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Open Channel Flow Simulation
(Sedimentation Problem in Rosaries Dam)

A thesis submitted in partial fulfillment of the requirements
for the degree of M.Sc. in Energy Engineering

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اﷲ قَالَ: ﴿وَجَعَلْنَا ﻲَﻫُودًا ﺷَﻲْﻛﻞَ إِﻝَى ﻣَنْ ﻓِيهِ ﻣَئِذٍ ﻟَمْ يُؤْمِنُوا ۚ يُبَارَءُ ﻓِيهِ ﻣَئِذٍ ۚ ﺑِلَّا تُؤْمِنُوا ۖ إِنَّا ﻋِنْدَكُمْ ﺑِدْرَءٍ ﻣَا ﻓِيهِ ﻣَئِذٍ.﴾‏

صدق الله العظيم
This work is dedicated to all those advised and directed me to the way of studying and toiled and moiled to put me on the right study tract.

To those who have made me get use of their experiences and experiments.

To Dr. Ali Mohammed Ali who has made the completion of this work easy and possible by his precious advice and by the generous aid that he has offered me.

He has also been kind and patient enough to follow me preparing the manuscript and to make constructive.
First, praise is to Alla, the first cherisher and substainer of the globe. Acknowledgments here are more than a decoration ritual. The teachers, laborers and Eng. Alnzeer saad from Rosaries Dam. I’m indebted to all of them because of their unlimited support and advice. They were all patient and generous in helping me.

I also acknowledge scholars and institutions. I am also indebted, a debt which one acknowledges with both delight and pride.
Abstract

Sedimentation problem, in Rosaries Dam, is one of the biggest problems facing the electrical hydropower generation, especially during autumn. Sedimentation reduces the storage capacity of the lake behind the dam and increases the cost of the MWH due to the high cost of silt removal.

This thesis is about a CFD application (SSIIM program) used to describe and simulate the water flow and sediment concentration (considered as solid particles) in the reservoir. SSIIM is designed for the analysis of such phenomenon. Simulations were done for three types of sediments according to their diameters and taken into account that the turbine gates are fully opened and all other gates are closed. These simulations and analysis lead to suitable solutions for silt removal and by consequence reduce the cost of such operations.

This study explains the direction of velocity vectors, vortices and sediment concentration that occur behind the dam in the three Cartesian coordinate (x, y and z). Results are presented, for samples of each type of sediment, for different longitudinal profiles and depths.
ت保护区

تعتبر مشكلة الاطماء من أكبر المشاكل التي تواجه توليد الطاقة الكهربائية في فترة الخريف في خزان الرصیرص مما يودي إلى ارتفاع كبير في تكلفة توليد الطاقة بسبب تكاليف إزالتها وكذلك يؤدي إلى تقليل الحجم التخزيني للبحيرة.

تناول هذا البحث تطبيق برنامج تحسين حركة المائع (CFD) في محاكاة سريان الماء وتركيز حبيبات الطمي (كأجسام صلبة) في بحيرة خزان الرصیرص.

استخدام هذا التطبيق يودي إلى إيجاد اتجاه التغييرات وكذلك متجهات السرعة ونسبة تركيز الاطماء خلف البحيرة مما يساعد في اختيار المعالجات المناسبة التي بدورها تودي إلى تقليل تكلفة إزالة الاطماء.

استخدم برنامج (SSIM) المخصص في عمل المحاكاة بالنسبة لسريان الماء وتركيز الاطماء وتم إجراء المحاكاة لثلاث عينات من الطمي حددت حسب أقطارها مع الأخذ في الاعتبار ان بوابات التوربينات مفتوحة وبقية الأبواب مغلقة.

هذه الدراسة وضحت شكل التيارات المائية ومتجهات السرعة وتركيز الاطماء خلف الخزان من الاعدادات الكارثية الثلاث لاعقاب مختلفه ومقاطع طولية مختلفه لكل نوع.
# List of Contents

<table>
<thead>
<tr>
<th>Page No.</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>Dedicating</td>
</tr>
<tr>
<td>iii</td>
<td>Acknowledgment</td>
</tr>
<tr>
<td>iv</td>
<td>Abstract</td>
</tr>
<tr>
<td>v</td>
<td>تجريد</td>
</tr>
<tr>
<td>vi</td>
<td>List of Content</td>
</tr>
<tr>
<td>ix</td>
<td>List of figures</td>
</tr>
<tr>
<td>xi</td>
<td>List of tables</td>
</tr>
<tr>
<td>xii</td>
<td>List of symbols</td>
</tr>
</tbody>
</table>

## CHAPTER -1 – INTRODUCTION

1.1 Motivation 1
1.2 Objectives 2
1.3 Thesis Outline 3

## CHAPTER – 2 -LITERATURE REVIEW

2.1 Introduction 4
2.2 3d Calculation Of Trap Efficiency Of A Sand Trap 4
2.3 Sediment Deposition And Bed Movements In A Sand Trap 5
2.4 Himalaya Intake 7
2.5 Calculation Of Water & Sediment Flow In A Hydropower Reservoir 8
2.6 Reservoir Flushing 9

## CHAPTER -3 – SEDIMENT AND WATER FLOW CALCULATION

3.1 Introduction 12
3.2 The Blue Nile River
  3.2.1 Hydrology
3.3 Roseires Power Station And Dam
  3.3.1 Dam (First Stage)
3.4 Sedimentation Engineering
  3.4.1 Sedimentation Classification In Engineering Hydraulics
  3.4.2 Siltation Of The Blue Nile
  3.4.3 Effect Of The Sediment
  3.4.4 How To Minimize The Effect Of Sediment:
3.5 Calculation Of Sediment Transport
  3.5.1 Transport Processes
  3.5.2 The Convection-Diffusion Equation
  3.5.3 Simple Turbulence Models
  3.5.4 Expressions For Fall Velocity
3.6 Calculation Of Water Velocity
  3.6.1 The Navier-Stokes Equations
  3.6.2 The SIMPLE Method
  3.6.3 Advanced Turbulence Models
3.7 Influence Of Sediment Concentration On The Water Flow
3.8 Grid Generation
  3.8.1 Grid Qualities
3.9 Boundary Conditions
  3.9.1 Navier-Stock Equation
3.10 Discretization Methods
3.10.1 The First-Order Upstream Scheme 34
3.10.2 The Power-Law Scheme 34
3.10.3 The Second Order Upstream Scheme 35

CHAPTER - 4 - SOFTWARE
4.1 SSIIM Program 36
4.2 Model Overview 36
4.3 Model Purpose 37
4.4 Limitation of the program 37
4.5 The File Structure 38
4.6 Modeling Complex Structures With SSIIM 40
4.7 Problem Setup 40
  4.7.1 Geometry 40
  4.7.2 Grid 40
  4.7.3 Inflow 41
  4.7.4 Out Flow 41
  4.7.5 Water Flow Parameter 41
  4.7.6 Sediment Flow Parameter 42

CHAPTER - 5 - RESULT & DISCUSSION
5.1 The Result 43
  5.1.1 The Velocity Vector 43
  5.1.2 Sediment Concentration: 45
5.2 Discussion 55

CHAPTER - 6 - CONCLUSION & RECOMMENDATION
6.1 Conclusion 56
6.2 Recommendation 57
References 58
Appendix A
Appendix B
Appendix C
Appendix D
Appendix E
Appendix F
Appendix H
## List of Figures

