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Master's Thesis:

Comparison of 2D Hydrodynamic models in River Reaches of Ecological Importance: Hydro_AS-2D and SRH-W

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Author’s Statement

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ABSTRACT

The use of two dimensional hydrodynamic models has become ubiquitous and indispensible tool for the study of natural rivers. Such models are especially useful when modeling results are required on scales relevant for ecological processes, where local details of velocity and depth distributions are significant especially in river reaches of ecological importance.

The main objective of this Master's Thesis was to compare two hydrodynamic models with respect to modeled parameter outputs (water surface elevation, flow depth, velocity, etc.), accuracy, computational time, and their relevance of application for scales of ecological importance. The two models used were Hydro_ As-2D and SRH-W. The spatial interpolation techniques Krigging and triangulation with linear interpolation were also compared for their accuracy of interpolation. Additionally, a sensitivity analysis was performed for the two models to investigate the effects of mesh resolution and the exclusion of boulders from the bathymetry data on model outputs. Three representative case study reaches with different bed morphologies and flow characterstics were selected for the study. Two of the reaches were from the Black Forest in Germany while the third is a reach from the Austrian Alps. Model calibration was performed by changing the bed roughness values such that observed and predicted water surface elevations had close agreement. The same number of roughness zones and bed roughness values were specified for both models to compare their outputs.

The results of the case studies indicated that both Hydro_As-2D and SRH-W predicted the observed water surface elevations quite well. The velocity outputs of the two models were also comparable. There was not any significant difference found between the accuracy of the two spatial interpolation methods. The sensitivity analysis showed that SRH-W is more sensitive to mesh resolution than Hydro_ As-2D and the inclusion of the boulders affected velocity outputs to a greater extent than the water surface elevation or water depth. It was also found that in order to capture the complex velocity patterns around the boulders, high resolution bathymetry data and the use of a finer mesh was absolutely necessary.

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1 Introduction

1.1 Background

Numerical models are increasingly being utilized for simulating the complex hydraulic processes in rivers. Two dimensional (2D) hydrodynamic models have become indispensible tools for water management studies of natural rivers. These models are especially useful for studies where local details of velocity and depth distributions are important. They normally make use of a representative investigation reach, where the morphologic and hydraulic characteristics can be studied in far greater detail than when considering the entire river as a whole. Examples include the evaluation of renaturalization measures, fish habitat evaluation, contaminant transport and mixing processes, etc. Two dimensional simulations provide, depending on the conceptual formulation, the following answers: flow velocities, water depth, flood plain extensions, inundation time discharge distribution between river and foreland, retention effect, bed shear stress, deposition of suspended sediments, sediment transport, etc. Compared to one dimensional models two dimensional models are more accurate and hold the promise of providing spatially explicit solutions of the flow field.

Depth Averaged Models

Depth averaged models (2D models) are based on a variety of numerical schemes and a large variety of acadamic and professional software can be found. The fundamental physics of all models is more or less common, however. All 2D models solve the basic mass conservation equation and the two (horizontal) components of conservation of momentum. Model outputs are two velocity components and the flow depth at each point or node. Vertical velocity distributions are assumed to be uniform and pressure distributions are assumed to be hydrostatic. Important three dimensional effects such as secondary flows in curved channels are not included. 2D model schemes based on finite difference, finite volume and finite element method are all commonly available. Each approach has its own advantages and disadvantages. Generally, the use of finite volume methods offer the best stability and efficiency while finite element methods offer the best geometric flexibility.

Data Requirement

As input data, 2D hydrodynamic models require channel bed topography, roughness and transverse eddy viscosity distributions, boundary conditions, and initial flow conditions. In addition, a discrete mesh or grid must be designed to capture the flow variations.
Obtaining an accurate representation of bed topography is likely the most crucial, difficult and time consuming aspect of the 2D modeling approach.

Bed roughness, in the form of Manning's value, is a less critical input parameter. Compared to traditional 1D models, where many two-dimensional effects are abstracted in to the resistance factor, the two-dimensional resistance accounts only for the direct bed shear stress. Observations of bed material and bed form size are usually sufficient to establish reasonable initial roughness estimates. Calibration using observed water surface elevations and/ or velocity measurements allows the user to determine the choice of final roughness values.

Transverse eddy viscosity distributions are important for stability in some finite difference and finite element models (Introduction to Depth Averaged Modeling and User's Manual, Peter Steffler and Julia Blackburn, 2002). They can be also used as calibration factors based on measured flow distributions. Stable and high resolution numerical schemes are not sensitive to these values. In cases where accurate determination of eddy viscosity is required, coupled turbulence models are considered.

Boundary conditions usually take the form of a specified total discharge at inflow sections

and fixed water surface elevations or rating curves at outflow sections. Since 2D models make no implicit assumption about flow direction or magnitude, discharge divisions in splitting channels and the discharge given inflow and outflow elevations can be calculated directly. Locating flow boundaries some distance from area of interest is important to minimize the effect of boundary condition uncertainties.
Initial conditions are important, even for steady flow, since they are usually used as the initial guess in the iterative solution procedure.

Mesh or grid design is very important in 2D modeling. The total number of degrees of freedom (number of computational nodes times three unknowns per node) is limited by the computer capacity and time available. The challenge is to distribute these nodes in such a way that the most accurate solution is obtained for a particular purpose. Closely spaced nodes in regions of high interest or flow variation, gradual changes in node spacing, and regularity of element or cell shape are important considerations.

Principles of 2D Hydrodynamic Modeling

The physical principles behind depth averaged modeling are based on the conservation of mass and momentum and on a set of constitutive laws relating the driving and resistance forces to fluid properties and their motions.

Given a set of governing equations, there are two essential steps in developing a commercial model:

1. Discretisation: The infinite number of equations for an infinite number of unknowns is reduced to a finite number of equations at a finite number of mesh or grid points in space and time. At this stage, calculus operations are reduced to algebraic operations.

2. Numerical solver: A scheme or process is devised where the algebraic equations developed in the first step can be solved for the unknown nodal values. The algebra is reduced to arithmetic which can be translated in to computer code.

Common discretisation methods include finite difference, finite volume and finite element methods. Solution methods include explicit and implicit solvers, the latter of which depend on a variety of iterative or direct non- linear and linear equation solution methods (River 2D, Peter Steffler and Julia Blackburn).

1.2 Objectives

The main objectives of this thesis are:

- To compare the two hydrodynamic models Hydro_As-2D and SRH-W with respect to their outcomes, accuracy, computational time, and the relevance of their application for scales of ecological importance.
- To compare the performance of the spatial interpolation methods Krigging and triangulation with linear interpolation on the surveyed bathemetry data.
- To carry out a sensitivity analysis for the two models investigating the effects of mesh resolution and the exclusion of boulders from the surveyed data
- To summarize the advantages and disadvantages of the two models and give recommendations for their further application.

Inorder to fulfill these objectives, three case study reaches with different channel bed morphology and density of bathymetry data were selected for the study. The reaches were selected to study how model performances change with the different bed morphologies and flow characterstics.

1.3 Report Outline

A brief introduction about the modeling principles behind the investigated two dimensional hydrodynamic models is provided in the first chapter.

Chapter 2 discusses the two models used in this thesis. The governing equations, mesh generation techniques and the modeling steps of the two models are described.

Chapter 3 compares of the spatial interpolation methods Krigging and triangulation with linear interpolation. The accuracies of the two interpolation schemes were compared using the test set cross validation method.

Chapter 4 presents the main core of this thesis work. Hydrodynamic modeling of three case study reaches was done using the two models. Sensitivity analysis of the two models was also performed for all the case study reaches.

Chapter 5 deals with the comparison of the outputs of the two models. Simulation outputs of the two models (water surface elevation, water depth, velocity, Froude number) are compared to each other. Furthermore, the two models are evaluated for their computation times, cost, and user friendliness.

Chapter 6 is the final chapter and it contains conclusions drawn and recommendations for further work.

2 Models Used

This chapter explains the two 2D hydrodynamic models used in this thesis. Model background, governing equations, mesh generation and modeling steps of each are discussed.

2.1 Hydro_As-2D

2.1.1 Model Bakground

Hydro_As-2D (NUJIC, 2003) is a two dimensional hydrodynamic numerical model which is applied in many research areas dealing with river management. It is primarily used in southern Germany, Austria and Switherland. Hydro_As-2D was primarily developed for the simulation of dam break and flood wave propagation. But it has been applied for a wide variety of two dimensional flow simulations. The range of applicability of Hydro_As-2D depends on the dimension of the problem at hand. Many practical problems in hydraulic engineering have been successfully described with the depth averaged flow equations used in the model (Hydro_As-2D users manual, Dr.- Ing. Marinko Nujic).

