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**Three-dimensional numerical
modelling of sediment
deposition in the Angostura
hydropower reservoir**

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Science and Technology

Preface

This master thesis is conducted at the Department of Hydraulic and Environmental engineering at the Norwegian University of Science and Technology in cooperation with the Costa Rican Institute of Electricity. The thesis consists of this report and a CD, containing the most important files from the simulations. None of the files on the CD are needed in order to understand or interpret any of the results.

The parent objective of this project is to test the CFD program SSIIM 2 on a sediment transport and deposition case in the Angostura hydropower reservoir in Costa Rica. The case involves running a time dependent deposition simulation and a steady state suspended concentration simulation. Both simulations will be compared to field measurements conducted in the reservoir in September 2011. The basis for this report is primarily previous work and publications of professor Nils Reidar B. Olsen, and the master thesis, “Three-dimensional numerical modelling of sediments in water reservoirs” by Lisa Hoven. Additionally some of the theory in this thesis originates from the unpublished “Three-dimensional numerical modelling of water flow in the Angostura hydropower reservoir”, written by myself in spring 2011.

I would like to thank Professor Nils Reidar B. Olsen for his involvement throughout my studies. Ever since I first got to know him during spring 2008 he has provided profound support and guidance in relation to my studies. His help and support during my work with SSIIM in spring and autumn 2011 has been invaluable. I would also like to thank PhD student Stefan Haun for providing great support, and especially for organizing an educational and memorable field trip to Costa Rica. M.Sc student Halvor Kjærås contributed greatly with his good humor and linguistic skills while in Costa Rica. The people in ICE all deserve great acknowledgment for welcoming and helping us with our measurements, and I would specially like to thank Ronny Zúñiga, head of the Angostura Hydropower plant.

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Abstract

The Angostura hydropower plant is located in the Reventazon river basin, Costa Rica. The daily peaking reservoir has since construction in 2000 experienced high sediment inflow, and after only six years of operation, 30% of the storage volume was lost. Sediment deposition occurs whenever the stabilizing forces acting on a given sediment particle exceeds the driving force. Sediment deposition represents a threat to the lifetime of the Angostura reservoir, and is in general considered a problem around the world. Traditionally the only way to estimate sediment transport and deposition has been a combination of empirically derived equations, physical model study, and field measurements. With the recent development in the field of computational fluid dynamics (CFD), it is now possible to simulate complex sediment transport and deposition situations. However, CFD is still in its mere childhood, and in terms of reservoir sedimentation cases, it is mostly used in research context. The main objective of this master thesis is to contribute to the global research on CFD modeling of sediments, by showing that a given scenario can be replicated without extensive numerical calibration. This is to be done by running a time dependent deposition simulation and a steady state suspended concentration simulation. The results of both compared to field measurements conducted in the Angostura reservoir in September 2011. The complex flow field in the Angostura reservoir requires a three dimensional numerical solver, and the numerical program SSIIM is used because of its ability to simulate complex flow fields with a unstructured, adaptive grid with wetting and drying algorithms. SSIIM is freeware and can be downloaded from the Internet.

The time dependent deposition simulation showed that $320\,273\text{ m}^3$ of dry sediments deposits over the 250 days of simulation. Compared to the measured deposition of $319\,190\text{ m}^3$, this represents a deviation of only 0.3%. The similarity of the deposition pattern is difficult to describe quantitatively, but except for one area with excess deposition, and one area with insufficient deposition, the simulation was able to replicate the major deposition pattern. The trap efficiency for the reservoir in the given period is estimated to about 52%. The steady state simulation was not able to recreate the high variability seen in the field data, and the

simulated downstream depth averaged concentration was in general a bit too high. However, the average concentration and the particle trap efficiency was comparable with the measured results. Little numerical calibration was required, and from a practical point of view the simulations were able to fairly accurately reproduce the specific situations. Nevertheless, it is believed that the accuracy can be increased by increasing the accuracy of the input data, specifically the inflowing water and sediment, and by simulating with higher temporal resolution.

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Chapter 1

Introduction

The Angostura hydropower plant, located in the Reventazón river basin, Costa Rica, has since construction in 2000 experienced high sediment inflow. Sediments transported by the inflowing water settle in the reservoir as the velocity is reduced. This is often mitigated with a reservoir flushing. A flushing is a process where the waterlevel is drawn down to a minimum level and the sediments exits the reservoir transported by the freeflowing water. Initially an annual flushing was conducted in order to bypass the flushed sediments from the upstream hydropower plant, Cachí. In 2006 over 30% of the storage was already lost. A bi-annual flushing was initiated, and from 2006 to 2009 8% of the storage was lost [Haun et al., 2010]. The loss of storage represents a major economic loss for the owner of the reservoir, especially if the lifetime of the reservoir is reduced. The flushing of a reservoir can be a very efficient way to remove sediments. However, releasing massive amounts of water also represents a loss in production. The more knowledge the owner of the power plant has about the inflowing sediment volume and deposition pattern, the more accurately various mitigating measures can be implemented. Sediment transport theory is generally considered fairly complex. Sir Horace Lamb said in 1931:

“I am an old man, and when I die and go to heaven, there are two matters on which I hope for enlightenment. One is quantum electrodynamics, and the other is turbulent motion of fluids. About the former, I am really rather optimistic” [Tabor, 1989].

Whether Sir Horace reached enlightenment or not, we don’t know. However, what we do know is that modern computational resources now enable complex sediment transport situations to be modeled using computational fluid dynamics, or CFD. This field of study combines computer programming, numerical solution of discretized differential equations, and traditional empirically derived equations. CFD modelling of sediments is still in its meek childhood, and more research is re-



Figure 1.1: Lake Angostura, Costa Rica. Photo: Google

quired before it can be utilized in consultant engineering. This master thesis aims to contribute to the global research on numerical modelling of sediment deposition by showing that fairly accurate results can be achieved without heavy calibration of the results. The full assignment text is given in Norwegian in appendix A.

The objective of this thesis is to as accurately as possible predict the deposited amount and pattern of sediments in the angostura reservoir. In addition to this, it is desirable to show that numerical software can accurately predict the suspended sediment concentration over a lake or reservoir. A numerical model relies on good input data, and in order to be able to evaluate the numerical outputs, field measurements are required. A three week long field trip to the Angostura reservoir was conducted in September 2011. The department of Hydraulic and Environmental Engineering at the Norwegian University of Science and Technology, NTNU, acquired during the summer of 2011 an advanced suspended sediment concentration analyzer, namely the LISST-SL from Sequoia instruments. This, in addition to bed sediment samples taken at the site forms the basis for the input and verification of the numerical simulations. The field trip and research is funded by the Research Council of Norway, and is a result of the cooperation between NTNU and the Costa Rican national Electrical institute, ICE.

Chapter 2

Angostura

The Angostura reservoir, *embalse Angostura*, is a part of the Reventazón river basin hydropower scheme i central Costa Rica. The Reventazón river basin consists of steep mountain sides covered in soil, which results in a fairly high sediment inflow rate to Angostura. This chapter briefly describes the Reventazón river basin, the Angostura reservoir and the current sediment situation.

2.1 Reventazón River Basin

Located in the central valley in Costa Rica, the Rio Reventazón stretches from the high mountains in the Meseta Central and flows 145 km east until it reaches the Caribbean sea. The Basin covers about 3000 km^2 and is Costa Rica's 3rd largest basin [Hoven, 2010] The river plays a major role in the everyday life of the central valley inhabitants. It provides drinking water for about 25 % of the population of the capital San Jose [Firestone et al., 2011], and in total over 400 000 inhabitants live within the boundaries of the river basin, and rely on the river for drinking water, household and farming [Catano et al., 2009]. As a source of hydroelectric power the entire nation relies on the Reventazón river. With its combined output of 450MW, it provides nearly 25 % of the nationwide installed capacity of 1900MW. The Scheme consists of the Rio Macho power plant, with a installed capacity of 120MW, and the Cachí Hydropower plant, with a installed capacity of 105MW [Jimenez et al., 2004]. Below Cachí lies the La Joya power plant (50MW), which has been in operation since 2006. La Joya utilizes the outflow from the Cachí powerhouse, and is operated by Union Fenosa Generators La Joya [Luis, 2006]. Angostura power plant is the 4th power plant in the scheme, and with its installed capacity of 180MW it is also the largest. Downstream of Angostura a 5th power plant is now under construction, the Reventazón hydropower plant, which is scheduled to start operation in 2016. It will have a installed capacity of 305MW



Figure 2.1: Gated spillway and intake structure, Angostura reservoir. Photo: S. Løvfall

and will thereby drastically increase the national energy production in Costa Rica [Zúñiga]. Rio Macho, Cachí, Angostura and the unfinished Reventazón power plant are all owned and operated by the national Instituto Costarricense de Electricidad, abbreviated ICE.

2.1.1 Sedimentation

The Reventazón river basin varies from sea level at the Caribbean side to peaks up to 3500 m.a.s.l in the inland mountainous regions. The prevalent rock are volcanic, and several volcanoes, all currently active and inactive, exist within the basin. Sedimentary and intrusive rock is also found in the river basin. The dominating soil is residual and alluvial soils of volcanic origin. The climate is humid tropical, and without a marked dry season [Hoven, 2010]. The annual rainfall varies between 1500 and 7500 mm [Brandt and Swenning., 1996]. The combination of precipitation pattern, high annual rainfall and topography and soil, makes the Reventazón river receives a very high sediment load [Hoven, 2010]

When a river enters a lake or a reservoir the velocity decreases, and the capacity of the river to transport material is reduced. This causes the sediment to settle. The annual sediment inflow to Angostura is estimated to be between 1 to 3.5M tonnes including 0.5M tonn which is flushed from Cachí every year [Hoven, 2010]. Often an average value of 1.5M tonn pr year is assumed [Haun et al., 2010]. Most of this material is transported as suspended load, but a sizable amount, about 10%

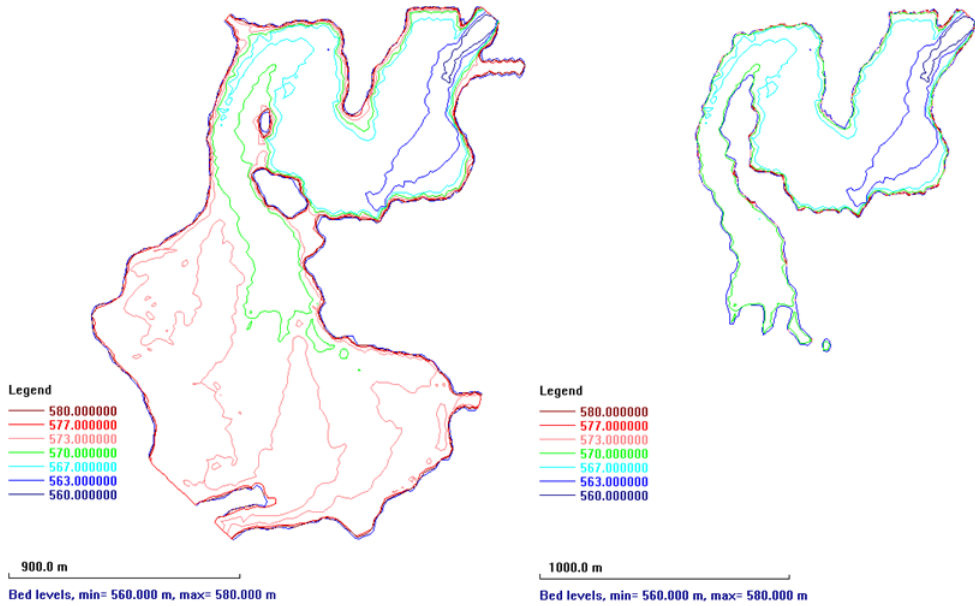


Figure 2.2: Angostura reservoir at HRWL and LRWL, bed levels from 2010 Bathymetry.

is transported as bed load [Jimenez et al., 2004].

Measurements of the suspended sediment concentration was conducted in September 2011, during normal conditions. The inflow varied from 100 to 120 m^3/s and the water level was approximately at 576 m.a.s.l. Results from measurements taken in the upper part of the reservoir showed a suspended concentration of about 45% clay and 55 % silt. However, it is reasonable to assume that the sediment inflow and size distribution vary greatly over the year, and between years. The size of the transported material relies heavily on the bed shear stress and turbulence, which is related to the discharge and geometry of the river. During floods and high discharges the river will have a higher transport capacity and thereby transport larger sized material. During these conditions it will be difficult, dangerous and often impossible to do measurements. Therefore the sediment distribution for flood scenarios are often estimated. The yearly sediment inflow is estimated in chapter 9.

2.2 Angostura reservoir

The Angostura Hydropower plant has been in operation since October 2000. It consists of a drainage area of 1463 km^2 and had at the time of construction a 17 Mm^3 reservoir. A 38 m high rock-fill dam and a nearly 30m gated spillway holds the artificial lake in place. The highest regulated water level, or HRWL, is at 577 m.a.s.l, while the LRWL is at 570. The 7 meters of operation level ensured about 11 Mm^3 of live storage in 2000 [Hoven, 2010]. Figure 2.2 shows Angostura at HRWL and at LWRL. Angostura is operated as a daily-peaking power plant, and even though only 2.5 Mm^3 is required for this purpose, a large reservoir was build in order to ensure a long lifetime [Jimenez et al., 2004]. From the intake, located near the spillway, the water flows through an underground tunnel, and drops about 140 meters to the power plant. The average annual inflow is about $120 \text{ m}^3/\text{s}$, with a flood discharge of about $350 \text{ m}^3/\text{s}$ [Hoven, 2010]. The main inflow is through the Reventazón river, but 3 more tributaries contribute to the total inflow. A smaller tributary river enter just to the south of the Reventazón, and two small man-made diversion channels enters the reservoir on the north and south side. Angostura's biggest problem is the high annual sediment inflow. The reservoir had a trap efficiency of about 60% at the time of construction, which means that if no special action was taken, the reservoir would have been completely filled with sediments within 2020 [Jimenez et al., 2004].

2.3 Flushing

2.3.1 Cachí

In the 70's the upstream hydropower plant, Cachí, faced the same challenges as Angostura faces today. From 1973 and until today Cachí has been flushed annually. These flushing operations have been very successful, and in 40 years only 10% of the reservoir volume has been lost due to sedimentation. About 0.5M tons are flushed out every year, [Jimenez et al., 2004]. However, unlike Angostura, Cachí has a very long and narrow shape which forces the river to dig through the bottom sediments when the water level is lowered. This makes Cachí ideal for flushing.

2.3.2 Angostura

As seen on figure 2.2, the Angostura reservoir is quite wide and shallow, and it has two 180 degrees turns in the flow field. The wide reservoir makes the flushing less efficient, as the water flow will dig out a flushing channel in the sediments, and not remove the deposited material on the banks. After the construction in 2000, it was decided that Angostura should be flushed annually. The flushing was undertaken in September, at the same time as the flushing of Cachí. This was in reality more of



Figure 2.3: September flushing, downstream of Angostura spillway. Photo: S. Løvfall

a sediment routing than an actual flushing, and over the first six years of operation, 30% of the storage volume was lost [Haun et al., 2010]. From 2006 and until today, Angostura has been flushed twice a year. In September the routing is conducted simultaneously with the Cachí flushing. Cachí is fully emptied, and the bottom gates kept open for 33 hours. The water level in Angostura is lowered to 565 m.a.s.l and the bottom outlet routes the sediments through. The second flushing is conducted in November, and Cachí does not take part, except to ensure that the inflow is sufficient. The water level is slowly lowered to 570, before a rapid draw-down to 556 m.a.s.l. The semi-annual flushing have so far been relatively successful. About 8% of the total storage, and 1% of the live storage was lost from 2006 to 2009 [Hoven, 2010].



Figure 2.4: Stefan Haun and Halvor Kjærås visits the Cachí damsite. Photo: S.Løvfall

Chapter 3

Sedimentation

Sediment generation, transport and deposition is a natural part of the geomorphological processes which has shaped the earth for million of years. When seen from a hydropower point of view, sediment handling can be quite a challenge. 1% of the reservoir capacity is lost annually due to sedimentation [Hoven, 2010]. In order to deal with the consequences of sediment related issues it is important to understand the process of sedimentation. This chapter briefly describes the theory related to sediment generation, transport, deposition and how this can be estimated using modern computer technology.

3.1 Sediment generation

Sediments are small particles, like sand, gravel, clay and silt, and the origin vary according to different climates. In tropical countries rock decompose naturally. Sediments can also be of organic origin. Organic material is usually found in lakes and quiescent river reaches. Mixtures with more than 30% organic material is usually termed organic [Lysne et al., 2003]. Fluvial sediment is a collective term meaning an accumulation of rock and mineral particles transported or deposited by flowing water. Sediments transported or deposited by air is usually refereed to as aeolian sediments [Vanoni, 2006]. Whenever the term “sediment transport” is used in this thesis, it refers to “fluvial sediment transport”.

Initially sediments are generated in the catchment area. Water in form of rain, temperature fluctuations and chemical reactions cause cracks in the rock. This weathering creates a layer of particles on the rock surface. The upper particles have the longest exposure to weathering, and therefore the smallest grain sizes. Closer to the bedrock, the grain size increases [Olsen, 2007]. Through the kinetic energy of the raindrop impact, or by the forces generated by flowing water, the

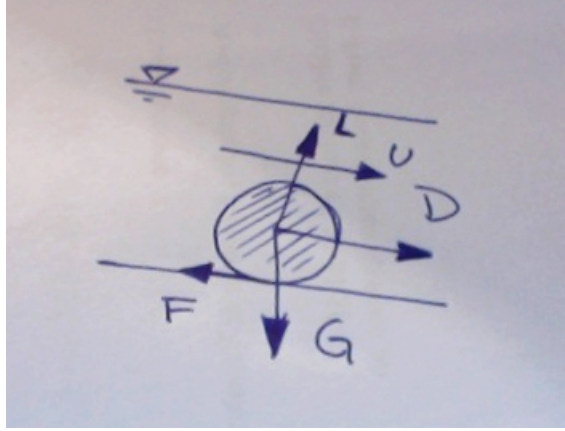


Figure 3.1: Forces on a particle on a river bed

particles are detached from the surroundings and transported away. This is called erosion [Vanoni, 2006].

Erosion in a catchment is a natural process, and in a geomorphological context land erosion and sediment transport processes are balancing the geological processes creating mountains. Different catchments generates different amount of sediments, and often the term sediment yield is used to quantify the sediment production. The sediment yield is defined as the amount of sediments transported by a river through a given cross section divided by the catchment area, on a annual basis. Often expressed in $\text{tons}/\text{km}^2/\text{year}$.

3.2 Sediment transport

The initial step in sediment transport, is erosion. If the driving forces are stronger than the stabilizing forces, a given particle will be transported. It then follows that the final step in sediment transport is deposition. After a sediment particle has entered a river it will be eroded, transported and deposited depending on the forces acting on the particle. Whenever the stabilizing forces overtake the driving forces, the particles will settle, causing deposition. Figure 3.1 shows a sediment particle resting on a river bed with a water velocity, U , and the four forces which influence the particle stability.

- Gravity: $G = k_1(\rho_s - \rho_w)gd^3$, where k_1 is a shape factor, and d is the sediment diameter.
- Drag works in the main direction of the flow, and is proportional to the square

of the ambient flow velocity, u and the exposed area, A . The Drag forces is expressed as follow:

$$D = \frac{1}{2}C_D\rho Au^2 = k_2u^2d^2 = k_2(IM^2r_h^{\frac{4}{3}})d^2 = k_2\frac{\tau}{\rho gr_h}M^2r_h^{\frac{4}{3}}d^2 \approx k_4\tau d^2$$

where $k_2 = \frac{1}{2}C_D\rho$, where C_D is the drag correction coefficient. Area normal to flow, A , is simplified to d^2 .

- Lift works transversely to the flow direction, and like the drag, is principally proportional to the square of the velocity and the exposed area:

$$L = \frac{1}{2}C_L\rho_w\frac{d^2}{4}\pi u^2 = \frac{1}{2}C_L\rho_w\frac{d^2}{4}\left(IM^2r_h^{\frac{4}{3}}\right)\pi \approx k_4\tau d^2$$

where $k_4 = \frac{1}{2}C_L\rho_w$, C_L is the lift correction coefficient.

- Friction forces works between the particle at rest and the river bed:

$$F = (G - L)\tan(\alpha) = \tan(\alpha) \{k_1g(\rho_s - \rho_w)d^3 - k_4\tau\} d^2$$

where $\tan(\alpha)$ equals the angle of repose for the material, μ .

If the frictional forces is set equal to the drag force, Shields equation can be derived with respect to the critical particle diameter. The critical particle diameter is the smallest particle diameter which will be eroded under the given circumstances:

$$d_c = \frac{\tau_c}{g(\rho_s - \rho_w)\tau^*}$$

Here τ^* is the Shields number, or Shields coefficient, and can be found from the empirically derived Shields curve, for a given particle Reynolds number. τ_c is the critical shear stress, expressed as $\tau_c = \rho ghI$. For a given diameter, erosion will take place if the bed shear stress exceeds the critical shear stress for the particle [Olsen, 2007]. The shear stress is the average force per area exerted by the water on the bed. The shear stress depends on the rate at which the velocity changes from zero at the bed towards the free flow above the bed. In natural flows, the shear stress is the result of turbulence, transferring momentum towards the bed [Lysne et al., 2003].

Shields data applies to reasonably uniform bed material. A natural riverbed, however, usually consist of material with different size. This means that the critical shear stress will vary over the bed, and it therefore follows that some particles will be eroded, and others not, for a given flow scenario. Therefore the threshold of motion is a somewhat subjective concept. The initiation of movement for a river bed can be divided into three stages of increasing shear stress [Coleman]:

1. Weak movement: A few smaller grains are in motion in isolated spots at any instant. Generally recognized as the threshold of motion.
2. Medium movement: Innumerable grains of up to mean diameter are moving, this motion being no longer local in nature, although sediment transport rate is not yet appreciable.
3. General movement: Up to the largest particles are moving, movement occurring in all parts of the bed, at all times.