<table>
<thead>
<tr>
<th>Figure No.</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>The Grid Of The Sand Trap</td>
<td>4</td>
</tr>
<tr>
<td>2.2</td>
<td>The Measured (X) And Calculated Concentration</td>
<td>5</td>
</tr>
<tr>
<td>2.3</td>
<td>The Grid Along The Bed And The Roof</td>
<td>6</td>
</tr>
<tr>
<td>2.4</td>
<td>A Contour Map</td>
<td>6</td>
</tr>
<tr>
<td>2.5</td>
<td>A Longitudinal Profile</td>
<td>6</td>
</tr>
<tr>
<td>2.6</td>
<td>Comparison Between Measured And Calculated Values</td>
<td>7</td>
</tr>
<tr>
<td>2.7</td>
<td>Longitudinal Profile Of The Himalayan Intake</td>
<td>8</td>
</tr>
<tr>
<td>2.8</td>
<td>The Velocity Vector</td>
<td>8</td>
</tr>
<tr>
<td>2.9</td>
<td>Velocity Vector</td>
<td>9</td>
</tr>
<tr>
<td>2.10</td>
<td>The Calculated Velocity</td>
<td>10</td>
</tr>
<tr>
<td>2.11</td>
<td>The Contour Map</td>
<td>11</td>
</tr>
<tr>
<td>3.1</td>
<td>Location of Roseires and Sennar dams</td>
<td>13</td>
</tr>
<tr>
<td>3.2</td>
<td>Vertical Distribution Of Diffusion</td>
<td>20</td>
</tr>
<tr>
<td>3.3</td>
<td>The Velocity In Turbulent Flow</td>
<td>21</td>
</tr>
<tr>
<td>3.4</td>
<td>Expansion/aspect ratio</td>
<td>29</td>
</tr>
<tr>
<td>3.5</td>
<td>Two Dimensional Cells</td>
<td>33</td>
</tr>
<tr>
<td>4.1</td>
<td>Flow Chart</td>
<td>39</td>
</tr>
<tr>
<td>4.2</td>
<td>Input Data</td>
<td>40</td>
</tr>
<tr>
<td>4.3</td>
<td>the Out Flow</td>
<td>41</td>
</tr>
<tr>
<td>5.1</td>
<td>illustrate the velocity in three dimension</td>
<td>45</td>
</tr>
<tr>
<td>5.2</td>
<td>sediment concentration of size one in three dimension</td>
<td>46</td>
</tr>
</tbody>
</table>
5.3  sediment concentration of size tow in three dimension  
5.4  sediment concentration of size three in three dimension  
5.5  sediment concentration of size four in three dimension  
5.6  sediment concentration of size five in three dimension  
5.7  sediment concentration of size six in three dimension  
5.8  longitudinal profile at the gates  
5.9  longitudinal profile before the gates  
5.10 Longitudinal after the gates
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>CFD Problem</td>
<td>11</td>
</tr>
<tr>
<td>3.1</td>
<td>Sedimentation Classification</td>
<td>16</td>
</tr>
<tr>
<td>4.1</td>
<td>Fall Velocity</td>
<td>42</td>
</tr>
</tbody>
</table>
# List of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_m, C_1, C_2$</td>
<td>constants in the k-ε model</td>
</tr>
<tr>
<td>$c$</td>
<td>concentration of sediments</td>
</tr>
<tr>
<td>$D^*$</td>
<td>parameter in van Rijn’s formula for sediment concentration</td>
</tr>
<tr>
<td>$d, d_s, d_{50}$</td>
<td>mean diameter of sediment particle</td>
</tr>
<tr>
<td>$d_{90}$</td>
<td>diameter of sediment particle for which 90% is smaller</td>
</tr>
<tr>
<td>$E$</td>
<td>constant in wall function</td>
</tr>
<tr>
<td>$g$</td>
<td>acceleration of gravity</td>
</tr>
<tr>
<td>$h$</td>
<td>depth of water flow</td>
</tr>
<tr>
<td>$k$</td>
<td>turbulent kinetic energy</td>
</tr>
<tr>
<td>$k_s$</td>
<td>roughness at wall</td>
</tr>
<tr>
<td>$M$</td>
<td>Manning’s friction coefficient</td>
</tr>
<tr>
<td>$P$</td>
<td>Pressure</td>
</tr>
<tr>
<td>$P_k$</td>
<td>term for production of turbulence</td>
</tr>
<tr>
<td>$P_e$</td>
<td>Pechelet number</td>
</tr>
<tr>
<td>$q_w$</td>
<td>water discharge pr. Unit width of canal</td>
</tr>
<tr>
<td>$S_c$</td>
<td>Schmidt number, ratio of turbulent eddy viscosity to diffusion</td>
</tr>
<tr>
<td>$T$</td>
<td>parameter in van Rijn’s formula for sediment concentration</td>
</tr>
<tr>
<td>$U$</td>
<td>average velocity</td>
</tr>
<tr>
<td>$u$</td>
<td>fluctuating velocity</td>
</tr>
<tr>
<td>$u^*$</td>
<td>shear velocity</td>
</tr>
<tr>
<td>$w_s$</td>
<td>particle fall velocity</td>
</tr>
</tbody>
</table>
x, y, z  Cartesians coordinates

Greek

$\delta_{ij}$  Kronecker delta: 1 if $i=j$, else zero

$\varepsilon$  dissipation rate of turbulent kinetic energy

$\Gamma$  turbulent diffusivity

$\kappa$  constant in wall function

$\nu$  kinematic viscosity of water

$\nu_T$  turbulent eddy viscosity

$\rho_s$  density of sediment

$\rho_w$  density of water

$\sigma_k, \sigma_e$  constants in the k-$\varepsilon$ equations

$\tau$  shear stress
CHAPTER - ONE
INTRODUCTION

1.1 Motivation:

Dams and reservoirs are constructed in rivers for the purpose of flood control, hydropower generation, irrigation, navigation, water supply, fishing and recreation. Among multipurpose dams, hydropower and irrigation dams are predominant. Environmental impacts and long-term morphological changes of the natural water course due to this human intervention are inevitable. Sedimentation is the major problem which endangers and threatens the performance and sustainability of reservoirs. It reduces the effective flood control volume, presents hazards to navigation, changes water stage and underground water conditions, affects operation of low-level outlets gates and valves and reduces stability, water quality and recreational benefits.

Alarming rates of storage depletion have been reported world-wide and especially in drought prone areas. Sedimentation is a complex hydro-morphological process which is difficult to predict. It has been underestimated in the past and perceived as a minor problem which can be controlled by sacrificing a certain volume of the reservoir for accumulation of the sediment (dead zone). However, today’s experience teaches us that it is of paramount importance to take design and implementation of sediment control measures into consideration in the planning, design, operation, and maintenance phases of the reservoirs.

The current state of the art in combating this problem of reservoir sedimentation ranges from, measures which intend to reduce sediment influx into reservoirs by bypassing, trapping or by watershed management, to measures which
use artificial means (dredging) or utilise natural forces (flushing and sluicing) to clear or release incoming sediment along with the flow. The application of one measure or the other depends on many factors among which are: geometry of the reservoir, operational rules, characteristics of the sediment and its distribution, and the possibility of the measure itself. Realising the fact that sedimentation has often greatly reduced and endangered the live storage of many existing reservoirs coupled with the limitations of the existing sediment control measures, the subject of reservoir sedimentation has been a focal research area in water resources engineering. Though the mechanics of reservoir sedimentation are not fully endangered, further research work to improve our understanding to upgrade the existing measures.

1.2 OBJECTIVES:

In this study case, a three dimensional simulations for Rosaries reservoir dam is presented. Simulations of the direction of water flow and sediment concentration for each type of sediment are calculated by using a Computational Fluid dynamics package (SSIIM1 program). Simulations are founded for a case where the power station gates are opened while spillways and the deep sluices are closed.

The main objectives of this thesis:

- To simulate the open channel flow of Rosaries dam.
- To study the effect of burden of siltation on Rosaries dam reservoir, on hydropower generation, pumping station intake and irrigation channel.
- To calculate the efficiency of trap after dredging in summer season.
- To understand the nature and the amount of sediment.
• To take measures for mitigation of sediment in reservoir intake and irrigation channel.

1.3 THESIS OUTLINE:

This thesis includes the following content:
Chapter one includes the background and objectives of this research. Chapter two include the literature review. Chapter three will cover deep introduction of research theoretical background and governing equation of water velocity and sediment calculation. Chapter four include the details about software use in this research and problem setup. Chapter five include the result and discussion. Chapter six include the conclusion and recommendation.
CHAPTER - TWO
LITERATURE REVIEW

2.1 INTRODUCTION

In recent years the science of Computational Fluid Dynamics has found its way to Hydraulic Engineering. A large number of hydraulic problems have been solved using CFD. Cases are given below.

2.2 3D CALCULATION OF TRAP EFFICIENCY OF A SAND TRAP

The primary goal of the SSIIM model was to calculate sediment trap efficiency of an intake construction. One of the main parts of the intake is the sand trap. Olsen and Skoglund (1994) calculated the flow pattern and sediment trap efficiency for a sand trap, and verified the calculation with concentration measurements in a physical model study. The grid of the sand trap is shown in the figure (2.1) below:

![Figure (2.1) the grid of the sand trap](image)

The figure above shows a 3D view of the grid along the bed and the surface, seen from the downstream upper side. The entrance is in the upper left corner and
the outlet in the lower right corner. There is an expansion region where the feeder channel flows into the sand trap.

The figure (2.2) below shows the measured and calculated concentration profiles in a longitudinal section. The lines are calculated concentrations and the crosses are measured values. There is fairly good agreement between the calculated and observed concentrations. [1]

Figure (2.2) the measured (x) and calculated concentration

2.3 SEDIMENT DEPOSITION AND BED_movements IN A SAND TRAP

The original trap efficiency calculation for the sand trap in paragraph 2.2 was for a steady situation. After some time, the sand trap will partly fill up with sediments before it is flushed. It is of interest to predict how the trap efficiency changes as the sand deposit. This requires calculation of the vertical bed movements in the sand trap. Olsen and Kjellesvig (1999) calculated sediment movements and bed changes in a tunnel-type sand trap. This was compared with results from a physical model study. The figure (2.3) below shows a 3D views of the grid along the bed and the roof. The upper left part of the figure is the entrance, and the lower right part is the outlet.
Water and sediments were added to the model and the bed elevation was measured. This compared fairly well with the calculated bed elevation. A contour map of the calculated bed elevation is given in the figure (2.4).

