Master's thesis

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Three-dimensional numerical modelling of sediments in water reservoirs

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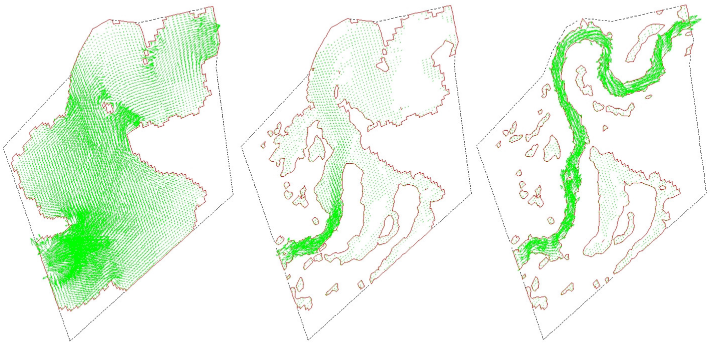

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Preface

This report is a master's thesis at the Department of Hydraulic and Environmental Engineering of the Norwegian University of Science and Technology. The object of the described project was to do three-dimensional numerical modelling of sediments in a water reservoir in Costa Rica using the SSIIM model.

The work on the thesis started 18 January and was to be concluded by 14 June. The first weeks were spent solely on getting to know the program SSIIM. A trip to Costa Rica and the Angostura Water Reservoir was made in February 2010 to collect the necessary data for the simulations. In Costa Rica a cooperation with ICE, the Costa Rican Institute of Electricity, was started and a trip was made to the Reventazón river basin and the Angostura reservoir.

I expected to receive data about Angostura during this visit in Costa Rica, but due to bureaucracy in ICE we could not get the data before an official written agreement was made. Unfortunately it took much longer to get this agreement than expected, the confidentiality contract was finally signed 20 April. Because of these difficulties, a lot of time has gone by waiting for input data for the model.

The work on modelling of sediment transport in the Angostura reservoir will be continued at the department of Hydraulic and Environmental Engineering after this project is finished.

I would like to thank Professor Nils Reidar B. Olsen for invaluable guidance on the use of SSIIM throughout the semester and for his work on developing the model as new problems were encountered. I would also like to thank Carlos Roberto Rodríguez Meza at ICE for his work on establishing the cooperation between ICE and NTNU and for his work on providing data for the modelling. I would like to give an additional thanks to Laura Ramón Lizano and Oscar Jiménez for their help in organising things in Costa Rica, and to Stefan Haun for his guidance on similar flushing simulation cases.

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Abstract

Many places in the world the rivers transport a lot of sediments. When these sediments enter slow flowing areas like a water reservoir, the sediments are deposited. This leads to a reduction in the volume of the reservoir. The object of this project is to do three-dimensional numerical modelling of sediments in a water reservoir in using the SSIIM model. The chosen reservoir is the Angostura reservoir in Costa Rica. This reservoir has significant sediment problems and is flushed two times per year. Both the deposition of sediments and the flushing of the reservoir should be modelled.

SSIIM is a computational fluid dynamics program tailor-made for hydraulic engineering. The program can model sediment transport in a reservoir with a movable bed and varying water level, because of this it is suited to model both sediment deposition and reservoir flushing. An unstructured grid with about 27 000 cells is made for the Angostura reservoir. This grid is used for all the simulations and for an analysis of the volume development of the reservoir.

The Angostura reservoir was put into operation in year 2000. The yearly inflow of sediments is estimated to be 1.5 million tonnes, this sediment inflow led to a reduction in the reservoir volume. Data from bathymetric surveys has been used as input data for SSIIM, to analyse the volume development of the reservoir. After six years of operation the reservoir had lost almost 30% of its volume. At this time it was decided to do two yearly flushings instead of one as had been done up to this time. After this the volume has remained quite stable with only a slight decrease.

The Angostura reservoir is flushed in September and in November every year. Three main simulations have been carried out: simulation of sediment deposition from November until September, simulation of the September flushing, and simulation of the November flushing. After countless tests, the algorithms and parameters giving solutions as close to the measured data as possible, is found. There are still many uncertainties concerning both input data and algorithms used. Further work on the model is therefore recommended. The model successfully simulates deposition and flushing of the reservoir. With further testing and development the model can be used to predict the future volume development of the Angostura reservoir.

Resumen

En muchos lugares en el mundo los ríos transportan una gran cantidad de sedimentos. Cuando estos sedimentos entran en zonas con flujo lento como en un embalse, los sedimentos se depositan. Esto conduce a una reducción en el volumen del embalse. El objetivo de esta tesis de maestría es hacer una modelación numérica tridimensional de los sedimentos en un embalse con el uso del modelo SSIIM. Se eligió el embalse Angostura en Costa Rica. Este embalse tiene problemas de sedimentos, por lo cual se hacen desembalses dos veces al año. Tanto la sedimentación como los procesos de desembalse deben ser modelados.

SSIIM es un programa computacional de dinámica de fluidos desarrollado para la ingeniería hidráulica. El programa puede modelar el transporte de sedimentos en un embalse con lecho móvil y con variación en los niveles del agua. Debido a esto, el programa es adecuado para modelar tanto el depósito de sedimentos como los desembalses. Se ha hecho una malla no estructurada con unas 27 000 celdas para el embalse Angostura. Esta malla se ha utilizado para todas las simulaciones y para el análisis de la evolución del volumen del embalse.

El embalse Angostura entró en operación en el año 2000. La afluencia anual de sedimentos se ha estimado en 1,5 millones de toneladas, este flujo de sedimentos ha llevado a una reducción en el volumen del embalse. Se han utilizado datos de levantamientos batimétricos como datos de entrada para SSIIM, para analizar la evolución del volumen de embalse. Después de seis años de operación el embalse había perdido casi el 30% de su volumen. En ese momento se decidió hacer dos desembalses cada año en lugar de uno como se había hecho hasta entonces. Después de esta medida, el volumen se ha mantenido bastante estable con sólo un ligero descenso.

En el embalse Angostura, cada año hay desembalses en septiembre y en noviembre. Se han realizado tres simulaciones principales en esta tesis de maestría: una simulación de la sedimentación desde noviembre hasta septiembre, una simulación del desembalse de septiembre, y una simulación del desembalse de noviembre. Después de numerosas pruebas, se han encontrado los algoritmos y los parámetros que dan las soluciones que se ajustan lo mejor posible a los datos medidos. Debido a que todavía hay muchas incertidumbres tanto en los datos como en los algoritmos usados, se recomienda trabajo adicional sobre el modelo. El modelo logró simular la sedimentación y los desembalses. Con más pruebas y desarrollo, el modelo puede ser utilizado para predecir el comportamiento futuro del embalse de Angostura.

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Chapter 1

Introduction

In many countries there is a significant transport of sediments in the rivers. When a river flows into a water reservoir, the water velocity is reduced resulting in suspended sediments being deposited. Over time this deposition leads to a reduced volume in the water reservoir. This is a problem in many water reservoirs used for hydropower around the world. We therefore want to know more about the deposition process and we want to know more about what happens during a flushing of a reservoir.

1.1 Background for the project

As a part of the increased focus on clean energy, the Department of Hydraulic and Environmental Engineering at NTNU has started a project on numerical modelling of sediment transport in water reservoirs. This project which is financed by the Research Council of Norway, aims to develop a three-dimensional computer model that can simulate sediment transport in water reservoirs, including the flushing of sediments from reservoirs.

Sediment transport is not a big problem in Norway. Because of this, this project works with a reservoir in Costa Rica where the sediment transport is very high. In this project the Department of Hydraulic and Environmental Engineering at NTNU is cooperating with ICE, the Costa Rican institute of electricity.

The Angostura reservoir in Costa Rica is a reservoir facing the challenge of sediment deposition. Angostura is owned by ICE and is located in the Reventazón river basin in central Costa Rica. Upstream of the reservoir the Reventazón river basin has steep slopes and high precipitation. This results in a high sediment production. The Angostura Power Plant was put in operation in October 2000. Throughout these ten years the reservoir has been regularly flushed to remove deposited sediments and to conserve the reservoir volume as much as possible. [Jimenez et al., 2004]

Reservoir sedimentation leads to reductions in reservoir volumes and this has economical consequences. As reservoirs are filled with sediments the volume of water that can be used to generate energy is reduced. This leads to a decreased income for the dam owner. During a flushing of a reservoir, large amounts of water is flushed through the reservoir. This process leads to a big loss of water that otherwise would be used for generation of energy. Because of this there are important financial reasons to know more about the sedimentation processes.

There are several reasons for choosing Angostura as the reservoir to be studied. ICE has a lot of good data on this reservoir. Therefore modelling with correct input data can be conducted, and verification of the results is also possible. The Angostura reservoir has a substantial sediment problem, therefore it is interesting for both ICE and for this research project to model the sediment transport in this reservoir. Angostura also has a special geometry, which makes it a bigger challenge to model, but also more interesting to model, as it requires a 3D model.

There are still uncertainties concerning the the sedimentation processes in the reservoir. There is a desire to have a better understanding of these processes to be able to predict future deposition, future development of the reservoir volume and to predict the effectiveness of flushing.

1.2 Master's thesis work

The purpose of this project is to model the sediment movement in a water reservoir using a three-dimensional model and to analyse the changes of the volume of the reservoir. The modelling will be done in the computational fluid dynamics program, SSIIM. The goal is to model both the sediment deposition throughout the year and the erosion processes during a flushing of the reservoir. To be able to do this there is a need of good input data.

Data needed in the model is the geometry of the water reservoir including measures of the topography of the bottom, values for the water discharge and concentrations and sizes of the inflowing sediments. To also be able to model the flushing of the reservoir there is a need for more detailed information about discharges and sediment concentration during flushings.

Chapter 2

Theory

This chapter deals with sediment problems in water reservoirs, how this is handled, and how a numerical model can be used to learn more about the sediment transport in a water reservoir.

2.1 Sediment problems in water reservoirs

Sediments are fragments of rocks and minerals that is broken down by erosion or weathering, and are subsequently transported by water, wind, or ice. Sediments have a higher density than water and the sediments will therefore sink in still-standing water. In a river, the sediments will be affected by the forces from water flow and turbulence. Sediments are picked up and carried by the river either in suspension or as bed load. The sediment transport capacity is dependent on the discharge of the river. High water velocities leads to more sediments being picked up. When water velocities are lowered, the heaviest sediments will settle. [Lysne et al., 2003]

The sediment transport processes can cause problems for water reservoirs. Tributaries which transport sediments enters the water reservoirs. In the reservoir the water velocity is very low. This decreases the sediment transport capacity, leading to parts of the sediments settling and being trapped in the reservoir. The bed load and the coarsest sediments are immediately deposited, while the finer fractions are transported further into the reservoir. The trapping efficiency of big water reservoirs where the water velocities are very low will approach 100%, meaning that all of the sediments entering the reservoir will settle. Over time, the trapping of sediments in the water reservoir will lead to a significant reduction in the reservoir volume. If not dealt with, the settling of sediments can lead to a water reservoir completely filling up with sediments and the whole volume being lost. [Morris and Fan, 1998]

The sediment yield, the amount of sediments transported in a basin over a period of time, is highly dependent on the geology and topography of the area. Factors leading to a high sediment yield can be steep slopes, heavy rainfall, volcanism, and soil disturbance by e.g. agriculture. In some areas of the world, including Costa Rica, the sediment yield is very high, and a big reservoir can be filled with sediments in less than twenty years. Other places, like in Norway, sediments pose little or no problems to water reservoirs. [Morris and Fan, 1998]

To calculate the lifetime of a planned water reservoir, an estimation of the sediment yield is often made. This is a complicated process, and the sediment yield is often underestimated, leading to a shorter lifespan for the water reservoir than predicted. [Morris and Fan, 1998]

To determine the loss of volume over time in a reservoir, bathymetric surveys may be conducted. Bathymetry is the study of the terrain of the land under the water. A bathymetric survey will find the depth at different points in the water reservoir and thereby finds the total volume of the reservoir. This information can be compared to previous surveys to find the development of the reservoir volume over time. The loss of volume for a reservoir is the amount of sediments trapped in the reservoir since the last bathymetric survey. This information can be used to find the sediment yield for the area and to find the remaining lifespan of the water reservoir. [Morris and Fan, 1998]

2.2 Flushing of reservoirs

Sediment deposition is the main problem affecting the useful lifetime of reservoirs. To avoid that water reservoirs lose their capacity, actions have to be taken. A common method used is flushing of the reservoir. In a flushing process the gates of the dam is opened and the water level is lowered. This leads to an increased water velocity in the reservoir which will induce the water to erode and pick up sediments and transport them out of the reservoir. Water with very high sediment concentrations is released from the reservoir. By regularly flushing a reservoir, the accumulation of sediments can be avoided or at least decreased. Normally, reservoirs with sediment problems are flushed annualy. [Morris and Fan, 1998]

The first phase of a complete flushing process is the lowering of the water level to the minimum operational level. This lowering is done slowly so that the water can be used to produce energy. The next phase is a rapid emptying of the reservoir by opening the bottom outlet gates. During the draw down, sediments from the upper parts of the reservoir may be mobilised, transported and redeposited further downstream in the reservoir.

The next phase of flushing is the erosion phase. Figure 2.1 on the facing page shows a longitudinal profile of a reservoir during this phase. The reservoir is completely empty at this point. The bottom outlet gates are kept open and water flows through the reservoir like a river, eroding sediments and transporting them out of the reservoir. This phase can go on for days or weeks, depending on the reservoir. In many cases this is the natural condition, the way the river used to flow before the dam was built. The final phase of a flushing process is the filling of the reservoir. The bottom outlet is closed, and the water level slowly rises back to an operational level. [Morris and Fan, 1998]

When the water level is drawn down and the water velocity is very high, a channel is usually eroded through the reservoir. This means that flushing is most effective for narrow reservoirs. For wider reservoirs a channel with floodplains will develop from the flushings. Sediments deposited on the floodplain will not be removed during future flushings. When a channel is eroded the slopes may become unstable and slide into the channel, this leads to the channel being widened. Flushing is an effective method for the removal of sediments from reservoirs, but a problem with flushing is that the coarse sediments are often

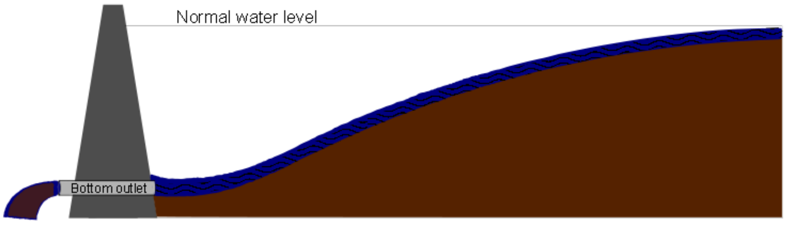


Figure 2.1: Flushing of a reservoir

not removed, leading to coarse material being accumulated in the reservoirs. [Morris and Fan, 1998]

A flushing can be complete, meaning the reservoir is completely emptied of water, or a flushing can be partial. In a partial flushing the water level is lowered to achieve higher water velocities but the reservoir is not emptied. Complete flushings are more effective than the partial flushings, especially when carried out in high flow periods when the discharges are larger and have more erosive energy. Flushing in high flow periods is also an advantage in regard to the filling of the reservoir after the flushing. Partial flushing is chosen when the environmental effects of complete flushing is unacceptable or when other constraints make it impossible to empty the reservoir, for example if the dam does not have a bottom outlet. The environmental consequences of reservoir flushing can be severe and should always be considered. [Morris and Fan, 1998] This report, however, will not deal with this topic.

2.3 Numerical modelling of sediment transport

Sediment transport is a very complicated process, so modelling is necessary to predict the future deposition in a water reservoir. The modelling can be either physical or numerical. The topic of this report is the numerical modelling of sediment transport.

2.3.1 CFD models

Several models have been developed for the simulation of sediment transport in one-, two, and three dimensions. Still most modelling of sediment transport has been carried out in the 1D models because these are more robust and require less input data and computing time. The 1D models can be good for solving problems for reservoirs that are long and narrow, but for reservoirs with a more complex geometry like the Angostura reservoir in Costa Rica, (see figure 3.1) a 1D model will not be appropriate. [Morris and Fan, 1998]

Computational fluid dynamics, or CFD, is a branch within fluid mechanics which uses numerical methods and algorithms to solve problems involving fluids in motion. CFD is a link between the disciplines of fluid mechanics, mathematics and computer science. [Tu et al., 2008] The program used is this project is SSIIM, a three-dimensional CFD model designed to simulate sediment movements in rivers and reservoirs. [Olsen, 2010] The model and some of its applications are described in chapter 4.

2.3.2 Accuracy

To achieve high accuracy a fine grid and a short time step is needed. The more cells a grid has, the more calculations are necessary. The smaller the time step is, the more iterations are needed to model the same time period. Therefore more calculations have to be performed. An increased number of calculations leads to increased computational time. The computational time needed to model a case is therefore often the limiting factor for the accuracy of the results. When modelling a case, a solution which is as accurate as possible is wanted, but it has to be modelled within a reasonable amount of time.

2.3.3 Errors and uncertainties

There are several uncertainties in CFD-modelling. Approximations in the algorithms used by the programs can in some cases lead to errors. The European research community on flow, turbulence and combustion (ERCOFTAC), has made a list of the most common errors in CFD-modelling.

1. Modelling errors: The model does not represent the real world conditions in a good way. This can be if the model uses one-dimensional algorithms when tree-dimensional effects play a role.

2. Errors in numerical approximations: These are errors due to the discretization of the equations, e.g. false diffusion.

3. Errors due to not complete convergence: These errors may occur when an iterative solver is used and solutions are used even though there is not complete convergence. This is especially a problem in time dependent computations, where convergence may not be reached for every time step.

4. Rounding errors: Rounding errors is a problem when using 32 bits floating point numbers as these have limited accuracy. Nowadays most programs use 64 bit floating point numbers. This is considered sufficient.