3.2.1 Sediment transport capacity

Sediment transport is usually divided into two main modes of transport, suspended load, and bed load. Often a transition mode is also included, called saltation. The definition originates from the study of particles transported by wind, and different opinions exist on where the boundary between the two transport modes is drawn [Olsen, 2007]. The transport mode is dependent on the difference between the bed shear stress and the critical shear stress. For a small difference the sediments will be transported as bed load, and will roll and slide along the river bed. As the difference increase, the particle will start to jump into the flow. The greater the bed shear stress, the longer the jumps. This is called saltation. At a certain point the particle will be in no, or very little, contact with the bed. This is the suspended load. Particles which are fully suspended, even at very low river velocities, and which have been carried far from their origin, are often referred to as wash load [Lysne et al., 2003].

The desire to be able to accurately predict the sediment inflow has led to several different formulas been developed over the years. However, the theory behind sediment transport is still not completely understood or described. Empirical relations and experimental data are therefore an integral part in every practical use of the theory [Lysne et al., 2003]. This results in a wide variety of equations, developed based on different physical scenarios. One must be aware of the basis which each formula is developed, and also for which conditions the formula is applicable to. Among the more recognized sediment transport formula's, is the Meyer-Peter and Müller formula for bed load [Lysne et al., 2003]:

$$g_s = \sqrt{\left(\frac{g\rho SR(k/k') - 0.047g(\rho_s - \rho_w)d_{50}}{0.25\rho_s^{\frac{1}{3}}((\rho_s - \rho_w)/\rho_s)^{2/3}} \right)^3}$$

This formula was developed to fit data from steep flumes, and can therefore be useful in many hydropower cases with steep rivers. Van Rijn's bed load formula is another formula, and does not include the water depth, [Olsen, 2007].



Figure 3.2: Sediment deposit in Angostura. Picture: S.Løvfall

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

Few suitable formulas for suspended load exist for practical cases, but in 1967 Engelund and Hansen developed a simple and rather accurate way to estimate the sum of bed load and suspended load [Lysne et al., 2003]:

$$g_s = 0.05g\rho_w U^2 \sqrt{\frac{d_{50}}{g(\rho_s - \rho_w)/\rho_w} \left(\frac{\tau_0}{g(\rho_s - \rho_w)d_{50}} \right)^3}$$

These formulas give an estimation of the potential river transport capacity. They do not say anything about the actual sediment transport in the river. The amount of transported material is dependent on both the river's capacity to carry sediments, and the catchment's ability to deliver sediments. If the capacity is greater than the sediment yield, erosion will occur for the bed material for all sizes lower than the critical diameter. If the yield is greater than the capacity, deposition occurs. If the inflowing sediment amount equals the sediment transport capacity, the river is said to be “in regime” [Coleman].

3.3 Reservoir Sedimentation

As a river enters a reservoir or a natural lake the velocity is reduced. The reduction in velocity results in a decrease in the shear stress, and consequently deposition occur. The particles with the largest grain size are deposited first. As with catchment erosion, sediment deposition is a natural phenomena, and is a part of the natural balance [Lysne et al., 2003]. Sediment deposition has in fact formed some of the earth most fertile places. The Nile delta facilitated the birth of modern agriculture, and thereby played a major role in the development of the human civilization. However, in relation to hydropower engineering, sediment deposition usually causes problems. Primarily three concerns are of interest to a hydropower engineer:

1. Wear on turbines due to suspended sediments in the inflowing water
2. Reservoir storage reduction due to sediment deposition
3. Erosion and environmental impacts

Wear on turbines is a problem for hydropower plants in areas with high wash load, and is usually solved by building settling basins, or by regularly maintenance of machinery. Erosion downstream of a reservoir occurs due to the fact that the water from a spillway is “sediment starved”, meaning the transport capacity is greater the sediment yield. This is often mitigated by hydraulic structures designed to dissipate energy and prevent erosion. The reduction in reservoir volume represents a treat to the lifetime of the hydropower plant. Usually this problem is mitigated by regularly flushings, dredging, hydraulic sluicing, trapping reservoirs and sediment diversion channels, or simply by building a large dam which ensures a long lifetime [Lysne et al., 2003]. The environmental aspects of hydropower schemes is heavily debated around the world. One aspect is the trapping of sediments in reservoirs. Sediment carries nutrients and bacterias which fish and other species rely on to survive. The deposition in reservoirs removes the sediments from the river, and in cases where flushings are conducted to try to mitigate the deposition, the river is suddenly “flooded” with sediments killing much of the ecosystem, This thesis only highlights the problems related to reservoir storage reduction due to sediment deposition.

3.4 Sediment modelling

In the design of a dam, it is important to assess the magnitude of sediment deposition in the reservoir. Mainly, the problem can be simplified to how much sediment enters the reservoir, and how much leaves [Olsen, 2007]. The deficit is the deposited material. The sediment inflow is dependent on the catchment yield and the transport capacity, and the sediment outflow is dependent on the shape and

size of the reservoir and dam and intake design. Detailed sediment inflow information is important when trying to design a optimal hydropower plant in a area with potential sediment problems. Often, between 6 to 10 years of continuous long term sediment monitoring is recommended as a minimum of input data [Lysne et al., 2003]. These data is often presented in a sediment rating curve, which shows the sediment concentration vs water discharge. Figure 9.1, in section 9.1 shows a rating curve for Angostura. A representative sediment rating curve can also be found by scaling geographically similar data.

The next step is to estimate the sediment deposition for a given reservoir design. Traditionally the only reliable method has been physical model studies. Several problems are related to physical models studies using sediments. When modelling a reservoir, a distorted model is often used to prevent problems related to shallow water depth. A distorted model is a model with a different depth scale than in the horizontal plane. A small horizontal scale is often desirable from an economical and practical point of view, but surface tension will quickly become a governing force for shallow water depths if geometric similarity is used for the model. Distorted models works well for model studies without sediment, but without geometric similarity, the shape of the sediments will differ from reality. Problems related to the model sediment material also occur for small scales. Inter particle forces like cohesion will occur for clay particles smaller than 0.1 mm. The solution is to use other material than natural sand and silt, usually plastic. However, the exaggerated shape of the particles will influence the bed stability [Lysne et al., 2003]. All in all the process of predicting reservoir sedimentation is fairly complex and involves several inaccuracies.

3.4.1 General about CFD modelling

Computational Fluid Dynamics, or simply CFD, is much used in fluid mechanics nowadays, and has been for some years now. The first modern principles can be traced back to 1910 when Richardson presented a paper at the Royal Society of London with a stress analysis of a masonry dam using finite difference method, FDM. It took another 50 years before the first Finite Element Method, FEM, was used in a published paper. Aeronautical Science Journal published a paper in 1956, by Turner, Clough, Martin and Topp on aircraft stress analysis [Chung, 2002]. The Finite Volume Method, FVM is based on the same principles as FEM. The idea is to define a finite fluid volume and divide it into several smaller cells with a given volume. On this volume three fundamental equations will govern [Wendit, 2009]:

- Conservation of mass
- Newton's 2nd law: $F=ma$

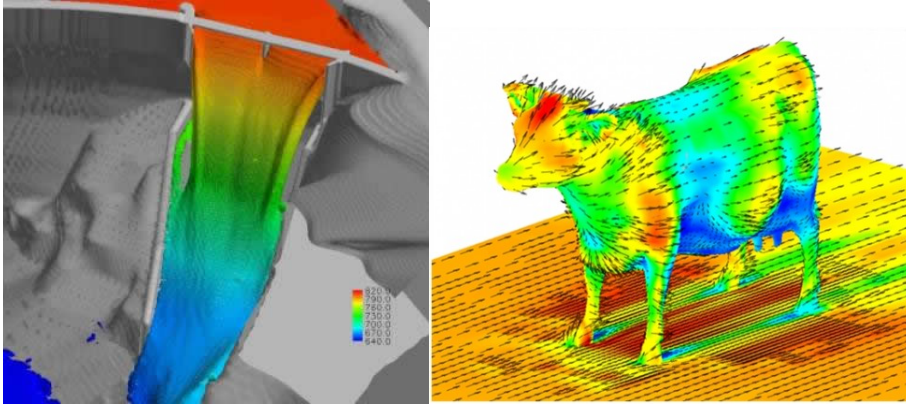


Figure 3.3: Colorful Fluid Dynamics. Hydrostatic pressure in a spillway (left), (Google, 2011b), and the pressure field around a cow (right), Google, 2011c)

- Conservation of energy

Expressed in partial differential equations these formulas form the basic for all CFD. Theory behind water flow and sediment modeling is more thoroughly described in chapter 5.

John F. Wendit gives an non all-inclusive description of CFD in his book, CFD: An introduction;

Computational fluid dynamics is, in part, the art of replacing the governing partial differential equations of fluid flow with numbers, and advancing these numbers in space and/or time to obtain a final numerical description of the complete flow field of interest

The end product of CFD is indeed a collection of numbers, in contrast to a closed-form analytical solution. However, in the long run the objective of most engineering analysis, closed form or otherwise, is a quantitative description of the problem, i.e. numbers [Wendit, 2009]. In recent years it has been quite common to illustrate results from CFD analysis using colors to represent changes in different parameters with respect to time or space. This has resulted in the humorous nickname CFD: Colorful Fluid Dynamics. Figure 3.3 shows the hydrostatic pressure distribution in a spillway, and the velocity vectors and pressure distribution around a cow. Nevertheless, the value of user friendly and easily grasping interpretation of the output is quite valuable when representing the results for an audience unfamiliar with hydraulic engineering.

Over the last 20 years CFD has become a widely accepted tool within the fields of fluid mechanics, aerospace and mechanical engineering and can generally be applied to any problem where a liquid is moving through a medium. In the field of Hydropower and hydraulics, CFD has mainly been used when looking at smaller components like turbines and penstock's. Over the last years however, there has been an increase in research on CFD and it is now being applied to larger scale problems like spillways, rivers and reservoirs. CFD modeling of sediments has a great potential, as a result of the problems related to physical modelling and the complex analytical physics. However, verification and calibration of the results are usually needed, and there is still some time before CFD will be accepted as standard river engineering tool for consultants and developers.

Chapter 4

LISST-SL

The LISST-SL is a iso-kinetic sediment grain-size analyzer from SEQUOIA. It is a tailor made suspended sediment size and concentration analyzer, and provides all the data necessary to compute suspended sediment transport in a river [Seq, 2011b]. The sensor utilizes laser diffraction technology to analyze the suspended sediment grain size distribution. The LISST-SL was used to measure suspended sediments in Angostura, and this chapter briefly describes the instrument and the fundamental theory.

4.1 Setup

The LISST-SL systems consists of 3 parts; the streamlined submersible LISST-SL sensor, A topside controller box (TCB) and a B-reel used to lower the sensor, transfer data and supply power.

4.1.1 Sensor - LISST-SL

The LISST-SL sensor, see figure 4.1, contains the laser optics, scatter light sensing photodiodes and amplifiers, and an iso-kinetic pump. Whenever power is applied to the LISST from the TCB, a dedicated microprocessor inside the LISST begins operation. It senses stream velocity from the pitot tube (5), and controls operation of the internal pump. When in iso-kinetic mode the pump will match the stream velocity. The LISST continuously transmit data to the TCB, regardless of whether the TCB is capturing or not. The sediment filled water enters the sensor via the intake tube (9), and exits through a plastic tube at the back (3). The large fin helps stabilize the sensor and point it to the flow [Scientific, 2011]

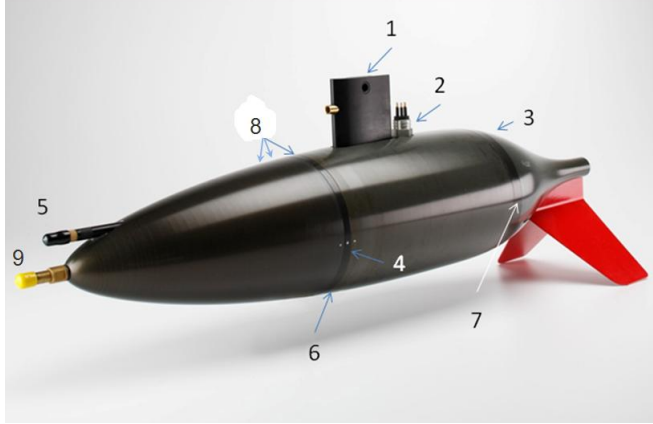


Figure 4.1: LISST-SL

4.1.2 Topside Control Box (TCB)

The TCB controls the sensor and provides the power needed to run the sensor. The TCB contains a 25V 19.2A-hr lithium-ion battery which ensures about 8 hr of field operation. The box also contains a built-in computer which is operated by a touch-screen with a Graphical User Interface. The main menu contains 3 options:

- Setup: Controls time and date settings, units and manage saved files.
- Calibrate: Collects a background scatter file.
- Measure: Collects field data.

The Calibrate and measure process is further described in section 4.3.

4.1.3 B-Reel

The B-reel serves as the connection between the sensor and the TCB. It has 3 main functions; physically holds the sensor in place, supplies power and transmits data. The LISST-SL system is developed to be used from bridges, but can be modified to for instance a boat setup. The length of the B-reel wire is 25 meters.

4.2 Theory

The measurements of sediment distribution and concentration is based on the principle of laser diffraction. Inside the LISST the river water passes between a pair of

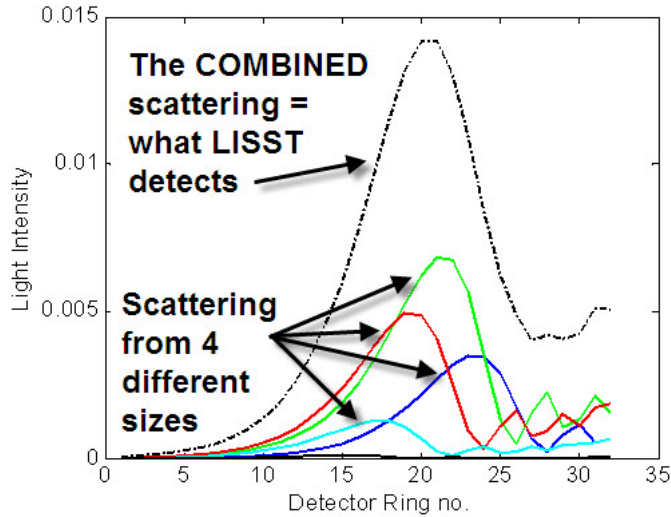


Figure 4.2: Combined and individual scattering pattern observed by the LISST for 4 particle sizes. Scientific [2011]

parallel glass windows, with a laser beam emitted from one side. The light scattered by particles in the river water is collected by a receiving lens on the other side. On the focal plane of this lens a detector is placed. It consists of 32 concentric rings of silicon, with a center $75\ \mu\text{m}$ diameter hole. The laser beam passes through these holes and is detected with a silicon photodiode (transmission sensor). In this manner the rings measure light scattered out of the laser beam, while the power of the beam that passes through the central hole is the beam transmission measurement. The 32 ring-shaped detectors increase logarithmically from the center; each one covering a small distinct angle sub range. The measurements are based on two fundamental facts concerning scattering of light from particles. First, the exact shape of the light scattering off a spherical particle with any size, composition and color can be computed. Second, no two particles of different size or composition have the same scattering pattern - they are unique. Each scattering pattern is like a fingerprint for a particle of a certain size. Since all particles scatter light to all the ring detectors, the LISST measures the combined scattering from all the particles in suspension, see figure 4.2. The combined scattering pattern detected by the LISST constitutes 32 known measurements. From principles of algebra, with 32 knowns, one can solve for 32 unknowns, and hence obtain the concentration of sediments in 32 size classes [Scientific, 2011].

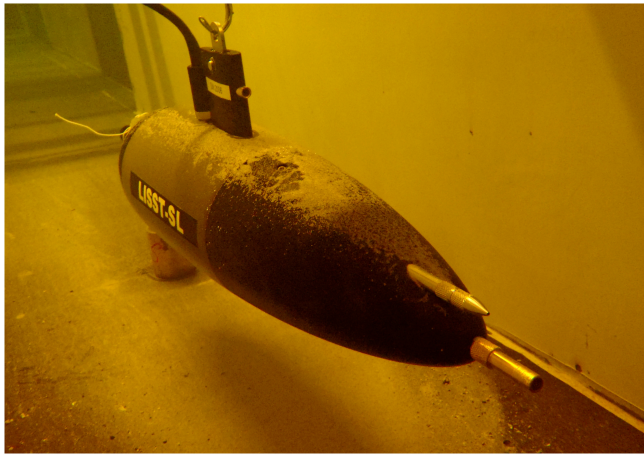


Figure 4.3: Lab measurements. Photo: S.Løvfall

4.3 Using the LISST-SL

4.3.1 Clear Water Calibration

Before a measurement can be conducted, a clear water calibration needs to be performed. The calibrate function in the setup menu records a background file. This file contains measurements of light scattered by imperfections of optics on the 32 ring detectors. The calibration should be performed either using filtered water, or using a $2\text{ }\mu\text{m}$ in-situ filter. If the function “view rings” is enabled in the TCB display, the values for each ring is shown compared to the ideal factory value. When the instrument is new the ring view should be very close to factory values. After some time the background values will increase due to sandblasting of the windows. For any clear water calibration it is important that the LISST-SL has the same temperature as the water and is free from air bubbles when the clear water calibration is preformed. A good background can only be obtained if the rings view is steady with minimal or no change. When the view rings display shows adequate values the background sample should be collected. By pressing “collect background” the TCB records and average 20 samples. This is stored as a asc file [Seq, 2011b].

4.3.2 Measurements

After the clear water calibration is preformed, the measurements can be conducted. When pressing the measure button, the LISST immediately starts to acquire data.

Parameter	Min	Max
Sediment concentration	10 <i>mg/l</i>	2000 <i>mg/l</i>
Size ranges	1.9 μm	381 μm
Depth	0 m	30 m
Temperature	0 °C	40 °C
Iso-kinetic velocity	0.3 m/s	3 m/s

Table 4.1: LISST-SL Operation limits

The TCB panel shows the current instrument depth, sediment concentration, river velocity, number of samples saved, file name, battery voltage and the pump drive voltage and current drain [Seq, 2011b]. The pump is by default in iso-kinetic mode, and starts with a velocity of 3 m/s. Based on the measured velocity in the pitot tube, the velocity gradually adjusts to the river velocity. If the velocity is below 0.3 m/s the pump eventually stops. The operation limits are listed in table 4.1.

4.3.3 Error and uncertainties

The reflected light from a particle depends on several different sediment parameters, but can be simplified as a function of sediment shape and size. For a given volume or mass concentration, small particles produce a lot more scattered light than large particles (the relationship is inverse with size). Also the main peak of of scattering occurs at small rings for large particles and at large rings for smaller particles. This means that the relationship between the particle size and the ring where maximum scattering occurs is also inverse with size. The result is that light on small rings is interpreted as the presence of large particles and vice versa. From this it follows that an error in the measurement of the background on the small rings is equivalent to a large error in the amount of large particles. A similar error on the outer rings would amount to a smaller error of the small particles. A good background measurement is therefore crucial to ensure reliable results. [Seq, 2011b].

Particles outside the size range

All particles which are carried through the LISST will give a reflection when illuminated by the laser. This means that particles smaller or bigger than the min/max threshold will also reflect light, which might affect the results. The drop off in light intensity on the outermost rings (smallest particles) is much slower than for the larger particles. By inverting the scattering pattern to the volume distribution, the influence of particles outside the size range can be evaluated. Figure 4.4 shows the response function in terms of volume for single sized particles across a wide size range. The steep cut-off at the coarse particle end shows that particles much larger

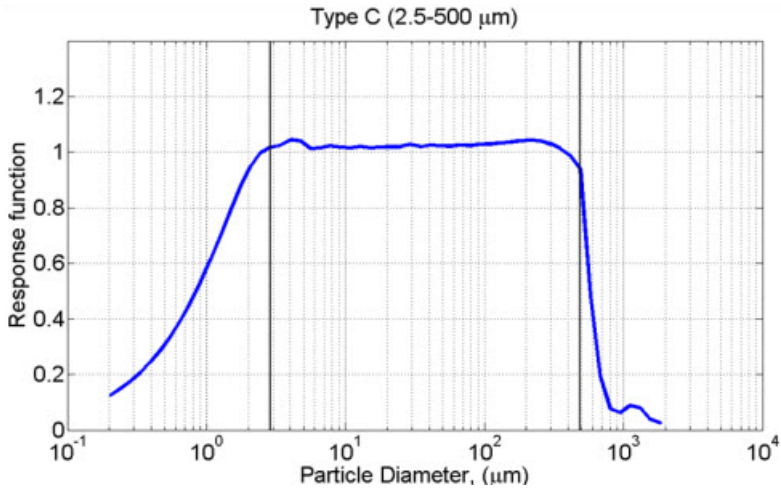


Figure 4.4: Response function vs particle size for particles outside the size range, [Seq, 2011a].

than twice the maximum size is strongly rejected. On the finer end however, the cut-off is less sharp, and particles smaller by a factor 10 or more than the smallest size, is rejected, [Seq, 2011a]. in practice this means that high concentration of particles in the min and max size range could be prone to error, especially in the fine end of the size distribution.



Figure 4.5: Marco Serrano Chaves and Franklin Solano conducts bathymetry survey in the turbid waters of Angostura, September 2011. Photo: S. Løvfall

Chapter 5

Theory

For any hydraulic model the critical unknown is the water velocity and the water depth. As the geometry is known, all other unknowns can be found when these two variables are obtained. The Navier-Stokes equations describe the motion of fluid substance and is derived for a situation with equilibrium of forces on a small volume of water in laminar flow [Olsen, 2007]. By solving the Navier-Stokes equation, the water velocity for each cell can be solved. For a waterflow computation this is the main goal. For a sediment computation the water velocity is used as basis for the sediment transport computation. This chapter describes the main principles behind solving the pressure, turbulent and transient terms in the Navier-Stokes equation, and the discretization of the convective-diffusive equation for suspended sediment concentration computation.