The figure (2.5) shows a longitudinal profile of the flume with concentrations. The dark area is the deposited material.

Figure (2.6) shows a comparison between the measured and calculated bed elevation changes. There is good correspondence between the calculated and measured values. Some deviation at the start and at the front of the deposition. [3]
2.4 HIMALAYA INTAKE

An intake construction sometimes has a very complex geometry. One of the most complex flow cases modeled with SSIIM was the Himalayan Intake. The intake was designed by Prof. H. Støle as a mean of decreasing sediment problems for run-of-the-river hydropower plants taking water from steep rivers. The geometry of the CFD model was made by H. Kjellesvig (1995). (Kjellesvig and Støle, 1996). The intake has gates both close to the surface and close to the bed. This allows both floating debris and bed load to pass the intake dam. The dam itself has a large intake in form of a tube, parallel to the dam axis. The longitudinal profiles shown in Figure (2.7) are cross-sections of the dam and the tube and the figure (2.8) shows the velocity vector of the dam. At the exit of this tube, the water goes to the hydropower plant. Most of the water enters at the upper part of the tube, where the sediment concentration is lowest. There is also an opening at the bottom of the tube, allowing deposited sediments to fall down into the river and be flushed out. [3]
2.5 CALCULATION OF WATER & SEDIMENT FLOW IN A HYDROPOWER RESERVOIR

Water and sediment flow in the Garita Reservoir in Costa Rica was calculated by Olsen et. al. (1994). This is a small hydropower reservoir designed for daily peaking. The figure (2.9) below shows the depth-averaged velocity vectors.
Olsen et. al. measured the velocities in the reservoir, and this is compared with the calculated velocities in the figure. The calculations captured all recirculation zones, and a parameter test with changes in the bed roughness did not influence the result. The sediment flow through the reservoir and the trap efficiency was also calculated, and it compared reasonably well with measurements. [1]

2.6 RESERVOIR FLUSHING

Sediment deposits in a reservoir can cause reduction in the effective storage volume and thereby an economic loss. For some cases, it has been possible to remove the sediments by flushing. Flushing is accomplished by lowering the water level at the dam, increasing the water velocity and causing erosion in the reservoir. It is of engineering and economic interest to be able to model the flushing process, to see how much sediments are removed and how the remaining sediments are distributed in the reservoir. In the example shown here the flushing of the Kali
Gandaki hydropower reservoir was simulated (Olsen, 1999). A physical laboratory model of this reservoir had been built, and could be used for verification of the numerical model. Initially, a layer of sand with horizontal surface was laid on top of the bed. Water was then carefully filled into the model to avoid disruption of the sediments. Above the bed, the flushing started using a constant water discharge. The downstream water level was lowered and the water flushed the sand forming a channel in the reservoir. The numerical model used a 2D depth-averaged water velocity calculation, together with a 3D solution of the convection-diffusion equation for sediment concentration. Figure (2.10) below shows the calculated velocities.

Figure (2.10) the calculated velocity

Figure (2.11) below shows a contour map of the calculated bed levels. There was reasonable agreement between measured and calculated bed elevations. [1]
Other cases of hydraulic engineering problems modeled using CFD is given in the table (2.1) below: [2]

**Table (2.1) CFD problem**

<table>
<thead>
<tr>
<th>The author</th>
<th>Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simons, 1974; Olsen and Lysne, 2000</td>
<td>Lake circulation</td>
</tr>
<tr>
<td>Oestberg and Johanson, 1992; Olsen and Stokseth, 1995</td>
<td>Flow pattern in a river</td>
</tr>
<tr>
<td>Olsen et. al. 1994</td>
<td>Flow pattern in a reservoir</td>
</tr>
<tr>
<td>Seed, 1997</td>
<td>Flow around groynes</td>
</tr>
<tr>
<td>Olsen and Kjellesvig, 1998; Roulund, 2000</td>
<td>Local scour</td>
</tr>
<tr>
<td>Wu et. al. 1999</td>
<td>Channel morphology</td>
</tr>
<tr>
<td>Olsen and Kjellesvig, 1998; Spaliviero and May, 1998</td>
<td>Determination of coefficient of discharge for a spillway</td>
</tr>
<tr>
<td>(Maurel et. al., 1998; Olsen, 1999</td>
<td>Reservoir flushing</td>
</tr>
<tr>
<td>Olsen et. al., 2000</td>
<td>Algae movements in a reservoir</td>
</tr>
</tbody>
</table>
CHAPTER -THREE
SEDIMENT AND WATER FLOW CALCULATION

3.1 INTRODUCTION

Reservoir sedimentation is the process of sediment deposition into a lake formed after a dam construction. A dam causes reduction in flow velocity and consequently in turbulence, which causes a settling process of the materials carried by the rivers. This is the mechanism that ultimately causes the sedimentation in reservoirs which is a problem for their designers and users. Depending on the amount of material deposited, the shortening of the reservoir useful lifetime will bring several unpredicted consequences. The consequences of reservoir sedimentation can be economically serious. A storage capacity loss in reservoirs means financial losses due to the shortening of their useful lifetime. Beyond the useful lifetime reduction, in reservoirs that are for hydropower generation, high sediment load in the reservoir water may cause turbine abrasion. In flood detention reservoirs, if the lake is filled up by sediments, floods cannot be detained and high water levels downstream may cause high economic or even human life losses. The reservoir sedimentation problem has increased worldwide year after year due to the increase not only of the number of dams but also in their size. Approximately 1% of the storage volume of the world’s reservoirs is lost annually due to sediment deposition [8].

3.2 THE BLUE NILE RIVER:

The Blue Nile River is originating from the Ethiopian plateau, it shows very high seasonal variation and it contains most highly devolved and productive agriculture region in the Sudan (75% of national total area under irrigation
cropping) [5]. Figure (3.1) shows two storage dams were constructed across the river (Sennar and Roseires). These two dams are used for irrigation and hydropower engineering. The Blue Nile is very silty due to many factors such as catchments soil erosion, high slope, and high water flow velocity and peak discharge.

![Figure (3.1) Location of Roseires and Sennar dam](image)

3.2.1 Hydrology: [5]

- Total annual flow of the blue Nile at Roseires 50,000,000,000 m³
- Average peak flood discharge 6,300 m³/s
- Maximum discharge capacity at 467.Om 6,400 m³/s
- Maximum discharge capacity at 480.Om 16,500 m³/s
• Maximum recorded flood (60 years) 10,800 m³/s
• Average low river flow 100 m³/s.

3.3 ROSEIRES POWER STATION AND DAM:

Roseires power station and dam are located in Damazin approximately 500km. south of Khartoum, on the Blue Nile River. The dam is constructed in 1966 primarily for irrigation purposes. Control and operation of the reservoir and dam are totally vested in the ministry of irrigation. The power station, which was commissioned about five years later, has a nameplate installed capacity of 130 MW (3 turbine*30 MW+1*40) (as against a total system capacity of approximately 225 MW). The gross generation at Roseires in 1978 -1979 was 540, 385 MWH as against a total system generation of 738, 269 MWH. It feeds into the system through signal 220kv line which runs from Damazin to Khartoum. Work on stringing of a second 220 kV line to Marignan on the same masts has commenced. [For more details see [6].

3.3.1 Dam (first stage)

The dam is concrete buttress type about 1,000 m long, flanked on both side by earth embankment, 8.5 Km long to the west and 4 Km long to the east. The deep sluice structure is sited in the main river channel and contains five sluice ways positioned as low as possible so that accumulations of silt in the reservoir can be kept to minimum.

To the west of the deep sluice is the surface spillway controlled by seven radial gates. Use to pass the peak of the load. During the peak of the flood all spillway gates are kept fully open the deep sluice use to maintain the reservoir at
R.L 467 m if possible at this time any floating debris reaching the dam can be pass down stream over the spillway. [5]

2.4 SEDIMENTATION ENGINEERING:

Sedimentation engineering is concerned with particle approaches to investigation and solution of sediment problem involved in the development, use, control, conservation of water and land resource. It is a serious problem if not well through off. Sedimentation phenomenon can be created for or it happens due to:

- Soil erosion at upper reaches of catchment’s area
- Deforestation (Human influences )
- Hot dry spells which speeding up the erosion process
- Means of transporting weathered particles (Wind or water).