5. Errors in input data and boundary conditions: The most common error in CFD modelling is errors in the boundary conditions or geometry. Computing flow in complex geometries with a moving grid is sometimes difficult. There are often uncertainties also when deciding input data like roughness, inflow of water, and sediment inflow.

6. Human errors due to inexperience of the user: The experience in using CFD models is limited. There are many parameters and algorithms to choose from.

7. Bugs in the software: All complex software has bugs. [Olsen, 2007]

Chapter 3

Angostura reservoir

The Angostura reservoir is located in the Reventazón river basin in central Costa Rica. This chapter describes the conditions in the river basin and the history and today's situation in the Angostura reservoir.

Figure 3.1: Angostura reservoir *Photo: ICE*

Figure 3.2: Costa Rica and the Reventazón river basin

3.1 The Reventazón river basin

The Reventazón river basin is located in central Costa Rica and drains into the Caribbean Ocean. The basin is shown in red in the map in figure 3.2. The basin is about 3000 km^2, and is the third biggest basin in Costa Rica. It is of great importance for the country as it generates one fourth of the total hydroelectric energy of Costa Rica.

In the upper parts of the basin at an elevation of 990 m.a.s.l. the Cachí reservoir and hydroelectric plant is located. Following the Reventazón river downstream from Cachí to the Turrialba valley at 580 m.a.s.l. we find the Angostura reservoir and hydroelectric plant. Downstream from Angostura the Reventazón river goes on to the Caribbean coast. [Unidad de Gestión Nacional Costa Rica, 2008]

The Reventazón river basin has a varied climate due to the elevations in the basin varying from sea level to 3500 m.a.s.l. Because of this, the basin does not have defined dry or wet periods. The precipitation in the basin varies and some areas have up to 8500 mm per year, but the mean precipitation for the basin is 3500 mm. [Unidad de Gestión Nacional Costa Rica, 2008] In the upper part of the Reventazón basin which is the catchment for Angostura, there is a period with less rain from January to May. [Jansson and Rodríguez, 1992]

The land use in the Reventazón basin is varied, in Angostura's catchment area, natural forest prevail, as much of this forest is protected by the law. Other than forest, most of the catchment area consists of pasture and crops. The hydroelectrical development in the Reventazón river basin started in the 1960s. Many hydroelectric project have been started throughout the years, and still there are several projects being planned and built in the following years to fully utilise the available energy in the rivers of the Reventazón basin. [Unidad de Gestión Nacional Costa Rica, 2008]

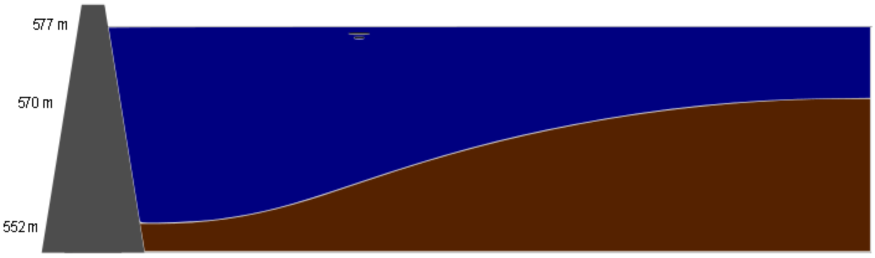


Figure 3.3: Sketch of Angostura longitudinal profile

3.2 Angostura hydropower reservoir

The Angostura Power Plant in the Reventazón river basin in Costa Rica has been in operation since October 2000. The power plant has a 38 metres high rock-fill dam and a drainage area of 1463 km^2. At the time of construction the reservoir had a volume of about 17 million cubic metres. The catchment area has steep slopes and large precipitation resulting in a high sediment production. [Jimenez et al., 2004] The average annual inflow to Angostura is about 120 $^{m^3}/_{s}$. [Meza, 2010a]

Angostura Power Plant is run as a daily peaking power plant. For the daily peaking purposes, a reservoir volume of 2.5 million cubic meters would be sufficient, but as the Reventazón river basin has a sediment problem a larger reservoir was built. The operational levels of the reservoir is between 570 and 577 m.a.s.l., and there is a dead storage volume from 570 m.a.s.l. down to the lowest bed level at 552 m.a.s.l. [Jimenez et al., 2004]

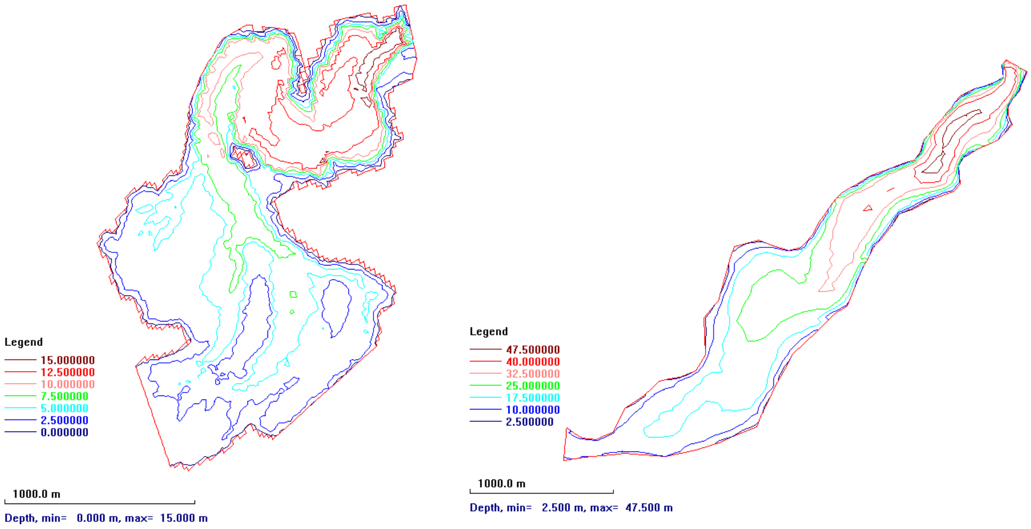
Figure 3.3 shows a sketch of a longitudinal profile of the Angostura dam and reservoir. The shape of Angostura is shown in figure 3.4a on the next page. The inflow to the reservoir is the straight line at the bottom left side, the outflow is at the top of the right side.

The upstream part of Angostura is very shallow and wide (see figure 3.4a). The flushings have little effect in on it, as this area dries up during the first phase of the flushing, the slow lowering of the water level, explained in section 2.2. This makes the Angostura reservoir very vulnerable to sediment deposition. [Jimenez et al., 2004]

Upstream from Angostura, the Reventazón river carries a sediment load of about 1.5 million tonnes per year. The estimates made of the sediment load in the inflow to Angostura are varying. ICE has operated with numbers from 1 million to 3.5 million tonnes per year. The number used in this report is the number ICE currently is using. Still, this could be an important source of error for the simulations. [Meza, 2010c]

The first years of operation the Angostura reservoir will have a trapping efficiency of about 60%. This trapping efficiency will decrease over time as the reservoir volume also decreases. [Jimenez et al., 2004]

With a trapping efficiency of 60% the yearly deposition of sediments in Angostura is $1.50 \cdot 0.60 = 0.90$ million tonnes. Sediments entering the reservoir consists of mostly silt, with parts of clay and sand. [Meza, 2007] When this ma-



(a) Angostura reservoir

(b) Cachí reservoir

Figure 3.4: Shape and depths of Angostura and Cachí

terial turns into submerged reservoir deposits they will have a specific weight of about $1\,{}^{tonne}/_{m^3}$ [Morris and Fan, 1998] This means that after only one year of deposition, the reservoir will have lost about $0.90 \cdot 10^6\, tonnes/1\, \frac{tonne}{m^3} = 0.90$ million cubic metres, which is more than 5% of the original reservoir volume. Calculations have indicated that Angostura would fill up with sediments in less than 20 years, if no actions were taken to prevent this. [Jimenez et al., 2004]

Fifteen kilometres upstream from Angostura is the Cachí reservoir which was built in the 1960s. This reservoir has a volume of 50 million cubic meters. Due to the sediment problem in the Reventazón river basin there has been annual flushings of the Cachí reservoir since 1973. These flushings have been very successful, and only about 10% of the reservoir volume was lost in 40 years of operation. The shape of the Cachí reservoir, in contrast to the Angostura reservoir, is very well suited for flushing as it is relatively long and narrow (see figure 3.4). Yearly, 500 000 tonnes of sediments are flushed from the Cachí reservoir. Since Angostura is downstream from Cachí, most of the flushed sediments are transported in the river directly to the Angostura reservoir. [Jimenez et al., 2004]

3.3 Operation of Angostura

Angostura reservoir is flushed at the same time as the upstream Cachí reservoir. The reason for this is that it is preferable to prevent the flushed sediments from Cachí from settling in Angostura. This flushing is conducted in September every year. In addition to this simultaneous flushing, Angostura has a second flushing later in the year since 2006. The flushings are conducted in this period of the year, the rainy season, to insure rapid refilling of the reservoirs so that power generation can be resumed as quickly as possible.

The objective of the simultaneous flushing is to remove deposited sediments from Cachí. Cachí is completely emptied, allowing free river flow through the reservoir for approximately 33 hours. During this flushing, Angostura is not completely emptied. The water level in Angostura is lowered to 565 m.a.s.l, leaving a relatively small volume of water in front of the dam. This is the dead storage volume of Angostura. This volume is in a way used as a retainer for the flushed sediments from Cachí, accumulating sediments and decreasing the sediment concentrations downstream of Angostura. Since this water volume cannot be used for power generation, the decreased volume does not have an effect on Angostura's useful volume.

In the second flushing, Cachí does not take a part except from insuring an appropriate water discharge as an inflow to Angostura. In this flushing, Angostura is completely emptied, first by a slow draw down to 570 m.a.s.l, then a rapid emptying of the remaining water down to 556 m.a.s.l. The objective of this flushing is to remove deposited sediments. This flushing also cleans the dead storage of Angostura. This is important so that it is possible to continue with the same flushing procedure year after year without decreasing the useful volume of Angostura. Angostura has several bottom outlets. It is not necessary to open all of these during flushing, but to insure as good removal of sediments as possible, they are all used one by one to increase the area being eroded. [Meza, 2010b]

3.4 Grain size distribution for bottom sediments

There is probably a big variation in grain sizes of the bottom sediments throughout the Angostura reservoir. This is because different sizes settles at different locations which generally leads to coarse material upstream and finer material downstream. The grain size distribution of the bottom sediments has an influence on the erosion potential and should therefore be considered in a sediment movement simulation. There is only taken only one sample of the submerged sediments in Angostura, this sample is taken at the flat area upstream in the reservoir. This sample had the grain size distribution shown in figure 3.5. The graph shows that the measured bed sediments consists of about 71% silt, 23% clay and 6% sand.

3.5 Earlier simulations of sediment transport in Angostura

Before the construction of Angostura dam, simulations in SSIIM and other CFD programs were executed as part of the planning process to estimate the lifetime of the reservoir. Simulations were conducted in the 1D program HEC-6, in the 2D program RESP and in SSIIM (3D). [Jimenez et al., 2004]

In the SSIIM simulation a 5000 cell grid was used. Several simplifications were made to be able to model the sediment transport in a reasonable amount of time. These simplifications were:

- Constant sediment load

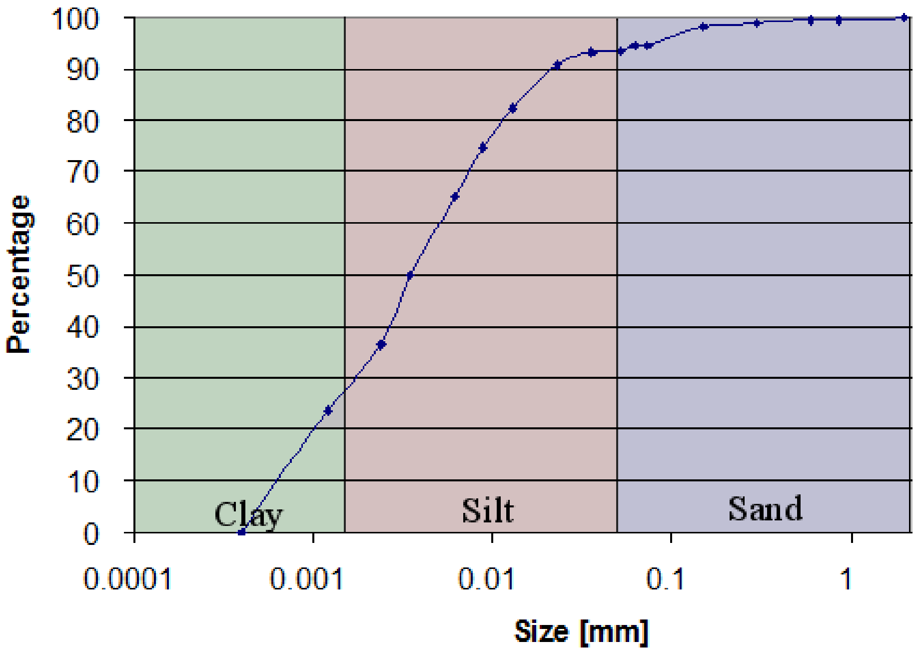


Figure 3.5: Grain size distribution [Meza, 2007]

- A constant discharge of 350 m^3/s . This is the yearly flood discharge, and this was considered representative.
- Constant water level. No draw downs or flushings were modelled.
- No erosion.
- Sediment granulometry was represented with three size fractions.
- Large time steps of more than 1 year were used.

One of the problems with this simulation was that very high time steps were used. The program did not handle the deposition very well. Because of the big time steps, sediments were sometimes deposited above the water level. This was solved by redistributing these sediments to neighbouring cells. This worked, but the algorithms used were not very scientific. This algorithm also ment that erosion could not be modelled. [Løvoll, 1994]

Both SSIIM and the computational power available has developed significantly since the time of this simulation. Therefore, simulations done today will probably give more realistic results. It is now possible to use much smaller time step and it is possible to also model a changing water level with wetting and drying of cells, thereby modelling flushing of reservoirs.

Chapter 4

SSIIM

SSIIM is an abbreviation for *Sediment Simulations In Intakes with Multiblock option.* It is a computational fluid dynamics program tailor-made for hydraulic engineering. The program was originally designed to simulate sediment movements, but has later been expanded to solve problems in many other areas. SSIIM solves the Navier-Stokes equations in a three-dimensional non-orthogonal grid, using the k-ε model for turbulence, the SIMPLE method for pressure and it solves the convection-diffusion equation for several parameters, including sediments. [Olsen, 2010]

The advantage of using SSIIM, compared to other CFD programs is that it can model sediment transport with a movable bed. SSIIM can handle multiple sediment sizes, compute time dependent changes in bed and surface levels, and can handle wetting and drying of cells resulting in a changing grid. This makes the program ideal for the modelling to be done in this project. [Olsen, 2010]

SSIIM is developed by professor Nils Reidar B Olsen at NTNU. It is a non-commercial program made for teaching and research purposes and it can be freely downloaded from the Internet. As the program has not gone through as much testing as comparable commercial programs, it has more bugs and might be less reliable. [Olsen, 2010] Both SSIIM and the SSIIM User's manual can be downloaded from http://folk.ntnu.no/nilsol/ssiim/. This report will not describe SSIIM in detail, only the topics that are most important for the modelling of sediment transport in Angostura will be covered. For more extensive information, see the user's manual.

4.1 SSIIM versions

There are two different versions of SSIIM: SSIIM 1 and SSIIM 2. The main difference between the to versions is that SSIIM 1 uses a structured grid while SSIIM 2 uses an unstructured grid. SSIIM 1 is easier to use, but can not handle wetting and drying of cells. [Olsen, 2010] For the simulations to be done in this project, wetting and drying of cells is necessary. Only SSIIM 2 will therefore be used. In the rest of this report, when the name SSIIM is used, it is referring to the Windows version of SSIIM 2.

There is also a Unix version of SSIIM 2. This version does not have a graphical interface as the windows version does, but it has the advantage that

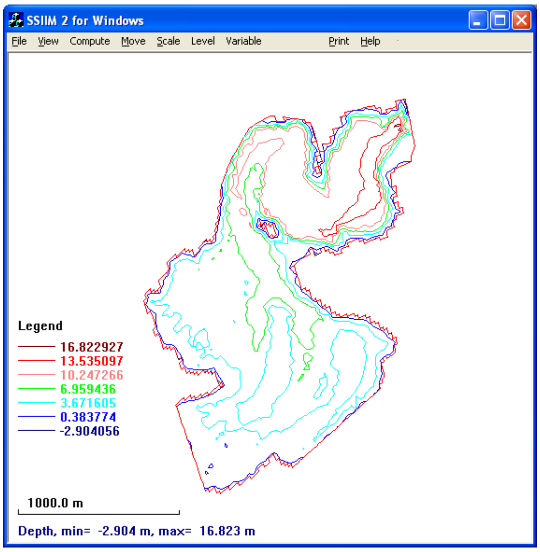


Figure 4.1: SSIIM graphical interface

it can be run on supercomputers which mostly use Unix. In this project a supercomputer located at NTNU has been used to do some of the simulations in less time. On this computer only the Unix version of SSIIM can be run. For the simulations done in the Unix version, both the pre-processing and post-processing has been done using the Windows version of SSIIM.

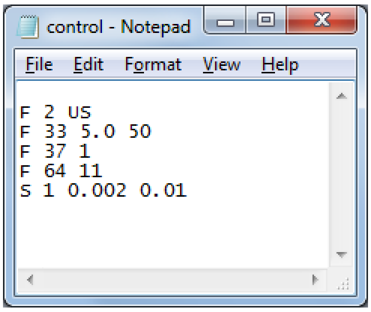
4.2 Graphical interface

In SSIIM's user interface, grids can be created, discharges defined and simulations can be initiated for only water flow or for water flow with sediments. It is also possible to follow the simulations and to view the results after a simulation. When viewing the results many different variables can be chosen, some of the most important variables are velocity vectors, water level, and bed changes. The results are shown as plots of the different variables. [Olsen, 2010]

Figure 4.1 shows SSIIM's graphical interface. In this case, the interface is showing a map of Angostura, and the chosen variable is "depth".

