmware Version 3.96)

A single measurement is divided into three parts: start edge, transect and end edge. The edges are distance from the bank when starting the measurement and transect is the measured area. Furthermore, the transect is divided in to measured area and estimated area which is not measured by the ADP due to its limitation. According to the RiverSurveyor Live manual, a technique called Velocity Profile Extrapolation is used to estimate the unmeasured area at the top and bottom.

Measuring the discharge in the pond is not a necessary task for this thesis but this method provides the velocity profile and bottom bathymetry. The Hydroboard with the

ADP system was tied in both sides with a rope, two people were assigned on the opposite banks to pull the Hydroboard from the one end to the other. This method of measurement of water velocity profile and bottom bathymetry for the cross section by the ADP Hydroboard is called as a moving boat method. Water level were also recorded during the survey.

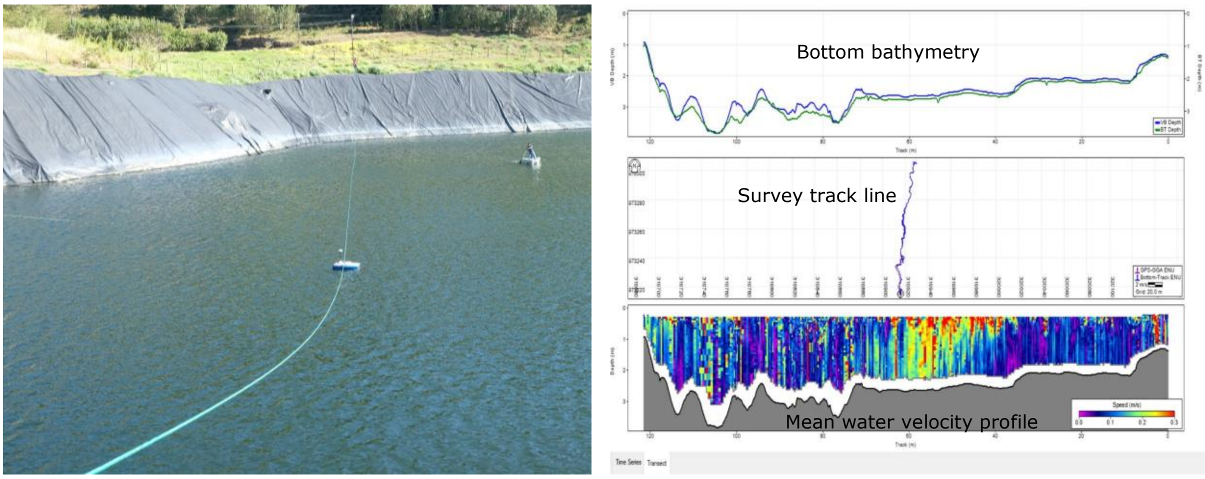


Figure 4-6 One of the measured cross sections (Left) and user interface of corresponding data collected in the software (Right)

Processing of the collected data begins in the RiverSurveyor Live software. There is a processing toolbox that lets you changes systems settings, edge estimates, heading correction and other parameters. After the required processing and changes, the data can be extracted in ASCII format or MATLAB format.

For this study, the data are extracted to MATLAB format. There are different types of data that can be extracted but for this study, Universal Transverse Mercator (UTM) coordinates, GPS altitude, vertical beam depth and velocity profile data is extracted. UTM coordinates gives the location of cross section survey lines. GPS altitude gives the altitude above mean sea level. Vertical beam gives vertical depth including the transducer depth and compensation for tilt of ADP. Bottom track velocity gives the water velocity for four direction (X, Y, up and difference velocity). Mean water velocity profile as seen in Figure 4-6 is average of X and Y direction velocity.

All these data are combined in a single workspace using MATLAB script for each cross section and copied to Microsoft Excel file. Each data point has a row compromising of Easting, Northing, GPS Altitude, Vertical Depth, Depth Average water velocity, Surface velocity. The depth average water velocity is average of mean water velocity profile whereas the surface velocity is velocity from the top cells of the mean water velocity profile. Finally, every data of each cross section is combined in one worksheet to have a single file data of whole pond. The total number of data points extracted is 11,750 from the ADP.

The software "ArcMap 10.6" and "AutoCAD Civil 3d" is used for processing, preparing bathymetric maps, velocity map and volume calculation in this study. The bathymetric surface map is created using Civil 3d as Triangulated Irregular Network (TIN) surface.

Contour is surface information and are supplemented by break lines and boundaries. The created surface is shown below:

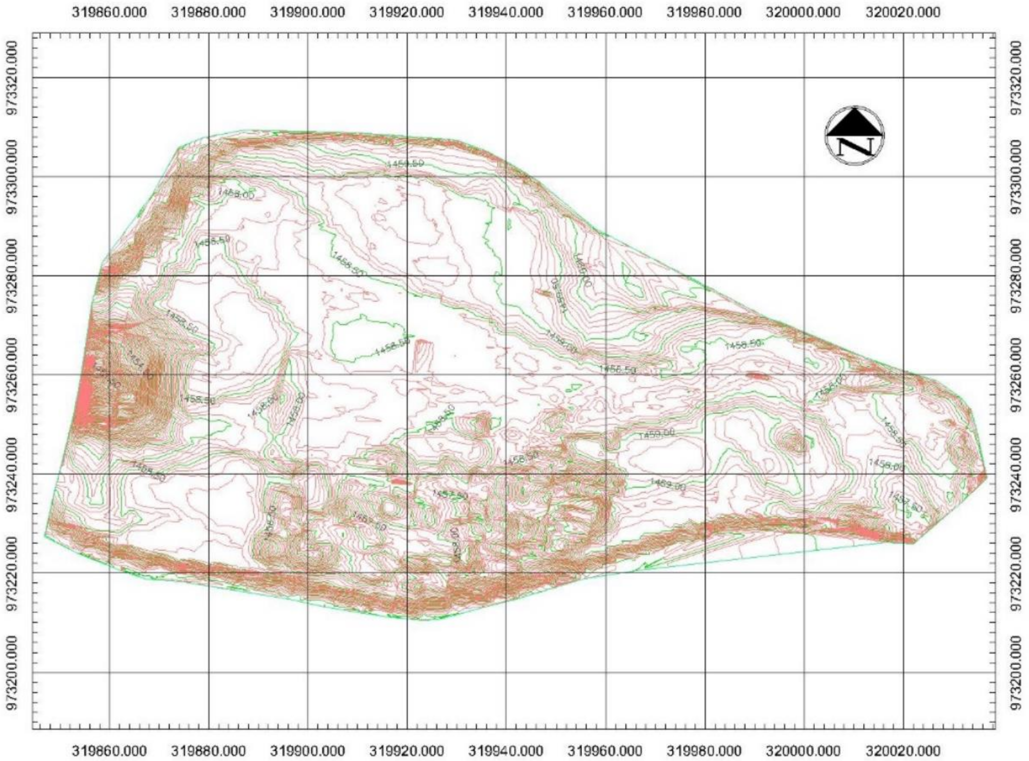


Figure 4-7 Contour Map from surveyed data

The extent of above contour map is up to water surface only. Geodata above water surface is obtained from the provided design drawing which consists of original layout of the pond without sediment deposition. Both the surface maps are combined to make a new map of the pond as shown below:

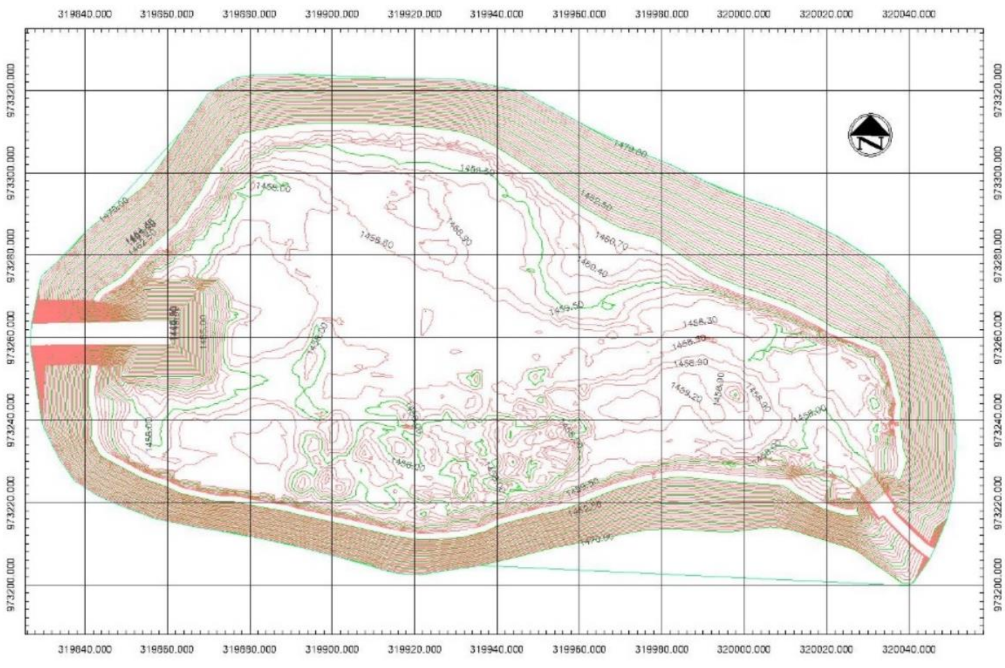


Figure 4-8 Contour Map from combined surfaces

The volume of sediment is analyzed in Civil 3d using the surveyed surface and provided design drawing surface map. The program uses surface elevation on both the surfaces as well as the positions where triangle edges of the two TIN surface model intersect and creates a surface difference. The net volume obtained is around 37,000m^3. This value of volume corresponds with the value of total amount of sediment in October 2018 minus the volume of sediment removed by the SediCon Dredge. However, the volume of sediment obtained cannot be assumed as accurate data. Since this is just based on a single bathymetry survey. Number of surveys and validation of data are required to confirm the exact amount of volume of sediment.

The final map prepared is the depth range of sediment deposition across the area of the pond.

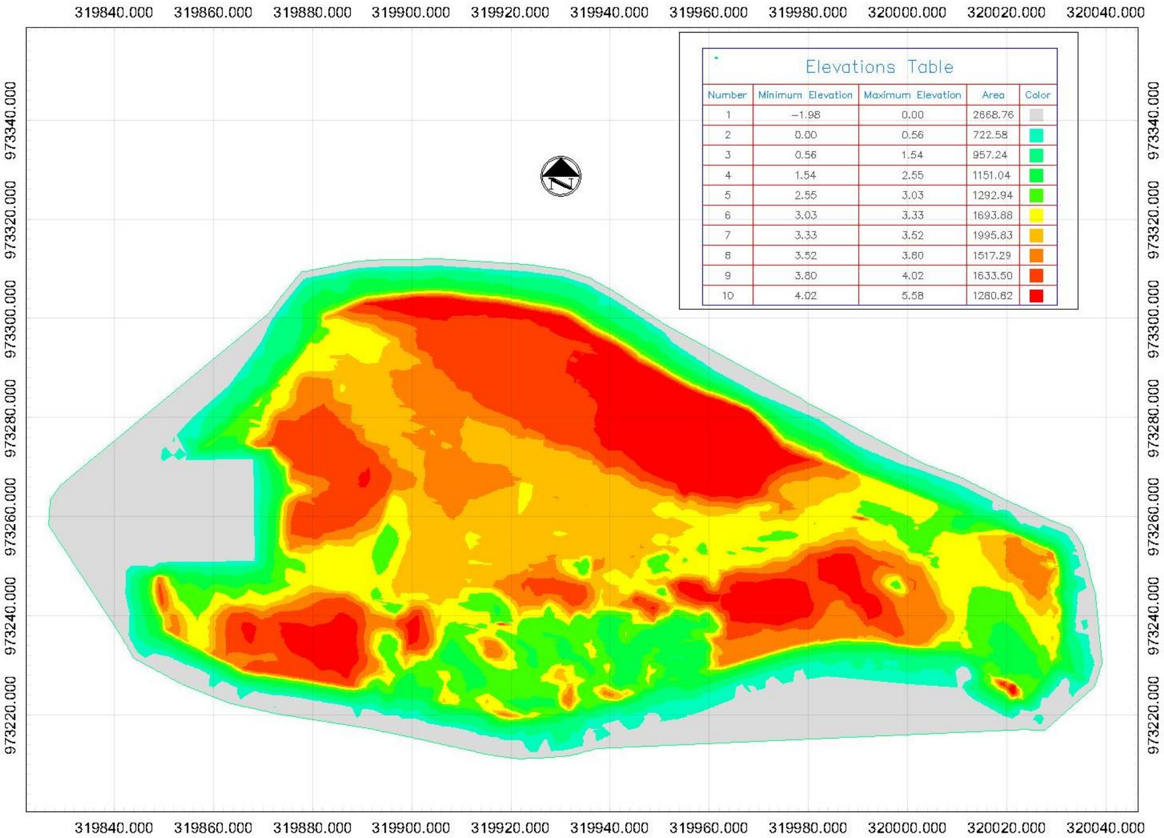


Figure 4-9 Sediment depth map

There is a pattern of sediment deposits in the pond. A channel with flood plain geometry like is represented by the yellow color near the inflow which matches with the stream flow directions as seen in Figure 4-10. Varying depth across the surface area can be seen. The sediment depth of 5.5 meters is seen at the side banks and the outflow whereas near inflow, the depth is around 3 meters. This channel formation resembles the formation of channels when reservoirs are drawn down and emptied to establish river line flow along the impounded reach, eroding a channel through the deposits and flushing the eroded through the outlet. But this interpretation of deposition pattern can only be confirmed from the repeated survey or visual inspection throughout the year.

Depth Averaged Horizontal Velocity maps are interpolated using Kriging method in ArcMap. Kriging is an advanced geostatistical procedure that generates an estimated surface from scattered set of points with Z-values.