Hydro_ As -2D can be effectively utilized for solving problems in:

- River flooding analysis
- Tidal wave propagation
- Pollutant dispersion and transport

2.1.2 Governing Equations and Numerical Methods

Two dimensional mathematical modeling of flow in natural rivers is based on the 2D depth averaged flow equations which are also called as shallow water equations (ABBOTT 1979). The equations originate from the integration of the three dimensional continuity equation and the Reynolds and/or Navior-Stokes equations for incompressible fluids over the water depth with assumption of hydrostatic pressure distribution (PIRONNEAU 1989). To perform numerical simulations, discretisation of the investigation area in to a finite number of elements is required. The algorithm implemented in Hydro_As-2D is based on numerical solution of the depth averaged shallow water equations using the Finite Volume Method (FVM) for spatial discretisation. The FVM uses the basic equations in an integral form. It is a conservative method where no mass deficit occurs and is strongly recommended to calculate discontinuities like hydraulic jumps, bottom sills and sudden cross section changes.

The FV equation can be written as:

$$\frac{\partial}{\partial t}\int w \cdot dV = -\oint\limits_{A} (f, g) \cdot n \cdot dA - \int\limits_{V} s \cdot dV \tag{2.1}$$

Where

t =time (s)

w =approximate solution of the shallow water equations

V =volume (m^3)

A =Area (m^2)

f, g = convective and diffusive flows (m^3/s)

n = unit vector (-)

The eddy viscosity is implemented in Hydro_As-2D based on the following equation:

$$\nu = \nu_o + c_\mu \nu^* h$$

Where

ν_o = basic kinematic eddy viscosity (a constant value)

c_μ = coeefficient (0.3-0.9)

ν^* = shear stress velocity

h = water depth

Viscosity plays a minor role for hydraulic modeling of riverine hydraulics (NUJIC, 1999) and therefore the constant value ν_0 can be neglected. The second term on the right side of the equation represents the eddy viscosity induced by bed friction, and is a function of shear velocity and water depth.

The calculation of the convective part in Hydro_As-2D is based on modern upwind methods like stream-line diffusion (Nujic 1995/1999, PIRONNEAU 1989, Lafon and Osher 1991). The discretisation of the diffusive terms is less critical, from numerical point of view, and was done with a Central Difference scheme. In this case, difficulties (oscillations in the numerical solution) can arise if there are distorted elements (narrow elements with small angles). Unsteady condition is always used in Hydro_As-2D for the calculation of flow and discharge. The explicit time step method implemented ensures the exact simulation of the flow.

2.1.3 Mesh Generation

Hydro_As-2D is directly coupled with the Surface Water Modeling System (SMS) software where SMS is used for pre- and post-processing (mesh generation, model control, visualsation, etc). Other programs like Arc GIS, GeoCAD, AutoCAD, etc can also be used based on availability and suitability. Hydro_As-2D uses an unstructured mesh of triangular and rectangular elements which can be well adapted to varying topographic or hydrodynamic situations. Only linear elements are used for computation. Figure 2.1 shows example of linear elements ised in Hydro_As-2D.

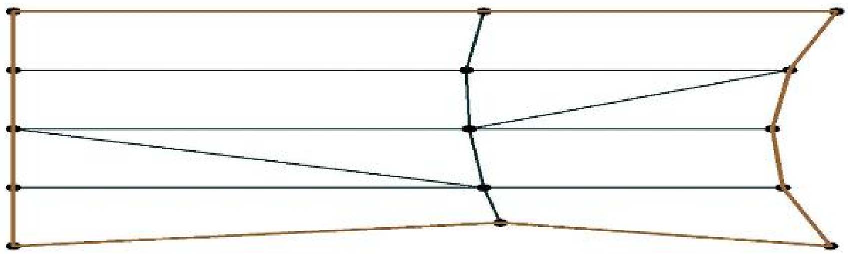

Figure 2.1: Example of linear elements used in Hydro_As-2D.

2.1.4 Modeling Steps

The flow simulation consists of three modules;

- Preprocessor,
- Calculation module,
- Post processor

The first step of the modeling is preparation of a mesh with a sufficiently high resolution and specifying the inflow and outflow boundary conditions. Roughness values for the elements have to be assigned, typically depending on material types. Additional parameters are also defined depending on the problem at hand.

The second step is running the simulation. The calculation or simulation model of Hydro_-As-2D consists of two modules:

1. Hydro_2dm which transforms data from SMS to the calculation module Hydro_As-2d and checks consistency and quality of data, and

2. Hydro_As/Hydro_As-1Step performs the calculations and gives outputs like depth, velocity, water level, etc.

The final step is the visualization of the computation results using SMS and calibration of the model till observed and computed values are as close as possible by changing different model parameters like roughness and viscosity values.

2.2 Sedimentation and River Hydraulics-Watershed (SRH-W)

2.2.1 Model Background

SRH-W is a two dimensional hydraulic model for rivers and watersheds under development under the United States Bureau of Reclamation (USBR). It is primarily used to solve various hydraulic problems. So far, SRH-W has been more applied for river flows and less for watershed runoff computations (Theory and user manual for SRH-W version 1.1, 2006).

Major capabilities of SRH-W are:

- Solving the two dimensional depth averaged diffusive wave or dynamic wave equations.
- Both steady and unsteady flows may be simulated.
- Unstructured or structured 2D meshes can be used.

  A structured mesh is one in which the elements have the topology of a regular grid. Unstructured meshes use arbitrarily shaped cells for geometry representation.
- Sub-, super-, and trans-critical flows can be solved.

The simulation outputs of the SRH-W main solver are: water surface elevation, river bed elevation, water depth, velocity, bed shear stress, Froude number. SRH-W is usually applied for problems where two dimensional effects such as local flow velocities, eddy patterns, lateral variations in the flow, etc are important.

2.2.2 Governing Equations and Numerical Methods

The two dimensional depth averaged dynamic wave equations (St Venant Equations) are used to solve river flow problems. The three-dimensional Navier-Stokes equations, may be vertically averaged to obtain a set of depth-averaged two-dimensional equations, leading to the following well known 2D St. Venant equations (Theory and user manual for SRH-W version 1.1, Yong G. Lai, Ph.D.):

$$\frac{\partial h}{\partial t} + \frac{\partial hU}{\partial x} + \frac{\partial hV}{\partial y} = e \tag{2.2}$$

$$\frac{\partial hU}{\partial t} + \frac{\partial hUU}{\partial x} + \frac{\partial hVU}{\partial y} = \frac{\partial hT_{xx}}{\partial x} + \frac{\partial hT_{xy}}{\partial y} - gh\frac{\partial z}{\partial x} - \frac{\tau_{bx}}{\rho} \tag{2.3}$$

$$\frac{\partial hV}{\partial t} + \frac{\partial hUV}{\partial x} + \frac{\partial hVV}{\partial y} = \frac{\partial hT_{xy}}{\partial x} + \frac{\partial hT_{yy}}{\partial y} - gh\frac{\partial z}{\partial y} - \frac{\tau_{by}}{\rho} \tag{2.4}$$

Where

x and y = cartesian coordinates

t = time

h = water depth

U and V = velocities in the x and y directions respectively

e = source or sink (for example excess rainfall)

g = acceleration due to gravity

T_{xx} ,T_{xy} and T_{yy} = depth averaged turbulent stresses

$z = z_b + h$ = water surface elevation

z_b = bed elevation

ρ= density of water

τ_{bx} and τ_{by} = bed shear stresses

Manning's equation is used to calculate the bed shear stresses

$$(\tau_{bx}, \tau_{by}) = \rho U_*^2 \frac{(U,V)}{\sqrt{(U^2+V^2)}} = \rho C_f \sqrt{U^2+V^2}\,(U,V)$$
$$C_f = \frac{gn^2}{h^{\frac{1}{3}}}$$

Where

n= Manning's roughness coefficient

U_*= bed frictional velocity

Bossinesq's equations are applied for computing the turbulence stresses.

$$T_{xx} = 2\left(\nu+\nu_t\right)\frac{\partial U}{\partial x} - \frac{2}{3}k$$
$$T_{yy} = 2\left(\nu+\nu_t\right)\frac{\partial V}{\partial y} - \frac{2}{3}k$$
$$T_{xy} = \left(\nu+\nu_t\right)\left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x}\right)$$

Where

ν= kinematic viscosity of water

ν_t = turbulent eddy viscosity

k = turbulent kinetic energy

The SRH-W model calculates the turbulent viscosity with the equation below (Rodi.1993).

$$\nu_t = \alpha V_* h$$

Where

V_*= the frictional velocity

h = water depth

The coefficient α ranges from 0.3 to 1.0.

Finite volume method, which is a conservative approach, is implemented for discretisation of the governing equations. Meshes with arbitrary element shapes can be adopted though triangular and rectangular elements are frequently used, (Lai 1997, 2000). The cell centered scheme is utilized giving all output variables at the center of a cell rather than cell vertices. The governing equations are integrated over a polygon using the Gauss theorem.