The phase describing the movement is complex, factors of influence are:

- Inflow discharge
- Velocity of flow
- Geometry of the channel
- The slope of the channel
- Bed material
- Operation process

3.4.1 Sedimentation Classification in Engineering Hydraulics:

Table (3.1) shows the British soil classification. There are other different classifications worldwide but with small variations, specifically in the limits between sand and silt and sand and gravel. [8]
Table (3.1) Sedimentation classification

<table>
<thead>
<tr>
<th>Types</th>
<th>Diameters range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>2µm</td>
</tr>
<tr>
<td>Silt</td>
<td>2 to 60µm</td>
</tr>
<tr>
<td>Fine sand</td>
<td>60 to 200µm</td>
</tr>
<tr>
<td>Medium sand</td>
<td>200 to 600µm</td>
</tr>
<tr>
<td>Coarse sand</td>
<td>600 µm to 2mm</td>
</tr>
<tr>
<td>Gravel</td>
<td>2mm to 60mm</td>
</tr>
</tbody>
</table>

3.4.2 Siltation of the Blue Nile:

Silt transportation in the flood waters of the Blue Niles is a well known phenomenon and has been the subject of many learned papers by eminent engineers and scientists. The arrival of silt annually at Roseires conservatively estimated at $81 \times 10^6$ tones. The creation of reservoir at Roseires in 1966 provided a huge silt-trap resulting in very rapid initial sedimentation. The Blue Nile posses the necessary properties to carry sediment load such as:

- Ready source of silt originating mainly from severe erosion in the upper catchments in Ethiopia and Sudan.
- Intensive rainfall in the upper reaches
- Steep gradients keep the silt in suspension ready to be deposition further downstream.
- The sediment load of the Blue Nile amounts to 140 million ton/year.
- Part of this amount will be deposited in Roseires and Sennar dam reservoir and minimizes their capacities.
3.4.3 Effect of the sediment:

- Need certain operations to keep certain upstream water level (minimize the head)
- Minimize the head; means lower power generation, especially during peak flows. (appendix A)
- Deposited sediment leads to the siltation of pumping station intake and irrigation canals. Then leads to less water shortage and decreases crop productivity.
- Fund is needed for desalting to restore original water level.
- Reduce the life time of the turbine parts (appendix B shows the parts cost and damage cost).
- Height cost to remove the silt and high cost in MWH losses due to remove (appendix C show the losses).

3.4.4 How to minimize the effect of sediment:

- Good watershed management over the whole catchments area to be enforced to step down soil erosion.
- To carry out annual bathymetric survey to estimate the amount of deposited sediment in order to choose the suitable process of desilting.
- Introduction of silt agitator to cut the sediment to be washed by water in the main channel.
- To improve the current dredging process, this gave good result at Roseires reservoir.
3.5 CALCULATION OF SEDIMENT TRANSPORT:

The following paragraphs describe methods to calculate suspended sediment transport in a water flow. The same methods can be used to calculate other parameters, for example water quality constituents, temperature etc. It is often easier to understand the physics of the problem when the unknown variable is a concentration of particles. Fluxes through cell surfaces are easier to understand when one can imagine particles drifting with the water through the cell surfaces. The transport processes are described first, and then the numerical algorithms are described in the next chapter. Note that the numerical methods described in the next chapter are also used for calculation of the water velocity field.

3.5.1 Transport processes

There are two main transport processes for suspended sediment transport: convection and diffusion.

a. convective of sediment

The convection of sediments is the transport by the average water velocity. The transport because of the fall velocity of the sediments is also a type of convective transport. When calculating the flux, \( F \), through a given surface with area \( A \), the following formula is used:

\[
F = c \times U \times A \tag{3.1}
\]

\( U \) is the average velocity of the sediments normal to the surface, and \( c \) is the average sediment concentration over the area. The sediment velocity will be the sum of the water velocity and the sediment fall velocity. As an example, we can look at a uniform flow, with zero vertical water velocity. If the surface is vertical, the sediment fall velocity component is zero normal to the surface.

Then the velocity \( U \) will be equal to the horizontal water velocity. If the surface is parallel to the bed/water surface, then the water velocity component
normal to the surface will be zero. The velocity $U$ in equation (3.1) will then be
equal to the fall velocity of the sediment particles.

**b. Diffusion of sediment:**

The other process is the turbulent diffusion of sediments. This is due to
turbulent mixing and concentration gradients. The turbulent mixing process is
usually modelled with a turbulence mixing coefficient, $\Gamma$, defined as the sediment
flux divided by the concentration gradient: [1]

$$\Gamma = \left( \frac{F}{A} \right) \left( \frac{dc}{dx} \right)$$

Normally, the convective transport will be dominating. But in some cases, the
diffusive transport is important. An example is the reduced settling in a sand trap
because of turbulence.

### 3.5.2 The convection-diffusion equation

The convection-diffusion equation for steady sediment transport is: [1]

$$U_j \frac{\partial c}{\partial x_j} + w \frac{\partial c}{\partial z} = \frac{\partial}{\partial x} \left( \Gamma_r \frac{\partial c}{\partial x} \right)$$

The Einstein summation convention/tensor notation is used, meaning repeated
indexes are summed over all directions. For three-dimensional flow this means that
the equation can be written

$$U \frac{\partial c}{\partial x} + \nu \frac{\partial c}{\partial y} + W \frac{\partial c}{\partial z} + w \frac{\partial c}{\partial z} = \frac{\partial}{\partial x} \left( \Gamma_r \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left( \Gamma_r \frac{\partial c}{\partial y} \right) + \frac{\partial}{\partial z} \left( \Gamma_r \frac{\partial c}{\partial z} \right)$$

Equation (3.4) is used to describe the process of sediment transport.
### 3.5.3 Simple turbulence models

The turbulence model determines the value of the sediment concentration diffusivity. The simplest turbulence model is the constant diffusivity model, when the turbulent diffusivity is set constant throughout the computational domain. As an example, a value of 1000 times the kinematics viscosity could be used. The approach is fairly crude, but has nevertheless given reasonable results in some cases. A better way to find the turbulent diffusivity for rivers is to use the following formula:[1]

\[ \Gamma = \alpha U^* H \]  

(3.5)

The parameter \( \alpha \) is an empirical constant. A value of 0.11 is often used.

Equation (3.5) gives the maximum diffusivity in a vertical profile. Some theoretical solutions give a parabolic shape of the profile, with zero at the water surface and at the bed. However, measurements gave a slightly different profile, as given on the figure (3.2) below. [1]

![Figure (3.2) vertical distribution of diffusion](image)

The diffusivity in the cell closest to the bed is given by the following formula:

\[ \Gamma_{\text{bed}} = 2.4 U \delta \]  

(3.6)

### 3.5.4 Expressions for Fall Velocity:

Several authors have proposed expressions for the particle fall velocity. Equation (3.7), will be used to compute the particle fall velocity in the present model. This explicit formula is of great simplicity and was developed for natural sand particles.
Where \( w_s \) is the particle fall velocity, \( d_{50} \) is the sediment particle diameter finer than 50%, \( \nu \) the fluid kinematic viscosity.

\[
d_* = \left( \frac{g \Delta}{\nu^2} \right)^{\frac{1}{3}} d_{50}
\]

Where \( \Delta = (\rho_s - \rho) / \rho \). Cheng also compared his equation with previous studies and found that his formula has a great degree of prediction accuracy. [8]

3.6 CALCULATION OF WATER VELOCITY:

This paragraph describes the solution procedures for the Navier-Stokes equations. These equations describe the water velocity and turbulence in a river or a hydraulic system.

3.6.1 Navier-Stokes equations

The Navier-Stokes equations describe the water velocity. The equations are derived on the basis of equilibrium of forces on a small volume of water in laminar flow. For turbulent flow, it is common to use the Reynolds’ averaged versions of the equations. The Reynolds’ averaging is described first.

We are looking at a time series of the velocity at a given location in turbulent flow in figure (3.3)

![Figure (3.3) the velocity in turbulent flow](image)
The velocity is divided into an average value \( U \), and a fluctuating value \( u \). The two variables are inserted into the Navier-Stokes equation for laminar flow, and after some manipulations and simplification the Navier-Stokes equation for turbulent flow emerges:

\[
\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = \frac{1}{\rho} \frac{\partial}{\partial x_j} \left( p \delta_{ij} - \rho \overline{u_i u_j} \right) \quad \text{(3.9)}
\]

\( \delta_{ij} \) is the Kronecker delta, which is 1 if \( i=j \) and 0 if \( i \neq j \). The last term is the Reynolds stress term, often modelled with the Boussinesq’ approximation:

\[
- \rho \overline{u_i u_j} = \rho \nu_k \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \frac{2}{3} \rho k \delta_{ij} \quad \text{(3.10)}
\]

Inserting Equation (3.10) into Equation (3.9) and regrouping the variables:

\[
\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = \frac{1}{\rho} \frac{\partial}{\partial x_j} \left[ - \left( p + \frac{2}{3} k \right) \delta_{ij} + \nu_k \frac{\partial U_i}{\partial x_j} + \nu_k \frac{\partial U_j}{\partial x_i} \right] \quad \text{(3.11)}
\]

There are basically five terms: a transient term and a convective term on the left side of the equation. On the right side of the equation there is a pressure/kinetic energy term, a diffusive term and a stress term. Important note: The convective and diffusive term are solved with the same methods as the solution of the convection-diffusion equation for sediment transport. The difference is that the sediment concentration is replaced by the velocity.