4.3 Input files

SSIIM various input files for control. To make the grid, a geodata file is usually needed. This is explained in chapter 5. When the grid has been made, the data about the grid is stored in a file called `unstruc`. To run the program a file called `control` is necessary. This is the file containing most of the parameters used in the simulations. In this file there are physical parameters like water level, discharge and friction factors, but there are also parameters like time step, number of iterations and parameters that decides what kind of formulae to be used. There are default values for most of the parameters, so for simple



```
F 2 US
F 33 5.0 50
F 37 1
F 64 11
S 1 0.002 0.01
```

Figure 4.2: Control file

situations the program can be run without a complicated control file. [Olsen, 2010]

The control file is organised in data sets, all the data sets which can be used are explained in the SSIIM manual. Figure C.1 shows an example of a simple control file. The first data set is *F* 2, this is a data set giving the run options. The *U* stands for read unstruc file, and the *S* is for compute sediments, by including this data set with the *U* and *S*, the program will automatically read the unstruc file and start the sediment simulation when the program is run. If this data set is not included, it can be done in the graphical interface. The next data set, *F* 33, is transient water flow parameters. *F* 33 defines the time step and the number of inner iterations per time step. Without the *F* 33 data set transient terms will be neglected. In the shown file there is a time step of 5 seconds, and 50 inner iterations per time step. The rest of the data sets are explained in the SSIIM manual. [Olsen, 2010]

For transient calculations, parameters can be given as time series. To do this, a file called `timei` has to be made. Examples of parameters which can vary over time are water level, discharge, and sediment concentrations. All inputs and outputs for the SSIIM model are given in SI units. [Olsen, 2010]

4.4 Output files

After a successful simulation, the results are written to a file called `result` and a file called `bedres`. The result file stores the information from the water flow simulation. This information includes velocities in three dimensions, k, ε, pressure, and fluxes. The bedres file is written only after sediment simulation, as it stores information about the bed sediments. This information includes bed roughness, grain size distribution, sediment thickness, and bedform height. The result and bedres files can be read by SSIIM to view all the graphical results from the simulation. [Olsen, 2010]

If there are problems with simulations, and the program crashes, is useful to see what has happened up to the point the program crashes, and to see the reason for the failure. This information can be found in the file called `boogie`. The boogie file shows print-outs from the intermediate results of the computations in SSIIM. When the program crashes, the reason for failure is also normally written in the boogie file. This file can be opened during a simulation, to see the results up until the point when it was opened. [Olsen, 2010]

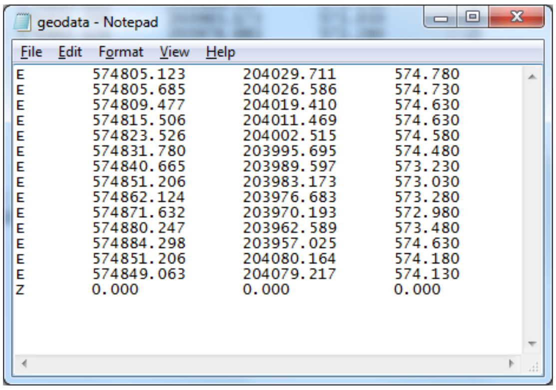
Chapter 5

Making a grid in SSIIM

The first step in modelling the sediment flow in a water reservoir is to make a grid of the reservoir. When making the grid, information about the topography of the reservoir is needed. This can be, for example, data from a bathymetric survey of the reservoir. For SSIIM to be able to read the topography data, a file called `geodata` must be made. The geodata file contains x, y and z coordinates for the reservoir bed. Figure 5.1 shows an example of a geodata file. This is just an extract of a file, as geodata files normally have thousands of lines The letter “Z” tells the program that this is the end of the file. [Olsen, 2010]

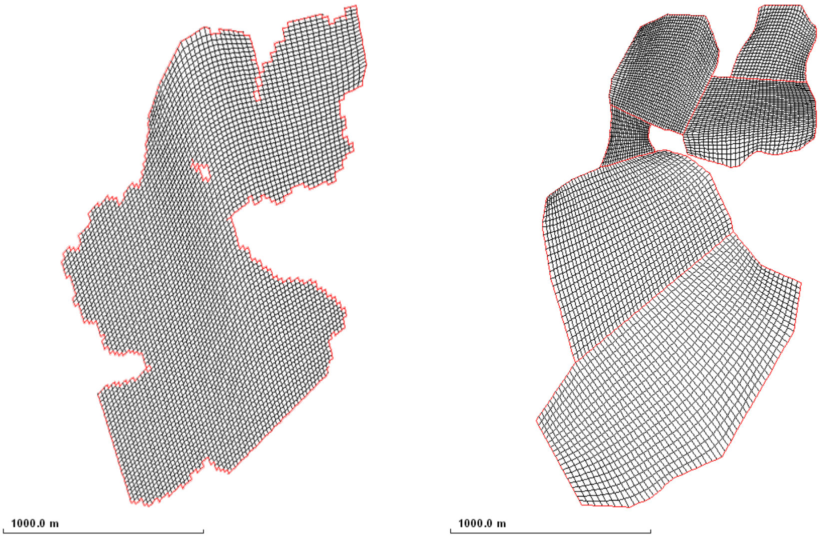
5.1 Grid editor

When the geodata file is present, the geodata points can be viewed in the graphical interface of SSIIM. What is shown in the grid editor is the xy-plane. The geodata point’s colour is dependent on the z-coordinate. In the graphical interface a grid for the plan view of the reservoir, that is the xy-plane, is made. The program generates the grid in the vertical direction according to the z-coordinates. The grid can either be multiblock or the simpler version with only one block. [Olsen, 2010]



```
E          574805.123          204029.711          574.780
E          574805.685          204026.586          574.730
E          574809.477          204019.410          574.630
E          574815.506          204011.469          574.630
E          574823.526          204002.515          574.580
E          574831.780          203995.695          574.480
E          574840.665          203989.597          573.230
E          574851.206          203983.173          573.030
E          574862.124          203976.683          573.280
E          574871.632          203970.193          572.980
E          574880.247          203962.589          573.480
E          574884.298          203957.025          574.630
E          574851.206          204080.164          574.180
E          574849.063          204079.217          574.130
Z          0.000               0.000               0.000
```

Figure 5.1: Geodata file



(a) one block grid (b) multiblock grid

Figure 5.2: Grids for Angostura

5.2 Multiblock or one block grid

A multiblock grid is an unstructured grid made up of several structured grids which are “glued” together. The water surface is first covered with blocks, then the boxes are connected. In the end there will be an unstructured grid covering the entire water body. The next step is to make the grid three-dimensional, this is done by first choosing “Generate bed levels” and then choosing “Generate 3D grid” in the interface. The program then generates the grid in the vertical direction according to the bed levels given in the geodata file. A three-dimensional multiblock grid for the given water body has then been generated.

When making the grid, some considerations should be taken to insure a well-functioning grid that will give stable calculations:

- The grid cells should be as close to orthogonal as possible. Non-orthogonality will slow down the simulation.
- Grid lines should be aligned with the direction of the flow, especially close to inflow and outflow areas. This will decrease false diffusion.
- The distortion ratio should not be to big. The distortion ratio is the dimension of a grid cell in one direction divided by the dimension of the cell in the other direction.
- The size of a grid cell should not differ too much from the size of the neighbouring cells. This could lead to physically impossible results. [Olsen, 2010]

Both of the grids shown in figure 5.2 were made in accordance to the criteria for a well-functioning grid stated above. The one-block grid is closer to compliance with the criteria since the cells are almost orthogonal and have about the same size. The reason the geometries of these grids are not exactly equal is that the multiblock grid is made with an old geodata file from 1990. The one-block grid is made with a newer and updated geodata file from a recent bathymetric survey.

Since natural water bodies are usually not rectangular, the blocks have to be fitted to the reservoir's geometry. There are two ways of making the grid fit the geometry. The first way is done graphically in the interface, by dragging points to the desired locations, and making new boundaries for each block. This method has been used in the multiblock grid (figure 5.2b). The other method is making a grid that is bigger than the reservoir. If the points in the geodata file are only for the area covered with water, the outer limits of the reservoir has to be defined. This is done by adding new geodata points with an elevation higher than the water level around the existing points. When the water level in the reservoir is defined, the grid will be generated with only the cells which are wet at the given water level. This method is used in the one block grid shown in figure 5.2a. [Olsen, 2010]

The advantages with the second method is that it is a quick way to make a grid that fits the geometry very well. In addition to this, the cells are orthogonal and all the cells have practically the same size. This will give more stable and faster calculations. Although not shown in the figures, it is possible to make a multiblock grid with this method, too. It is also possible to make a single block grid with the graphical adjustment method, but for complex geometries it could be difficult to adjust the grid to the geometry while still being in compliance with the criteria for a well functioning grid. A disadvantage of using multiblock grids is that the time needed for the simulation will increase because of the extra boundaries. [Olsen, 2010]

5.3 Discharge editor

In the discharge editor, the location of inflows and outflows in the grid is defined. The magnitude of the discharges is also defined. There can be several groups of inflows and outflows in the grid, but total discharge in and total discharge out must be equal to each other to achieve continuity. [Olsen, 2010]

5.4 Saving the grid

The grid is saved by choosing “write unstruc”. SSIIM then generates a file called `unstruc`. This file contains all the information about the grid, including the discharges. [Olsen, 2010]

5.5 Grid for Angostura

For the simulations of sediment flow in Angostura, experiments have been made with both the multiblock and the one-block grids shown in figure 5.2. The two grids were tested for equal situations and the conclusion was that the simulation converged faster for the grid with only one block. Due to this, only the one-block grid has been used for the simulations in this report.

The grid for Angostura has about 27 000 cells at the start of the calculations with a water level of 577 m.a.s.l. The grid has up to ten cells in the vertical direction depending on the depth of the specific location in the reservoir. The number of cells may decrease during calculations. If the water level goes down, or if the bed level rises due to sedimentation, there might be a decrease of cells in the vertical direction. As cells dry up there will also be a decrease of cells in the *xy*-plane.

Chapter 6

Volume development

The Angostura hydropower plant has been in operation for almost ten years. Because of the severe sediment problem in the Reventazón river basin, the volume of the Angostura reservoir has been closely monitored since the start-up in 2000. In this chapter bathymetric surveys from 2005 to 2009 will be used to analyse the development of the volume and to look at the bed changes in Angostura.

6.1 Calculating the volume of a reservoir with SSIIM

When a bathymetric survey of a reservoir is made, the volume of the reservoir can be found in SSIIM. A geodata file has to be made from the bathymetric survey and an unstruc file (the grid) has to be made for the geometry of the reservoir. This procedure is explained in chapter 5.

It is not necessary to make a new unstruc file for every geodata file to be used. The 3D-grid can be adjusted to the given geodata file by choosing "generate bed levels" in SSIIM's graphical interface. When the bed levels are generated, the grid is adjusted to the bed levels given in the geodata file. To find the volume of the reservoir it is also necessary to define which water level the volume is to be found for. By choosing "define surface points" and "generate surface", the water level can be adjusted. After this point, the grid has to be regenerated and saved by first choosing "generate 3D grid" and then choosing "write unstruc".

SSIIM does not have a specific option to find the volume of the reservoir. To find the volume a sediment simulation has to be initiated. The first thing SSIIM does when a sediment simulation is started, is to print the volume of the reservoir to the boogie file. Since the reservoir volume is instantaneously printed in this file, it is not necessary to wait until the sediment simulation is completed. Olsen [2010]

Often the volume to be calculated is the live volume of the reservoir. To find this in SSIIM, the steps explained above for the maximum operational level is performed and the total volume of the reservoir is found. Then, the water surface should be adjusted to the minimum operational level. The grid has to be regenerated and a sediment simulation is started to find the new volume. This volume, which is below the minimum operational level, is the dead storage

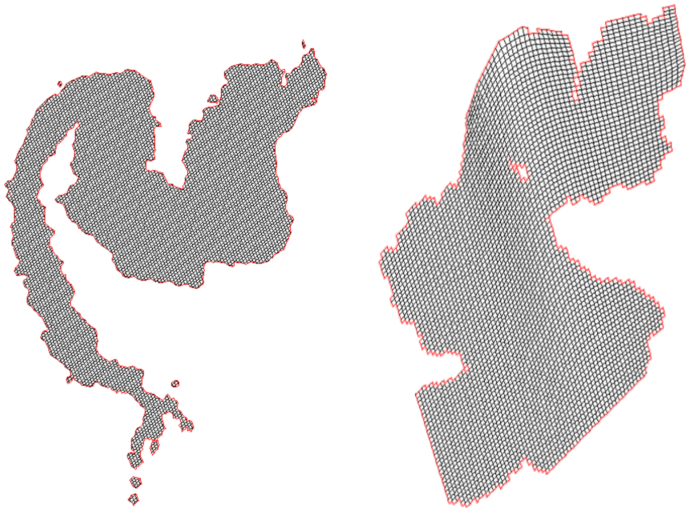

(a) Dead storage (b) Total storage

Figure 6.1: Total storage and dead storage for Angostura

of the reservoir. The live storage is the total volume of the reservoir minus the dead storage. This is the volume of water that can be used to generate energy.

Figure 6.1a shows a grid of Angostura's dead storage. This is the part of the reservoir filled with water when the water level is at the lowest operational level at 570 m.a.s.l. Figure 6.1b shows the grid when the water level is at the highest operational level, 577 m.a.s.l.

6.2 Analysing bed level development in SSIIM

The bathymetric surveys are not only useful to find the development of the volume, they can also be used to show where in the reservoir there has been changes from one survey to the next. SSIIM can display the bed changes of a water body in a map. Examples of this is shown in section 6.4 on page 23. Using this information, the deposition of sediments in the reservoir throughout the year can be studied and, maybe more importantly, the bed changes during flushings can also be studied.

To find the bed changes from one survey to another using SSIIM, the following procedure is used:

1. Geodata files of the two surveys and a grid are made (see chapter 5).
2. The grid is adjusted to the first geodata file by choosing "generate bed levels" and then "generate 3D grid" in the graphical interface.
3. By choosing "write unstruc" the grid is saved in the unstruc file and also a file called `koomin.bed` is generated. This file defines the surface of the bed levels. To prevent the file being overwritten in the next steps, its name should be changed.

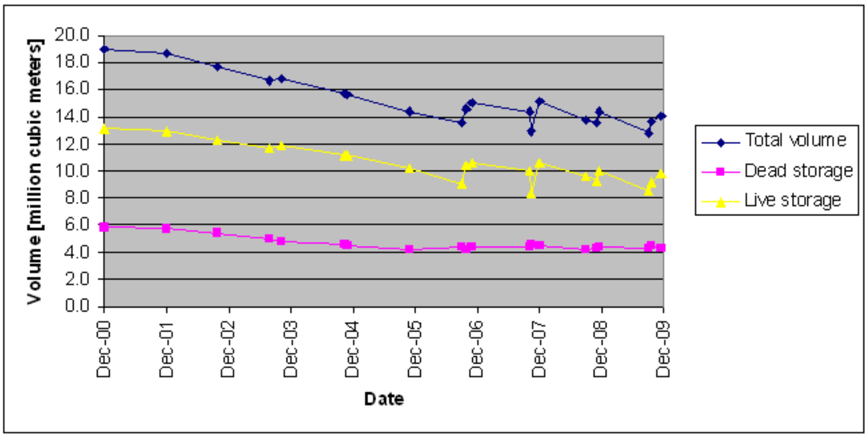


Figure 6.2: Volume development of Angostura reservoir

4. An F 249 1 data set has to be added to the control file. This will allow both negative and positive bed changes.

5. SSIIM should be opened with the original unstruc file and the second geodata file. The grid is adjusted to the geodata file by choosing "generate bed levels" and then "generate 3D grid" in the graphical interface. Then, to save the grid, "write unstruc" is chosen.

6. The new unstruc file is opened with the koomin file from point 3. For the program to read the koomin file it has to be renamed "koomin" (without an extension).

7. The program will now find the difference in bed levels between the koomin file from the first geodata file and the unstruc file from the second geodata file. The results are displayed by choosing the "sediment thickness" variable in the SSIIM map. To find the difference in volume between the two geodata files, use the method described in section 6.2 on the preceding page. Olsen [2010]

6.3 Volume development for Angostura

By using the method explained in section 6.1 on page 20, the volume development over the last years for the Angostura reservoir has been found. The results are shown in figure 6.2.[1]

There was a steady decrease in the volume of Angostura the first years, even with the yearly flushing. From the start-up in 2000 to September 2006 the reservoir lost almost 30% of its original volume. The reduction rate of the reservoir volume was 0.9 million cubic metres per year. This was a serious development, and it was therefore decided to do a second flushing of Angostura every year, starting in 2006. The change in the volume development from this point can clearly be seen in the graph.

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[1] The exact numbers are shown in appendix B.1 on page 56.

After four years of doing two flushings per year it seems like this procedure is working. The volume has so far been relatively stable since 2006. There is still a small decrease in the volume over these years, but the rate is significantly reduced, giving Angostura a much longer life expectancy. Since 2006 the reduction rate of the reservoir volume has been only 0.2 million cubic meters per year.

For several of these years the inflow of sediments from the end of November to the beginning of September has led to a volume reduction of more than 1 million cubic metres. Since this period is about 9 months and the trapping efficiency should be lower than 60%, this indicates that the the inflow of sediments might be higher than the number currently used, which is 1.50 million cubic meters[2].