5.1 Navier-Stokes

The Navier-Stokes equation describes the water velocity. In order to be solved numerically, the equation has to be discretized in time and space. The main goal of the discretization is: “To transform the partial differential equation into a new equation where the variable in one cell is a function of the variable in the neighbor cells” [Olsen, 2007]. The Navier-Stokes equation then becomes:

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = \frac{1}{\rho} \frac{\partial}{\partial x_j} \left(-P \delta_{ij} + \rho \nu \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \right)$$

The subscript i denotes the three dimensions in space and j denotes time. For turbulent flow it is common to use the Reynolds averaged version of the equation, often called RANS. The Reynold averaging divides the turbulent velocity into an

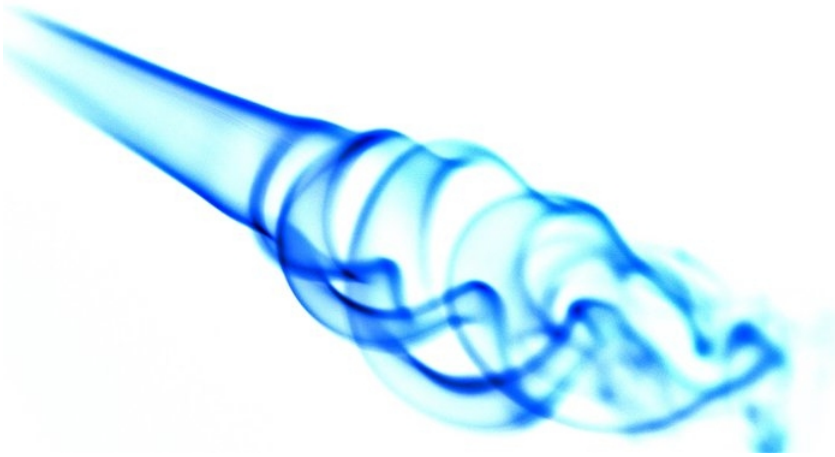


Figure 5.1: Viscous fluid flow. Photo: Zdenko Tudor

average value, U , and a fluctuating value, u . The RANS equation then becomes:

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = \frac{1}{\rho} \frac{\partial}{\partial x_j} (-P\delta_{ij} - \rho \overline{u_i u_j})$$

The RANS equation consists of 4 terms. On the left side of the equation, there is a transient and a convective term. On the right side there is a pressure term and the Reynolds stress term. In SSIIM default settings, the convective term is discretized and solved by the power law scheme or the second order upwind scheme. The remaining three terms to be solved are then the Reynolds stress term, the pressure term and the transient term. In order to evaluate the Reynolds term a turbulence model is required, The transient term is neglected for static water levels, but has to be invoked if a free water surface is to be computed [Olsen, 2007].

5.2 Turbulence

Several different turbulence models exist. SSIIM uses the Boussinesq approximation to model the Reynold stress term:

$$-\overline{u_i u_j} = \nu_T \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) + \frac{2}{3} k \delta_{ij}$$

The first term on the right side is the diffusive term in the NS equation. The second term is a stress term which is neglected in SSIIM. The third term includes the variable k , which is the turbulent kinetic energy. This however is small and

usually insignificant compared to the other term. This approximation introduces the new variables eddy-viscosity, v_T [Olsen, 2007]. Simply speaking this viscosity can be seen as the internal friction resulting from the transfer of momentum by the eddies. In his definition of turbulence Prof. H. Wengle says:

Turbulence is a cascade of eddies, from large eddies to small eddies. The largest eddies take their energy from main flow. The larger eddies give energy to smaller eddies etc., until the eddy size is at the Kolmogorov micro scale. There the energy is killed by viscosity.

At such a small scale the internal friction is greater than the energy needed to create an eddy. There are several different ways to model the eddy viscosity and they vary greatly in complexity. One of the simplest zero equation 2D models denote the vertical eddy viscosity to be given by

$$v_T = 0.11yu_*$$

Where y is the water depth and u_* is the shear velocity. The models are called zero-equation models since they do not solve any differential equations [Olsen, 2007]. In SSIIM several different turbulence models can be used. SSIIM 1 can solve the one-equation Spallart-Allmaras model, but for both SSIIM 1 and SSIIM 2 The default model is the k-epsilon model. The k-epsilon model is the most popular two equation model [Olsen, 2007]. It computes the eddy viscosity as:

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

The two variables k , turbulent kinetic energy, defined as $k \equiv \frac{1}{2}\overline{u_i u_j}$, and ε , the dissipation of k , are modeled with two differential equations. The turbulent kinetic energy is modeled as:

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\frac{v_T}{\sigma_k} \frac{\partial k}{\partial x_j} \right) + P_k - \varepsilon$$

where P_k is given as:

$$P_k = v_T \frac{\partial U}{\partial x_i} \left(\frac{\partial U_j}{\partial x_i} + \frac{\partial U_i}{\partial x_j} \right)$$

ε , the dissipation of k , is modeled as:

$$\frac{\partial \varepsilon}{\partial t} + U_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\frac{v_T}{\sigma_k} \frac{\partial \varepsilon}{\partial x_j} \right) + C_{\varepsilon 1} \frac{\varepsilon}{k} P_k + C_{\varepsilon 2} \frac{\varepsilon^2}{k}$$

$C_{\varepsilon 1}$ and $C_{\varepsilon 2}$ are constants which, in SSIIM, can't be changed by the user. [Olsen, 2007].

The main disadvantage with the k-epsilon model is that it gives a isotropic eddy viscosity which is modeled as average for all three directions. Research has shown that the eddy-viscosity in the streamwise direction is almost one magnitude greater than in the cross-streamwise direction. In order to deal with this a more advanced turbulence model can be used. For instance, the Reynold stresses can be modeled with all terms, this involves solving 6 differential equations. This of course requires more computational power. An even more advanced method is called Large Eddy Simulation and builds on the principles from H.Wengle's definition of turbulence. By using a very fine grid, so small that the size of the turbulent eddies are much greater than each cell size, only the eddies smaller than the cells need to be modeled with a turbulence model. If the cells are so small that no eddies can exist without being killed by viscosity, the method is called Direct Solution. This requires enormous computational resources and is not available for engineering purposes [Olsen, 2007].

5.3 Pressure

By the use of k-epsilon or any other turbulence model the Reynold stress term can be modeled. This leaves the last terms, the pressure term, to be solved. Several methods exists, but with the control volume approach, the most commonly used method is the SIMPLE method [Olsen, 2007]. SIMPLE is an abbreviation for Semi-Implicit Method for Pressure-Linked Equations. In SSIIM, the control volume approach with the SIMPLE method is default. The slightly more accurate SIMPLEC method can be invoked if desirable [Olsen, 2007].

The purpose of the method is to find the unknown pressure field. Briefly speaking the main idea is to assume the value for the pressure, then use the continuity defect to obtain an equation for a pressure correction [Olsen, 2007]. The pressure, P , and the velocity, U , can then be written;

$$P = P^* + P',$$

$$U_k = U_k^* + U_k',$$

where $*$ denotes variables that do not satisfy continuity, and $'$ denotes the correction. The subscript k denotes directions for the velocity (x , y and z for 3 dimensions) [Olsen, 2007]. By inserting these two expressions into the Navier-Stokes equation, and discretizing with respect to time and space we get the following expression for the corrected variables U and P :

$$a_p U_{k,p} = \sum a_{nb} U_{k,nb} + B_{u_k} - \left(A_k \frac{\partial P}{\partial \xi} \right)$$

5.3.1 Velocity correction

The following expression for the velocity correction can then found by subtracting the guessed values from the real values:

$$U'_k = \left(\frac{A_k}{(a_p - \sum a_{nb})} \frac{\partial P'}{\partial \xi} \right)$$

Or, if we neglect the a_{nb} term in the denominator, we get:

$$U'_k = \left(\frac{A_k}{a_p} \frac{\partial P'}{\partial \xi} \right)$$

The SIMPLEC method uses the first expression, while SIMPLE uses the second. The second term is less accurate, and gives a lower corrected value as the denominator is larger. This means that the SIMPLEC method will move faster towards convergence than the SIMPLE method. This can be a disadvantage if there are problems with instabilities [Olsen, 2007].

5.3.2 Pressure correction

The above equations are functions of the pressure correction, P' . In order to get an expression for the pressure correction the continuity equation is used for cell P . The water fluxed through each cell side is summed up:

$$\sum A_k U_k = \sum A_k U'_k + \sum A_k U_k^* = 0$$

The sum of the estimated velocity times the cell area is equal to the sum of the estimated flux, or the water continuity defect, and is denoted delta ΔV . By inserting the expression for the velocity correction, U'_k , and summing up over each side of the cell, the pressure correction gradient can be discretized for each of the four sides in a 2D situation [Olsen, 2007]. The sum of the inflow and outflow over the four sides plus the continuity deficit has to equal zero, and the following expression with only one unknown is obtained:

$$a_e^o P'_p = \sum a_{nb}^o P'_{nb} + b$$

Here the index o denotes the new set of a_{nb} coefficients, the water continuity deficit from the guessed velocity field is denoted b . When water continuity is satisfied, b is zero, and there are no more corrections to the pressure [Olsen, 2007]. Then a_e^0 can be expressed:

$$a_e^0 = \frac{A_e^0}{a_{p,e}}$$

The other a_{nb}^0 coefficients holds similar expression (w, n, s, t and b). $a_{p,e}$ is the average value in cell p and e [Olsen, 2007].

5.4 Transient term

For static water levels the transient term is usually neglected. However, for most time dependent simulations the water level is not static, and the transient term has to be taken into account. Different algorithms exist for computing a free surface. If fixed grid algorithm is used, a two-phase flow scenario is modeled and the volume of fluids (VOF) method is used. When using a adaptive grid, the grid will change so that the free surface is always aligned with the the top, and all the cells will be filled with water. Based on the scenario under investigation, different algorithms is used.

Gravity and control volume

Includes the gravity term in the Navier-Stokes equation. It a linear interpolation between the cell below and the surface cell to compute the pressure, instead of the continuity defect in the SIMPLE method. The gravity terms is a large source term and can make the algorithm fairly unstable, therefore a short time step is required. This algorithm is used for cases with steep water surface gradients, for instance spillway or flood waves [Olsen, 2010].

Pressure and Bernoulli

For any situation where a short time step is difficult to obtain, the gravity term can not be used. An alternative is to use the energy equation to compute the changes in the free surface. By assuming that one location of the surface is kept at a known elevation, the elevation difference, dh , can be computed if the pressure difference, dp , is known [Olsen, 2007]:

$$dh = \frac{dp}{\rho g}$$

5.5 Sediment computation

The fluid flow can be fully described by the Navier Stokes equation, and based on the input data the different terms in the NS is solved. Then the velocity, the waterdepth and water flux in each cell is known. The sediment concentration in one cell will be a result of the concentration in the neighbouring cells.

First order upwind scheme

When looking at a two dimentional steady state dispersion situation in terms of the Finite Volume method, the Convective-Diffusive equation will describe the suspended sediment concentration, c :

$$U_i \frac{\partial c}{\partial x_i} = \frac{\partial}{\partial x_i} (\Gamma \frac{\partial c}{\partial x_i})$$

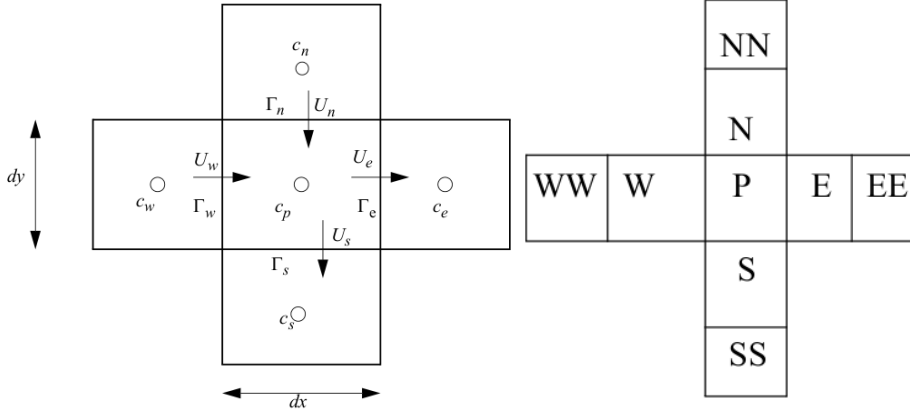


Figure 5.2: Schematic diagram showing the First and Second order upstream scheme.

The left is the convective term, and the right is the diffusive term. This can be discretized using a discretization molecule, which expresses the concentration in the given cell, i , as a function of the neighbouring cells. For a two dimensional case the concentration is expressed as:

$$c_p = \frac{a_w c_w + a_e c_e + a_n c_n + a_s c_s}{a_p}$$

Where $a_p = \sum a_i$, and a_i represent the weighting factor for the neighbouring cell. Different methods exists to estimate these weighting factors. The first order upwind scheme uses the discretization molecule shown i figure 5.2, and calculates the flux:

- Convective Flux: UAc
- Diffusive Flux: $\Gamma A \frac{dc}{dx}$

Where Γ is the turbulent diffusion. The sedimentflux into cell no i from the west neighbouring cell can then be described as:

$$F_w = U_w A_w c_w + \Gamma_w \frac{A_w (c_w - c_p)}{dx}$$

The expression is derived similary for the other sides, north, east and south. For a steady state situation, sediment continuity is assumed, and consequently $F_w - F_e + F_n - F_s = 0$, for sediment inflow from west. This is solved with respect to the weighting factors a , and the concentration in the given, c_p , cell is calculated. For a three dimensional case, a bottom and upper cell is added.

Second order upwind scheme

A common problem with the first order upwind scheme is the approximations in the convective terms in the discretization scheme. This is a phenomena which causes the convective term to be reduced inversely compared to the diffusive term, and is known as false diffusion. This can be solved by using the second order upwind scheme. The two dimensional discretization molecule is given additional four cells, and the inflowing convective concentration from direction i , is a function of the concentration both in the first and second cell. The diffusive term is calculated as before, and the expression for the flux though the west side of cell p for a two dimensional steady state situation then becomes:

$$F_w = U_w A_w \left(\frac{3}{2} c_w - \frac{1}{2} c_{ww} \right) + \Gamma_w \frac{A_w (c_w - c_p)}{dx}$$

Where the coefficients $2/3$ and $1/2$ are given as a function for the expansion ratio between the cell sizes. The weighting factors are calculated and the concentration in cell p , is expressed as:

$$c_p = \frac{a_w c_w + a_e c_e + a_n c_n + a_s c_s + a_{ww} c_{ww} + a_{nn} c_{nn}}{a_p}$$

where a_{ee} and $a_{ss} = 0$. For a three dimensional model four cells is added, two on top, and two on the bottom, giving four extra coefficients [Olsen, 2007].

Time dependent situations

For a time dependent sediment simulation a sediment deficit will govern the erosion or deposition in the reservoir. This means that the assumption of sediment continuity over a cell can't be maintained. The mass change in cell p is expressed as follow:

$$m = \Delta c V_p = (c_{p,t} - c_{p,t-1}) V_p$$

The fluxes in and out of cell p is computed as previously, but multiplied with the timestep to get the mass instead of the flux. The expression for the concentration using the first order upstream scheme then becomes:

$$a_p c_p = a_w c_w + a_e c_e + a_n c_n + a_s c_s - \frac{(c_{p,t} - c_{p,t-1}) V_p}{\Delta t}$$

Where the expression for the coefficients are the same as for the steady state equation. The additional term on the right hand side is called a source term, often express by two terms:

$$S_C + S_p c_{p,t} = \frac{c_{p,t-1} V_p}{\Delta t} + \frac{V_p}{\Delta t} = \frac{(c_{p,t} - c_{p,t-1}) V_p}{\Delta t}$$

The suspended sediment concentration in cell p can then be expressed as:

$$c_p = \frac{a_w c_w + a_e c_e + a_n c_n + a_s c_s + S_c}{(a_p + S_p)}$$

Where the weighting coefficients a_{nb} and a_p is similar to the steady state. The transient convective-diffusive equation can then be written as:

$$\frac{\partial c}{\partial t} + U_i \frac{\partial c}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\Gamma \frac{\partial c}{\partial x_i} \right)$$

This computation gives the suspended sediment load for each cell, based on the results from the solution of the Navier Stokes equation for each timestep. The Bed load is computed using known bed load formulaes, for instance the Van Rijn formula, this is usually specified in the user interface of the CFD program.

Chapter 6

SSIIM

Due to the complex flow field and the need to simulate secondary currents, a three-dimensional numerical solver is required for the Angostura case. The numerical program SSIIM have been chosen for the task. SSIIM is made for cases involving complex flow field and sediment transport, and is freeware. This chapter briefly describes the program, how to make and run a simulation and common errors and uncertainties in relation to CFD.

6.1 General about SSIIM

SSIIM is a computational fluid dynamics program tailor-made for hydraulic engineering. SSIIM is an abbreviation for Sediment Simulations In Intakes with Multiblock option. The program is developed by professor Nils Reidar Bøe Olsen at NTNU, and was originally designed to simulate sediment movement in rivers and channels. The program have later been extended to include other hydraulic engineering topics, like spillway modelling and stage-discharge relationships, and can also perform water quality simulations. SSIIM's greatest advantage compared to other CFD programs is the ability to model sediment transport with a movable bed in a complex geometry. SSIIM solves the Navier-Stokes equations using the k-epsilon turbulence model and the SIMPLE method for pressure coupling, as described in chapter 5. By using a implicit solver to find the velocities, the convective-diffusive equation can be solved for the sediment transport. SSIIM is made for teaching and research and is a non-commercial program. The program and the user manual can be freely downloaded from <http://folk.ntnu.no/nilsol/ssiim> [Nils Reidar B Olsen, 2010].

Two versions of SSIIM is available, SSIIM 1 and SSIIM 2. SSIIM 1 uses a structured grid, while SSIIM 2 uses an unstructured grid. Because of this SSIIM

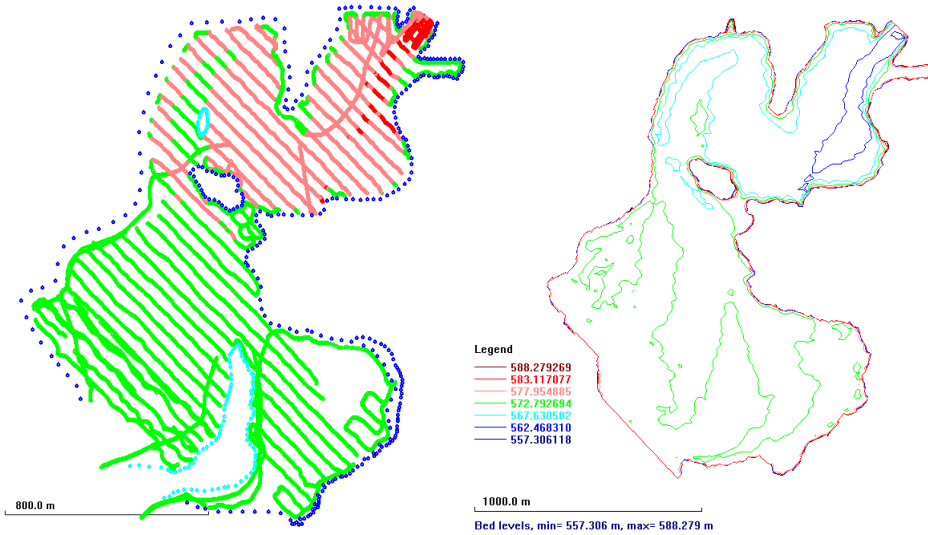


Figure 6.1: Geodata from bathymetric survey and bed levels in SSIIM

2 can handle wetting and drying of cells and a adaptive grid can be used. SSIIM 2 handles multiple sediment sizes, transport of both bed and suspended load and bed forms. Both versions consist of a user interface and a numerical algorithm. There is also a Unix version of both versions, but they can not be operated with the graphical user interface Nils Reidar B Olsen [2010]. SSIIM 2 is used for this case, and whenever the term SSIIM is used, it is refereed to SSIIM 2.

6.2 Using SSIIM

The user interface consists of several editors. In the grid editor the user can read geodatapoints and specify the shape, size and resolution of the grid. In the discharge editor the extent and amount of inflow is specified. SSIIM can read up to ten inflow and outflow groups, but the sum of the inflow has to equal the sum of the outflow. In the roughness editor, different Strickler number can be given to the various parts of the grid. After the grid is made, all the information is stored in a file called *unstruc*.

The windows version of SSIIM reads a set of DLL files (Dynamic Link Libraries). The DLL's are modules where other programmers can code new algorithms and formulas. The DLL's needed to run SSIIM can be download from the web. The Unix version are compiled to run without DLL's. In addition to the DLL files, a control file is need for any advanced SSIIM simulation. The control file contains

most of the parameters which controls the simulation; Sediment parameters like size distribution, fall velocity and roughness, numerical parameters; time step, inner iterations and relaxation coefficients, and grid parameters like cell size, and number of cells. It also governs which formulas and algorithms that are activated, like whether to use van Rijn or Englund/Hansens formulas to calculate sediment concentrations. The control file is further explained in section 6.4

When the simulation have either converged or reached the maximum number of iterations, the results can be viewed directly in the graphical user interface, or exported to files which can be read in ParaView or Techplot. The graphical user interface can display hydraulic variables like water depth, velocity vectors, horizontal and vertical diffusion and pressure. It also displays sediment variables like bed form height, sediment sieve size and secondary current angle. In order to save the results the menu “write result” have to be chosen in the graphical user interface. Then two files are written from SSIIM. The first, simply called *result* contains hydraulic information: velocities in three dimensions, k , epsilon, pressure and fluxes on all the walls of the cells. The other file is called *bedres* and contains sediment information: bed roughness, grain size distribution, sediment thickness and bedform height. If the program somehow does not reach convergence or maximum iterations the file named *boogie* should be inspected. This file contains intermediate results of the computations, and the reason for a failure is written here [Olsen, 2010].