The stress term is sometimes neglected, [1] as it has very little influence on the solution for many cases. The pressure/kinetic energy term is solved as a pressure term. The kinetic energy is usually very small and often negligible compared with the pressure.

A difference between Equation (3.11) and the convection-diffusion equation for sediments is the diffusion coefficient. Equation (3.11) includes an eddy-viscosity instead of the diffusion coefficient. The relationship between these two variables is:
Where Sc is the Schmidt number. This is usually set to unity, meaning that the eddy-viscosity is the same as the turbulent sediment diffusivity.

This leaves the problem of solving the pressure term. Several methods exist, but with the control volume approach, the most commonly used method is the SIMPLE method.

### 3.6.2 The SIMPLE method

SIMPLE is an abbreviation for Semi-Implicit Method for Pressure-Linked Equations. [1]. The purpose of the method is to find the unknown pressure field. The main idea is to guess a value for the pressure and use the continuity defect to obtain an equation for a pressure-correction. When the pressure-correction is added to the pressure, water continuity is satisfied. To derive the equations for the pressure-correction, a special notation is used. The initially calculated variables do not satisfy continuity and are denoted with an index *. The correction of the variables is denoted with an index ‘. The variables after correction do not have a superscript. The process can then be written:

\[
P = P^* + P' \tag{3.13}
\]

\[
U_k = U_k^* + U_k' \tag{3.14}
\]

\(P\) is the pressure and \(U\) is the velocity. The index \(k\) on the velocity denotes direction, and runs from 1 to 3 for a 3D calculation. Given guessed values for the pressure, the discretized version of the Navier-Stokes equations is:

\[
a_p U_p^* = \sum_{np} a_{np} U_{np}^* + B_{Mk} - \left( A_k \frac{\partial p^*}{\partial \zeta} \right) \tag{3.15}
\]

The convective and diffusive terms have been discretized as described in (3.5.2). The variable \(B\) contains the rest of the terms besides the convective term, the diffusive term and the pressure term. In the pressure term, \(A\) is the surface area on the cell wall, and \(\zeta\) is an index for the non-orthogonal coordinate system. The
discretized version of the Navier-Stokes equations based on the corrected variables can be written as:

\[ a_p U_p = \sum_{np} a_{np} U_{np} + B_{nk} - \left( A^j_k \frac{\partial p}{\partial \xi} \right) \] (3.16)

If this equation is subtracted from Equation (3.15), and the two Equations (3.14) and (3.15) are used, the following equation emerges for the velocity correction:

\[ U_k' = \left( A_k^j \frac{\partial p}{\partial \xi} \right) \left( a_p - \sum_{np} a_{np} \right) \] (3.17)

The SIMPLEC method uses the formula above. The SIMPLE method omits one term in the above equation:

\[ U_k' = \left( A_k^j \frac{\partial p}{\partial \xi} \right) \] (3.18)

The above equations give the velocity-corrections once the pressure-corrections are known. To obtain the pressure-corrections, the continuity equation is used for the velocity correction for a cell:

\[ \sum_{np} A_k U_{np} = 0 \] (3.19)

\[ (k=1,2,3) \]

Equation (3.18) is inserted into Equation (3.19) The result is an equation of the following form:

\[ a_p P_p = \sum_{np} a_{np} P_{np} + b \] (3.20)

The source term, \( b \), in Equation (3.20) turns out to be the water continuity defect. The equation is solved in the same way as the other equations. The procedure is therefore:
1. Guess a pressure field, $P^*$
2. Calculate the velocity $U^*$ by solving Equation (3.15)
3. Solve equation (3.20) and obtain the pressure-correction, $P'$
4. Correct the pressure by adding $P'$ to $P^*$
5. Correct the velocities $U^*$ with $U'$ using equation (3.18)
6. Restart calculation from step 2 to find a converged solution

An equation for the pressure is not solved directly, only an equation for the pressure correction. The pressure is obtained by accumulative addition of the pressure-correction values. The SIMPLE method can give instabilities when calculating the pressure field. Therefore, the pressure-correction is often multiplied with a number below unity before being added to the pressure. The number is a relaxation coefficient. The value 0.2 is often used. The optimum factor depends on the flow situation and can be changed to give better convergence rates. Regarding the difference between the SIMPLE and the SIMPLEC method, the SIMPLEC should be more consistent in theory, as a more correct formula is used. Looking at Equations (3.17) and (3.18), the SIMPLE method will give a lower correction than the SIMPLEC method, as the denominator will be larger. The SIMPLE method will therefore move slower towards convergence than the SIMPLEC method. If there are problems with instabilities, this can be an advantage.

3.6.3 Advanced turbulence models

The following paragraph is a rather brief overview of advanced turbulence models. In (3.6.1), the Boussinesq approximation was introduced for finding an expression for the Reynolds’ stress term:

$$-ho u_i u_j = \rho v_T \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \frac{2}{3} \rho k \delta_{ij} \tag{3.21}$$
$v_T$ is the turbulent eddy viscosity. The kinematics viscosity is a fluid property, while the turbulent eddy-viscosity depends on the velocity field. Some simpler turbulence models were described in (3.5.3). These models require calibration before being used on new cases.

**a. The k-$\varepsilon$ model**

The k-$\varepsilon$ model describes the eddy-viscosity as:

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

$k$ is turbulent kinetic energy, defined by:

$$k = \frac{1}{2} u_i u_j$$

$k$ is modelled as:

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

Where $P_k$ is given by:

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

The dissipation of $k$ is denoted $\varepsilon$, and modelled as:

$$\frac{\partial \varepsilon}{\partial t} + U_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \frac{\nu_T}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j} \right) + C_{\varepsilon_1} \frac{\varepsilon}{k} P_k + C_{\varepsilon_2} \frac{\varepsilon}{k}$$

The constants in the $k$ model have the following standard values [2]:

$$C_\mu = 0.09$$
$$C_{\varepsilon_1} = 1.44$$
$$C_{\varepsilon_2} = 1.92$$
$$\sigma_k = 1.0$$
$$\sigma_\varepsilon = 1.3$$

The main advantage of the k-$\varepsilon$ model is the almost universal constants. The model can thereby be used on a number of various flow situations without
calibration. For river engineering this may not always be the case, because when
friction along the bed is influencing the flow field, the roughness of the bed also
needs to be given. If the roughness can not be obtained from direct measurements,
it has to be calibrated with measurements of the velocity. As seen from Equation
(3.21), the eddy-viscosity is isotropic, and modelled as an average for all three
directions. Several authors investigated the eddy-viscosity in a laboratory flume in
three directions. His work shows that the eddy-viscosity in the stream wise
direction is almost one magnitude greater than in the cross-stream wise direction
[2]. A better turbulence model could therefore give more accurate results for many
cases.

b. More advanced turbulence models

To be able to model non-isotropic turbulence, a more accurate representation
of the Reynolds stress is needed. Instead of using the Boussinesq approximation
(Equation 3.19), the Reynolds’ stress can be modelled with all terms.

\[
-\rho u_i u_j = -\rho \begin{bmatrix}
uu & vu & vu \\
vu & vv & vv \\
vw & vw & vw
\end{bmatrix}
\]

(3.28)

The following notation is used: \(u\) is the fluctuating velocity in direction 1, \(v\)
is the fluctuating velocity in direction 2 and \(w\) is the fluctuating velocity in
direction 3. The nine terms shown on the right hand side of Equation (3.28) can be
condensed into six different terms, as the matrix is symmetrical. A Reynolds’ stress
model will solve an equation for each of the six unknown terms. Usually,
differential equations for each term are solved. This means that six differential
equations are solved compared with two for the \(k\) model. It means added
complexity and computational time. An alternative is to use an Algebraic Stress
Model (ASM), where algebraic expressions for the various terms are used. It is also
possible to combine the \(k\)- model with an ASM to obtain non-isotropic eddy
viscosity [1]. An even more advanced method is to resolve the larger eddies with a very fine grid, and use a turbulence model only for the smaller scales. This is called Large-Eddy Simulation (LES). If the grid is so fine that sub-grid eddies do not exist because they are dissipated by the kinematics viscosity, the method is called a Direct Solution (DS) of the Navier-Stokes equations. Note that both LES and especially DS modelling require extreme computational resources, which presently is not feasible for engineering purposes.

