Master's thesis

2022

Moyinjah Bello

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

Master's thesis

NTNU
Norwegian University of
Science and Technology

Moyinjah Bello

2D NUMERICAL MODELLING OF HYDRAULICS AND SEDIMENT IN A RESERVOIR

June 2022

NTNU
Norwegian University of
Science and Technology

NTNU
Norwegian University of
Science and Technology

2D NUMERICAL MODELLING OF HYDRAULICS AND SEDIMENT IN A RESERVOIR

Moyinjah Bello

HYDROPOWER DEVELOPMENT
Submission date: June 2022
Supervisor: NILS RUTHER
Co-supervisor: DIWASH LAL MASKEY

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

Abstract

Sediment transport in rivers has been an active and expanding field of research for years due to its complexity and dynamics. The field is quite important due to its application in river basin management, erosion control, flood control, and other economic importance of the water bodies. Sediment transport is a very wide field consisting of several aspects of importance. Numerous methods have been researched for the mitigation of sedimentation in reservoirs. Modeling has been one of the several ways in which sediment transport in rivers and reservoirs are been analyzed to understand the hydraulic conditions of the sediments in a reservoir

Softwares such as REEF 3D and, SSIIMS have been used in the past to model sediment transport in reservoirs with reasonable results. The 2D sediment transport capability of HECRAS is put into test in this research. This was done by investigating how the sediments behave when introduced into a reservoir model. The model scale of the Binga reservoir that was developed in the Hydraulic Laboratory at NTNU was used as a case study. Two model scenarios were experimented. The first is with a hydrograph consisting of both low and high flow periods. This would enable us understand how different transport formula perform under large variation in discharge. The second scenario experiments how the transport formula responds to high constant discharge for long durations.

The result of the hydrograph with both low and high discharge suggested that both Van Rijn and MPM transport functions simulated good results in comparison to the results observed from the physical model. Van Rijn's transport function further proved to be suitable in the second scenario of constant high discharge. Although, other transport functions seem to simulate comparably good results during low flows.

It is recommended that HECRAS developer improves the software capabilities by introducing the possibility of combining different transport equations temporally or spatially in a model.

Acknowledgement

The present report is a master's thesis on 2D numerical modeling of hydraulics and sediment in a reservoir. The case study is the physical model of the Binga reservoir that is located in the Hydraulic Laboratory in NTNU. This report is submitted to the Department of Civil and Environmental Engineering of the Norwegian University of Science and Technology, Trondheim. As a fulfillment of one of the requirements for Master of Science in Hydropower Development, this report was started in January 2022 and completed in June 2022. The task included the use of HECRAS (a CFD program named) to simulate the hydraulics and sediment transport in a reservoir.

I would like to thank Professor Nils Ruther for supervising this research and for his timely advice and scientific approach. I am extremely grateful to the Co-supervisor Diwash Lal Maskey, Ph.D. candidate at Department of Civil and Environmental Engineering for his continuous support throughout the research duration. His valuable support, suggestions and co-operation helped me in achieving success in the completion of this research.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

HECRAS	Hydrologic Engineering System - River Analysis System
SSIMS	Sediment Simulation in Intakes with Multi-block option
1D	One Dimensional
2D	Two Dimensional
3D	Three Dimensional
CFD	Computational Fluid Dynamics
HPP	Hydropower Plant
GUI	Graphical User Interface
NTNU	Norwegian University of Science and Technology
WSE	Water Surface Elevation
DWE	Diffusion Wave Equation
ELM-SWE	Eulerian Lagrangian Shallow Water Equation
EM-SWE	Eulerian Shallow Water Equation
s	Seconds
m	Meters
g	Grams
min	Minutes
MPM	Meyer-Peter and Müller
VR	Van Rijn
A&W	Ackers and White
E&H	England and Hansen

Chapter 1 – Introduction

Approximately one-third of the world's population now lives in nations where water scarcity is a problem. Due to a lack of vegetation cover, short but powerful rainfall following dry spells or a lengthy dry season, and typically steep topography immediately connected to the channel system mixed with erodible soils, such dryland areas are particularly vulnerable to erosion processes. As a result, sediment dynamics produced by run-off on the soil surface, sediment transport in river systems, and deposition in lakes or reservoirs are all significant factors to consider when managing catchments in such situations. For the residential, agricultural, energy, and industrial sectors, drylands rely largely on the storage of run-off water in reservoirs. Reservoir sedimentation as a result of rapid hillslope erosion reduces reservoir life expectancy, thereby posing a major economic burden on the entire region. (Axel Bronstert, 2001–2018 (2014))

Reservoirs have and will be of important economical and societal benefits in the past, present and future. They serve purposes such as flood control, hydropower, irrigation, fishing and navigation. A major challenge to all reservoirs is silting. If not adequately taken care of through prevention strategies and remedial measures can ultimately lead to complete loss of reservoir volume. This could also lead to blockage or damage to the hydraulic structures in the reservoir. The downstream section of the reservoir also suffers implications from the sedimentation of the reservoir in terms of change in river morphology and ecology resulting in loss of aquatic habitat and poor water quality.

1.1 Sustainability Challenges

Sustainable energy production is the new song around the world today with developed countries decommissioning energy sources that are not renewable and investing more in renewable sources. Hydropower today is one of the most used renewable power source ahead of solar and wind sources.

Reservoirs have been a major support for hydropower generation. Though hydropower in itself is a sustainable means of power production, Reservoirs that serve as major storage of water has been deemed to be less sustainable in several part of the world due to the sedimentation of the reservoir capacity over its life time. A lot of reservoirs around the world has lost their capacity significantly over the years some rather much earlier after operation than later. An example is the Sanmenxia Reservoir in China that required urgent renovation due to the influx of sediment only 4 years after it was commissioned. This major challenge coupled with significant amount of infrastructure construction needed to construct dams has discouraged new construction over the years.

Sediment transport in rivers has been an active and expanding field of research for years due to its complexity and dynamics. Sediment transport is a very wide field consisting of several aspects of importance. Numerous methods have been researched for the mitigation of sedimentation in reservoirs. Modelling has been one of the several ways in which sediment transport in rivers and reservoirs are been analyzed to understand the hydraulic conditions of the sediments in a reservoir. Modelling can either be done physically or numerically. Regarding physical modelling, high-resolution instruments are being used to discover better insight into the morphology and hydrodynamic of reservoirs. These instruments allow for measurements such as flow velocities, concentration and internal stresses to be characterized in sediment-laden flow. They have also made it possible to be done out in field and/or in the laboratories. In numerical models, there are 3 options, ranging from 1D to 3D models. 1D models have been used due to their low computational cost and reduced data requirement. 2D/3D models are now required due to the presence of complex topography and/or hydraulic structures. 2D shallow water models may provide accurate predictions for the depth averaged flow velocity and water depth, requiring though a fine topographic representation. However, 3D models are also required where 2D simulations may not adequately predict the instabilities of sediment deposits.

1.2 Purpose and Project Background

In this project, the sediment transport in a physical model of a hydro power reservoir will be modelled numerically using the HECRAS 2D. The results would be compared with the results from the physical model in the hydraulic laboratory situated at NTNU.

1.3 Master’s Thesis Work

The thesis shall cover, though not necessarily be limited to the main tasks listed below. The candidate collected available documents such as reports, relevant studies and maps. Based on the available documentation the following was carried out:

1. Literature review on sediment transport, reservoir sedimentation and 2D numerical modeling
2. Short description of the experiments and the data available
3. Setting up the grid for the reservoir in HEC RAS 2D.

4. Conduct simulations so that it is possible to model the deposition and erosion rate in the reservoir for test discharges
5. Documentation of the numerical results compared to the experiments.
6. Conclusions
7. Proposals for future work
8. Presentation

Chapter 2 – Theory

Dams are unique sort of infrastructure that provide a regulated water supply and tends to gain value over time as water supplies become scarcer in comparison to demand. Reservoirs' relevance to civilization is predicted to rise over time as population, economic activity, and irrigation requirements increase. While contemporary hydraulic systems have several components to appropriate both surface and groundwater supplies, reservoirs are the most significant component in many areas. Storage reservoirs, on the other hand, are a crucial non-sustainable component of modern water delivery systems due to uncontrolled silt accumulation. (Gregory L. Morris, 1997)

Recreation, flood control, navigation, cooling water supply, reservoir-based fisheries, and ice jam control are all key benefits of reservoir storage. While the twentieth century saw a relative availability of water and numerous water resource development initiatives, the twenty-first century is predicted to see increased water scarcity as a result of sustained population and economic growth. There is enough water to feed and clothe the growing global population, but due to uneven water distribution and population growth, water-scarce countries in areas like northern Africa can expect to see population outstrip available irrigation supplies, making them increasingly reliant on food imports. (Gregory L. Morris, 1997)

2.1 Sediment Transport

Sediment is a term used to describe fine particulates that settle to the bottom of a body of water. However, the phrase sediment transport technically refers to the transportation of both fine and big materials (e.g. clay, silt, gravel and boulders). The word "sediment transport" refers to the movement of material (such as silt, sand, gravel, and boulders) through rivers and streams. The sediment load refers to the amount of material moved. There is a distinction established between the suspended load and the bed load. The bed load refers to grains that roll along the bed, whereas the suspended load refers to grains that are kept suspended by turbulence. When both loads are made of the same material, the distinction can be arbitrary.

Natural stream and river waters have the potential to erode channel beds, transport particles and to deposit materials, resulting in a change in the topography of the bed. This is known as sediment transport. This is crucial in terms of economics and preventing disaster such as, bridge collapse (pier foundation erosion), formation of sand bars in estuaries and navigable rivers, destruction of banks and levees and many more (Chanson, 2004).

The size of the grains and the amount of turbulence in the stream determine how they are classified by mode of transport. Clays and fine silts are likely to be transported in suspension, while most gravel and cobbles are likely to be delivered as bed load. Sand, on the other hand, may be stable on the bed, roll or bounce along the bottom, or be carried in suspension, depending on the turbulent energy. At low flows, the suspended load in a stream may be entirely made up of silts and clays. High discharges, however, include sands, leading the suspended load's grain size distribution to coarsen as flow increases. In many streams, the bed material load is a modest percentage of the total load (less than 15%). (Gregory L. Morris, 1997). Sediment transfer is frequently observable in mountain streams, torrents, and creeks. Larger rivers, such as the Nile River, the Mississippi River, and the Yellow River, are known for their sediment-carrying capacity. (Chanson, 2004)

2.2 Impact of Sedimentation in Reservoirs

Although sedimentation of the world's reservoirs poses a severe danger to reservoir's long-term viability, there is no guidance on how to best handle the issue. Dam safety is harmed by sedimentation, which limits storage, discharge capacity, and flood attenuation. It puts more strain on the dam and gates, destroys mechanical equipment, and has a variety of environmental consequences. (Greg Schellenberg, 2017)

Air pollution is a likely environmental impact of sediments in reservoirs on the environment. This can occur in seasonally empty reservoirs where Wind can erode and transfer dehydrated fine sediment deposits, causing discomfort and health hazards to surrounding communities.

Low-level exits designed to allow reservoir drawdown are frequently blocked by sediments. Clogging of spillway tunnels or other conduits may occur as sedimentation continues. When the sediment front approaches the dam, it might reduce spillway capacity due to a loss of approach depth. The reservoir transforms into a delta-filled valley with a meandering flow, preventing flood waves from spreading out and allowing flood routing.

Increased flooding of infrastructure, towns, and agricultural fields on floodplains; increased groundwater levels, causing waterlogging and soil salinization; reduced navigational clearance beneath bridges; and submerged upstream intakes are all possible consequences of channel aggradation. If delta areas become extensively vegetated, greater hydraulic roughness can force upstream flood levels to rise even higher, and the vegetation can trap sediment, causing more aggradation.

The downstream section of a reservoir also suffers from the aggradation of sediments in the reservoir. This is largely due to the barrier caused by the dam, preventing sediment flow downstream of the reservoir. This causes an ecological imbalance as the nutrients carried downstream by the sediments becomes scarce. Reductions in the supply of bed material silt downstream of dams can have a significant impact on stream shape. The clear water in the river channel downstream of the dam will scour the streambed, coarsening, degrading, and armoring it. The coarsening of the bed can make it unsuitable as an ecological habitat and spawning location for native and invasive species alike. Increased scour at downstream bridges, lower water levels at intakes, reduced navigational depth in important points, and lower groundwater tables in riparian areas are all effects of channel degradation, which are harmful to both wetlands and agricultural areas. (Greg Schellenberg, 2017)

Any dam will result in some sediment depletion downstream. Plant and animal species are affected by changes in sediment supply and flow regimes. Turbid waters with a reduced euphotic zone might result from increased sediment content. Plant productivity is reduced, which has a negative influence on fish and bird species and causes abrasion of fish gills, increasing the risk of disease or mortality. Turbidity can also impair predatory fish's vision, influencing their eating patterns. Finally, suspended contaminants such as nitrogen, phosphorus, and heavy metals are carried by sediment. Sediments released as a result of sediment management or a dam break can have long-term environmental consequences. (Greg Schellenberg, 2017)

The vast majority of dams are built and operated with the intent of continuously trapping sediment, with no plans for long-term use. If today's inventory of storage reservoirs is lost to sedimentation, neither present nor predicted levels of population and economic activity can be sustained, and as population and economic activity expand, demand on dam services grows.

Reservoir-dependent societies span from highly developed urban and agricultural systems in the western United States to Indian peninsula village irrigators. The sudden loss of the world's reservoir capacity would be a massive disaster, but the progressive loss of reservoir capacity due to sedimentation receives little attention or corrective action. (Gregory L. Morris, 1997)

2.3 Reservoir Sedimentation

The erosion, entrainment, transit, deposition, and compaction of sediment brought into reservoirs constructed and contained by dams is known as reservoir sedimentation. Sediment processes are reasonably balanced in unregulated, mature rivers with stable catchments. The construction of a dam reduces flow velocities, which initiates or accelerates sedimentation, resulting in the deposit of even finer materials. (Greg Schellenberg, 2017). The sediment transport capacity, as well as the inflow circumstances, influence the erosion or aggradation of the channel bed.

2.4 Sediment Management in Reservoirs

Reservoir sediment management strategies must be considered at the project's conception and throughout its life cycle in order to develop and maintain sustainable storage to meet global needs. Depending on the type of facility, these procedures differ. This goal, as well as enhancing reservoir longevity, are critical in a storage project. Sediment management solutions for extending reservoir longevity can be divided into three categories:

- Those that redirect some sediment through or around the reservoir;
- those that remove or rearrange sediment previously deposited and
- those that reduce the amount of sediment reaching the reservoir from upstream.

Many dam operators have put in place sediment control measures to meet these objectives. The following are some examples of sediment management techniques:

- ✓ Reduce sediment production (watershed management)
- ✓ Trap sediment upstream of the reservoir
- ✓ Bypassing
- ✓ Sluicing/drawdown routing
- ✓ Mechanical Excavation / Dredging
- ✓ Pressure / Empty Flushing
- ✓ Erosion control
- ✓ Venting turbid density currents
- ✓ Modifying the operating level (International Hydropower Association, 2022)

2.5 Numerical Modelling

Numerical models are complementary alternative to physical models that are been used to study hydraulic conditions in rivers and other water bodies. Their development became more prominent due to the expensive cost of setting up physical model and the increasing evolution of computers capabilities. Numerous software has been developed around the world to study the transport of sediment in water bodies such as:

- The HECRAS model, developed by the US Army Corps of Engineers, includes a moveable boundary sediment transport calculation module that was recently added to simulate sedimentation processes.
- MIKE 21 is a two-dimensional hydrodynamic model that is used to examine sediment deposition patterns and forecast the results of future flushing operations.
- SSIIM 2 is a software developed at NTNU by Professor Nils Reidar B. Olsen. It is capable of modelling sediment transport with a movable bed and varying water level. Due to this reason, it is a powerful tool to simulate both sediment deposition and reservoir flushing.
- REEF 3D: SFLOW a 2D numerical modelling is used for the simulation of hydrodynamics and sediment transport for water bodies.

For the purpose of this research, an HEC-RAS model was developed to simulate the different flow scenario in comparism to the physical model in the Hydraulic Laboratory at NTNU.

Chapter 3 - HECRAS

3.1 Introduction

HEC-RAS (Hydrologic Engineering System - River Analysis System) is a CFD program made for modelling one- and two-dimensional hydraulic flow for a full network of natural and constructed channels. The software was developed mainly to help in the determination of floodplains and flow analysis in a channel. Over the years, the program has been modified for other capabilities such as sediment transport modelling and water quality analysis. The software has a user friendly and efficient GUI (Graphical User Interface) that makes it convenient for users to interact with the program. The GUI allows functions such as:

- File management
- Data Entry and Editing
- Hydraulic Analyses
- Displays of Input and Output Data (Tables and Graphs)
- 3D view of results
- Help

The HEC-RAS system contains four one-dimensional river analysis components for:

1. steady flow water surface profile computations;
2. unsteady flow simulation (one-dimensional and two-dimensional hydrodynamics);
3. quasi unsteady or fully unsteady flow movable boundary sediment transport computations (1D and 2D); and
4. water quality analysis.

3.1.1 Steady Flow Water Surface Profile

The steady flow water surface profile is one of the hydraulic analysis components of HECRAS. It is used to calculate the surface water level for a steady gradually varied flow in a single river reach or network of channels. The one -dimensional energy equation solution is the basis for the computational process of the water level. The steady flow component can describe water surface profiles in subcritical, supercritical, and mixed flow regimes. Friction (Manning's equation) and contraction/expansion are used to calculate energy losses. In instances where the water surface profile is quickly changing, the momentum equation might be applied. Mixed flow regime calculations (hydraulic jumps), bridge hydraulics, and evaluating profiles at river confluences are examples of these circumstances.

3.1.2 Unsteady Flow Simulation in One and Two Dimensions

This component of the HEC-RAS modeling system can simulate unsteady flow in one dimension, two dimensions, and a combination of one and two dimensions over a network of open channels and floodplains. In the unsteady flow computations module, the unsteady flow component can be utilized to perform subcritical, supercritical, and mixed flow system calculations. Extensive hydraulic structure capabilities; levee breaching and overtopping; automated calibration features; User defined rules; and combined one and two-dimensional unsteady flow modeling are some of the unique features of the unsteady flow component.

The steady flow component's hydraulic computations for cross-sections, bridges, culverts, and other hydraulic structures were merged into the unstable flow module. The unstable flow component can also represent storage areas and hydraulic linkages between storage areas, as well as 2D Flow Areas and stream reaches. (US ARMY CORPS OF ENGINEERS, 2020)

3.1.3 Computations for Stable Transport and Movable Boundaries

This part of the modeling system is used to simulate one-dimensional sediment movement and moveable boundary calculations caused by erosion and deposition over a period. The sediment transport potential is calculated by grain size fraction, allowing hydraulic sorting and armoring to be simulated. The capacity to model a comprehensive network of streams, channel dredging, multiple levee and encroachment options, and the use of several distinct equations for sediment transport computation are all notable features.

The model is intended to mimic long-term erosion and deposition patterns in a stream channel as a result of changing the frequency and duration of water discharge and stage, as well as changing the channel shape. This approach can be used to estimate maximum feasible erosion during significant flood events, design channel contractions required to maintain navigation depths, anticipate the effect of dredging on the rate of deposition, and analyze sedimentation in fixed channels.

3.1.4 Analysis of water quality

The user can do riverine water quality evaluations with this component of the modeling system. HEC–RAS includes an advection-dispersion module, which allows you to model water temperature. This module solves the one-dimensional advection-dispersion equation utilizing a control volume technique with a fully integrated heat energy budget using the QUICKEST-ULTIMATE explicit numerical scheme. HEC-RAS includes transport of a limited set of water quality elements. Dissolved Nitrogen; Dissolved Phosphorus; Algae; Dissolved Oxygen (DO); and Carbonaceous Biological Oxygen Demand are the currently accessible water quality constituents (CBOD).

3.2 2D Sediment Transport Modelling

We will discuss the fundamental equations used by HEC-RAS to do one-dimensional (1D) steady flow and unsteady flow calculations, as well as two-dimensional (2D) unsteady flow calculations. The various equations' solution schemes are described. There are discussions on how to apply the equations as well as any limits that may apply.

3.2.1 1D Steady Flow Water Surface Profile

The standard step method is used to calculate water surface profiles from one cross section to the next by solving the Energy equation iteratively. The following is the Energy Equation:

$$Z_2 + Y_2 + \frac{a_2 V_2^2}{2g} = Z_1 + Y_1 + \frac{a_1 V_1^2}{2g} + h_e \qquad (1)$$

The elevation of the main channel inverts is represented with Z_1 and Z_2. h_e is the energy head loss. The average velocities are denoted V_1, V_2. Y_1, Y_2 represents the depth of water at cross sections. a_1, a_2 are the velocity weighting coefficients.

The diagram below shows the terms of the energy equation.

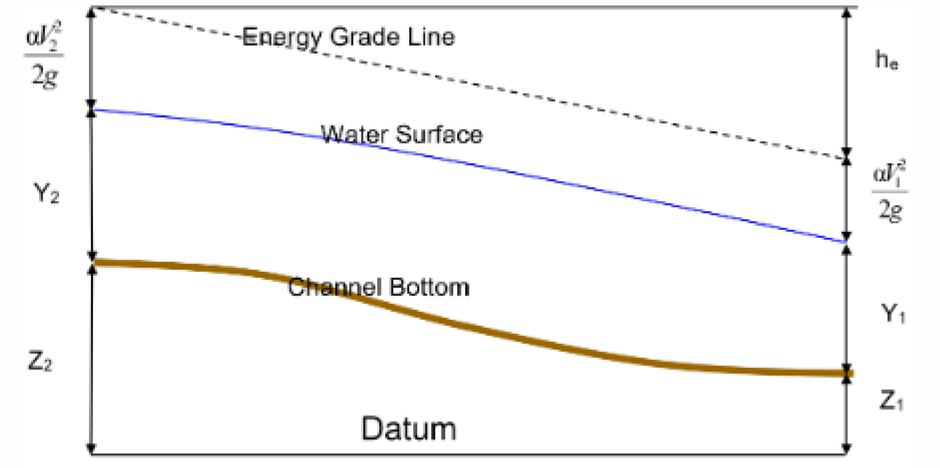

Figure 1: Representation of Terms in the Energy Equation((US Army Corps of Engineers, 2016)

Friction losses and contraction or expansion losses make up the energy head loss h_e between two cross sections. The following is the equation for energy head loss:

$$h_e = LS_f + C\left[\frac{a_2V_2^2}{2g} - \frac{a_1V_1^2}{2g}\right] \tag{2}$$

The friction slope between the two sections is denoted with S_f while L and C are the discharge weighted reach length and the expansion or contraction loss coefficient respectively.

An iterative solution of the Energy Equation and Energy Head Loss determines the unknown water surface height at a cross section. In the iterative approach, the parameter used to estimate water surface elevations varies for each experiment. The initial experiment water surface is calculated by projecting the water depth of the previous cross section onto the present cross section. The water surface height for the second attempt is set to the assumed water surface elevation plus 70% of the error from the first trial (computed W.S.E - assumed W.S.E). To put it another way, W.S.E new = W.S.E assumed + 0.70 (W.S.E computed - W.S.E assumed).

The rate of change of the difference between computed and assumed heights for the previous two trials is often projected using a "Secant" approach in the third and subsequent trials. The secant method's equation is as follows:

$$WS_I = WS_{I-1} - Err_{I-1} \times \frac{Assum\_Diff}{Err\_Diff} \tag{3}$$

$$Assum_{Diff} = WS_{I-2} - WS_{I-1} \tag{4}$$

$$Err_{Diff} = Err_{I-2} - Err_{I-1} \quad (5)$$

WS_{I-2}, WS_{I-1} are the assumed water surface while Err_{I-2}, Err_{I-1} are the error for each trial. Using the equation above the new assumed water surface value can be calculated.

There are some limitations to the use of HEC-RAS 1D steady flow program. Since time-dependent variables are not included in the energy equation, the flow is believed to be steady. Also, due to the Energy Equation basis on the assumption that a hydrostatic pressure distribution occurs at each cross section, flow is expected to be gradually varied. The program shifts to the momentum equation or other empirical equations at locations where the flow is rapidly varied. Since Critical Depth Determination is based on the assumption that the total energy head is the equal at all points in a cross section, flow is considered to be one-dimensional.

3.2.2 1D /2D Unsteady Flow Hydrodynamics

The principle of conservation of mass (continuity equation) and the principle of conservation of momentum (momentum equation) are the physical laws governing the flow of water in a stream. There are 3 methods through which HECRAS solves 2D Unsteady Flow hydrodynamics.

- Diffusion-Wave Equation Solver (DWE)
- Eulerian-Lagrangian Shallow Water Equation Solver (ELM-SWE)
- Eulerian Shallow Water Equation Solver (EM-SWE)

The DWE is derived from the discretization of both the continuity equation and the momentum equations. The new SWE solution method is more momentum conservative, but smaller time increments and longer run periods may be required. The 2D Diffusion Wave equation set is the default. Many flood applications will work well with the 2D Diffusion Wave equations in general. The Diffusion Wave equation set is intrinsically more stable and will run faster. However, in some cases, the 2D SWE should be employed for more precision. However, this new solver is only required when users want to examine changes in water surfaces and velocities at and near hydraulic structures, piers/abutments, and tight contractions and expansions in great detail. For most situations needing the full momentum equation-based solution strategy, the original SWE solver is sufficient. For the purpose of this project, the ELM-SWE was used.

3.3 Basic Data Requirement

The basic data needed to run hydraulic simulation on HECRAS are divide into the following category:

- geometric data;
- steady flow data;
- unsteady flow data;
- sediment data; and
- water quality data.

The geometric data is required for any simulation on HECRAS, while the other input data types depends on the type of simulation that is been carried out. For this project, only the geometric, unsteady and sediment data is required.

3.4 RAS Mapper

HEC-RAS has geospatial features to help design and revise model geometry and assess computed results. This ability to visualize a combination of geometric data (terrain, river networks, cross section locations, cross section parameters, 2D meshes, and so on) and simulation results (water surface depths, velocities, and so on) allows HEC-RAS users to quickly identify flaws and make improvements in hydraulic model. RAS Mapper not only gives users the ability to modify HEC-RAS data layers, but it also lets them edit generic shapefiles. In addition to displaying HEC-RAS results, you can also symbolize and query data in a variety of ways to aid in river hydraulic modeling studies.

Chapter 4 - Simulation of Hydraulics

A 2D unsteady flow model was the choice of modelling the reservoir due to the variation in the event that is been modelled. Two similar hydraulic models were simulated. The first model was use for calibration while in the second model, a hydropower intake was introduce to the first model setup to study any differences in the hydraulic conditions.

4.1 2D Computational Mesh

HEC-RAS can be used to create a 2D model. A Finite-Volume solution approach is used in the HEC-RAS 2D modeling capabilities. This algorithm was created so that a structured or unstructured computational mesh could be used. This indicates that the computational mesh can have up to 8 sides in a computational cell. Users often choose a nominal grid resolution and HEC-RAS builds the computational mesh using automated methods. The user can enhance the grid with break lines, refinement regions, and mesh editing tools once the original mesh is produced. In HEC-RAS Mapper, the procedure used in setting the model is discussed below.

4.1.1 Terrain

Before doing any model computation that contains a two-dimensional (2D) flow area in HEC-RAS Mapper, we must first establish a terrain model using HEC-RAS Mapper. We can create one or more terrain models, each of which can be associated to a geometry input file or a results output file. To develop a detailed and realistic hydraulics model, a thorough and accurate terrain model is required. The ability to develop a high-quality hydraulic model may be limited by the quality of the topographical data. Terrain data comes in a variety of forms, sources, and levels of information. HEC-RAS currently models terrain using gridded data. The user can collect data from several sources and convert/export it into a gridded data format that HEC-RAS can read. The data for this project terrain was produced from the scanned las file of the physical model in the Hydraulic Laboratory, NTNU. This model is a scaled version of the Binga reservoir in the Philippines (Nils Ruther, 2021). The scan was made using a total station and the results were converted to a raster format using ArcMap.