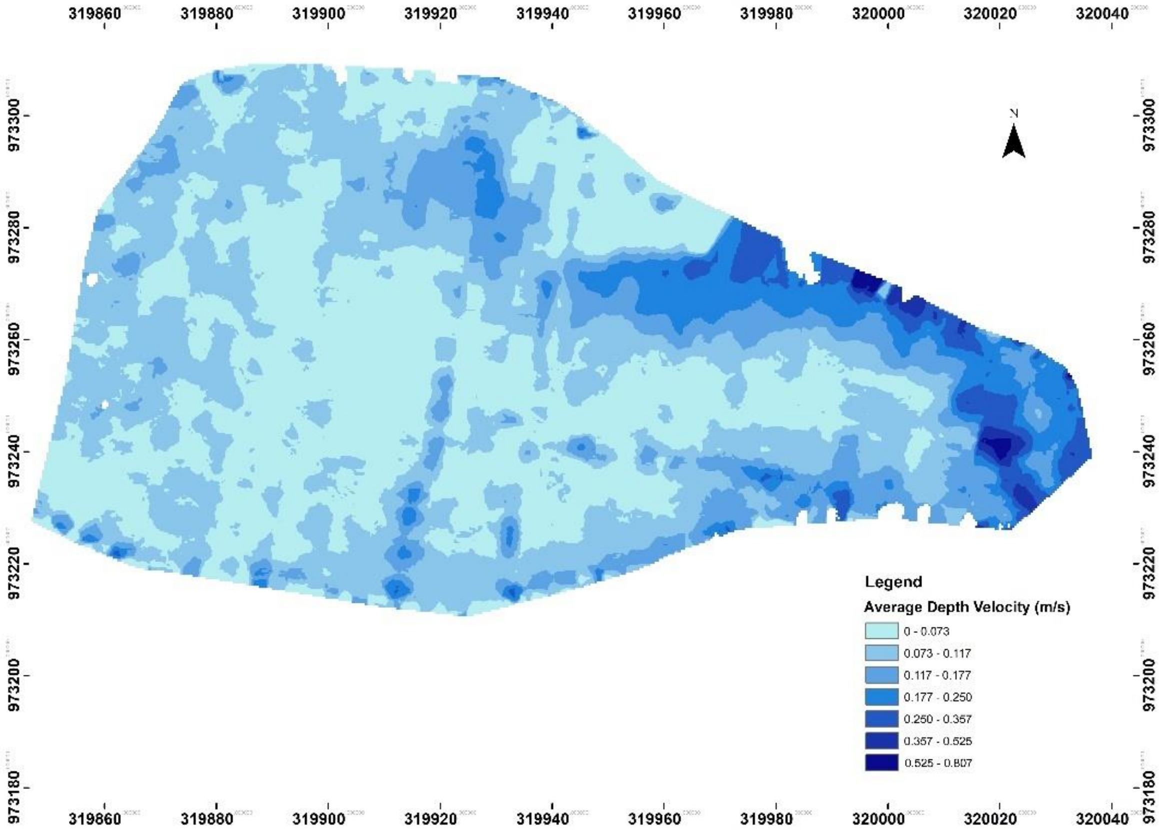


Figure 4-10 Depth Averaged Horizontal Velocity

This velocity map has an inflow discharge of 3.24m^3/s. This map is compared with the water flow simulation result from the SSIIM.

4.3. Sediment Sampling

During site visit, 7 sediment samples each weighing around 1-2kg were taken from the pond and sent to the laboratory at David, Chiriquí, Panama for the grain size distribution (GSD) analysis. The result is summarized is figure below;

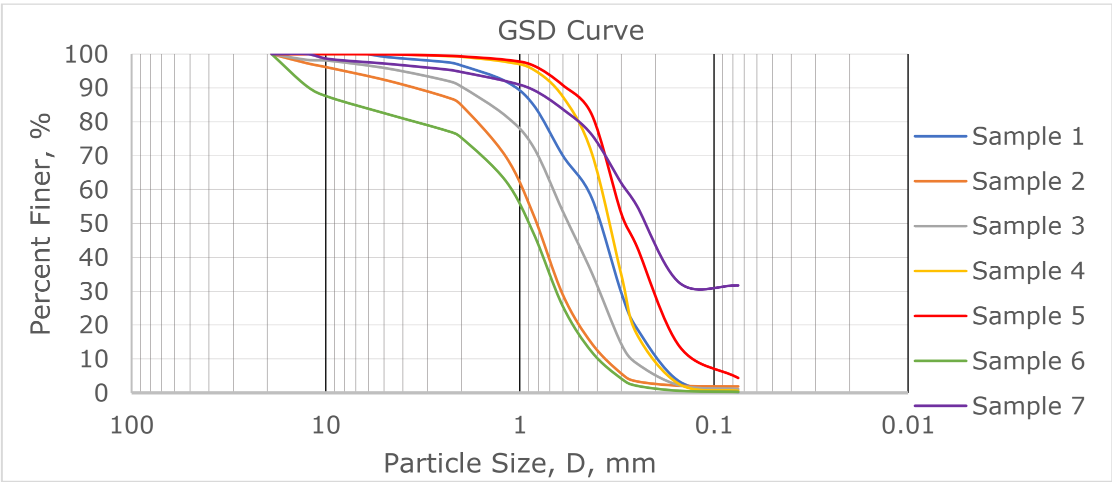


Figure 4-11 Grain size distribution (LABSA Report)

Sample Summary Table										
Sample	Location		Particle Size, mm							Unified Soil Classification
number	Easting	Northing	D90	D60	D50	D30	D10	Cu	Cc	ASTM D-2487
1	320006.60	973240.12	1.09	0.48	0.39	0.30	0.18	2.67	1.04	SP
2	319996.17	973242.37	3.73	0.96	0.82	0.62	0.36	2.67	1.11	SP
3	319986.80	973252.51	1.96	0.67	0.57	0.39	0.27	2.48	0.86	SP
4	319974.35	973268.18	0.68	0.38	0.35	0.29	0.20	1.90	1.11	SP
5	319938.89	973275.00	0.58	0.33	0.28	0.20	0.12	2.74	1.00	SP
6	319964.45	973244.84	12.05	1.20	0.91	0.65	0.40	3.00	0.88	SP
7	319891.94	973234.46	0.93	0.29	0.21					SC

Table 4-1 Summary of sediment samples

Figure 4-12 Location of the samples

4.4. Discharge Measurement

The discharge measurement was done at headworks in front of the intake using the ADP system. As per U.S. Geological Survey, 2002b, measurement from a minimum of four transects (two in each direction) should be done in a steady flow condition to obtain a discharge and if discharge of any of the four transects differs by 5 percent from the mean measured discharge, a minimum of four additional transects should be obtained, and the mean of all the eight transects will be the measured discharge. The total of 10 transects were measured and the obtained discharge is 3.24m^3/s. Full report of the discharge is attached in the Appendix 8.4.

4.5. Sediment inflow data

The sediment concentration data is provided at site as a measurement reading from an Imhoff cone as a volume of sediment in milliliters per one liter of water. The measurements are taken from the desander. Data is attached in Appendix 8.2.

4.6. Water level data

During the ADP survey, water level data were taken simultaneously. The water level data chart is shown below as follows;

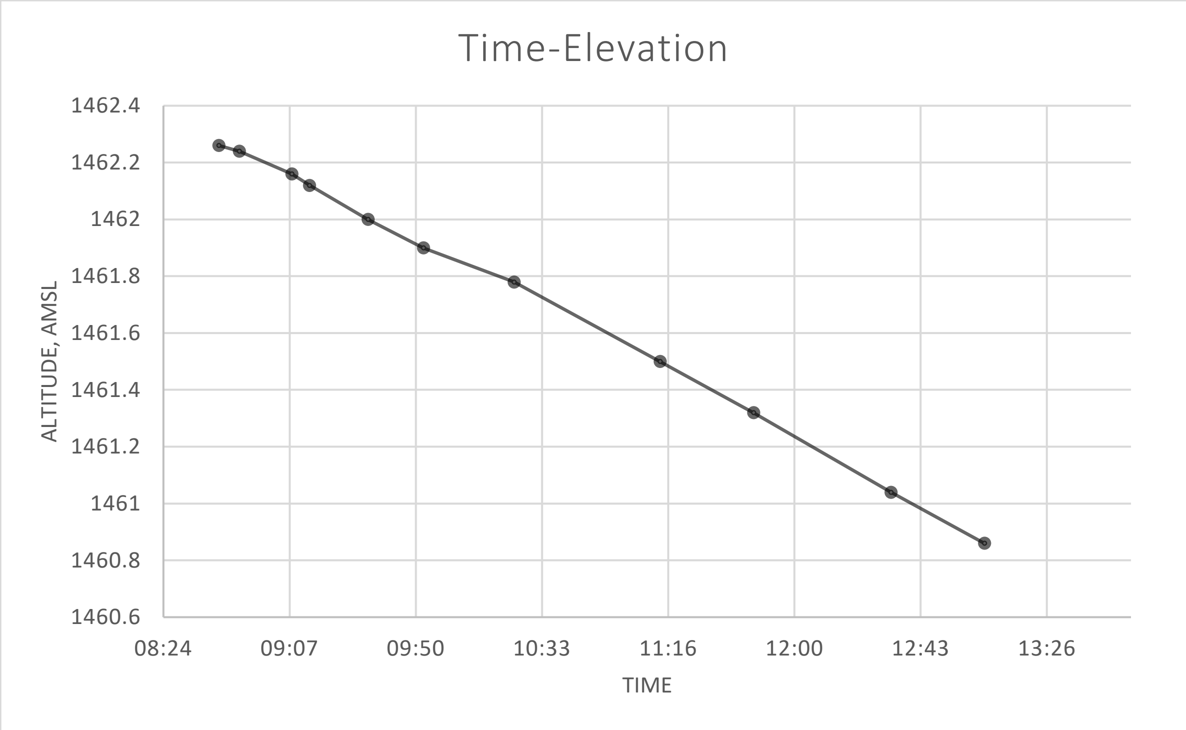


Figure 4-13 Water level at the pond. Draw down rate of around 0.53 cm/min.

5. SSIIM

5.1. Simulations

The simulation procedure in the SSIIM 2 consists of grid generation, water flow simulation and sediment transport simulations. Simulations are done for the three cases of pond: two cases with the sediment filled which is the current situation of the pond and one case with the original geometry of the pond which has no sediments. Solution from both simulation cases is compared with the field data.

5.2. Grid Generation

The first step of modelling is to prepare the grid of the pond. This require information about the topography which is obtained from the bathymetry survey and design drawing. The geodata file is created as described in section 2.4.2.1.2. SSIIM can read the file and points can be viewed in the Grid Editor interface of the SSIIM. A grid used in SSIIM 2 is unstructured. This makes it easier to adapt the grid to complex geometries to make good grid. The grid created in this study is shown below and steps for creating the grid is attached in Appendix 8.5.

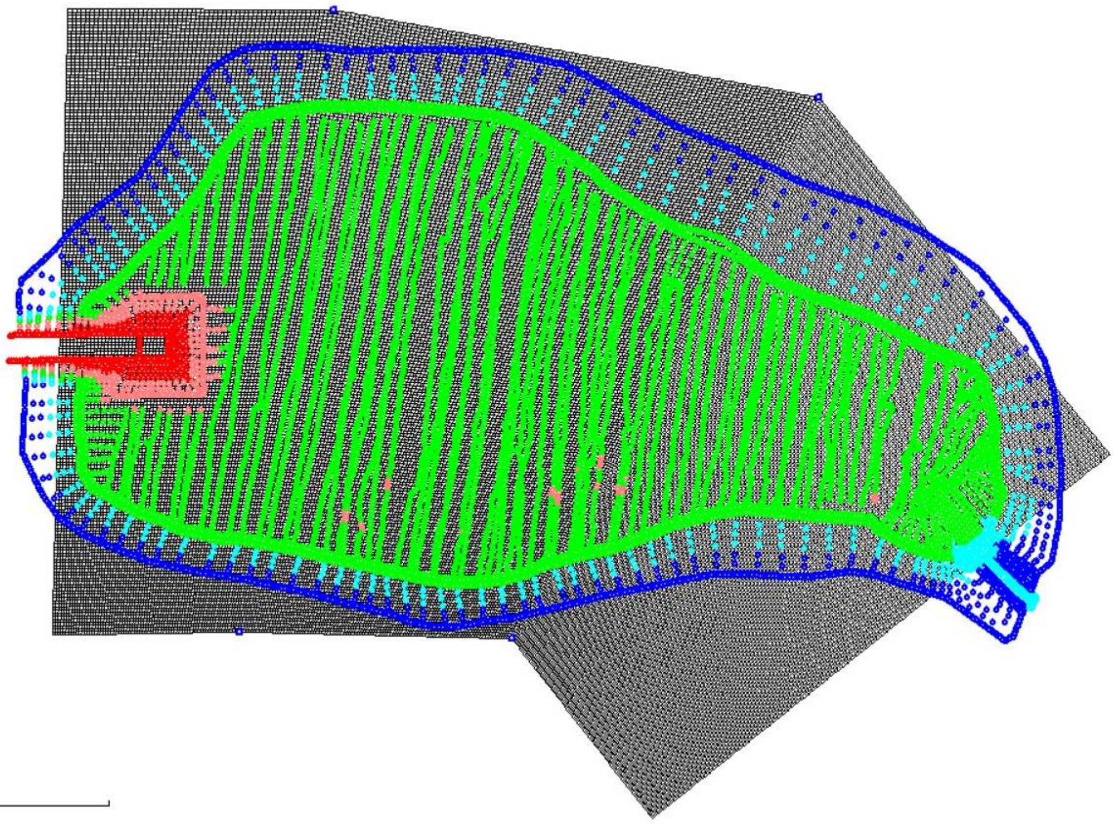


Figure 5-1 Grid of the model

5.3. Water Flow Simulation

Water flow simulation is done for three cases of the pond. The first case is compared with the field data for validation and other two are done to be used for sediment transport simulation.

The cases of water flow simulation are summarized in the table below:

Description	First Case	Second Case	Third Case
Geometry	Surveyed Geometry	Surveyed Geometry	Original geometry
Discharge	3.24 m^3/s	8.52 m^3/s	8.52 m^3/s
Water Level	1461.79	1461.79	1461.79
Objective	Compare with field data for model validation	From the result of first case, the program is simulated for the second case.	From the result of first case, the program is simulated for the third case
Sediment Simulation objective	D50 Sediment size distribution	D50 Sediment size distribution	D50 Sediment size distribution
Remarks	Low discharge	High discharge during wet seasons when high sediment volume inflows	High discharge during wet seasons when high sediment volume inflows

Table 5-1 Different cases of water flow simulation

5.3.1.1. Inlet and Outlet

Inlet and Outlet for the geometry is modified to simplify the water flow simulation. The pond has a circular pipe inflow and outlet is a penstock to the turbine. These structures are changed to an open surface channel by adding geodata points. Also due to operation strategy of the peaking pond, in an actual site condition, the inflow and outflow discharge is not equal, however this is not in case in simulation because both the discharges need to equal in SSIIM. (Olsen, 2018)

5.3.1.2. Simulation Parameters

Different parameters are given for simulation by using control file. The control files are attached in the Appendix 8.6. The water flow computations are run for an 86400sec with 10 iteration per 1 sec time step. The Second order upwind scheme is used in the simulation. It uses extrapolation of the concentrations in the two cells following each other in different directions away from the target cell to find the concentration value on the target cell wall between the target cell and the adjacent cell. The difference is first and second order upwind scheme is that the first order uses the concentration only in the upstream cell which is used as basis for calculating the concentration in the target cell. Both the schemes are simulated, and results are compared to see the difference between solutions.