6.4 Bed changes in Angostura

Figure 6.3 on the next page shows the bed changes in Angostura from the start-up in 2000 until the last bathymetric survey which was made in November 2009. The dark blue lines show the erosion, the other lines are deposition. During these years the reservoir has lost about 30% of its original volume. There has been deposition of sediments in the entire reservoir. There are some areas with erosion close to the edges of the reservoir. This erosion is most likely due to small landslides which may happen during reservoir flushings.

Figure 6.4 shows the bed changes from November 2008 until November 2009. Figure 6.4a shows the bed changes during the deposition period from November 2008 to September 2009. There was no erosion during this period, so all lines are deposition according to the values shown in the legend. This will be simulated in chapter 7.

Figure 6.4b shows the bed changes from 2 September, 2009 to 17 September, 2009. The September flushing of Cachí and Angostura takes place during this period. Figure 6.4c shows the bed changes from 17 September, 2009 to 18 November, 2009. The November flushing of Angostura takes place during this period. These bed changes will be simulated in chapter 8.

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[2] See section 3.2 on page 9.

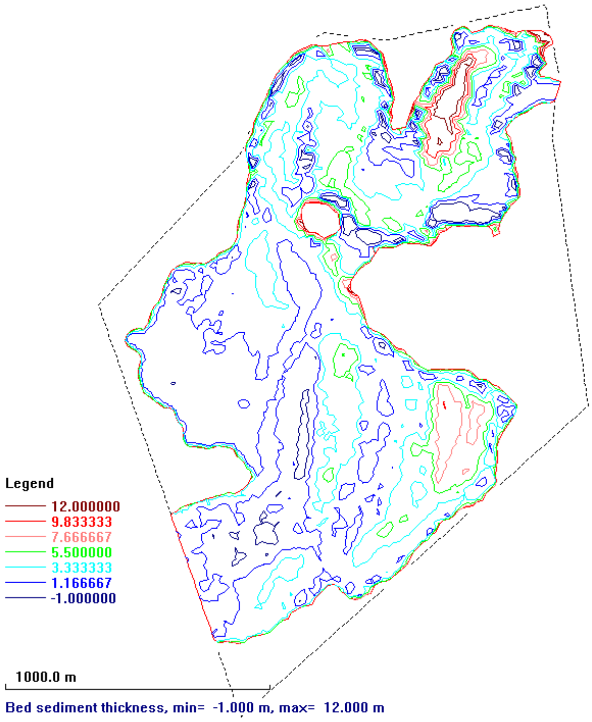
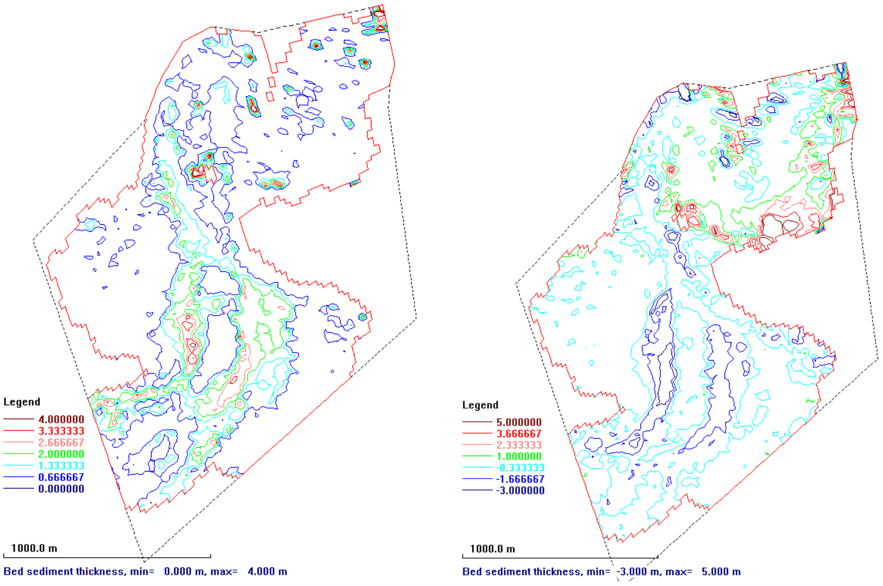
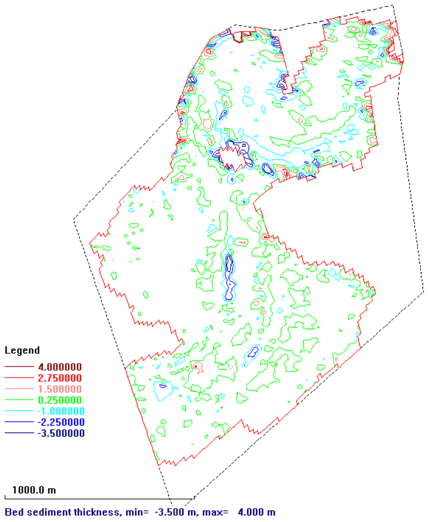


Figure 6.3: Bed changes 2000–2009



(a) Bed changes November 2008–September 2009

(b) Bed changes for September flushing



(c) Bed changes for November flushing

Figure 6.4: Bed changes 2008–2009

Chapter 7

Simulation of sediment deposition

To deal with Angostura's sediment problem, it is advantageous to know more about what happens with the inflowing sediments from the Reventazón river. SSIIM makes it possible to simulate what happens with these sediments.

As we want to see what happens during sediment deposition, there is a need for a simulation with a moving bed where areas with deposition and areas with erosion can be seen. When the bed levels are not constant, the bed changes can affect the water flow. The simulation will therefore have unsteady water flow. The period simulated will not include the flushings. To simplify the calculations a constant water discharge is assumed. The simulation done in SSIIM for the sediment deposition will be an unsteady flow with sediments, fixed water surface, and moving bed simulation.

7.1 Input data

The inflow of sediments to Angostura, including bed load and flushed material from Cachí, is 1.5 million tonnes per year and the average yearly discharge is 120 $^{m^3}/_{s}$ as stated in section 3.2. Table 7.1 on the facing page shows the duration of different inflows to Angostura in one year, and the corresponding sediment loads. Even though only 30 days of the year have a discharge higher than 170 $^{m^3}/_{s}$, these days account for almost 80% of the sediment inflow. This means that most of the sediment inflow is connected to flood discharges in the Reventazón river.

The last number in the table, labeled Cachí, is the inflow to Angostura during the flushing of Cachí. The flushing of Cachí leads to a very high sediment concentration in the river, and is a big part of the yearly inflow of sediments to Angostura.

In the simulation of the deposition of sediments in Angostura, we want to simulate what happens from after the flushing in November until the next flushing in September. Ideally the model would simulate a period of 280 days with a time series for water and sediment inflows, but a time series for sediment inflow to Angostura does not exist. In addition to this, the computational time

Discharge [m^3/s]	Days	Sediment load [tonnes]	% of yearly sediment load
30	54.0	315	0.02
50	54.0	2310	0.15
70	30.0	4772	0.32
90	56.0	23756	1.58
110	68.0	63132	4.21
130	36.0	64153	4.28
150	22.0	68533	4.57
170	15.0	76161	5.08
190	8.0	62700	4.18
210	5.5	63708	4.25
230	3.6	59476	3.96
250	3.2	73202	4.88
270	1.8	55604	3.71
290	1.8	73491	4.90
310	1.0	52967	3.53
330	1.0	67606	4.51
350	1.0	85060	5.67
370	0.3	31699	2.11
500	0.8	172000	11.46
Cachí: 200	2	400000	26.66

[Alvarado et al., 1993]

Table 7.1: Discharges' duration and sediment load

necessary for this simulation would be too high. This means that it is not possible with the current computer power and available time.

For simulating the sediment deposition using only one discharge, a discharge of 350 $^{m^3}/_{s}$ is chosen. This discharge corresponds to the yearly flood discharge in the Reventazón river. [Jimenez et al., 2004] The model uses a time step of 120 seconds.

SSIIM needs input data for sediment sizes, sediment fall velocities, and sediment concentrations. For the simulation, three sediment sizes are used. These are 0.13 mm, 0.02 mm, and 0.002 mm. The fall velocities for these sediment sizes are given in table 7.2. [Løvoll, 1994] The concentrations are calculated from the percentages of each sediment size for the given water discharge and its sediment load. The calculation and assumptions made are explained in appendix D.1 on page 60. With a discharge of 350 $^{m^3}/_{s}$, the sediment inflow will be 984.5 $^{kg}/_{s}$. The total amount of sediment inflow during these 280 days is 848,485 tonnes. To achieve this sediment inflow, the discharge of 350 $^{m^3}/_{s}$ has to be simulated for 10 days. The resulting sediment concentrations given as cubic metres sediments per cubic metres water, are shown in table 7.2. These sizes, concentrations, and fall velocities are used as input data in the model. The calculation of the concentrations are shown in appendix D.1 on page 60.

It is probable that cohesive forces in the deposited sediments will affect the erosion processes in the reservoir. Fine sediments have cohesive forces that helps them stick together. This increases the critical shear stress and prevents erosion. Deposited sediments are compacted over time by consolidation and dewatering.

Sediment size $[mm]$	Concentration $[m^3/m^3]$	Fall velocity $[m/s]$
0.13 (sand)	0.00024	0.01
0.02 (silt)	0.00053	0.00035
0.002 (clay)	0.00029	0.0000036

Table 7.2: Sediment characteristics

The more compacted cohesive sediments are, the better the resistance against erosion becomes. There may be a big variation in the cohesion in a reservoir. Measurements throughout the entire reservoir is therefore necessary to have the complete picture of the cohesive forces. [Morris and Fan, 1998] It would be benefitial to include these forces in the model. There are plans to measure the cohesion of the deposited sediments in Angostura, but these measurements will not be completed soon enough to be included in this simulation.

7.1.1 Simplifications

Simplifications are necessary because of limited data, but most of all simplifications has to be made to insure a reasonable computational time for the simulation. The simplifications made for the simulation of sediment deposition in Angostura are:

- Constant water discharge. A discharge of 350 m^3/s is chosen as representative.
- Constant sediment concentration corresponding to the chosen discharge.
- Three sediment sizes of 0.13 mm, 0.02 mm and 0.002 mm are chosen to represent the granulometry.
- A constant water level of 577 metres.
- A time step of 120 seconds is used.

7.1.2 Input files

The most important input files made for the sediment simulation `control` and `timei`. The control file was made after several tests concluded in what algorithms would give a good and stable solution. The timei file is made by simply inserting the chosen values for discharges, water levels and sediment concentrations.

In addition to these files, the unstruc file for the grid shown in figure 5.2a has been used in the simulations. A file called `koordina` stores the information about cells outside of the grid is also used in case new cells become wet.

It is important to specify a maximum erosion depth. There is a limit to how far down into the bed level sediments can be eroded. The exact limit for the erosion is not known, but we have chosen to assume that there will be no erosion beyond the original bed level of the reservoir. Because of this a koomin file which contains information about the bed levels from year 2000 is used. This will prevent erosion to take place below the original bed level.

	Sediment size [mm]	Fall velocity [$^m/_s$]
S 1	0.13 (sand)	0.01
S 2	0.02 (silt)	0.00035
S 3	0.002 (clay)	0.0000036

Table 7.3: S data set

The unstruc file is adjusted to the bed levels from the bathymetric survey performed in November 2008, this means that the simulated period is from November 2008 to September 2009. The following control and timei input was used in the simulation of sediment deposition in the Angostura reservoir.

Control file input

Only part of the data sets in the control file is explained in this section. More of the algorithms used are explained in section 9.3, the control file is shown in appendix C.2 on page 58.

The simulation uses "van Rijn's formula" to calculate the concentrations at the bed. This is given in the $F10$ data set. The $F6$ data set gives the coefficients for this formula. This data set has been used to calibrate the model to give a total bed change as close to the measured amount as possible. The roughness in the reservoir is not measured, but it is used as input for the simulations. The value is set to 0.1 metres in the F 16 data set.

In the F 33 data set the time step of the simulation is set to 120 seconds, with 30 inner iterations per time step. This simulation is a transient sediment computation with free water surface, specified on the F 36 and F 37 data sets. Since wetting and drying may happen for this simulation, an algorithm that changes the shape of the grid cells close to the boundaries is necessary, this is given in the F 102 data set. Algorithms that help to stabilise triangle cells are also included in data sets F 113 and F 235. The F 159 data set is used, invoking different algorithms to improve stability by avoiding grid problems. To avoid problems concerning inflow and outflow areas drying up, the G 62 data set is used.

The chosen sediment sizes that represent the granulometry and their fall velocities are given in the S data sets. These numbers are listed in table 7.3. The N data set gives the granulometry of the bed sediments which is taken from section 3.4 on page 11. This means that the bed sediments given in the control file is 6% sand which is group *S 1*; 71% of silt, group *S 2*; and 23% of clay, group *S 3*.

The deposition simulation uses a 120 second time step. To simulate 10 days, 7182 iterations is necessary. This is given in the K 1 data set in the control file.

Timei input

The timei file used in this simulation gives the concentrations of sediments entering the reservoir. As stated in section 7.1, for simplification we use three sediment sizes and we assume a constant discharge and constant sediment concentrations. Since constant conditions is assumed for this simulation the timei file is very simple.

The timei file is shown in appendix C.3 on page 58. The data given in the file is an upstream water level of 78, and downstream water level of 76, and a water discharge of 350 $^{m^3}/_{s}$. In addition to this, the file specifies the concentrations of the three sediment groups given in the control file.

- Group 1: 0.00024 $^{m^3}/_{m^3}$
- Group 2: 0.00053 $^{m^3}/_{m^3}$
- Group 3: 0.00029 $^{m^3}/_{m^3}$

7.2 Problems faced

For the deposition simulation, large amounts of sediments enter the reservoir. This has led to some problems: As the sediments entered the reservoir, large amounts of these setted as soon as they entered. There was lot of deposition in the inflow area which led to this area drying up which again led to the simulation crashing.

Another problem for the deposition simulation, was that the calculated amount of sediment inflow for this period was in fact much lower than the actual bed changes in the reservoir. This means that the sediment inflow this year was much higher than the average inflow or that the yearly sediment inflow estimates are wrong. To achieve results that were close to the measured bed changes the sediment concentrtions had to be increased. By increasing the concentrations with a factor of 4, the bed changes corresponds to the measured bed changes. Therefor the concentrations in the timei file was changed to the following:

- Group 1: 0.00098 $^{m^3}/_{m^3}$
- Group 2: 0.00212 $^{m^3}/_{m^3}$
- Group 4: 0.00114 $^{m^3}/_{m^3}$

7.3 Results

Figure 7.1 shows the bed changes for the deposition simulation. Figure 7.2 shows the velocity vectors in the Angostura reservoir at the end of the deposition period. The sediment deposition has led to several areas in the reservoir drying up as can be seen in the figures. There has been a lot of deposition in the upstream part of the reservoir and little changes in the downstream part.

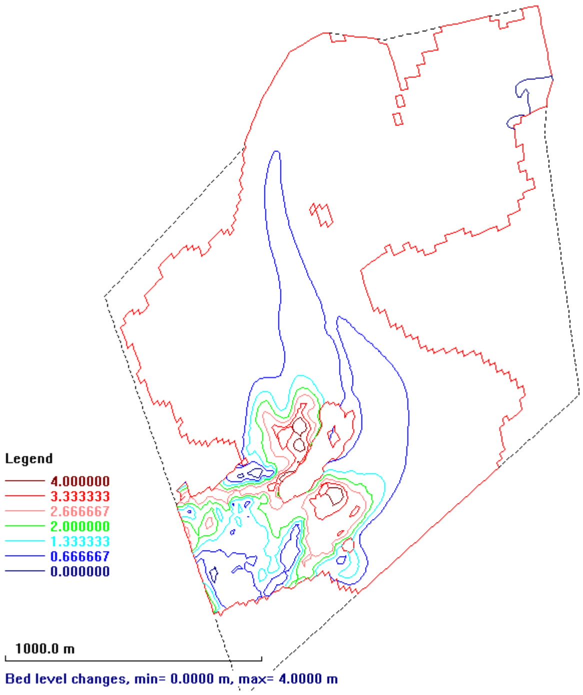


Figure 7.1: Bed changes for deposition simulation

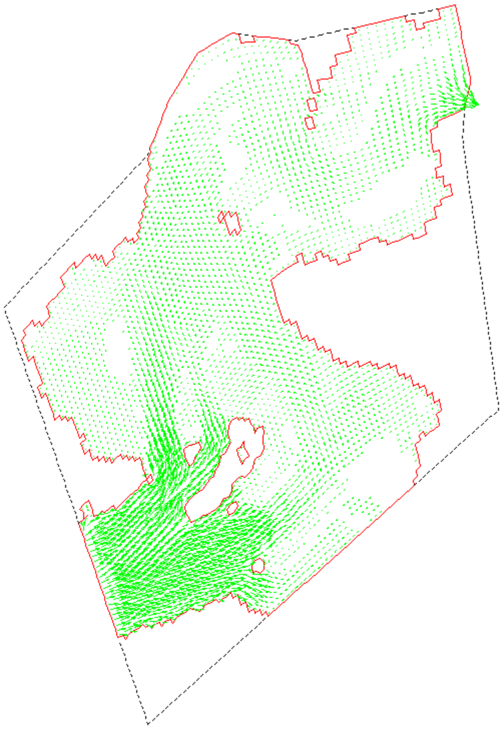


Figure 7.2: Velocity vectors for deposition simulation

Chapter 8

Simulation of reservoir flushing

To maintain the volume in the Angostura water reservoir, the reservoir is flushed two times a year. The goal of these flushings is to remove as much sediments as possible from the reservoir and to restore some of the capacity that has been lost. There is an increasing interest in knowledge about flushing problems as many reservoirs around the world are facing sediment problems. We want to know as much as possible about what happens during the flushing process. There are no well-developed methods for calculating many of the parameters relating to the erosion processes during flushing. Modelling of this process is therefore very useful. [Morris and Fan, 1998]

The simulation of reservoir flushing is one of the most complex situations that can be modelled in SSIIM. This is an unsteady water flow computation with sediments, moving surface, and moving bed. It also has to include the wetting and drying of cells, as the reservoir is emptied and many cells will dry up. The simulation of reservoir flushing in three dimensions is a very new process, until now successful simulations has only been conducted a couple of times.