Once the data for the geometry is ready to be imported into HECRAS, we set the spatial reference projection to UTM Zone 32N to enable HECRAS project the terrain. Then we load the terrain data which will be utilized to create the HEC-RAS terrain model.

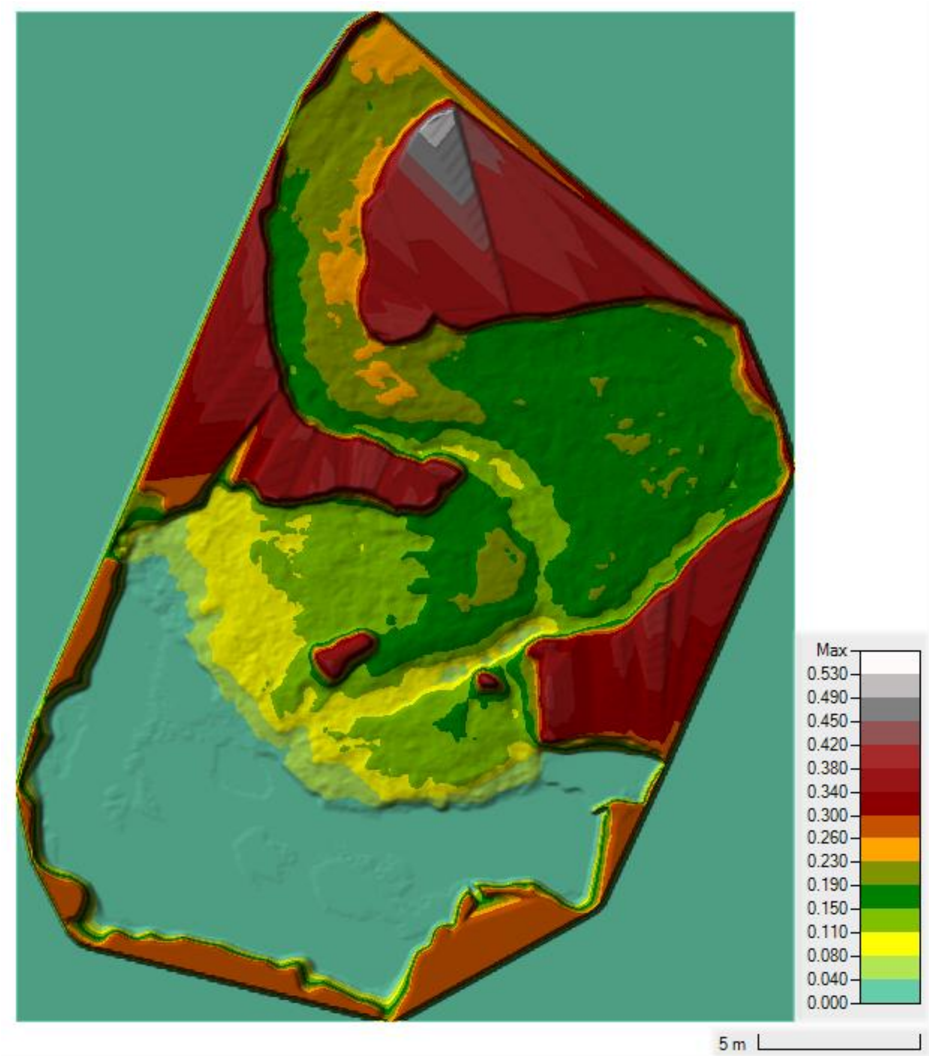

Figure 2: Image of the Terrain File in HECRAS

4.1.2 Flow Area and Computational Grid Generation

Using the geometry editing tools in HEC-RAS, a 2D flow area polygon is drawn to represent the 2D area's boundary. Adequate care is taken to ensure the polygon doesn't fall out of the terrain area and that it lies on the boundary of the terrain.

After creating the 2D flow areas, selecting the right mesh cell size (or sizes) and computing time step (T) is critical. The first step is to create a computational mesh with cell sizes that are suitable for both simulating the terrain and the water flowing over it. Creating a decent computational mesh in HEC-RAS requires making sure that the cell faces capture the high point of flow barriers. Changes in the water surface slope and velocity must also be taken into account.

Due to the rapid change in the velocity within a time frame in the model, smaller cell sizes are more suitable the changing water surface and velocity. The grid size to use for the model is determined using a calibration methodology that is discussed in 5.3

4.1.3 Boundary and Initial Condition

HEC-RAS allows you to apply a wide range of boundary and initial conditions to a model. There are 3 types of boundary condition that can be applied to a model in HECRAS.

- External Boundary Condition - These are the conditions applied on the external perimeter of the 2D Flow Area. External boundary conditions can be linked directly to the boundary of 2D Flow Areas in four different ways:
    - Normal Depth – This is typically only used to take out flow from a 2D flow area. This is usually done using a user defined friction slope for the 2D flow area
    - Rating Curve – This can only be used to take flow out of a 2D flow area. This is usually done using a user defined Stage-Flow relationship
    - Flow Hydrograph - A flow hydrograph is typically used to introduce and remove flow in a 2D flow area.
    - Stage Hydrograph - A Stage Hydrograph can be used to introduce or remove flow from a two-dimensional flow region. Flow will enter the 2D cells if the water surface elevation in the Stage hydrograph is higher than the cell water surface height (or dry elevation). When the Stage Hydrograph's water surface height is lower than the water surface in the 2D flow area, flow will exit the 2D area.
- Internal Boundary Condition
- Global Boundary Condition

This project makes use of external boundary conditions for the inflow and outflow of discharge in the model. The flow hydrograph and stage hydrograph are the applicable form of boundary condition for the model. There are three boundary condition in the model.

- The Inflow is set to be a flow hydrograph with discharge of 0.0267 for a duration of 8 hours
- The Spillway is set to be a stage hydrograph with a stage of 0.311m for a duration of 8 hours

- The Hydropower intake is used in the second model to predict the inflow and water surface elevation when an intake is added to the system. It is set to be a flow hydrograph with a discharge of $0.003 m^3/s$ for a duration of 8 hours

4.1.4 Break Lines

Break lines are polylines that are used to ensure the faces of cells align towards the direction of a linear feature. It can be used to show the movement of water along a 2D flow area. Three different break lines were used in the geometry of this model. The first one was the centerline showing the movement of water from the upstream to the downstream. This was to align the faces of the cells in the middle of the geometry towards the direction of water. The second and third break lines were on the left and right banks of the geometry, allowing the faces of the cell to align with the transition to high grounds along the banks for detailed processing.

4.2 2D Flow Equation Set / Computational Time Step

After creating a decent computational mesh, the user must choose a computational time step that is compatible with the mesh and the event being represented. The size of the cells and the velocity of the flow going through them determine the appropriate time step. The computational time step also depends on the flow equation been used. There are 3 different 2D Flow Equations that can be used for the model. The Diffusion Wave equations, the Shallow Water Equations, Eulerian-Lagrangian Method (SWE-ELM), and a Shallow Water Equations, Eulerian Method (SWE-EM). The Diffusion Wave equations can have greater time steps than the SWE and still produce numerically stable and accurate results. The SWE-EM is more momentum conservative, thereby requiring smaller computational time steps.

For this model, the SWE-EM was unable to solve the model successfully with the smallest computational time step due to the preferred grid size (0.1) for the model. The model runs unstable for low grid sizes. The SWE-ELM was then chosen for solving the model. The computational interval was calculated using the equation below.

$$C = \frac{V\Delta T}{\Delta X} \leq 1.0 \ (with\ a \max C = 3.0) \tag{6}$$

Or

$$\Delta T \leq \frac{\Delta X * C}{V} \ (with\ C = 1.0) \tag{7}$$

Where:

V is the Flood wave velocity (m/s)

ΔT is the Computational time step (s)

ΔX is the Average cell size (m)

C is the Courant Number

Using the above equation, the computation interval was computed to be 0.4secs for a grid size of 0.1m.

4.2.1 Courant Based Computational Time step

This method is used to vary the computational time step at different time during an hydraulic simulation. It determines the appropriate time step to use based on the maximum and minimum courant predefined by the user. This is the most widely used method of determining the computational time step in a model. This method was used in this model with a maximum courant of 0.5 and a minimum courant of 0.1.

4.3 Model Calibration

Model calibration is the process of identifying a unique set of model parameters that accurately describe the system's behavior. It is accomplished by comparing model predictions to real measurements taken on the system. (Simon Judd, 2011). At least, two sets of data are required in order to calibrate a numerical model. For this model, the water surface elevation and the inflow velocity from the laboratory experiment was used for calibration. (Nils Ruther, 2021)

4.3.1 Grid Size Calibration

The grid size selected for the geometry is very important to determine the quality of the result of the simulation. A fine grid size produces better result but takes more computational time and also require low computational interval. It is therefore important to figure out a middle ground between a detailed result provided by a fine mesh and a feasible computational interval and processing time. In order to determine the most appropriate grid size to select for the geometry of the model. The water surface elevation and inflow velocity was used for calibration. Different grid sizes were tested with the model and the results were compared to each other. The result is show in the table below.

Table 1: Grid Size Calibration

Grid Size	**0.25**	**0.2**	**0.15**	**0.1**	**0.05**
Inflow Velocity (m/s)	0.31	0.29	0.32	0.33	0.33
Water level 1 (m)	0.3119	0.312	0.31195	0.31195	0.31195
Water level 2 (m)	0.311595	0.31168	0.31162	0.31162	0.31155
Water level 3 (m)	0.31159	0.31166	0.31162	0.31161	0.31155
Difference		0.019745	0.02985	0.00999	0.00013

Using an assumed Manning's number of 0.02, the Grid size of 0.05m shows the least difference from the preceding grid size of 0.1 showing that there isn't a significant difference between the results produced by an 0.1m grid sized model compared to 0.05m. Therefore, its preferable to use a grid size of 0.1m for lesser computational time and higher computational interval.

4.3.2 Manning's Number Calibration

Manning's number is a coefficient that signifies the roughness or friction the channel applies to the flow. The higher the manning's number, the higher the resistance caused by the boundary to the flow causing a lower velocity in water. It was therefore important to calibrate the model using the inflow velocity and water level data from the physical model in the laboratory together with the calibrated grid size. This is done manually by trial and error. This involves running the model several times with different manning's number and finding the closest match to the laboratory data. The table below shows the result of the calibration.

Table 2: Simulated Values for WSE and Inflow Velocity

Manning's Number	0.01	0.015	0.02	0.025	0.0275	0.03	Physical Model Values
Inflow Velocity (m/s)	0.59	0.45	0.37	0.32	0.3	0.28	0.3082
Water level 1 (m)	0.31225	0.31221	0.31193	0.31192	0.3119	0.31188	0.311761397
Water level 2 (m)	0.31134	0.31126	0.3115	0.31159	0.31159	0.31158	0.311093215
Water level 3 (m)	0.31183	0.31143	0.31152	0.31159	0.31159	0.31158	0.310525106
Difference (m)	0.28385	0.14333	0.06338	0.01353	0.00649	0.02653	

Manning number of 0.0275 has the closest WSE and inflow velocity values to the laboratory observed data. Figure 3 below shows that the correlation between the simulated and observed WSE using Manning's number of 0.0275 has an R square value of 0.79.

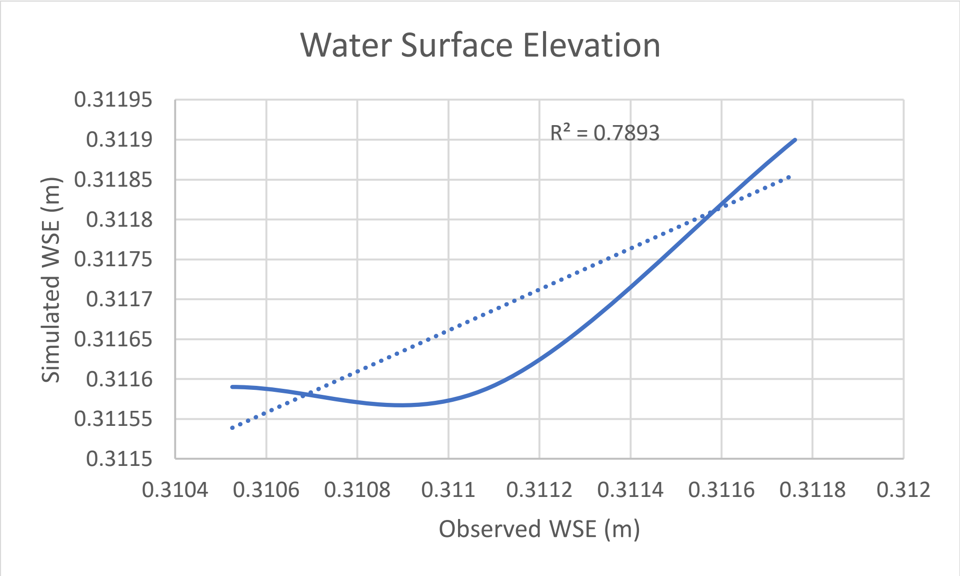

Figure 3: Graph of Simulated WSE vs Observed WSE

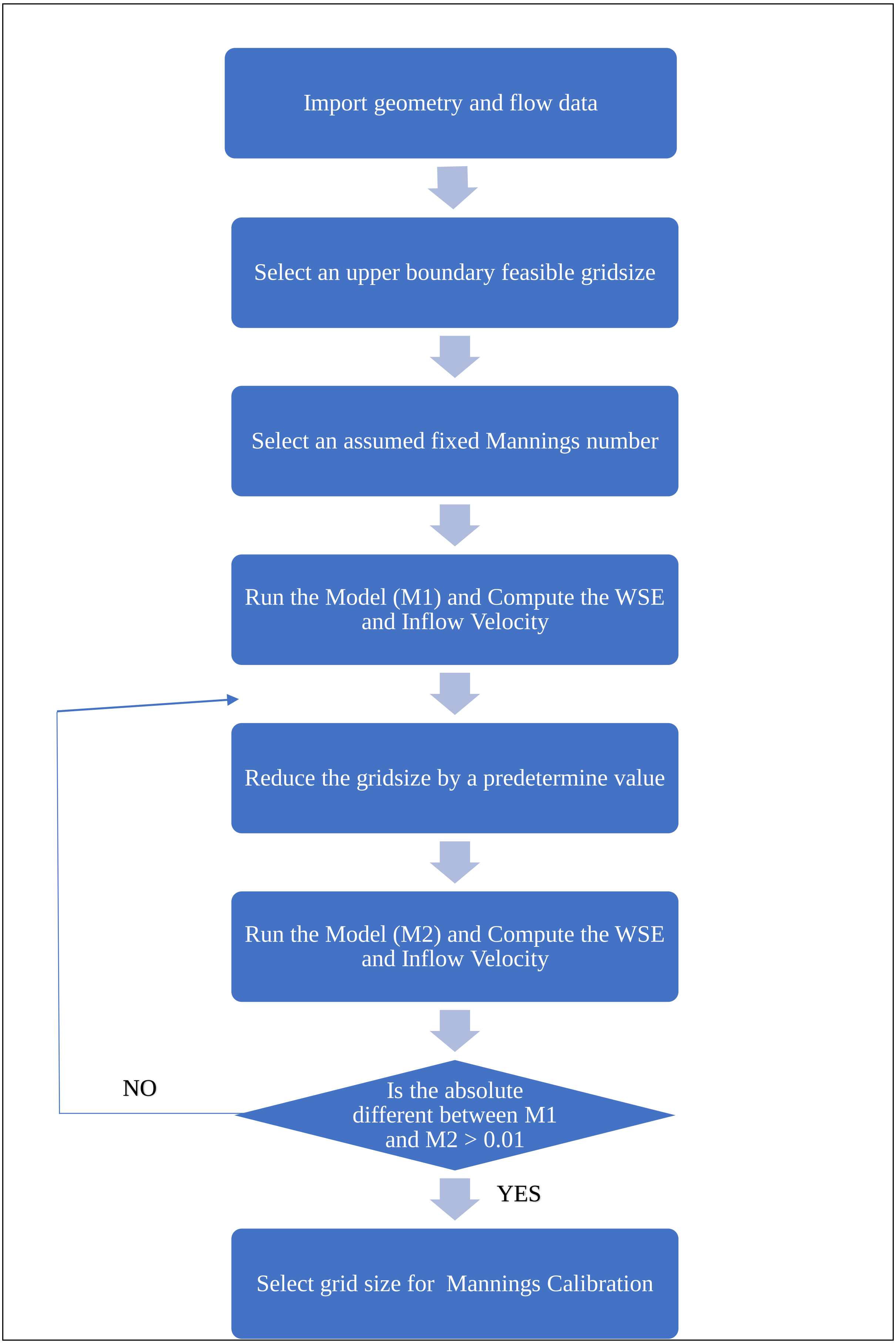

Figure 4: Flowchart of Manning’s coefficient calibration

4.4 Results

A hydropower intake was incorporated into the first model layout. This was to detect the effect of the intake on the WSE and Inflow velocity of the model. The intake is located south west of the spillway. It has a discharge of $0.003m^3/s$. After a completed simulation, the 2D output results can be viewed using RAS Mapper. The image below shows the geometry of the reservoir with and without the HPP intake. The are no significant difference between the two model's inflow velocity and WSE. There are other differences between the two models such as the velocity distribution. This is not of interest in this project an wasn't analyzed further.

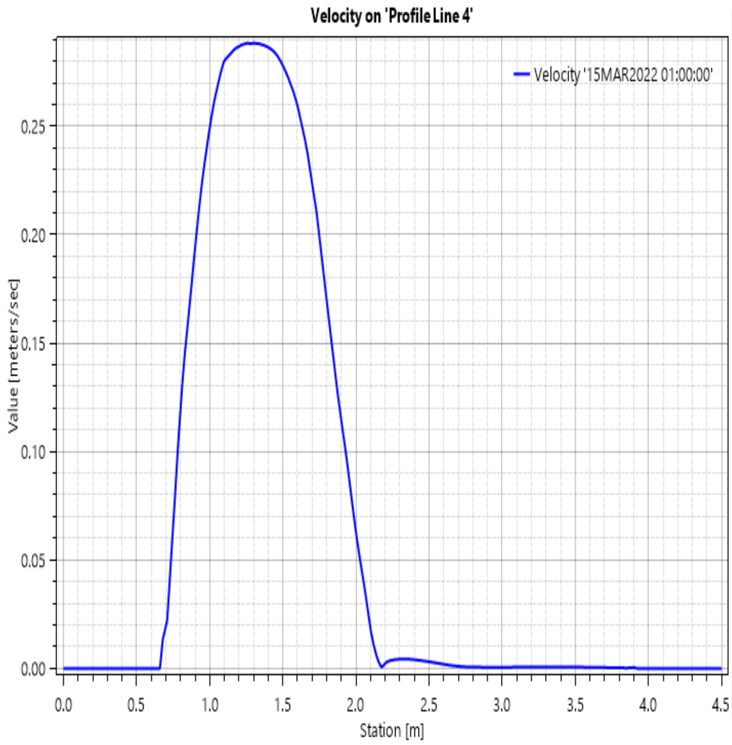

Figure 5a: Inflow Velocity of Simulated Model

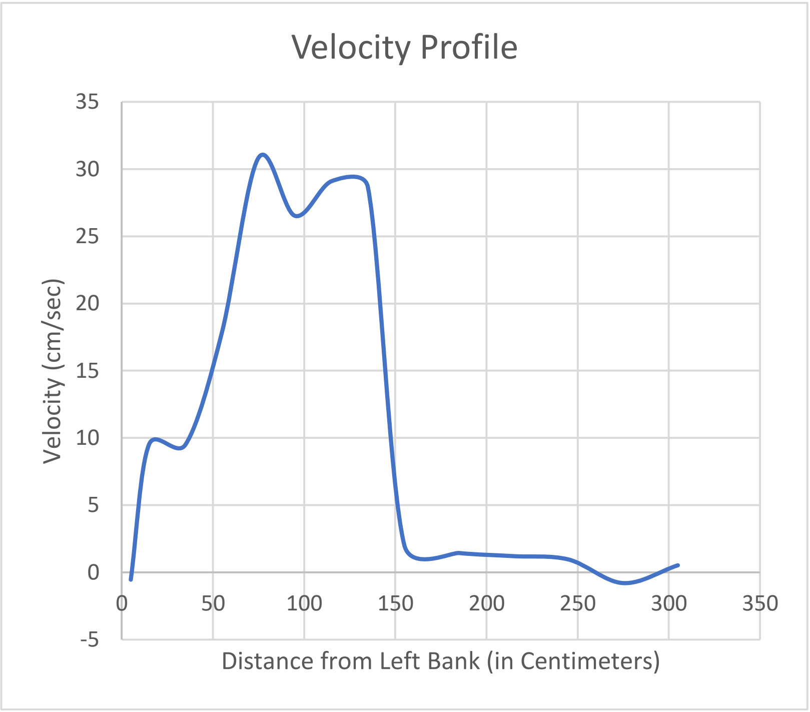

Figure 5b: Inflow Velocity of Physical Model

Tabell 3: WSE Values

	Without HPP	With HPP
WSE Sensor 1 (m)	0.3119	0.31186
WSE Sensor 2 (m)	0.31159	0.31156
WSE Sensor 3 (m)	0.31159	0.31156

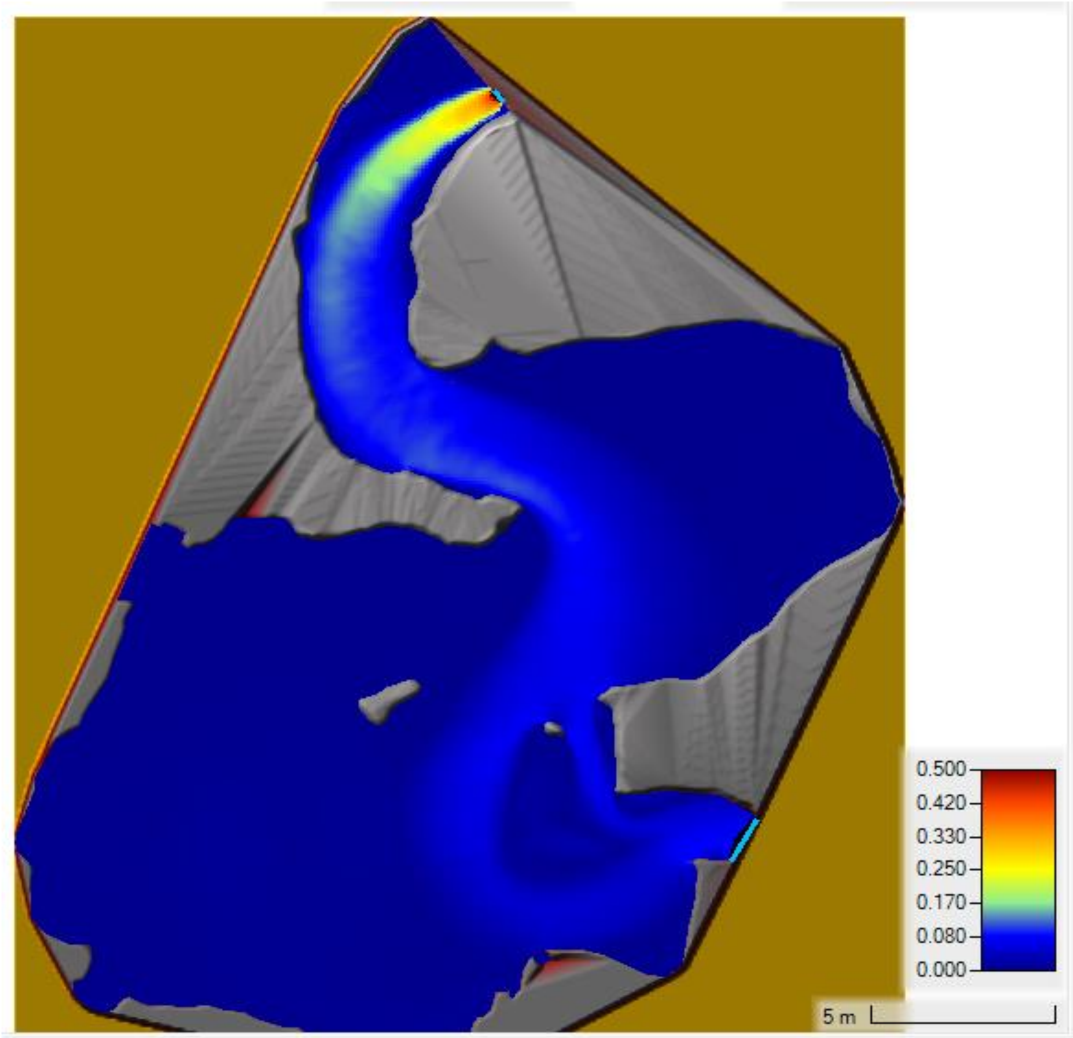

Figure 6: Hydraulic Simulation without HPP Intake

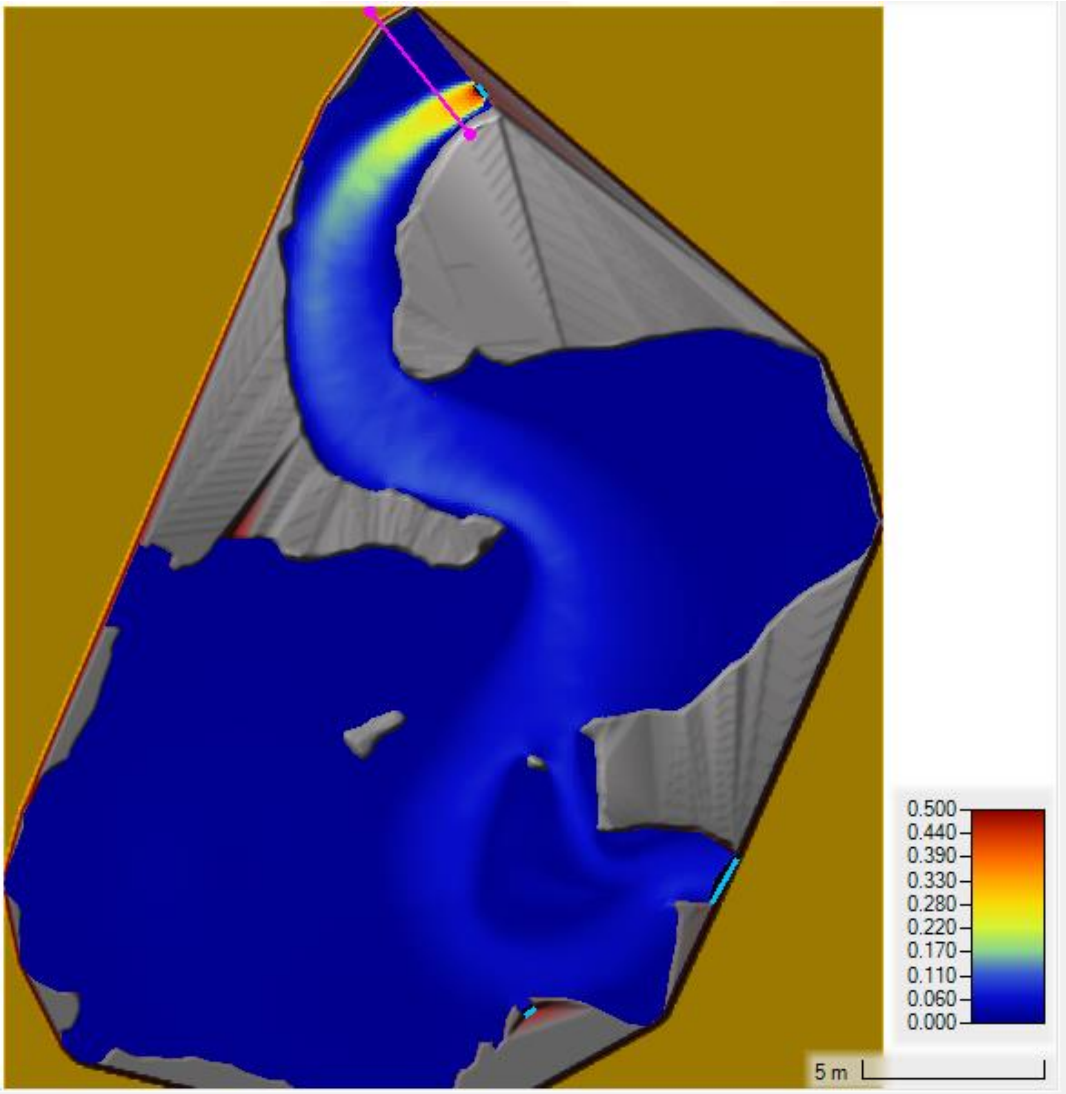

Figure 7: Hydraulic Simulation with HPP Intake

4.5 Problem Faced

The initial data that was converted to a raster format had a few missing data. This missing data caused a lot of errors when making grid of smaller sizes (< 0.5m). An attempt to use cross-sectional data to improve the terrain on HECRAS came out well but the model becomes unstable at those points. The Figure below shows the terrain with the missing data and the modified terrain.