3.7 INFLUENCE OF SEDIMENT CONCENTRATION ON THE WATER FLOW:

Note that there is still a discussion about the following arguments in the science of sediment transport. Some of the theories below are not generally agreed upon. The effect of the sediment concentration on the water flow can be divided in two physical processes: [9]

1. The sediments close to the bed move by jumping up into the flow and settling again. This causes the water close to the bed to lose some of its velocity, because some of the energy is used for moving the sediments.
2. The other process is the sediment concentration increasing the density of the fluid, changing the flow characteristics. A typical example is a density current. This effect is added as an extra term in the Navier-Stokes equations.

3.8 GRID GENERATION:

A basic concept of CFD is to divide the fluid geometry into elements or cells, and then solve an equation for each cell. Grids can be classified according to several characteristics: Shape, Orthogonally, Structure, Blocks, Position of variable, and Grid movements. The accuracy and convergence of a finite volume
calculation depends on the quality of the grid. Three grid characteristics are important: non-Orthogonality, aspect ratio, and expansion ratio. When drawing the grid, the following points should be kept in mind:

1. The grid lines should follow the streamlines as much as possible
2. The grid line intersections should be as orthogonal as possible
3. The grid aspect ratio should not be too great
4. The grid expansion ratio should not be too great
5. There should be higher grid densities in areas with high velocity/concentration

An **out blocked** region is a part of the grid where water is not allowed to flow. It can be used for making islands or obstacles in the flow.

### 3.8.1 Grid Qualities

The accuracy and convergence of a finite volume calculation depends on the quality of the grid. Three grid characteristics are important: non-orthogonality, aspect ratio, and expansion ratio.

The non-orthogonality of the grid line intersections is the deviation from 90 degrees. If the grid line intersection is below 45 degrees or over 135 degrees, the grid is said to be very non-orthogonal. This is a situation one should avoid. Low non-orthogonality of the grid leads to more rapid convergence, and in some cases better accuracy. The aspect ratio and expansion ratio is described in the figure (3.4) below: The figure shows two grid cells, $A$ and $B$. The lengths of the cells are $\Delta x_A$ and $\Delta x_B$.

![Figure (3.4) Expansion/aspect ratio](image-url)
The **expansion ratio** of the grid at these cells is $\Delta x_A / \Delta x_B$. The **aspect ratio** of the grid at cell A is $\Delta x_A / \Delta y_A$. The expansion ratio and the aspect ratio of a grid should not be too great, in order to avoid convergence problems and inaccuracies. Aspect ratios of 2-3 should not be a problem if the flow direction is parallel to the longest side of the cell. Experience shows that aspect ratios of 10-50 will give extremely slow convergence for water flow calculations. Expansion ratios under 1.2 will not pose problems for the solution. Experience also shows that expansion ratios of around 10 can give very unphysical results for the water flow calculation.

**3.9 BOUNDARY CONDITIONS:**

Boundary conditions are required on all boundaries for the sediment flow calculation. The two most used types of boundary conditions are:

- Zero gradients
- Dirichlet

Zero gradient boundary conditions means the derivative of the variable at the boundary is zero. In other words, the value at the boundary is the same as the value in the cell closest to the boundary. This boundary condition is often used at the outflow boundary for the sediment concentration calculation. It can also be used at walls.

Dirichlet boundary conditions means the values of a variable is given at the boundary. For example, zero sediment concentration is usually set at the water surface. Also, at the upstream boundary the sediment concentration has to be given. One of the most challenging problems is the boundary condition for the sediment concentration at the bed. For a general calculation, the sediments should be able to both settle and erode, depending on the shear stress at the bed, the sediment particle size distribution, the in and outflow of sediments from a section and the availability of sediments for erosion. This can be done in two ways:
i. Define a pick-up rate of sediments where erosion occurs.

ii. Use an equilibrium concentration in the cell close to the bed.

**Method (ii)** is used in the SSIIM program, so this is further described in the following text. The theory of equilibrium concentration at the bed was first described by Einstein (1950), in his formula for sediment transport. The method has since then been expanded by Toffalletti, and the latest contribution is from van Rijn (1987). Van Rijn made a formula for the equilibrium concentration at the bed:

\[ c = 0.015 \frac{d_{50}}{a} \frac{T^{1.5}}{D^*^{0.3}} \]  \hspace{1cm} (3.29)

The parameter \( a \) is the distance from the concentration point to the bed, the mean sediment particle diameter is denoted \( d_{50} \), \( T = (\tau - \tau_c)/\tau \), where \( \tau \) is the shear stress, \( \tau_c \) is the critical shear stress for movements of sediment particles, and \( D^* \) is given by:

\[ D^* = d_{50} \left[ \frac{\rho_s - \rho_w}{\rho_s \nu^2} \right] \]  \hspace{1cm} (3.30)

Here, \( \rho_s \) is the density of the sediment; \( \rho_w \) is the density of water and \( \nu \) is the kinematics viscosity of water. This formula is used in the cells close to the bed, as a boundary condition at the bed.

**3.9.1 Navier-Stock equation:**

Boundary conditions for the Navier-Stokes equations are in many ways similar to the solution of the convection-diffusion equation. In the following text, a division in four parts is made: Inflow, outflow, water surface and bed/wall.

In the **Inflow** Dirichlet boundary conditions have to be given at the inflow boundary. This is relatively straightforward for the velocities. Usually it is more difficult to specify the turbulence. It is then possible to use a simple turbulence
model, to specify the eddy-viscosity. Given the velocity, it is also possible to estimate the shear stress at the entrance bed. Then the turbulent kinetic energy $k$ at the inflow bed is determined by the following equation:

$$k = \frac{\tau}{\rho \sqrt{c_\mu}}$$

This equation is based on equilibrium between production and dissipation of turbulence at the bed cell. Given the eddy-viscosity and $k$ at the bed, Equation (3.22) gives the value of $\varepsilon$ at the bed. If $k$ is assumed to vary linearly from the bed to the surface, with for example half the bed value at the surface, Equation (3.22) can be used together with the profile of the eddy-viscosity to calculate the vertical distribution of $\varepsilon$.

In the **Outflow** Zero gradient boundary conditions can be used at outflow boundaries for all variables.

In the **Water surface** Zero gradient boundary conditions are used for $\varepsilon$. The turbulent kinetic energy, $k$, is set to zero. Symmetrical boundary conditions are used for the water velocity, meaning zero gradient boundary conditions are used for the velocities in the horizontal directions. The velocity in the vertical direction is calculated from the criteria of zero water flux across the water surface.

In the **Bed/wall** the flux through the bed/wall is zero, so no boundary conditions are given. However, the flow gradient towards the wall is very steep, and it would require a significant number of grid cells to dissolve the gradient sufficiently. Instead, a wall law is used, transformed by integrating it over the cell closest to the bed. Using a wall law for rough boundaries (Schlichting, 1980)

$$\frac{U}{u_*} = \frac{1}{k} \ln \left( \frac{30y}{k_\varepsilon} \right)$$

(3.32)
Also takes the effect of the roughness, \( k_s \), on the wall into account. The velocity is denoted \( U \), \( u^* \) is the shear velocity, \( k_s \) is a coefficient equal to 0.4 and \( y \) is the distance from the wall to the centre of the cell. The wall law is used both for the velocities and the turbulence parameters.

### 3.10 DISCRETIZATION METHODS

The discretization described here is by the control volume method. The main point of the discretization is: To transform the partial differential equation into a new equation where the variable in one cell is a function of the variable in the neighbour cells. The new function can be thought of as a weighted average of the concentration in the neighbouring cells. For a two-dimensional situation, the following notation is used, according to directions north, south, east and west:

\[
\begin{array}{c}
\text{c}_n \\
\text{c}_w & \text{c}_p & \text{c}_e \\
\text{c}_s
\end{array}
\]

Figure (3.4) two dimensional cells

c\(_n\) concentration in cell n

c\(_e\) concentration in cell e

c\(_s\) concentration in cell s

c\(_w\) concentration in cell w

c\(_p\) concentration in cell p

\( a_e \): weighting factor for cell e

\( a_w \): weighting factor for cell w

\( a_n \): weighting factor for cell n

\( a_s \): weighting factor for cell s
\[ a_p = a_e + a_w + a_n + a_s \]

The formula becomes:
\[ c_p = \frac{a_w c_w + a_e c_e + a_n c_n + a_s c_s}{a_p} \] (3.32)

The weighting factors for the neighbouring cells \( a_e, a_w, a_n \) and \( a_s \) are often denoted \( a_{nb} \).

There are a number of different discretization methods available for the control volume approach. The difference is in how the concentration on a cell surface is calculated. Some methods are described in the following.

### 3.10.1 The First-Order Upstream Scheme

This method is also called the First-Order Upwind Scheme, as it was. For a non-staggered grid, the values of the variables are given in the centre of the cells. Using the finite volume method, it is necessary to estimate variable values on the cell surfaces. The main idea of the upstream methods is to estimate the surface value from the \textit{upstream} cell. The first order method uses information in only one cell upstream of the cell surface. In other words: the concentration at a cell surface for the first-order upstream method is the same as the concentration in the cell on the upstream side of the cell side. The control volume method is based on continuity of sediments. The basis of the calculation is the fluxes on a cell surface.