5.3.1.3. Results of water flow computation

First case:

Residual Values

Residual Values for all six partial differential equation solved are equal to less than 10^{-3}.

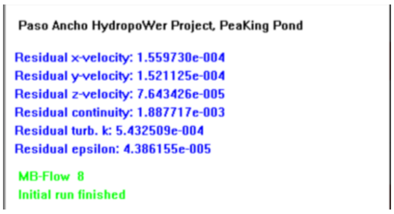


Figure 5-2 Residual value for first case

Depth Averaged Horizontal Velocity

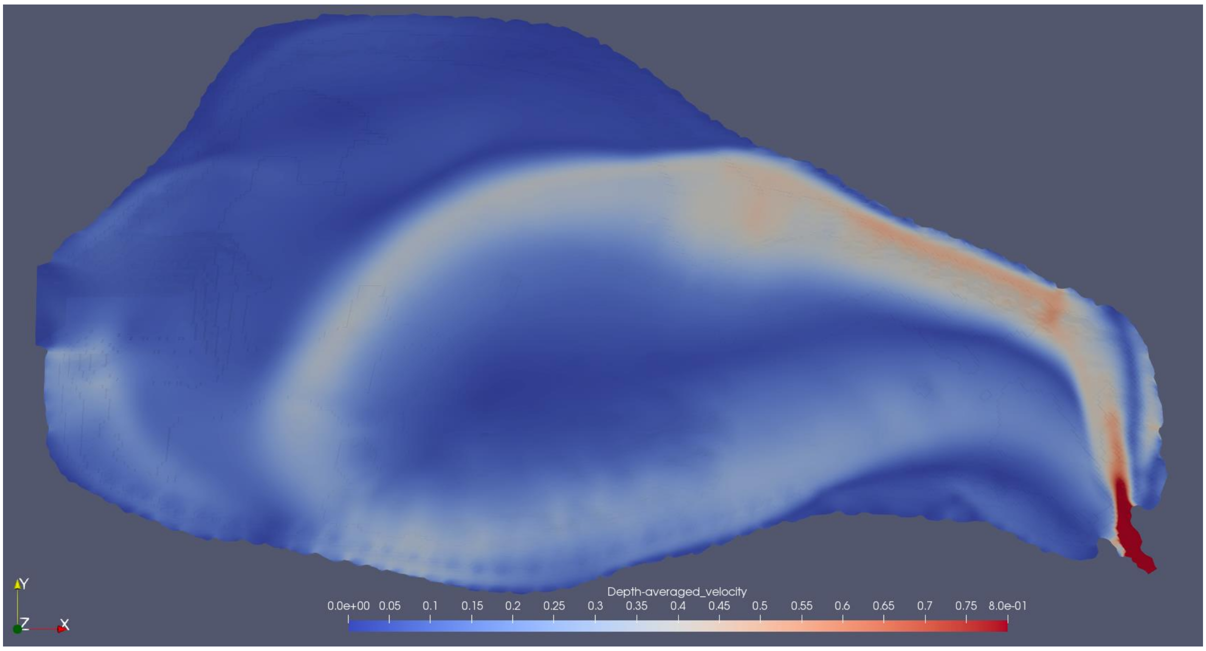


Figure 5-3 Depth-Averaged Horizontal Velocity

Figure 5-3Figure 5-3 shows the depth averaged horizontal velocity for the first case of the pond. This simulation is done with *Second Order Upwind Scheme.* The inflow and outflow discharge are 3.24 m^3/s. There is no uniform velocities distribution and most of the velocities are between 0 m/s to 0.8 m/s. The maximum horizontal velocity is 7.73 m/s, which is in the inflow. There is defined flow region with velocities higher than 0.4 m/s.

Horizontal Water Velcoity Flow Fields

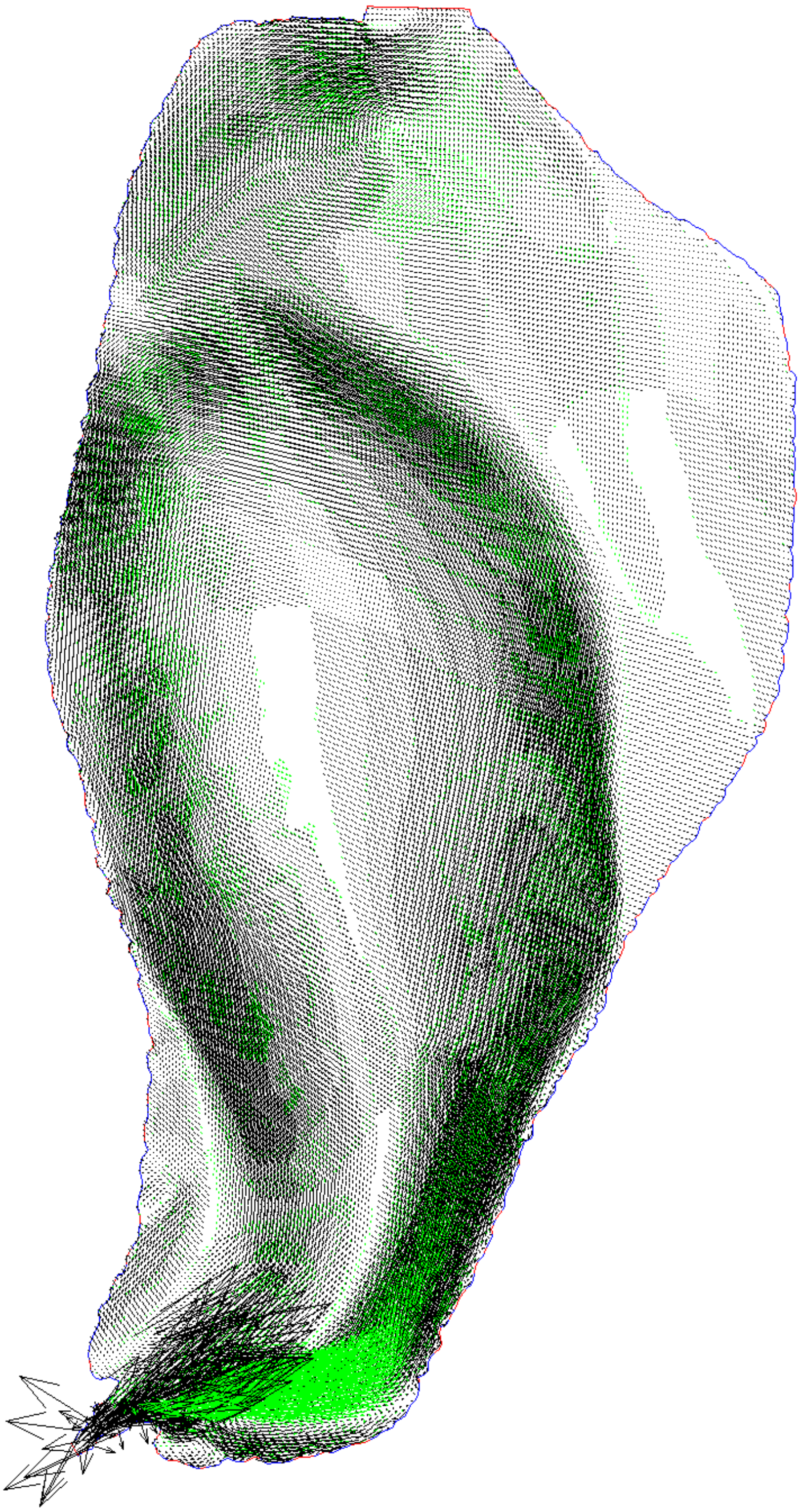


Figure 5-4 Velocity Vector of first case

The velocity vector represents the flow direction. There are number of circulation zones. Some portion of main flow circulates in the outlet zone back to the inflow and some to the outflow.

5.3.1.3.1. First order upwind scheme simulation

This simulation is done by using data set K 6 0 0 0 0 0 0 in the control file instead of K 6 1 1 1 0 0 0. In early trials of simulations during changing of the inflow location and geometry, there were differences in the flow patterns between the first and order scheme. After finalizing the inflow geometry, simulation is done in the first order to see the differences.

Residual Values

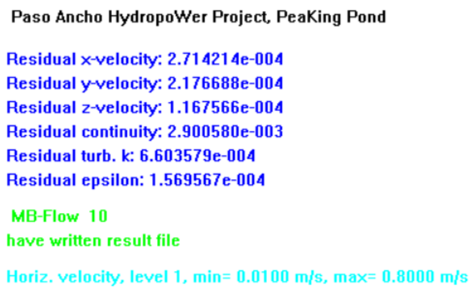


Figure 5-5 Residual value for First order scheme

All values for all six partial differential equation solved are equal to or less than 10^{-3}.

Depth Averaged Horizontal Velocity

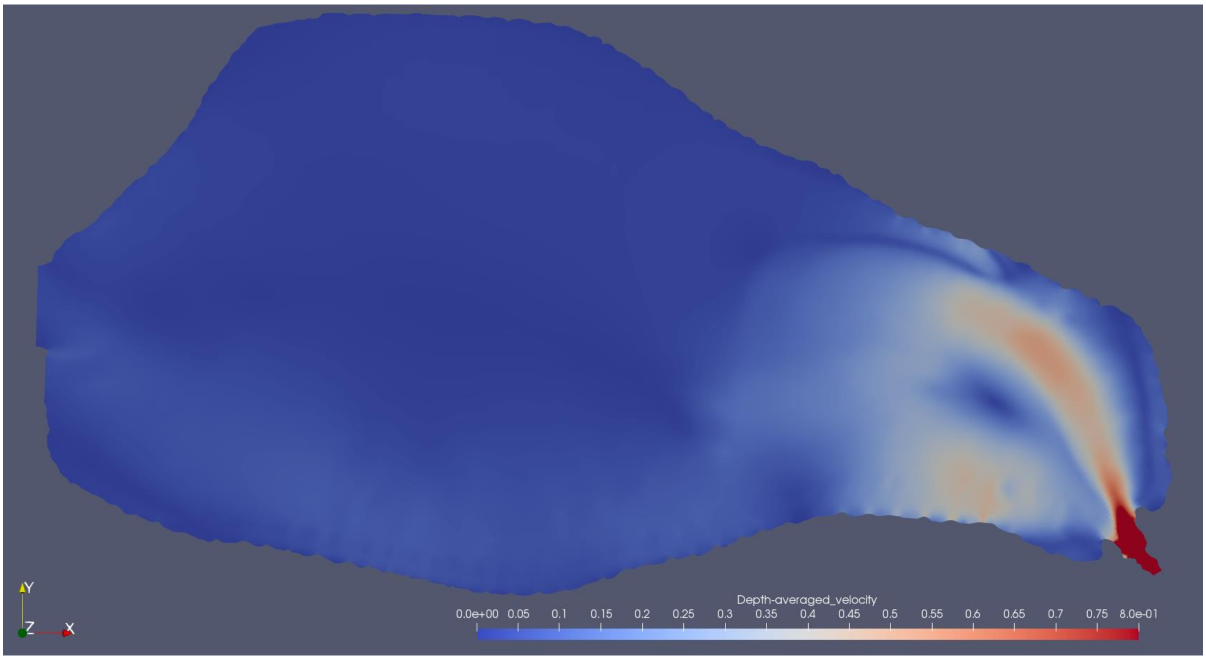


Figure 5-6 Depth Averaged Horizontal Velocity of First Order Upwind Scheme.

Figure 5-6 shows the depth averaged horizontal velocity for the first order upwind scheme. Most of the velocities are between 0 m/s and 0.8 m/s. The maximum horizontal velocity is 7.5 m/s. The water flow velocities circulate near the inflow region.

Horizontal Water Velcoity Flow Fields

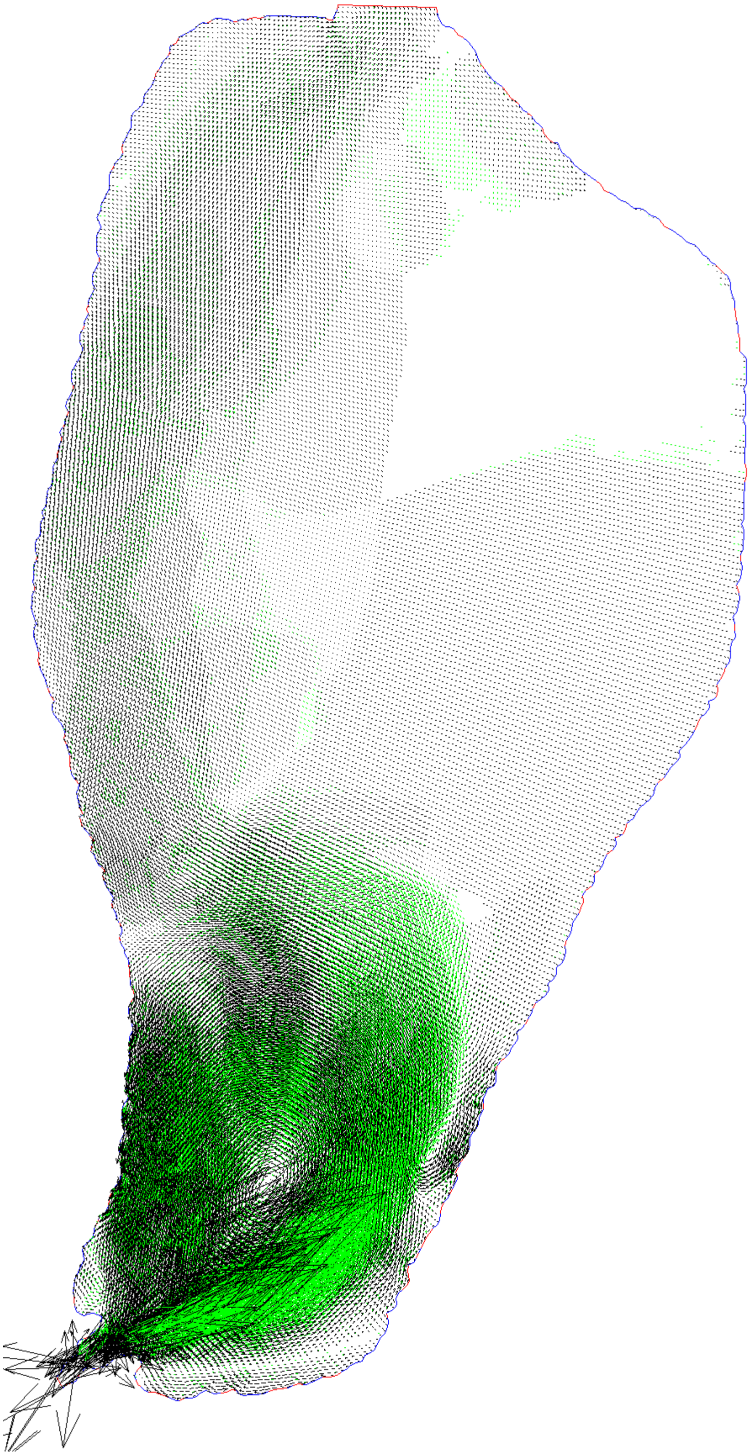


Figure 5-7 Velocity vector of first order upwind scheme

The circulation occurs nearer to the inflow compared to the second order scheme. The big portion of flow circulates back to inflow and other to the outflow.