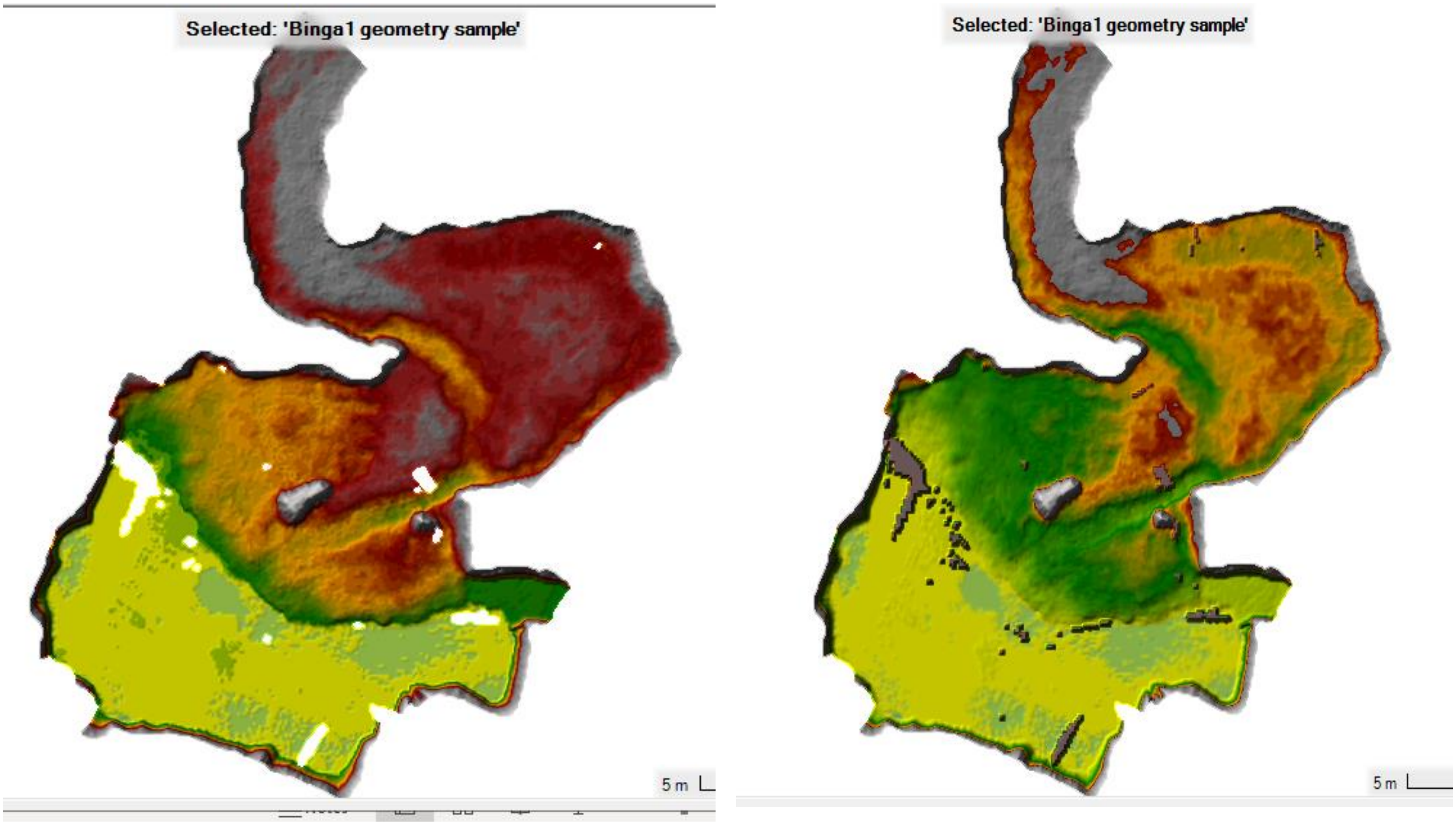

Figure 8: Terrain with missing data and modified terrain

Chapter 5 - Simulation of Sediments

Here we investigate how the sediments behave when introduced into a reservoir model. Two model scenarios were experimented. The first is with a hydrograph consisting of both low flows and high flow period. This would enable us understand how different transport formula perform under large variation in discharge. The second scenario experiments how the transport formula responds to high constant discharge for long durations. It is impossible to simulate a sediment model without a properly configured hydraulic model. The sediment model is more sensitive than the hydraulic model and can easily give wrong results. It is therefore important to ensure the hydraulic model is properly set up before proceeding to sediment modelling

5.1 Grid Refinement

The quality of the grid influences the accuracy of the numerical solution. Therefore, a poorly defined grid can result in poor convergence and the model running unstable. Although grid quality is important in hydraulic model, it is more important while simulating sediment transport. To attain a high quality of grid, the cells in the gird are aligned to face the direction of flow using the refinement region and break lines. 3 break lines (2 boundary break lines and a center break line) and a refinement region were enforced. This helps to reduce the numerical diffusion and improve the accuracy of the computation. Also, a thorough check was done throughout the grid to delete irregularities in the computational point

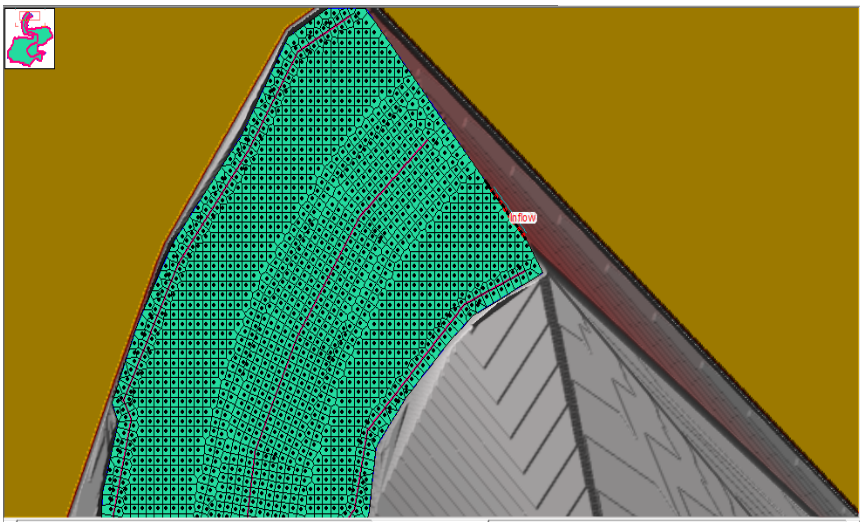

Figure 9: Close up view of the cell alignment in a section of the grid

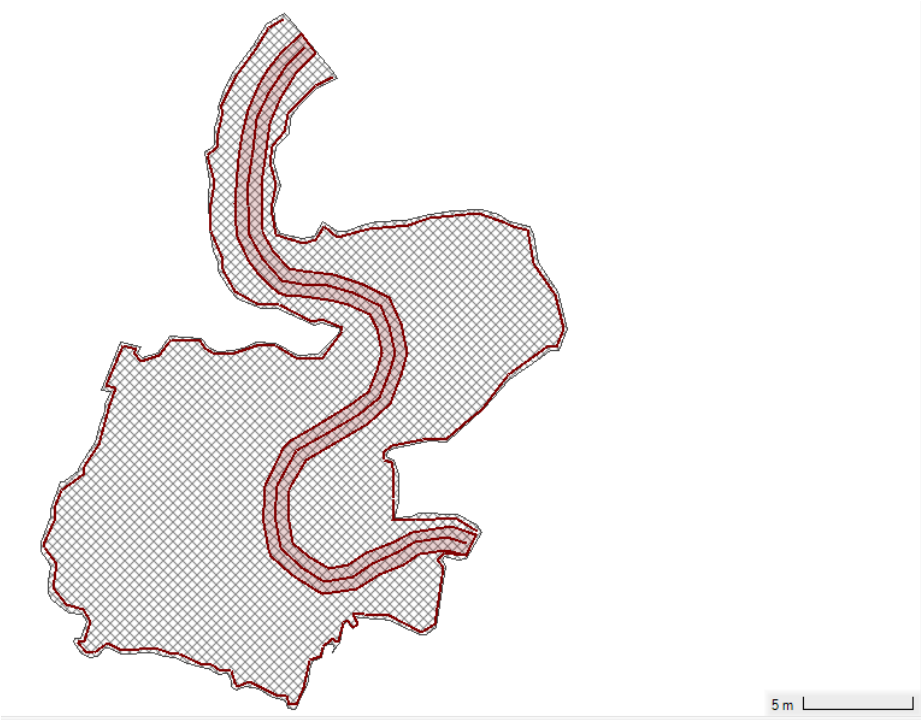

Figure 10: Break lines and Refinement Region

5.2 Hydraulic Warm Up

This is a very important parameter when modeling sediments. This is to prevent scouring of the bed at the initial time step causing a wrong result. The model needs a timeframe of warmup in a steady hydraulic state before sediment begins to move. This is usually determined by the ramp up fraction function. For this project we set the warm up period to be 0.1 of the initial warm up period.

5.3 Sediment Data

There are four files needed to run a 2D sediment transport model on HECRAS. They are

- Geometry File – This file usually contains the map layer of the terrain, the 2D flow area, together with any break line or refinement region used in the geometry.
- Sediment File – The sediment file stores information regarding the initial conditions and transport parameters. It also has data regarding sediment flow in the boundary conditions and sediment gradations.
- Unsteady Flow File – The unsteady flow file gives data regarding the initial hydraulic conditions and also the flow at the boundary conditions.

- Plan File – This file is used to combine all other files together for the simulation. It contains the duration of the simulation, the computation interval and the format to produce the result.

5.4 Sediment Transport Function

There are 11 transport functions available on HEC-RAS 6.2. They include:

- Ackers and White
- England and Hansen
- Laursen-Copeland formula
- Meyer-Peter and Müller
- Toffaleti
- MPM-Toffaleti
- Yang
- Wilcock and Crowe
- Soulsby-van Rijn
- van Rijn
- Wu et al.

Five different transport formulas were used in this model. The choice of the equations to use were based on transport formulas that were developed for calculating Bed load and/or Total Load.

5.4.1 Ackers and White

This is a transport formula that was developed from a flume experiment using relatively uniform sediment gradations ranging from sand to fine gravel. The sediment shear partition was not included in the dimensional analysis of the equation. The equation is based on the sediment flux as a function of a transport parameter.

$$X = \frac{G_{gr} s d}{D(\frac{u_*}{V})^n} \tag{8}$$

Where:

X = Sediment Flux

G_{gr} = Transport Parameter

s = Specific gravity of the sediment

d = median particle size

D = Effective depth

u_* = Shear Velocity

V = Average Channel Velocity

n = Transition exponent

The Transport parameter can equally be derived as a function of sediment mobility and threshold mobility

$$G_{gr} = C(\frac{F_{gr}-A}{A})^m \tag{9}$$

F_{gr} is the sediment mobility while A represents the threshold mobility. C and m are both empirical power coefficients which can be calibrated. They are not fixed parameter, therefore, they keep changing with sediment properties and flow. (Ackers, 1973)

5.4.2 Engelund-Hansen

This is the simplest of the transport formulas. It is a transport equation for the total load transport developed using relatively uniform sediment sizes between 0.19mm and 0.93mm in a laboratory flume. Due to the range of sediment it was developed from, it is usually not applicable for sediment with larger grain sizes. The equation is represented by: (Hansen, 1967)

$$g_s = V^2\left(\frac{\tau_b}{(\gamma_s-\gamma)d_{50}}\right)^{\frac{3}{2}}\sqrt{\frac{d_{50}}{g\left(\frac{\gamma_s}{\gamma}-1\right)}} = V^2(\tau^*)^{\frac{3}{2}}\sqrt{\frac{d_{50}}{g\left(\frac{\gamma_s}{\gamma}-1\right)}} \tag{10}$$

Where:

g_s = Sediment transport by unit width

γ = Unit weight of water

γ_s= Unit weight of sediment

V = Average channel velocity

τ_b= Bed shear stress

τ^*= Dimensionless Shields Number

d_{50} = Median particle size

5.4.3 Meyer-Peter Muller

This is one of the earliest and most widely used transport formula that was developed. It is mainly catering for bed load and does not take suspended load into account. It was developed in a flume experiment using sand and gravel under plane conditions. It tends to under predicts when tested with finer materials. HEC RAS makes use of the Vanoni version of MPM which has the formula below (Meyer-Peter, 1948) (Vanoni, 1975)

$$(\frac{K_r}{K'_r})^{\frac{3}{2}}\gamma RS = 0.047\,(\gamma_s-\gamma)d_m + \left(\frac{\gamma}{g}\right)^{\frac{1}{3}}(\frac{\gamma_s-\gamma}{\gamma_s})^{\frac{2}{3}}\,g_s{}^{\frac{2}{3}} \qquad (11)$$

Where:

g_s = Unit sediment transport rate in weight/time/unit width

kr = A roughness coefficient

kr' = A roughness coefficient based on the grains

γ = Unit weight of water

γs= Unit weight of sediment

g = Acceleration of gravity

dm = Median particle diameter

R = Hydraulic radius

S = Energy gradient

5.4.4 Yang

This equation calculates the total load sediment transport using the product of velocity and shear stress. The equation was developed and tested using series of field data and flume experiments. There are two different equation used depending on the sediment size.

For sediment with grain class lesser than 2mm

$$\log C_t = 5.435 - 0.286 log\frac{\omega d_m}{v} - 0.457 log\frac{U*}{\omega} + \left(1.799 - 0.409\frac{\omega d_m}{v} - 0.314 log\frac{U*}{\omega}\right)\log(\frac{VS}{\omega}-\frac{V_{cr}S}{\omega}) \qquad (12)$$

For sediment with grain class greater than 2mm

$$logC_t = 6.681 - 0.633 log\frac{\omega d_m}{v} - 0.282 log\frac{u_s}{\omega} + \left(2.784 - 0.305\frac{\omega d_m}{v} - 0.282 log\frac{u_s}{\omega}\right)\log(\frac{VS}{\omega}-\frac{V_{cr}S}{\omega}) \qquad (13)$$

Where

C_t = Total sediment concentration

ω = Particle fall velocity

d_m = Median particle diameter

ν = Kinematic viscosity

$u*$ = Shear velocity

V = Average channel velocity

S = Energy gradient

5.4.5 Van Rijn

The transport formula was developed for particles in the range of 200 - 2000μm (Rijn, 1984)

$$\frac{q_b}{((s-1)g)^{0.5}D_{50}^{1.5}} = 0.053\frac{T^{2.1}}{D_*^{0.3}} \tag{14}$$

Where

q_b = Bed load transport

T = Transport stage parameter

s = Specific density

g = Acceleration due to gravity

D_{50} = Particle diameter

D_* = Particle Parameter

5.5 Bed Gradation

This contains the sediment grain class sizes of the bed in the model. This grain class sizes are uniform for both the bed and the sediment inflow into the system. The figure below shows the classification that was used for this model.

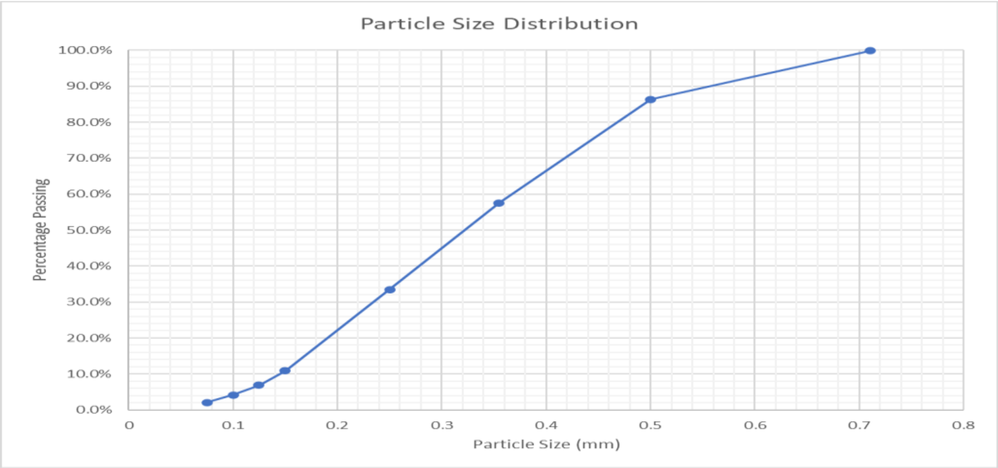

Figure 11: Particle size distribution for bed gradation

5.6 Sediment Boundary Conditions

There are 4 different sediment boundary conditions that may be specified in a 2D sediment model on HEC-RAS. They are

- Rating Curve – This boundary condition makes use of the sediment load (tons/day) or sediment concentration (mg/l) as a function of the flow discharge. It also requires the specification of the fractional bed-load composition for each grain class
- Sediment Load Series – This boundary condition uses the sediment load in tons per hour of the computation period
- Equilibrium Load
- Clear Water

Below is the external boundary condition in the model and the type of boundary condition used for each:

- Inflow – Sediment Load Series
- Spillway – Equilibrium load
- HPP Intake – Equilibrium load
- SBT – Equilibrium load

5.7 Model 1 – Hydrograph Model

The model was based on an experiment performed in the laboratory using the physical model. An inflow from a hydrograph was passed through the model with also an increasing sediment intake. The same scenario was modelled to compare the observed result from the laboratory test to the simulated result from the model.

5.7.1 Input File

The experiment lasted 8 hours. There was a constant flow of 0.03m^3/s for the first 5 hours before suddenly peaking to 0.11m^3/s in 30 minutes. The peak discharge was sustained for an hour before it was reduced rapidly to 0.3m^3/s in 30 minutes for the rest of the experiment. The sediment inflow was also constant at 110g/min for the first 5 hours. After which the sediment inflow rapidly peaked together with the discharge to about 12000g/min.

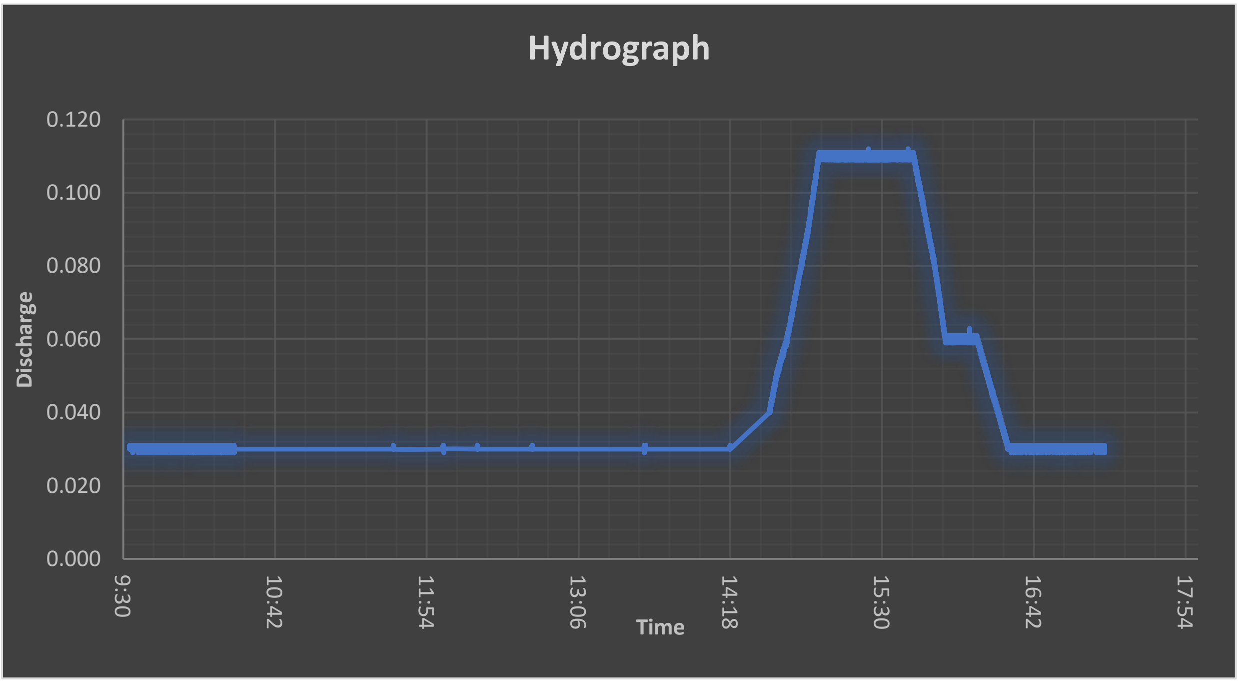

Figure 12: Inflow Hydrograph

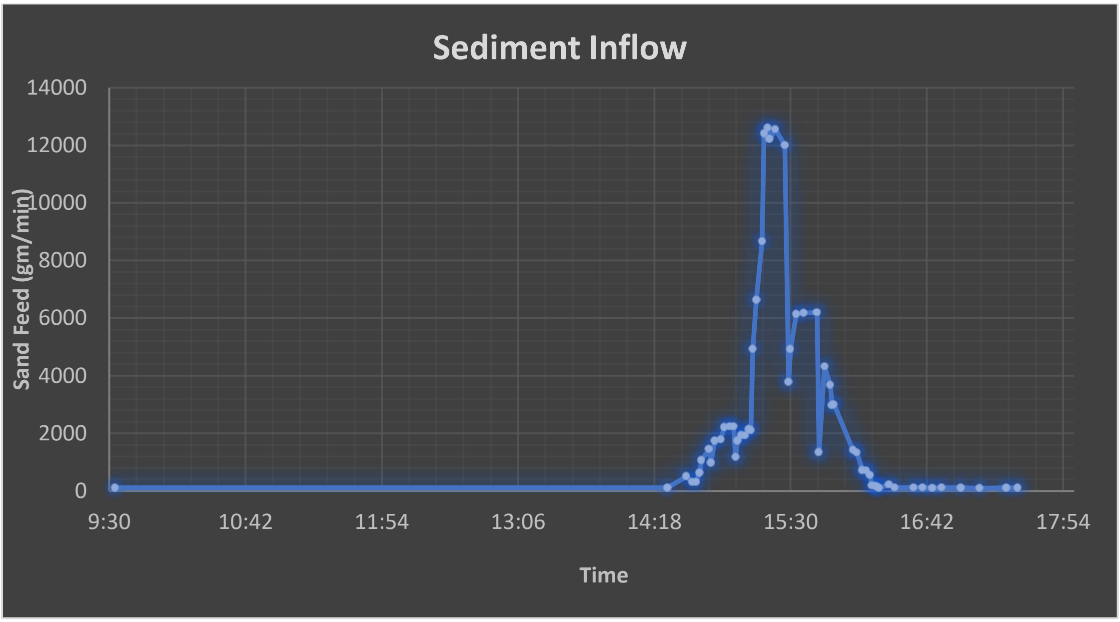

Figure 13: Sediment Inflow

5.7.2 Result

Using the calibrated hydraulic values from the hydraulic simulation in chapter 4, the model was tested using 5 different transport formulas available in HECRAS. The figure below shows the terrain file together with the profile line that will be used to compare the terrain with the result from the physical model and the simulated result from the model. Several profile line were drawn as cross-section across the terrain and numbered as seen in figure 14. For each profile line the cross-sectional terrain profile was computed with the 5 transport equations and compared against the original terrain and the result from the laboratory.