6.3 Making a grid

Whenever a complex geometry makes the basis for a simulation, the most convenient way to generate a grid is to import a file named *geodata*. This file contains information about the bed level at different locations, usually from a bathymetric survey. In the grid editor in the graphical user interface this file can be viewed. Points can be added or removed in order to adjust the geometry. When the *geodata* file is imported, either a single block or a multiblock grid is added. The multiblock option allows the user to make several blocks of structured grids which can be “glued” together. The given geometry, the situation and the problem under investigation will dictate the different grid parameters. However, there are three characteristics which are crucial to ensure reliable results:

- **Orthogonality.** The grid line intersections should be as close to 90 degrees as possible. This is often impossible, but one should try to avoid sharp turns. A grid with intersections less than 45° or more than 135° is called “very non-orthogonal”.
- **Aspect ratio.** The ratio between two perpendicular sides of a cell should not be too large. Values up to 2 or 3 is accepted.

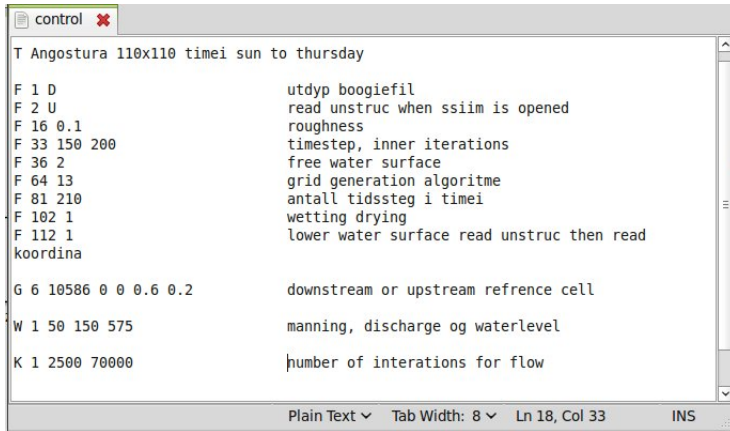


Figure 6.2: Control file for a simple water flow computation in SSIIM.

- **Expansion ratio.** The ration between the size of one cell and the neighboring cell should be as close to unity as possible.

For a wetting and drying simulation with an adaptive grid, the easiest way to make a grid is to add one single block which covers the entire area under investigation. The grid is made by “generate bed levels” in the grid editor. Defining the upper limitation of the grid is done by “add surface point”. The minimum number of surface points is three. Specifying a water surface which is higher than the maximum water level ensures that no cells are omitted and unwanted dried up. After the surface points are added the grid can made in three dimensions by first “generate surface” and then “generate 3D”. The discharge is defined in the discharge editor. Here the in and outflow areas are specified by clicking on the current cells. Only the border cells of the block can be assigned inflow and outflow. The discharge data are saved together with the grid in the unstruc file by “generate unstruc” from the file menu [Olsen, 2010]

6.4 Running a simulation

When the grid is made a control file automatically appears in the SSIIM directory. by default this contains no data, and this have to be specified by the user. In the control file the parameters used to control the simulation can be specified. The control file consists of data sets which are organized by capital letters according to what category they control. Figure 6.2 shows a control file with the most common data sets for a free surface time dependent water simulation.

- The F 33 data set specifies the time step, and the number of inner iterations

pr time step.

- The F 36 data set invokes the use of free surface algorithm. If the following integer is 2, the Pressure and Bernoulli approach, described in section 5.4 is used. This requires the G 6 data set to specify a reference cell, in which the water surface will be kept constant.
- The F 64 13 data set give information about the grid generation, giving a better vertical grid distribution.
- F 102 1 enables the wetting/drying algorithms.
- K 1 data set specifies the number of iterations for flow procedure and the minimum number of iterations between each update of the water surface.

The F 112 1 data set is important when using a adaptive grid. After the grid is made with a unnatural high water level, as previously described, the water level can be lowered at the beginning of the computation. This saves computational time. In order to do this the *koordina.t* file is copied to a excel sheet. This file contains information about the xyz coordinates and the water level. In excel the initial high water level can be lowered to a water level closer to the expected water level. The water level can either be flat or skewed. After the water level has been changed, the file is saved and named *koordina*. It is important that the file is saved without extensions, so that SSIIM can read it. After this point the unstruc file should not be rewritten, as this will remove the dry cells from the grid [Olsen, 2010].

If a time dependent free surface simulation with varying discharge is to be conducted, a *timei* file has to be made. This file can be made in excel and then saved without extension in the same directory as SSIIM. The *timei* file contains information about the discharge, water level and sediment inflow concentration for each given time step. SSIIM can not handle situations with unequal inflow and outflow, so when modelling a filling or flushing scenario, the different water levels have to be specified. In order to start the simulation, “Compute water flow” is chosen in the menu. In order to start a sediment computation, either a water flow simulation have to be conducted first, or a combined simulation is implemented by defining F 2 S in the control file. The water flow will be computed first, then the sediment computation for each time step [Olsen, 2010].

6.5 Analyzing results

When SSIIM has either converged or reached the maximum number of iterations the results can be viewed in the graphical user interface. Different parameters can be assessed, such as bedforms, velocity vectors, kinetic energy and vertical diffusion. The result file can be written from the main menu in the user interface,

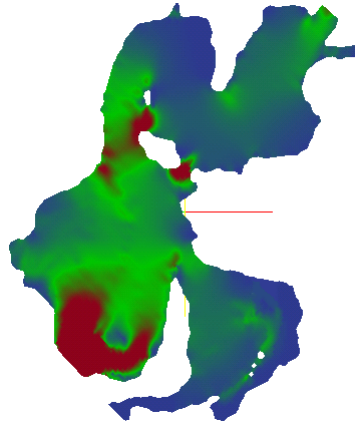


Figure 6.3: Velocity distribution in ParaView.

or automatically by adding F 2 M in the control file. This file contains velocity in three dimensions, k , epsilon, pressure and the flux on all the cells [Olsen, 2010]. At the same time as the result file is written, a file named *bedres.t* is also written. This file contains information about the bed sediment and the roughness. If this file is renamed to *bedres*, without extension, SSIIM will search for this when “read result file” is activated. It will then use the *bedres* file to update the grid so that it will be similar to the grid written to the result file [Olsen, 2010].

When a time dependent computation have been made it is often interesting to see the changes in different parameters over time. This is not possible to view in SSIIM user interface. In order to make a animation, a ParaView or Techplot file can be written. Either a 2D or 3D file can be written from the user interface after the simulation. By specifying the P 10 data set in the control file, SSIIM will write a result file at certain intervals, for instance every 100th time step. These files can then be read by either ParaView (freeware) or Techplot. Figure 6.3 shows the velocity distribution in the reservoir for a steady state simulation with a 575.2 masl water level, from ParaView. The red color indicates high velocities, and the blue low velocities. Different output files can be written from SSIIM with the interval given in the P 10 data set. The F 48 data set specifies which file. If the integer is 5, a habitat file will be written, if the integer is 17 a file named *halvor* is written. This file contains the outline coordinates for the grid. If F 293 1 is used a file named *sigurd* will be written for the specified time step in the P 10 data set. This file contains the residuals for each time step. If a vertical profile is wanted, a *interpol* file is added. This file contains a array of coordinates, for instance the coordinates for a cross section or longitudinal profile. The desired output format for the vertical profile is then specified in the F 48 data set. For instance F 48 16

will write a 2D ParaView file containing the sediment concentration over the depth for the coordinates in the interpol file.

6.6 Accuracy, Errors and Uncertainties

The main purpose behind making a CFD model is to simulate a real world scenario. The more similar the model is to the real world, the better the result. There are numerous different parameters which will affect the output from a CFD simulation. The European Research Community on Flow, Turbulence and Combustion, ERCOFTAC, have published Best Practice Guidelines for CFD. 7 common errors are listed [Olsen, 2007]:

1. **Modelling errors:** Whenever the real world is expressed with a number of mathematical equations, modelling errors are introduced. For instance, the assumption of a isotropic turbulent eddy-viscosity is a simplification of the real world.
2. **Errors due to numerical approximation:** Errors due to numerical approximations occur when discretizing equations. False diffusion is a example of this.
3. **Errors due to not complete convergence:** When using a iterative solver without getting complete convergence, there is a risk of information being lost. When doing time dependent computations this should be taken into account.
4. **Round-off errors:** If a CFD program which runs on 32 bits floating point number with a 6 digit accuracy is used, rounding errors could represent a problem. Today, most of the CFD programs use 64 bits floating point number which have a accuracy of 12 digits. this is usually sufficient.
5. **Boundary conditions and input data errors:** Boundary conditions and geometry errors are the most common problems in CFD modelling. Especially when computing flow in complex geometries with a moving grid, this can be a problem. The model is never better than the poorest of the input data. Therefore input data like velocity distribution, roughness or sediment inflow should be as accurate as possible.
6. **Human errors:** many CFD models have user friendly user interface with default settings, making it fairly easy to run a simulation. In order be able to assess and interpret the output experience and knowledge about CFD is important.
7. **Software bugs:** All complex software have bugs, and one bug per 1000-10 000 line of code is expected.

In addition to avoiding all these sources of error, it is desirable to make the model as accurate as possible. Grid resolution, time step and number of iterations are important parameters when making a accurate model. However, reducing the time step and/or increasing the number of iterations pr time step leads to longer computational time. The challenge is then to compromise between trying to limit the errors, maximizing the accuracy and minimizing the computational time.

Chapter 7

Simulation scenario

In order to simulate a real world scenario, an advanced and reliable numerical model is required. However, any given model is never any better than the poorest of the input. To achieve accurate results for the deposition and concentration simulation of sediments in Angostura, SSIIM needs reliable and trustworthy input data. Any sediment deposition case is a function of 6 variables; the amount of inflowing water and sediments, the geometry of the reservoir, the outflow of water and sediments, and time. Chapter 8 and 9 describes the estimated inflow of water and sediments. In order to utilize an advanced numerical solver and reliable input, a simulation scenario needs to be constructed. This chapter describes the simulation case, the simulation time and the possibility of verifying the results.

7.1 Simulation case

Based on the field measurements from the field trip to Costa Rica in September 2011, it was decided that two different scenarios should be simulated for the 2011 Angostura case. The first case is a time-dependent 250 days simulation which aim to replicate the amount and pattern of the deposited material. This case is referred to as “the deposition case”. The second case is a steady state simulation which aims to replicate the suspended concentration distribution over the length of the Angostura reservoir on the 13th of September 2011. This case is referred to as “the steady state case”. The grid is made as specified in chapter 6, and consists of 110x110 cells.

7.1.1 Deposition case

For ICE it is important to know the reservoir deficit from year to year, in order to evaluate the efficiency of the measures undertaken to extend the lifetime of the

reservoir. It is also important to estimate the remaining lifetime of the reservoir. The deposited material and the deposition pattern is of great interest. The main goal of the time dependent simulation is therefore to as accurately as possible estimate the total deposited sediment quantity and the deposition pattern between the November and September flushing. Bathymetry survey conducted in November 2010 forms the basis for the model.

7.1.2 Steady state case

During the 13th of September measurements of the suspended sediment concentration was conducted over the length of the Angostura reservoir, using the LISST-SL. The concentration was measured at the inflow area, where the Reventazón river meets the reservoir, and additional 24 measurements along the main channel, all the way to the weir. Vertical profiles was measured, the lowest about 0.5 meters above the bottom to avoid bed load. Depending on the depth, about 10 to 16 samples were taken at each point. The simulation is based on the same model as the time dependent simulation; that is the geodata from the 2010 survey, but has a slightly different grid. The goal is to be able to replicate the sediment concentration distribution over the reservoir on the 13th of September 2011. This is to be done by performing a simulation with the the same input data as for the measurement.

7.2 Time

Total simulation time and time step are important parameters in numerical modelling. The total simulation time is a product of the time step and the number of iterations. A small time step will generally give a more stable simulation, but will require more iterations to reach the same total simulation time. This requires more computational resources, and the computation time will be greater.

7.2.1 Deposition case

The time window of interest for the deposition simulation is from after the second flushing in November 2010, until just before the first flushing in September 2011. The simulation time is set equal to the number of days from the end of November to the beginning of September, a total of 250 days. A fairly small time step of 1000 seconds is chosen in order to prevent problems with high residuals and divergence. 250 days equal 21 600 000 seconds, and with a time step of 1000 seconds, 21 600 iterations has to be preformed. For each time step 20 iterations is performed. This is specified in the control file, and the F 2 S data set is used to invoke the sediment computation.

7.2.2 Steady state

When simulating the suspended concentration a steady state model is used. For such a case the simulation consist of to parts. First, a water flow simulation is conducted. For such a simulation, time is not really of interest, and the F 33 data set is removed. After the water flow simulation has converged or reached the maximum number of iterations, the result file is written. The program is restarted and the result file is read back in. Then a sediment computation is performed. SSIIM needs a time step in order for the sediment transport algorithms to work, and a time step of 50 seconds is chosen. This is low enough to prevent high residuals. With 10 000 iterations, the total simulation time is 500 000 sec, or nearly six days. This ensures a fully steady state suspended sediment concentration over the entire length of the reservoir. 10 iterations pr time step is used.

7.3 Verification

As mentioned in section 7.1, field data from Angostura is used both as input, and as verification for the simulation. For both cases, bathymetry data from 2010 forms the basis for the grid, and even though the two grids differ slight, they will more or less give the flow field.

For the deposition case, the 2011 bed level measurements performed by ICE in September, will form the basis for the verification. The bathymetry data from 2010 and 2011 is compared in SSIIM. Here the difference in bed levels, and thereby the deposition pattern can be visualized. The total volume for the geometry can be found, and compared for equal water levels, which in turn is used to estimate the volume deficit between the two years. This process is briefly described in chapter 11. The simulated total quantity and deposition pattern is then compared to the actual deposition and pattern.

For the steady state simulation, measurements taken on the 13th of September form the basis for the verification. The 25 vertical suspended sediment concentration profiles ensures a fairly good spatial resolution for the data. Figure 7.1 shows the location of the measurements, the sediment bed samples and the borderline marking the Angostura shoreline. The measurements are taken in the main channel, and the coordinates from the measurements is used as input data in the interpol file, briefly explained in 6.5.

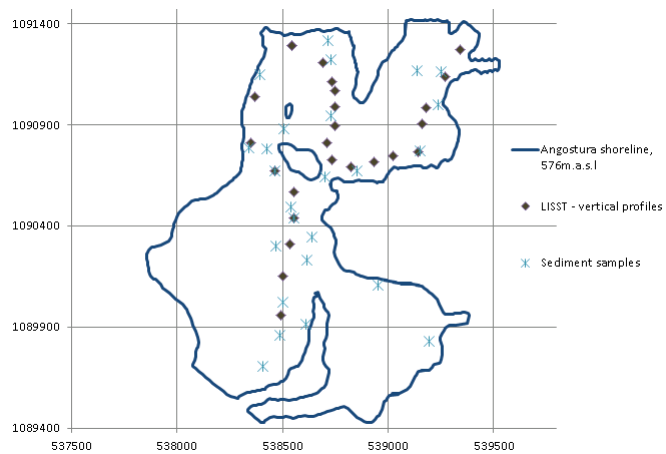


Figure 7.1: LISST measurements and sediment sample coordinates, by Halvor Kjærås.

Chapter 8

Water Input

Sediments are transported by the waterflow in a river or reservoir, and the amount and size of transported material is depends the bed shear stress. The bed shear stress is a result of the current water flow, water level and geometry. This chapter describes the water input for the two simulated cases, and is closely related to the next chapter, Sediment input.

8.1 Water level

Angostura is a regulated artificial lake, where the water level is controlled by the inflow of water from the Reventazón river, and the outflow to energy production. ICE continuously logs the water level at the intake, and because of the relative small surface area of the reservoir, it can be assumed that the water level is approximately the same over the entire lake. The water level is specified in the timei file for SSIIM.

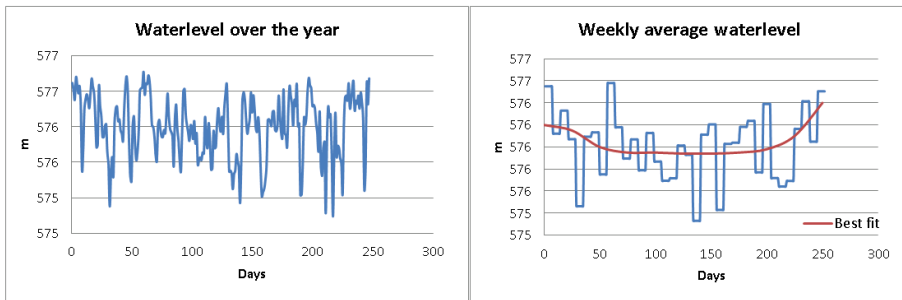
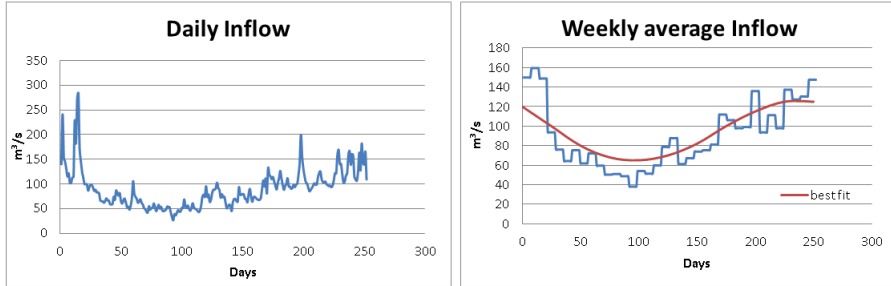


Figure 8.1: Daily and weekly averaged water level over the simulation period for the deposition case

Figure 8.2: Daily and weekly averaged inflow over the simulation period for the deposition case



8.1.1 Deposition case

As mentioned in section 2.2, Angostura is a daily peaking reservoir, and therefore the waterlevel fluctuates quite rapidly with time. However, most of the time the fluctuations do not represent a drastic change in the water level, and are usually within 1 to 2 meters. A frequent change in the water level will induce instabilities in the numerical model, and most likely the small daily variations do not affect the sediment deposition to a high degree. Therefore an averaged scenario is simulated. The left graph in figure 8.1 shows the daily variation in water level for the simulation period, November 2010 to September 2011. The right figure shows the weekly average vs time. This weekly average forms the basis for the “best fit” line which is marked red. The best fit values are used as input for the model. Summed up over the year, the total difference between the real and the simulated water level is only 0.8%.

8.1.2 Steady state case

During the LISST verification measurements undertaken on the 13th of September 2011, the water level in Angostura was 576.2 meters. This is therefore used for the steady-state simulation.

8.2 Water inflow

Angostura lies downstream of three other power plants, and the inflow to the reservoir is therefor heavy regulated. Nevertheless, the discharge varies quite alot over the year, and also between years. The water inflow is specified in the timei file.

8.2.1 Deposition case

A frequent variation in the discharge will decrease the stability of the numerical model. Figure 8.2 shows the daily inflow on the left graph, and the weekly averaged inflow on the right, plotted over the simulation period. The Best fit line on the right graph shows the inflow fluctuations in the simulation. The difference between the combined real inflow and the simulated inflow over the year is 2.6%.

As mentioned before, the bed shear stress, which governs the sediment transport capacity, is dependent on the water flow. The water inflow is therefore an important parameter in a numerical model, as it to a high degree influences the sediment inflow. A river with frequent change in water flow might not have the sediment transport characteristics as a more stable and uniform river, but over time, the total deposition might very well be the same. Another, and quite important factor when considering input data, is that sediment inflow data are quite rare for unusual flows. However, as described in the next chapter, data can be quite consistent for flows in the normal range. The rating curve in section 9.1, figure 9.1, shows that a fair amount of sediment inflow data exist for flows in the normal range. This indicates that a higher accuracy in the reliability of the input data can be achieved by using normal flows. It is previously shown that numerical simplifications in both time and inflow data can give quite accurate results [Hoven, 2010]. It is therefore believed that the best fit curve will give a stable numerical model and correct total sediment and water inflow over the simulation time.

The inflow to Angostura does in reality consist of 4 channels. The Rio Reventazón, which is the main dominant contributor, a tributary river entering parallel to the Rio Reventazón, and two small man made diversion channels. It is assumed that 1% of the total inflow enters through each of the diversion channels, 18% through the tributary river, and the remaining 82% origins from the Rio Reventazón.

8.2.2 Suspended sediment case

During the measurements on the 13th of September 2011, the inflow to Angostura was $120 \text{ m}^3/\text{s}$, and is therefore used in the steady state simulation. During the measurements the dominant flow originated from the lowering of the water level in Cachi. Therefore it is assumed that 88% of the inflowing water entered through the Reventazón river, 10% through the tributary river, and the remaining 2 percent through the diversion channels.

Time [days]	Water level [m]	Discharge [m^3/s]
0	576.20	130
25	576.15	100
50	576.00	80
75	575.95	68
100	575.95	65
125	575.94	70
150	575.94	82
175	575.95	100
200	575.98	115
225	576.1	125
250	576.4	125

Table 8.1: Input data for time dependent deposition simulation

Chapter 9

Sediment input

The amount and grain size distribution of the inflowing sediments will influence the outcome of any sediment model to a high degree. Sediment concentration and size are closely related, and with increased transport capacity, the mean size and concentration of the transported material will increase, given that the river is in regime. This chapter describes the estimated sediment concentration and grain size distribution for the two simulation cases, based on the water flow data from chapter 8.