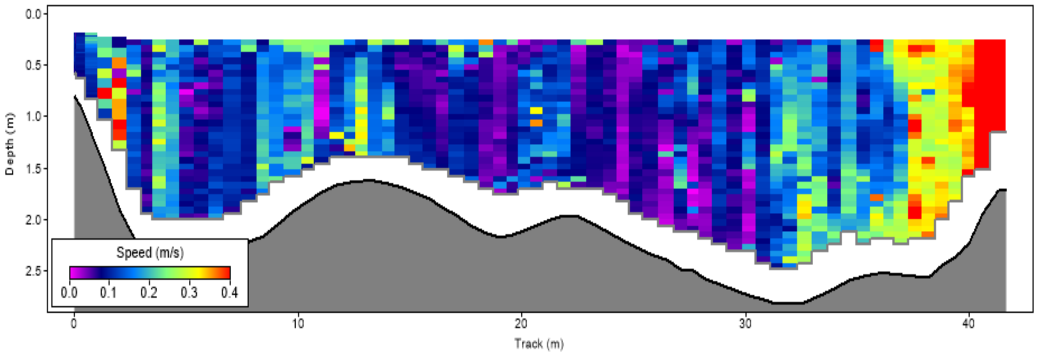
5.3.1.3.2. Comparison

Depth averaged horizontal velocity and the water velocity profile of both first order and second order schemes are compared with the field data.

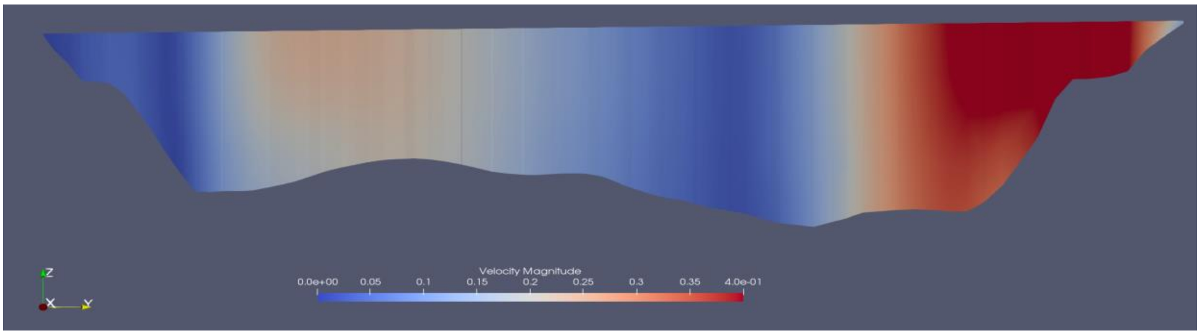
Comparing the depth averaged velocity from the second order simulation (Figure 5-3) and the first order simulation (Figure 5-6) with the measured velocity map (Figure 4-10), the second order simulation comes close to the measured data.

Figure 5-8 shows the mean flow velocities profile for the section in the pond 40m downstream from the intake. The comparison is made for the field data (a) and SSIIM simulation results (b and c)

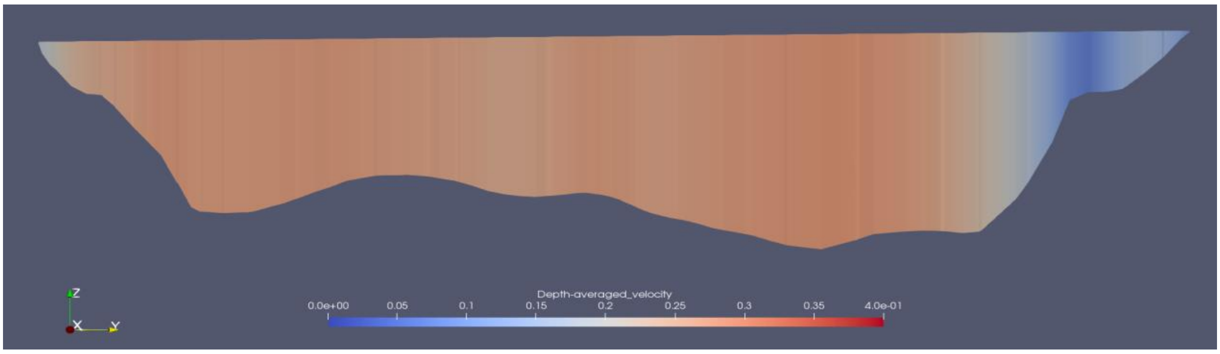
Left Bank UTM: 319990.23, 973229.05; Right Bank UTM: 319997.32, 973269.43



(a)



(b)



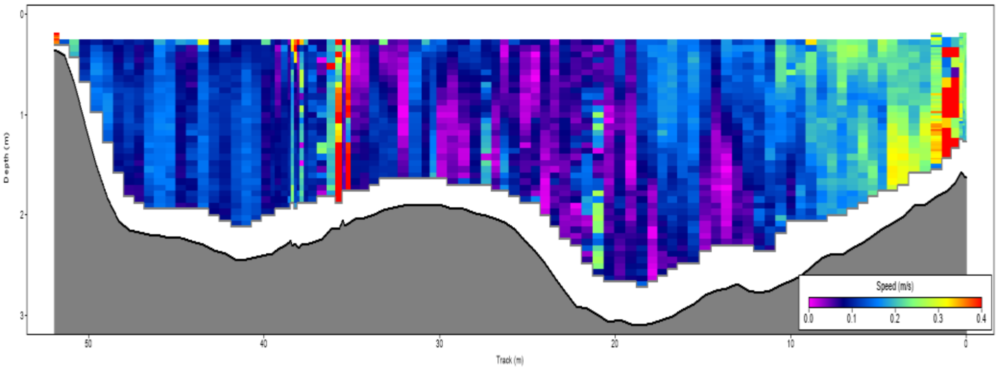
(c)

Figure 5-8 Velocity spatial distribution (a) Field Measurement from ADP, (b) SSIIM second order simulation, and (c) SSIIM first order simulation

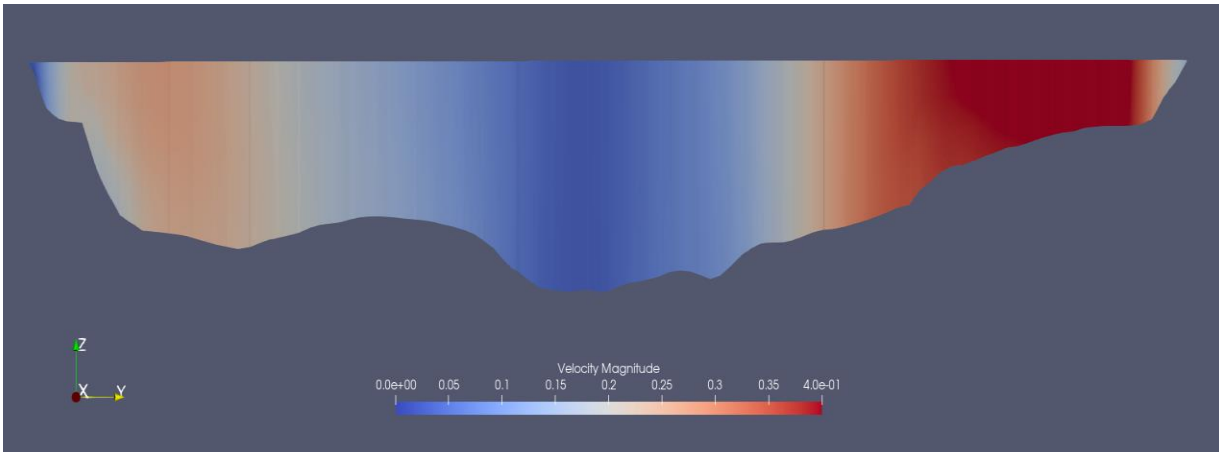
The range of velocities are very similar in case of "a" and "b", whereas figure "c" does not show any similarity and has a constant distribution of velocity.

Next comparison is made for the section 100 meters from the intake to verify the above comparison.

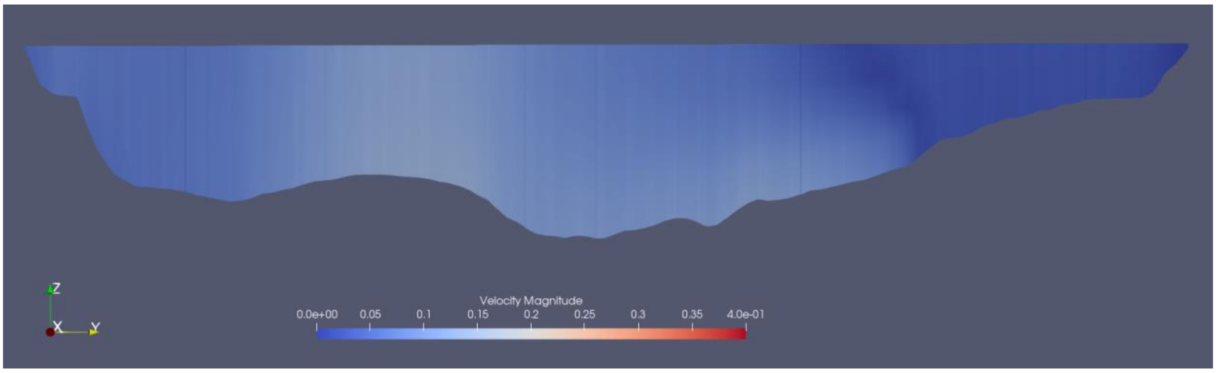
Left Bank UTM:319974.16, 973273.644; Right Bank UTM: 319965.89, 973222.803



(a)



(b)



(c)

Figure 5-9 Velocity spatial distribution (a) Field Measurement from ADP, (b) SSIIM second order simulation, and (c) SSIIM first order simulation

Again, the range of velocities are similar in case of “a” and “b”, whereas figure “c” does not show any similarity and has a constant distribution of velocity.

The choice of order for the second and third case of simulation is the second order upwind scheme based on the above comparisons.

Second case:

The second case is run with the discharge of 8.52 m^3/s. This is the average monthly flow of October, where the highest sediment inflow has been recorded for the year of 2018. The objective of this simulation is to use the model in sediment transport simulation and see the bed grain size distribution in the pond and compare with the field sediment samples.

Residual Values

Paso Ancho HydropoWer Project, PeaKing Pond

Residual x-velocity: 6.632139e-004
Residual y-velocity: 5.468267e-004
Residual z-velocity: 1.369989e-004
Residual continuity: 8.890067e-004
Residual turb. k: 1.951647e-003
Residual epsilon: 8.077715e-005

MB-Flow 5
Initial run finished

All Values for all six partial differential equation solved are equal to or less than 10^{-3}.

Depth Averaged Horizontal Velocity

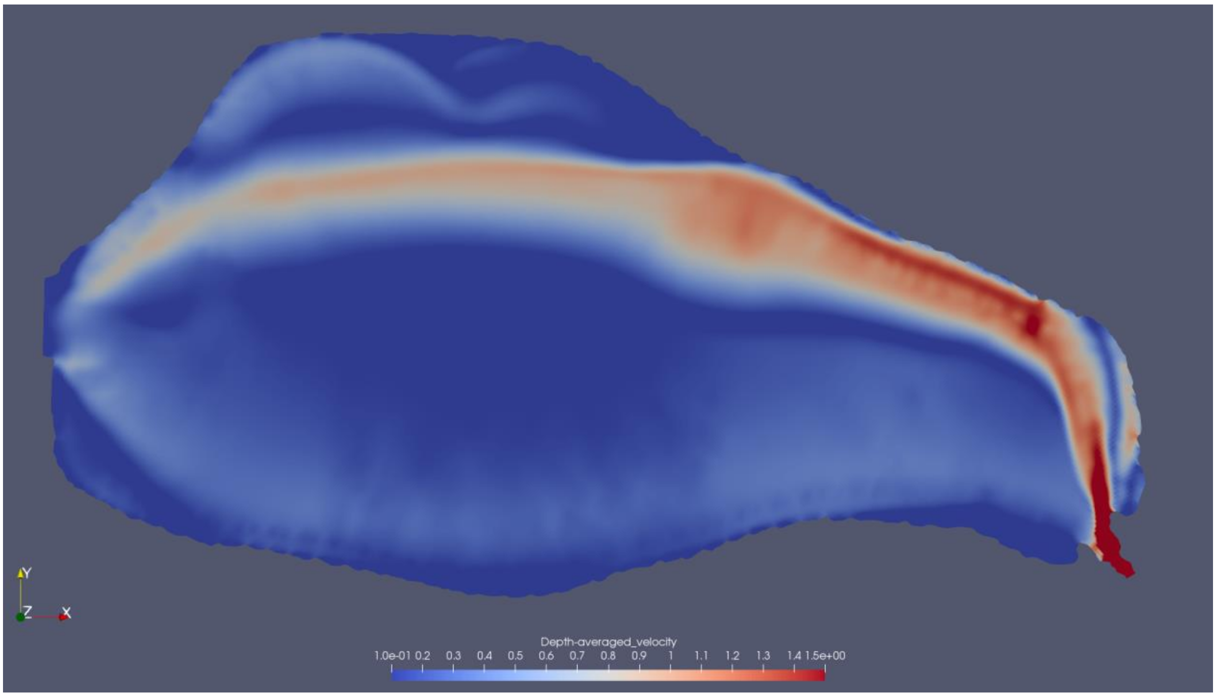


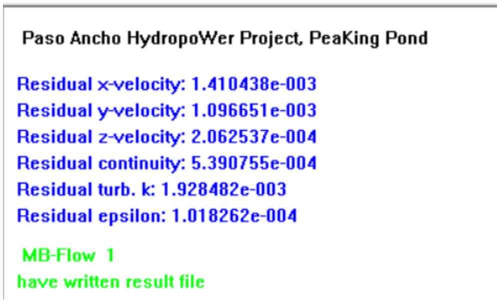
Figure 5-10 Depth Averaged horizontal velocity of second case

Figure 5-10 shows the depth averaged horizontal velocity between range of the 0.1 m/s to 1.5 m/s for the first case. Due to unsymmetrical structure, the velocity is not evenly distributed but defined flow region can be observed shown by different shades of color red. The velocity higher than 0.8 m/s can be observed till the outlet of the pond. The minimum horizontal velocity in this case is 0.00055 m/s and the maximum horizontal velocity is 20.32 m/s, which is in the inflow.