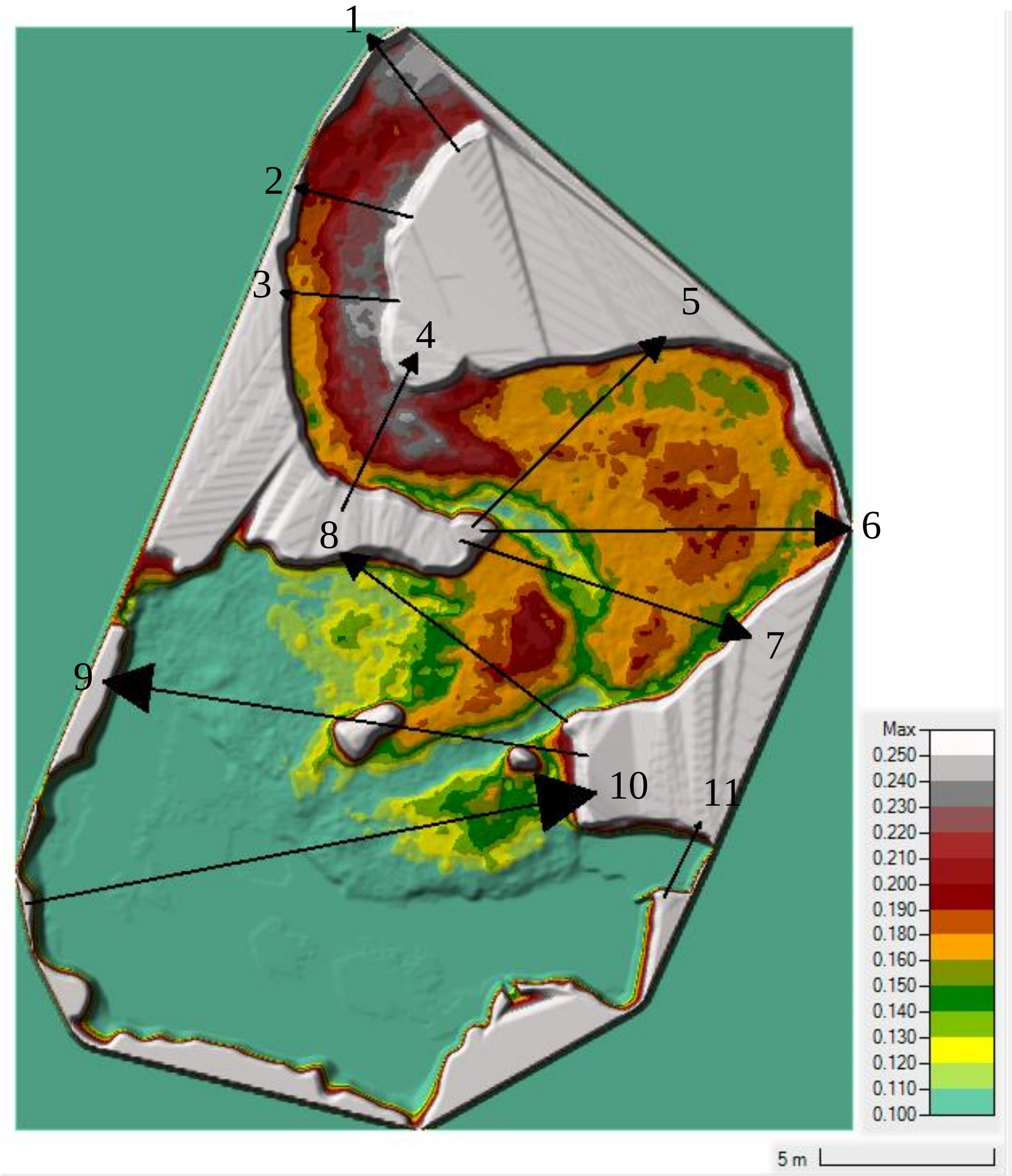

Figure 14: Original Terrain for Model 1

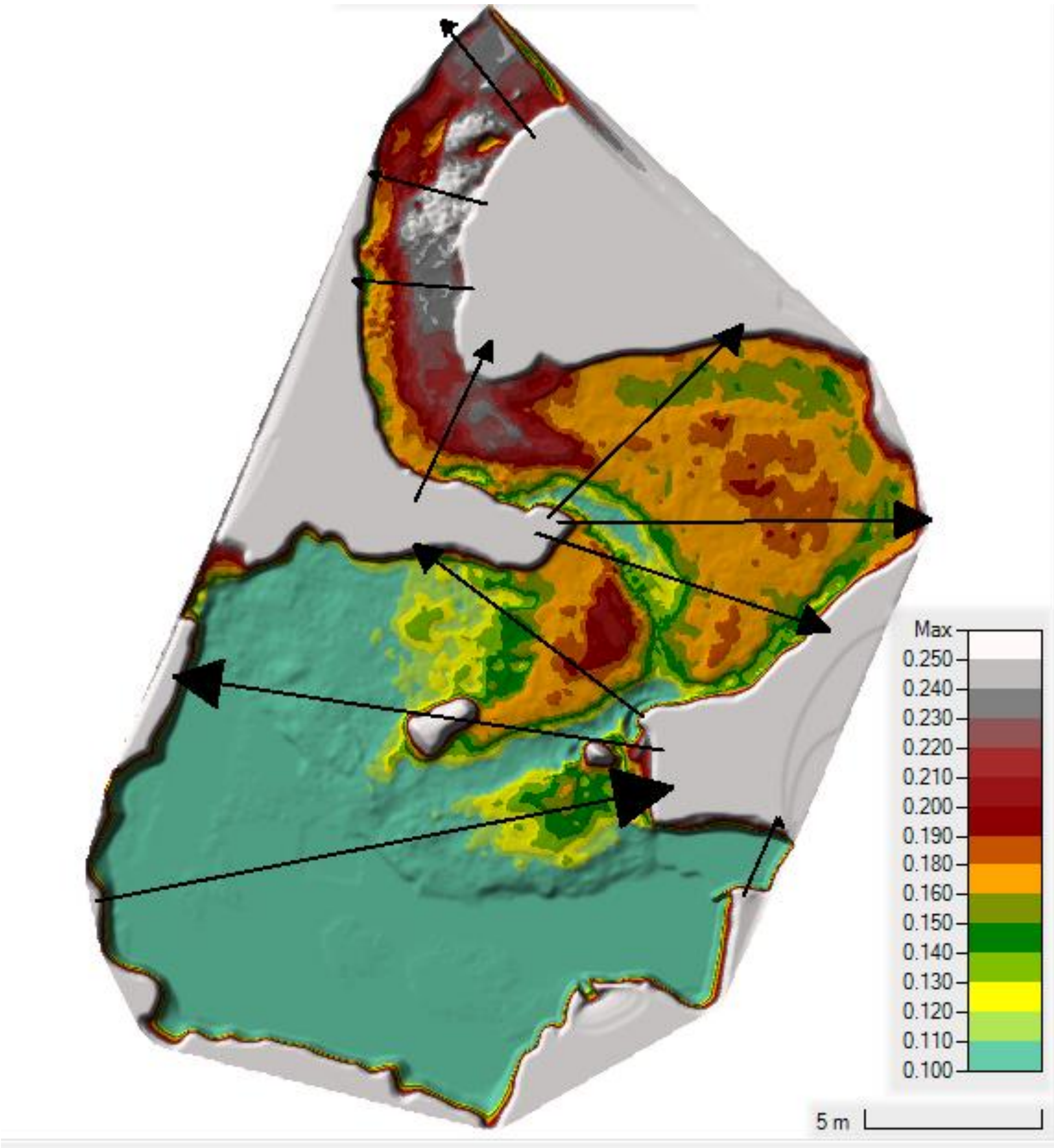

Figure 15: Physical Model Terrain Result for Model 1

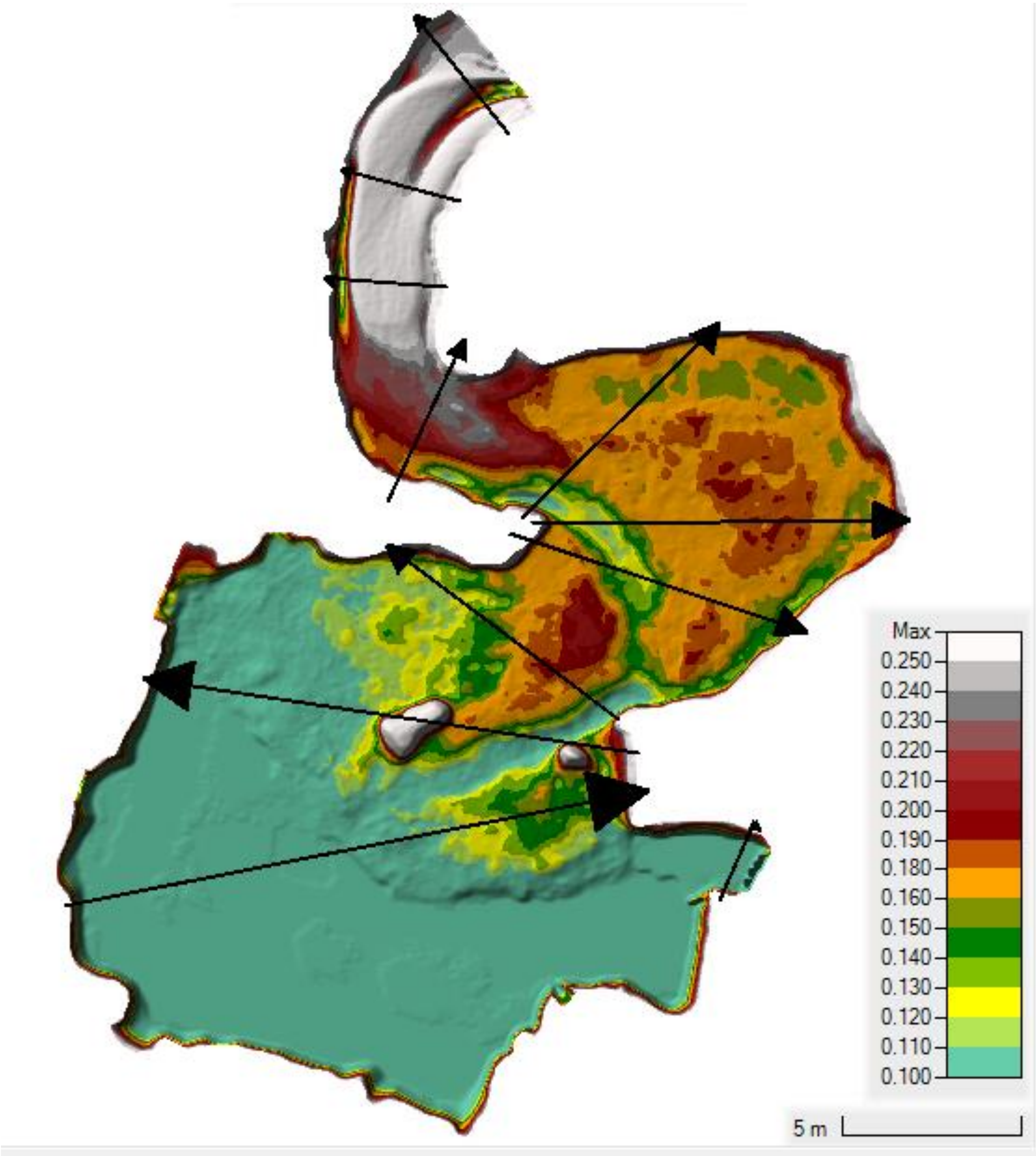

Figure 16: Terrain Result for Model 1 using Van Rijn Transport Function

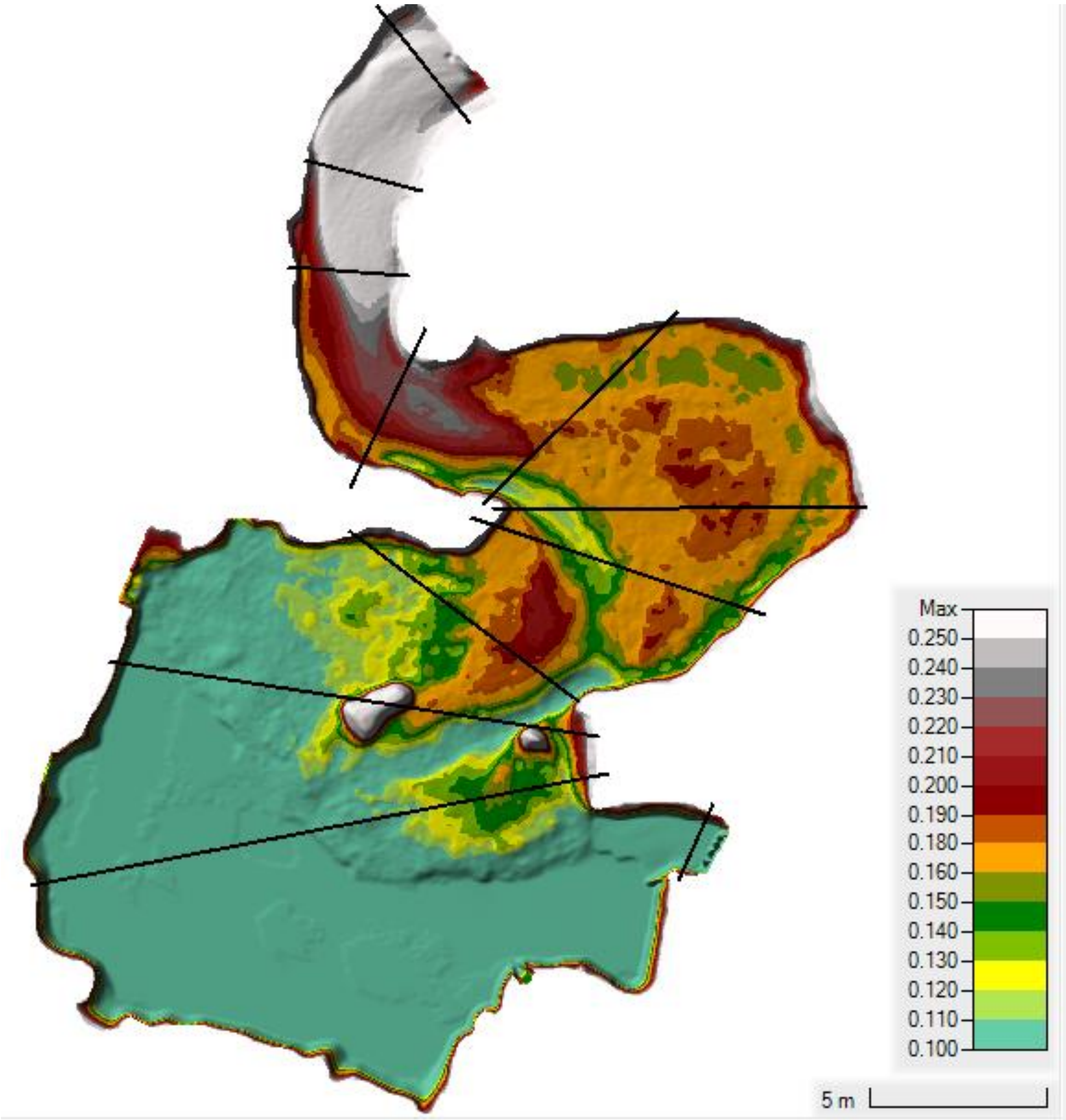

Figure 17: Terrain Result for Model 1 using MPM Transport Function

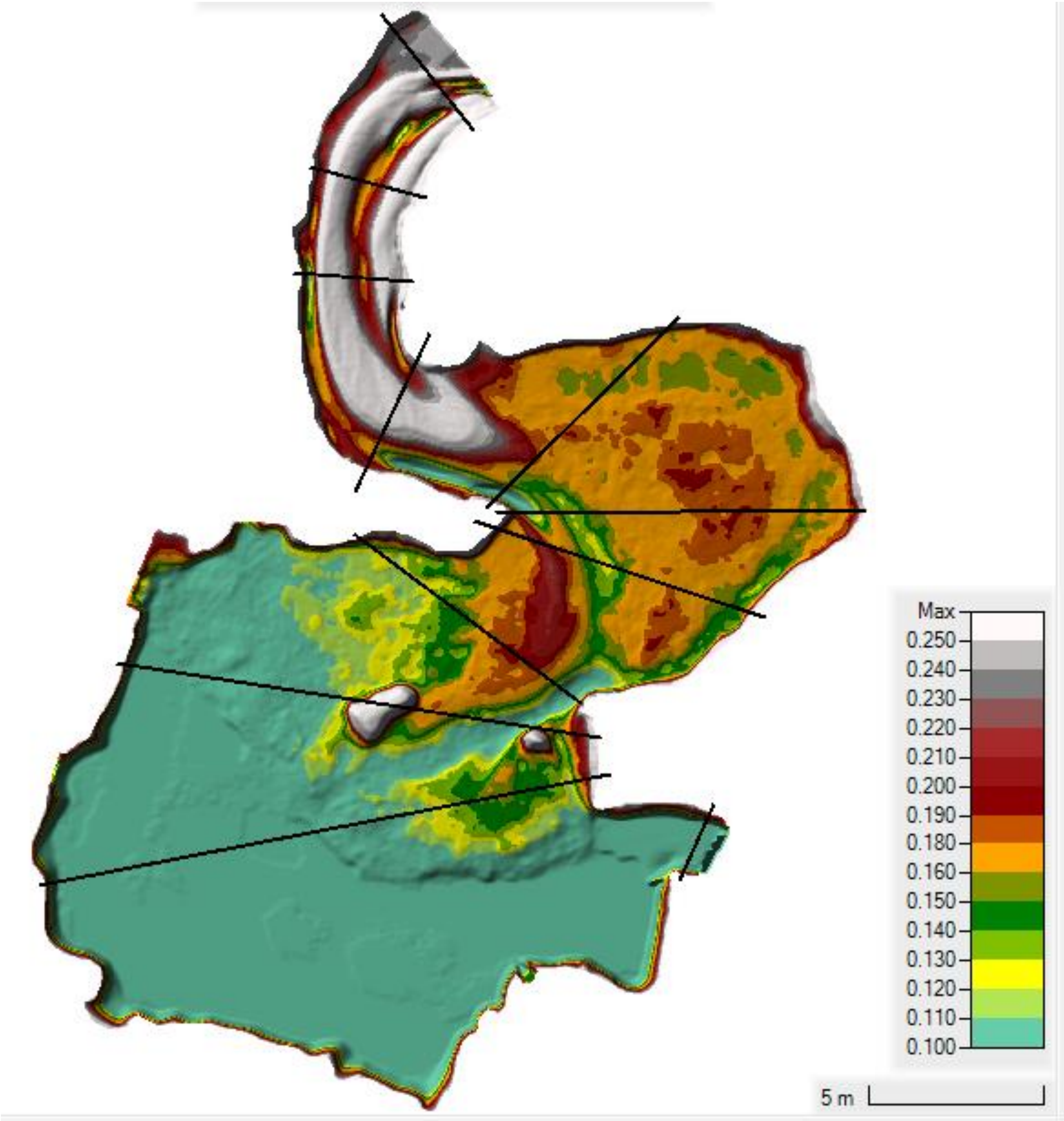

Figure 18: Terrain Result for Model 1 using A&W Transport Function

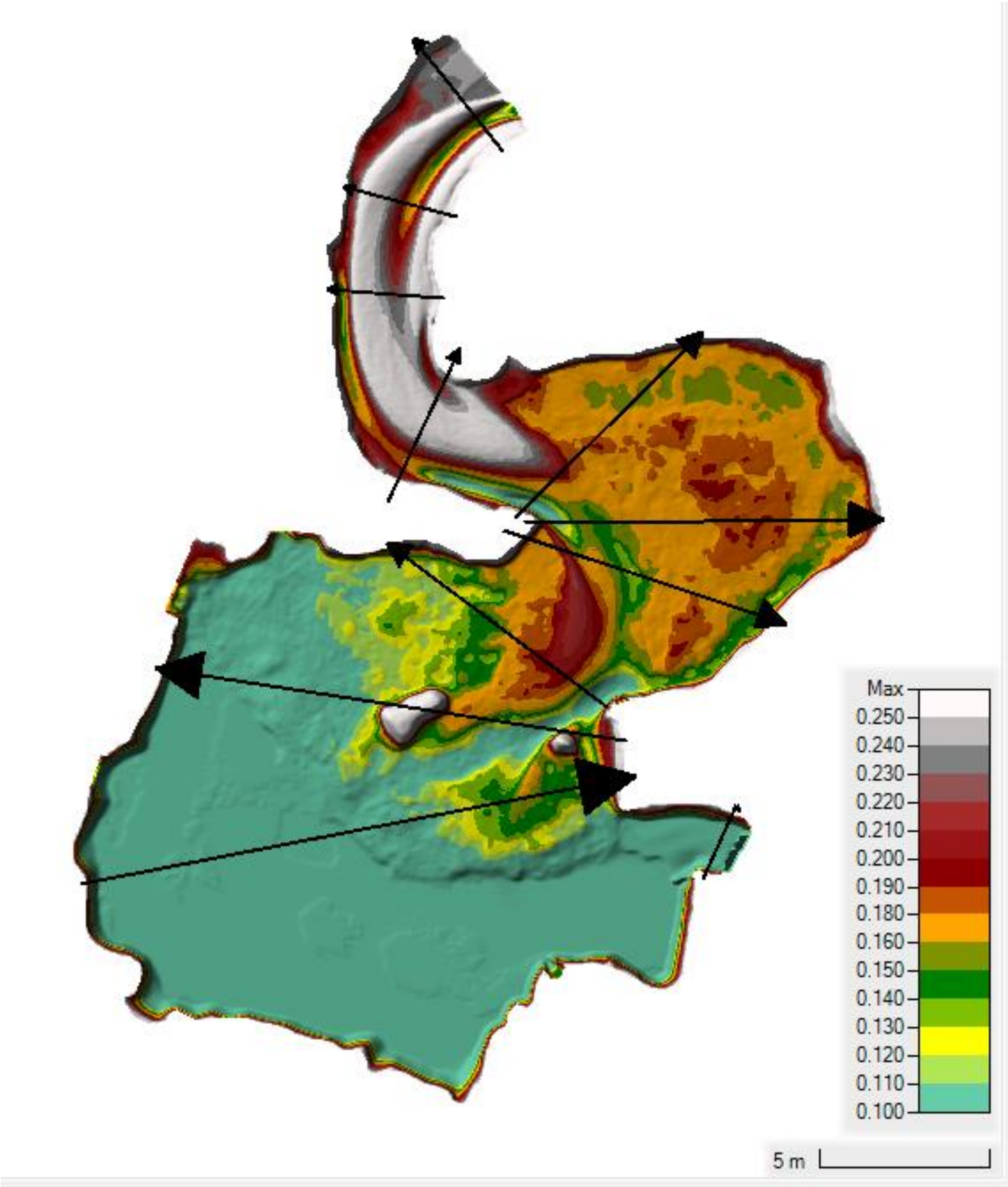

Figure 19: Terrain Result for Model 1 using E&H Transport Function

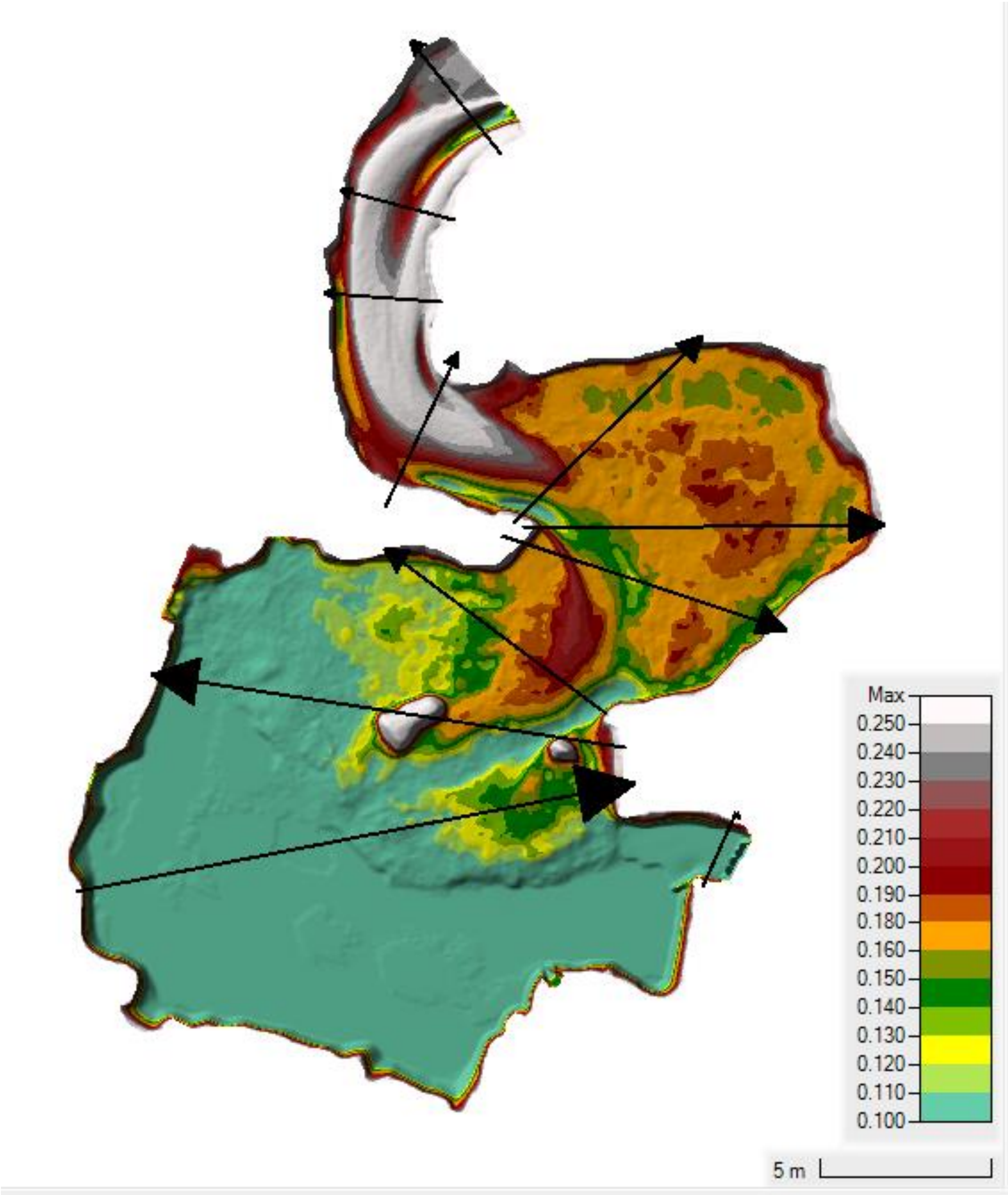

Figure 20: Terrain Result for Model 1 using Yang Transport Function

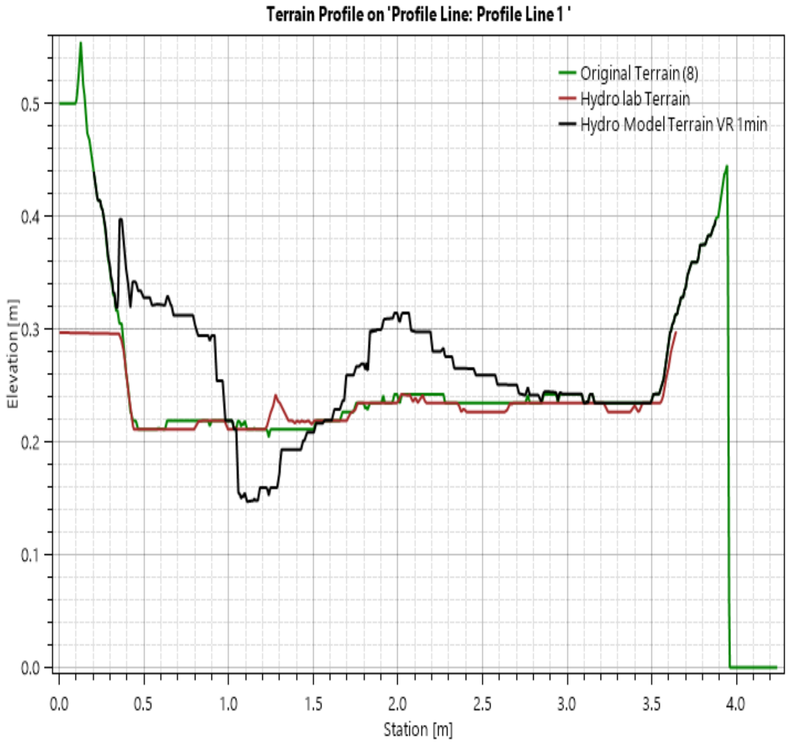

Figure 21: Elevation Profile for Profile Line 1using Van Rijn

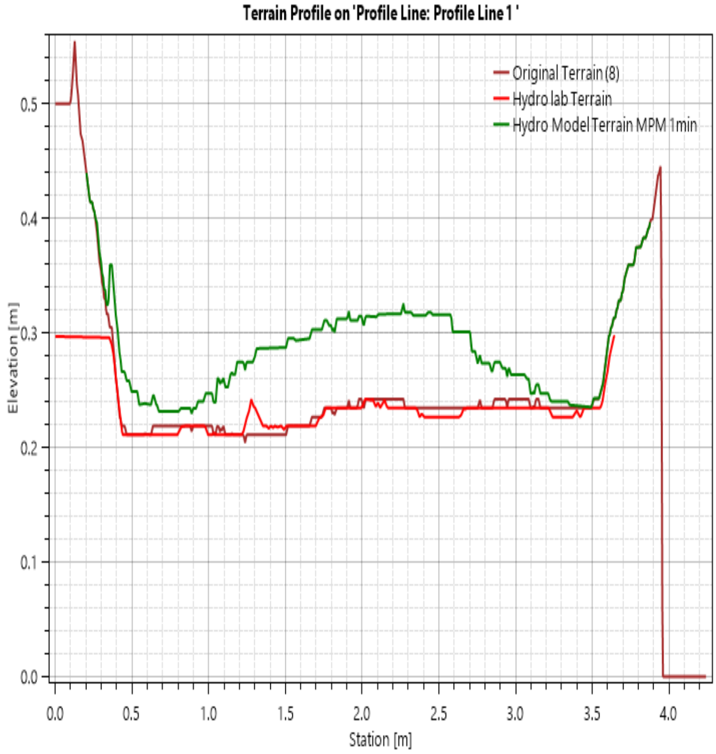

Figure 22: Elevation Profile for Profile Line 1using MPM

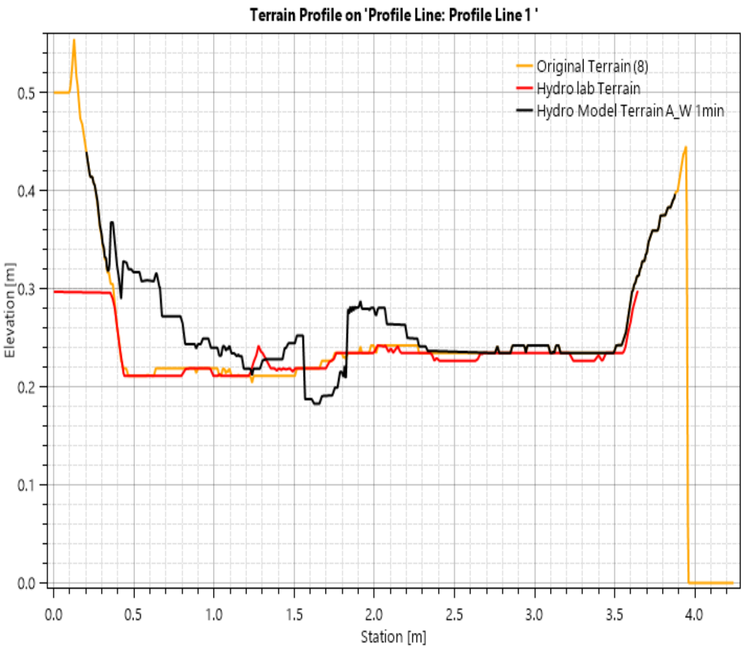

Figure 23: Elevation Profile for Profile Line 1using A&W

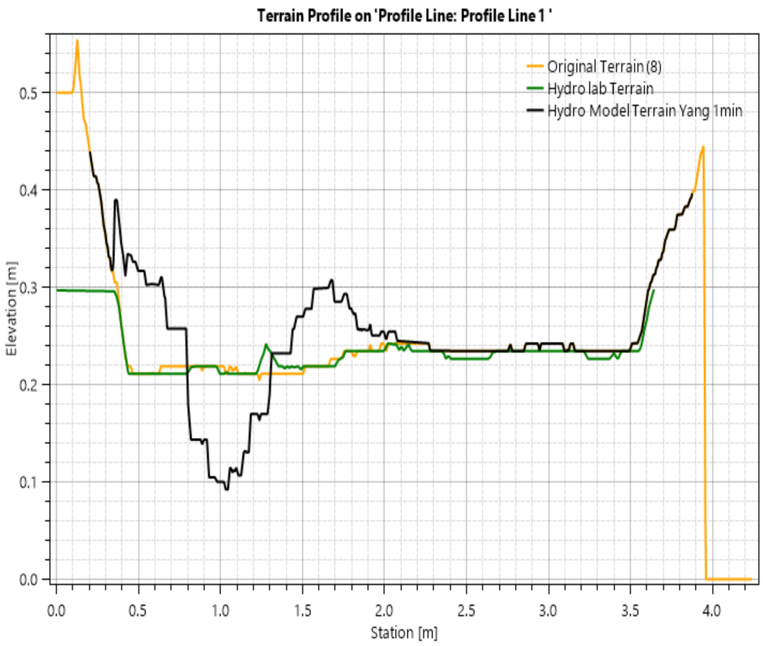

Figure 24: Elevation Profile for Profile Line 1using Yang

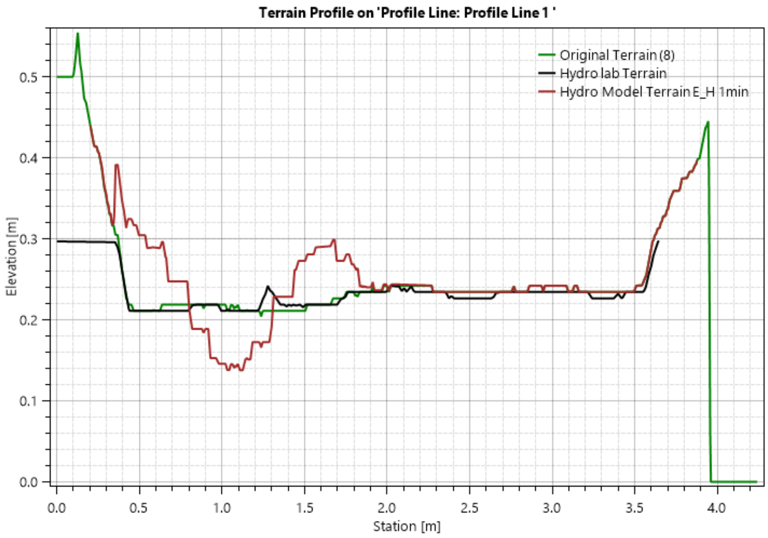

Figure 25: Elevation Profile for Profile Line 1using E&H

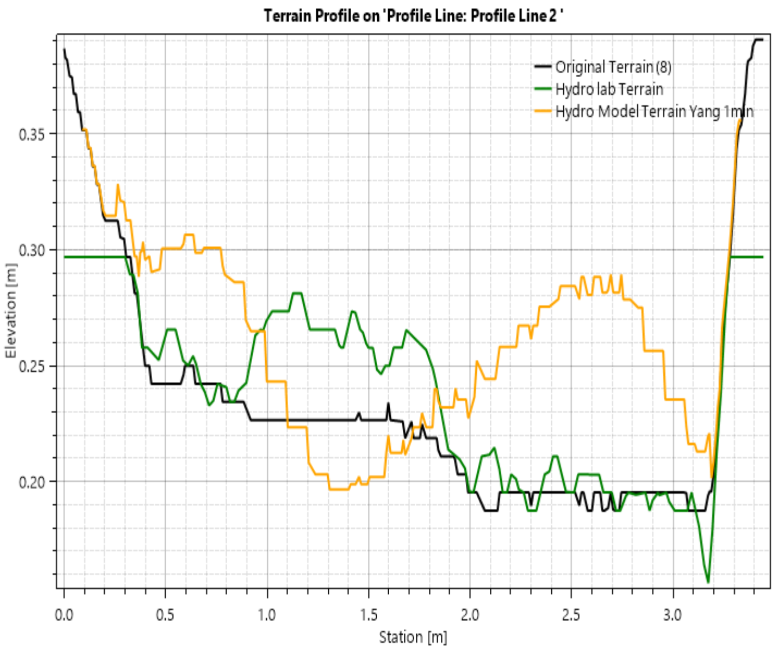

Figure 265: Elevation Profile for Profile Line 2 using Yang

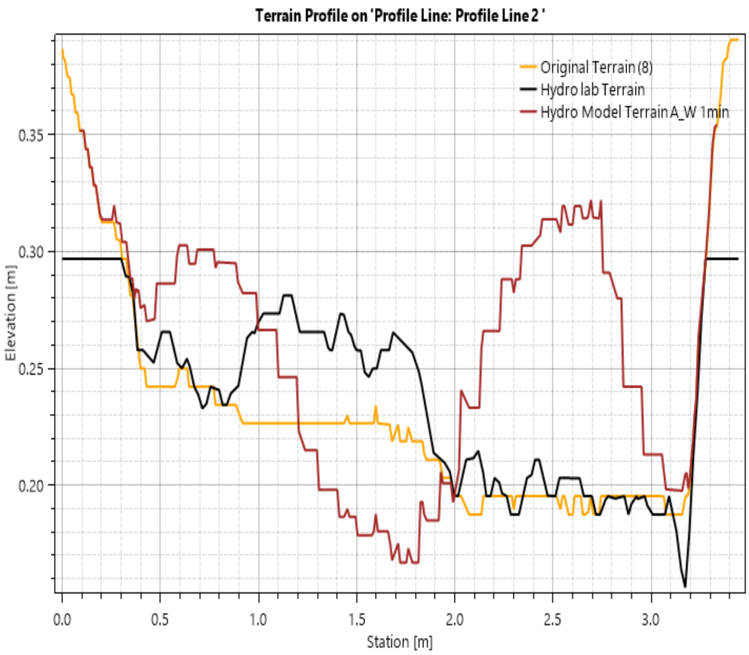

Figure 27: Elevation Profile for Profile Line 2 using A&W

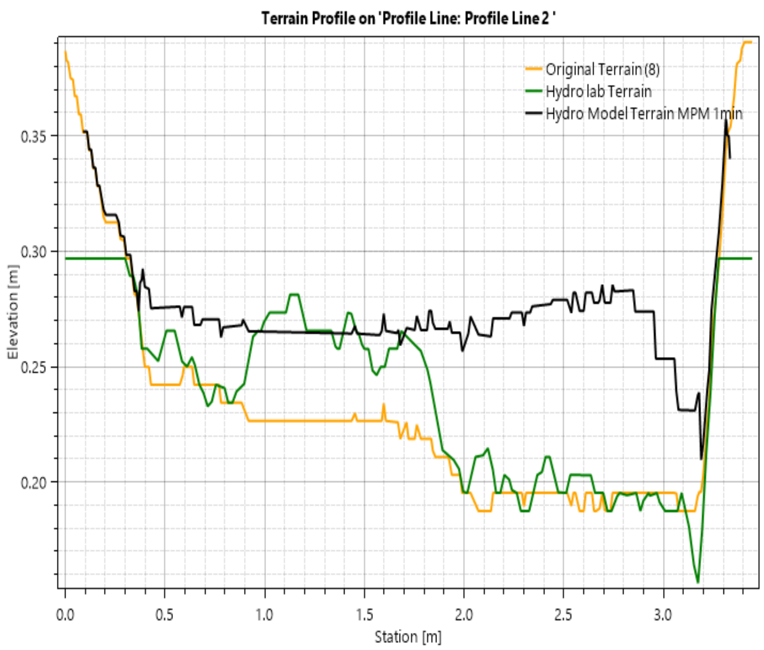

Figure 28: Elevation Profile for Profile Line 2 using MPM

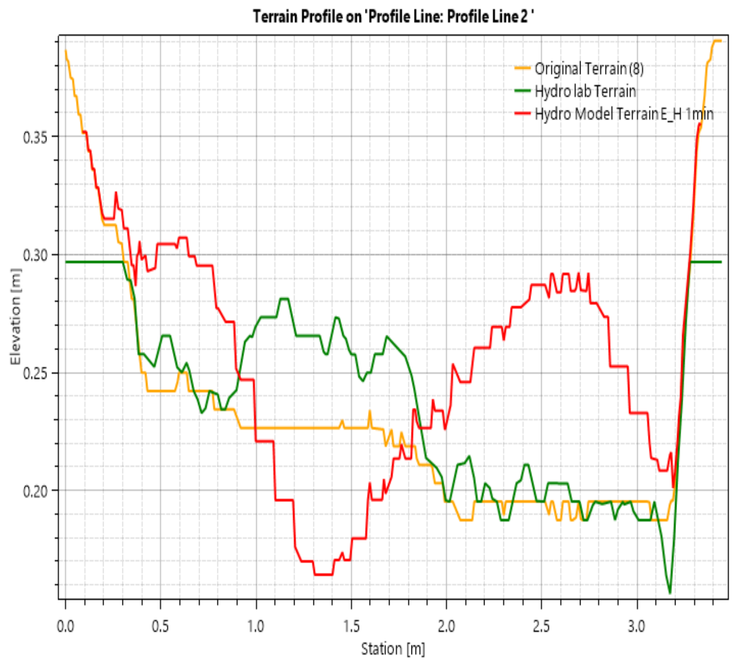

Figure 6: Elevation Profile for Profile Line 2 using E&H