2.2.3 Mesh Generation

SRH-W requires the use of an external mesh generation program for mesh preparation. The Surface Water Modeling System (SMS) is commonly used for mesh generation. In general, a mesh with combination of triangular and quadrilateral elements is used in SRH-W. Only the map, mesh and scatter modules of SMS are needed to prepare 2D mesh for SRH-W and run a model.

2.2.4 Modeling Steps

Three programs are required for a complete analysis with SRH-W:

- A mesh generation program (SMS,PLOT3D).
- SRH-W package (srhpre11 and srhw11).

Srhpre11 is a text-based interactive user interface which is used as a preprocessor to prepare an input file to run SRH-W.
Srhw11 is the main solver which carries out the simulation and gives the final output files.

- A post processing program.

Three formats of output files (SMS, TECPLOT, GENERIC) are currently available.

The following four steps are followed to run a simulation using SRH-W:

1. The first step is preparing a 2D mesh using a mesh generation program.
2. Preprocessor execution: after a mesh is ready, the second step is to run the srhpre11 which is used to assign boundary conditions, bed roughness coefficients, etc and creates the input file to the main solver.
3. Main solver execution: in this step the output file from the preprocessor is used as input to the main solver (srhw11). Srhw11 performs the simulation and gives final output files of different variables like velocity, water depth, water surface elevation. A number of additional output files giving general information about the simulation performed are also generated.
4. Post processing: the final step is the post processing of simulation results. This includes the comparison of measured and computed values of some variables. The model has to be calibrated so that computed and observed values of water surface elevation and/or

flow velocity are as close as possible by changing model parameters like bed roughness values.

3 Comparison of Spatial Interpolation Methods

3.1 Introduction

Numerical modeling of the flow dynamics in river channels requires the spatial interpolation of scattered measurements of bathymetry elevations to obtain elevations of mesh nodes. Bathymetry data describing river bed geometry and is collected via a field survey and stored electronically in the form of xyz coordinates. Collection of sufficient bathymetry data representing channel geometry and the use of accurate spatial interpolation method to assign elevations of mesh nodes are very key to obtain accurate model results. According to USACE (1996), 80% of the ability to produce accurate model results depends on using appropriate bathymetry data, mesh design and boundary conditions. Choosing an appropriate interpolation scheme is a critical step in producing an accurate surface for river channels from scattered bathymetry points. A bathymetry surface that has a better description of small scale channel features is important in studies involving two or three dimensional hydrodynamic models. Such models simulate complex flow patterns around small scale channel features, which are very important in fish habitat studies and other studie in scales of ecological importance.

In this chapter, two spatial interpolation methods namely krigging and triangulation with linear interpolation will be compared using bathymetry data obtained from three river reaches. The river reaches used are the Schneitbach, Neumagen and Gurgler Ache. The first two are rivers located in southern Germany where as the third one is a reach from Austria.

A brief description of the river reaches and other available data used for modeling of them will be provided in the next chapter.

3.2 Spatial Interpolation Methods

Interpolation is the process of using known data values to estimate unknown data values. There are a number of different interpolation algorithms used in many different fields of study. Commonly used interpolation schemes are: kriging, triangulation with linear interpolation, inverse distance to a power, modified Shepard, natural neighbor, etc. A large variety commercial interpolation software programs are available. In this study, Surfer 8, a software developed by Golden Software company was utilized. Surfer is a contouring and 3D surface mapping program, which quickly and easily transforms random surveying data, using interpolation, in to a square grid, with a user defined resolution. The new version, Surfer 8 provides twelve interpolation methods each with specific functions and related parameters. Most of the gridding methods in Surfer use a weighted average interpolation algorithm (except for linear interpolation). This means that, all other factors being equal, the closer a data point is to a grid node, the more weight it carries in determining the value to be interpolated at a particular grid node. Two of the interpolation methods; kriging and triangulation with linear interpolation were compared in this study.

3.2.1 Kriging

Krigging is a geostatstical gridding method that has proven useful and popular in many fields. Krigging uses a linear combination of all sampling values, where their weights determined by their distance from the interpolation point. It is a very flexible interpolation method. Krigging can be custom-fit to a data set by specifying the appropriate variogram model. Krigging incorporates anisotropy and underlying trends in an efficient and natural manner (Surfer 8 user's guide). Surfer includes two krigging types: point krigging and block krigging.

Point kriging estimates the value of the points at the grid nodes whereas block kriging estimates the average value of the rectangular grids centered on the grid nodes. Point kriging is the default method in Surfer. Here, the Kriging default settings were applied for interpolating the data sets to be analyzed. It should be mentioned that the user must be careful when using kriging, as it can extrapolate data values beyond the observed data range.

3.2.2 Triangulation with Linear Interpolation

Triangulation with linear interpolation method in Surfer uses the optimal Delaunay triangulation. This algorithm creates triangles by drawing lines between data points. The original points are connected in such a way that no triangle edges are intersected by other triangles. The result is a patchwork of triangular faces over the extent of the grid. Delaunay triangulations maximize the minimum angle of all the angles of the triangles in the triangulation; they tend to avoid skinny triangles. The triangulation was invented by Boris Delaunay in 1934. Triangulation is an exact interpolator (Lawson, 1997; Lee and Schachter, 1980). Each triangle defines a plane over the grid nodes lying with in the triangles, with the tilt and elevation of triangle determined by the three original data points defining the triangle. All grid nodes within a given triangle are defined by the triangular surface (Surfer 8 user's guide, 2002). The most common interpolation method on triangles is linear interpolation. Triangulation with linear interpolation works best when the data are evenly distributed over the grid area. Triangulation with linear interpolation does not extrapolate values beyond the range of data.

3.3 Comparison of Interpolation Methods

Before the scatter data is imported to SMS, Surfer is used to interpolate the data and obtain a high resolution scatter data with grid sizes approximately the same as mesh sizes. Then the interpolated scatter data is read in to SMS and used for interpolating in to the mesh in order to obtain elevations of individual mesh nodes. The bathymetry data for the study reaches comprise a set of (x, y, z) coordinates.

The interpolation accuracy can be measured by different methods. The method used here is the test set cross validation. First, the original data set was split in to two subsets: the training dataset and the test dataset. The test data set was created by randomly removing 10%, 20% and 30% ...70% of the data from the original dataset. Random selection for creating a test dataset works well for regularly spaced data (Optimization of interpolation parameters; Jaroslav Hofierka and Marcel Suri, 2007). The remaining dataset (training data) was used to perform the interpolation and the interpolation accuracy is evaluated by comparing the interpolated values against the observed values in the test dataset. Visual comparison of the three dimensional surface maps created by using the two interpolation methods was also be done. Total available scatter data describing channel bed and boulders for the three reaches is shown in table 3.1 below.

Table 3.1: Number and density of bathymetery data availiable for the three reaches

Reach	Schnaitbach	Neumagen	Gurgler Ache
Total Bathymetery data	4737	3214	1530
scatter data for boulders	3111	439	56
scatter data without boulders	1626	2775	1474
Total surface area of site (m^2)	391.24	621.31	703.92
Density of total bathymetery (points/m^2)	12	5	2

3.3.1 Accuracy of Interpolated Values of the Test Set

Comparison of performance between interpolation techniques, in terms of accuracy of estimates, was achieved by comparing the deviation of estimates from the measured data of the test data set using the following statistics: the mean error (ME), the mean absolute error (MAE) and the root mean square error (RMSE) (Zar 1999).

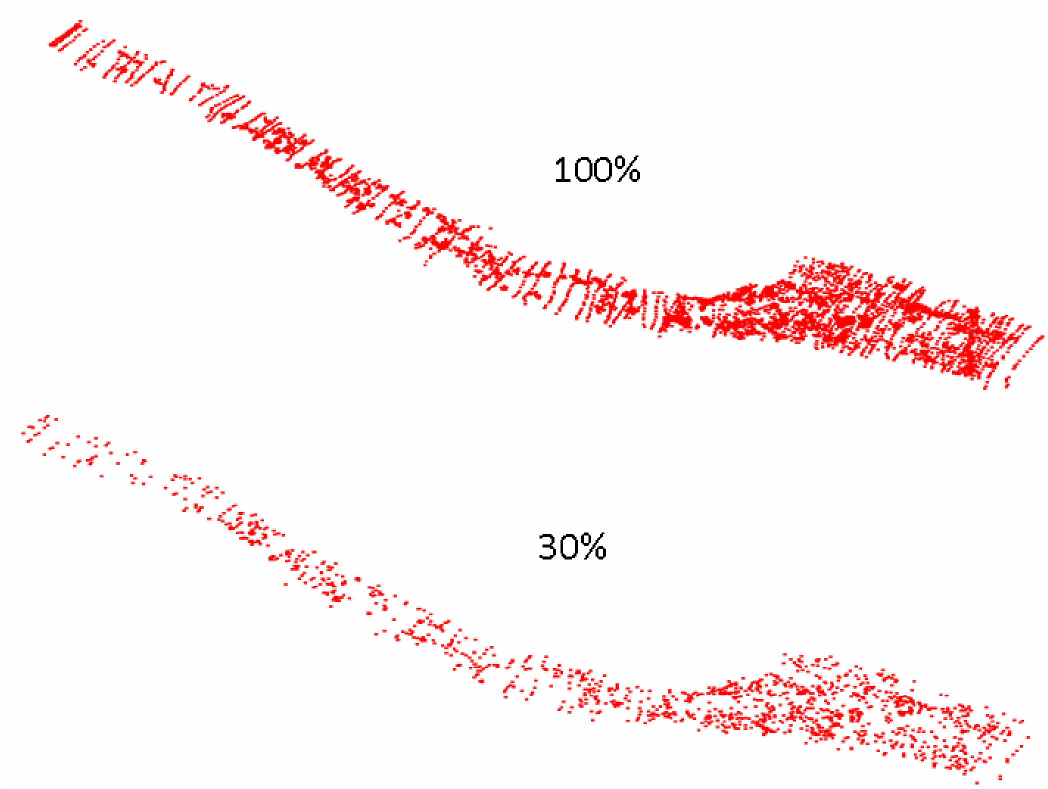

Figure 3.1: Distribution of 100% and 30% of surveyed data for the Schnaitbach.