Third case:

This case is also run with the discharge of 8.52 m^3/s. But the original geometry data of pond is used for the simulation. This allows to see the difference between flow pattern from the second case and the model is also used for the sediment transport simulation.

Residuals Values


Paso Ancho HydropoWer Project, PeaKing Pond

Residual x-velocity: 1.410438e-003
Residual y-velocity: 1.096651e-003
Residual z-velocity: 2.062537e-004
Residual continuity: 5.390755e-004
Residual turb. k: 1.928482e-003
Residual epsilon: 1.018262e-004

MB-Flow 1
have written result file

All Values for all six partial differential equation solved are equal to or less than 10^{-3}.

Depth Averaged Horizontal Velocity

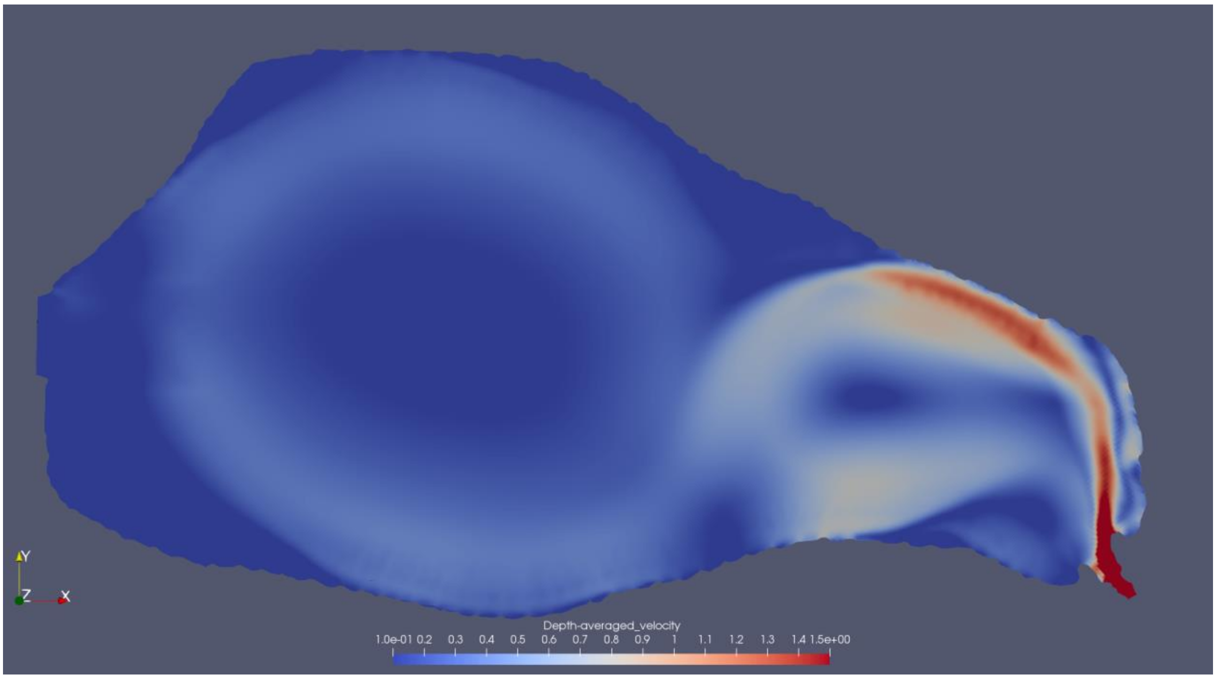


Figure 5-11 Depth Averaged Horizontal Velocity for third case

Figure 5-10Figure 5-11 shows the depth averaged horizontal velocity between range of the 0.1 m/s to 1.5 m/s. The minimum horizontal velocity in this case is 0.00055m/s and the maximum horizontal velocity is 20.35 m/s. Like the case 2, the velocity is not evenly distributed across the surface area, but a different flow pattern can be observed. The difference from the second case is the depth of the pond. While the second case has average depth of around 2.8 m, this case has an average depth of 6.8 m. Number of recirculation zones of water flow can be seen.

5.3.1.4. Limitation

The fluctuation of the water level in the pond is not simulated. Due to position of inflow, which resembles an inflow from a pipe in a top of a tank, the grids cells of the inflow dry up, if the water level is lowered and inflow cannot be simulated.

The water level fluctuation has been simulated in one of previous master thesis studies for the flushing behavior in the reservoir where model successfully simulated sediment deposition and flushing of the reservoir (Lisa Hoven, 2010). However, it cannot be applied in this study.

Secondly, in actual conditions of the pond, there are energy dissipation chutes with stepped blocks in the inflow area which reduces the velocity in the pond. This may also be the reason that the measured velocity map (Figure 4-10) has low velocity further down from the middle of the pond whereas the simulation results (Figure 5-3) shows higher velocities till the outflow.

5.4. Sediment transport simulation

5.4.1. General

The primary aim of the sediment transport simulation is to see where which type of grain size particles settles in the pond and compare with the field sediment sample (Figure 4-12). The flow patterns are determined by the water flow simulation and the results are used to compute sediment transport. To see the distribution pattern of sediment, F 68 2 data set is used in the control files which invokes a computation where the water velocities are not recomputed for each time step, only the sediment concentration. This saves the computational time and does not deteriorate the results. (Olsen, 2018).

This kind of simulation requires very small bed elevation changes, so the possible lowest sediment concentration is taken to do the computation to see the distribution pattern.

Sediment computation is done for the particle sizes from the grain size distribution report from the lab analysis. Sample 3 is taken as an average grain size distribution curve and is used in the control file for the sediment size groups. The sample curve is divided equally to 10% to obtain 10 different sediment sizes ranging from the 0.15mm to 6mm.

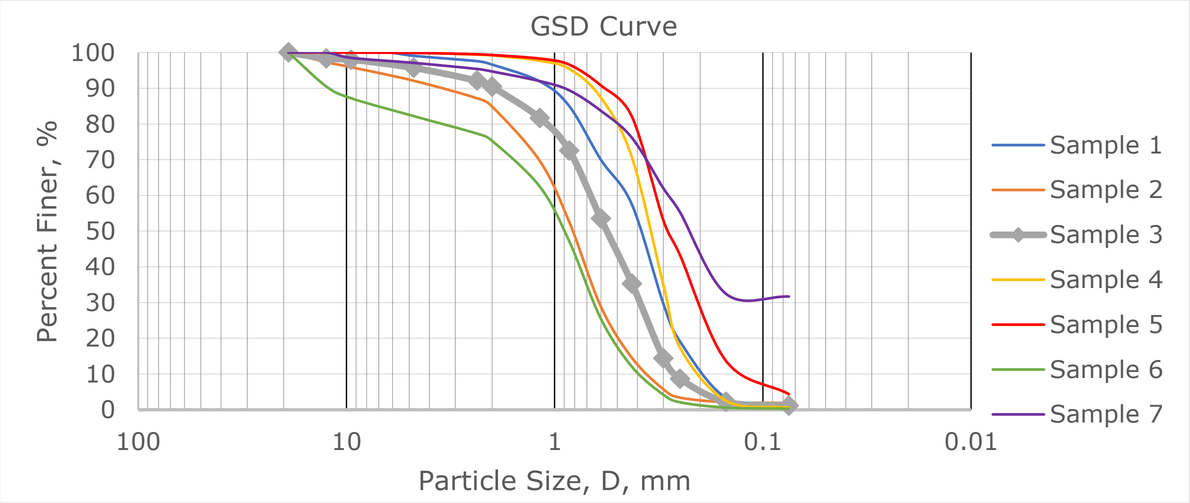


Figure 5-12 Sample 3 for the Sediment simulation

The specific gravity of the sediment size is taken as 2.65 and critical shield coefficient is taken as -0.047 as a default value in the SSIIM.

The fall velocity of particles sizes is calculated using the Rubey's Equation are shown in table below;

S.No.	Particle Size, mm	Fall Velocity, m/s	%, finer
1	6	0.254	95
2	1.5	0.123	85
3	0.95	0.095	75
4	0.74	0.082	65
5	0.62	0.073	55
6	0.52	0.064	45
7	0.43	0.055	35
8	0.36	0.047	25
9	0.3	0.040	15
10	0.15	0.016	5

Table 5-2 Sediment Size and Fall Velocity

5.4.2.Input Files

Sediment distribution pattern is run for 86400 days with time step of 100 sec. A control file for sediment transport simulation is attached in the Appendix 8.6.

This average sediment concentration values are taken from the sediment inflow data, which is summarized as follows;

Year	Month	Monthly Average discharge (m^3/s)	Monthly Average (ml/L)	Maximum Value (ml/L)	Minimum Value (ml/L)
2017	December	8.73	0.10	0.10	0.10
2018	January	6.55	0.29	0.50	0.10
	February	5.06	0.10	0.10	0.10
	March	4.23	0.10	0.10	0.10
	April	4.38	0.20	0.30	0.10
	May	5.48	3.86	17.25	0.10
	June	6.61	4.43	50.67	0.10
	July	6.24	1.57	5.86	0.10
	August	7.28	0.30	1.99	0.01
	September	6.82	3.98	21.25	0.20
	October	8.52	6.90	68.03	0.10
	November	8.14	0.38	1.50	0.10
	Yearly Average		1.85	13.97	0.10

Table 5-3 Sediment Inflow data

Constant sediment concentration of 0.1ml/L is used for the simulation because there is no provided data of hydrograph for the sediment inflow. Lack of consistent sediment concentration measurement implies that the results of the simulation are less likely to represent the actual sediment transport.

There are two cases for sediment transport simulation summarized as below:

Description	First case	Second case
Objective	Bed grain size distribution	Bed grain size distribution
Water flow simulation	Second case	Third Case
Discharge	8.52m^3/s	8.52m^3/s
Sediment Concentration	0.1ml/L	0.1ml/L
Model Run time	86400 sec	86400 sec

5.4.3.Results of Sediment Simulation

First case:

This case is simulated to see the bed grain size distribution during the wet season when the sediment inflow is high in the pond.

Distribution of sediments

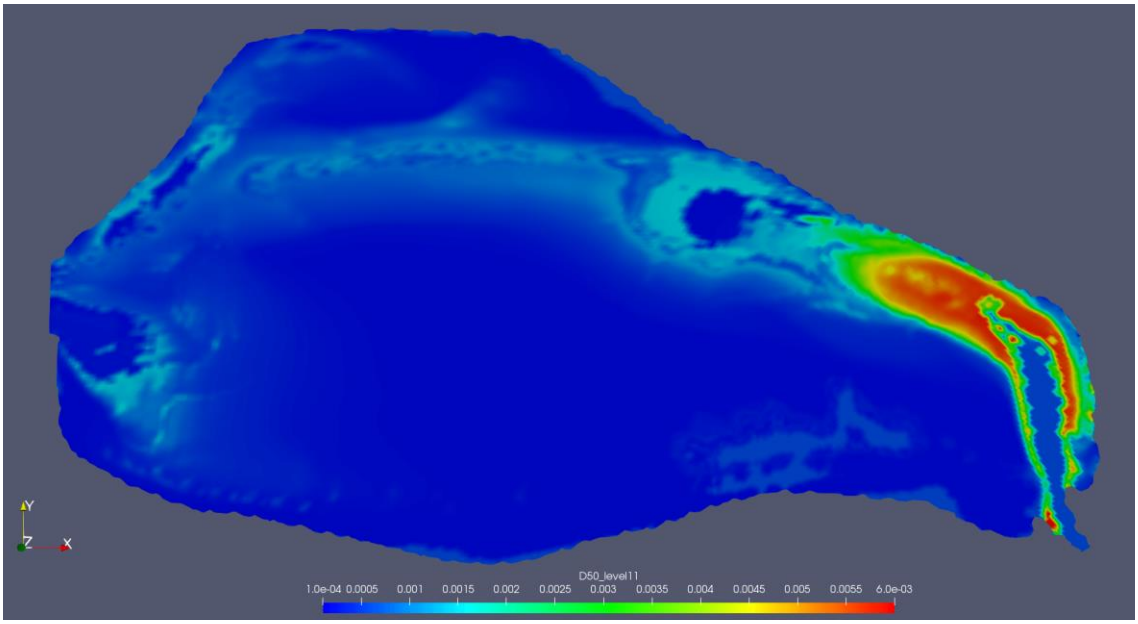


Figure 5-13 Bed Grain Size Distribution, D 50, minimum= 0.1mm, maximum= 6mm

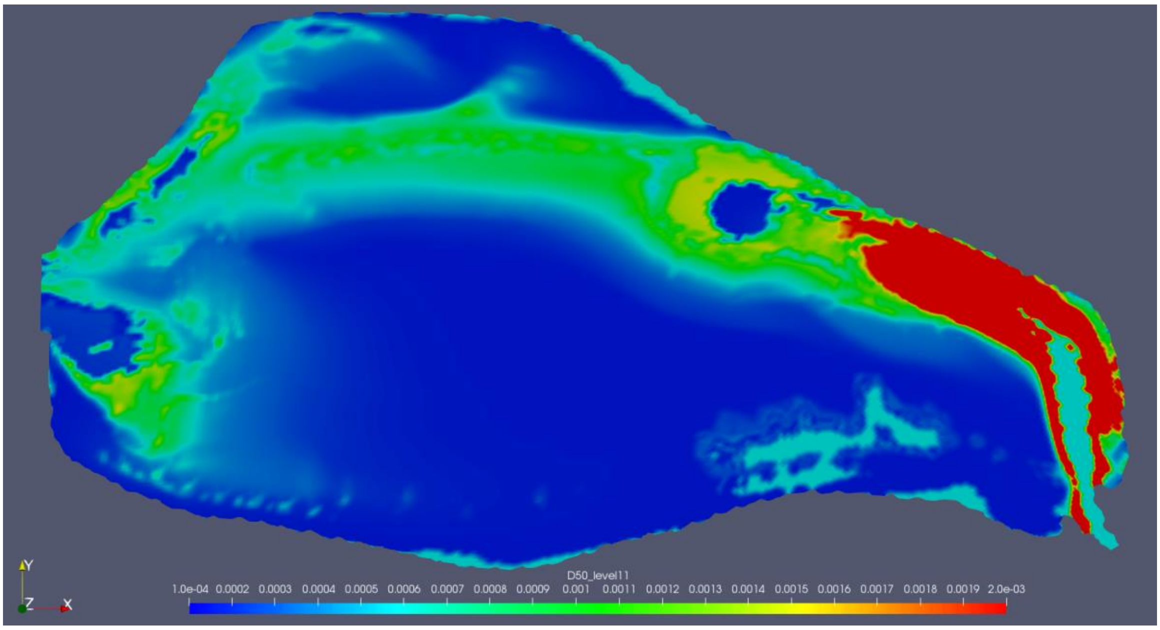


Figure 5-14 Bed Grain Size Distribution, D 50, minimum= 0.1 mm, maximum= 2 mm

Figure 5-13 shows the map for D50 size of active layer bed sediment between 0.1 mm and 6 mm and Figure 5-14 shows between 0.1 mm and 2 mm. Particles size less than or equal to 1.5 mm is transported till the outflow the pond. The *boogie* file gives the result for the trap efficiency. There is an inflow of 195074 kg of sediments and outflow of 14148.2 kg of sediments, which accounts to trap efficiency of 92.75%, corresponding to sediment inflow of 0.1ml/1000ml.