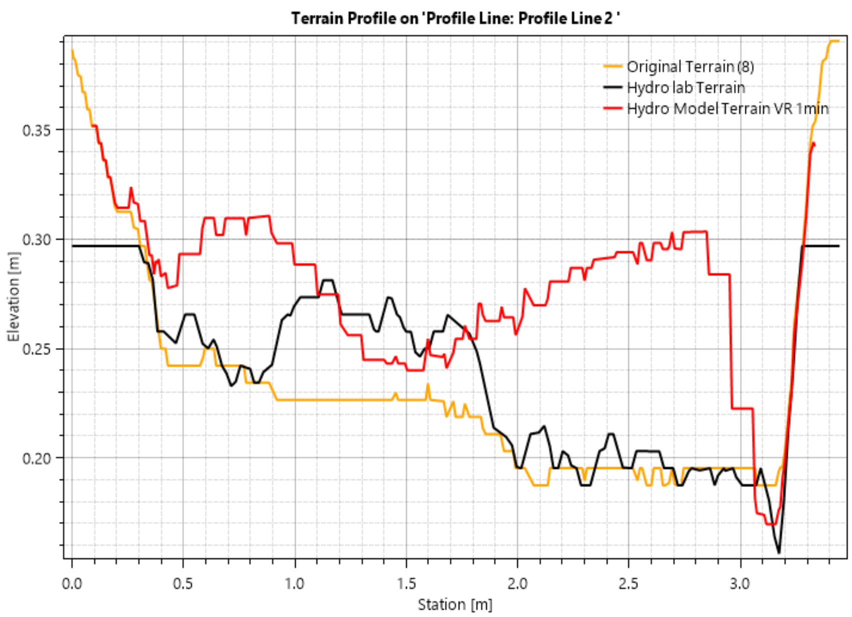

Figure 70: Elevation Profile for Profile Line 2 using Van Rijn

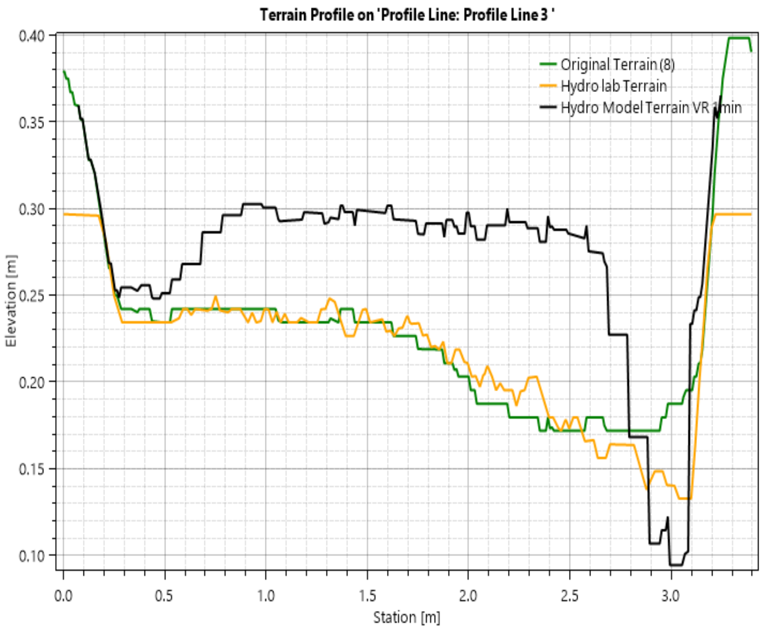

Figure 39: Elevation Profile for Profile Line 3 using Van Rijn

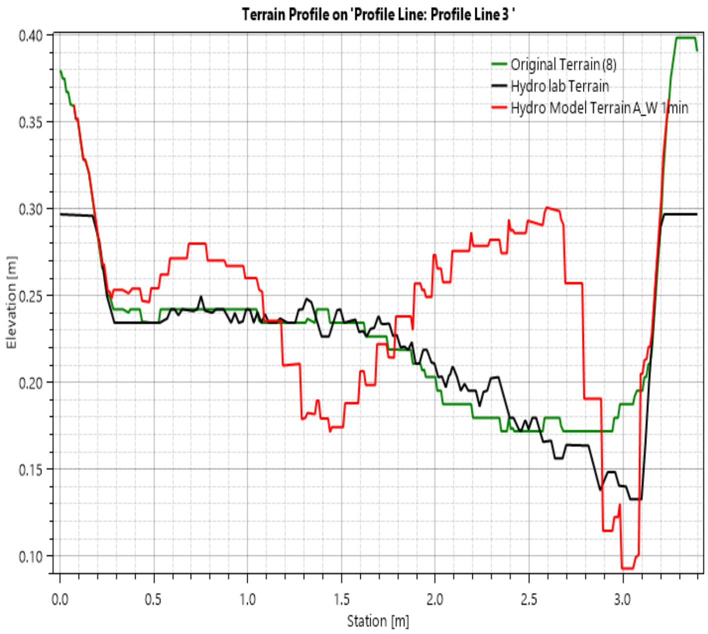

Figure 8: Elevation Profile for Profile Line 3 using A&W

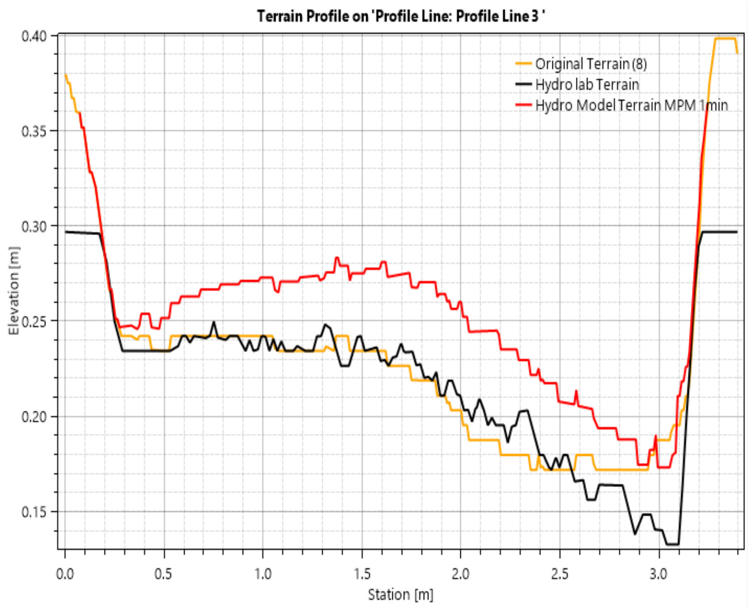

Figure 11: Elevation Profile for Profile Line 3 using MPM

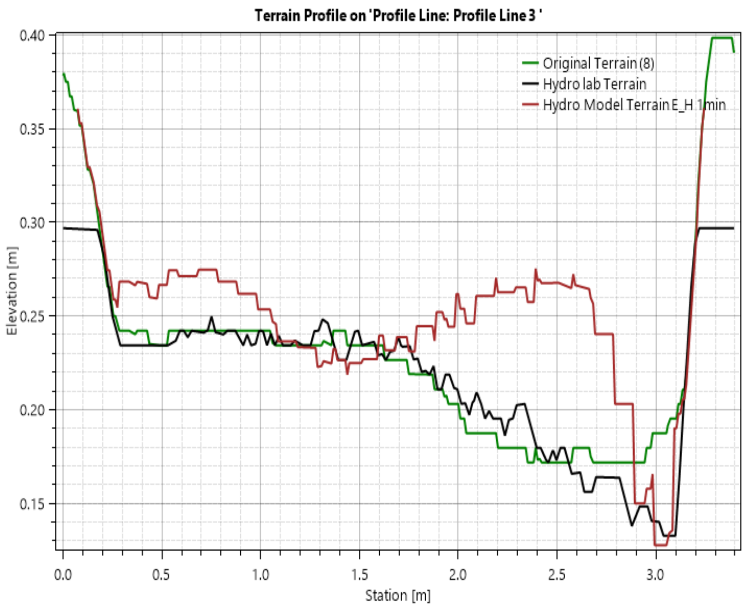

Figure 34:10 Elevation Profile for Profile Line 3 using E&H

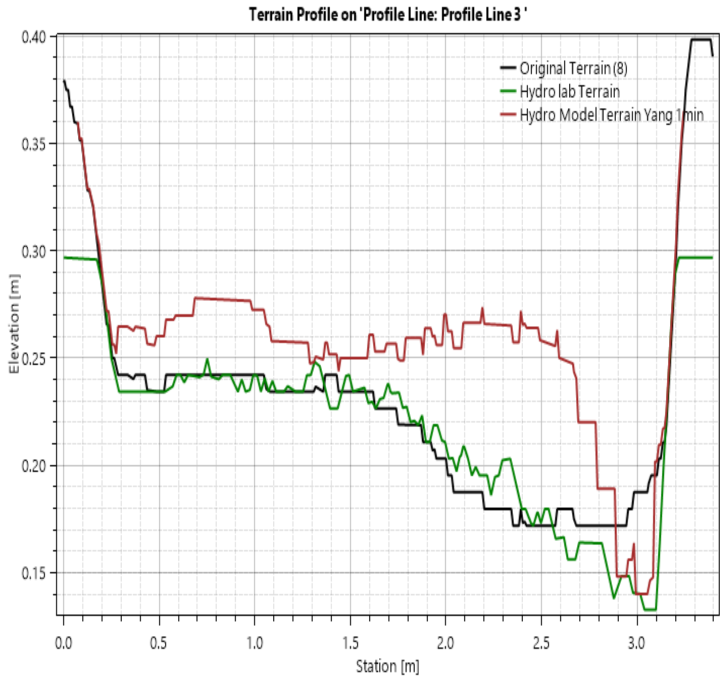

Figure 35: Elevation Profile for Profile Line 3 using Yang

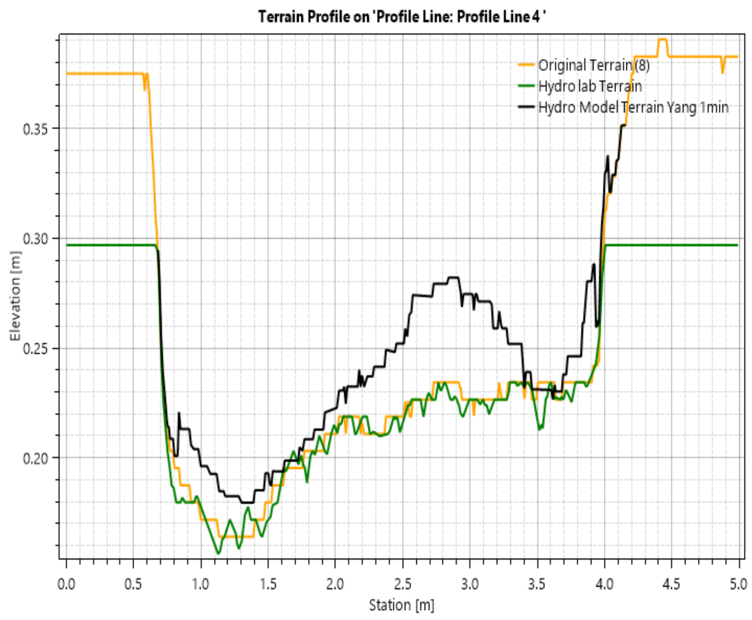

Figure 12: Elevation Profile for Profile Line 4 using Yang

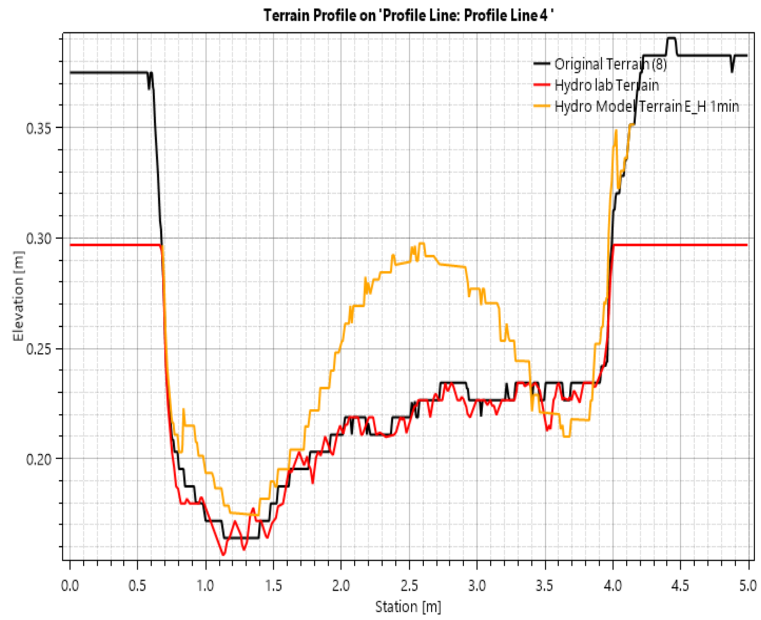

Figure 37: Elevation Profile for Profile Line 4 using E&H

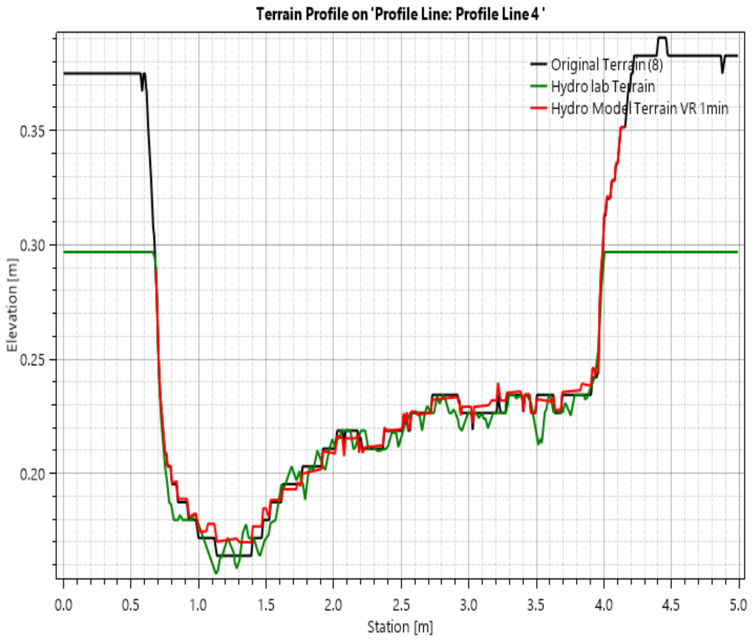

Figure 38: Elevation Profile for Profile Line 4 using Van Rijn

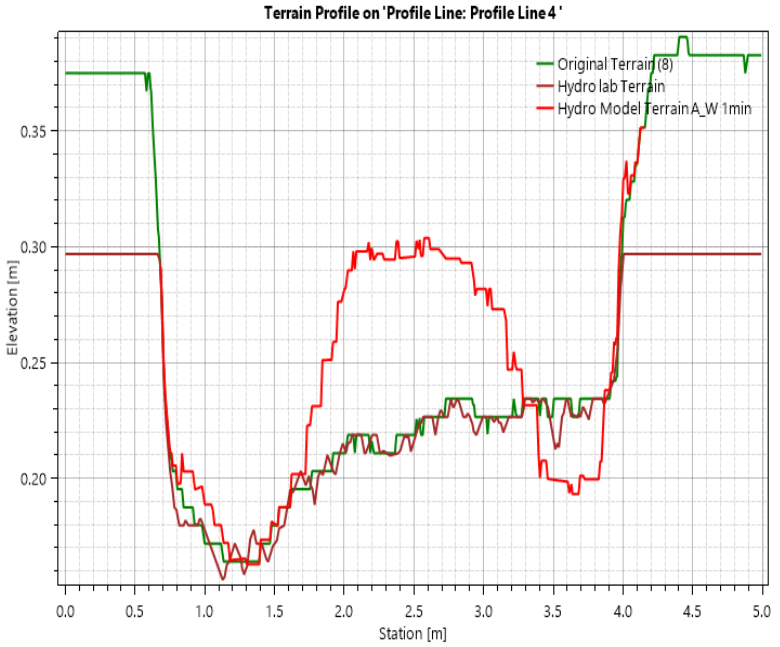

Figure 39: Elevation Profile for Profile Line 4 using A&W

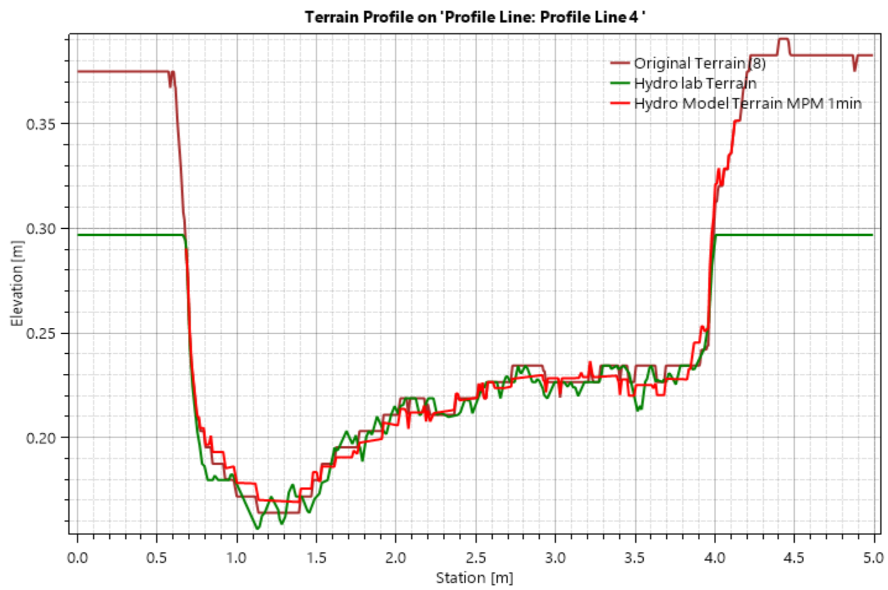

Figure 40: Elevation Profile for Profile Line 4 using MPM

5.8 Model 2 – Constant Flow

In this scenario, a constant discharge of 0.110 was ran through the model for 19 hours with a consistent sediment inflow of 3kg/min. amounting to a total sediment load of 3.42 tons for the duration of the simulation. The calibrated functions in the first scenario were also used to run the model. Other transport methods were tried to see their performance compared to the result from the laboratory experiment. Figure 42 shows the terrain of the physical model after the experiment in the laboratory.