Both the September and the November flushings have been simulated. The September flushing is a simultaneous flushing with the upstream Cachí reservoir. In the November flushing the water level is lower than in the September flushing to insure good erosion in the dead storage area of Angostura. The flushing procedures are explained in section 3.3. The bed levels used for the simulations is the bed levels from 2009, but the model can easily be adjusted to model other years as well.

It is probable that cohesive forces in the deposited sediments will affect the erosion processes in the reservoir, as explained in section 7.1 on page 26. Due to lack of data this is not taken into account in these simulations.

8.1 Input data for the September flushing

The most important input data for the reservoir flushing simulation is the changes in water level. The water level in the September flushing is at its lowest at 565 m.a.s.l. The water inflow for this flushing is influenced by the fact that the upstream reservoir Cachí is flushed at the same time. Therefore, there are large variations in water flow and sediment inflow during the flushing.

The inflow during the emptying of Angostura is $150\,{}^{m^3}\!/_{s}$. [Meza, 2009a] The outflow will be much higher than the inflow during this phase, but SSIIM does not handle differences between inflow and outflow, so the same discharge is used for both inflow and outflow. The water level in SSIIM is lowered independently of inflow and outflow. Most erosion takes place when the water level is at its lowest, when the outflow is equal to the inflow. Because of this the error in outflow will not have a big effect on the results.

8.1.1 Simplifications

- Six different situations for water inflow and sediment concentrations are used. These represent the variation in water and sediment inflow during the flushing.
- Three sediment sizes of 0.13 mm, 0.02 mm, and 0.002 mm are chosen to represent the granulometry.
- A time step of 60 seconds is used.

8.1.2 Input files

This simulation uses the same grid and unstruc file as the sediment deposition simulation, including the koordina and koomin files. The unstruc file is slightly changed. Water in the flushing procedure leaves the reservoir at a different location than during normal operation when it is used for power generation. The outflow area therefore is now moved from the intake to an area in the dam with gates. In addition to this, the unstruc file is adjusted to the bed levels from the bathymetric survey performed before the September flushing in 2009.

The following control and timei file input was used for the September flushing simulation. The control file was made after countless tests concluded in what combination of algorithms would work in the simulation. As for the sediment deposition, the timei file is made by simply inserting the chosen values for discharges, water levels, and sediment concentrations.

Control file

The control file is almost identical to the control file from the sediment deposition simulation. One difference is the coefficient for "van Rijn's formula" given in data set $F\,6$. This is explained in section 7.1.2. In addition to this, the time step and the number of iterations differs from the deposition simulation. The control file is shown in appendix D.2 on page 62.

Timei file

The data in the timei file is time series for the water level, water inflow and sediment inflow. The water level is lowered down from 577 metres to 566 metres, the level is then kept between 565 and 566 metres for 50 hours. After this the filling of the reservoir is started, the water level is increased from 565 metres back up to 577 metres. The input data is shown in table 8.1. The time is given

	Time [hours]	Inflow [m^3/s]	Sediment concentrations m^3/m^3			Water level [m]
			0.13(sand)	0.02(silt)	0.002(clay)	
Emptying	0	150	1.81E-05	3.81E-05	3.45E-05	577.0
_ _ _ _ _ _ _ _	18	150	1.81E-05	3.81E-05	3.45E-05	566.0
	28	450	1.79E-03	3.88E-03	2.10E-03	566.0
Erosion	34	150	8.13E-04	1.71E-03	1.55E-03	565.5
_ _ _ _ _ _ _ _ _	68	37.5	5.28E-04	1.46E-03	1.12E-03	565.0
	77	37.5	1.98E-07	5.47E-07	4.19E-07	568.0
Filling	88	75	1.57E-06	4.35E-06	3.33E-06	572.1
	102	75	1.57E-06	4.35E-06	3.33E-06	577.0

Table 8.1: Timei input

as hours from the start of the flushing process. The process from the start of the flushing to the reservoir water level is back at the original water level takes in total 102 hours, that is 4 days and 6 hours. [Meza, 2009b]

At the start of the flushing the water inflow to Angostura is 150 m^3/s. During this time period the water level in Angostura is lowered to prevent the arriving sediments from Cachí from settling in the upstream part of the reservoir. The lowering of the water level is completed in 18 hours. 28 hours after the start of the flushing process, water and sediments from the rapid emptying of Cachí reservoir reach Angostura. This leads to an increase in the water inflow to 450 m^3/s. This inflow lasts for 6 hours. After this, the water level is back at 150 m^3/s for 33 hours. 67 hours after the start of the flushing, the effects from the refilling of Cachí reach Angostura. During this phase there is very little water downstream of Cachí, and the inflow to Angostura is only 37.5 m^3/s. This process lasts for 20 hours. The remaining 15 hours of the flushing process the water inflow to Angostura is 75 m^3/s. [Meza, 2009a]

The sediment inflow during the first period is not effected by the Cachí flushing. Therefore, the sediment concentrations are assumed to be the normal concentrations, corresponding to 150 m^3/s. These concentrations are found as for the water flow and sediment simulation in section 7.1 on page 26.

As shown in table 7.1, the sediment inflow effects of the Cachí flushing lasts for 48 hours. Since there are no good measurements of the inflow of sediments to Angostura other than the total sediment load during these 48 hours, some assumptions had to be made. It is assumed that 50% of the sediment inflow enters the first 6 hours with the discharge of 450 m^3/s, 48% enters during the following 34 hours with the discharge of 150 m^3/s, and 2% enters in the remaining 9 hours with the 37.5 m^3/s inflow. After this there are 11 more hours with 37.5 m^3/s and 15 hours with 75 m^3/s. During these periods normal inflow of sediments corresponding to the discharges is assumed. The resulting sediment concentrations are shown in table 8.1, the calculations are shown in appendix D.1.1, and the entire timei file is shown in appendix D.3 on page 62.

8.2 Input data for the November flushing

During the November flushing the water level is lowered to 556 ma.s.l, so that the Angostura reservoir is completely empty with only a canal running through

Sediment size $[mm]$	Concentration $[^{m^3}/_{m^3}]$		Fall velocity $[^{m}/_{s}]$
	Discharge: 100 $^{m^3}/_{s}$	Discharge: 130 $^{m^3}/_{s}$	
0.13 (sand)	0.0000069	0.0000101	0.01
0.02 (silt)	0.0000191	0.0000212	0.00035
0.002 (clay)	0.0000146	0.0000192	0.0000036

Table 8.2: Sediment characteristics

it. At the beginning of the flushing, the water inflow is 100 $^{m^3}/_{s}$. This is about the average inflow during the emptying and the erosion phase. For the filling of the reservoir, the inflow is around 130 $^{m^3}/_{s}$. [Meza, 2010b]

There is sediment inflow to the reservoir also during the flushing procedure, therefore SSIIM needs input data for sediment sizes, sediment fall velocities, and sediment concentrations. The inflow of sediments is calculated as in the sediment deposition simulation and the same three sediment sizes are used to represent the granulometry. The concentrations are calculated from the percentages of each sediment size for the given water discharge (see appendix D.1). Table 8.2 shows the resulting sediment concentrations given as cubic metres of sediments per cubic metres of water.

8.2.1 Simplifications

- Two different situations for water inflow and sediment concentrations are used to represent the variation in water and sediment inflow during the flushing.
- Three sediment sizes of 0.13 mm, 0.02 mm and 0.002 mm are chosen to represent the granulometry.
- A time step of 60 seconds is used.

8.2.2 Input files

This simulation uses the same grid and unstruc file, including the koomin and koordina files, as the September flushing. The unstruc file is adjusted to the bed levels from the bathymetric survey performed before the November flushing in 2009.

The following control and timei input was used in the simulation of the November flushing of the Angostura reservoir.

Control file

The control file used in this simulation is almost identical to the one for the September flushing. One difference is the coefficient for “van Rijn’s formula” given in data set *F* 6. This is explained in section 7.1.2. The other difference is the number of iterations, which is larger for the November flushing as this flushing process lasts longer than the September flushing. The control file is shown in appendix D.2.

	Time [hours]	Inflow [m^3/s]	Sediment concentrations m^3/m^3			Water level [m]
			0.13(sand)	0.02(silt)	0.002(clay)	
Emptying	0	100	0.0000069	0.0000191	0.0000146	577.0
	18	100	0.0000069	0.0000191	0.0000146	566.0
	24	100	0.0000069	0.0000191	0.0000146	560.0
Erosion	24-74	100	0.0000069	0.0000191	0.0000146	560.0
Filling	74	130	0.0000101	0.0000212	0.0000192	560.0
	80	130	0.0000101	0.0000212	0.0000192	565.0
	114	130	0.0000101	0.0000212	0.0000192	577.0

Table 8.3: Timei input

Timei file

The data in the timei file is time series for the water level, water inflow and sediment inflow. There are no good time series for the water level during the November flushing, therefore time series from the September flushing are used as a basis for this flushing.

The water level is according to the data lowered to 556 metres during the November flushing. The lowest points along the outflow areas of the reservoir is located at 559 metres according to the bathymetric surveys from 2009. Because of this, the simulation can not handle downstream water levels lower than 560 metres.

In the September flushing the water level is lowered from 577 metres to 566 metres in 18 hours. This data is assumed to be equal for the November flushing, and the data is extrapolated to a water level of 560 metres. It reaches this level 24 hours after the start of the flushing. At this time the erosion phase, which lasts for 50 hours, is started.

After the erosion phase the water level is increased until it is back at the original level of 577 metres. The process from the start of the flushing to the reservoir water level is back at the original water level takes 114 hours, that is 4 days and 18 hours. The water levels and inflows, together with the sediment concentrations, are shown in table 8.3. The time is given as hours from the start of the flushing process.

8.3 Problems faced

The simulation of reservoir flushing has been complicated. Many problems had to be solved and many algorithms had to be tested before the simulations were successful. The main problems of the flushing simulations have been issues connected to the wetting and drying of cells. One of these problems has been splitting of the grid. This can occur when sediments are deposited and the bed level increases. If enough sediments are deposited the cells may dry up so that the grid is split in two. This situation is shown in figure 8.1 on the next page. When this happens the simulation eventually crashes.

A similar problem is that the inflow and outflow areas can dry up. This has the same causes and effects as the split grid problem. To avoid this, two new algorithms had to be included. This was the F 246 and F 222 data sets explained in section 9.3 on page 46. The first is an algorithm that prevents

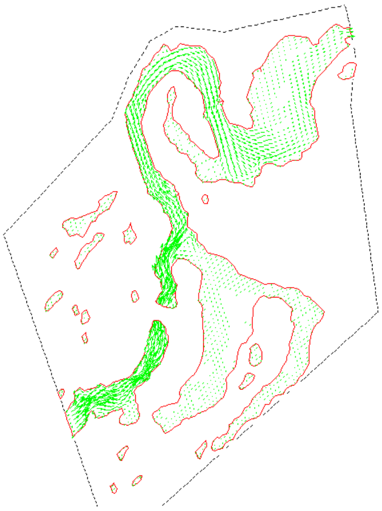


Figure 8.1: Split grid

supercritical flow, the second algorithm prevents sedimentation in these areas. These algorithms together prevent the inflow and outflow areas from drying up.

When cells dry up, the cells are first turned into triangle cells. There has been some problems with this. Sometimes the simulations have diverged because of problems in the triangle cells. This has been resolved by reducing the relaxation factor for all the triangle cells in the grid.

For the November flushing the water level was to be lowered to 556 metres. In the bathymetric survey there was no points lower than 559 metres. Due to this, some geodata points close to the outlet were lowered to 556 metres to be able to model this. This attempt did not work; the simulations crashed when the water level was lowered below 560 metres. Because of this, the geodata points close to the outlet were kept at the lowest level in the bathymetric survey, 559 metres, and the water level in the November flushing simulation was only lowered to 560 metres.

8.4 Results

8.4.1 September flushing

Figure 8.2 on the next page shows the bed changes that has happened during the September flushing. The red and green lines show the deposition while the blue lines show the erosion. This flushing is simultaneous with the Cachí flushing and there is therefore a very high sediment inflow to Angostura. The plan for this flushing is that sediments from Cachí can settle in Angostura's dead storage. As can be seen in the figure, this has happened. There has been a lot of deposition in the dead storage area. There has been some erosion in the upstream area where a channel formed during the flushing. Very little sediments have settled in the upstream parts of Angostura. This is exactly the desired effect of this flushing.

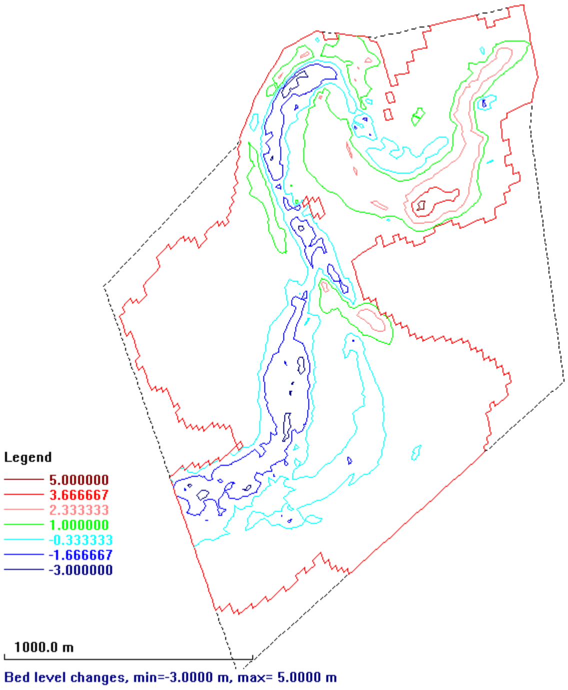
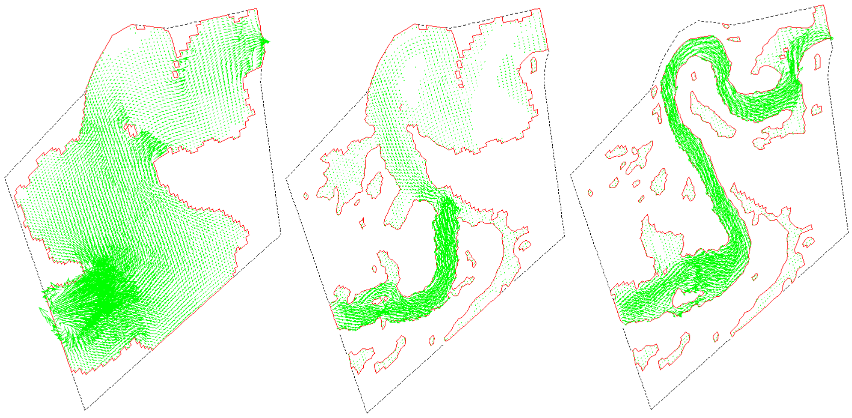


Figure 8.2: Bed changes for September flushing



(a) (b) (c)

Figure 8.3: Velocity vectors for September flushing

Figure 8.3 shows plots of the velocity vectors during different phases of the flushing. Figure 8.3a shows the velocity vector at the beginning of the simulation when the water level is still at 577 metres. After 8 hours the water level is lowered to 573 metres. The velocity vectors for this situation is shown in figure 8.3b. The lowest water level of this simulation is at 565 metres. When the water level is this low only a small part of the reservoir is covered with water and the water moves through the reservoir as a channel as shown in figure 8.3c.

8.4.2 November flushing

Figure 8.4 shows the bed changes in the November flushing. The blue and green lines are erosion while the red lines are deposition. When comparing with the September flushing in figure 8.2 on the preceding page, one can see that the results are significantly different. This is because the water level is lower in this flushing and because the inflow of sediments is much lower since Cachí is not flushed this time.

The results for the bed changes are as expected. A channel is formed through the entire reservoir and erodes about 1.5 metres down into the bed of the reservoir. The flushing has little effect outside of this channel.

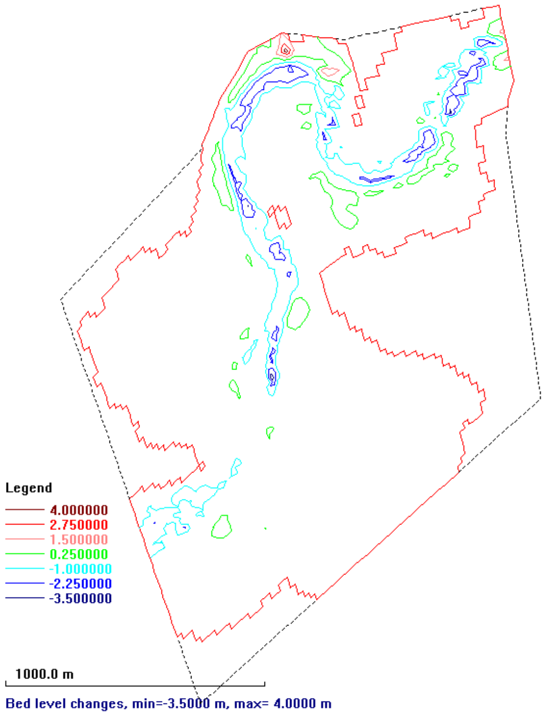
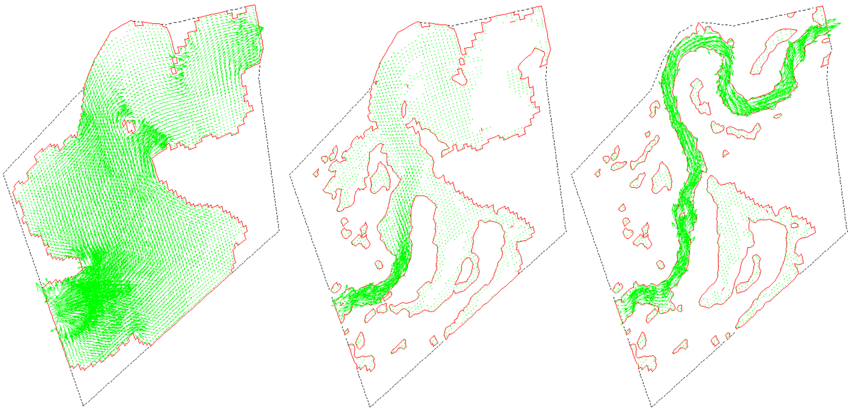


Figure 8.4: Bed changes for November flushing

Figure 8.5 on the following page shows water velocity plots for the November flushing. Figure 8.5a shows the velocity vectors at the beginning of the simulation, figure8.3b shows the velocity vectors when the water level is 573 metres and figure 8.3c shows the velocity vectors for the lowest water level of the simulation, 560 metres.