Second Case:

Distribution of sediments

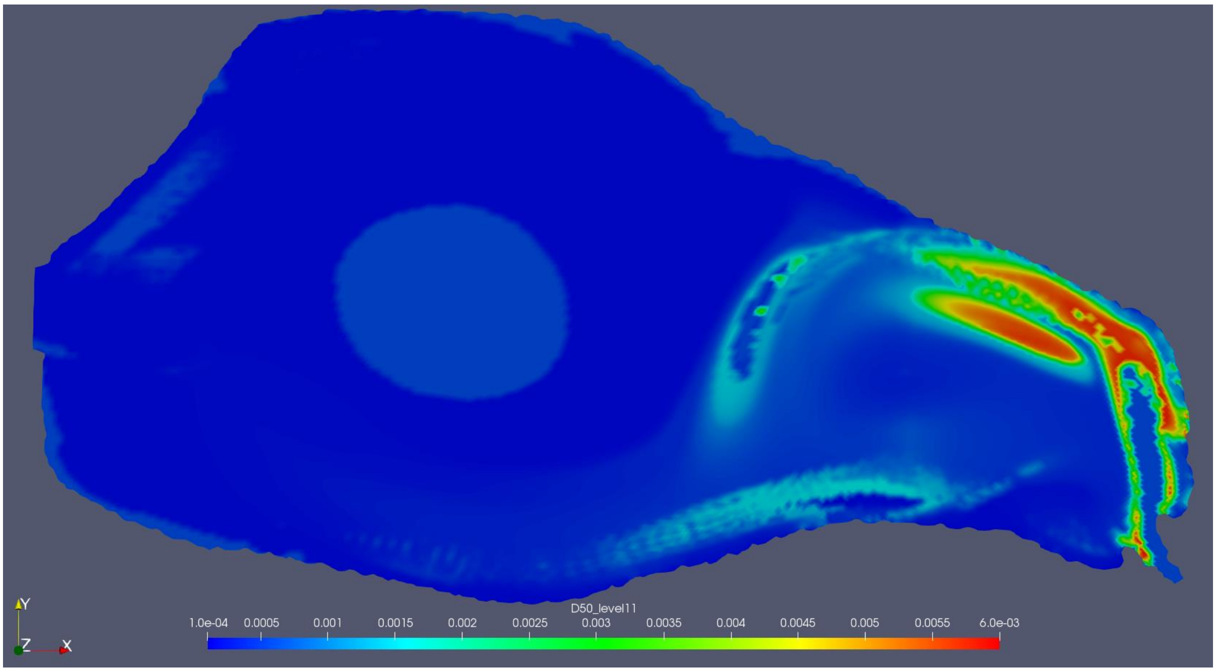


Figure 5-15 Bed Grain Size Distribution, D 50, minimum= 0.1mm, maximum= 6mm

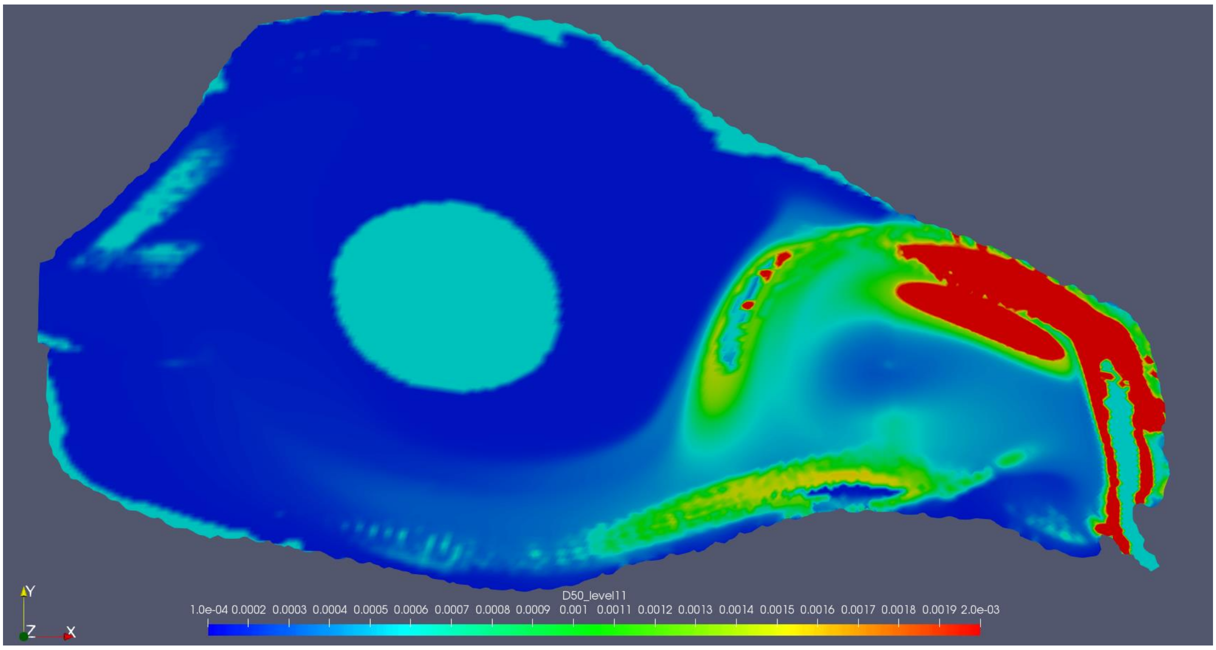
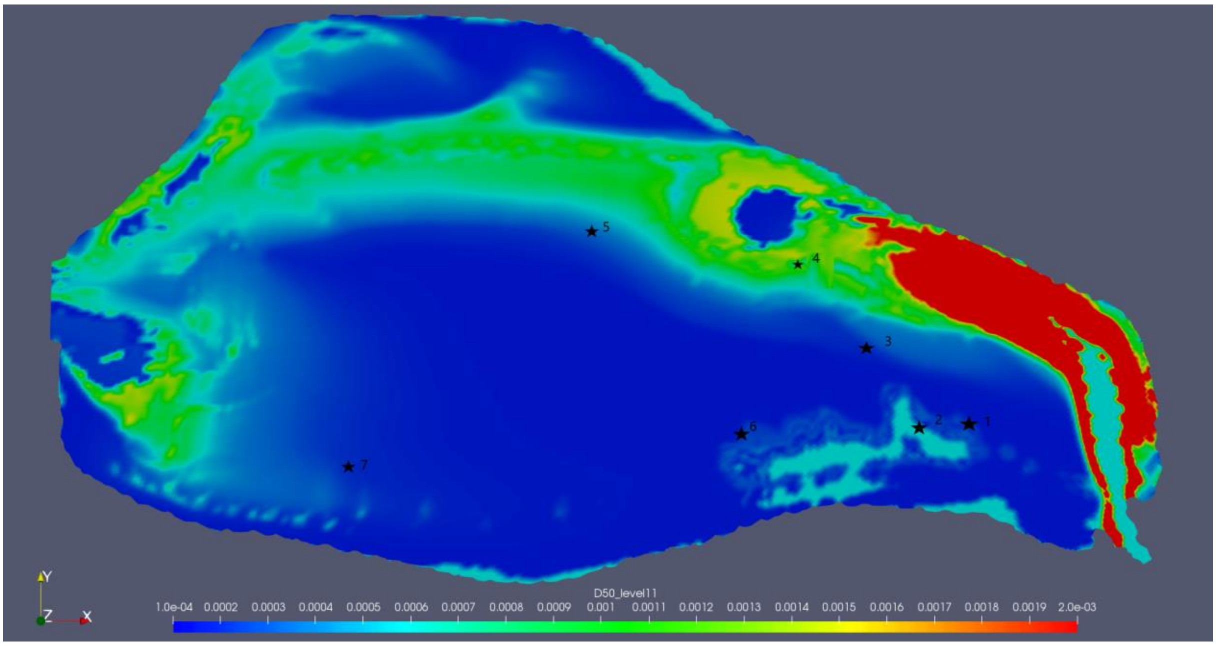


Figure 5-16 Bed Grain Size Distribution, D 50, minimum= 0.1 mm, maximum= 2 mm

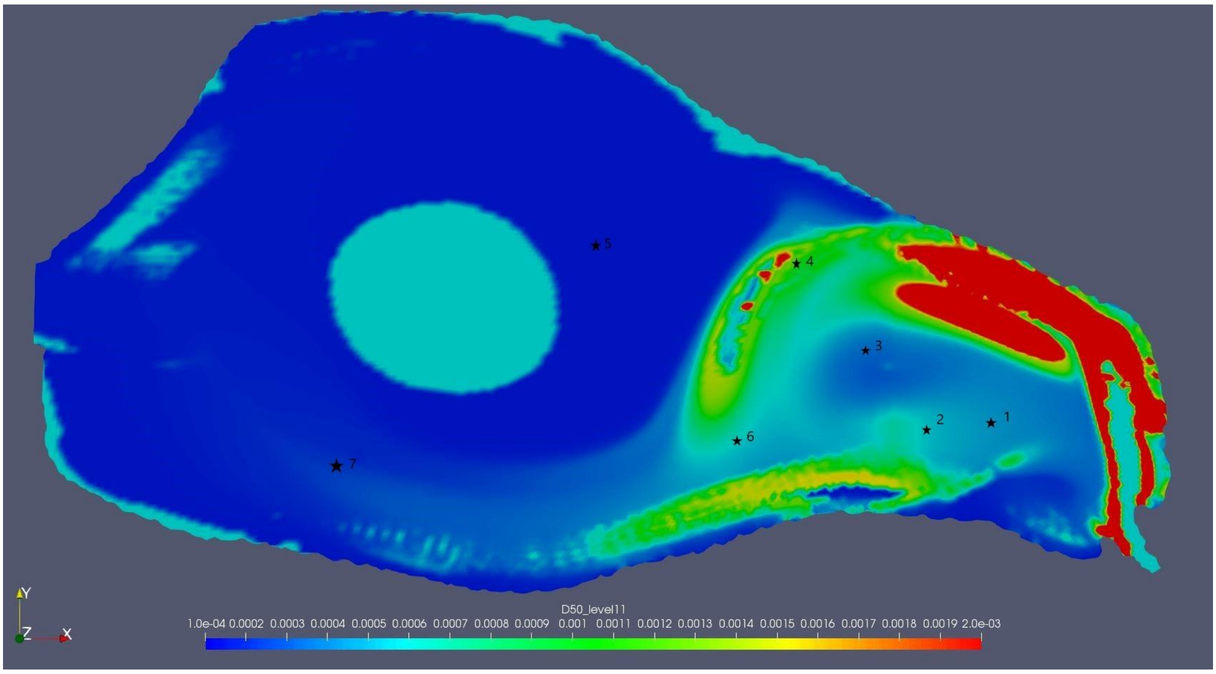
Figure 5-15 shows the map for D50 size of bed sediment between 0.1 mm and 6 mm and Figure 5-16 shows between 0.1 mm and 2 mm. Particles size greater than or equal to 1mm are settled within the middle region of the pond. Particles size greater 2 mm are settled in the right bank near the inflow. There is an inflow of 195074 kg of sediment and outflow of 338.264 kg. The trap efficiency thus is 99.83 %.

Comparison:

Figure 5-18 and Table 5-4 shows the comparison of sediment sample from the field and simulation results of the two cases. The location of sediment sample is placed on the simulation results, that can be seen in Figure 5-17. Using the “tooltip selection mode” on Paraview Program, the point data on simulation result can be found.



(a)



(b)

Figure 5-17 Simulation result and sediment sample (a) first case, and (b) second case

The obtained values are shown below:

Sample number	Location		D 50 size, mm		
	Easting	Northing	Field data	First case	Second case
1	320006.60	973240.12	0.39	0.17	0.46
2	319996.17	973242.37	0.82	0.23	0.53
3	319986.80	973252.51	0.57	0.18	0.34
4	319974.35	973268.18	0.35	0.10	0.95
5	319938.89	973275.00	0.28	0.39	0.15
6	319964.45	973244.84	0.91	0.15	0.80
7	319891.94	973234.46	0.21	0.21	0.22

Table 5-4 D50 sediment size comparison

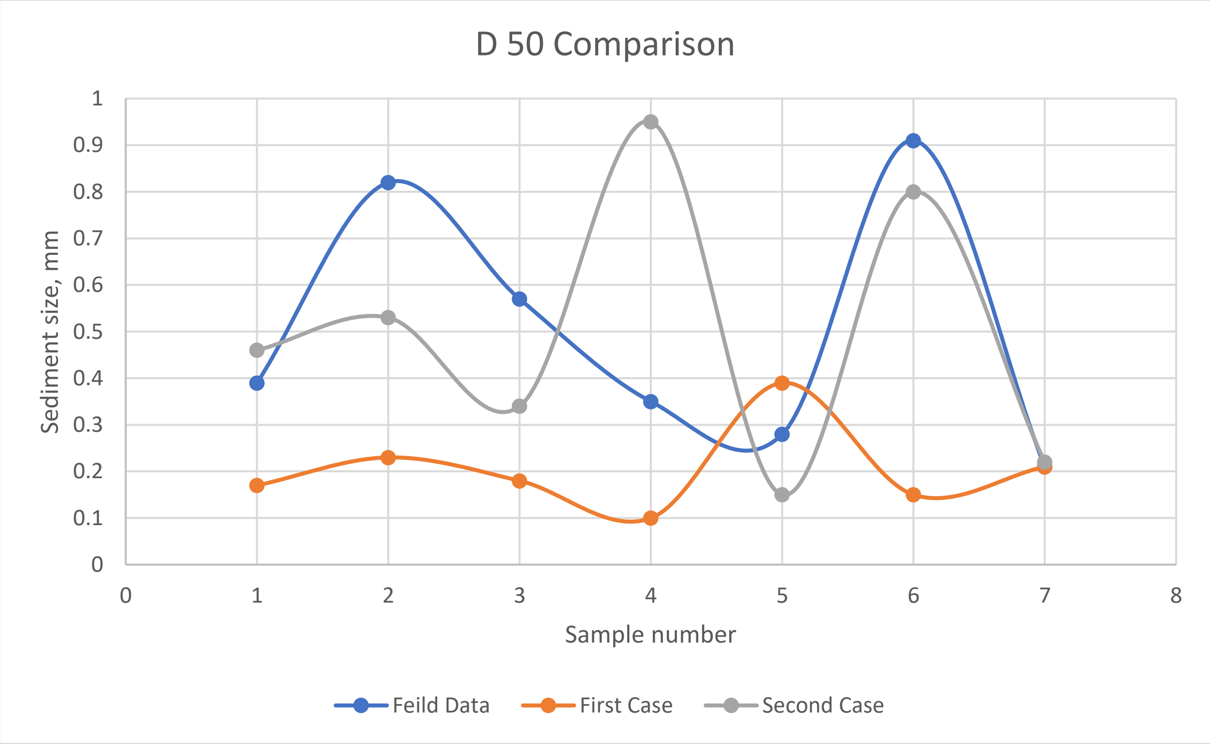


Figure 5-18 D50 Sediment Size comparison between field data and simulation results

The comparison shows the variations in the D50 sediment size between sediment samples and SSIIM results, except for the sample 7, which has identical values. Sample 5 also has some similarities and result of sample 6 from second case shows similarity to the field data.