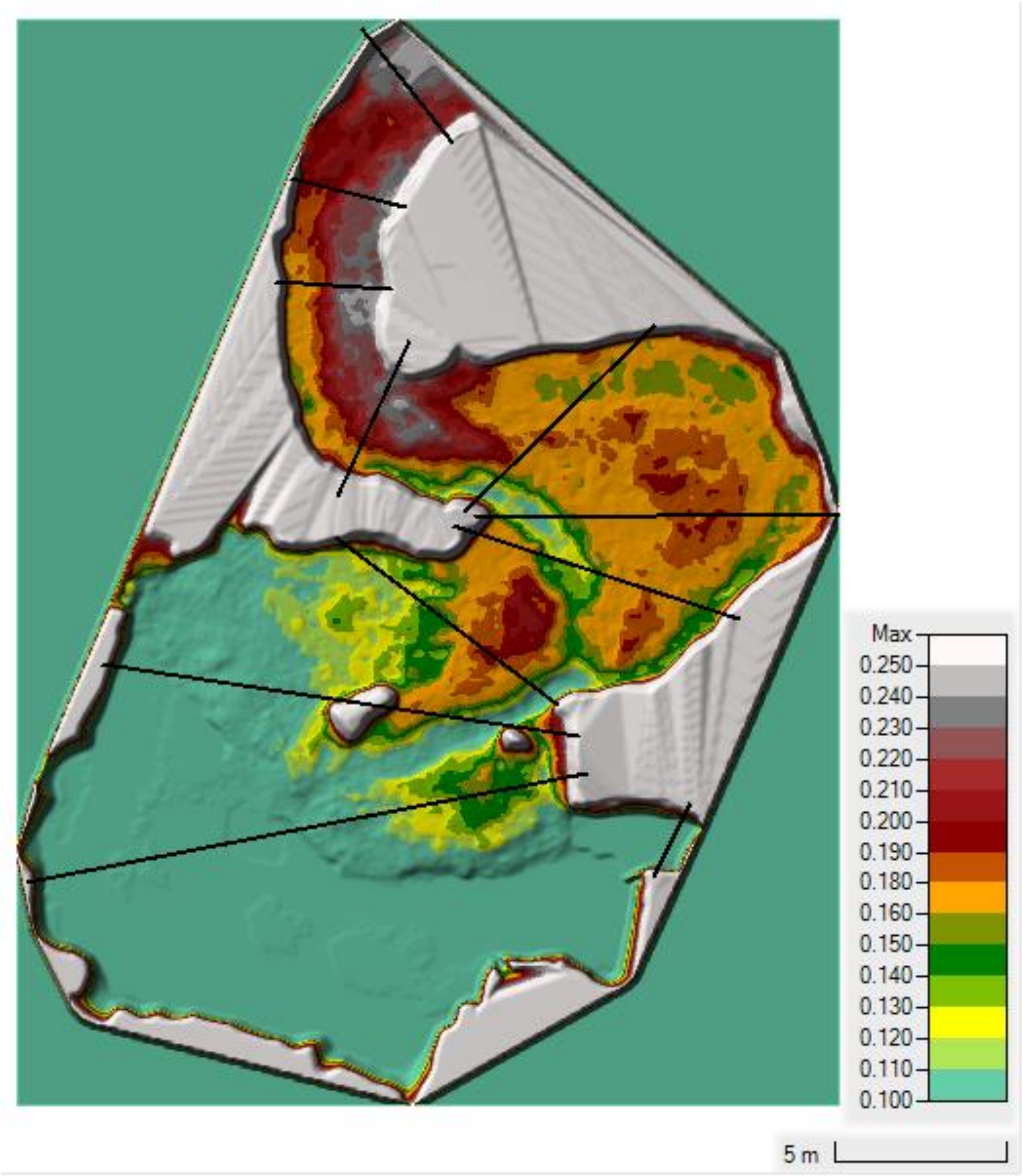

Figure 13: Original Terrain for Model 2

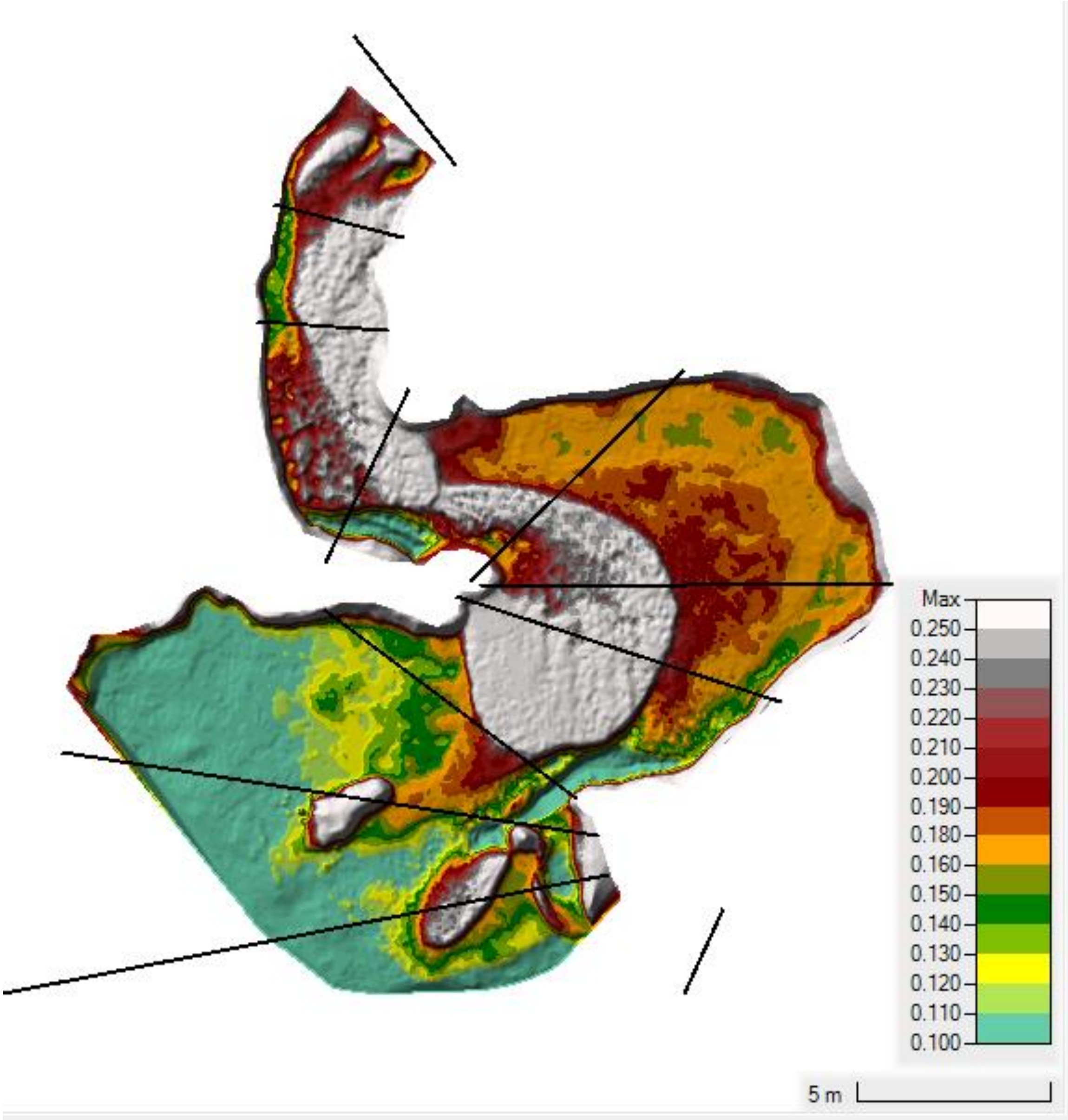

Figure 42: Laboratory Result Terrain for Model 2

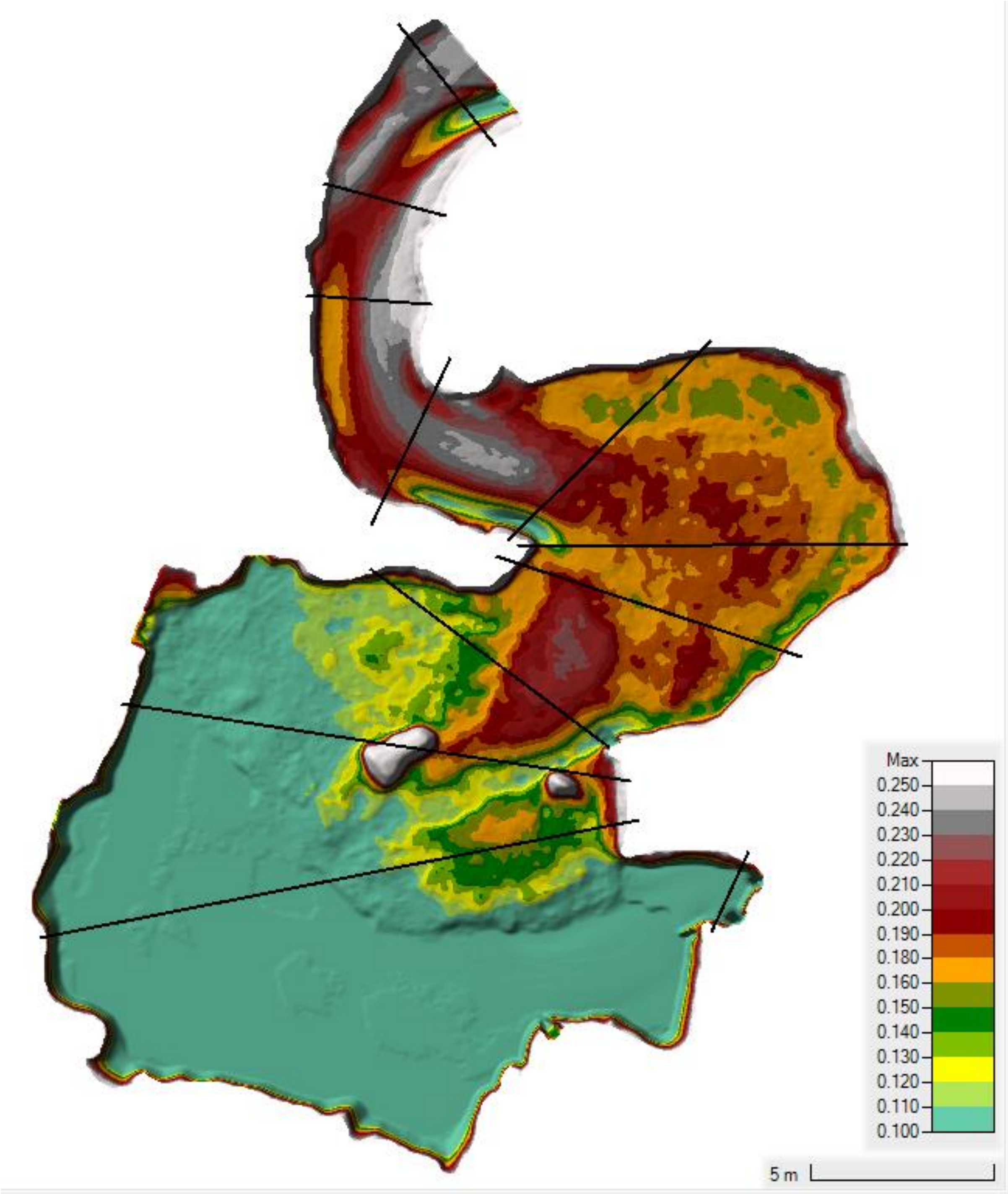

Figure 143: Terrain Result for Model 2 using Van Rijn Transport Function

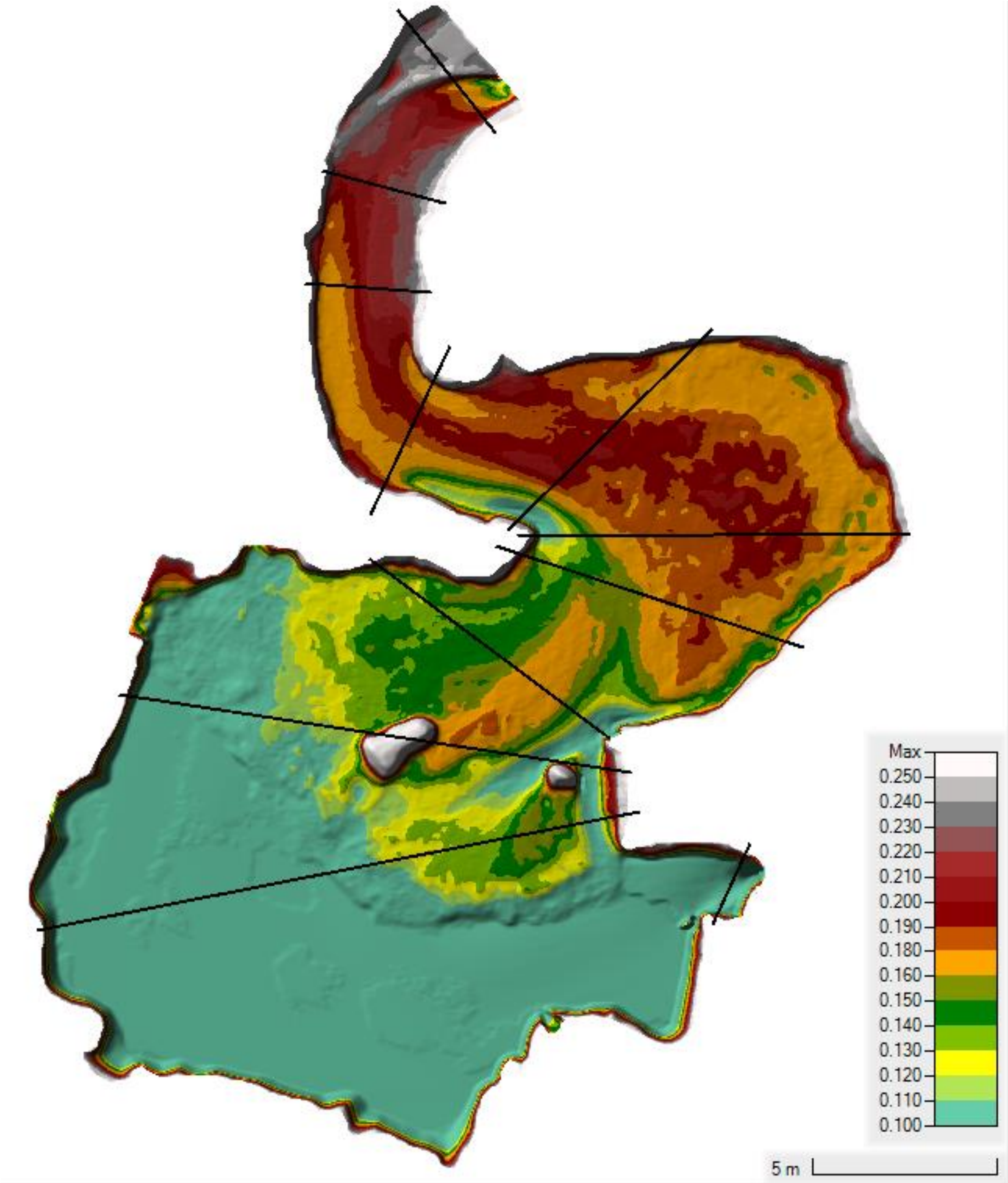

Figure 4415: Terrain Result for Model 2 using MPM Transport Function

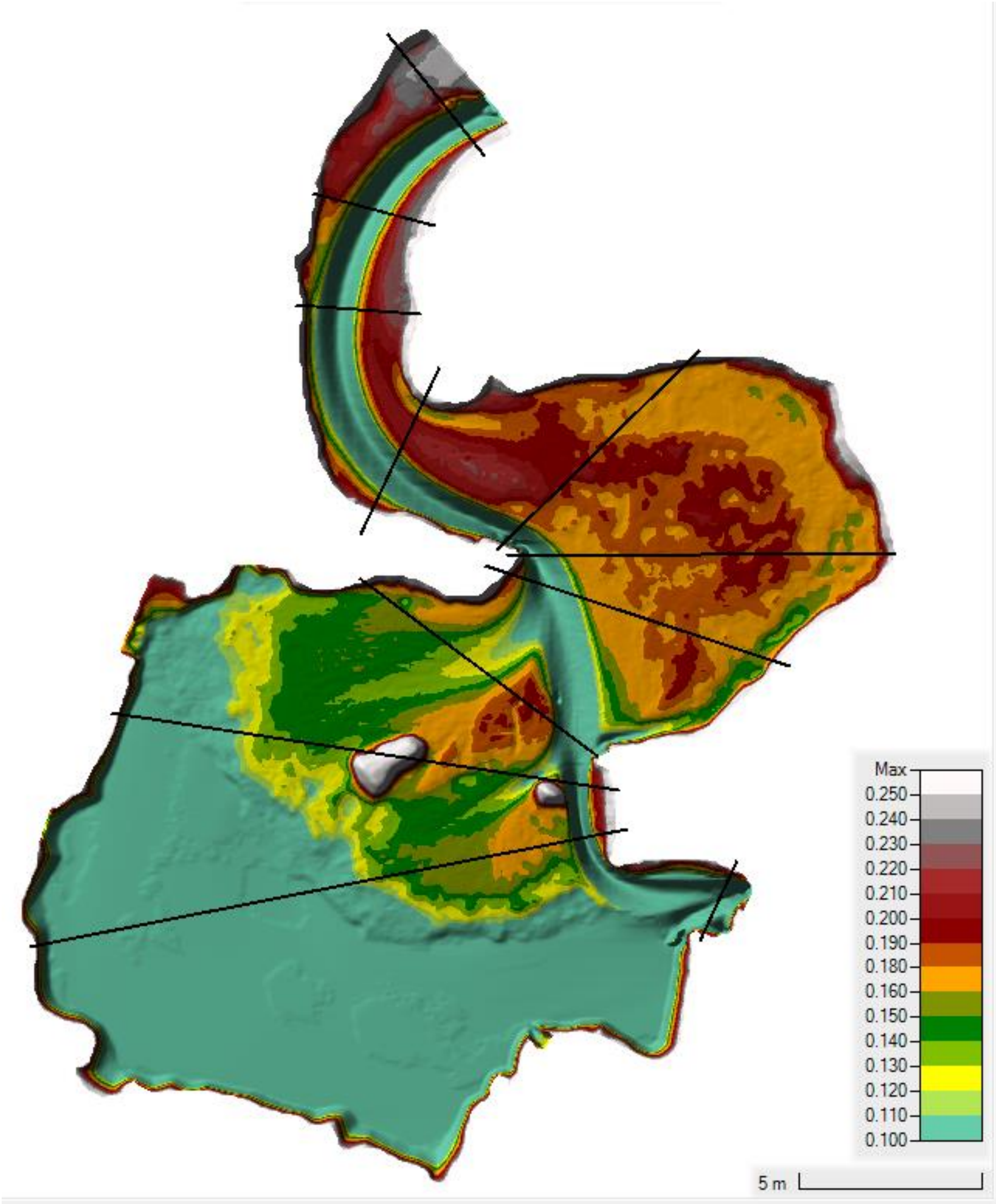

Figure 45: Terrain Result for Model 2 using A&W Transport Function

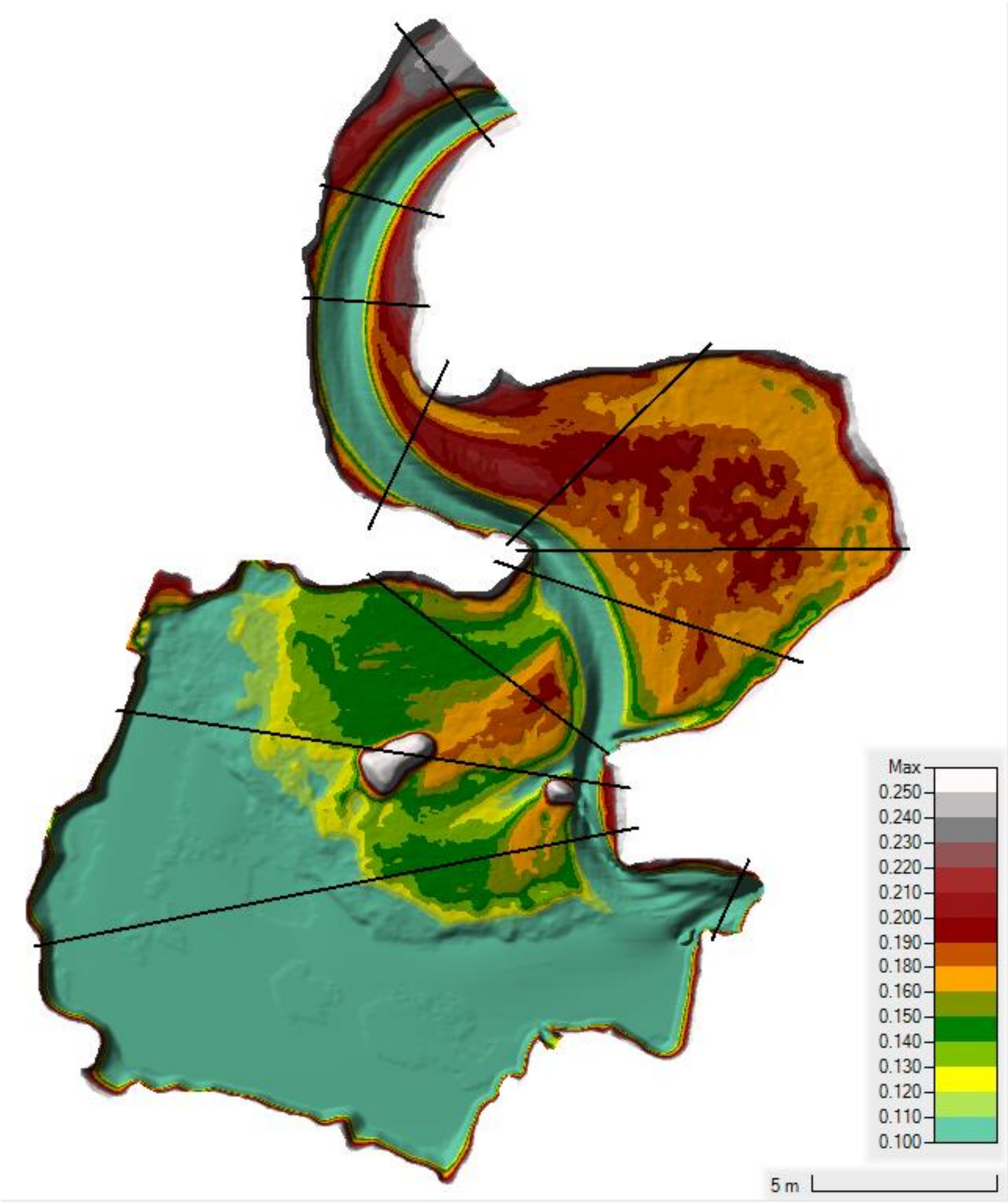

Figure 16: Terrain Result for Model 2 using E&H Transport Function

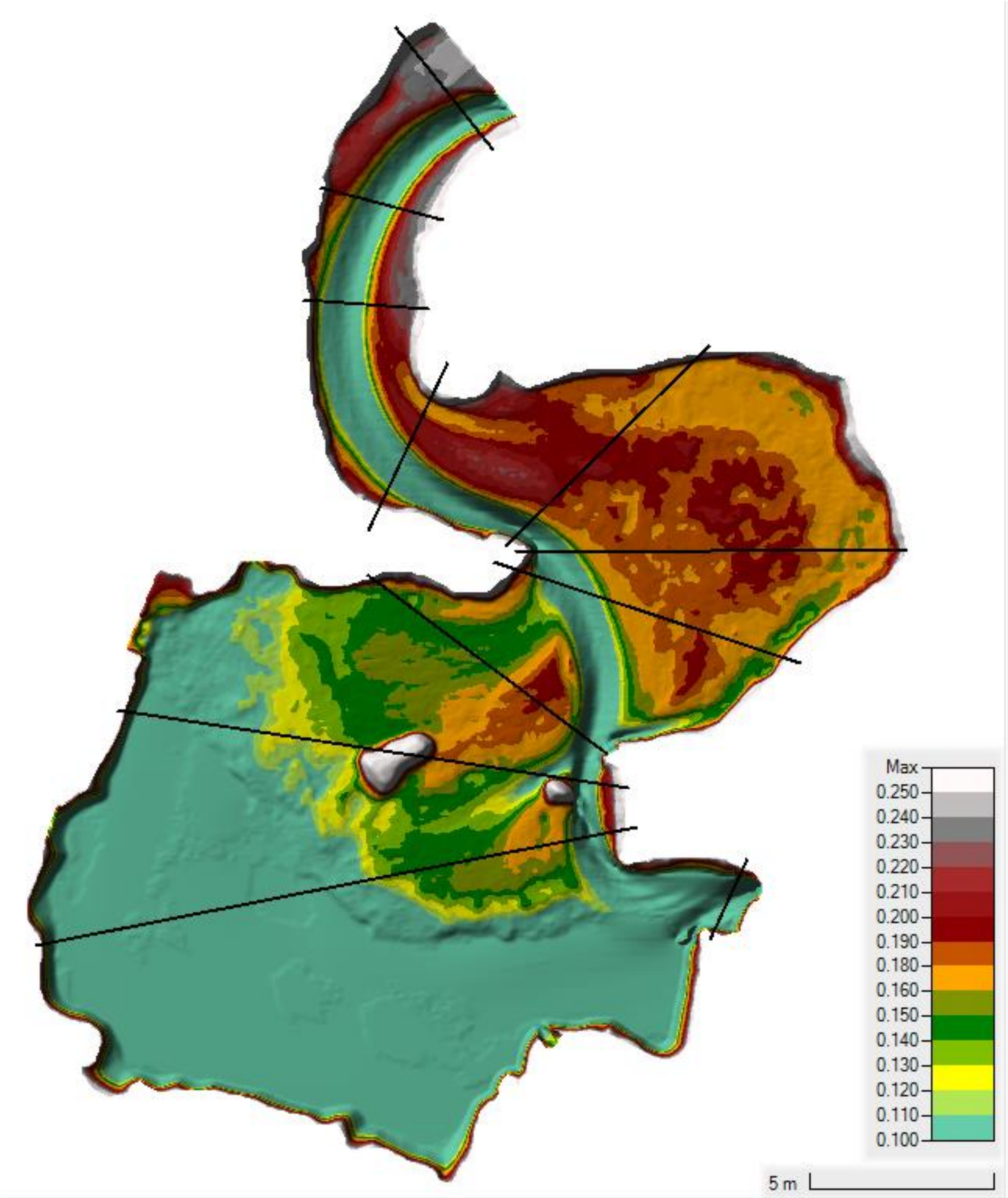

Figure 47: Terrain Result for Model 2 using Yang Transport Function

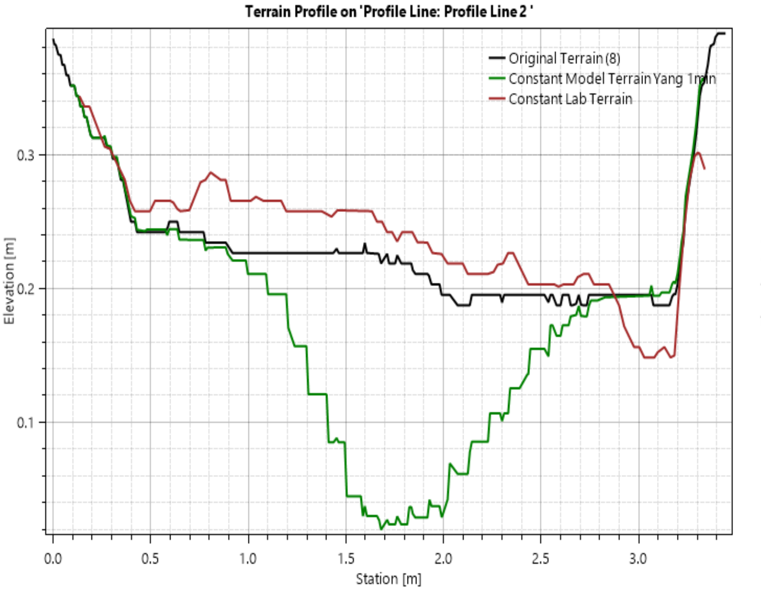

Figure 17: Model 2 Elevation Profile for Profile Line 2 using Yang

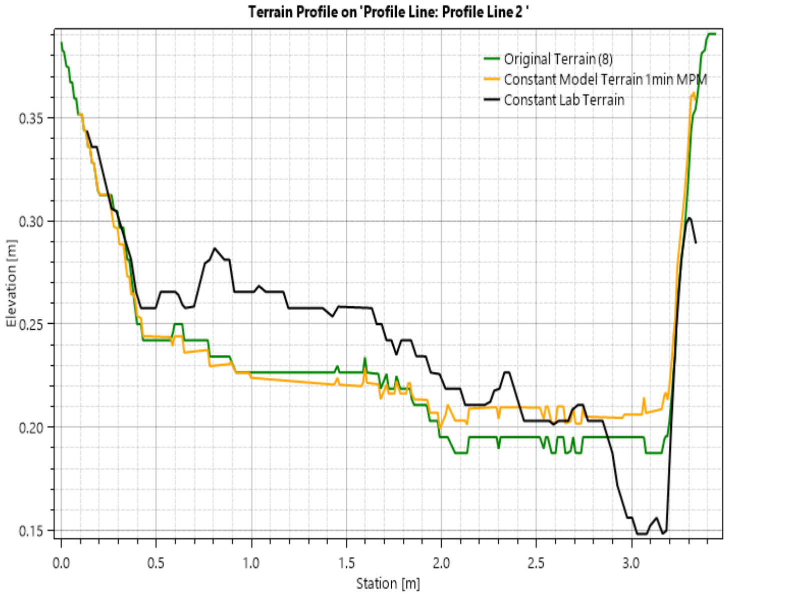

Figure 49: Model 2 Elevation Profile for Profile Line 2 using MPM

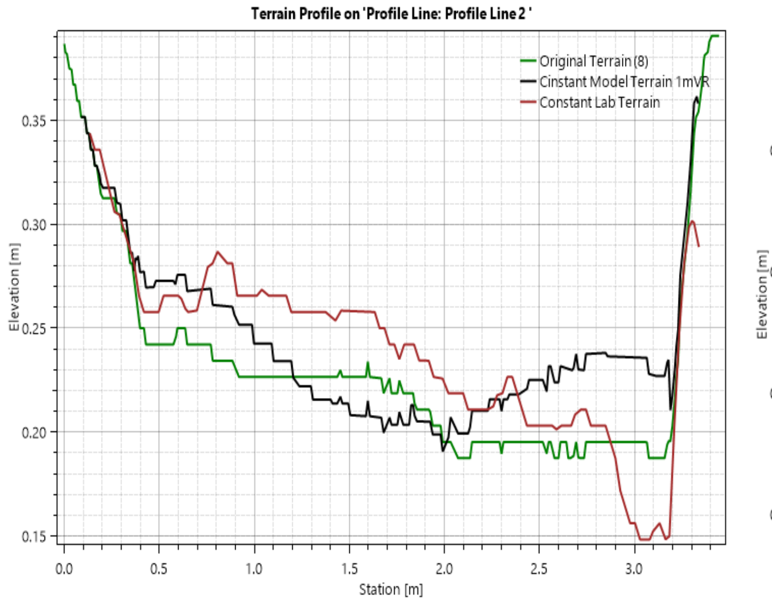

Figure 19: Model 2 Elevation Profile for Profile Line 2 using VR

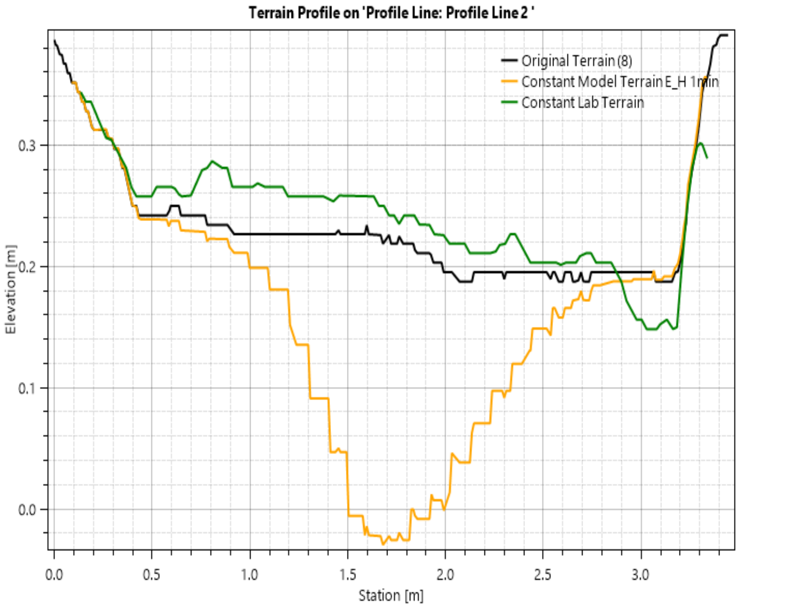

Figure 18: Model 2 Elevation Profile for Profile Line 2 using E&H

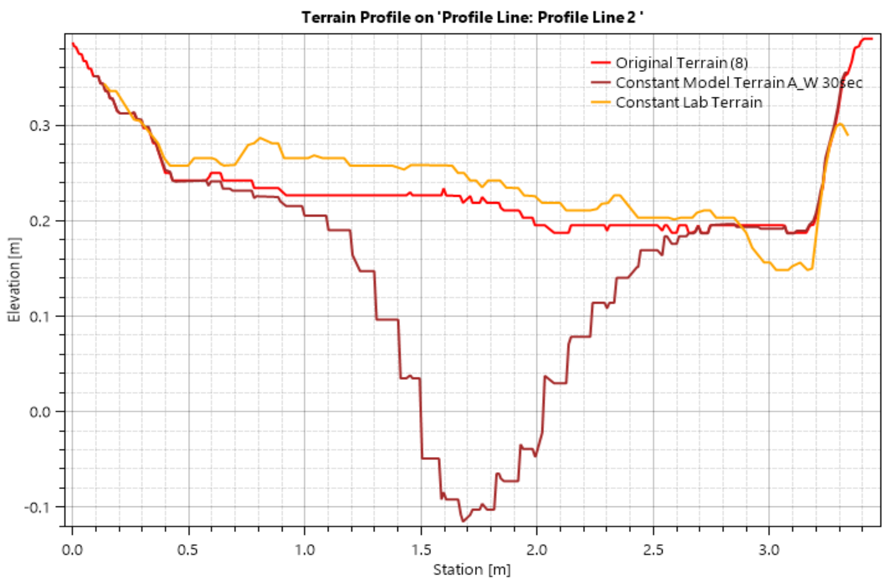

Figure 52: Model 2 Elevation Profile for Profile Line 2 using A&W

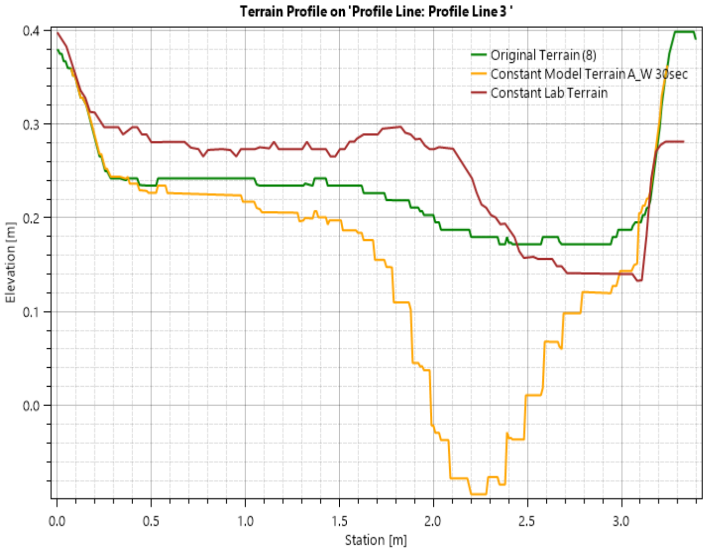

Figure 520: Model 2 Elevation Profile for Profile Line 3 using A&W

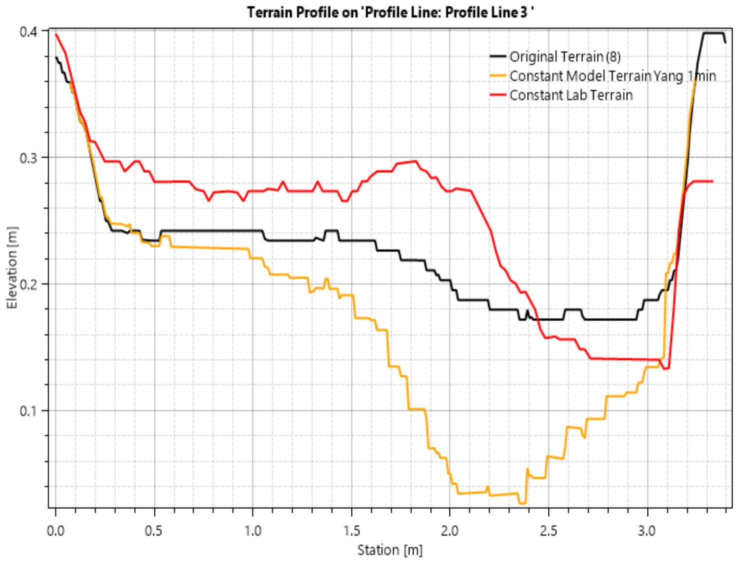

Figure 214: Model 2 Elevation Profile for Profile Line 3 using Yang

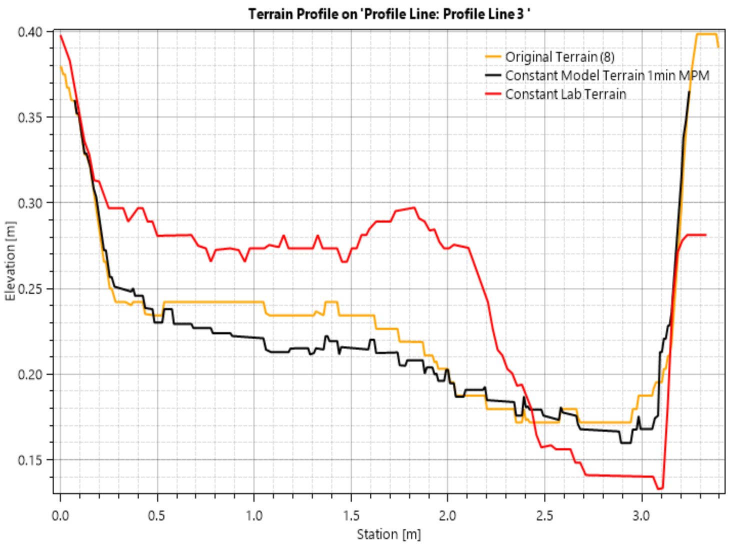

Figure 55: Model 2 Elevation Profile for Profile Line 3 using MPM