The ME is used to determine the degree of bias in the estimates and is calculated using Equation 3.1.

$$ME = \frac{1}{n}\sum_{i=1}^{n}(Zin_i - Zob_i) \tag{3.1}$$

The MAE provides the absolute measure of the size of the error. The MAE was computed by calculating the absolute difference between the interpolation values and the test values, averaged over the number of points. Thus lower MAE should mean a better interpolation accuracy. It is calculated by Equation 3.2.

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |(Zin_i - Zob_i)| \tag{3.2}$$

The root mean square error (RMSE) provides a measure of the error size that is sensitive to outliers. RMSE values can be calculated with Equation 3.3.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (Zin_i - Zob_i)^2} \tag{3.3}$$

Where

$Zobs_i$ = oberved values

$Zint_i$ = interpolated values

n = number of points in the test data set

The table 3.2 summarizes the interpolation error for all the three reaches

The results in table 3.2 showed that the two interpolation methods estimated the observed values of the test data well. The mean absolute error and the root mean square errors of interpolation are quite similar for the two methods. But the accuracy of interpolation depends on the availiable bathymetry data for the reaches and the complexity of the bed morphology. The denser the bathymetery data availiable,the better the accuracy of interpolation. Krigging was found to be slightly better than the triangulation with linear interpolation.

From table 3.2 and figures 3.2 and 3.3, the interpolation error is not increasing significantly even when 70% of the data was removed for the Schnaitbach and Neumagen reaches. This is because the MAE and RMSE show only the average error and there was a high resolution bathymetry data for the two reaches.

Table 3.2: Interpolation error summary (m)

Interpolation Method		Trianguation			Krigging		
		ME	**MAE**	**RMSE**	**ME**	**MAE**	**RMSE**
10%test data	**Gurgler Ache**	-0.033	0.163	0.235	-0.035	0.164	0.235
	Neumagen	0.005	0.077	0.123	0.004	0.075	0.118
	Schneitbach	-0.005	0.087	0.12	-0.005	0.087	0.12
		ME	MAE	RMSE	MAE	MAE	RMSE
20% test data	**Gurglerb Ache**	-0.005	0.158	0.224	-0.005	0.158	0.22
	Neumagen	0.002	0.076	0.113	0	0.074	0.109
	Schneitbach	0.001	0.087	0.121	0	0.086	0.12
		ME	MAE	RMSE	MAE	MAE	RMSE
30% test data	**Gurgler Ache**	0.003	0.151	0.212	0.004	0.154	0.213
	Neumagen	0	0.076	0.113	-0.003	0.074	0.108
	Schneitbach	0.005	0.09	0.129	0.002	0.089	0.128
		ME	MAE	RMSE	MAE	MAE	RMSE
50% test data	**Neumagen**	-0.002	0.082	0.12	-0.008	0.08	0.116
	Schneitbach	0.003	0.093	0.132	-0.003	0.093	0.133
		ME	MAE	RMSE	MAE	MAE	RMSE
60% test data	**Neumagen**	0.002	0.084	0.122	-0.009	0.085	0.122
	Schneitbach	0	0.098	0.139	-0.006	0.097	0.138
		ME	MAE	RMSE	MAE	MAE	RMSE
70% test data	**Neumagen**	0.006	0.085	0.123	-0.07	0.088	0.126
	Schneitbach	0.006	0.104	0.144	-0.004	0.104	0.147

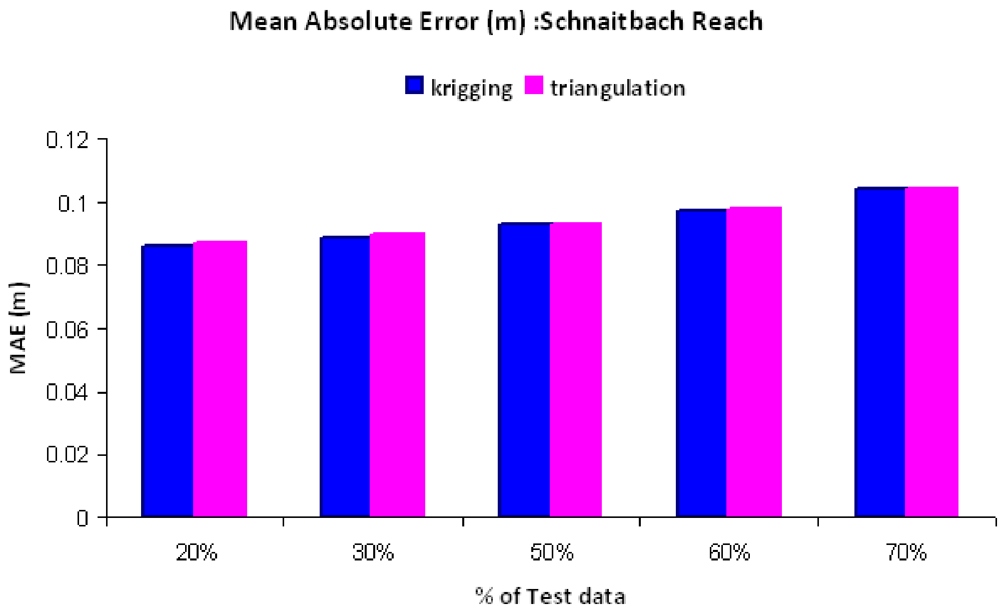

Figure 3.2: Interpolation mean absolute error summary (m) .

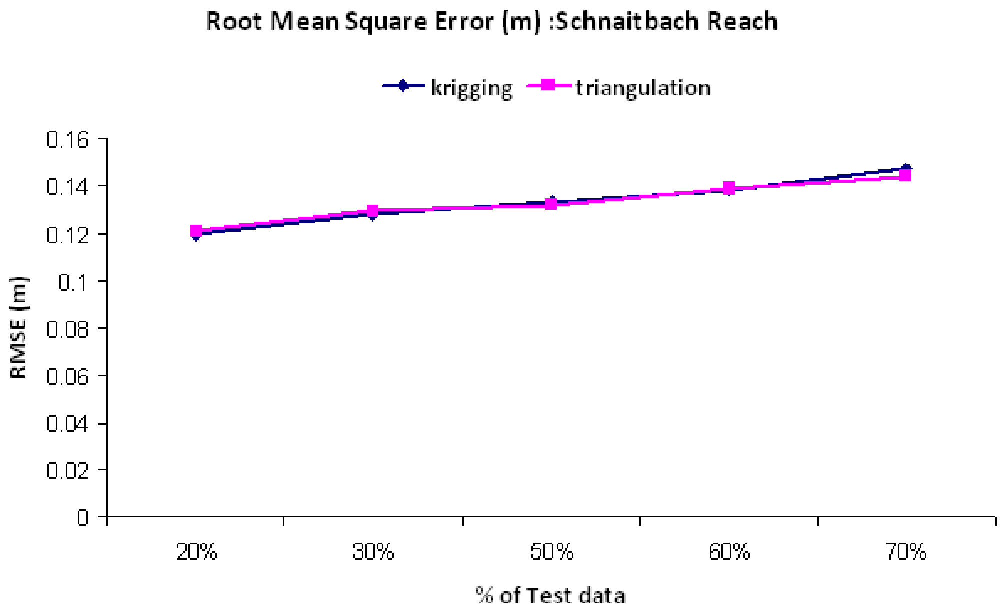

Figure 3.3: Root mean square error of the two interpolation methods (m).

Figure 3.4 shows the spatial distribution of the interpolation error after 70% of the available data was removed and used as a test data for the Schnaitbach. It shows that the interpolation error is very high near the boundary and places with big boulders for both Krigging and triangulation with linear interpolation.