The two simulation results show different type of sediment distribution in the pond. This is due to fact that the pond has different geometries. The average depth of water for the first case is 2.8 m and the second case is 6.8 m. Due to the less depth in first case, there is a higher velocity of water flow in the pond as seen in Figure 5-10, which transports the sediments further in to the pond. The first case represents the current state of the pond. From the simulation results, it is seen that, particles size up to 1.3 mm are transported to the outflow region and it is natural, when there is a high concentration of sediment inflow in the pond, sediment volume will increase changing the hydraulics, which will cause more higher sediment particles to reach the outflow and even pass through the penstock pipe to the turbine. It is recommended that, the deposited sediment in pond should be removed before the wet season arrives at site.

6. Conclusion and Further work

6.1. Conclusion

In this thesis, a 3D numerical model has been setup for the simulation of water flow and sediment transport using SSIIM 2. Bathymetry survey was done on the pond to obtain the bed profile and the mean flow velocities. Geodata from the bed profile is used to setup a geometry for the numerical model and mean flow velocities are compared with the water flow simulation results. It has been shown that the first order and second order upwind scheme produced different flow patterns and the velocities from the second order upwind scheme came close to the surveyed data. And the model with the second order is used for further water flow and sediment transport simulations.

Sediment transport simulation has been done to see the distribution of D50 sediment size in the bed of the pond. Results were compared with the deposited sediments sample from the site and in general the results were not same. It should be noted that the simulation results are obtained through a lowest sediment concentration value and 1-day timestep but the sample from the pond consists of sediments that is deposited and distributed throughout the year along with the daily fluctuation of water level and sediment concentration. The daily water level fluctuation of pond could not be simulated due to limitation of the SSIIM and lack of consistent sediment concentration data likely produced different results. However, the model can be used to see and predict the sediment transport in the pond if the proper sediment input data is available and operation strategy of peaking pond can be simulated.

In addition to the SSIIM, the failure reason of the desander is also observed and analyzed. The study shows the importance of desander in the run of the river type projects. The observation showed that there were significant flaws in the structure related to the basic design of desander. The water velocity was high and high turbulence was seen. Furthermore, the size of settling zone is also very small and layout of desander does not match with the typical desander structure. It is difficult to suggest an improved design within the structure to make it fully functional. A new desander should be constructed with proper design if the incoming sediments are to be trapped in the desander and not transported to the pond. However, a construction cost can be a factor. So, a financial analysis should be done comparing between the current sediment removal method and constructing a new desander. Since the project is in the early years of operation, this can save a significant amount of cost within the life time of the project.

6.2. Further work

The important part of SSIIM is to feed the model with accurate input data, which can be the data like geometry of the pond, discharge, sediment data and other variables. So, the accuracy of the results depends on the input of the data.

In future, if the daily peaking operation of the pond can be simulated in the SSIIM, this model can be used to produce more likely results which then can be compared to the actual site conditions. A more consistent sediment concentration data can also help the model to produce results that can be validated by the measured data in the site.

Furthermore, the bed changes, sediment concertation and trap efficiency of the pond can be computed with SSIIM and compared with the site conditions.

7. References

Dagfinn Lysne et al., B. G. (2003). *Hydraulic Design* (Vol. 8). Trondheim: Norwegian University of Science and Technology, Department of Hydraulic and Environmnetal Engineering.

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8. Appendix

8.1. Inflow design drawing file

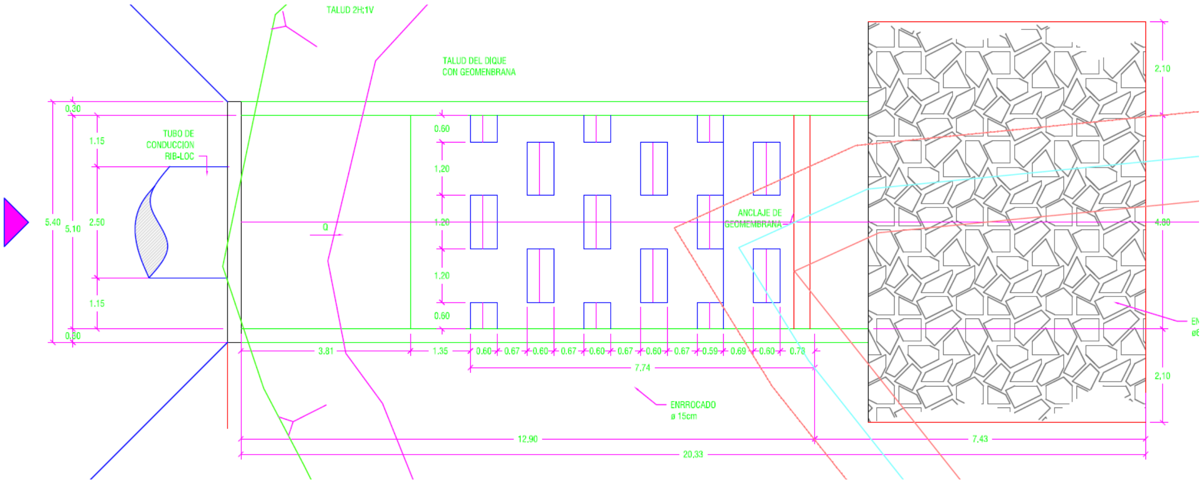

Figure 8-1 Plan view of inflow area

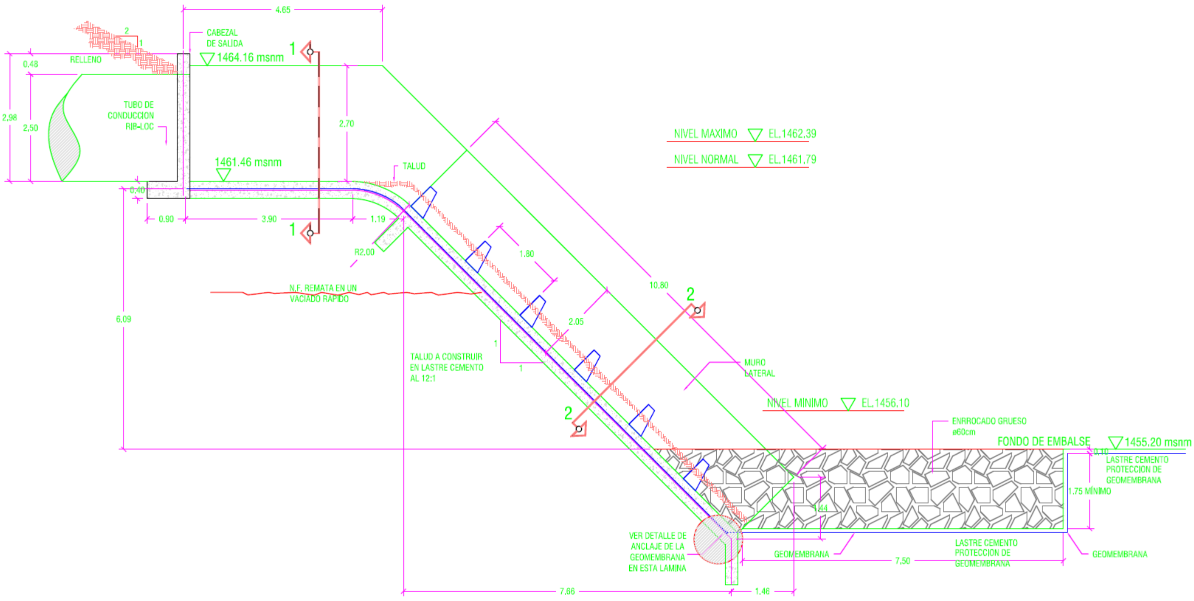

Figure 8-2 Sectional view of the inflow

8.2. Sediment Inflow data

Season	Month	Date	Volume of sediment	total volume of sample(ml)
Wet Season	December	20.12.2017	0.1	1000
		24.12.2017	0.1	1000
Dry season	January	01.01.2018	0.3	1000
		05.01.2018	0.5	1000
		08.01.2018	0.5	1000
		15.01.2018	0.5	1000
		19.01.2018	0.2	1000
		25.01.2018	0.1	1000
		26.01.2018	0.1	1000
		30.01.2018	0.1	1000
	February	01.02.2018	0.1	1000
		02.02.2018	0.1	1000
		03.02.2018	0.1	1000
		05.02.2018	0.1	1000
		13.02.2018	0.1	1000
		21.02.2018	0.1	1000
	March	09.03.2018	0.1	1000
	April	06.04.2018	0.1	1000
		07.04.2018	0.3	1000
	May	13.05.2018	0.5	1000
		18.05.2018	5.0	1000
		19.05.2018	0.6	1000
		20.05.2018	2.9	1000
		21.05.2018	17.3	1000
		22.05.2018	6.3	1000
		26.05.2018	4.0	1000
		27.05.2018	1.5	1000
		29.05.2018	0.5	1000
		30.05.2018	0.1	1000
Rainy season	June	01.06.2018	0.1	1000
		02.06.2018	0.2	1000
		03.06.2018	0.1	1000
		04.06.2018	0.0	1000
		07.06.2018	0.1	1000

		10.06.2018	0.3	1000
		11.06.2018	0.1	1000
		12.06.2018	0.5	1000
		15.06.2018	3.8	1000
		16.06.2018		1000
		17.06.2018		1000
		18.06.2018	0.1	1000
		19.06.2018	0.6	1000
		20.06.2018	0.8	1000
		21.06.2018	0.2	1000
		22.06.2018	0.0	1000
		23.06.2018	50.7	1000
		24.06.2018	14.9	1000
		25.06.2018		1000
		26.06.2018		1000
		28.06.2018	2.4	1000
		29.06.2018	0.5	1000
		30.06.2018	0.1	1000
	July	01.07.2018	1.3	1000
		04.07.2018	0.0	1000
		05.07.2018	0.0	1000
		06.07.2018	0.1	1000
		07.07.2018	0.0	1000
		08.07.2018	0.0	1000
		09.07.2018	0.0	1000
		10.07.2018	0.0	1000
		14.07.2018	5.2	1000
		15.07.2018	3.8	1000
		16.07.2018	0.8	1000
		17.07.2018	5.9	1000
		18.07.2018	0.6	1000
		19.07.2018	0.1	1000
		20.07.2018	0.0	1000
		21.07.2018	0.1	1000
		22.07.2018	0.5	1000
		24.07.2018	0.3	1000
		25.07.2018	1.1	1000

		27.07.2018	0.0	1000
		28.07.2018	0.0	1000
		29.07.2018	0.0	1000
		30.07.2018	0.8	1000
		31.07.2018	0.0	1000
	August	01.08.2018	0.0	1000
		02.08.2018	2.0	1000
		03.08.2018	0.3	1000
		04.08.2018	0.0	1000
		07.08.2018	0.0	1000
		08.08.2018	0.0	1000
		09.08.2018	0.0	1000
		10.08.2018	0.7	1000
		11.08.2018	0.1	1000
		12.08.2018	0.1	1000
		13.08.2018	0.1	1000
		14.08.2018	0.1	1000
		15.08.2018	0.1	1000
		16.08.2018	0.2	1000
		17.08.2018	0.1	1000
		18.08.2018	0.1	1000
		20.08.2018	0.1	1000
		23.08.2018	0.0	1000
		26.08.2018	0.0	1000
		28.08.2018	0.0	1000
	September	02.09.1018	0.0	1000
		03.09.1019	0.0	1000
		06.09.2018	0.3	1000
		08.09.2018	10.0	1000
		09.09.2018	1.0	1000
		10.09.2018		1000
		11.09.2018	0.2	1000
		19.09.2018	0.3	1000
		23.09.2018	21.3	1000
		26.09.2018	0.6	1000
		27.09.2018	1.0	1000
		28.09.2018	1.2	1000

	October	01.10.2018	0.1	1000
		02.10.2018	0.2	1000
		03.10.2018	0.1	1000
		04.10.2018	0.2	1000
		05.10.2018	68.0	1000
		11.10.2018	0.1	1000
		13.10.2018	0.1	1000
		14.10.2018	0.3	1000
		24.10.2018	0.1	1000
		28.10.2018	0.1	1000
		29.10.2018	13.0	1000
		31.10.2018	0.5	1000
	November	01.11.2018	0.1	1000
		03.11.2018	0.1	1000
		10.11.2018	0.1	1000
		11.11.2018	0.1	1000
		20.11.2018	1.5	1000