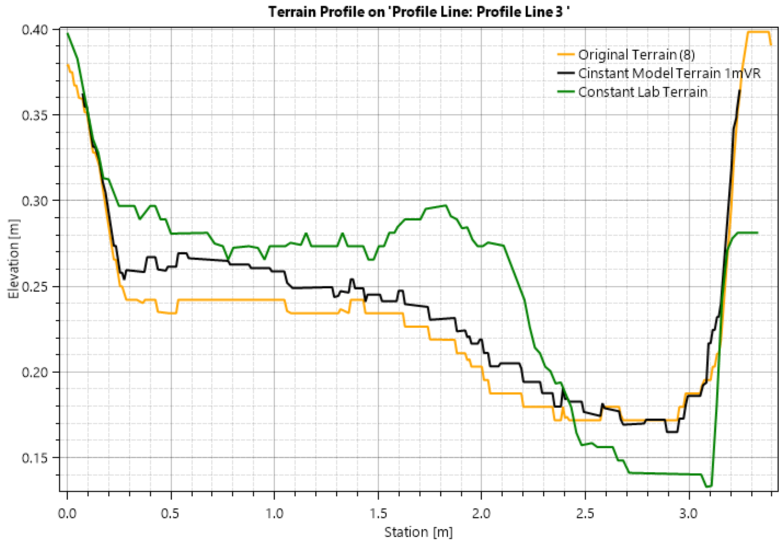

Figure 5226: Model 2 Elevation Profile for Profile Line 3 using VR5

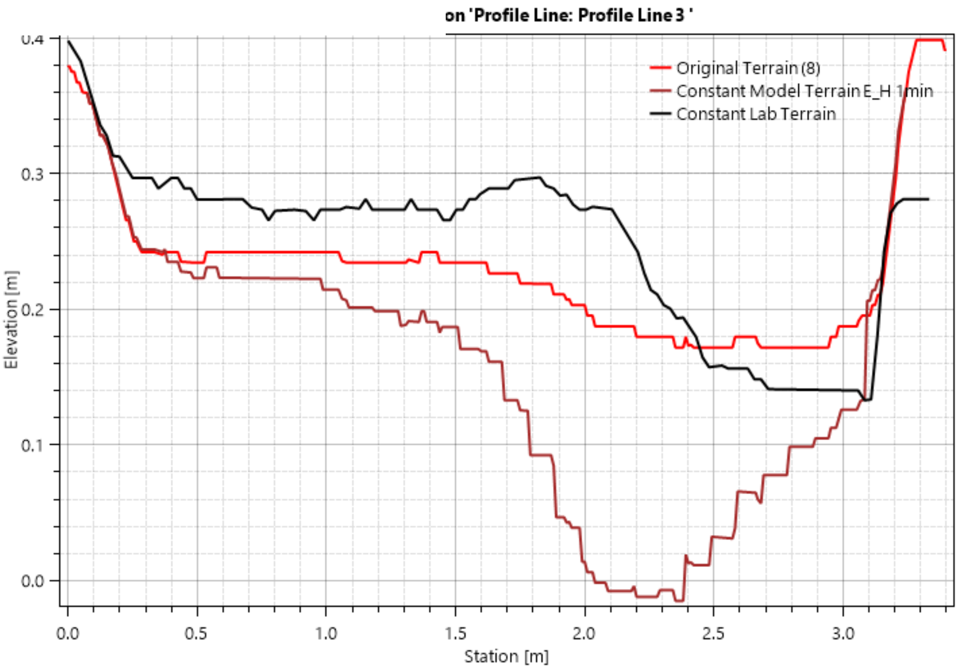

Figure 57: Model 2 Elevation Profile for Profile Line 3 using E&H

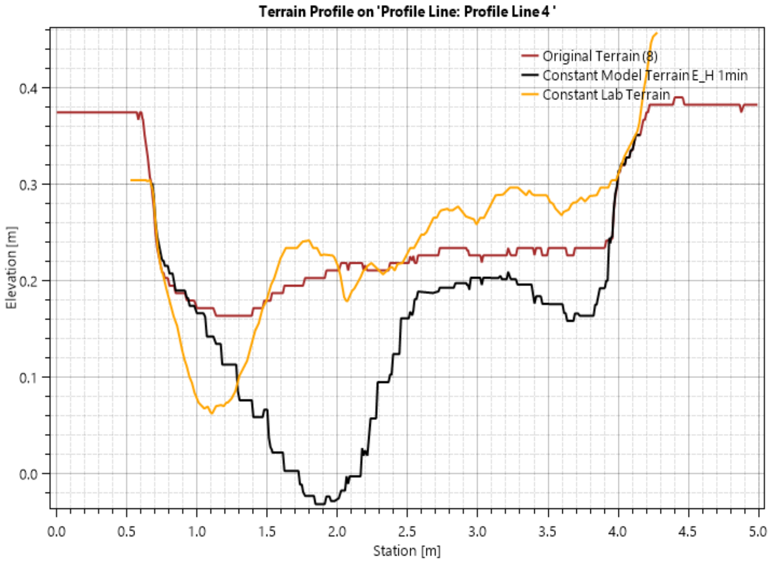

Figure 58: Model 2 Elevation Profile for Profile Line 4 using E&H

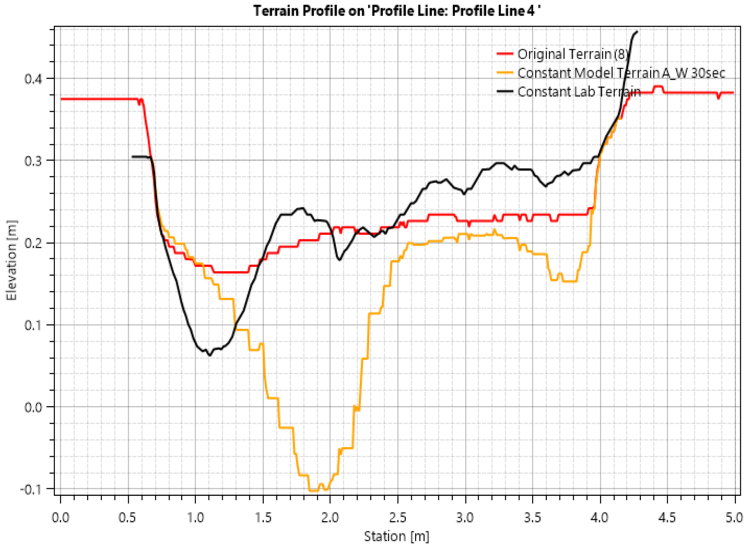

Figure 59: Model 2 Elevation Profile for Profile Line 4 using A&W

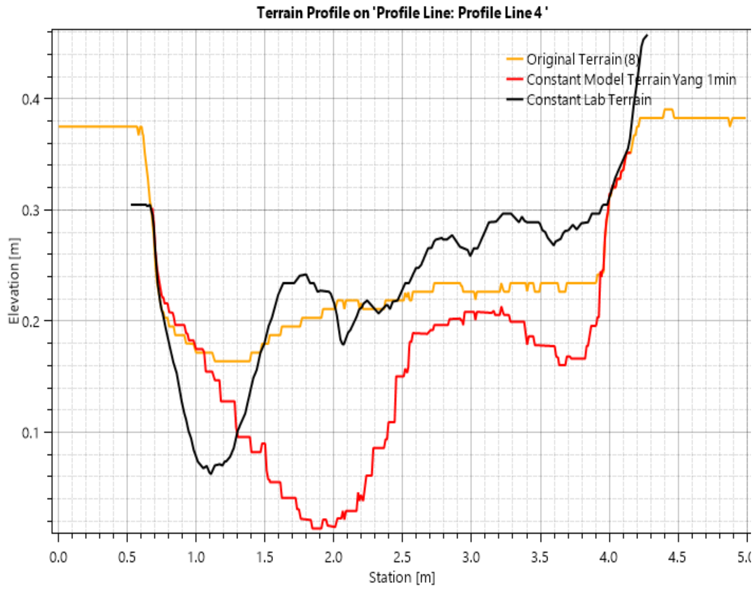

Figure 60: Model 2 Elevation Profile for Profile Line 4 using Yang

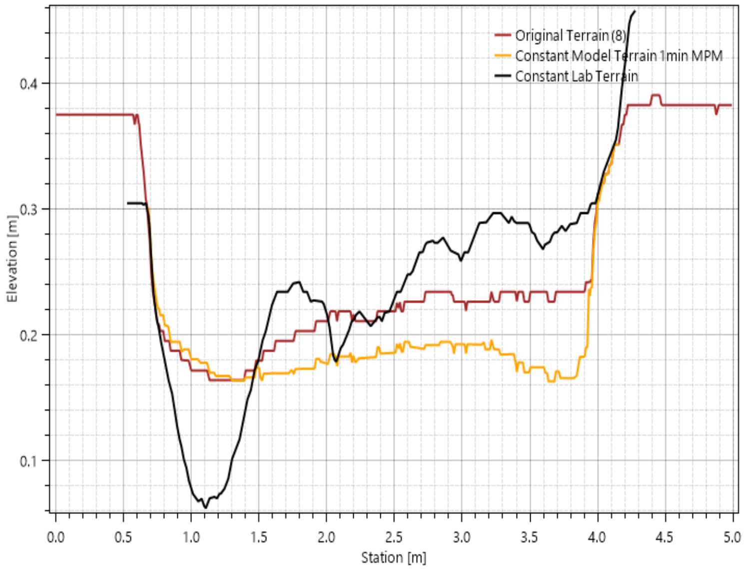

Figure 23: Model 2 Elevation Profile for Profile Line 4 using MPM

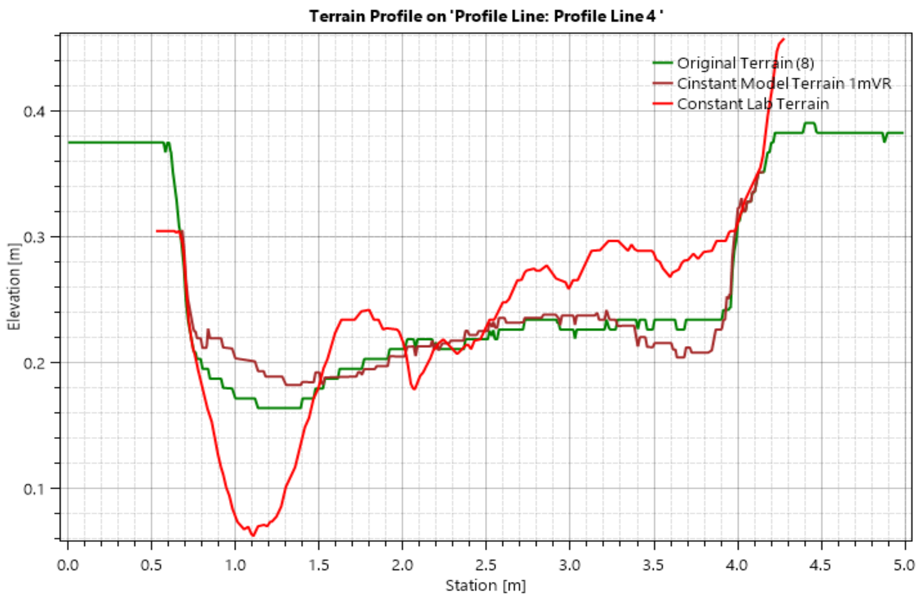

Figure 62: Model 2 Elevation Profile for Profile Line 4 using VR

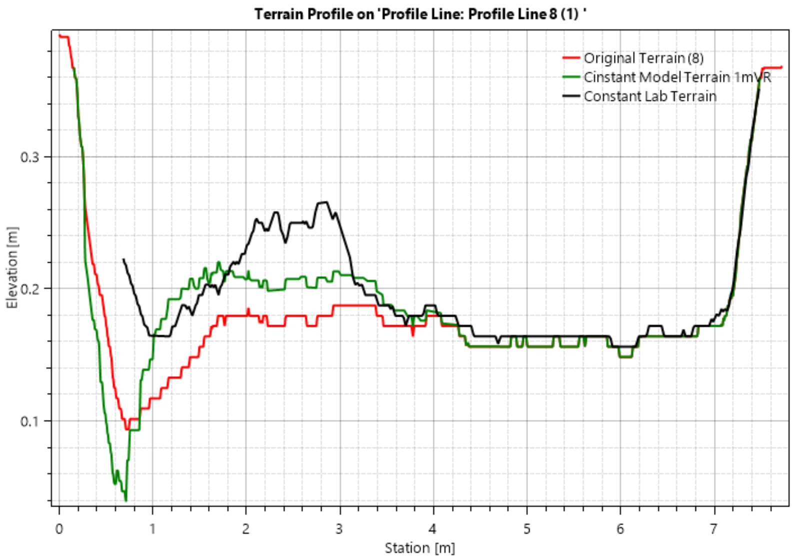

Figure 63: Model 2 Elevation Profile for Profile Line 5 using VR

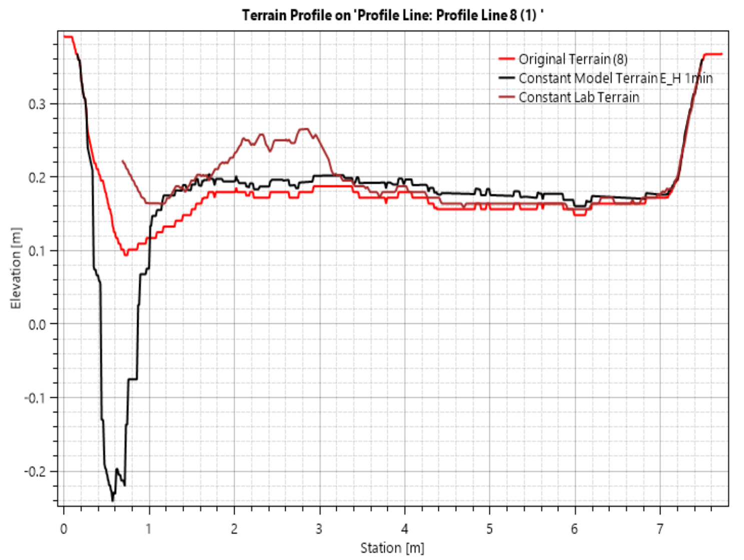

Figure 64: Model 2 Elevation Profile for Profile Line 5 using E&H

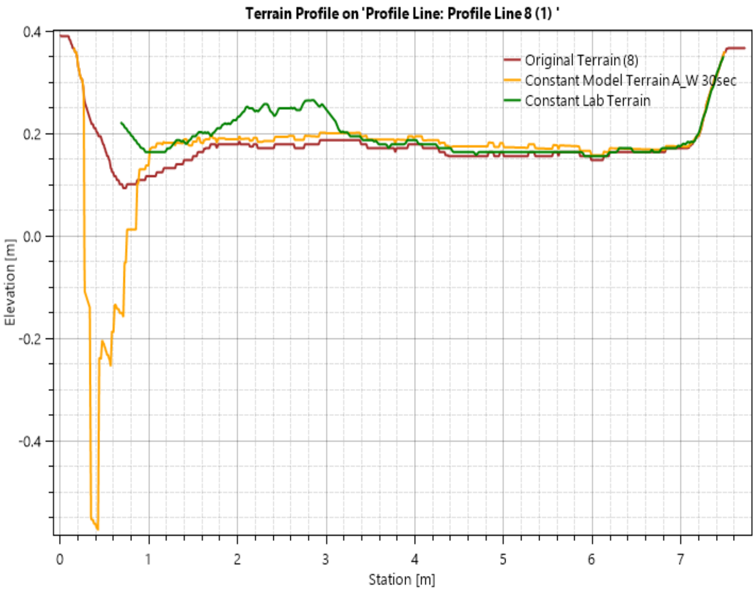

Figure 65: Model 2 Elevation Profile for Profile Line 5 using A&W

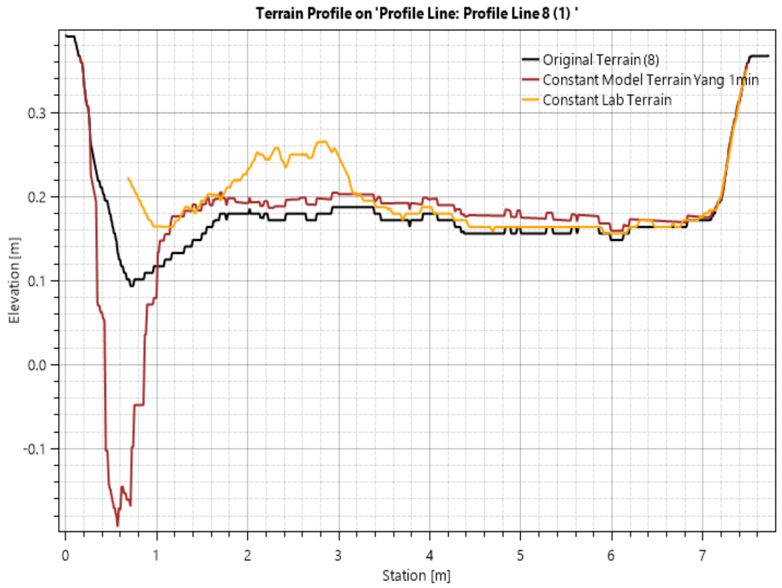

Figure 246: Model 2 Elevation Profile for Profile Line 5 using Yang

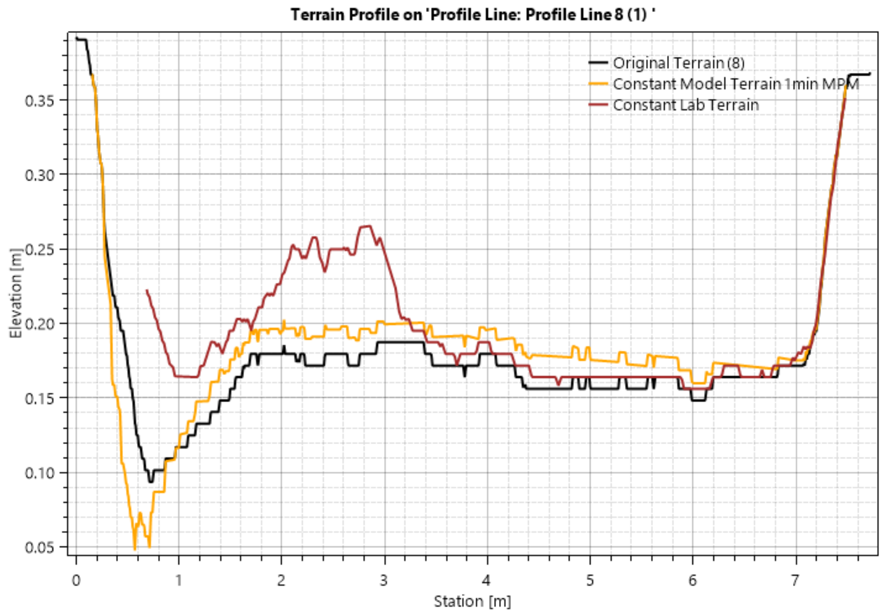

Figure 67: Model 2 Elevation Profile for Profile Line 5 using MPM

5.9 Model 3 – Physical Model Scale

In this model, the model 1 was scaled up to the prototype scale using the scale ratio of 66.67. This involved scaling the geometry, discharge, time and sediment inflow into the model to a prototype scale. The conversion was done using the following scaling formula.