9.1 Sediment inflow concentration

As mentioned in section 3.3, sediment transport is divided into two groups; Bed load and suspended load. Here it is assumed that the bed load is the load which are transported within the lowest 0.3-0.5 meter of the water depth, and is about 10% of the total load [Jimenez et al., 2004]

9.1.1 Deposition case

ICE has sporadically logged sediment and water flow data from the Reventazón river upstream of Angostura since the 60's. Some of the series contains consecutive data, but most are taken either quite rarely, or lacks certain data. Nevertheless, these data are quite useful when represented in a sediment rating curve. Such a curve is a plot of water inflow vs sediment concentration. A total of 724 measurements make the basis for the rating curve made for this simulation. Some of the values has been removed after visual investigation as they showed unrealistic results. For instance, a sediment concentration of 13 000 PPM (Parts Pr Million) at a discharge of $130 \text{ m}^3/\text{s}$, or 500 PPM at $700 \text{ m}^3/\text{s}$, both seems fairly unrealistic. Figure 9.1 shows the adjusted rating curve for the inflowing water and sediments.

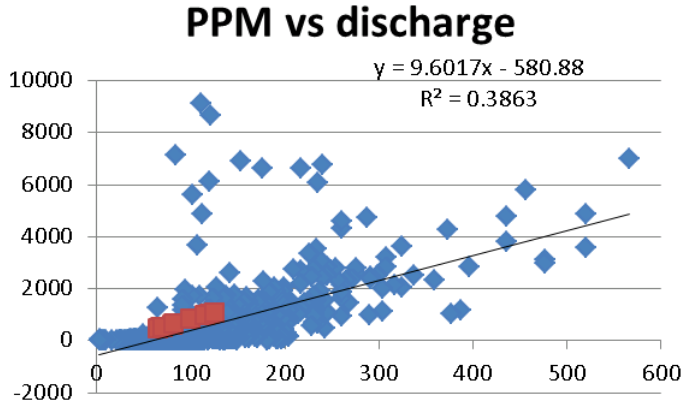


Figure 9.1: Sediment rating curve for the inflow to Angostura

As mentioned in section 8.2, quite a few measurements exist for flows in the normal flow regime, with a high variability in concentration for each water flow. A trend line with a R^2 value of 0.38 gives a formula which forms the basis for the estimated sediment inflow. The red points show the values used in table 9.1.

SSIIM reads the sediment size and fall velocity in the control file, and sediment concentration as m^3/m^3 for each grain size, in the timei file. Based on the water inflow from section 8.2.1 the corresponding sediment inflow is calculated using the sediment rating curve function. However, it is known that most of the deposition in a reservoir happens during floods and extreme inflow situations Lysne et al. [2003]. At the same time, very scarce data exist for these floods, and also the variability in concentration is very high for the few data which exist. Therefore the formula from the rating curve is based on the normal flows, and then adjusted to give a higher average inflow to compensate for the lack of floods in the simulated inflow. For the deposition case the sediment inflow is assumed to be about twice the values from the rating curve. The estimated values has to be transformed from PPM to m^3/m^3 in order to be read by SSIIM. Table 9.1 shows the time, inflow and water levels from chapter 7 and 8, together with the corresponding sediment inflow concentration. The estimated total inflow of sediments over the simulation time is approximately $610\,000\,m^3$.

9.1.2 Steady state case

The goal of the steady state simulation is to replicate the suspended sediment concentration over the reservoir, based on the values from the uppermost LISST measurement from Angostura. Unfortunately, when the LISST data was investigated,

Time [days]	Water level [m]	Discharge [m^3/s]	Sediment inflow [m^3/s]
0	576.20	120	0.0464
25	576.15	100	0.0314
50	576.00	80	0.0192
75	575.95	68	0.0134
100	575.95	65	0.0121
125	575.94	70	0.0143
150	575.94	82	0.0203
175	575.95	100	0.0314
200	575.98	115	0.0424
225	576.1	125	0.0506
250	576.4	125	0.0506

Table 9.1: Time, Water level and Water and Sediment inflow for Time dependent simulation

they showed that the two most upstream measurements contained very low concentration values. The reason for this is unknown, but one explanation could be that the situation changed during the measurements. Whatever the reason, it appeared impossible to be able to replicate the remaining 23 sediment measurements with such a low inflow concentration. Therefore the values from measurement number three is used as the basis for the inflow concentration. Measurement number three is taken 330 meters downstream of measurement number one. In addition to this, a linear interpolation of the depth averaged concentrations is used to extrapolate the suspended concentration at the inflow area. When comparing adjusted values from measurement no 3 to the extrapolated values, the input to SSIIM is about 30 % higher. Table 9.3 shows the input concentration for the grain size distribution which is elaborated in section 9.2.

The total inflow concentration for the steady state is $1.55 \text{ e-}4 \text{ } m^3/m^3$, or approximately half the inflow used in the deposition case for a water inflow of $120 \text{ } m^3/s$. The concentration for the steady state simulation is in other words smaller than for the time dependent simulation for the same discharge. This is due to the fact that the steady state simulation aims to replicate the scenario as it actually was on the 13th of September 2011, while the time dependent simulation aims to replicate a long period of deposition. During the rain season the sediment inflow will increase, and it is therefore likely to assume that the suspended concentration is higher in other parts of the year. This needs to be taken into account with a higher average sediment inflow concentration.

9.2 Grain size distribution

SSIIM reads the sediment grain size and corresponding fall velocity in the control file. In the timei file a sediment concentration is assigned to each specified size. This means that the sediment concentration from section 9.1 has to be distributed over the different inflowing grain sizes. This section describes the process of estimating the inflowing sediment grain size distribution for the two different simulation scenarios.

9.2.1 Deposition case

The size of the transported material is dependent on the transport capacity of a river or a reservoir. This means that as the discharge increases, so does the size of the transported material. This, however, is not possible to incorporate in SSIIM, and a grain size distribution which is representative for the entire range of the chosen water inflow has to be used. This further supports the choice of a water inflow distribution in the normal flow range, as elaborated in section 8.2. SSIIM reads up to 9 different sediment sizes, for this simulations however, 5 different sizes is used. The inflow concentrations from section 9.1 is the total concentration for a given discharge. This concentration needs to be distributed over a corresponding grain size distribution.

As stated previously, sediment transport is principally divided into two categories, suspended load and bed load. It is usually assumed that about 90% of the material is transported as suspended load. From this it follows that about 10% of the material is in the size range bigger than the threshold for suspended transport. Further it can be assumed that some of the material is smaller than a certain threshold, so that it do not settle in the reservoir under normal operation conditions. As it does not exist any grain size distribution curves for different flows for Angostura, this have to be estimated. Measurements undertaken in September 2011, using the LISST-SL and sediment bed samples from 2010, forms the basis for the estimation of grain size distribution.

Suspended particles

LISST-SL measurements conducted over the length of the reservoir on the 13th of September shows that sediments smaller than 5 microns do not settle in the reservoir. Figure 9.2b shows the depth averaged concentration for different grain sizes of 25 measurements taken over the length of the reservoir. As clearly can be seen in the figure, there is little, or no reduction in the concentration of material in size range C4 and C6, which corresponds to material of median size 3.40 and 4.73 μm . The smallest sediment diameter in the grain size distribution is therefore set to 5 micro meters. The same measurements show that the concentration of

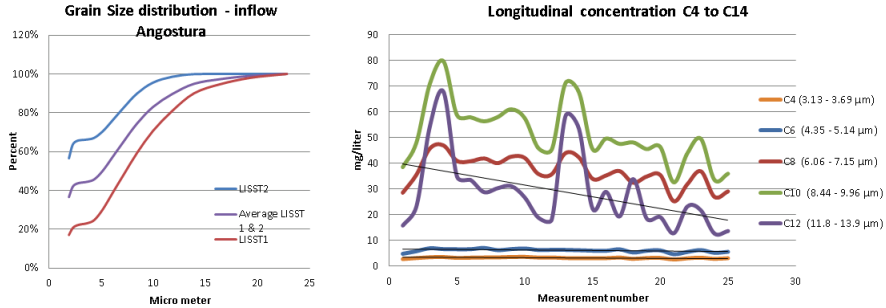


Figure 9.2: a) Grain size distribution for suspended sediments at the inflow to Angostura. b) Depth averaged suspended concentration over the length of the reservoir.

Size [μm]	Mass %	Cumulative %	Transport
5	25	25	Suspended
8	30	55	Suspended
16	35	90	Suspended
40	8	98	Bed
130	2	100	Bed

Table 9.2: Grain size distribution input data for time depended deposition computation

particles larger than size range C14, or 16.4 to 19.3 μm , is about 26 mg/l, or about 5% of the total suspended concentration. The largest suspended particles is therefore set equal to 16 μm . Figure 9.2a shows the depth-averaged suspended grain size distribution at the inflow area. The figure shows that nearly all the suspended sediments for a discharge of 120 m^3/s , is smaller than 16 micrometers. Table 9.2 shows the selected grain sizes and the corresponding mass percentage for both suspended and bed load.

Bed load

Sediment bed samples taken by ICE at the inflow area of Angostura in 2010 shows a range in sediments from about 10 to 1000 μm . Figure 9.3 shows that 50% of the bed sample is smaller than 40 microns, and about 20 % of the bed sample is larger than 100 microns. The remaining two sediment sizes is therefore set to 40 and 130 microns and the correlated total mass percentage, respectively 8 and 2 percent. It is reasonable to assume that the bed size distribution will not differ drastically from last year. The Simulated bed sediment distribution is specified in the N data set in SSIIM, and can be seen in the control file in appendix C. The estimated

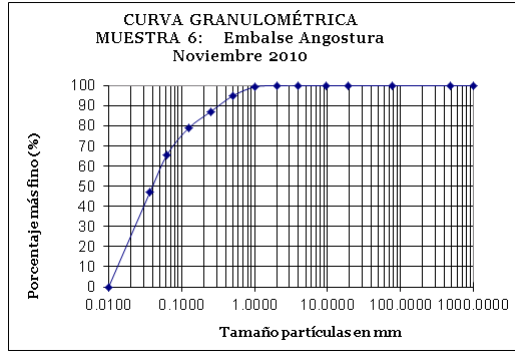


Figure 9.3: ICE 2010 Sediment bed sample from inflow area, Angostura

inflow grain size distribution can be seen in figure 9.4b).

Fall velocity

A important parameter for sediment simulation is the fall velocity of the particles. Fall velocities for quartz particles with a density of 2650 kg/m^3 , and larger than 10 microns can be found from diagrams, such as appendix D. For particles smaller than this, it is more difficult to estimate the fall velocity. These particles are so small that cohesive forces will affect the fall velocity. In order to try to mitigate this the fall velocity of these small particles are calculated using the following formula developed for algae from Stokes law [Olsen, 2007] :

$$w = d^2 g \frac{\rho_s - \rho_w}{18\rho_w \nu}$$

Where ν is the kinematic viscosity, a function of the water temperature. In this case with approximately 20 degrees, ν is equal to $1.6\text{e-}06$. The fall velocity for the different grain sizes can be seen as the second float in the S data set in appendix C.

9.2.2 Steady state case

No bed load measurement were conducted with the LISST, and only suspended load is simulated in the steady state simulation. The LISST measures sediments in 32 size groups, from $1.9 \mu\text{m}$ to $381 \mu\text{m}$. Nearly all the measurements shows zero concentration for material larger than 20 microns. As mentioned in section 9.1, the LISST measurements also show that material less than $5 \mu\text{m}$ do not deposit in the reservoir. This means that material larger than 20 microns and less than 5

Size [μm]	concentration [mg/l]	concentration [m^3/m^3]	Cumulative %
5.58	23.1	8.8 e-06	6.0
6.59	48.4	1.84 e-05	18.7
7.77	62.7	2.4 e-05	35
9.17	75.6	2.9 e-05	54.8
10.8	86.8	3.3 e-05	77.4
12.8	53.2	2.0 e-05	91.3
15.1	31.5	1.2 e-05	99.5
17.8	1.7	6.6 e-07	100

Table 9.3: Steady state simulation grain size distribution. Concentrations for a water inflow of $120 m^3/s$.

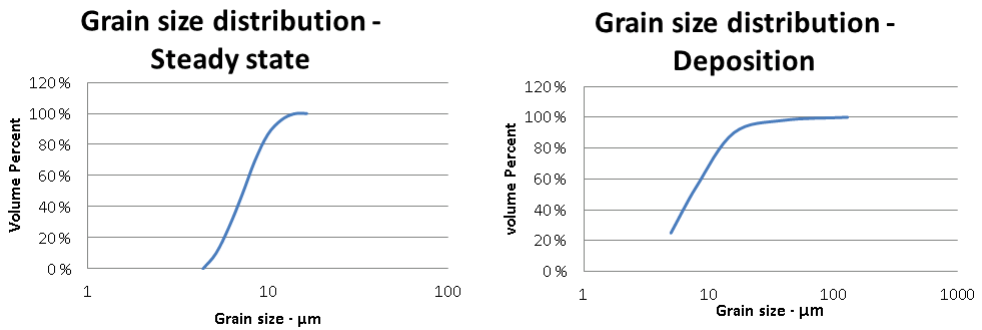


Figure 9.4: a) Input grain size distribution for the steady state simulation and b) Deposition simulation.

microns are not interesting for the steady state simulation.

Between 5 and 20 μm the LISST holds 8 size groups. The mean size in each group is used as the input size in SSIIM, and assigned a concentration, as specified in section 9.1. The same sizes are assumed to make the bed sediments, and the distribution is shown in the N data set in appendix B. Table 9.3 shows the grain size and corresponding inflow concentration for the steady state simulation. The fall velocity is calculated using the same formula as for the deposition case. The estimated inflow grain size distribution can be seen in figure 9.4a).

Chapter 10

Results

John F. Wendit had a good point when he said that “the end product of CFD is a collection of numbers”. The output from SSIIM is indeed a collection of numbers, and in order to be useful, some sort of representation is needed. This chapter presents the results from the two simulations, using the graphical presentation in SSIIM, and the post-processing program ParaView.

10.1 Time dependent deposition simulation

When a sediment simulation has reached the maximum number of iterations, the total sediment quantity is printed at the end of the boogie file. The total inflow and total outflow is given in kilograms, and by assuming a density of 2650 kg/m³, the dry volume of the sediment amount can be found. In total 14 simulations was performed until satisfactory results was obtained.

10.1.1 Deposited Quantity

The total simulated sediment inflow to Angostura is 1 616 150 tonnes, or 609 868 m³ of dry material. Of this, 767 260 tonnes exits the reservoir, leaving 848 890 tonnes of deposited material in place. This gives a total bed change of 320 273 m³ of dry sediments. In the boogie file, SSIIM also gives the continuity bed change, which is the simulated change in the bed. The continuity gives a total bed change of 842 998 tonnes, or 318 112 m³. The difference between the inflow and outflow deficit, and the estimated bed change is 2 161 m³, or about 0.67%. The mean between the two give a total deposition of 319 192 m³. The corresponding trap efficiency of the reservoir is calculated as follow:

$$TrapE = \frac{V_{Deposited}}{V_{Inflow}} = \frac{320273}{609868} = 52.52\%$$

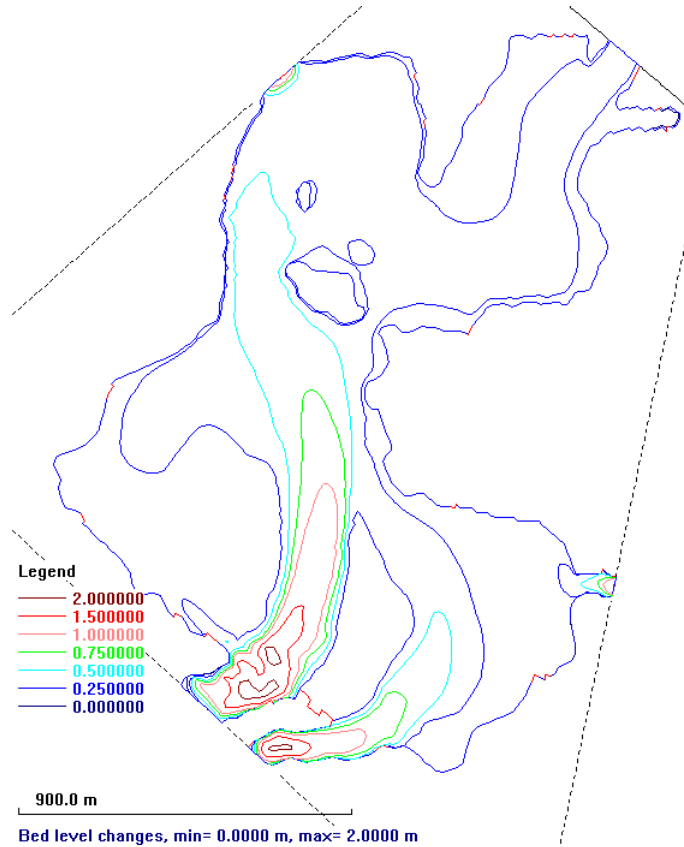


Figure 10.1: Simulated sediment deposition pattern in Angostura after 250 days of deposition.

10.1.2 Deposition Distribution

Figure 10.1 shows the simulated deposition pattern in Angostura. The largest deposition, up to 2 meters, can be seen at the inlet to the reservoir, mainly in the Rio Reventaz3n channel and the tributary river. In general the deposition is mostly concentrated in the main channel, and gradually decrease over the length of the reservoir. About 60% of the reservoir do receive a sediment deposition of 0.25 meters or more.

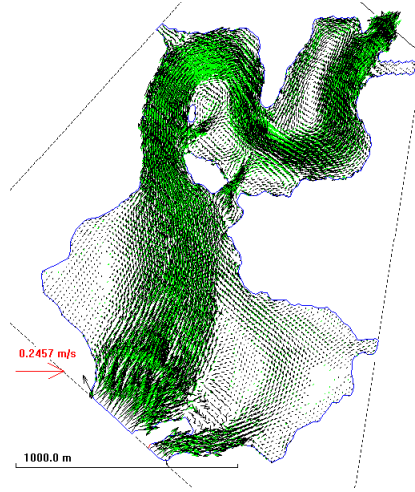


Figure 10.2: Bed and Surface velocity vectors for the water flow simulation for the steady state scenario.

10.2 Steady state concentration simulation

As elaborated in chapter 7, the steady state simulation consist of two simulations. First a water flow simulation is conducted, then a sediment simulation is preformed based on the flow field. The bed and surface velocity vectors used for the steady state sediment simulation is shown in figure 10.2. In total, 20 simulations was performed before satisfactory results was obtained.

10.2.1 Total concentration

The total concentration is the sum of the suspended concentrations from the 8 different grain sizes. Figure 10.3 show the total concentration in m^3/m^3 , plotted in ParaView, and a 2D plot of the depth averaged total concentration. The x-axis shows the number of points in the interpol file, which corresponds to the measurement numbers from the LISST. Figure 10.4 show the suspended concentration over the reservoir for D25, which is equivalent of about $8 \mu m$ for this case.

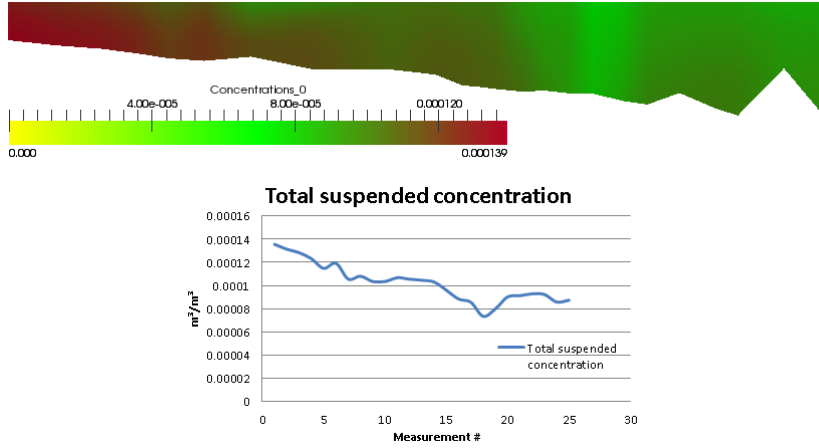


Figure 10.3: Total suspended concentration [m^3/m^3] and total depth averaged concentration.

10.2.2 Single size distribution

For the steady state simulation 8 different grain sizes is given as input. Each of these has an unique concentration distribution over the reservoir. Based on the size and fall velocity, the different grain sizes will be distributed differently over the reservoir for equal flow conditions. Figure 10.5 and 10.6 shows the simulated suspended sediment concentration for each grain size plotted in ParaView. These results make the basis for the verification and discussion chapter.

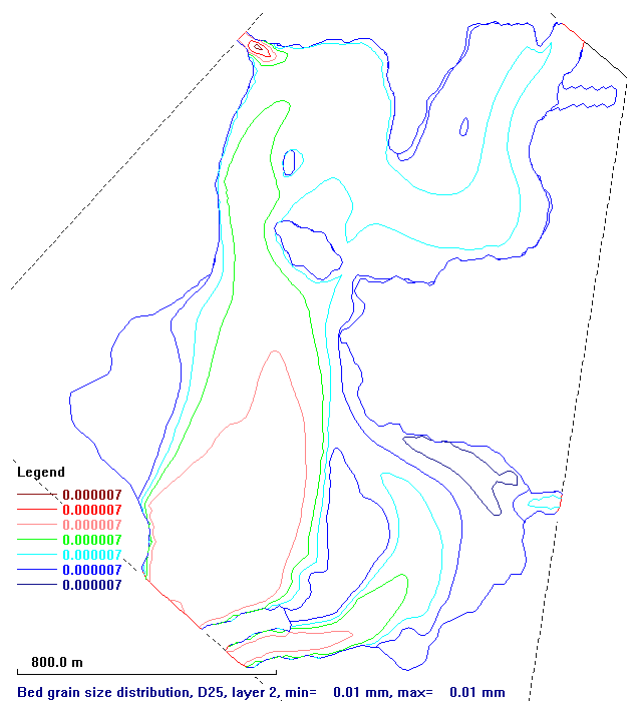


Figure 10.4: Suspended sediment concentration for the D25 grain size.