8.3. MATLAB Script

```
%% Read vel data
start_path= 'C:\Users\bijuk\Desktop\Data post processing file\Velocity Extract Matlab\Bottom Track matlab for velocity\Reshape Error' % put your directory
cd (start_path)
DIR = dir('*.mat');
[AA, SS]=fileparts(DIR(1).name)
  saveDir=[start_path '\' SS(1:end-4)];

 NewDir=  mkdir(saveDir); % directory automatic make
cutStart= 1; cutEnd= 0 % put 0 for entire section
for i= 1: length(DIR)

  % i=45
[AA, SS]=fileparts(DIR(i).name)
load(DIR(i).name)

%Average Depth Velocity
V_E = WaterTrack.Velocity(:,1,cutStart:end-cutEnd);
V_E = reshape(V_E,size(V_E,1),size(V_E,3),1);
V_N = WaterTrack.Velocity(:,2,cutStart:end-cutEnd);V_N = reshape(V_N,size(V_N,1),size(V_N,3),1);
c=nanmean(V_E);V_Emean=nanmean(V_E); (V_N); V_Nmean=nanmean(V_N);V_magMEAN=sqrt(V_Emean.^2+V_Nmean.^2);
Vmagmean=transpose(V_magMEAN)

%Surface Cells
V_E_1 = WaterTrack.Velocity(1,1,cutStart:end-cutEnd);V_E_1 = reshape(V_E_1,[],size(V_E_1,2),1);
V_N_1 = WaterTrack.Velocity(1,2,cutStart:end-cutEnd);V_N_1 = reshape(V_N_1,[],size(V_N_1,2),1);
V_mag1=sqrt(V_E_1.^2+V_N_1.^2);

%mean of 2 surface cells
V_E_12 = nanmean(WaterTrack.Velocity(1:2,1,cutStart:end-cutEnd),1);V_E_12 = reshape(V_E_12,[],size(V_E_12,2),1);
V_N_12 = nanmean(WaterTrack.Velocity(1:2,2,cutStart:end-cutEnd),1);V_N_12 = reshape(V_N_12,[],size(V_N_12,2),1);
V_mag12=sqrt(V_E_12.^2+V_N_12.^2);

% GPS points
x= GPS.UTM(cutStart:end-cutEnd,1);y= GPS.UTM(cutStart:end-cutEnd,2);

% PUT all the values
velData=[x, y, Vmagmean, V_mag1, V_mag12]

% save
save(fullfile(saveDir,['velData', SS]), 'velData')
end
```

8.4. Headworks Discharge measurement summary

Discharge Measurement Summary

Date Measured: Saturday, January 1, 2005

Site Information	
Site Name	Paso Ancho hpp
Station Number	1
Location	Intake weir

Measurement Information	
Party	P,m,e
Boat/Motor	Hydroboard
Meas. Number	1

System Information	
System Type	RS-M9
Serial Number	1233
Firmware Version	3.99
Software Version	3.9.50

System Setup	
Transducer Depth (m)	0.13
Salinity (ppt)	0.0
Magnetic Declination (deg)	-2.6

Units	
Distance	m
Velocity	m/s
Area	m2
Discharge	m3/s
Temperature	degC

Discharge Calculation Settings			
Track Reference	Bottom-Track	Left Method	Vertical Bank
Depth Reference	Bottom-Track	Right Method	Vertical Bank
Coordinate System	ENU	Top Fit Type	Power Fit
		Bottom Fit Type	Power Fit
		Start Gauge Height (m)	0.00
		End Gauge Height (m)	0.00

Discharge Results	
Width (m)	17.662
Area (m2)	11.772
Mean Speed (m/s)	0.276
Total Q (m3/s)	3.244
Maximum Measured Depth	1.109
Maximum Measured Speed	1.272

Measurement Results

Tr		Time			Distance				Mean Vel		Discharge							%
#		Time	Duration	Temp.	Track	DMG	Width	Area	Boat	Water	Left	Right	Top	Middle	Bottom	Total	MBTotal	Measured
1	R	12:19:28 AM	0:02:00	19.9	18.20	16.03	18.033	12.093	0.152	0.253	0.14	0.13	0.84	1.51	0.44	3.064	--	49.3
2	R	12:23:34 AM	0:01:48	19.7	18.00	15.99	17.985	12.061	0.167	0.331	0.12	0.08	1.13	2.00	0.66	3.990	--	50.0
3	L	12:25:35 AM	0:01:26	19.6	18.71	16.43	18.427	12.133	0.218	0.269	0.13	0.06	0.92	1.63	0.52	3.261	--	50.1
4	R	12:27:19 AM	0:01:38	19.4	18.93	15.44	17.441	12.040	0.193	0.259	0.10	0.06	0.89	1.59	0.46	3.114	--	51.0
5	L	12:29:16 AM	0:01:18	19.4	17.13	15.41	17.408	11.426	0.220	0.309	0.09	0.08	1.11	1.61	0.64	3.526	--	45.8
6	R	12:30:52 AM	0:01:16	19.3	17.64	15.51	17.507	11.513	0.232	0.267	0.00	0.05	0.96	1.57	0.49	3.076	--	51.2
7	R	12:33:51 AM	0:01:18	19.2	16.97	14.94	16.939	11.438	0.218	0.296	0.06	0.09	1.07	1.60	0.56	3.384	--	47.4
8	L	12:35:26 AM	0:01:14	19.1	17.19	15.32	17.322	11.547	0.232	0.228	0.00	0.06	0.82	1.26	0.49	2.627	--	47.9
9	R	12:37:42 AM	0:01:24	19.0	17.00	15.24	17.236	11.451	0.202	0.272	0.10	0.05	0.95	1.52	0.50	3.119	--	48.7
10	L	12:39:17 AM	0:01:08	19.0	17.29	16.32	18.323	12.017	0.254	0.273	0.10	0.08	0.95	1.59	0.57	3.281	--	48.4
			Mean	19.4	17.71	15.66	17.662	11.772	0.209	0.276	0.08	0.07	0.97	1.59	0.53	3.244	0.000	49.0
			Std Dev	0.3	0.68	0.47	0.471	0.300	0.030	0.028	0.05	0.02	0.10	0.17	0.07	0.336	0.000	1.6
			COV	0.0	0.038	0.030	0.027	0.025	0.142	0.101	0.562	0.316	0.105	0.107	0.128	0.104	0.000	0.033

Exposure Time: 0:14:30

Tr1=20050101001927r.rivr; Tr2=20050101002333r.rivr; Tr3=20050101002534r.rivr; Tr4=20050101002717r.rivr; Tr5=20050101002915r.rivr; Tr6=20050101003050r.rivr; Tr7=20050101003351r.rivr; Tr8=20050101003525r.rivr; Tr9=20050101003739r.rivr; Tr10=20050101003916r.rivr;

8.5. Grid generation steps

Steps used in creating the grid in this study is described below.

1. The *geodata* is read from the *Grid Editor.* F 65 dataset is used in the control file to allow SSIIM 2 to allocate the array before the grid is read. Because it is possible to expand the grid after it is read, it is necessary to give the grid array sizes in the input. (Olsen, 2018). This helps in stopping crashing of program when 3D grid is generated. The dataset of F 65 10000000 10000000 10000000 100000 10000 is used. Five integers are read.
2. The next step is making a block in *Grid Editor.* This is done from the menu, by choosing *Blocks* and *Add Block*. A block larger than the area of the geometry of the pond is added. Four point of the block is defined. The first point is on the right bank of the upstream cross section. The second point on the left bank of the upstream cross-section. The third point on the left bank and fourth point on the right bank of the downstream cross section.
3. Then the size of block is defined. On the menu choose *Blocks* and *Size block*. A dialogue box emerges, with question about the grid size. The grid in this study has 251 cells in i direction, 200 in j direction and 11 in k direction where "i", "j" and "k" represents the steam wise, cross stream and vertical elevation respectively.
4. The next step is to align the grid. The block has a straight side and does not follow the shape of the pond. To make the side more aligned, select some point called *NoMovePoints*. These are indicated with blue squares. From the menu, choose *Define* and *Set NoMovePoints mode*. Then click with the mouse on some of the grid lines intersections to choose the points and choose the *Set NoMovePoints* again. This allows to make adjustment to lateral movement of grid.
5. From the menu, choose *Generate* and *Boundary*, and then *Generate* and *Transfinite I*. The individual *NoMovepoints* can be moved as required and repeat the *Boundary* and *Transfinite* grid generation, until the grid looks okay. At the end choose *Generate* and *Elliptic*.
6. The grid is now be saved to the unstruc file. The is done by the menu options *Generate* and *bed levels* and again *Generate* and *3D grid*. Then *File* and *Write unstruc file*. After the file is made, make a copy of this file which stores the grid data.
7. After the grid is generated, close the program. Add data set F 2 U in the control file which reads the unstruc file automatically after the program starts.
8. The next step is to specify inflow and outflow discharge. From the menu, choose *view* and *Discharge Editor*. The grid appears. From the menu again, choose *Side discharge*, *Group no.* and *1*. A dialog box appears. In the edit field for discharge, a value of 3.24m^3/s is set, which is the measured discharge during the survey. Then from the menu, choose *Side discharge* and *Add area series* and select the cells for the inflow. The selected area will turn blue. Now repeat the same procedure for the Outflow. Only now we choose the Discharge group 2 as outflow and in the dialog box we cross off "inflow", meaning this will be outflow. The SSIIM requires to have equal total inflow and outflow to achieve continuity. (Olsen, 2018).
9. The next step is to save a *unstruc* file from the menu: *File* and *Write unstruc*. This saves information about the discharges area in the unstruc file.
10. The next step is to specify the required maximum water level of the pond to be used in the simulation. When *3D grid* is made stated in step 6, the file name *koordina.t* is also written in the same directory. A copy of this file is made, and the required level is replaced to every row. A *replace all* command in the *note file*

is used to change the level. Finally, the extension ".t" is removed, and SSIIM reads this copy file instead of original.

11. The next step is to add data set F 112 1 to the control file and start the program. This will regenerate the grid automatically right after it has read the *unstruc file*. The regeneration will be made from the water levels given in the new *koordina file*.
12. The next step is to add the required datasets in the control and start the hydraulic computation. Add data set F 2UW in the control file, which when the program opens automatically reads the *unstruc file* and start hydraulic computation.

8.6. Control File

8.6.1. Control File for Water flow simulation

T Paso Ancho HydropoWer Project, PeaKing Pond

F 2 UW	read unstruct
F 16 0.00132	d90 bed size particles for bed roughness,
F 33 1 10	time step and number of iterations per time step, time dependent computation
F 48 10	3D Paraview file
F 64 11	non-horizontal grid, for sediment transport computation
F 65 10000000 10000000 10000000 100000 10000	to allocate the arrays before the grid is read
F 92 0.1 0.3	reduce velocity in cells with small depth
F 94 0.1 0.1	minimum cell corner heights
F 102 1	invoke an algorithm to change the shape for grid cells close to the boundaries or smooth the boundaries
F 112 1	regenerates grid after unstruct file is read at level given at koordina file
F 113 7	avoid unphysical velocities in partially dry cells
F 159 1 9 0 1 0	algorithms to improve stability by avoiding grid problems, disconnecting cells in shallow areas, ask for explanation
F 168 8	multi grid solver, 8 in the number of levels in grid nesting
F 235 10	triangular cell damping

G 1 300 300 11 1

g 3 1448.180000 1450.362000 1452.544000 1454.726000 1456.908000 1459.090000 1461.272000 1463.454000 1465.636000 1467.818000 1470.000000 vertical grid distribution

G 24 3 u 1 0 u 11 o D 1 0 m 1 0	u for horizontal velocity, D depth average velocity m bed shear stress
W 1 55.0000 3.24 1461.79	sticklers' numbers, discharge and downstream water level
K 1 86400 50000	number of iterations for flow procedure and number that determines the minimum iterations between updates of water surface
K 2 0 1	laws of wall being
K 3 0.8 0.8 0.8 0.2 0.5 0.5	relaxation coefficients for less instabilities, for the three velocities, pressure correction and the k-epsilon equation.
K 4 1 1 1 5 1 1	number of iterations for each equation
K 5 0 0 0 10 0 0	multi block solver, convergence speed
K 6 1 1 1 0 0 0	second order

8.6.2.Control File for Sediment Transport Simulation without bed changes

T Paso Ancho HydropoWer Project, PeaKing Pond,	
F 1 D	
F 2 URIS	read unstruct, read result, initiate sediment
F 4 0.5 50 0.001	relaxation order for second order, relaxation, iteration convergence
F 16 0.00132	d90 bed size particles for bed roughness
F 33 100 50	time step and number of iterations per time step, time dependent computation
F 37 2	TSC for computing changes in bed level
F 48 10	3D Paraview file
F 64 11	non-horizontal grid, for sediment transport computation
F 65 10000000 10000000 10000000 100000 10000	to allocate the arrays before the grid is read
F 68 2	will not recompute water
F 84 2	bed and suspended load
F 92 0.1 0.3	reduce velocity in cells with small depth
F 94 0.1 0.1	minimum cell corner heights
F 102 1	invoke an algorithm to change the shape for grid cells close to the boundaries or smooth the boundaries
F 112 1	regenerates grid after unstruct file is read at level given at koordina file
F 113 7	avoid unphysical velocities in partially dry cells
F 159 1 9 0 1 0	algorithms to improve stability by avoiding grid problems, disconnecting cells in shallow areas, ask for explanation
F 168 8	multi grid solver, 8 in the number of levels in grid nesting
F 222 3	decrease inflow/outflow sedimentation
F 235 10	triangular cell damping

G 1 300 300 11 10
g 3 1448.180000 1450.362000 1452.544000 1454.726000 1456.908000 1459.090000 1461.272000 1463.454000 1465.636000 1467.818000 1470.000000 vertical grid distribution

G 24 1 a 0 0	d50 bed sediment in Paraview File
W 1 55.0000 8.52 1461.79	stricklers numbers, discharge and downstream water level
K 1 864 50000	number of iterations for flow procedure and number that determines the minimum iterations between updates of water surface
K 2 0 1	laws of wall being used
K 3 0.4 0.4 0.4 0.1 0.2 0.2	relaxation coefficients for less instabilities, for the three velocities, pressure correction and the k-epsilon equation.
K 4 1 1 1 5 1 1	number of iterations for each equation
K 5 0 0 0 10 0 0	multi block solver, convergence speed
K 6 1 1 1 0 0 0	second order upwind scheme

S 1 0.006 0.2535 sediment group, size and fall velocity
S 2 0.0015 0.1233
S 3 0.00095 0.0952
S 4 0.00074 0.0816
S 5 0.00062 0.0727
S 6 0.00052 0.0643
S 7 0.00043 0.0556
S 8 0.00036 0.0479
S 9 0.0003 0.0403
S 10 0.00015 0.0167

N 0 1 0.1
N 0 2 0.1
N 0 3 0.1
N 0 4 0.1
N 0 5 0.1
N 0 6 0.1
N 0 7 0.1
N 0 8 0.1
N 0 9 0.1
N 0 10 0.1
B 0 0 0 0

NTNU
Norwegian University of
Science and Technology