(a) (b) (c)

Figure 8.5: Velocity vectors for November flushing

Chapter 9

Discussion

9.1 Verification

In this section the results from the simulations are compared with measurements to verify whether the results are correct.

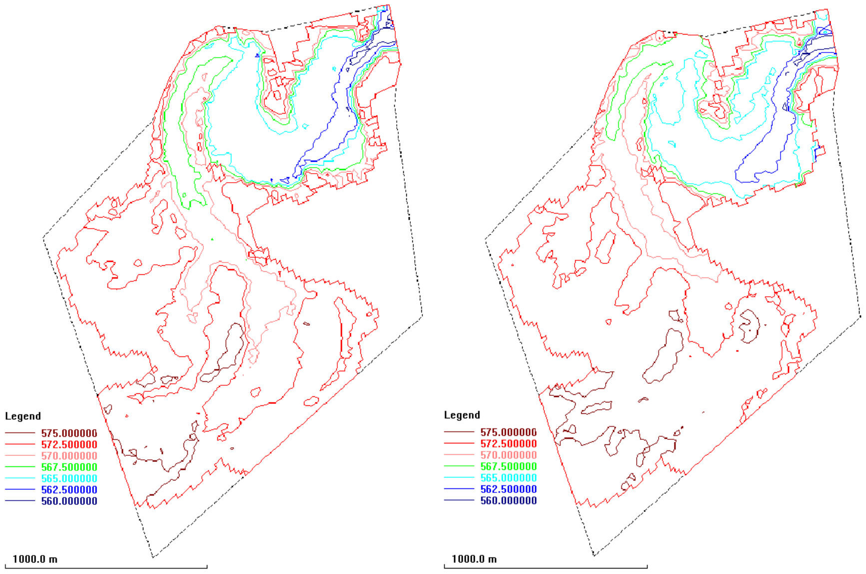
9.1.1 Deposition simulation

Figure 9.1a on the next page shows the measured bed levels in the Angostura reservoir from November 2008, this is the bed levels from before the deposition simulation. Figure 9.1b shows the measured bed levels after the deposition, from September 2009. To verify the results, these bed levels can be compared with the bed levels measured after the deposition. After the deposition, the bed levels have changed to what is shown in figure 9.1c. The deposition simulation has not been able to replicate the measured changes in bed levels, there are big differences between the measured and simulated bed levels. This can also be seen when comparing the simulated bed changes from figure 7.1 on page 31 to the measured bed changes from figure 6.4a on page 25.

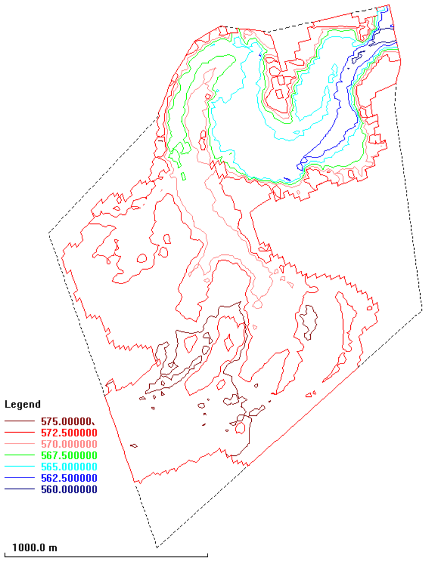
In section 6.3, the volumes of the Angostura reservoir at different times were found. From November 2008 to September 2009 there was a reduction in the volume of Angostura of 1.59 million cubic metres due to sediment deposition in the reservoir. Using the updated concentrations from section 7.2, the simulation concludes with a total bed change of 1.55 million cubic metres, this is a deviation of 2.5%.

9.1.2 September flushing

Figure 9.2a on page 43 shows the measured bed levels in Angostura before the September flushing and figure 9.2b shows the measured bed levels after the flushing. To verify the results, these bed levels can be compared with the bed levels measured after the flushing. After the simulation, the bed levels have changed to what is shown in figure 9.2c. There are some similarities between the simulated and measured bed levels, but the simulation has not been able to completely replicate the measured results. This can also be seen by comparing the simulated bed changes in figure 8.2 to the bed changes found in section 6.4.

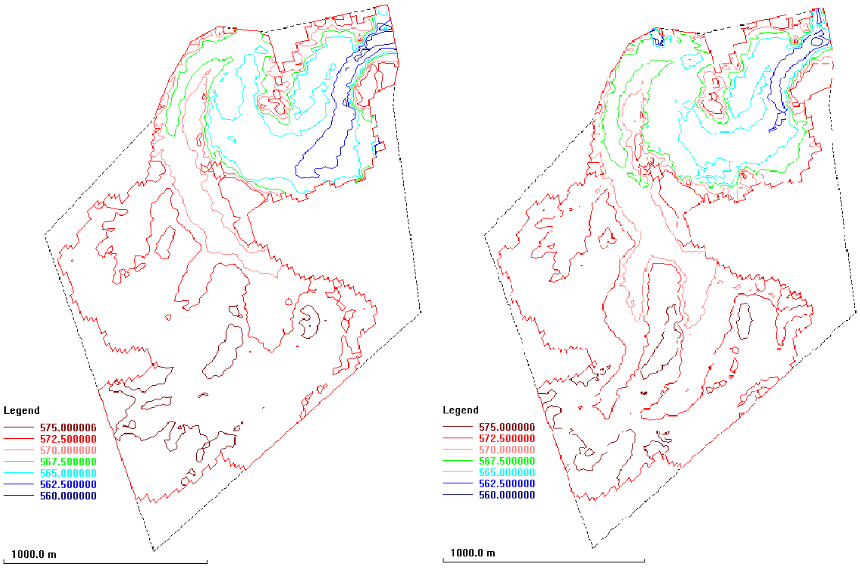


(a) Before deposition (b) After deposition, measured

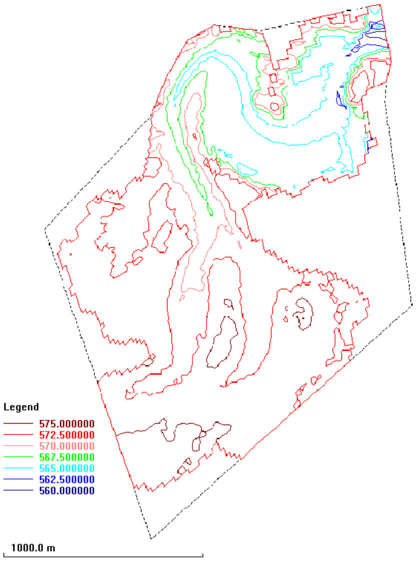


(c) After deposition simulated

Figure 9.1: Bed levels for deposition simulation



(a) Before flushing (b) After flushing, measured



(c) After flushing, simulated

Figure 9.2: Bed levels for September

In section 6.3, the volumes of the Angostura reservoir at different times were found. In September 2009 there was an increase in the volume of Angostura of 92,500 cubic metres. This increase was between the bathymetric survey 2 September and a bathymetric survey 17 September. After calibration, the simulation concludes with a total bed change of 93,893 cubic metres. This is a deviation of only 1.5%.

9.1.3 November flushing

Figure 9.3 on the next page shows the measured and simulated bed levels for the November flushing. Figure 9.3a shows the measured bed levels before the flushing and figure 9.3b shows the measured bed levels after the flushing. Figure 9.3c shows the resulting bed levels from the simulation. The simulation has not been able to replicate the measured data in a good way. This can also be seen by comparing the simulated bed changes in figure 8.4 to the bed changes found in section 6.4.

In the November flushing of Angostura 349,000 cubic meters of sediments was removed from the reservoir. This increase in the reservoir volume happened between the bathymetric survey September 17 and a bathymetric survey November 18. After calibration the simulation concludes with a total bed change of 356,543 cubic meters. This is a deviation of 2.1%.

9.2 Errors and uncertainties

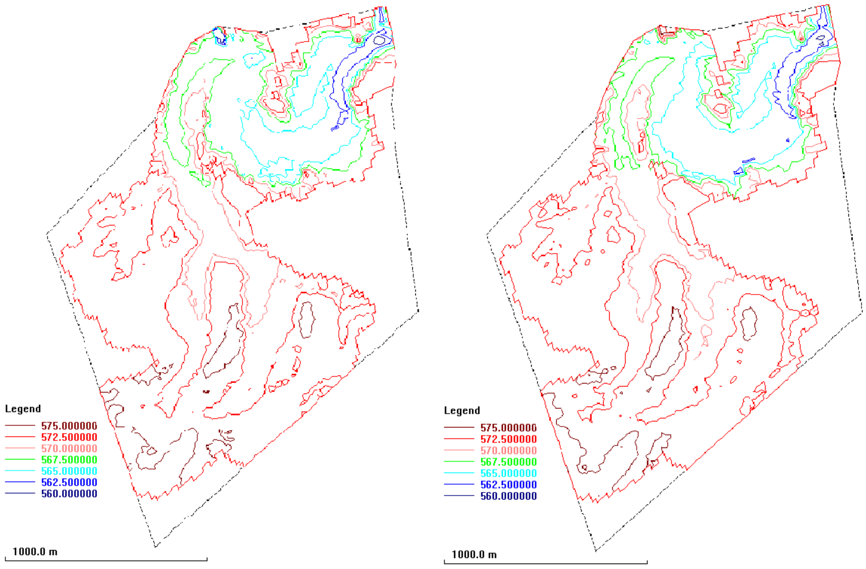
In section 2.3.3 on page 6, the most important errors and uncertainties in the use of CFD models were discussed. It is important to consider these when discussing the results. The following list goes through the errors and uncertainties stated in section 2.3.3 and discusses whether they are relevant for this case.

1. Modelling errors: The model uses some algorithms that does not reflect the real world conditions. One example is that the water level is lowered even though the inflow is equal to the outflow. This is discussed in section 8.1.

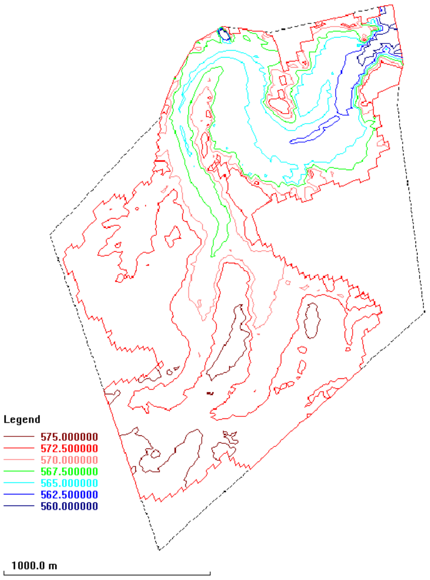
2. Errors in numerical approximations: The discretisation method used in these simulations is the first-order power-law. This could give some false diffusion problems. The grids are made in accordance to the criteria for a well functioning grid, which will reduce false diffusion.

3. Errors due to not complete convergence: For these simulations an iterative solver is used, and complete convergence has not been achieved for every time step. Achieving this would be too time consuming. There is a risk that incomplete convergence has led to inaccuracies in these simulations.

4. Rounding errors: The SSIIM version used for these simulations uses 32 bit floating point numbers. This means the accuracy is not perfect. There are however other sources of inaccuracy and uncertainty in these simulations that are much more significant than the accuracy of the floating point numbers.



(a) Before flushing (b) After flushing, measured



(c) After flushing, simulated

Figure 9.3: Bed levels for November

5. Errors in input data and boundary conditions: There are several uncertainties relating to the input data. This might lead to inaccuracies in the results.

6. Human errors due to inexperience of the user: As this project is performed with guidance from the creator of the program, this should not be a problem in this case.

7. Bugs in the software: As SSIIM has been used by a limited number of people and thus has relatively little testing, it may have many bugs. Most of these will not lead to wrong solutions, but rather lead to the program crashing.

9.3 Numerical algorithms

For the simulations, several numerical algorithms are chosen to be able to model the deposition and flushing of the Angostura reservoir.

The combination of algorithms in the control files in chapter 7 and 8 is the first combination of algorithms that led to a successful simulation. A choice of other algorithms may give different result or may lead to the simulation crashing. For more details on the algorithms, see the SSIIM manual.

9.3.1 Algorithms used

Data set $F\,36\,7$ is used for the computation of the vertical elevation of the water surface. The data set reads one integer. If this integer is 2 the water surface is updated based on the computed pressure field. If the integer is 7, as it is in these simulations, the water surface is updated based on the pressure in only its neighbouring cells. If the integer is 15, the water surface elevation is computed using gravity algorithms.

For the grid generation an algorithm to generate the grid lines in the longitudinal and lateral direction has to be chosen. This is done in the $F\,64$ data set. The algorithm used in these simulations is $F\,64\,11$. This is the most tested option for sediment transport computations in rivers and is believed to be the best option for these simulations. The algorithm gives a fitted grid with priority to hexahedral cells close to the bed which will insure better results in sediment computations than tetrahedral cells would.

The $F\,70\,1$ option has been implemented in the flushing simulations to prevents the computations from using bed laws on the sides. This is implemented because these wall laws have led to problems in simulations with wetting and drying. The $F\,102\,1$ algorithm is also implemented for the flushing simulations. This algorithm is used to change the shape of the grid cells close to the boundary for wetting and drying simulations. When an area dries up, the cells are converted to triangular cells, which leads to the boundary of the grid moving in and the grid shrinking.

Algorithms to stabilise the solution in the shallow areas close to the side walls are implemented. This is done on the $F\,113$ data set. The algorithm used in these simulations is the $F\,113\,7$ algorithm which defines that the extra term from the Rhie and Chow interpolation should not be more than 20% of the linear interpolation term.

There are a few algorithms that can be implemented to avoid grid problems, these are given on the F 159 data set. The F 159 data set reads five integers, each defining an algorithm to be used to solve a specific problem. In these simulations F 159 1 2 0 1 5 is used. If the integer is zero, the algorithms will not be invoked. The first integer invokes an algorithm that tries to remove dead-end channels with only one cell in the width. The second integer which can be from 1 to 10 chooses algorithms for dealing with the problem of ridges between wet cells. The number used for this simulation, 2, sets the water depth in these cells to minimum the minimum grid corner height given on the F 94 data set. The third integer invokes an algorithm which is not used in this simulations, but which tries to remove holes in the grid, where one cell has no connection to side neighbours. The fourth integer invokes an algorithm which removes single wet cells. The fifth integer invokes an algorithm which increases the water depth in partially dry cells by lowering the bed levels. The integer can be from 1 to 5. In this case 5 is used. This algorithm disconnects neighbouring cells if the area between them is smaller than a given small number.

The F 222 data set invokes algorithms which prevents the downstream bed level to rise to a height which may block the outflow. The data set reads one integer which is between 1 and 3.

The F 233 data set invokes algorithms that, instead of using the pressure in the surface cells to compute the water level, uses a depth-averaged pressure field. To improve the stability in triangular cells, the F235 data set may be used. F 235 10 which is used in this case, is the most successful of these algorithms. This option invokes an algorithm that gives extra relaxation in the triangular cells.

The F 246 data set has algorithms to stabilise the free surface algorithm. The data set reads three integers and a floating point number. The algorithms works on the connections between a cell and its neighbouring cells. The first integer invokes a limiter on the water depth in each cell. The second integer invokes an algorithm which deals with supercritical flow. The third integer deals with the value of the algorithm invoked by the first integer. If the third integer is -1, the value is the depth in the cell. If the third integer is -3, as it is in this case, the value is a function of the Froude number and the water depth. If the Froude number is higher than 1.0, the water level will be increased. This will prevent supercritical flow in the reservoir. The float given on the F 246 data set is a limiter on the surface slope.

The discretisation scheme used for the water flow equations in these simulations is the first-order power-law scheme given on the K 6 data set. Using the second-order upwind scheme could prevent false diffusion and thereby give a better solution. The first-order power-law scheme was chosen because it gives a more stable simulation. [Olsen, 2010]

9.3.2 Analysis of algorithms effect on the results

Changing the algorithms used to simulate the sediment deposition and flushing of the Angostura reservoir might affect the results of the simulation. Some alternative algorithms have been tested to consider their effects on the results of the simulations. The data sets and algorithms are explained above. The total bed change for September with the original algorithms was 93,893 cubic metres.

- F 159 1 9 0 1 5 instead of F 159 1 2 0 1 5
- No F 159 data set
- F 222 2 instead of F 222 3
- F 222 1 instead of F 222 3
- F 36 2 instead of F 36 7
- F 36 15instead of F 36 7??
- No F 70 data set
- Second-order upwind scheme instead of first-order power-law
- F 246 1 1 -1 0.01 instead of F 246 1 1 -3 0.01
- Using F 60 data set

When a different algorithm on the F 159 data set was chosen, the simulation was still stable, but it led to a different result. The total bed change using F 159 1 9 0 1 5 was 68,533 cubic metres. When using no F 159 data set, the simulation concluded with a total bed change of 90,863 cubic metres.