To obtain a reasonable interpolation accuracy removing more than 50% of the data is not recommended for the Schnaitbach and Neumagen reaches.
The available bathymetry data for the Gurgler Ache was not sufficient and a bathymetry data with higher density is required to get a better accuracy.

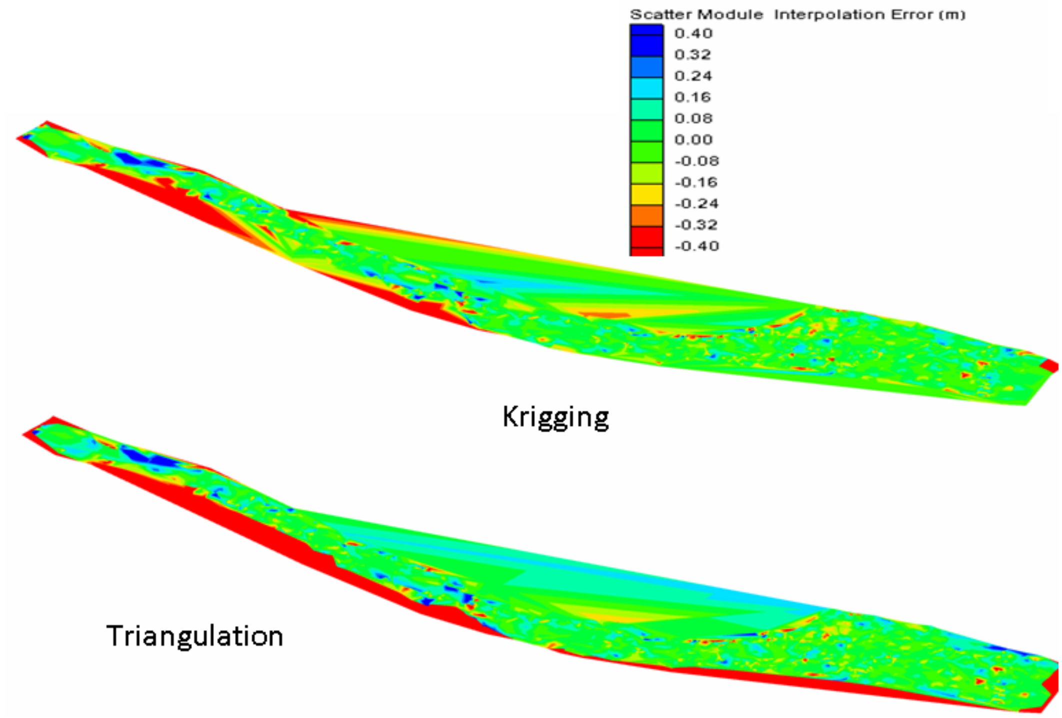

Figure 3.4: Spatial distribution of interpolation error for 70% test data for the Schnaitbach.

3.3.2 Visual Comparison Using 3D Surface Maps Obtained by Interpolation

Visual comparison is done by creating the 3D surface maps of the interpolated surface of the case study reaches using surfer.
Visual comparison is necessary:

- to see if there are systematic errors found which cannot be picked via the statstical analysis alone.
- so that the modeler can compare the morphology to that which he has seen in the field.

Surface details produced by the two interpolation methods using the training datasets are shown in figure 3.5.

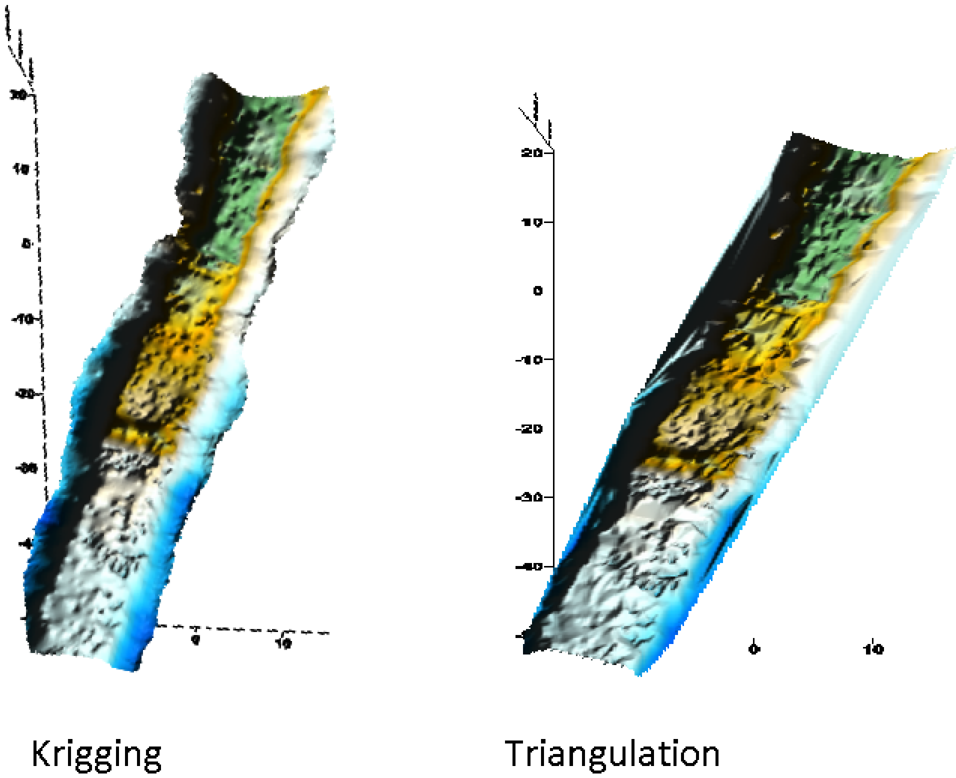

Figure 3.5: Surface map for the Neumagen reach.

From the surface maps obtained from the two methods, it can be seen that the surface details created by the two interpolation methods are more or less the same. There are not significant differences in the resulting surface morphology. Both of these methods are consistent in describing the location of important features of the river bed such as the location of pools, boulders, etc.

The results of Krigging are still a bit more accurate than triangulation and Krigging was therefore chosen for interpolating the bathymetry data in the next chapter dealing with the hydrodynamic modeling of the three case study reaches.

4 Case Studies

4.1 Introduction

In this chapter the results of the two dimensional hydrodynamic modeling of the three case study reaches is compiled for Hydro_As-2D and SRH-W. The three reaches were selected based on their different bed morphological characteristics, flow patterns, and their ecological importance. The first reach, the Schnaitbach has a highly natural, complicated bed morphology. It contains many obstructions such as boulders, which result in complex flow patterns. The second reach, the Neumagen is a channelized river with very few obstructions. This reach has two locations where there are large, man made swells. The third case study reach is the Gurgler Ache. It is a wide gravel river with a highly hetrogeneous bed morphology. The resolution of the available measured bathymetry data is also quite different for the three reaches. The modeling results from these three reaches under different flow characteristics will be used in the next chapter for the comparison of the two models.

4.2 Case Study One: Schnaitbach

4.2.1 Site Description

Schnaitbach is a mountaineous river reach in southern Germany in the state of Baden-Wurttemberg. A representative reach of 90 m was selected as the first case study reach.

The reach has many naturally-ocurring obstructions with complicated bed morphology. The modeled section has a width of approximately 6.2 m at the upstream end and 3.3 m at downstream. The river reach contains many boulders which create complex flow pattern and potentially good habitat conditions. This reach is assumed to be a spawning habitat for locally important species, such as bullhead and brown trout. A new hydropower plant is planned to be constructed by diverting water from the Schnaitbach upstream of the study reach and the main aim of the hydrodynamic modeling of this reach is to determine the velocity and water depth distribution along the whole reach and then the results will be used for habitat modeling from which the minimum flow requirements for suitable habitat conditions can be made.

Figure 4.1: The Schnaitbach.

4.2.2 Data Available

Hydraulic modeling in two dimensions requires detailed information about the whole river reach. The following data are required to run the models successfully: Bathymetry data describing the channel geometry, boundary conditions (discharge and water level), channel roughness coefficients and eddy viscosity values.

Bathymetry Data

Accurate representation of the channel bed and other morphological features are very crucial in determining the quality of outcome of two dimensional hydrodynamic models (D.W. Crowder and P. Diplas, 2000). Detailed river topography for this site was collected in the form of xyz coordinates using Lecia L-7945 total station. A total of 4737 spot elevations were collected over the entire reach. The bathymetry data was collected in two classes. First 1626 xyz data representing the channel bed was collected. Additional xyz coordinates were surveyed to describe obstructions such as large boulders which greatly affect local flow patterns. A total of 3111 xyz coordinates were surveyed for the boulders. Bathymetry data for the boulders was typically collected with five xyz coordinates: four surveyed at the base of the obstruction, and one surveyed at the top.

Discharge and water level

A discharge of 0.18 m^3/s was measured for the upstream boundary condition and a water surface elevation of 197.66 m was surveyed at exit for downstream boundary condition for the same discharge. Additional seventy (70) water surface elevation measurements were taken at different points in the reach for calibrating the models.