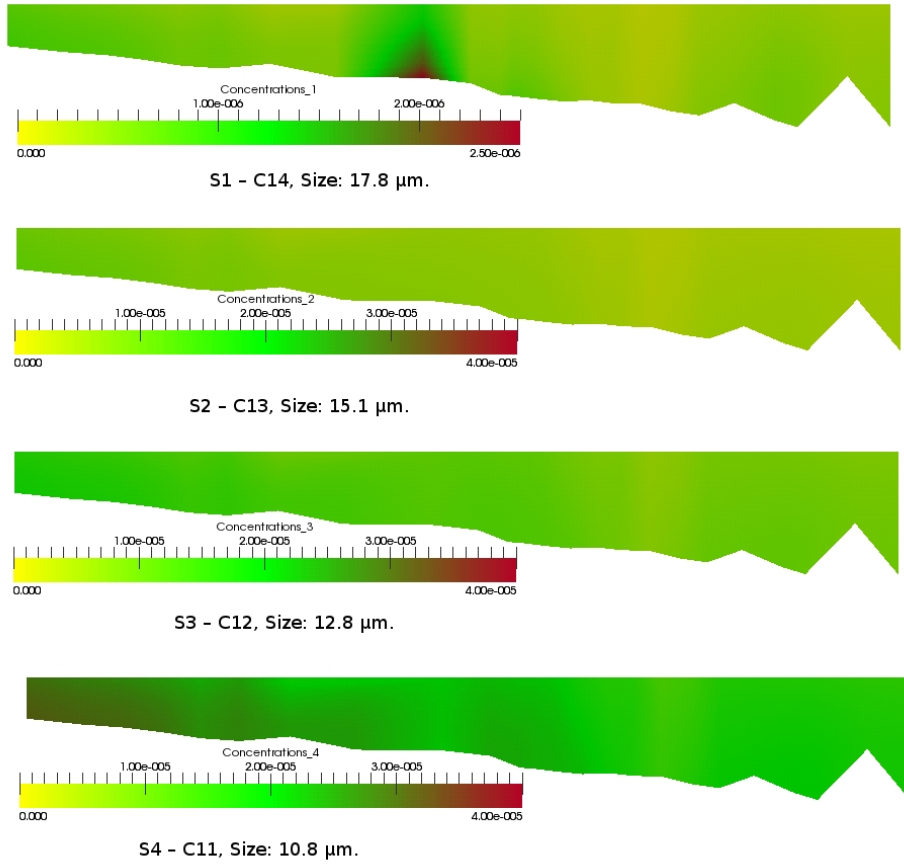


Figure 10.5: Suspended concentration distribution for size S1 to S4, $[m^3/m^3]$

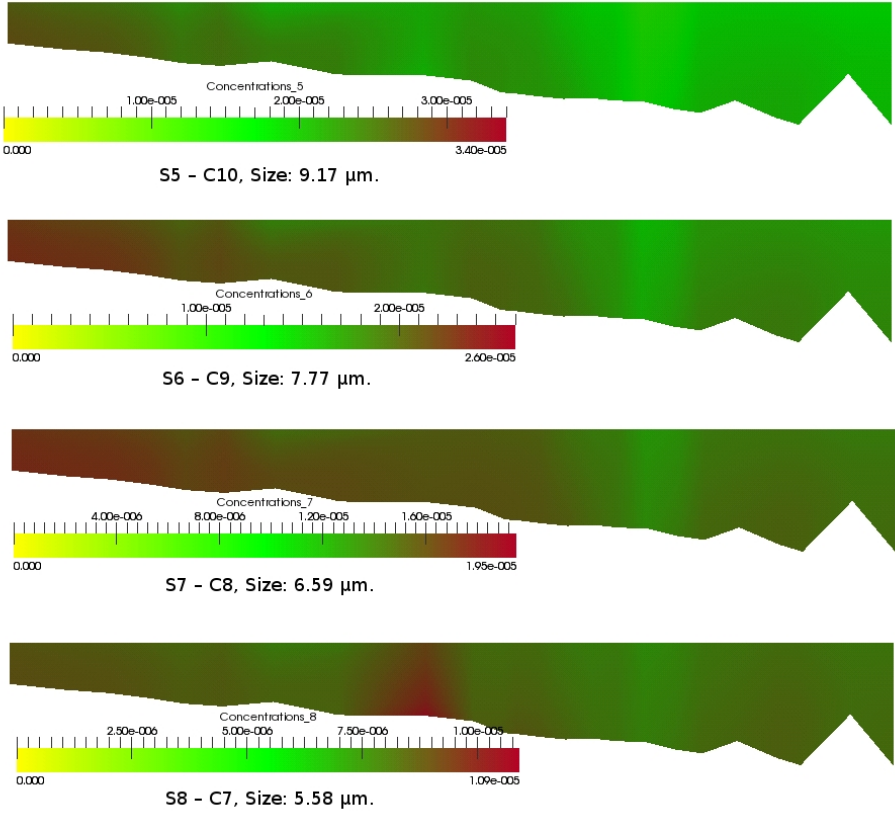


Figure 10.6: Suspended concentration distribution for size S4 to S8, [m^3/m^3]

Chapter 11

Verification & Discussion

The output from a numerical model is often represented with contour plots or colorful presentations, like the results in chapter 10. The main goal of any simulation is to describe or predict a given scenario, and it is therefore important to be able to evaluate the outcome. This chapter describes how the simulated results differ, or match the field measurements from Angostura.

11.1 Time dependent deposition simulation

The real inflow and outflow of sediments to Angostura is not known, and therefore the trap efficiency of the reservoir can not be verified by calculation. Consequently, it is of great interest to be able to accurately predict the trap efficiency. The deposited amount and deposition pattern is known from the two Bathymetry surveys conducted in November 2010, and September 2011. The deposited quantity and the deposition pattern is compared to the measured values, while the trap efficiency is compared with measured values for certain grain sizes, using the LISST data.

11.1.1 Deposited quantity

The actual deposited quantity is found using SSIIM with the grid and geodatapoints from 2010 and 2011. When a sediment simulation is conducted, SSIIM writes the volume of the geometry to the boogie file. The volume for the 2010 grid is found first, and then the grid is remade with the 2011 geodata file. A sediment simulation is initiated with the same water level. The output is now the 2011 volume. The difference will equal the reduction in storage below the given water level. For a water level at HRWL, 577 m.a.s.l, the volume deficit is 638 378 m³. SSIIM assumes a 50-50 mixture of water and sediments, meaning the dry volume of sediments which have settled in the reservoir from November 2010 to September 2011 is 319 190 m³.

Size	Volume	Volume	Trap efficiency	Weighted Trap E.
$[\mu m]$	$[\%]$	$[cum\%]$	$[\%]$	$[\%]$
5	25	25	13.68	3.42
8	30	55	29.80	8.94
16	35	90	61.85	21.65
40	8	98	90.0	7.2
130	2	100	100.0	2.0
			sum:	43.21

Table 11.1: Trap efficiency estimation for Angostura with a inflow of $120 m^3/s$.

The simulated deposition is $320\,273 m^3$, meaning the simulations show $1083 m^3$ of excess deposited material. This gives a deviation between the simulated and actual deposition of about 0.3 %.

Trap efficiency

The trap efficiency is a parameter which is quite useful when estimating the future lifetime of a reservoir. It is therefore interesting to try to validate the simulated trap efficiency of 52.52%. As the simulated deposited volume is very close to the measured deposition, it is assumed that this is correct. The LISST measurements from September 2011 can be used as a estimate for the trap efficiency for three of the sizes in the inflowing grain size distribution. The concentration is measured over the reservoir, and the difference between the in and outflow would give the trap efficiency. The red line in figure 11.1 show the measured trap efficiency for material of size 5, 8 and 16 μm . It can be assumed that material smaller than 5 microns will not settle. This is supported from figure 9.2 in chapter 9. Figure 11.1 shows the calculated trap efficiency from the LISST together with estimated values for material outside the measured range. The blue line crossing the x axis at 3 microns, assuming all material smaller than this will have a negligible trap efficiency. The LISST measurements were conducted during a water flow of about $120 m^3/s$, and the discharge will affect the trap efficiency. However, as the average inflow to Angostura is approximately $120 m^3/s$, it is reasonable to assume these values will be representative. Further it can be assumed that material of a greater size than 40 microns will be transported as bed load for normal flows. This will not be able to pass through the intake, and must therefore deposit in the reservoir.

Table 11.1 shows the grain size, the volume-percent and the measured and estimated trap efficiencies. The weighted trap efficiency for each grain size is calculated, and the total trap efficiency can be calculated as 43%. It important to know that this calculation is fairly conservative, as all floods carrying larger material will be deposited in front of the weir, if the gates are not opened. Smaller

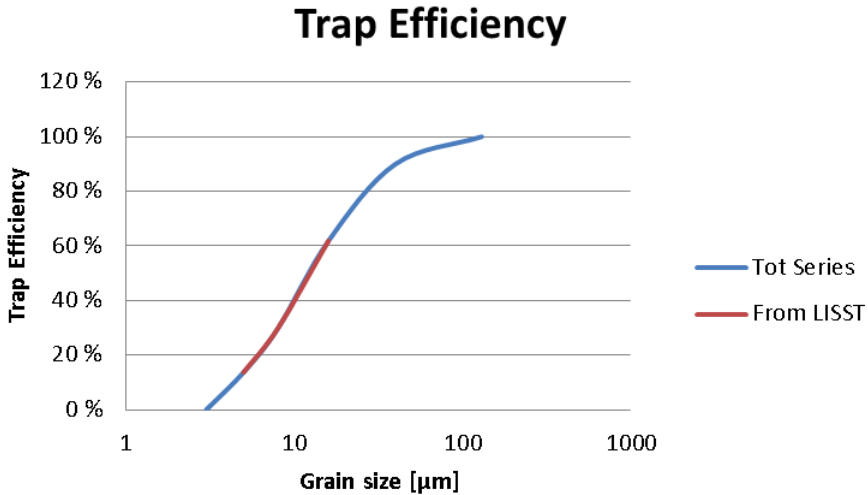


Figure 11.1: Trap efficiency from LISST measurements, and estimated values

flows will have a lower transport capacity, causing smaller material to settle. The lower inflow is most likely the reason for the nearly 10% increase in simulated trap efficiency compared to the estimated. The simulated inflow is below $120 \text{ m}^3/\text{s}$ for most of the simulation time, resulting in a lower transport capacity through the reservoir, and increased deposition of the small material.

This estimation of trap efficiency is not accurate science, and is depended on gate operation during floods, variation in inflowing water and sediments, and also how much of the wash load which leaves the reservoir through the turbines. Nevertheless, Angostura was estimated to have a trap efficiency of about 60% at the time of construction, [Jimenez et al., 2004]. As the reservoir volume decreases due to sedimentation, so does the trap efficiency. The conservative estimation based on the LISST values show 43%. The simulated value of 52.5% places itself pretty much in the middle between these two, and is therefore reasonable to assume that the actual trap efficiency of Angostura is in the vicinity of 52 % for the period November 2010 to September 2011.

11.1.2 Deposition pattern

The actual deposition pattern can be visualized in SSIIM, based on the two geodata files. The procedure is briefly mentioned here, but is more throughout described in the master thesis “Three-dimensional numerical modelling of sediments in water

reservoirs” by Lisa Hoven, from 2010. First, a grid is made containing the 2011 geodata file, and stored securely. Then the 2010 geodata file is imported, and a new grid is generated based on the new bed level. When the new unstruc file is written a file named koomin is also generated. This file contains information about the bed. If this file is renamed without extension and read together with the first unstruc file, SSIIM will read the koomin values as the original river bed, and the unstruc values as the new bed. For a deposition case the values will be positive. If “sediment thickness” is chosen from the menu in the user interface, the sediment deposition will be visualized with 7 contour lines.

Figure 11.2 shows the actual deposition distribution visualized in SSIIM, next to the simulated bed change. The raw data from the bathymetry shows, as expected, a much higher degree of variation. This is seen as scattered deposited areas all over the geometry. Along the sides of the reservoir it can also be seen scattered areas of high deposition. This is most likely due to the measurements not being performed at the same location every year. This gives a slightly different geometry from year to year. When geodata points of 590 m.a.s.l is added around the reservoir to make the grid, the bed levels at the shore is interpolated. This will cause a difference in the slope of the shore, and some areas will then get an artificial deposition or erosion. It could also be due to physical phenomenas such as landslides related to the flushing. In general the deposition pattern do fit quite well. Some points worth commenting on is marked with numbers:

1. The simulated deposition in the tributary river do not fit very well to the actual deposition. SSIIM shows a gradual reduction in the deposited material, while the actual deposition is fairly constant until the channel widens drastically, and marks a steeper end to the deposition zone. The reason for this could be that the channel width has been reduced at some point between the two measurements. The wide channel used in the simulation would thereby have a greater cross sectional area and lower velocity, leading to a different deposition scenario.
2. The bathymetry data shows a marked deposition zone just to the left of where the rio Reventazón enters the reservoir. The same tendency can be seen in the simulation, however only for the 0.25 contour line. Further to the left a marked scattered deposition can be seen for the bathymetry data. This tendency is not replicated in the simulated deposition. When analyzing the simulated bed development over time, it can be seen that the left tending deposition occurs at approximately day 180. This corresponds to the time where the water inflow exceeds $100 \text{ m}^3/\text{s}$. The deposited zone keeps building until the simulation ends at day 250. Is it therefore reasonable to assume that the deposition in this area of the reservoir occurs during high inflow. This corresponds with theory, which say that deposition on the floodplains

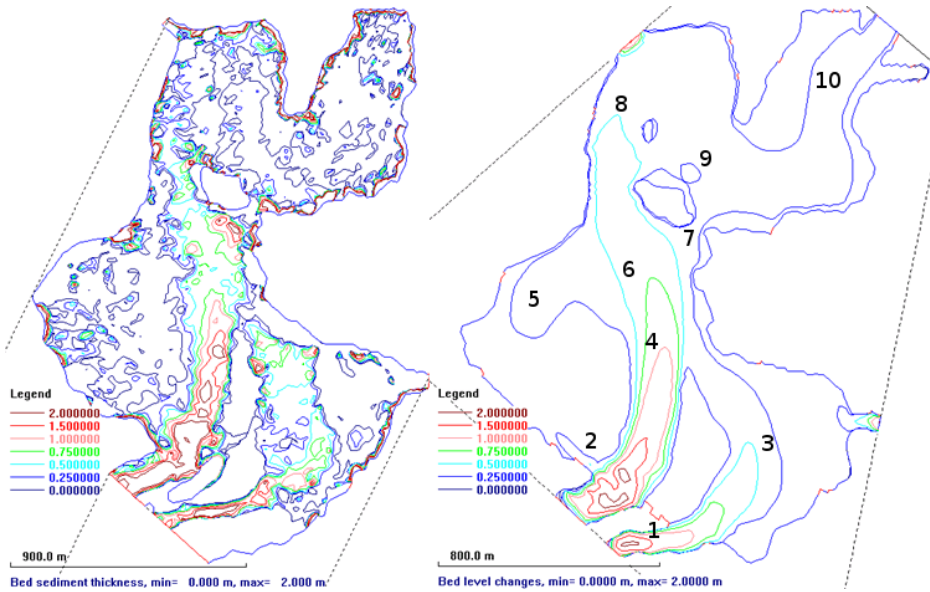


Figure 11.2: a) Actual and b) simulated sediment deposition pattern

mainly occur during high floods.

3. The actual deposition at the end of the tributary river shows that the 0.5m deposition contour line goes about 100 meters further than the simulated. This indicates that even though the deposition pattern do not fit in the tributary river itself, it is fairly accurate in the area which has not experienced a change in geometry.
4. The simulated 0.25 contour line follows the 0.25 deposition line quite accurate between no 2 and 4. This could be because most of the deposition will occur in the channel, which follows approximately this line. From no 4 however, the simulated line differs drastically.
5. The simulated deposition in area no 5 is due to a recirculation zone in the numerical model. The velocity vectors from the steady state simulation shown i figure 10.2 shows the same recirculation. There is no sign of this deposition pattern in the bathymetry data.
6. The simulated 0.75 contour line extends to nearly the exact same point as the bathymetry data. However, the bathymetry data shows a much steeper drop than the simulated.

7. The area between the peninsula and the first island shows deposition just upstream of the contracted cross section. This is not replicated in the simulation. This area was investigated during the field trip, and consists of a variety of sandbanks and vegetation. Peggy Zinke showed in her PhD thesis [Zinke, 2011], that sediment deposition will increase in areas with high vegetation. This is not incorporated in the simulation and could be the cause of the deposition deficit. In the area between the two islands scattered deposition occurs. This is artificial deposition due added geodata points for the 2010 bed levels.
8. If the rapid variations in the field data is neglected, the extent of the 0.5 contour line is fairly consistent with the final 0.5m bathymetry contour line. After point 8, only very small and scattered areas do contain deposition of more than 0.25 meters.
9. Both the simulation and the bathymetry data show that the area just downstream of the largest island has not received much deposition.
10. From the bathymetry data, the area in front of the weir show scattered deposition, while the simulation shows a more consistent deposition in the main channel. This could be due to a underestimation of the roughness in the simulation, which in turn could lead to reduced shear stress and thereby increased sedimentation. Another reason could be false diffusion. This is further discussed in chapter 12.

In general the simulated deposition do show the same tendency as the bathymetry data, and the areas of high deposition is mostly correct. However, some areas shows additional or lack of deposition, mainly around 1, 2 and 5.

11.1.3 Problems and uncertainty

When the 2010 bed levels were compared to the 2011 data, it became apparent that the 2010 data was a bit inconsistent. Near the inlet of the most upstream diversion channel, close to no 3 in figure 11.2, quite allot of data was missing. Figure 6.1 shows the 2010 geodata, and the area with missing data. This meant that the interpolation algorithms had made the bed level for 2010 based on the data which existed, and interpolated the bed level for the area which lacked data. This gave a flat area with a bed level at about 573 m.a.s.l. For the 2011 data, this area had a very shallow water depth, and a bed level of approximately 575 m.a.s.l. When comparing the two bed levels it then appeared as if a massive deposition had occurred over the year. The most likely reason for the lack of data is that the boat was unable to measure due to a shallow water depth. Values from a bathymetry data is obtained by boat. This means that if the water depth is below about 0.5 -1.0 meter, it could be impossible to acquire data. The geodata was collected on the

17th of November 2010, and at that day the water level was down to 575.8 m.s.s.l. This indicates that the reason for the missing data could be that the bed levels in this area was 574.8 or more. For the verification of the deposition simulation it is therefore assumed that the bed level in this area was 575 m.a.s.l in 2010. This gives negligible deposition in this area.

11.2 Steady state concentration simulation

11.2.1 Suspended concentration

The simulated suspended concentration is shown for all the 8 grain sizes in chapter 10, and a two dimensional plot of the suspended concentrations from the LISST measurements is shown in appendix E. In this chapter, four of the 8 simulated concentration profiles is compared to the measured data. This is due to space limitations, and because the difference between each size is relatively small. The distribution for size 15.1, 10.8, 7.77 and 5.58 μm is presented here. The LISST data is raw, unprocessed data and does thereby show occasional rapid and high variation.