### 3.10.2 The Power-Law Scheme

The Power-Law scheme (POW) is a first-order upstream scheme, where the turbulent term is reduced by multiplying it with a factor \( f \). The factor \( f \) is between 0 and 1. The formula for \( f \) can be derived mathematically by solving the 1D convection-diffusion equation analytically. The factor then becomes:
\[ f = \frac{1}{e^{Pe} - 1} \] (3.33)

Where \( Pe \) is the Peclet number defined by:
\[ \text{Pe} = \frac{\rho UL}{\Gamma}, \]

\(L\) is the length of the cell.

### 3.10.3 The Second Order Upstream Scheme

The Second-Order Upstream (SOU) method is based on a second-order accurate method to calculate the concentration on the cell surfaces. The method only involves the convective fluxes
CHAPTER - FOUR

SOFTWARE

4.1 SSIIM PROGRAM

SSIIM is an abbreviation of Sediment Simulation in Intakes with Multiblock option. The program is made for use in hydraulic and sedimentation engineering. It is based on the control volume approach with a 3D structured non-orthogonal grid. The Navier Stokes equations are solved, and also the convection-diffusion equation for sediment transport. SSIIM has been used in a number of studies relating to water flow and sediment transport in river and hydropower engineering. This includes trap efficiency of sand traps and hydropower reservoirs, turbidity currents, erosion and local scour, flood waves, head loss and spillways.

4.2 MODEL OVERVIEW

The SSIIM program solves the Navier-Stokes equations with the $k-\varepsilon$ model on a three-dimensional almost general non-orthogonal grid. A control volume method is used for the discretization, together with the power-law scheme or the second order upwind scheme. The SIMPLE method is used for the pressure coupling. An implicit solver is used, producing the velocity field in the geometry. The velocities are used when solving the convection-diffusion equations for different sediment sizes. This gives trap efficiency and sediment deposition pattern. The user interface of the program can present velocity vectors and scalar variables in a two dimensional view of the three-dimensional grid, in plan view, a cross-section or a longitudinal profile. The model includes several utilities facilitating the creation of input data. Some data can be given in dialog boxes. There is also an
interactive graphical grid editor with elliptic and transfinite interpolation together with a discharge editor

4.3 MODEL PURPOSE

The program is made for use in River/ Environmental/ Hydraulic/ Sedimentation Engineering. Initially, the main motivation for creating the program was to simulate the sediment movements in general river/channel geometries. This has shown to be difficult to do in physical model studies for fine sediments. Later, the use of the program has been extended to other hydraulic engineering topics, for example spillway modelling, head loss in tunnels, stage-discharge relationships in rivers, turbidity currents and the main strength of SSIIM compared to other CFD program is the capability of modelling sediment transport with moveable bed in a complex geometry. This includes multiple sediment sizes, sorting, bed load and suspended load, bed forms and effects of sloping beds. The latest module for wetting and drying in the unstructured grid further enables complex geomorphological modelling. Over the years, SSIIM has also been used for habitat studies in rivers, mainly for salmon. In the last years, free-flowing algae have also been modelled, as a part of extending the model for use in water quality engineering. However, the main focus of our research is on sediment transport.

4.4 LIMITATION OF THE PROGRAM

SSIIM for OS/2 requires OpenGL graphics libraries to be installed with the operating system. These are included in OS/2 version 4.0 and later. The OpenGL graphics for Windows will run on Windows NT and Windows 2000. It may not run on Windows 95 or Windows 98. Some of the limitations of the program are listed below.
• The program neglects non-orthogonal diffusive terms.
• The grid lines in the vertical direction have to be exactly vertical.
• Kinematic viscosity of the fluid is equivalent to water at 20 degrees Centigrade. This is hard-coded and can not be changed.
• The program is not made for the marine environment, so all effects of density gradients due to salinity differences are not taken into account.

In computer science, a very well tested program still contains about one bug per 2000 lines of 9 source codes. The SSIIM programs contains over 100 000 lines of source code, and several modules have not been much tested. Also, combinations of modules may not have been tested at all. It is therefore likely that there are a number of bugs in the program. The user is advised to take this into consideration when evaluating the results of the program. Some modules are especially not much tested: The time-dependent flow in connection with free surface and any modules involving density gradients. These modules are also prone to instabilities.

4.5 THE FILE STRUCTURE

The OS/2 and Windows versions use the same input files and produce the same result files. The files can be interchanged between the versions. A flow chart describing the various files is given in Figure (4.1). Note that most of the files are only used for special purposes and they are normally not required. Some of the files are output files. The program can produce many of the input files. For simpler cases all the necessary input files can be generated by the program.
All the files are ASCII files. Note that the names of the files can not be changed. The best way to run different simulations is therefore to create a sub-directory for each case. The two main input files are the *control* file and the *koordina* file for SSIIM 1. The *koordina* file contains the grid geometry. The *control* file contains many of the other parameters. The files have to be present when the program starts. If not, a dialog box will emerge and the user is prompted for the main parameters. The program then generates default files. The control file can then be edited afterwards, using a standard editor. The *koordina* file may also be generated by a spreadsheet. For more details see [9]
4.6 MODELLING COMPLEX STRUCTURES WITH SSIIM

Often, a hydraulic structure is best modelled by SSIIM 1. This is because of its outblocking options and the possibility to create walls along grid lines. A hydraulic structure often has vertical walls with channel openings, and this is problematic to model for SSIIM 2. The outblocked areas are modelled in the control file, by changing the G 13 data sets (For more information about all data sets see [9]). The walls between cells are modelled with the W 4 data set. [3]

4.7 PROBLEM SETUP

We take three dimensional models from Rosaries reservoir before the dam according to

4.7.1 Geometry

We take rectangular shape 1000 m wide (concrete body), 2000 m long in the reservoir and 68 m depth. All the inputs data are shown in figure (4.2).

![Figure (4.2) input data](image)

4.7.2 Grid

- Number of cross section = 2001 (length of the cell \( \Delta x = 1m \))
- Number of point in cross section = 3001 (width of cell \( \Delta y = 0.3m \))
- Number of cross section in the vertical direction \( \Delta z = 21 \) the depth of the cell = 0.3 m)
Refer to figure () of § 3.8.1, the expansion and aspect ratio are within the optimum range to give a converged solution.

**4.7.3 Inflow**

We take whole the upstream as inflow by using G7 data set.

**4.7.4 out flow**

We take only one case. The power station gates opened and the spill way and deep sluice gates is closed. The power station has seven gates. The gates is setup by using G7 data set and the rest of the geometry at out flow taken as out block region (the out block region of the region blocked out by solid object). We use 10 out blocks by using G13 data set figure (4.3) shows the out flow and the location of power station gates.

![Figure (4.3) the Out Flow](image)

**4.7.5 Water flow parameter**

- Discharge of each gate 100000 kg/s
- Time setup 1 s and 20 inner iterations per time step using F33 data set (300 s by using K1 data set).
- Second order up wide is used for the velocities and the Power-Law scheme for the turbulence equations. The pressure correction is used different approach (using K6 data set)
4.7.6 Sediment Flow Parameter

In the Rosaries dam we have three types of sediment according to figure (2.1) silt, Medium sand and the coarse sand. In flow of sediment = 3000,000 Ton/day. We take 40% for silt 35 for medium sand and 25% for coarse sand by using I data set. We take the following diameter:

- 0.00003 m and 0.00055 m for silt
- 0.0004 m and 0.0008 m for medium sand
- 0.0013 m and 0.002 m for coarse sand

To calculate the fall velocity for each diameter we use the equation (3.7) with $v=0.877\times10^{-6}$ m$^2$/s, $\rho =10^3$ Kg/m$^3$ for water and $\rho_s= 2650$ Kg/m$^3$ for sediment the result in the table (4.1):

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The data of this table are used to initialize the size and the inflow of the sediment. We take 1 s time setup by using F33 data set and 100 inner iterations per time setup by using F4 data set.

For all others “data sets” inputs in the control file are defined and described in appendix D.
CHAPTER - FIVE

RESULT & DISCUSSION

This chapter described the result and discussion of the SSIIM program according to the input data in chapter four and control file in appendix (D).

5.1 The Result:

After the definition of all parameters of the problem (in the control file or other). The solution of the problem takes about three days according to the available used hardware (2 GHz ram and 1 processor of 3 GHz).