4.2.3 Mesh Preparation

The mesh was generated using the map and mesh modules of the Surface Water Modeling System (SMS). Scatter data were used to define the boundaries of the study site. The patch method was applied to create the mesh. Bed elevation of each node was obtained by linear interpolation of the xyz coordinates of the scatter data in to the mesh. The shapes of elements in a mesh and the quality of the mesh have a pronounced effect on the quality of a hydraulic model output. Therefore, the mesh quality was checked after the preparation of the mesh. The average grid size of the mesh with the highest resolution was 0.249 m. Table 4.1 summarizes the property of the mesh.

Table 4.1: Mesh used to model the Schnaitbach reach

Number of elements	Number of nodes	Average grid size(m)
9965	10381	0.249

Figure 4.2: Mesh for the Schnaitbach.

4.2.4 Modeling Using Hydro_As-2D

Boundary Conditions and Model Parameters

Calculations in Hydro_As-2D are always performed using unsteady conditions and therefore the upstream boundary condition must be defined as time dependent. For modeling of a constant discharge, the unsteady condition must be adopted to the steady condition. Constant discharge will be reached after a certain time interval . The downstream (outlet) boundary condition was specified as a rating curve which is the relationship between water level and discharge for a specific cross section. For every discharge defined upstream a corresponding water level has to be defined downstream. For this reach, a discharge of 0.18

m^3/s was measured for the upstream boundary condition and a water surface elevation of 197.66 m was measured for the downstream boundary condition.

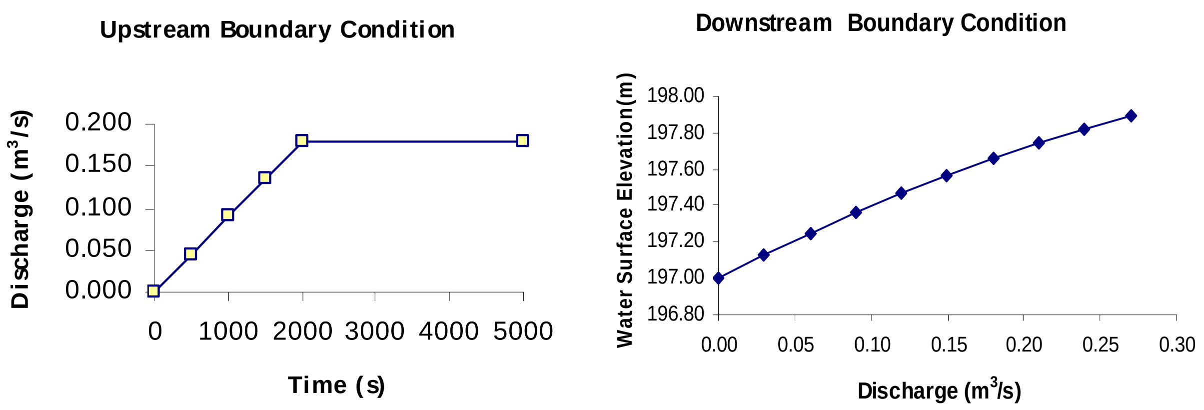

Figure 4.3: Upstream and downstream boundary conditions for Schnaitbach reach.

Model Parameters

Distributions of bed roughness and viscosity must be specified for the model area before running the model. Channel bed roughness values were assigned for every element using the Strickler coefficient.

Through out this thesis a constant value of c_μ =0.6 was used for the eddy viscosity coefficient. This is the default value given in Hydro_As-2D.

A total run time of 5000 seconds and a time step of 500 seconds were defined to run the simulation.

Default values given in Hydro_As-2D were used for the following parameters:

- Minimum water depth (Hmin) = 0.01 m
- Maximum admissible magnitude of velocity (VELMAX) = 15 m^3/s
- Minimum allowable control volume area (Amin) =1.0e-15 m^2

Model Calibration and Simulation Outputs

Calibration of simulated data with observed field data is an important step in the modeling process. Roughness and turbulence parameters are adjusted to calibrate the model such that model results match measured water surface elevations and/or velocity values taken in the field as closely as possible. In this case, 70 water surface elevation values measured at different points in the reach were used to calibrate the model. The trial and error procedure was used for calibration, where the bed roughness coefficients were increased or decreased according to the agreement of simulated vs. measured water surface elevations. Two roughness zones with strickler values of Kst_1= 12.5 and Kst_2= 10 were obtained as final roughness values after calibrating the model. The maximum deviation of $\pm 5cm$ was considered as adequate accuracy for the water surface elevations.

SMS includes a suite of tools to assist in the visualization of results for the calibration process. One of those is the calibration target. Both point or flux observations can be used. The size of the target is based on the confidence interval specified by the user.

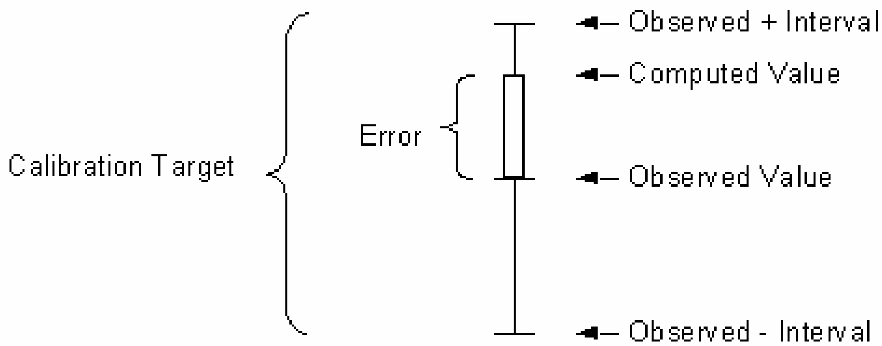

Figure 4.4: Calibration target.

The calibration error at each observation point can be plotted using the calibration target. The components of the calibration target are illustrated in the figure 4.4. The center of the target corresponds to the observed value. The top of the target corresponds to the observed value plus the interval and the bottom corresponds to the observed value minus the interval. The colored bar represents the error. If the bar lies entirely within the target, the color bar is drawn in green. If the bar is outside the target, but the error is less than 200%, the bar is drawn in yellow. If the error is greater than 200%, the bar is drawn in red (SMS 10 user's manual).

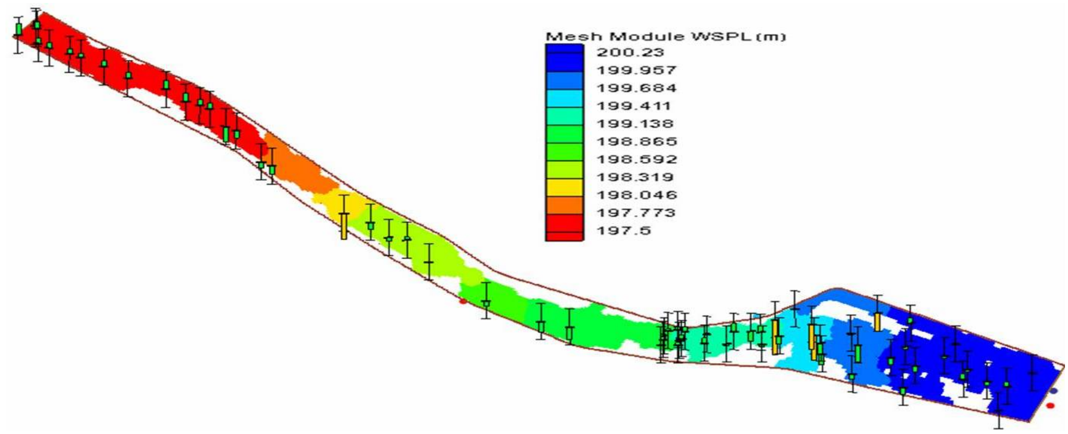

Figure 4.5: Calibration outputof water surface elevation for the Schnaitbach.