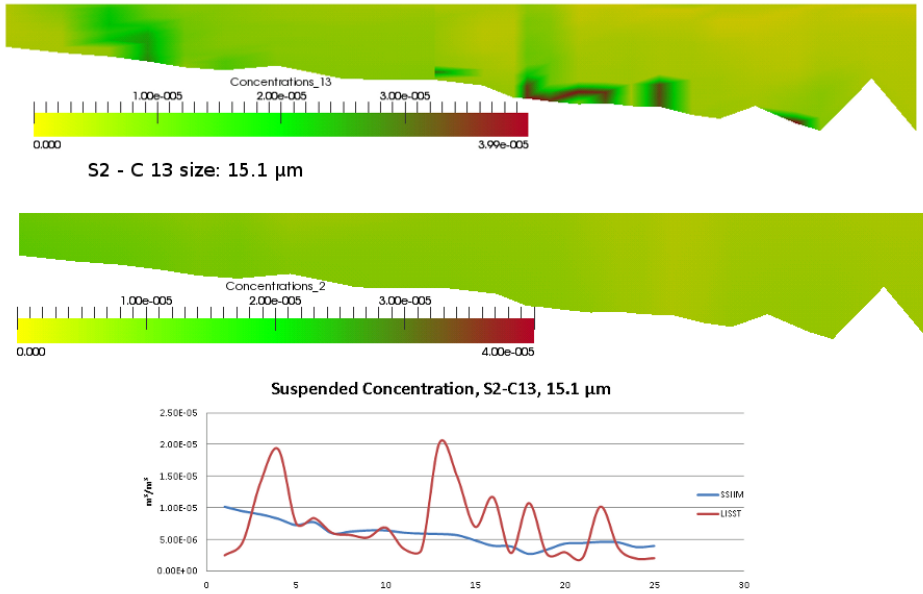
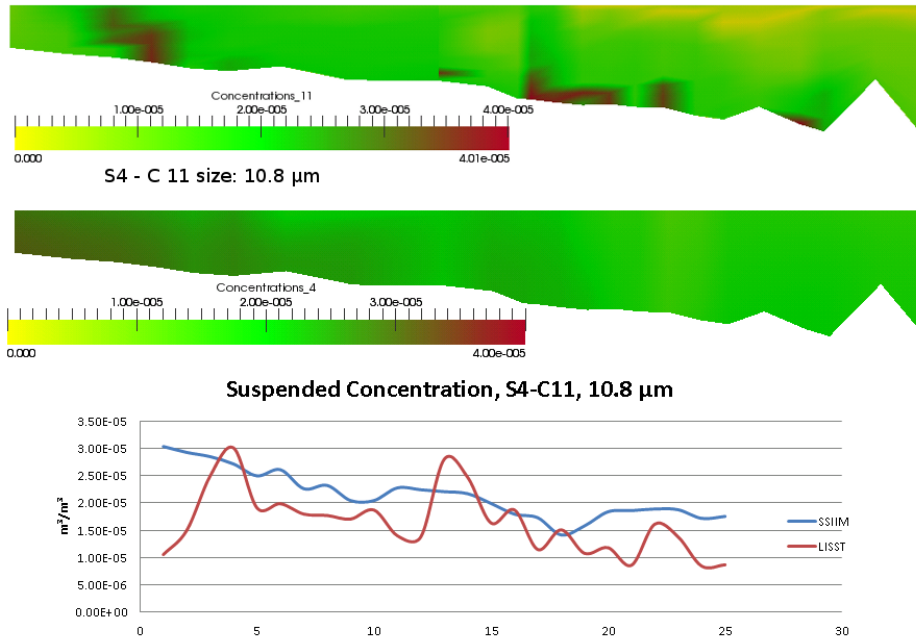
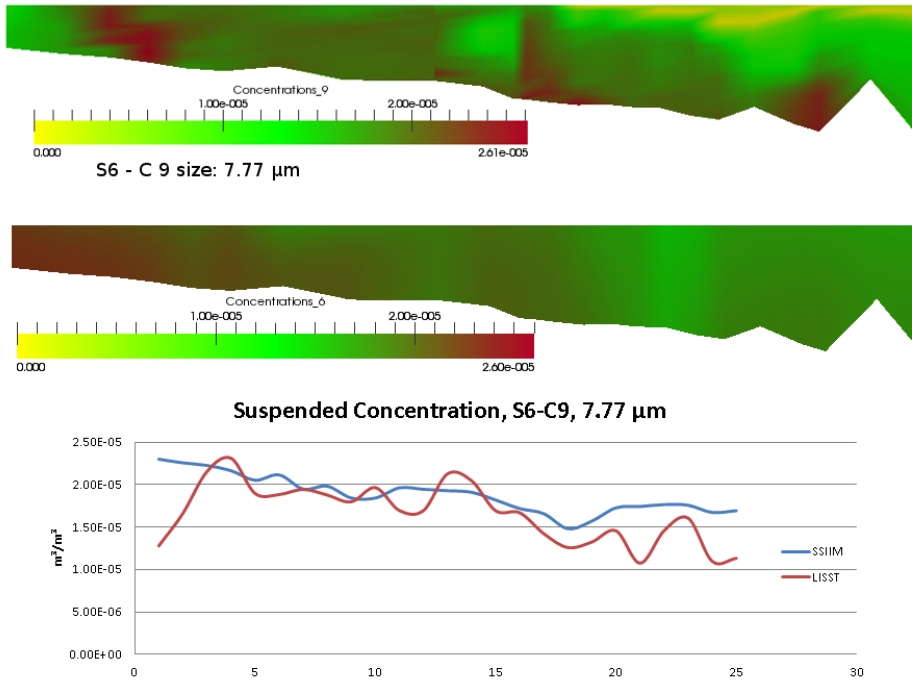
Figure 11.3: Suspend sediment concentration S2-C13, 15.1 μm **S2 - 15.1 μm**

Figure 11.3 shows that the main difference between the simulated and the measured suspended concentration, is the occasional high concentrations measured with the LISST. Especially measurement number three and twelve show high values of up to $4.0e-05 \text{ m}^3/\text{m}^3$. This is not surprising, as raw data usually shows a higher variability than simulated results. The average concentration, on the other hand, looks quite good, and a decrease in the concentration from left to right can be seen for both cases. When analyzing the depth averaged concentration shown in the 2D plot, it is clearly seen that the simulations show a more stable reduction in concentration. The area around measurement 7 shows a interesting correspondence between the simulated and measured data. The small increase is most likely due to a contraction of the cross section area. If a trend line is added to the depth averaged LISST data, a linear curve with a R^2 value of 0.14 can be used to estimate the deposition. The difference between the inflow and outflow give a trap efficiency of 61.85%. For the simulated concentration the trap efficiency is about 60.97%. This is considered fairly accurate. However, the low R^2 value for the trend line induces a high uncertainty.

Figure 11.4: Suspend sediment concentration S4-C11, $10.8 \mu m$

S4 - $10.8 \mu m$

Figure 11.4 shows the same tendency as figure 11.3, with high concentrations for measurement no 3 and 12, but shows a good correspondence between the simulated and measured data for the other measurements. The average concentration for figure 11.4 is higher than for figure 11.3, and the same tendency with a gradually reduced concentration over the length of the reservoir is seen. The depth averaged simulated values show an increase in the concentration for measurements 18 to 25. This is discussed in the next section, S6. If a linear trend line is added to LISST values, a R^2 value of 0.276 is obtained. This gives a trap efficiency of 45.5% when the difference between measurement 1 and 25 is calculated. From SSIIM the trap efficiency is 42.2%. This is considered fairly accurate.

Figure 11.5: Suspend sediment concentration S6-C9, 7.77 μm **S6 - 7.77 μm**

The difference between the simulated and actual inflowing suspended concentration in figure 11.5 is smaller than for the two previous figures. The variation in the measured concentrations is not as large, nor as rapid as for the larger sediments. This results in a better correlation between the concentration distributions, and in general the concentration profiles match very well. The very low values (zero) close to the surface for measurement 17 and up is not represented in the simulated distribution. On the contrary, the simulated concentration seems to increase from about point 17. This corresponds to some extent with the increased bottom concentration from the LISST. The 2D depth-averaged plot shows that in general the simulated concentration is a bit too high for the downstream part. The same tendency is observed for S4. If the roughness is underestimated in SSIIM, the shear stress will be lower, and the sediment concentration will be higher. This could be the reason for the increased concentration and is further investigated with a parameter sensitivity analysis in chapter 12

The trap efficiency from the simulated values is calculated to be 26.4%. The linear trend line added to the LISST measurements, shows a relatively high R^2 value of 0.34 due to the low variation in the data. The calculated trap efficiency for the LISST data is 29.8%. The difference in the trap efficiency is most likely due to the slight increase in the simulated depth averaged concentration close to the weir.

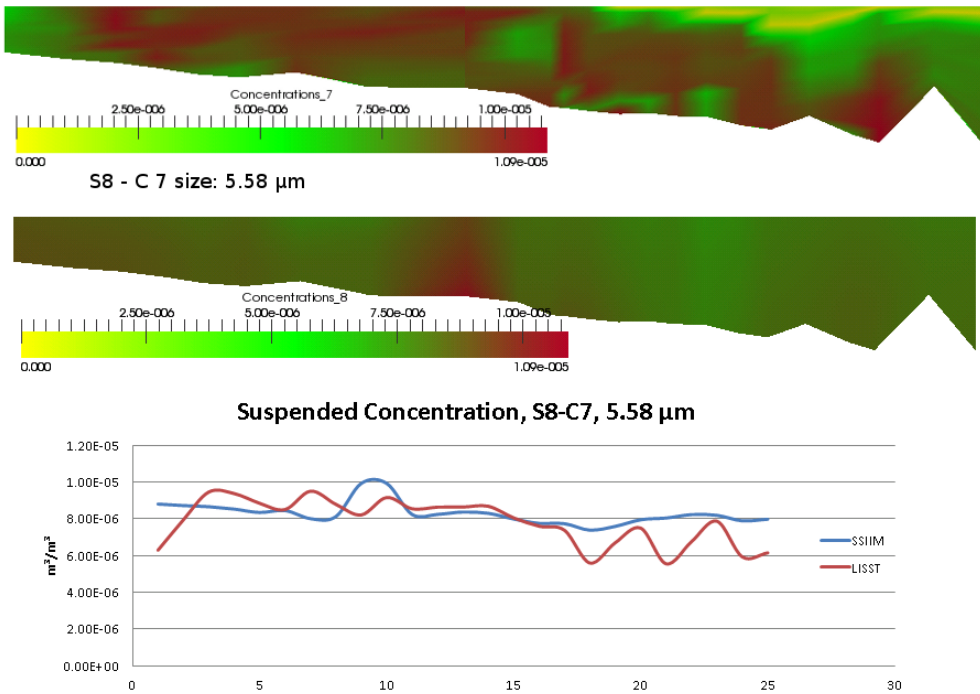
Figure 11.6: Suspend sediment concentration S8-C7, 5.58 μm **S8 - 5.58 μm**

Figure 11.6 shows the suspended sediment concentration for the finest particles. It can be seen that the variation in the LISST concentration is smaller than for the larger grain sizes. The simulated average concentration is about $8.0e-06$, which is quite close to the average measured concentration of between $6.0e-06$ to $1.0e-05$ m^3/m^3 . A increase in the simulated concentration is seen around measurement 10, at the same time as the measured concentration drops. The reason for this negative correlation is not known.

The simulated trap efficiency for this particle size is fairly low. Only 9.35% of the inflowing sediments settle in the reservoir. The LISST data shows that about the double amount will settle, with a calculated trap efficiency of 18.8%, using a linear trend line with a R^2 value of 0.26. The reason for this large difference is probably mostly due to the increased concentration from SSIIM close to the weir.

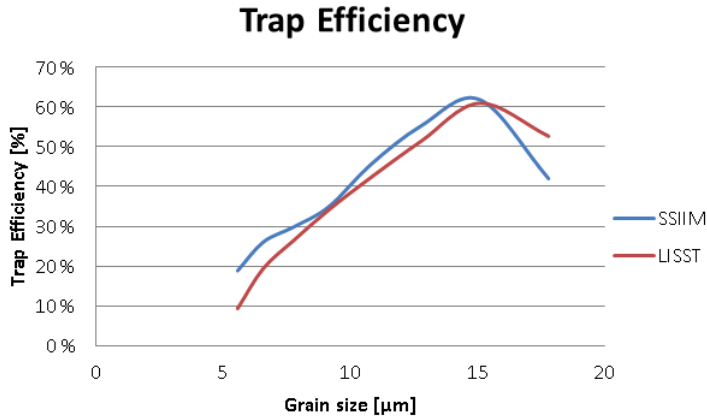


Figure 11.7: Grain size specific trap efficiency, from SSIIM and LISST measurements.

General trend

A interesting phenomena can be seen from the raw LISST data around measurement 21-24. The concentration at the surface is zero (yellow color), while the concentration at the bottom is very high. This is quite clear for S6 and S8 but is also seen for S4 and S2. This could be due to increased velocity at the bottom and reduced or even negative velocity at the surface. Unfortunately the ADCP measurements conducted at the same time as the LISST measurements is untrustworthy due to problems with the ADCP, so the velocity distribution is not known.

11.2.2 Trap Efficiency

Figure 11.7 shows the trap efficiency for the 8 different sediment sizes from the measurements, compared to the estimated trap efficiency from the LISST. It can be seen that the simulated values do not differ much from the measured values. For the largest size, S1 - 17.8 μm the trap efficiency is reduced. This is most likely due to the rapid, and quite high variations which govern the distribution for S1. Figure 11.8 shows the depth averaged concentration for this grain size, and the high variability is clearly seen. This gives a very low R^2 value, only 0.016, for the trend line which is used as basis for the trap efficiency calculation. It can be seen that SSIIM also gives a reduced trap efficiency for the largest grain size, only 52%. This could be due to the fact that the inflow concentration is quite small, only $8.0e-06 m^3/m^3$, which makes the calculation vulnerable to variations. With the exception of the trap efficiency for S1, the trap efficiency curve seems realistic.

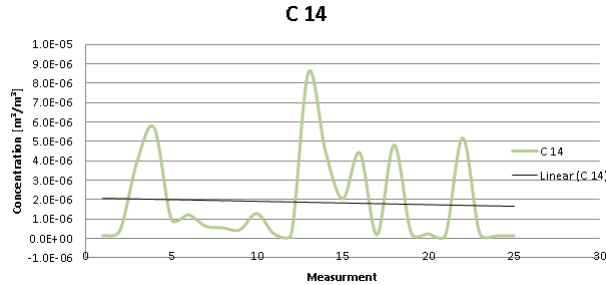


Figure 11.8: Depth averaged concentration for sediment size S1- $17.8\mu m$

11.2.3 Problems and uncertainty

The measurements used as basis both for the inflow and for the verification is conducted using the LISST-SL. As stated in chapter 4, the LISST is made for use in rivers. This means that it has been adapted to a river environment, and not particularly for use in reservoirs. As discussed in section 4.3.2, the iso-kinetic pump causes problems for low velocities. During the field measurements this was solved by hoisting the LISST rapidly from deep to shallow water, to prevent the pump from stopping. This could have affected the accuracy of the measurements. Another, and more serious matter is that material transported by a river is often larger in size than the suspended material in a reservoir. For some LISST measurements from Angostura, more than 50% of the material is smaller than the minimum LISST particle size, $2\mu m$. As discussed in section 4.3.3, particles registered outside the particle range will not be measured accurately. This is mitigated by only simulating particles larger than 5 microns, so the verification of the simulation results should not be affected by this.

Chapter 12

Parameter sensitivity test

In order to evaluate the outcome of a numerical simulation, a parameter sensitivity test is often performed. This is done by systematically changing certain variables and evaluating the outcome. In any numerical simulation some variables will be easier to determine than others. It is therefore important to get an estimate of how much a given change in any inaccurate variables will affect the output from the model. Due to limited time, only a few variables have been evaluated in this chapter, and only one variable is changed at the time. The outcome is compared to results from the simulations presented in chapter 10. In general this chapter tries to provide a verification of some of the numerical choices and assumptions being made in order to achieve the output similarity described in chapter 11.

12.1 Deposition case

For the deposition simulation the interesting output from a variable variation will be the change in total deposition volume and deposition pattern. However, as small changes in the deposition pattern could be hard to detect, a 2D depth average concentration plot over the length of the cross section is used for comparison. The values are taken from the last time step in the simulation, equivalent of day 250. The Total deposition is shown in table 12.1.

12.1.1 Roughness

The bed roughness of the reservoir is fairly hard to accurately predict. The total roughness will be a combination of the skin friction and bed forms. The shape and size of bedforms will vary over the reservoir, and change with time. The skin friction will also vary according to the size and shape of the deposited material. A large number of formulas to predict both the skin friction and the bedform

Number	Parameter	Inflow	Outflow	Deposition	Difference
		[m ³]	[m ³]	[m ³]	[%]
#14	Final simulation	609 868	289 595	320 273	0
#15	Double iterations	609 868	289 894	319 974	0.09%
#16	Roughness 0.001	609 868	286 551	323 317	0.96%
#17	Roughness 0.01	609 868	287 392	322 476	0.69%

Table 12.1: Deposition volume from parameter sensitivity analysis.

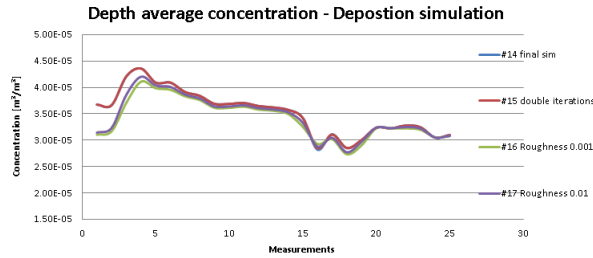


Figure 12.1: Depth averaged concentration for deposition simulation

friction exist. For the Angostura case however, it is reasonable to assume that the roughness contribution from bedforms is fairly small. No indication of any large bedforms was found during the field measurements. If only skin friction is assumed, the roughness can be calculated using a simple formula [Olsen, 2007]: $k_s = 3D_{90}$. For Angostura, D_{90} is fairly small, and the corresponding theoretical roughness is only 6.0e-5m. This is unrealistically small, and for the final simulation a roughness of 0.1 meter is used. This is compared to simulations using a roughness of 0.01m and 0.001m. The results can be seen in Table 12.1.

Deposited volume

Table 12.1 show that as the roughness is reduced, the deposition increase. However, with a reduction in the roughness with a factor of 100, the change in total deposited volume is only about 1%. The deposition amount is therefore not very dependent on the roughness.

Concentration distribution

The depth averaged concentration distribution over the reservoir, figure 12.3, show that the decrease in roughness do affect the concentration to some extent. However, a interesting tendency is that the change in concentration is largest at the inflow area, and then gradually reduced over the length of the reservoir. At the

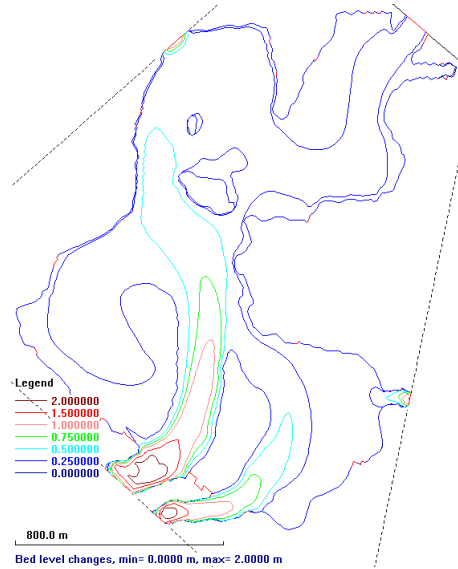


Figure 12.2: Deposition pattern for time depended simulation using a roughness of 0.001meter.

outflow the concentration is about exactly the same regardless of the roughness. A reason for this could be that the particles with a larger grain size is more sensitive to changes in the shear stress. After a while these particles will have settled, nearly regardless of the roughness. The downstream concentration will be fairly constant as the particles which are left, is well within the threshold for transport capacity for the given inflow.

Table 12.1 shows that for reduced roughness, the deposited amount increases. It is therefore interesting to see where this excess amount deposits. Figure 12.2 shows the deposition pattern using a roughness of 0.001 m. It can be seen that the deposition pattern is generally very similar to the results in chapter 10, with one exception. The area on left floodplain shows increased deposition in the simulated recirculation zone. This indicates that deposition in this area is more dependent on the roughness than the rest of the reservoir. This could be a indication that the actual roughness in this area might be higher than what is modeled.

12.1.2 Number of iterations

Figure 12.1 and table 12.1 show that neither the total deposition or concentration distribution do change to any significant degree when the number of iterations

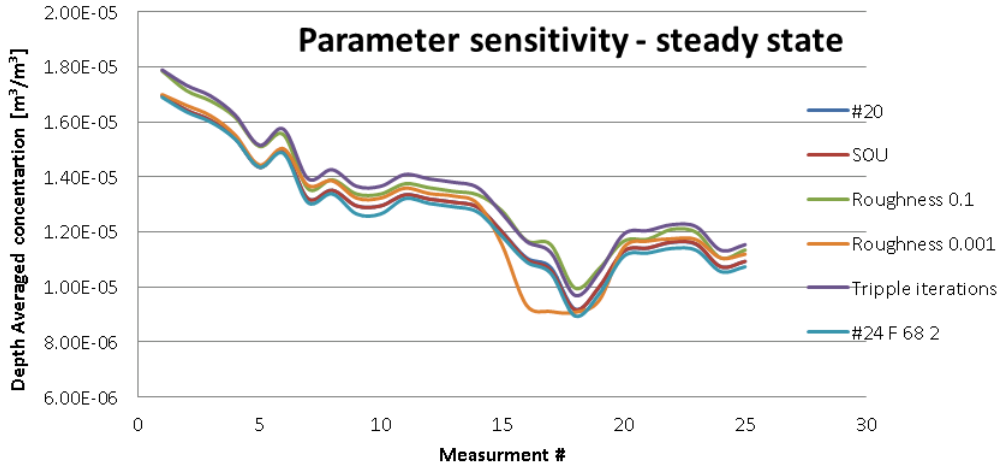


Figure 12.3: Depth averaged concentration from steady state simulation

is doubled. It is therefore reasonable to assume that any additional increase in number of iterations will not give a different result.

12.1.3 Additional parameters

Test simulations using the second order upwind scheme was tried for the deposition case. Unfortunately the simulations diverged quite fast, and due to limited time, this was not investigated further. Also, a couple of test simulations was conducted using the F 82 2 data set, which includes the Van Rijn bed load formula. Unfortunately this was neither successful, and the simulation diverged quite fast.

12.2 Steady state

As for the deposition simulation, the basis for comparison is a 2D depth average concentration plot over the length profile of Angostura. The influence of higher order upwind scheme, roughness, increased number of iterations and the influence of a quasi-steady simulation is investigated.

12.2.1 Higher order Upwind scheme.

As mentioned in section 5.5, SSIIM computes the suspended sediment concentration using either the first or second order upwind scheme. The first order Upwind scheme can experience problems related to false diffusion. One simulation using the second order upwind scheme was performed. The result does not differ to any

degree from the final simulation. The Depth averaged total concentration is plotted in figure 12.3, marked “SOU”. This indicates that the increased downstream concentration shown in, figure 11.5, is not a result of false diffusion.

12.2.2 Roughness

As for the deposition simulation, the roughness was changed for the steady state simulations. In the final simulation, a roughness of 0.01 meters is used. Both 0.1 and 0.001 is tested. As mentioned in chapter 11, the high concentrations at the downstream part could be a result of an inaccurate roughness estimation. However, the result from the two test simulations show the same tendency. The reason for the high concentration from 17 to 25 is therefore probably not a result of a inaccurate roughness estimation.

Roughness 0.1

The depth averaged total concentration in figure 12.3 shows that when the roughness increase, the total concentration increases slightly. This corresponds with the theory presented in chapter 3, which states that the shear stress increases with increased roughness and it then follows that the transport capacity will increase, carrying larger and more material.

Roughness 0.001

The same figure shows that when the roughness is decreased the concentration is reduced slightly. Around measurement 15 however, the concentration drops prematurely compared to the other simulations. The reason for this is not known.