Using F 222 2 or F 222 1 instead of F 222 3 did not affect the results in any way. When testing the use of F 36 2, the simulation gave a total bed change of 81,581 cubic metres. Using F 36 15, the gravity algorithms for the water surface elevation, the velocity field becomes very unstable with vectors pointing in all directions and the simulation quickly crashes.

The simulation ran smoothly without the F 70 data set which has been known to cause problems in previous reservoir simulation cases. When not using this algorithm the simulation concluded with a total bed change of 90,863 cubic metres.

Using the second-order upwind scheme instead of first-order power-law led to a total bed change of 191,042 cubic metres, which is more than the double of the original results. When testing the F 246 1 1 -1 0.01 algorithms the the simulation was very similar to the original simulation, resulting in a bed change of 93,134 cubic metres.

Using the F 60 data set gives an erosion pattern that differs more from the measured results than the original simulation does. In addition to this, this data set gave a very high bed change. The total bed change using the F 60 data set became 699,938 cubic metres, almost 8 times more than the measured results.

It is clear that changes to algorithms *do* affect the results of the simulations. The algorithms giving a stable simulation and giving an erosion pattern similar to the measured results should be chosen. The total bed changes can be adjusted by changing the values in the F 6 data set.

9.4 Parameter sensitivity analysis

A parameter sensitivity analysis has been performed to assess the effect of changes in unclear parameters. The total bed change for September with the original parameters was 93,893 cubic metres. The following parameters are tested for the September flushing to see if a change in these parameters will lead to a significant change in the total bed changes:

- Bed roughness
- Shields parameter
- Effect of sloping bed correction
- Time step size
- Number of inner iterations
- Minimum grid corner height

The bed roughness in the original simulations was 0.1 metres. By changing this value down to 0.07 the total bed change became 82,611 cubic metres.

The Shield's coefficient used in these simulations is the default value, which the program calculates for each cell from Shield's curve. Using a value of 0.06 gives a total bed change of only 29,856 cubic metres. A value of 0.03 gives a total bed change of 149,473 cubic metres. This means that even small changes in Shield's coefficient will have a big effect on the results of the simulation.

When an algorithm for correction of sloping bed is included in the simulation, the resulting bed change becomes 96,885 cubic metres. This is a relatively small change from the original value. This algorithm will therefore not have a significant effect on the results.

A change in the time step length unfortunately had an effect on the results. Using a time step of 30 seconds (the original time step was 60 seconds) led to a total bed change of 74,746 cubic metres. A doubling of the number of inner iterations from 30 to 60, led to a total bed change of 89,174 cubic metres.

The original minimum grid corner height was 0.5 metres. By changing the minimum grid corner height to 0.4 metres the total bed change becomes 95,843 cubib metres. This means that the grid corner height has an effect on the results, but the effect is not very big.

9.5 Reasons for inaccuracies

There are several possible reasons for the results not matching the measurements. A potential source of error, especially for the sediment deposition, is the sediment inflow. The sediment transport in rivers is hard to measure and there are big variations in the estimates made for sediment transport in the Reventazón river. The volume development analysis indicates that the sediment inflow might be underestimented.

Only one measurement of the granulometry of the bottom sediments of the Angostura reservoir has been taken. Because of this lack of data, the granulometry of the bottom sediments had to be assumed to be constant in the reservoir, even though this is very unlikely. This will have an effect on the erosion taking place in the reservoir. In addition to the granulometry, the cohesion of the sediments also has an important effect on the erosion. The cohesion has not been measured and is therefore ignored in the simulations. If cohesion was included it would lead to reduced erosion potential in the reservoir. This might therefore be an important reason for that the simulations of reservoir flushing gave more erosion than what was measured. Another reason for the fact that the flushing simulations results do not fit completely with the measured data is that some time has passed between the measurements. The measured total bed change for the September flushing includes two weeks of deposition and the measured total bed change for the November flushing includes one month of deposition. This could help explain the slightly higher reduction in volume for the simulations compared to the measurements and it could also be an explanation for some of the deviations in the plots of bed changes and bed levels.

A problem in the simulations of reservoir flushing is that when the water level is lowered and there is only a channel through the reservoir, the width of this channel consists of only a couple of cells. This could have an effect on the results.

The choice of some essential parameters and algorithms unfortunately also had an effect on the results. For example, a change in the time step had a big effect on the resulting change in bed levels. The choices of algorithms affected both the erosion and deposition patterns and the total bed change.

There are many possible reasons for inaccuracies in the results of the simulations of sediment deposition and flushing for the Angostura reservoir, therefore further testing of the simulations should be done.

Chapter 10

Conclusion

The object of the project described in this master's thesis was to do three-dimensional modelling of sediment transport in a water reservoir and to analyse the volume development of the reservoir. This has been accomplished. SSIIM successfully runs simulations of both sediment deposition and flushing of the Angostura reservoir in Costa Rica. A volume development analysis showed that the volume of Angostura decreased rapidly the first six years of operation even though the reservoir was flushed yearly. At this time it was decided to do two yearly flushings of the reservoir. This strategy was very efficient and after this, the volume has remained stable with only a slight decrease. The analysis of the volume development also indicated that the sediment inflow to the reservoir might be higher than what has been estimated.

There are some deviations between the simulations and the measured results. For the deposition simulation the deposition pattern does not match the measured pattern. The measured data for the deposition period indicates a volume reduction of 1.59 million cubic metres, the simulation had a deviation of 2.5% from this result.

The results for the September flushing are very good. The erosion and deposition pattern is similar to the measured results with two eroded channels in the upstream area and deposition in the downstream area of the reservoir. The measuered data say that the September flushing led to a volume increase of 92,500 cubic metres. After calibration the simulation gives a volume change very close to this, with a deviation of only 1.5%.

The simulation of the November flushing was also sucessful, but it was not able to replicate the measured data as well as the September flushing simulation. The resulting erosion pattern for the simulation gave an eroded channel through the entire reservoir with little changes outside of the channel. The measured data does not show a clearly eroded channel. The measured data indicates a volume increase of 349,000 cubic metres while the simulation had a deviation of 2.1% from this result.

There are many uncertainties concerning these simulations. The sediment inflow to the reservoir and the cohesion of the sediments are examples of input data which is very uncertain, but has a big effect on the results. There should still be done some more work on improving the input data and in testing the algorithms used. Further work is necessary to assess whether these simulations can be used to predict the future conditions in the Angostura reservoir.

Chapter 11

Further Work

There is a lot of work that can be done to improve the results of these simulations. This work can also be used to predict future volume development of the Angostura reservoir .

The first thing that should be done is to collect the data which were missing during these simulations. Amongst this lacking data is the bed sediments. Measurements of the granulometry and cohesion of the bed sediments in the reservoir should be taken as this will give more correct results for the erosion taking place in the reservoir. Other than this, measurements of water levels and discharges in and out of the reservoir during the flushings should also be taken. This will give more realistic flushing simulations. It would also be good to have better data about the inflowing sediments throughout the year. The value used for roughness in these simulations is not based on measurements, it would therefore be useful to make some estimates on this parameter, if possible.

The flushing simulations should be tested with a finer grid to see if this will make a difference on the results. The reason for this is that there was very few cells in the grid when the water level was low. The Angostura reservoir has several bottom outlets which are used one by one during the flushing. The location of these outlets affect the erosion pattern in the reservoir and it would therefore be interesting to model the flushings with this moving outlet.

Since the analysis of algorithms and parameter sensitivity concluded that there is a lot of uncertainties concerning the algorithms and parameters used, it is important to have further testing of these effects.

In this project only one year of deposition and flushings has been simulated. If it is possible to fit these simulations better to the measured data, simulations can be run to predict the future volume development of the Angostura reservoir. This could be a 20 year simulation including the two yearly flushings. By running a simulation like this it will be possible to predict the lifetime of Angostura. It will also be possible to see whether today's procedure is sufficient to prevent the reservoir from filling up too soon. The model can also be used to test different flushing scenarios to see what will be most effective, and insure as much erosion as possible in the reservoir.

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Appendix A

Assignment

The following text is the assignment for this project, the text is only produced in Norwegian:

Tredimensjonal numerisk modellering av sedimenter i vannreservoirer

Bakgrunn

I mange land er det stor transport av sedimenter i elvene, og dette fører til problemer for vannreservoirene. Sedimenter deponerer der en har minsket vannhastighet, og reservoirene får mindre kapasitet. Et av disse landene er Costa Rica, der de lokale kraftselskapet ICE (Instituto Costariccense de Electricidad) eier flere reservoirer med slike problemer. I et prosjekt finansiert fra Norges Forskningsråd arbeider Institutt for vann og miljøteknikk ved NTNU med denne problemstillingen. NTNU samarbeider med ICE om å modellere sedimentbevegelsene med en tredimensjonal numerisk modell.

I dette prosjektet er ønskelig å gjøre innledende beregninger av sedimenttransporten i et reservoir i Costa Rica. Det er også ønskelig å samle inn data som trengs for beregningen, både inputdata og data for verifisering av modellen. I dette vil det inngå et feltarbeide i Costa Rica, der det samles inn data for romlig fordeling av sedimentegenskaper i reservoiret. Disse sedimentegenskapene er i første rekke kornfordeling, men også in situ tetthet og kritisk skærspenning for potensielle kohesive materialer vil være nyttig å måle, hvis dette er mulig.

I feltarbeidet vil en samarbeide med de avdelingene i ICE som arbeider med sedimenter i reservoirer. En ønsker også å få data fra ICE når det gjelder topografiske forhold i reservoirene, slik som bunntopografi på forskjellige tidspunkter. En ønsker også å få hydrologiske data, slik som vannføringene inn i reservoiret og vannstandene over tid. Mengden sedimenter som strømmer inn i reservoiret og dens kornfordeling er også nødvendige data for den numeriske modelleringen.

Viktigste spørsmål i oppgaven

Oppgaven skal besvare følgende spørsmål:

- Hvordan lage et grid for reservoiret i Costa Rica?

- Hva er kornfordelingen for bunnsedimentene i reservoiret?
- Hvordan lager man input-data for berergningen av sedimentene i reservoiret?
- Hva blir hastighetsfeltet i reservoiret?
- Er det mulig å beregne hvor de innstrømmende sedimentene deponerer?
- Hvordan stemmer deponeringsberegningene med målingene?
- Er det mulig å beregne utspyling av sedimenter fra reservoiret?
- Hvordan stemmer spyleberegningene med målingene?
- Hvordan påvirkes resultatene av bruk av forskjellige numeriske algoritmer?

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 Rüther, og Peggy Zinke 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

Volume development

B.1 Volume development for Angostura

Table B.1 shows the numbers used to make the graph in figure 6.2 on page 22. The numbers are found by comparing bathymetric surveys from the last 10 years using SSIIM.

Date	Total volume [m^3]	Dead storage [m^3]	Live storage [m^3]
01-Dec-00	1.8928E+07	5.7822E+06	1.3146E+07
01-Dec-01	1.8635E+07	5.7011E+06	1.2934E+07
23-Sep-02	1.7743E+07	5.4250E+06	1.2318E+07
01-Aug-03	1.6626E+07	4.9695E+06	1.1656E+07
01-Oct-03	1.6732E+07	4.8326E+06	1.1900E+07
12-Oct-04	1.5767E+07	4.5905E+06	1.1177E+07
28-Oct-04	1.5628E+07	4.5136E+06	1.1114E+07
01-Nov-05	1.4406E+07	4.1531E+06	1.0253E+07
05-Sep-06	1.3502E+07	4.4224E+06	9.0794E+06
22-Sep-06	1.4587E+07	4.1659E+06	1.0421E+07
01-Nov-06	1.5051E+07	4.4232E+06	1.0628E+07
04-Oct-07	1.4363E+07	4.3601E+06	1.0003E+07
16-Oct-07	1.2886E+07	4.5491E+06	8.3367E+06
28-Nov-07	1.5115E+07	4.4536E+06	1.0662E+07
03-Sep-08	1.3783E+07	4.2110E+06	9.5715E+06
29-Oct-08	1.3593E+07	4.3034E+06	9.2900E+06
12-Nov-08	1.4352E+07	4.3807E+06	9.9709E+06
02-Sep-09	1.2765E+07	4.2310E+06	8.5339E+06
17-Sep-09	1.3690E+07	4.5296E+06	9.1602E+06
18-Nov-09	1.4039E+07	4.2636E+06	9.7755E+06

Table B.1: Volume development for Angostura

Appendix C

Input for simulation of sediment deposition

C.1 Calculation of sediment concentrations

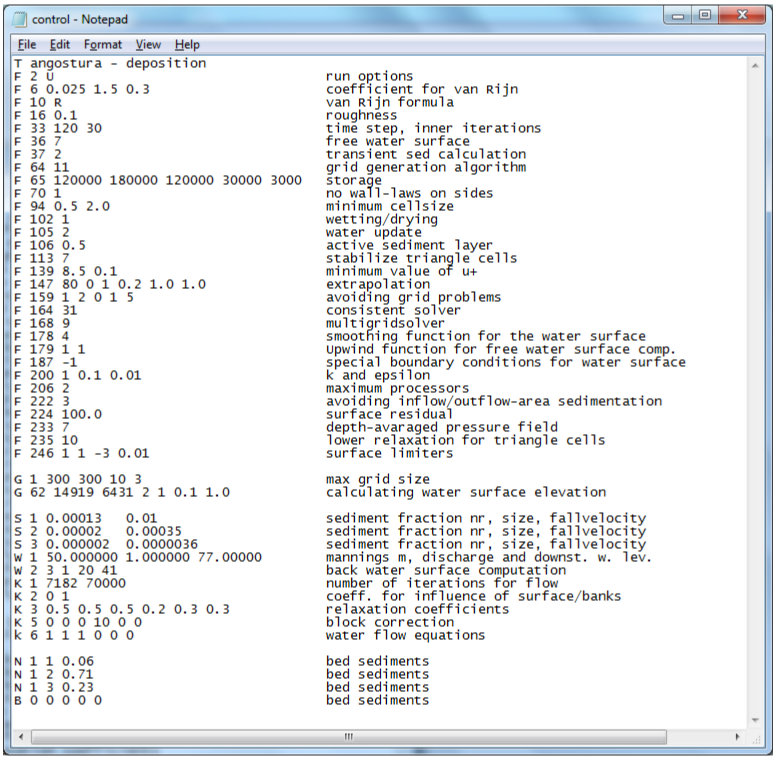
A discharge of 350 $^{m^3}/_s$ is chosen for the simulations. We need a sediment concentration in cubic metres sediments per cubic metres water as input for the simulation. Table 7.1 on page 27 shows that the discharge of 350 $^{m^3}/_s$ accounts for 5.67% of the yearly sediment load and that the discharge has a duration of 24 hours. The inflow of sediments in one day is 85,060 tonnes. This equals to a sediment inflow of 1.0 tonne/s, with a standard sediment density of 2.65 tonnes/m3, this again equals to 0.37 $^{m^3}/_s$. The sediment concentration as a volume fraction will therefore be $0.37\,^{m^3}/_s / 350\,^{m^3}/_s = 0.00106$.

With a discharge of 350 $^{m^3}/_s$ the granulometry can be represented by 23% sand, 50% silt and 27% clay. [Løvoll, 1994] This gives us the concentrations shown in table C.1.

The model is supposed to simulate a time period of 280 days. We therefore have to calculate the total amount of sediments entering the reservoir in this time period. Since the flushing of Cachí is after the end of this simulation and accounts for a big part of the yearly sediment load, it is not natural to include this when finding the average daily sediment load for the rest of the year. When finding the sediment load for the 280 days I have assumed an even distribution of the sediment inflow throughout the year except during the Cachí flushings. The sediment load from the Cachí flushing which lasts for 2 days is first subtracted from the yearly sediment load to find the sediment load for the remaining 363 days. The total sediment load for the simulation period is then calculated. $(1,500,000 - 400,000)\,tonnes \cdot {}^{280}/_{363} = 848,485\,tonnes$.

Sediment size $[mm]$	Percentage	Concentration $[^{m^3}/_{m^3}]$
0.13 (sand)	23	0.00024
0.02 (silt)	50	0.00053
0.002 (clay)	27	0.00029

Table C.1: Sediment concentrations



```
T angostura - deposition
F 2 U                                  run options
F 6 0.025 1.5 0.3                      coefficient for van Rijn
F 10 R                                 van Rijn formula
F 16 0.1                               roughness
F 33 120 30                            time step, inner iterations
F 36 7                                 free water surface
F 37 2                                 transient sed calculation
F 64 11                                grid generation algorithm
F 65 120000 180000 120000 30000 3000   storage
F 70 1                                 no wall-laws on sides
F 94 0.5 2.0                           minimum cellsize
F 102 1                                wetting/drying
F 105 2                                water update
F 106 0.5                              active sediment layer
F 113 7                                stabilize triangle cells
F 139 8.5 0.1                          minimum value of u+
F 147 80 0 1 0.2 1.0 1.0               extrapolation
F 159 1 2 0 1 5                        avoiding grid problems
F 164 31                               consistent solver
F 168 9                                multigridsolver
F 178 4                                smoothing function for the water surface
F 179 1 1                              Upwind function for free water surface comp.
F 187 -1                               special boundary conditions for water surface
F 200 1 0.1 0.01                       k and epsilon
F 206 2                                maximum processors
F 222 3                                avoiding inflow/outflow-area sedimentation
F 224 100.0                            surface residual
F 233 7                                depth-avaraged pressure field
F 235 10                               lower relaxation for triangle cells
F 246 1 1 -3 0.01                      surface limiters

G 1 300 300 10 3                       max grid size
G 62 14919 6431 2 1 0.1 1.0            calculating water surface elevation

S 1 0.00013   0.01                     sediment fraction nr, size, fallvelocity
S 2 0.00002   0.00035                  sediment fraction nr, size, fallvelocity
S 3 0.000002  0.0000036                sediment fraction nr, size, fallvelocity
W 1 50.000000 1.000000 77.00000        mannings m, discharge and downst. w. lev.
W 2 3 1 20 41                          back water surface computation
K 1 7182 70000                         number of iterations for flow
K 2 0 1                                coeff. for influence of surface/banks
K 3 0.5 0.5 0.5 0.2 0.3 0.3            relaxation coefficients
K 5 0 0 0 10 0 0                       block correction
k 6 1 1 1 0 0 0                        water flow equations

N 1 1 0.06                             bed sediments
N 1 2 0.71                             bed sediments
N 1 3 0.23                             bed sediments
B 0 0 0 0 0                            bed sediments
```

Figure C.1: Control file

With a discharge of 350 $^{m^3}/_{s}$ and a sediment inflow of 85,060 tonnes/day it will take 10 days for the inflow of the total sediment load of the simulation period calculated above. With a time step of 120 seconds the model will have to do 7182 iterations.