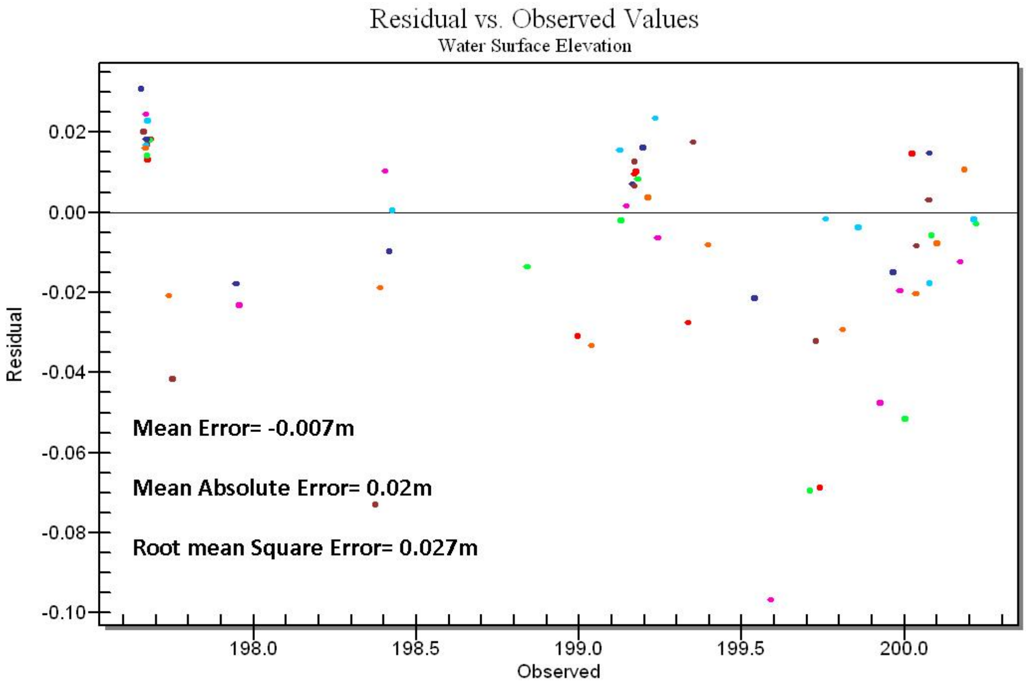

Figure 4.6: Error summary for water surface elevation outputs from HydroAs-2D model.

For most of the observed water surface elevations, the calibration error was less than 3 cm as seen with the green bars in figure 4.5. From the calibration error summary shown in figure 4.6, it can be concluded that the model predicted the observed water surface elevations quite satisfactorily. A mean absolute calibration error of 2 cm is a very good result.

The outputs of Hydro_As-2D that can be visualized in SMS are:

- Flow velocity (m/s)
- Water depth (m)
- Water levels (m)
- Bottom shear stress (N/m^2)

These values are calculated for each node of the mesh. Additional results can be obtained by using the 'data calculator' in SMS linking the simulation outputs with mathematical operations.

4.2.5 Modeling Using SRH-W

SRH-W was used to model the Schnaitbach investigation reach modeled with Hydro_As-2D in the previous section. The mesh which was calibrated using Hydro_As-2D was utilized (same number of material zones and identical roughness coefficients).Then the outputs of the two models were compared.

Boundary Conditions and Model Parameters

The total discharge through the inlet was specified for the upstream (inlet) boundary condition. This discharge may be a constant value for steady state simulation or a hydrograph (discharge versus time) for unsteady simulation. In this paper only a steady state condition was simulated and a discharge of Q=0.18 m^3/s was defined as the upstream boundary condition. There are three approaches for specifying the velocity distribution at the inlet so that the total specified discharge is satisfied. The uniform-q approach which assumes a constant unit discharge normal to the inlet boundary was chosen for the velocity distribution.

At the exit, only the water surface elevation is needed as a downstream boundary condition if the flow is subcritical. A constant measured value of 197.66m was specified for the water surface elevation as a downstream boundary condition.

Model Parameters

The most important model parameter is the Manning's roughness coefficient. This was specified for two materials zones identified while modeling the reach with Hydro_As-2D.

Additional input parameters defined are summarized below.

- The dynamic wave solver (Type 3) was chosen as a flow solver as this deals with modeling of river reaches

- At present, unsteady simulation is used to simulate even steady state conditions and the following values were specified as unsteady simulation parameters:

  TSTART =0, for the simulation starting time in seconds

  DT (time step in seconds) =1

  NTSTEP (total number of time steps to be simulated) =5000

- A constant kinematic viscosity with a default value of 1.0e-6 was used for molecular viscosity of water

- A depth averaged parabolic model (type 2) was selected as a turbulence model. The default value α= 0.7 was used for the coefficient.

- Specifying initial condition is required for all simulations. There are four methods to specify this. These are: Constant value setup, dry bed setup, automatic wet bed setup and restart setup. The dry bed setup which assumes the whole solution domain to be dry (zero velocity and zero water depth) initially was selected here. This option works well for almost all cases (SRH-W user manual version 1.1).

- No special properties within mesh zones were used.

Model Calibration and Simulation Outputs

Calibration of the model can be done by changing the Manning's roughness coefficients for each zone and/or by changing the coefficient of the eddy viscosity, α. Here the Manning's coefficients obtained from calibrating the model using Hydro_As-2D in the pervious section were used. The simulation results were not very sensitive to α and the default value α= 0.7 was used for the coefficient of eddy viscosity. The final Manning's coefficients used were n_1=0.08 and n_2=0.1 for the two roughness zones identified while calibrating using the Hydro_As-2D model.

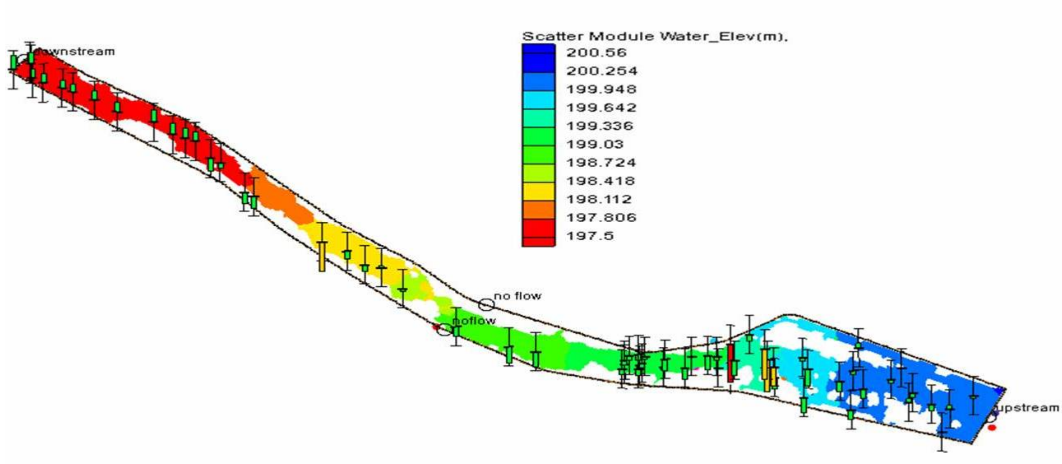

Figure 4.7: Water surface elevation output from SRH-W for the Schnaitbach.

From figures 4.7 and 4.8, it can be seen that SRH-W predicted the measured water surface elevations quite well. For most of the observed water surface elevations, the simulation error is less than 3 cm. The model simulation outputs of Hydr_As-2D and SRH-W are very comparable. Detailed comparison of all the model outputs will be performed in the next chapter.

The following outputs of SRH-W are given for the center of each element and can also be visualized in SMS :

- Water surface elevation (m)

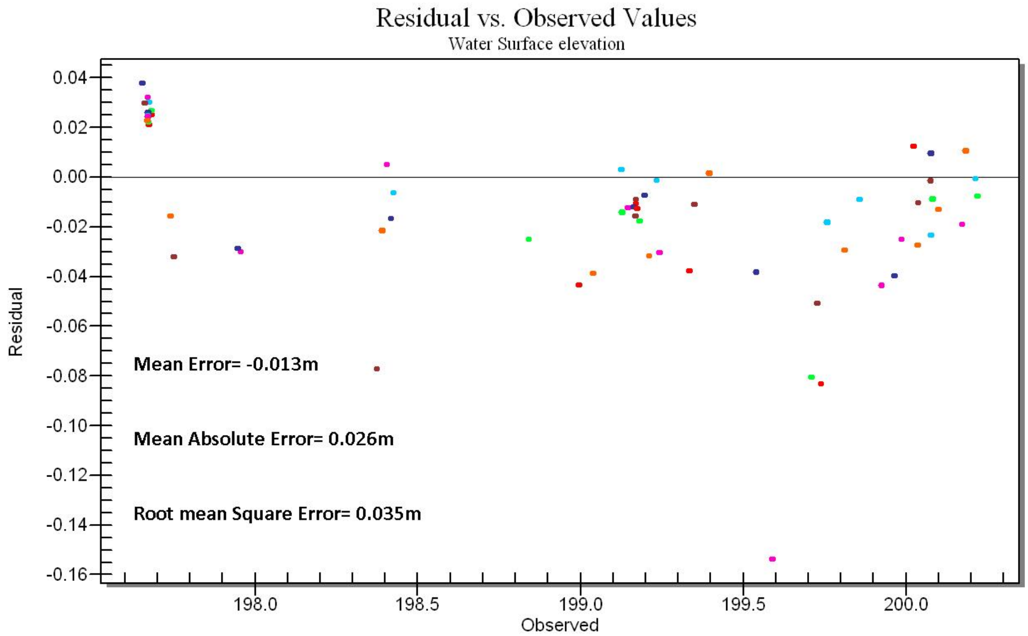

Figure 4.8: Error summary for water surface elevation outputs from the SRH-W model.