12.2.3 Increased number of iterations

For the final steady state simulation, 10 iterations per time step is used. The sensitivity of this parameter is checked by increasing the number of iterations per time step to 30. Figure 12.3 shows that the influence of number of iterations is fairly small, but do present a variation in the concentration. The depth averaged concentration increase to about the same level as for the increased roughness, but shows the exact same variation over the length of the reservoir. Based on this it can be assumed that the accuracy of the simulation would not increase much with increased number of iterations per time step.

12.2.4 Quasi steady situation

When the F 68 2 data set is included in the control file, the transient sediment computation will not re-compute the water flow field after an update of the bed.

This means a quasi-steady situation is modeled [Olsen, 2010]. Figure 12.3 shows that this does not give any noticeable change compared to the final simulation.

12.3 Residuals

Initially the simulations faced problem of high residuals. For a time dependent simulation it is quite interesting to see the variation in residuals over time. To mitigate this prof. Olsen Incorporated the F 293 1 data set in SSIIM, which writes the six residuals for each iteration to a file. This proved very useful, especially when used to evaluate the influence of the F 292 data set. The F 292 1 data set reads a float which gives a time step for the internal solution of the Navier Stokes equation. This proved very stabilizing for high epsilon residuals, especially when combined with the F 200 data set. This data set reads two floats, the initial residual values for k and epsilon. Using this data set a simulation can be initiated with low residual values. However, moderate values are needed to ensure a combination of low residuals and natural velocity vectors. For very low values in F 200 and high values for the F 292, divergent velocity vectors were seen. For both the steady state simulation and the deposition case F 200 1 0.1 0.01 and F 292 1 2.0 have been used.

12.4 General trends

As stated previously in this chapter, only a very simple parameter sensitivity test has been performed. The parameter most thoroughly tested in this parameter sensitivity test is the roughness, and the simulated output has shown surprisingly low sensitivity to this parameter. The reason for the low sensitivity in this model is not known, but it could be a result of the simulation scenario. The simulation is based on a 250 day simulation with a relatively low and stable inflow of both water and sediments. The relatively fine inflow material might also give the model a higher resistance to variations in the roughness parameter.

Chapter 13

Conclusion

The main goal of this master thesis is to analyze how well a numerical simulation can estimate the deposition and transport of sediments in a hydropower reservoir. This involves learning to operate numerical software, estimating inflow, calibrating boundary and numerical parameters and setting up and running time dependent sediment simulations. In order to verify the results, and to ensure reliable input to the model, field data has to be collected, analyzed and systematized. Finally an equal platform for comparison needs to be established.

For ICE, or any other hydro powerplant owner, the problems related to sediment transport and deposition are often complex, difficult to predict and involves high economic consequences. If a potential future scenario could be modeled using CFD, a optimized solution to a given sediment related problem could be achieved without a economic and environmental costly trail and error process. However, CFD is still in its mere childhood, and substantial research are required before future scenarios can be predicted with satisfactory probability.

The simulated deposited amount shows a good correspondence with the measured deposition. A total of $320\,273\text{ m}^3$ was simulated, compared to the $319\,190\text{ m}^3$ from the field measurement. A deviation of only 0.3% is considered very accurate. However, the uncertainty related to input data and numerical simplifications could be large. The field measurements will also include a uncertainty, so the actual deposition could differ substantially from the simulated results. The accuracy of the simulated deposition pattern is hard to describe quantitatively, but in general the simulations replicated the measured deposition pattern quite well. The floodplain near the rio Reventazón inflow area showed a clear lack of deposition, and the area just downstream showed a excess deposition, compared to the measurements.

The suspended concentration simulation was not able to recreate the rapid vari-

ations shown in the measurements from the 13th of September. The simulations also showed a slightly higher concentration at the downstream end of the reservoir, compared to the measured concentration. However, the simulation was able to recreate the average concentration and showed a satisfactory accordance with respect to particle trap efficiency for the given input data and the field data from the 13th of September. Combined with the accuracy of the deposited amount, it is reasonable to believe that the trap efficiency in Angostura in the period between November 2010 and September 2011 is in the vicinity of 52.5%.

The parameter sensitivity test showed that the model in general is little sensitive with respect to roughness and increased number of iterations. However, one of the main problems with the simulated deposition pattern could in fact relate to improper roughness estimation on the floodplains. In general several more parameters should be tested to in order to increase the credibility of the model. It is believed that better results could have been achieved if a more accurate scenario was simulated for the deposition simulation. By including daily variance in inflow and water level, the simulation would mirror the actual scenario. However, problems related to accurate sediment input and a longer computational time could present a challenge.

The simulations presented here was relative successful in replicating the two given scenarios. Little numerical calibration was required, and from a practical point of view, the deviations are within a reasonable margin, when the sum of uncertainty is considered. However, it is crucial to point out that the model was only able to replicate the given scenario, and does not give any indication of the accuracy to predict any other situation.

Chapter 14

Further works

As the main goal of any model study, physical or numerical, is to describe real physical phenomenas using simplifications, there is always a potential for improvement. The results presented in chapter 10 show potential for improvement, and this chapter briefly describes some of the issues which could be further investigated.

14.1 Deposition

An increased accuracy in the deposition pattern, could probably be achieved by increasing the accuracy of the input data. The weekly averaged water inflow omits the big floods which carries much of the sediments. ICE logs the daily average water inflow and water level, so no new measurements need to be conducted for this. However, including the daily variation will most likely result in a less stable model, and will require a smaller time step. This will result in longer computational time. It will also present a challenge to estimate the sediment size distribution and concentration inflow during the large floods.

The roughness is a parameter which affects the sediment deposition. In general the model used in this case was only affected to a small extent by changes in the roughness. However, one area received a high excess deposition. The same area showed a increased deposition correlated to a reduction in the roughness. This area should be investigated further with respect to roughness estimation. A method which estimates the roughness based on the bed levels could for instance be used for the Angostura case. The roughness in each cell can be estimated using the standard deviation between the point measurements. With more a accurate roughness estimation, a more accurate deposition pattern could be obtained, and hopefully the correct deposition in the upstream floodplain could be simulated.

14.2 Steady state

The greatest problem related to the suspended sediment concentration simulation is the scattered values from the LISST. This is because only one complete measurement series was conducted for the longitudinal suspended concentration. It is advised that several measurement series should be conducted for the same water level and inflow. This will clarify if the scattered high concentrations is only a occasional phenomena or a stable situation. Additionally increased data logging of the inflowing sediment size and concentration at the most upstream part of the reservoir would be interesting.

If a new field trip to Angostura is conducted, the area close to the weir should be investigated further with a ADCP with respect to the velocity distribution mentioned in 11.2.1. If it is apparent that the velocity distribution do not conform to the normal logarithmic distribution, it could be quite interesting to try to model this phenomena. All the ADCP measurements conducted in September 2011 is at this time still considered untrustworthy until more is known about the reason for the ADCP problems. If the problem is fixed, and the data is trustworthy, the analysis can be done without a new field trip.

During the field trip to Angostura in September 2011, a huge amount of suspended sediment data was collected using the LISST. Only a fraction of this is used in this thesis. Several different scenarios could be modeled and compared to the measured data. For instance could much of the data be used to give a more accurate estimation of the inflowing sediment grain size and concentration. The inflowing grain size distribution is assumed to have a great influence on the deposition pattern and amount, but due to time limitations is was not possible to analyze the effect varying the inflowing size distribution. For future simualtions, is advised that this be investigated as part of the parameter sensitivity test.

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Ronny Bonilla Zúñiga. Personal communication with ronny zúñiga, head of the angostura hydropower plant.

Appendix A

Assignment

Sedimentdeponering i Angostura vannkraftreservoir

Bakgrunn

Sedimenter som fyller opp vannreservoarer er et stort problem på verdensbasis. Det fører til at tilgjengelig reguleringsvolum for et vannkraftverk vil minske over tid, med tilhørende økonomiske konsekvenser. Viktige spørsmål er da hvor fort prosessen skjer, og hvor mye av sedimentene som deponerer i reservoiret i forhold til de som transporteres til overløp/turbiner. Deponeringsmønsteret for sedimentene i reservoiret er også interessant å kunne beregne. Et spørsmål er om en tredimensjonal numerisk modell som kan regne ut sedimentkonsentrasjonene i et reservoir.

For å undersøke dette nærmere har det vært foretatt en innsamling av feltdata for Angostrakraftverket i Costa Rica. Disse dataene kan brukes til å teste hvor godt den numeriske modellen kan beregne sedimenttransport under deponering. Feltmålingene er gjort i samarbeide med det lokale kraftselskapet ICE (Instituto Costarricense de Electricidad) og med støtte fra et prosjekt finansiert fra Norges Forskningsråd.

En av problemstillingene i prosjektet er hvor godt den numeriske modellen kan beregne sedimentkonsentrasjonene i reservoiret. Dette kan sammenlignes med målingene tatt med et LISST instrument. Det er også ønskelig å se hvordan det beregnede sedimentdeponeringsmønsteret passer med de målte verdiene

Viktigste spørsmål i oppgaven

Opgaven skal besvare følgende spørsmål:

- Hvordan ser sedimentkonsentrasjonsprofilene ut i Angostura reservoiret for forskjellige sedimentstørrelser?
- Hva er oppfagningsevnen (trap efficiency) for reservoiret for forskjellige komfraksjoner?
- Hvordan repliserer den numeriske modellen konsentrasjonsfordelingen i reservoiret?
- Hvordan ser det målte sedimentdeponeringsmønsteret i reservoiret ut?
- Hvor godt kan den numeriske modellen beregne deponeringsmønsteret?
- Hvilke algoritmer og input-parametre for den numeriske modellen er viktige for kvaliteten av resultatet?

Veiledning og rapportering

Prof. Nils Reidar Olsen vil være hovedveileder for oppgaven. I tillegg kan kandidaten få støtte av PhD student Stefan Haun, som arbeider med samme problemstilling. Kandidaten kan også søke hjelp hos Dr. Nils Rütther som også arbeider med numerisk modellering ved vårt institutt. I Costa Rica kan kandidaten få støtte og veiledning fra Carlos Rodriguez ved ICE.

En profesjonell strukturering av oppgaven er viktig. Oppgaven skal bl. a. inneholde innholdsliste, figurliste og referanseliste. Det er ønskelig at oppgaven inneholder sort/hvitt strekfigurer av bl. a. grid, hastighetsvektorer og sammenligninger mellom målinger og beregninger, i tillegg til fargefigurer av vesentlige parametre.

I tillegg til papirkopier av oppgaven, skal det leveres en CD med en PDF fil og en Word/Framemaker/Tekstbehandlingsfil av oppgaven, samt separate filer av oppgavens figurer og de viktigste input-filene for de numeriske beregningene. Anta at målgruppen for oppgaven er vassdragsingeniører med noe kjennskap til numerisk modellering, men uten detaljert kjennskap til SSIIM eller Costa Rica.

Denne teksten skal inkluderes i oppgaven, og vil bli brukt under sensureringen.

Appendix B

Steady state control file

```

T steady sim#20 8 des

F 1 0 detailed boogiefile
F 2 UR read unstruc when ssiim is opened
F 16 0.01 roughness
F 33 50 10 timestep, inner iterations
F 36 2 free water surface algorithm
F 37 2 sediment computation
F 48 16 output option for post-processing
F 64 13 grid generation algorithm
F 65 180000 3300000 180000 50000 6000 number of cells, points and surfaces
F 81 866 number of timesteps in time1
F 94 0.01 0.1 cells smaller than 0.1m wont be generated and cells less than
F 102 1 wetting and drying algorithm is enabled
F 105 2 number of iterations between each time the water surface is up
F 106 0.3 thickness sedimentlayer
F 112 1 lower water surface read unstruc then read koordina
F 113 7 stabilizing triangular cells
F 159 1 2 0 1 0 avoiding grid problems
F 168 9 multigrid solver
F 200 1 0.1 0.01 k and epsilon scaling values
F 206 8 use all 8 cpus
F 235 10 stabilizing cells
F 291 1 3 0.01 stabilization of edge cells
F 292 1 2.0 timestep inner iteration ns equation
F 293 1 write residual file
G 1 300 300 15 8 grid size xyz and number of sedisizes
G 6 18516 0 0 0.5 0.5 downstream or upstream cell
P 10 100 periodic writing of result or output files
W 1 50 150 576 manning, discharge og water level
K 1 10000 100 number of iterations for flow
K 3 0.4 0.4 0.4 0.2 0.2 0.2 relaxation faktor for hastighet, continuity, k, e
K 5 0 0 0 10 0 0 multigrid algorithm

S 1 0.0000164 0.000146843
S 2 0.0000139 0.000105486
S 3 0.0000118 7.60203E-05
S 4 0.00000996 5.41607E-05 sediment size and fall velocity
S 5 0.00000844 3.88911E-05
S 6 0.00000715 2.79112E-05
S 7 0.00000606 2.00498E-05
S 8 0.00000514 1.44242E-05

N 0 1 0
N 0 2 0.15
N 0 3 0.15
N 0 4 0.175
N 0 5 0.175
N 0 6 0.15
N 0 7 0.1
N 0 8 0.1
B 0 0 0 0 0 0 0 0
bedsediment distribution

```

Appendix C

Time dependent control file

```
T sim#14 8des time dep

F 1 0 detailed boogiefile
F 2 US read unstruc when ssiim is opened
F 16 0.1 roughness
F 33 1000 20 timestep, inner iterations

F 36 2 free water surface algorithm
F 37 2 sediment computation
F 48 16 output option for post-processing

F 64 13 grid generation algoritme
F 65 180000 3300000 180000 50000 6000 number of cells, points and surfaces
F 81 866 number of timesteps in time1
F 94 0.01 0.1 cells smaller than 0.1m wont be generated and cells less than 1
F 102 1 wetting and drying algorithm is enabled
F 105 2 number of iterations between each time the water surface is upd
F 106 0.3 thickness sedimentlayer
F 112 1 lower water surface read unstruc then read koordina
F 113 7 stabilizing triangular cells
F 159 1 2 0 1 0 avoiding grid problems
F 168 9 multigrid solver
F 200 1 0.1 0.01 k and epsilon scaling values
F 206 8 use all 8 cpus
F 235 10 stabilizing cells
F 291 1 3 0.01 stabilization of edge cells
F 292 1 2.0 timestep inner iteration ns equation
F 293 1 write residual file
G 1 300 300 15 5 grid size xyz and number of sedisizes
G 6 18516 0 0 0.5 0.5 downstream or upstream cell
P 10 100 periodic writing of result or output files
W 1 50 150 576 manning, discharge og waterlevel

K 1 21600 1000 number of iterations for flow
K 3 0.4 0.4 0.4 0.2 0.2 0.2 relaxation faktor for hastighet, continuity, k, e
K 5 0 0 0 10 0 0 multigrid algorithm

S 1 0.00013 0.009226831
S 2 0.00004 0.000873546
S 3 0.000016 0.000139767
S 4 0.000008 3.49418E-05
S 5 0.000005 1.36492E-05

sediment size and fall velocity

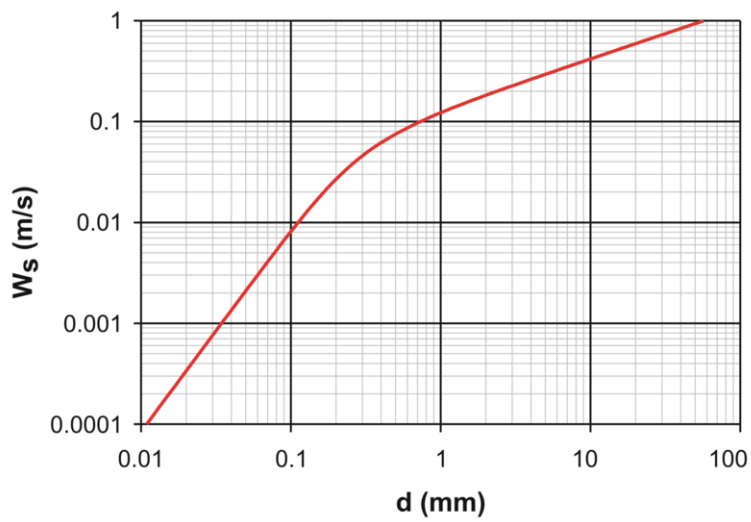
N 0 1 0.1
N 0 2 0.2
N 0 3 0.4
N 0 4 0.2
N 0 5 0.1

bedsediment distribution

B 0 0 0 0 0
```

Appendix D

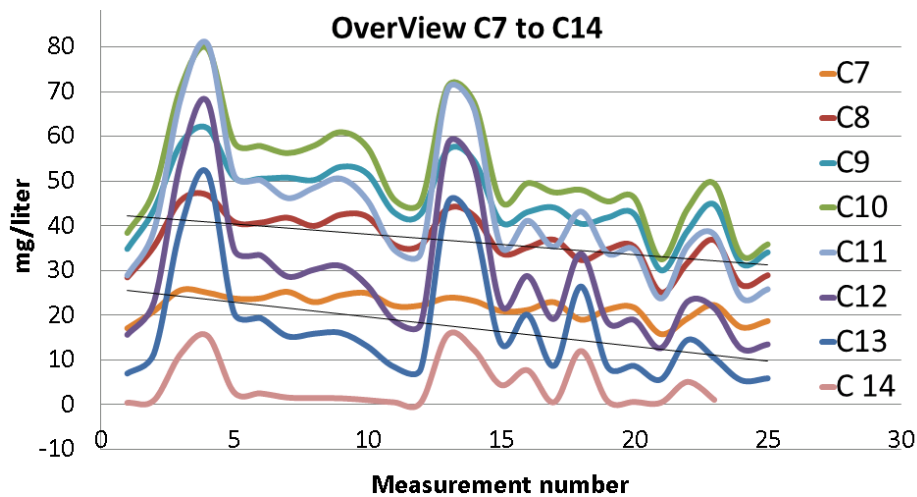
Fall velocity diagram

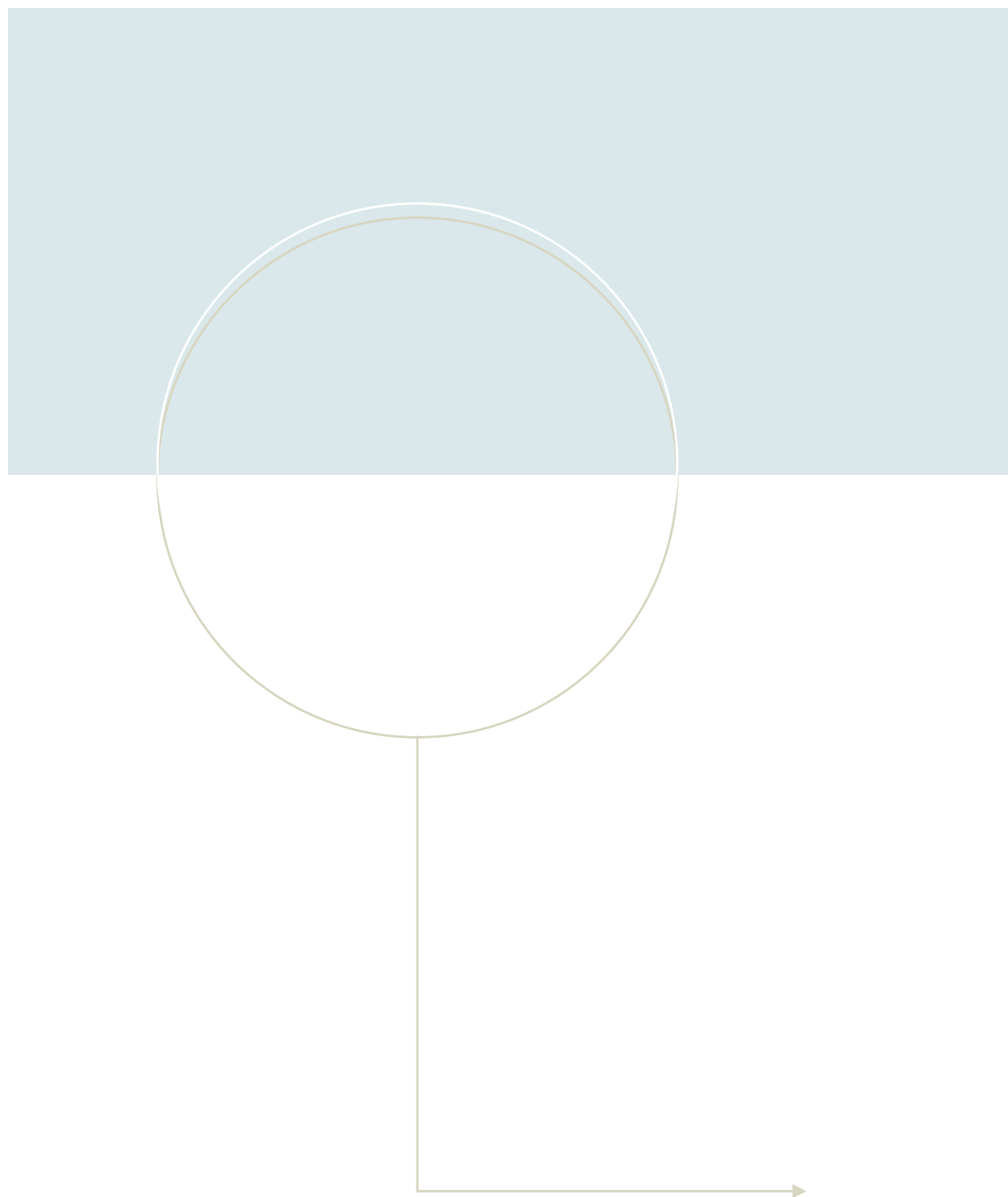


Appendix E

LISST-SL measurment

Suspended concentration over the reservoir for the grain size C7 to C 14 (5.14 to 19.3 μm).





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