For discharge

$$Q_p = Q_m * SF^{\frac{5}{2}} \tag{15}$$

For Time

$$\sqrt{SF} * T_m = T_p \tag{16}$$

For Elevation

$$H_p = H_m * SF \tag{17}$$

Using the above equations, the simulation will run for 65 hours. The discharge from the SBT and HPP intake were 290m3/s and 108m3/s respectively. The hydrograph of the inflow into the model in represented in the Figure 68. The geometry was also scaled up by exporting the terrain file into a DWG format using ArcGIS and using the scaling factor to Enlarge it in AutoCAD. The resulting DWG file was then converted back to raster with ArcGIS and imported to HECRAS. The sediment size could not be scaled up as it would result in a grain class that’s unrealistic in this scenario.

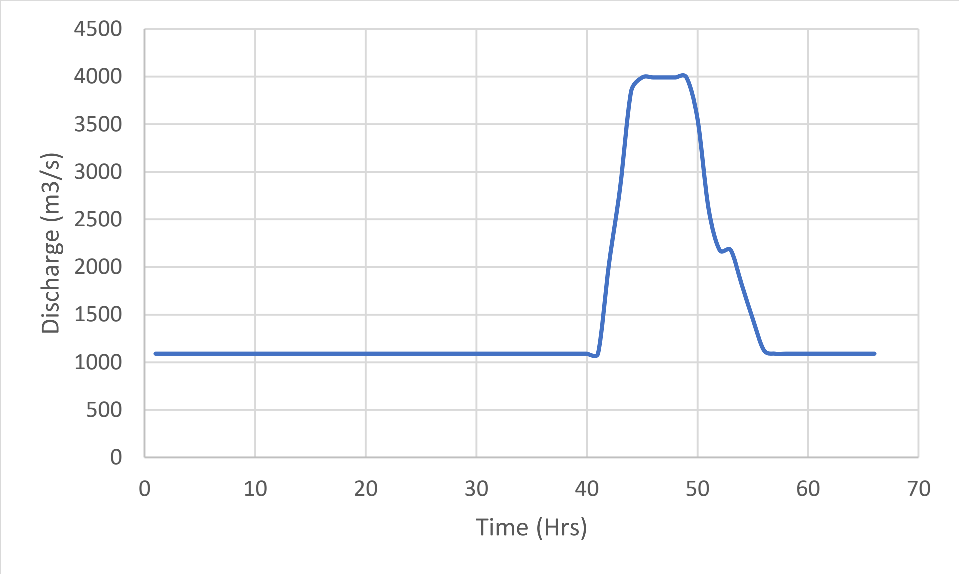

Figure 68: Prototype Scale Hydrograph

5.9.1 Results

This result was generated using the model calibration and transport formula (MPM) that was closest to the laboratory result observed in Model 1.

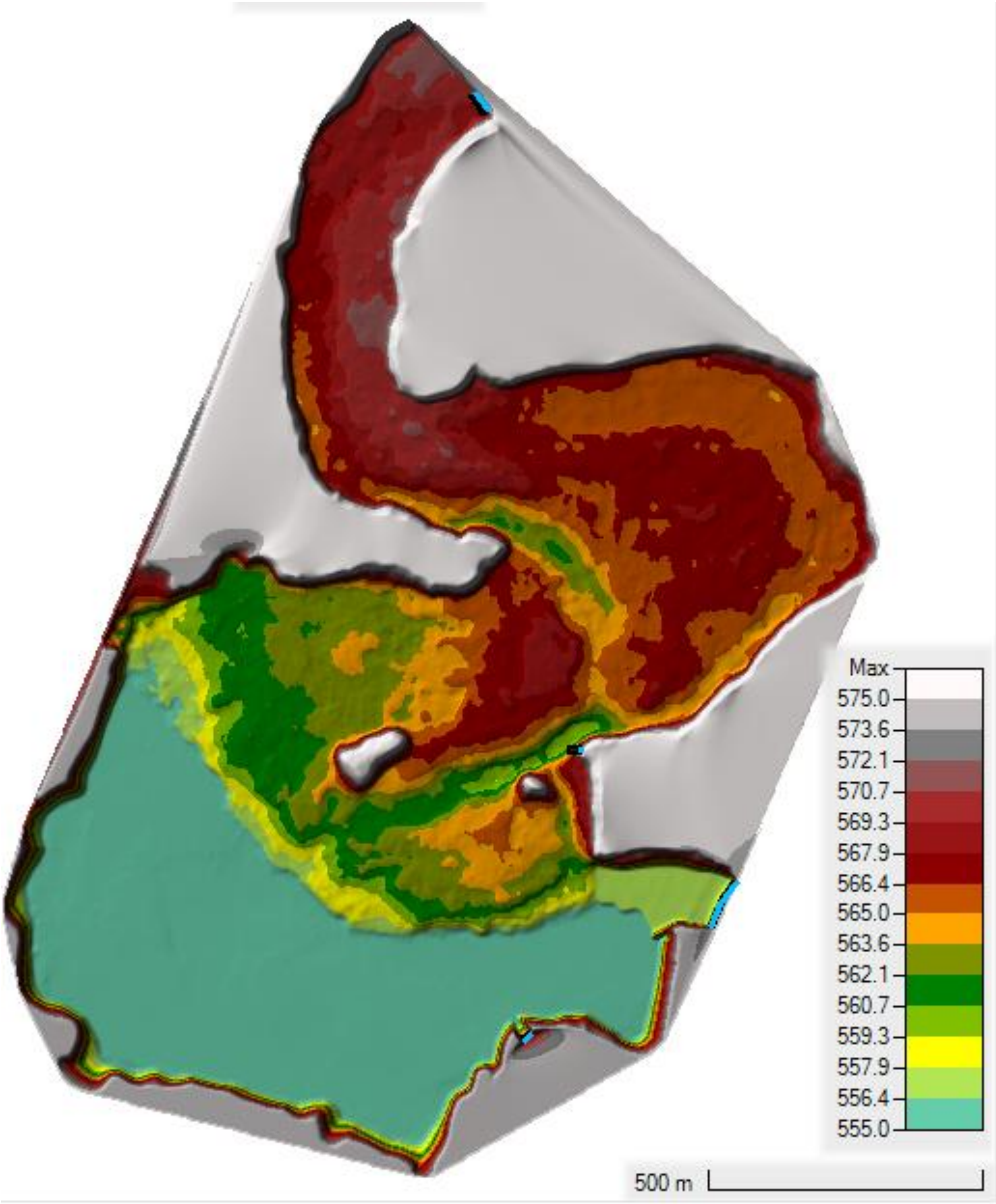

Figure 69: Original Terrain (Prototype Scale)

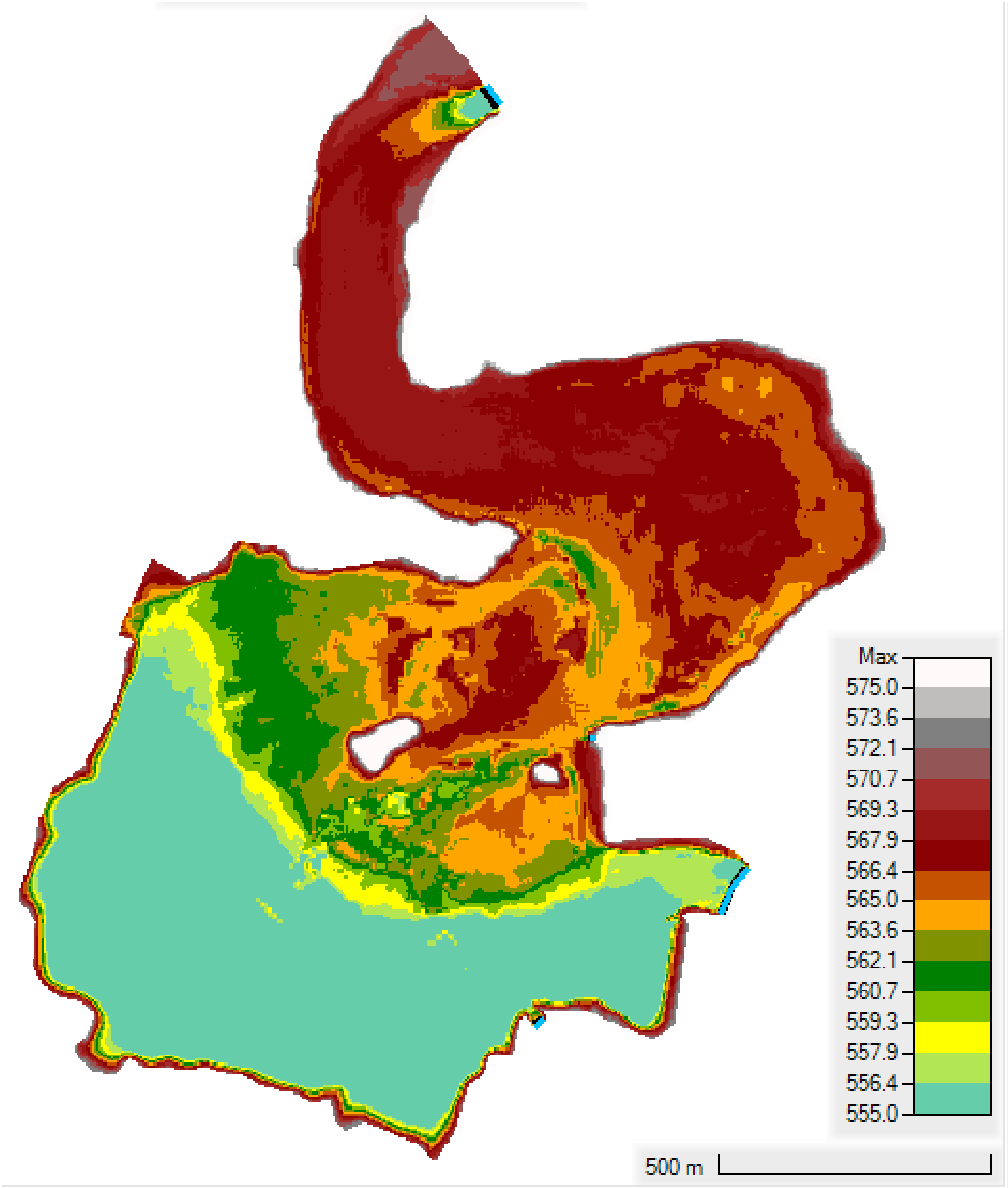

Figure 25: Prototype scale model result

Chapter 6 – Discussion

6.1 Hydraulic Model

The model simulated on HECRAS has fair correlation in terms of hydraulic conditions with the physical model in the laboratory. The WSE and inflow velocity has similar results. The calibration process shows that there are 3 main parameters that greatly influences the result in the simulation. The manning's coefficient, the grid size and also the computation interval. The manning's number is govern by what's representative of the roughness in the bed and boundaries. It has a range of which values that are practically possible.

The result also shows that the grid size influences the accuracy of the model. Finer grids are more detailed and likely to be more accurate compared to larger grid sizes. Also, when other parameters are not properly calibrated, finer grid sizes can easily overestimate the hydraulic conditions present in the model. Therefore, the grid size should always be the first parameter to be calibrated in the model and should be kept consistent for other calibration simulations. The computation interval can be calculated but should only be used as a guide when setting up the courant condition, ensuring the minimum courant fulfils the time step that was calculated.

The little or no difference between the WSE and Inflow velocity of the model with and without the HPP intake signifies there are usually no significant influence on the hydraulic condition upstream of a reservoir when an intake is introduced downstream.

6.2 Sediment Model 1

Upstream of profile line 1 shows significant erosion ranging between 2cm to 10 cm for 4 of the transport equation with the exception of MPM which shows deposition in this area. The erosion could be largely due to the restricted inlet into the terrain which was only about 1/4 of the total upstream length. causing high velocity at the inlet to erode the sediments along the flow path. The result from the physical model didn't show this expected erosion which could be due to the hydraulic dynamics present in the physical boundary that are not replicable in the numerical model. It is also possible that most of the sediment inflow and erosion in the physical model travels downstream during the high flood period and subsequently during the low discharge period the sediment inflows settles upstream causing the eroded area to be filled which would be the case in the terrain in Figure 17 (MPM).

Between profile 1 and 2, the erosion caused by the flood flow persist in a tunnel manner while the remaining area experiences deposition. This is consistent in VR, AW, EH and Yang. MPM continues to simulate erosion similar to the result observed in the physical model only in lower quantities

Between profile 2 -4, erosion was observed on the inner bend of the terrain, this was also simulated in all the transport functions used. A closer look at the terrain of profile 3 shows erosion on the right bank which is also consistent with all transport functions tested and the result observed from the experiment in the laboratory. This is interesting has the inner bends are usually where deposition takes place due to the lower velocity in that area. This shows HECRAS is able to simulate sediment movement in bends and boundary walls

Downstream of profile line 5 had very little difference in the terrain for most of the transport function similar to the situation in the physical model. This could likely be that most of the sediments settled between profile 1-5 while the rest are either carried out through the spillway or are too small to cause significant deposition downstream of profile 5

6.3 Sediment Model 2

Upstream of the profile had similar results for all the transport formulas tested. The left side where the inflow opening experiences heavy erosion while the left side does not virtually undergo significant changes. This part of the terrain was not captured by the total station in the physical model done in the laboratory, therefore there could not be any comparism with the model results. This significant erosion is due to the constant discharge throughout the experiment and the indifference in the elevation on the right side of the channel could be due to the high discharge moving downstream and taking all the eroded sediments with-it, leaving no avenues for deposition in the upstream area of profile 1.

Similar scenario continues between profile 1 and 2 with a tunnel erosion (narrow inlet, high velocity) due to the discharge in most of the transport functions with the exception of MPM and VR which shows some deposition in this area. This is consistent with the result in the lab. A closer look at the terrain profile of profile 2 (Fig 48 to 52) for the different transport formulas shows that only MPM (Fig 49) and VR (Fig 50) simulates a different profile within the range of the bed elevation in the laboratory.

Similar to the phenomenon above, Yang, E&H and A&W transport formula displayed similar prediction with erosion in the area between profile 2 and profile 4. MPM and VR continue to exhibit similar prediction with deposition which is a little different to the laboratory result that showed high erosion in the outer bend and deposition in the inner bend. This might suggest that they are not accurate at bends with high constant discharge. Although Yang, E&H and A&W displayed similar erosion on the outer banks of the curve within the area, the inner bend inaccurately predicted erosion as opposed to deposition in the physical model.

The area between profile line 5 and 8 shows significant deposition in both the outer and inner bend of the physical model. This is likely due to the increase in area leading to lower velocities causing the sediments to settle. This phenomenon is closely replicated only in the model with Van Rijn transport function. Other models predicted erosion in the inner bed of the area and deposition on the other bend. The area below profile 8 does not show any significant difference in erosion or deposition showing that most of the deposition or erosion occurred upstream of profile line 8 which is consistent with the results from the physical model.

6.4 Sediment Model 3

The result from the prototype simulations indicates erosion occurring in the intake for about 200m. Significant deposition was noticed in the upper half of the terrain down to the delta area. This is consistent with the result from MPM terrain in the hydrograph model scale simulation.

6.5 Limitations

There are several limitations faced in this research that could have affected the results. They included

1. Exact coordinates of the inlet and its length were not available which made calibration much more difficult
2. Few locations for WSE and Inflow Velocity reduced the efficiency of the model calibration
3. Approximation of numerical values due to scaling calculation and unit conversion
4. Bed depth is fixed in the physical model unlike the bed in the numerical model causing the erosion to sometimes get to a negative depth (below 0)
5. HECRAS is continuously been developed with updates, bugs in the software sometimes cause it to crash during simulation

Chapter 7 – Conclusion and Recommendation

7.1 Conclusion

This research aims to find out the possibility of using HECRAS to perform 2D numerical solution of sediment transport in a reservoir. This research has shown that the software exhibited good performance when simulating the hydraulic conditions present in a reservoir. It also shows the simulation results provided by the software relies heavily on the manning's coefficient, grid size and computational interval which are all user defined. Therefore, extra caution is recommended when calibrating these parameters to simulate valid results.

The visual inspection of the terrain from the hydrograph of the Model scale scenario results showed that using the MPM transport formula in HECRAS simulated the closest result to the results observed in the physical model. This is mainly due to the lack of visible erosion pattern in the upstream that is common in other transport formulas. Also, the formula exhibited similar deposition area to the physical model. Van Rijn's transport formula also simulate a close result to MPM in this regard. This results shows that transport formulas such as Yang, A&W and E&H find it difficult to simulate hydrograph scenarios with high and low flows within area of high velocity.

The result from the second model with constant high discharge for longer duration confirms the observation from the first model. The heavy erosion simulated in the result from the Yang, E&H and A&W, transport formulas as opposed to the deposition observed in the physical model suggest these formulas are not suitable for simulating sediment transport in high discharge and high velocity areas. Van Rijn's transport formula continues to give similar deposition upper and middle area of the terrain. MPM transport formula was able to predict deposition in the upper part of the terrain but unable to predict similarly results in the middle area. This goes ahead to prove that Van Rijn's transport formula is suitable for simulating high and low discharges in reservoir sediment transport. This could be attributed to the development of the formula from field measurement and testing as opposed to others that were developed from flume experiment in the laboratory. This result is consistent with the research by Sabin (2021) where he used Van Rijn's transport formula to perform numerical model on the same reservoir using REEF 3D: SFLOW

7.2 Recommendation

For future research, the following recommendation could be taken into perspective.

1. Multiple measured points for WSE and also observed velocity to improve the calibration
2. Due to time constraint, automation of the calibration process using a programming script was not carried out, this should be attempted in future research to reduce the time spent manually carrying out calibration using trial by error.
3. Present version of HECRAS is only capable of carrying out Numerical Modelling in 2D, Improved version in the future might provide capabilities to simulate models in 3D which would be interesting to test.
4. This research made use of a single manning coefficient for the whole geometry. Future research can attempt varying the manning's coefficient with respect to location and / or time
5. The scale of the prototype to the model was huge and made it impractical to scale some parameters such as the sediment size, future research can investigate with smaller scale sizes to simulate a more natural scenario.
6. Further studies could investigate the performance of the transport equation under low steady flow.
7. It is recommended that HECRAS developer improves the software capabilities by introducing the possibility of combining different transport equations temporally or spatially in a model.

References

Ackers, P. a. (1973). Sediment Transport: New approach and analysis. *Journal of the Hydraulics Division*.

Axel Bronstert, J.-C. d.-T. (2001–2018 (2014)). Process-based modelling of erosion, sediment transport and reservoir siltation in mesoscale semi-arid catchments. *Journal of Soils and Sediments volume* , 14.

Bhandari, S. (2021). *2D Numerical Simulation of Sediment Flushing in a Hydropower Reservoir.* Trondheim: NTNU.

Chanson, H. (2004). *The Hydraulics of Open Channel Flow: An Introduction.* Elsevier Butterworth-Heinemann.

Greg Schellenberg, C. R. (2017, February 22). *Dealing with Sediment: Effects on Dams and Hydropower Generation*. Retrieved from Hydro Review: https://www.hydroreview.com/world-regions/dealing-with-sediment-effects-on-dams-and-hydropower-generation/#gref

Gregory L. Morris, J. F. (1997). *Reservoir Sedimentation Handbook.* New York: McGraw-Hill.

Hansen, F. E. (1967). Sediment Transport in Alluvial Streams. *Hydraulic Laboratory, Technical University of Denmark.*

International Hydropower Association. (2022). *Philippines - Binga*. Retrieved from International Hydropower Association: https://www.hydropower.org/sediment-management-case-studies/philippines-binga

Lopez, E. G. (2014, April 7). *Transforming the Binga hydroelectric plant*. Retrieved from Waterpower and Dam Construction: https://www.waterpowermagazine.com/features/featuretransforming-the-binga-hydroelectric-plant-4210583/

Meyer-Peter, E. &. (1948). Formulas for bedload transport. *Proceedings of the 2nd Meeting of theInternational Association of Hydraulic Structures Research(IAHSR)*, (pp. 39-64). Stockholm, Sweden.

Nils Ruther, D. L. (2021). *The Hydraulic Scale Model Study of the Binga Reservoir - towards a sustainable sediment management strategy.* Trondheim: NTNU.

Rijn, L. V. (1984). Sediment Transport: Bed Load Transport. *J Hydraul Div, Proc ASCE*, 1431-1456.

Simon Judd, C. J. (2011). Design, Operation and Maintenance. In Butterworth-Heinemann, *The MBR Book* (pp. 209-288).

US Army Corps of Engineers. (2016). *HEC-RAS River Analysis System. 2D Modeling User's Manual.*

US ARMY CORPS OF ENGINEERS. (2020). *HEC-RAS, River Analysis System Hydraulic Reference Manual.* California.

Vanoni, V. A. (1975). *Sedimentation Engineering.* New York: American Society of Civil Engineers.

Appendix A

Task Description

NTNU

M.Sc. THESIS IN HYDRAULIC ENGINEERING

Candidate: Mr. Moyinjah Micheal Bello

Title: 2D numerical modeling of hydraulics and sediment in a reservoir

1. Background

Reservoirs have been of important economical and societal benefits in the past, present and future. They usually serve purposes such as flood control, hydropower, irrigation, fishing and navigation. A major challenge to all reservoirs is silting. If not adequately taken care of through prevention strategies and mitigation measures can ultimately lead to complete loss of reservoir volume. This could also lead to blockage or damage to the hydraulic structures in the reservoir. The downstream section of the reservoir also suffers implications from the sedimentation of the reservoir in terms of river morphology and ecology resulting in loss of aquatic habitat and poor water quality.

Sediment transport in rivers has been an active and expanding field of research for years due to its complexity and dynamics. The field is quite important due to its application in river basin management, erosion control, flood control and other economic important of the waterbodies. Sediment transport is a very wide field consisting of several aspects of importance. Numerous methods have been researched for the mitigation of sedimentation in reservoirs. Modelling has been one of the several ways in which sediment transport in rivers and reservoirs are been analyzed to understand the hydraulic conditions of the sediments in a reservoir. Modelling can either be done physically or numerically.

Regarding physical modelling, high-resolution instruments are being used to discover better insight into the morphology and hydrodynamic of reservoirs. These instruments allow for measurements such as flow velocities, concentration and internal stresses to be characterized in sediment-laded flow. They have also made it possible to be done out in field and/or in the laboratories. In numerical models, there are 3 options, ranging from 1D to 3D models. 1D models have been used due to their low computational cost and reduced data requirement. 2D/3D models are now required due to the presence of complex topography and/or of hydraulic structures. 2D shallow water models may provide accurate predictions for the depth averaged flow velocity and water depth, requiring though a fine topographic representation. However, 3D models are also required where 2D simulations may not adequately predict the instabilities of sediment deposits.

In this project, sediment transport in a hydro power reservoir will be modelled using the HEC-RAS 2D. The results would be compared with the data gain from a physical model in a hydraulic laboratory.

2. Work description

The thesis shall cover, though not necessarily be limited to the main tasks listed below.
The candidate must collect available documents such as reports, relevant studies and maps. Based on the available documentation the following shall be carried out:

1 Literature review on sediment transport, reservoir sedimentation and 2D numerical modeling
2 Short description of the experiments and the data available
3 Setting up the grid for the reservoir in HEC RAS 2D.
4 Conduct simulations so that it is possible to quantify the deposition rate in the reservoir in the next decades
5 Documentation of the numerical results compared to the experiments.
6 Conclusions
7 Proposals for future work
8 Presentation

The literature review should outline the previous contributions on the topics mentioned in 1. and 2. The length of the literature review should be limited to 5 pages.

3 Supervision

Professor Nils Rüther will be the main supervisor. PhD candidate Diwash L Maskey will be co-supervisors. The supervisors shall assist the candidate and make relevant information available.

NTNU

Discussion with and input from other research or engineering staff at NTNU or other institutions are recommended. Significant inputs from others shall be referenced in a convenient manner.

The research and engineering work carried out by the candidate in connection with this thesis shall remain within an educational context. The candidate and the supervisors are free to introduce assumptions and limitations which may be considered unrealistic or inappropriate in a contract research or a professional/commercial context.

4 Report format and submission

The report should be written with a text editing software. Figures, tables and photos shall be of high quality. The report format shall be in the style of scientific reports and must contain a summary, a table of content, and a list of references.

The report shall be submitted electronically in B5-format .pdf-file in Blackboard, and three paper copies should be handed in to the institute. Supplementary working files such as spreadsheets, numerical models, program scripts, figures and pictures shall be uploaded to MS Teams. The summary shall not exceed 450 words. The Master's thesis should be submitted within 15th of June 2022.

The candidate shall present the work at a MSc. seminar towards the end of the master period. The presentation shall be given with the use of powerpoint or similar presentation tools. The data and format for the MSc. seminar will be announced during the semester.

Trondheim, 15. January 2022

Nils Rüther
Professor
Department of Civil and Environmental Engineering
NTNU