The convergence occurs for precision of $10^{-4}$ for all residuals (u, v, w, p, k, and $\varepsilon$) this value of $10^{-4}$ is hard coded in the program. [9]

The program output data consists of many variables like velocity vectors, sediment concentration, pressure, and turbulence kinetic energy…etc. The focus of the analysis is in velocity vector and sediment concentration. The result shows in the figures illustrate the velocity vectors and the sediment concentration from the plane view (x-y plan), cross section (x-z), and longitudinal profile (y-z). This result illustrate as velocity vectors and contour map of the sediment concentration. The result in details and the coordinates of the geometry are given in result, conres, boogie, and koordina files in appendix E, Appendix F, appendix G and appendix H respectively.

5.1.1 The Velocity Vector

The velocity vector in three dimensions is shown in figure (5.1). Figure 5.1-a is the plane section, and figures (5.1-a-A) and (5.1-a-B) show the zooming areas A and B. they illustrate the existence of vortices by the two sides of the gates
Figure (5.1) illustrate the velocity in three dimensions
(a. plane     b. longitudinal     c. cross sectional)

5.1.2 Sediment Concentration:

How to read sediment concentration contours?

m.

The values of the different lines are given on the colored scale. The text at the lower part of the figure gives the values of the maximum and minimum values,
and it is shown, there are six equal intervals between maximum and minimum values. The figure (5.2) shows the sediment concentration of size one silt type.

Figure (5.2)
Sediment Concentration of size one in three Dimensions
(a. plane  
b. longitudinal  
c. cross section)
(iii) Figure (5.3) show the sediment concentration for size two with diameter 0.000055 meters (silt type)

![Figure (5.3)](image-url)

- **Figure (5.3)** sediment concentration of size tow in three dimensions
  - (a) plane
  - (b) longitudinal
  - (c) cross section
(iv) Figure (5.4) show the sediment concentration for size three with diameter 0.0004 meters (Medium sand type)
(v) Figure (5.5) show the sediment concentration for size four with diameter 0.0008 meters (Medium sand type)
(vi) Figure (5.6) show the sediment concentration for size five with diameter 0.0013 meters (coarse sand type).
(vi) Figure (5.7) show the sediment concentration for size six with diameter 0.002 meters (coarse sand type)
The next figures (5.8 - 5.9 - 5.10) will show the contour of sediment concentration and velocity vectors taken at different longitudinal sections for one size of sediment (size 1). These figures illustrate and confirm the relation between the vortices formation and the sediment concentration, 1 section at the gates show in Fig (5.8), 3 sections before show in Fig (5.9), and 1 section after the gates show in Fig (5.10).
Figure (5.9) longitudinal profile before the gates at (J= 2, J= 15 and J= 100)
Figure (5.10)
Longitudinal after the gates

Concentration, profile 300, size 1, min=5.373e-007, max=5.424e-007
5.2 Discussion

Generally, it is observed that at the gates, at the lower part of the dam and the out block region, affect on the velocity vectors figure (5.1), it can be also observed the reverse flow of water and vortices formation shows in figures (5.8, 5.9, and 5.10).

The sedimentation is obviously observed and that the largest concentration of all types of sediments corresponds to the vortices area compared with longitudinal profile of all available types of sedimentation. And these observations are confirmed on the figures where different longitudinal sections are taken for one type of sediment.

All the plan views (5.1) illustrate that the concentration of sedimentation is located on the sides of reservoir and this leads consequently to the formation of islands. Comparing these different sediments concentration results with the actual real topology of the lake, It is found that the islands are situated on the same sides as the results obtained.

Cross section views show that the concentration of sedimentation decreases as we go downstream at the turbines gates.
CHAPTER SIX

CONCLUSION & RECOMMENDATION

6.1 CONCLUSION:

The results obtained in the previous chapter for sediments confirm clearly the utility of the CFD for designing, predicting the motion of fluids.

The sediments concentrations obtained and shown in the figures of last chapter illustrate that each type of sediment concentration location is different according to its diameter.

The SSIIM program is so useful for the sediment transportation phenomenon on open channel flow, it has more functions that are not used in this study, like the export of results to another post-processing software helping and giving more powerful simulations (i.e. animation of sediment movement with time)

The CFD results illustrate that the coincidence the sediments deposit with the vortices formation in the dam

The CFD can be used for presenting and finding less costly solutions to the sediments in the lake of Rosaries dam
6.2 RECOMMENDATION:

Our recommendation includes the following:

- Realising a small dam prototype model to validate the result that obtained and to re-produce out of the open channel sedimentation.
- Carrying out the study with others packages so as to complete the comparison between results obtained by and that by the SSIIM1 program.
- Increasing the accuracy by increasing the number of inner iterations per time step to give more accurate results for the calculations of water and sedimentation. To realise this, a more developed computer (RAM and processor) will be needed so as to results can be completed in suitable time.
- To perform the study case while the seven gates of the turbines and the seven gates of the spillway are opened and to know the effect of this on the concentration of the sedimentation.
- To carry the program in case all gates (turbine, spill way, and deep sluices) are open to study the changes that will take place of sedimentation and the direction of flow.
- To reproduce the actual lake topology and re-calculate all the sediment concentration. This production, can be done from an aerial satellite image of the Dam
- To suggest a solution to stop sedimentation during autumn and to carry out the suggest solution through the program to fined out its usefulness and this will reduce the expense.
- To use the calculated efficiency of trap (the most accurate location for dredging and to know the exact quantities of sediments) after the summer season.
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Ref:
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6. Messrs. Keohane an Quinn, report on operating and maintenance of Rosaries hydro power station for public eletricty and water corporation sudan,1980
7. Rosaries operation manual
8. Rog’erio Campos, Three-Dimensional Reservoir Sedimentation Model, Newcastle-upon-Tyne, December 2001

Web:
1. http://www.ntnu.no/~nilsol/beta
نتائج المسح المائي لبحيرة خزان الروصيرص

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Appendix B

**POWER PLANT EQUIPMENT DEPERCIATION**

*Cost Calculated by Euro*

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## Appendix C

(2) LOSSES DUE TO SILT REMOVAL

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**NOTE:**

1MWH COST = 0.1$
1M3 OF MUD REMOVED COST = 2$
Appendix D

rosiers dam

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F 33 1 20
F 37 1
g 1 201 300 21 6  grid and array sizes
g 3 0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100  vertical grid distribution
g 7 0 1 2 300 2 21 0 0 70000.0 1 0 0
g 7 1 -1 221 222 4 5 0 0 10000.0 1 0 0
g 7 1 -1 225 226 4 5 0 0 10000.0 1 0 0
g 7 1 -1 229 230 4 5 0 0 10000.0 1 0 0
g 7 1 -1 233 234 4 5 0 0 10000.0 1 0 0
g 7 1 -1 237 238 4 5 0 0 10000.0 1 0 0
g 7 1 -1 241 242 4 5 0 0 10000.0 1 0 0
g 7 1 -1 245 246 4 5 0 0 10000.0 1 0 0
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g 13 3 201 201 2 300 2 3
g 13 3 201 201 2 220 4 5
g 13 3 201 201 2 223 224 4 5
g 13 3 201 201 2 227 228 4 5
g 13 3 201 201 2 231 232 4 5
g 13 3 201 201 2 235 236 4 5
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Appendix E
sample of RESULT FILE

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Roughness : 0.019771

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Appendix F
sample of CONRES FILE

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Appendix G
Sample of data in BOOGIE FILE

Multi-block version of SSIIM
In kread

Transient inner iterations: 20
In osio1: IONo = 8
TurbulenceModel = 0
In initial - arrays

End of initial - arrays
Have allocated 798.28 Mbytes

In initial - velocity

Loop1,iter,area,radius,velocity,waterlevel: 9 1.560713e+003 1.560713e+001 4.485130e+001
1.560713e+001
Loop1,iter,area,radius,velocity,waterlevel: 17 1.732627e+003 1.732627e+001 4.040108e+001
1.732627e+001

Waterlevel = 6.887199 meters for cross-section i = 200
Waterlevel = 6.974399 meters for cross-section i = 199
Waterlevel = 7.061598 meters for cross-section i = 198
Waterlevel = 7.148797 meters for cross-section i = 197
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Waterlevel = 7.584794 meters for cross-section i = 192
Waterlevel = 7.671993 meters for cross-section i = 191
Waterlevel = 7.759192 meters for cross-section i = 190
Waterlevel = 7.846391 meters for cross-section i = 189
Waterlevel = 7.933591 meters for cross-section i = 188
Waterlevel = 8.020790 meters for cross-section i = 187
Waterlevel = 8.107989 meters for cross-section i = 186
Waterlevel = 8.195188 meters for cross-section i = 185
Waterlevel = 8.282388 meters for cross-section i = 184
Waterlevel = 8.369587 meters for cross-section i = 183
Waterlevel = 8.456786 meters for cross-section i = 182
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Waterlevel = 8.631185 meters for cross-section i = 180
Waterlevel = 8.718384 meters for cross-section i = 179
Waterlevel = 8.805583 meters for cross-section i = 178
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Waterlevel = 9.939174 meters for cross-section i = 165