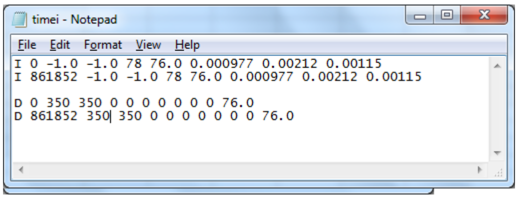
C.2 Control file

Figure C.1 shows the control file for the deposition simulation. The most important data sets are explained in section 7.1.2 on page 28, the rest can be found in the SSIIM manual.

C.3 Timei file

The timei file used for the simulation of sediment deposition is shown in figure C.2 on the next page. The *I* data set sets the water level for the discharge groups and sets the sediment concentrations. The number after the *I* is the time when the values are to be used. The time is given in seconds after the start of the process. The fourth number gives the water level for the first discharge group, this is the upstream water level. The fifth number gives the level of the second discharge group, the downstream water level. The three following numbers give the concentration of the three sediment groups given in the S data set

Figure C.2: Timei file



```
I 0 -1.0 -1.0 78 76.0 0.000977 0.00212 0.00115
I 861852 -1.0 -1.0 78 76.0 0.000977 0.00212 0.00115

D 0 350 350 0 0 0 0 0 0 0 76.0
D 861852 350 350 0 0 0 0 0 0 0 76.0
```

in the control file. These concentrations are taken from table 7.2 on page 28. The second and third numbers represents the upstream and downstream water discharges. When they are set to “-1.0”, the program will calculate these values.

The *D* data set gives the discharges for the inflow and outflow groups. The first value is the time, as in the *I* data set. The following numbers are discharges for up to nine discharge groups. In the Angostura case, only one inflow and one outflow is used, therefore the two first values are given and the rest are set to zero. The last number in the *D* data set is the downstream water level.

Appendix D

Input for simulation of reservoir flushing

D.1 Calculation of sediment concentrations

D.1.1 September flushing

The September flushing has six different sediment inflow situations:

1. Water inflow 150 $^{m^3}/_{s}$, normal sediment inflow. Sediment concentration
2. Water inflow 450 $^{m^3}/_{s}$, sediment inflow dependent on Cachí flushing
3. Water inflow 150 $^{m^3}/_{s}$, sediment inflow dependent on Cachí flushing
4. Water inflow 37.5 $^{m^3}/_{s}$, sediment inflow dependent on Cachí flushing
5. Water inflow 37.5 $^{m^3}/_{s}$, normal sediment inflow
6. Water inflow 75 $^{m^3}/_{s}$, normal sediment inflow

Group 1, 5 and 6

Table D.1 shows the data used for calculating sediment concentrations. The sediment load and discharge durations are taken from table 7.1 on page 27. The percentages are from Løvoll 1994. The percentages from the 100 discharge is used for both 75 and 37.5, this is because there is no information about lower discharges. Since the sediment concentrations for these discharges are very low, this will not have a big effect.

The concentration are calculated as for the sediment deposition simulation (see section C.1). The results are shown in table D.2 on the facing page.

Group 2, 3 and 4

Group 2, 3 and 4 are the discharges that carries the flushed sediments from Cachí to Angostura. This is a 48 hour process where in total 400,000 tonnes of sediments enter Angostura. It is assumed that 50% of the sediments enters

	$150\,{}^{m^3}\!/_{s}$	$37.5\,{}^{m^3}\!/_{s}$	$75\,{}^{m^3}\!/_{s}$
0.13 (sand)	20%	17%	17%
0.02 (silt)	42%	47%	47%
0.002 (clay)	38%	36%	36%
Sediment load	68533 tonnes	315 tonnes	4772 tonnes
Discharge duration	22 days	54 days	30 days

Table D.1: Sediment inflow data

	Sediment concentrations $[{}^{m^3}\!/_{m^3}]$		
Group	0.13(sand)	0.02(silt)	0.002(clay)
1	1.81E-05	3.81E-05	3.45E-05
2	1.79E-03	3.88E-03	2.10E-03
3	8.13E-04	1.71E-03	1.55E-03
4	5.28E-04	1.46E-03	1.12E-03
5	1.98E-07	5.47E-07	4.19E-07
6	1.57E-06	4.35E-06	3.33E-06

Table D.2: Sediment concentrations

with group 2 in 6 hours, 48% with group 3 in 33 hours and 2% with group 4 in 9 hours. This leads to the following calculations for group 2:

50 % of 400,000 tonnes of sediments in 6 hours is equal to $400,000\,tonnes \cdot 50\%/(6 \cdot 60 \cdot 60\ sec) = 0.93\ {}^{tonnes}\!/_{s}$. With a standard sediment density of $2.65\ {}^{tonnes}\!/_{m^3}$, this again equals to $3.49\ {}^{m^3}\!/_{s}$. The sediment concentration as a volume fraction will therefore be $3.49\,{}^{m^3}\!/_{s}/450\,{}^{m^3}\!/_{s} = 0.007765$. The calculations for group 3 and 4 is done in the same way as group 2 and the results are shown in table D.2.

D.1.2 November flushing

In the November flushing there are two different discharges. One discharge of $100\ {}^{m^3}\!/_{s}$ for the emptying and erosion phase and $130\ {}^{m^3}\!/_{s}$ for the filling of the reservoir. Sediment concentrations in cubic metres sediments per cubic metres water is needed as input for the simulation. Table D.3 shows the data used for calculating sediment concentrations. The sediment load and discharge durations are taken from table **??** on page ??. The percentages are from Løvoll 1994.

The discharge of $100\,{}^{m^3}\!/_{s}$ accounts for 63,132 tonnes of sediments with a duration of 68 days. This means the inflow of sediments in one day is $53132/68 = 0.93\,tonnes$. This equals to a inflow of $0.011\,{}^{tonnes}\!/_{s}$. With a standard sediment density of $2.65{}^{tonnes}\!/_{m^3}$, this again equals to $0.004{}^{m^3}\!/_{s}$. The sediment concentration as a volume fraction will therefore be $0.004\,{}^{m^3}\!/_{s}/100\,{}^{m^3}\!/_{s} = 4.05491 \cdot 10^{-5}$.

With a discharge of $100\ {}^{m^3}\!/_{s}$ the granulometry can be represented by 17% sand, 47% silt, and 36% clay. The sediment concentrations for $130\ {}^{m^3}\!/_{s}$ is calculated in the same way. This gives us the concentrations shown in table D.4.

	100 $^{m^3}/_{s}$	130 $^{m^3}/_{s}$
0.13 (sand)	17%	20%
0.02 (silt)	47%	42%
0.002 (clay)	36%	38%
Sediment load	63132 tonnes	64153 tonnes
Discharge duration	68 days	36 days

Table D.3: Sediment inflow data

	Sediment concentrations $^{m^3}/_{m^3}$		
Discharge	0.13(sand)	0.02(silt)	0.002(clay)
100	6.89E-06	1.46E-05	1.46E-05
130	1.01E-05	2.12E-05	1.92E-05

Table D.4: Sediment concentrations

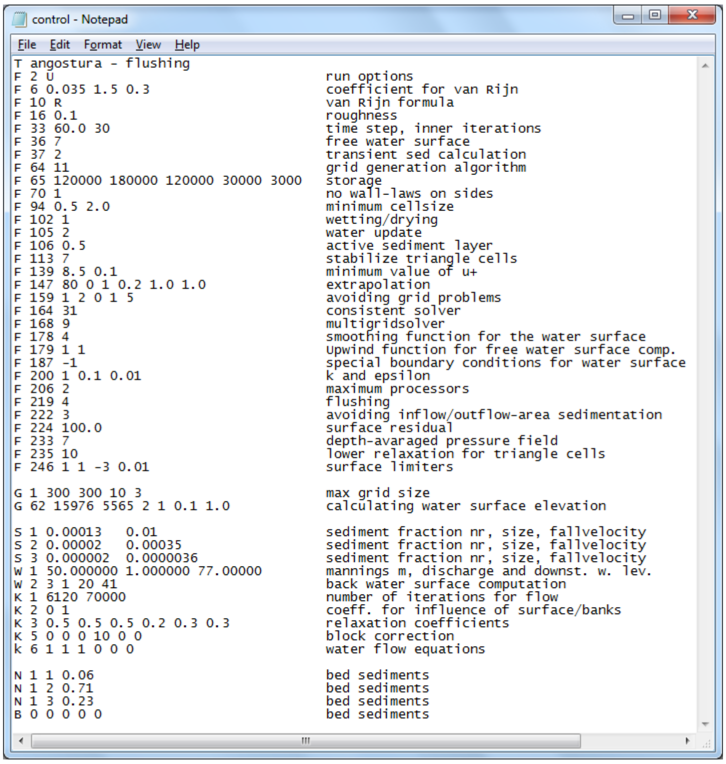
D.2 Control files

Figure D.1 on the next page shows the control file for the September flushing. The control file for the November flushing is identical to the one for the September flushing except for the F 6 data set and the number of iterations. The F 6 data set has coefficients for "van Rijn's formula" which is used for the calibration of the total bed changes. While the September flushing uses F 6 0.035 1.5 0.3, the November flushing uses F 6 0.020 1.5 0.3. The September simulation has 6120 iterations while the November simulation has 6840 iterations. The most important data sets are explained in section 8.1.2 on page 33 and 9.3 the rest can be found in the SSIIM manual.

D.3 Timei files

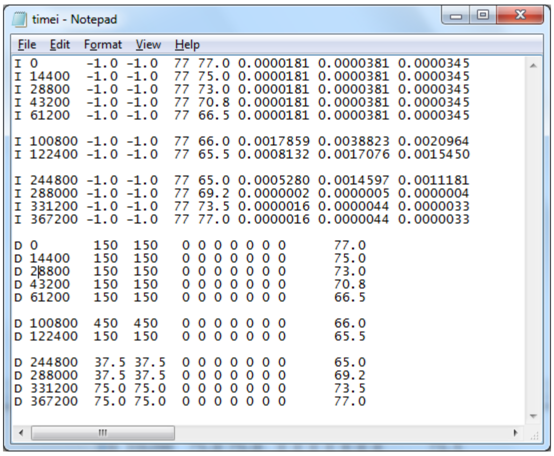
The timei file used for the September reservoir flushing simulation is shown in figure D.2 on the next page. See section C.3 on page 58 for explanation of the data sets in the timei file. During a reservoir flushing the water level changes over time, therefore a time series is used for the simulation. In the timei file the time series are inserted as several *I* and *D* data sets. Table D.5 on page 64 shows a more comprehensible overview of the time series used in the file.

The timei file used for the November flushing is shown in figure D.3.



```
T angostura - flushing
F 2 U                                  run options
F 6 0.035 1.5 0.3                      coefficient for van Rijn
F 10 R                                 van Rijn formula
F 16 0.1                               roughness
F 33 60.0 30                           time step, inner iterations
F 36 7                                 free water surface
F 37 2                                 transient sed calculation
F 64 11                                grid generation algorithm
F 65 120000 180000 120000 30000 3000   storage
F 70 1                                 no wall-laws on sides
F 94 0.5 2.0                           minimum cellsize
F 102 1                                wetting/drying
F 105 2                                water update
F 106 0.5                              active sediment layer
F 113 7                                stabilize triangle cells
F 139 8.5 0.1                          minimum value of u+
F 147 80 0 1 0.2 1.0 1.0               extrapolation
F 159 1 2 0 1 5                        avoiding grid problems
F 164 31                               consistent solver
F 168 9                                multigridsolver
F 178 4                                smoothing function for the water surface
F 179 1 1                              Upwind function for free water surface comp.
F 187 -1                               special boundary conditions for water surface
F 200 1 0.1 0.01                       k and epsilon
F 206 2                                maximum processors
F 219 4                                flushing
F 222 3                                avoiding inflow/outflow-area sedimentation
F 224 100.0                            surface residual
F 233 7                                depth-avaraged pressure field
F 235 10                               lower relaxation for triangle cells
F 246 1 1 -3 0.01                      surface limiters

G 1 300 300 10 3                       max grid size
G 62 15976 5565 2 1 0.1 1.0            calculating water surface elevation

S 1 0.00013   0.01                     sediment fraction nr, size, fallvelocity
S 2 0.00002   0.00035                  sediment fraction nr, size, fallvelocity
S 3 0.000002  0.0000036                sediment fraction nr, size, fallvelocity
W 1 50.000000 1.000000 77.00000        mannings m, discharge and downst. w. lev.
W 2 3 1 20 41                          back water surface computation
K 1 6120 70000                         number of iterations for flow
K 2 0 1                                coeff. for influence of surface/banks
K 3 0.5 0.5 0.5 0.2 0.3 0.3            relaxation coefficients
K 5 0 0 0 10 0 0                       block correction
k 6 1 1 1 0 0 0                        water flow equations

N 1 1 0.06                             bed sediments
N 1 2 0.71                             bed sediments
N 1 3 0.23                             bed sediments
B 0 0 0 0 0                            bed sediments
```

Figure D.1: September control file



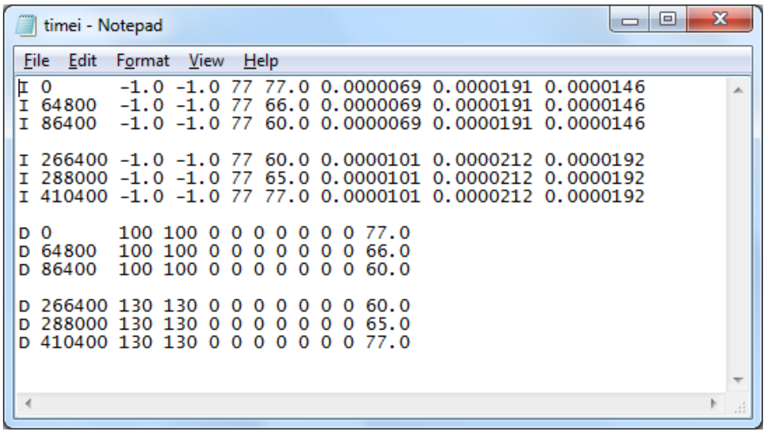
```
I 0      -1.0 -1.0  77 77.0 0.0000181 0.0000381 0.0000345
I 14400  -1.0 -1.0  77 75.0 0.0000181 0.0000381 0.0000345
I 28800  -1.0 -1.0  77 73.0 0.0000181 0.0000381 0.0000345
I 43200  -1.0 -1.0  77 70.8 0.0000181 0.0000381 0.0000345
I 61200  -1.0 -1.0  77 66.5 0.0000181 0.0000381 0.0000345

I 100800 -1.0 -1.0  77 66.0 0.0017859 0.0038823 0.0020964
I 122400 -1.0 -1.0  77 65.5 0.0008132 0.0017076 0.0015450

I 244800 -1.0 -1.0  77 65.0 0.0005280 0.0014597 0.0011181
I 288000 -1.0 -1.0  77 69.2 0.0000002 0.0000005 0.0000004
I 331200 -1.0 -1.0  77 73.5 0.0000016 0.0000044 0.0000033
I 367200 -1.0 -1.0  77 77.0 0.0000016 0.0000044 0.0000033

D 0       150  150   0 0 0 0 0 0 0      77.0
D 14400   150  150   0 0 0 0 0 0 0      75.0
D 28800   150  150   0 0 0 0 0 0 0      73.0
D 43200   150  150   0 0 0 0 0 0 0      70.8
D 61200   150  150   0 0 0 0 0 0 0      66.5

D 100800  450  450   0 0 0 0 0 0 0      66.0
D 122400  150  150   0 0 0 0 0 0 0      65.5

D 244800  37.5 37.5  0 0 0 0 0 0 0      65.0
D 288000  37.5 37.5  0 0 0 0 0 0 0      69.2
D 331200  75.0 75.0  0 0 0 0 0 0 0      73.5
D 367200  75.0 75.0  0 0 0 0 0 0 0      77.0
```

Figure D.2: September timei file

Time [hours]	Time step [sec]	Water level [m]
0	0	77.0
4	14400	75.0
8	28800	73.0
12	43200	70.8
17	61200	66.5
68	244800	65.0
80	288000	69.2
92	331200	73.5
102	367200	77.0

[Meza, 2009b]

Table D.5: Time series



```
I 0      -1.0 -1.0 77 77.0 0.0000069 0.0000191 0.0000146
I 64800  -1.0 -1.0 77 66.0 0.0000069 0.0000191 0.0000146
I 86400  -1.0 -1.0 77 60.0 0.0000069 0.0000191 0.0000146

I 266400 -1.0 -1.0 77 60.0 0.0000101 0.0000212 0.0000192
I 288000 -1.0 -1.0 77 65.0 0.0000101 0.0000212 0.0000192
I 410400 -1.0 -1.0 77 77.0 0.0000101 0.0000212 0.0000192

D 0      100 100 0 0 0 0 0 0 0 77.0
D 64800  100 100 0 0 0 0 0 0 0 66.0
D 86400  100 100 0 0 0 0 0 0 0 60.0

D 266400 130 130 0 0 0 0 0 0 0 60.0
D 288000 130 130 0 0 0 0 0 0 0 65.0
D 410400 130 130 0 0 0 0 0 0 0 77.0
```

Figure D.3: November timei file