- Water depth (m)
- Bed elevation of a mesh point (m)
- Velocity magnitude (m/s) and Froude number
- Bottom shear stress (N/m^2)

4.2.6 Sensitivity Analysis for the Two Models

Conducting a sensitivity analysis allows for the investigation of the relationship between input quantities and output quantities of a model. In this paper, a sensitivity analysis was carried out for the two models to investigate how model performances change with different mesh resolutions and to evaluate the effects of the exclusion of boulders from the bathymetry data.

Effects of Different Mesh Resolutions

To investigate how model performance changes with mesh resolution, predictions made using three courser meshes were compared with outputs of the calibrated model using the finest mesh. Each mesh was created using an adaptive tessellation algorithm within SMS. The high resolution model results may differ from the benchmark in two ways : The two types of errors reflect different effects of mesh resolution on model performance; the ability to represent small scale processes, and their effect on large scale flow properties (Effects of mesh resolution and topographic representation in 2D finite volume models, M.S. Horritt and P.D. Bates, 2006). While coarse mesh elements reduce computer time and allow modeling of large river segments, they may not be able to accurately quantify important local flow features that influence stream habitat. Therefore, when modeling ecologically important river reaches one must not only assure that the bathymetry data is capable of reproducing flow patterns of interest, but that the numerical model's mesh is capable of accurately quantifying these patterns (D.W. Crowder and P. Diplas, 2000).

The three additional meshes created to investigate the responses of both Hydro_As-2D and SRH-W models are summarized in the table 4.2. The same roughness zones and bed roughness values as the finest mesh were specified for all the three meshes.

Table 4.2: Different mesh resolutions used for the Schanitbach

Mesh	Calibrated Mesh	Mesh 1	Mesh 2	Mesh 3
Total number of elements	9965	2824	1484	706
Total number of nodes	10381	3037	1642	817
Average distance between vertices (m)	0.249	0.466	0.691	0.929
Minimum distance between vertices (m)	0.198	0.348	0.564	0.75
Maximum distance between vertices (m)	0.335	0.587	0.907	1.166

The differences between the observed water surface elevations and the model simulation outputs are summarized in table 4.3.

From table 4.3 and figure 4.10, it can be concluded that SRH-W is more sensitive to mesh resolution than Hydro_As-2D. If the interest is in predicting water surface elevation or water depth rather than local flow patterns and velocities (as in the case of habitat studies), the

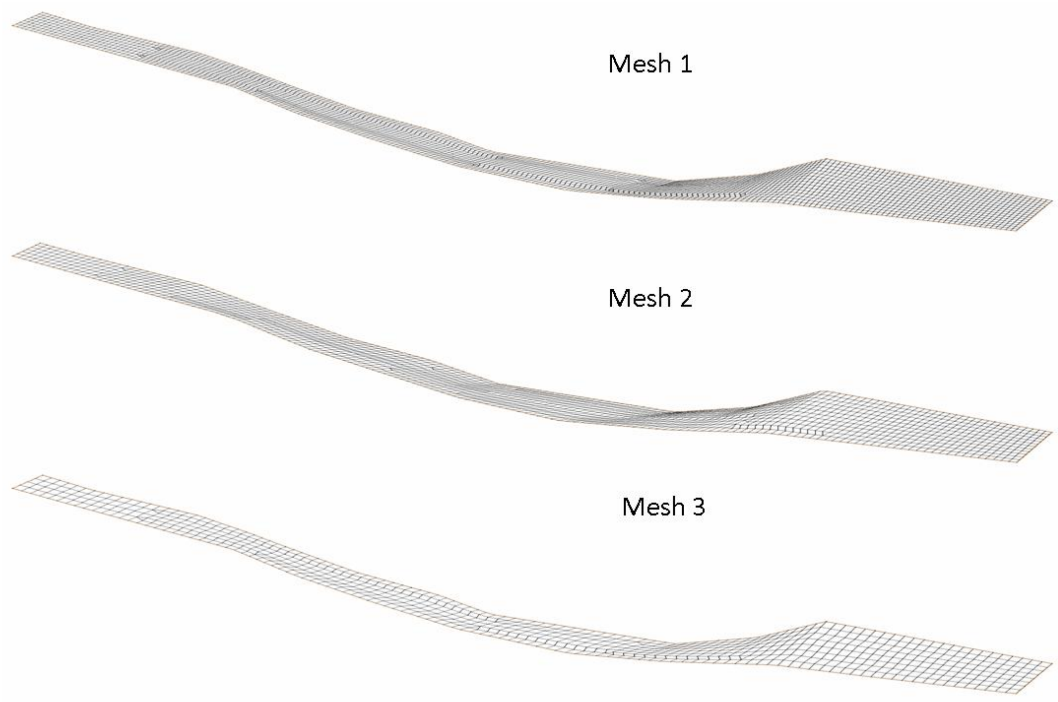

Figure 4.9: Figure of meshes used for sensitivity analysis for the Schnaitbach .

Table 4.3: Error summary for water surface elevations for the Schnaitbach

	M.A.Error (m)		R.M.Square Error (m)		# of points not estimated	
Mesh	Hydro_As-2D	SRH-W	Hydro_As-2D	SRH-W	Hydro_As-2D	SRH-W
calibrated	0.02	0.026	0.027	0.035	5	6
Mesh 1	0.028	0.04	0.039	0.05	5	6
Mesh 2	0.033	0.061	0.043	0.072	5	8
Mesh 3	0.032	0.042	0.044	0.051	5	9

courser meshes can also be used.

In addition to the calibrated mesh, Mesh 1 and Mesh 2 for Hydro_As-2D and Mesh 2 for SRH-W predicted the water surface elevations in this reach with a reasonable level of accuracy for use in habitat models.

Velocity Output

There were no velocity measurements taken in the field for comparing the measured and predicted velocity magnitudes for the two models under the different meshes utilized. Only qualitative analysis was done by comparing the velocity contours. It was assumed that

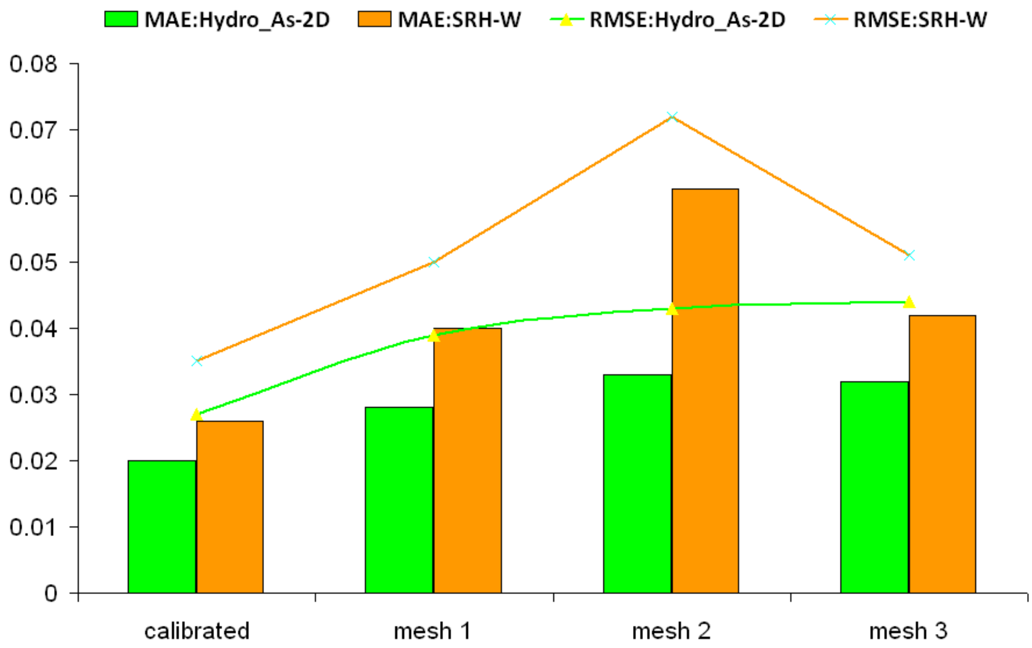

Figure 4.10: Mean absolute error and root mean square error for water surface elevation (m).

velocities predicted with the finest mesh resolution are relatively more accurate and therefore it was used as a benchmark for comparison.

From figure 4.11, it can be seen that the velocitiy outputs of Hydro_As-2D and SRH-W are highly sensitive to element sizes. Finer meshes with small elements are required to accurately capture velocity gradients. Additionally, the finer meshes gave a much more reasonable approximation of drying and wetting of elements. Using large elements in areas of rapidly changing topography will provide poor resolution of the meso-scale flow predictions. Therefore meshes with average element sizes greater than that of Mesh 2 are not recommended for this site.

Table 4.4: Maximum velocities predicted by the two models for differrent meshes (m/s)

Mesh	Hydro_As-2D	SRH-W
Calibrated	1.855	1.795
Mesh 1	1.478	1.191
Mesh 2	1.333	1.093
Mesh 3	1.253	0.942

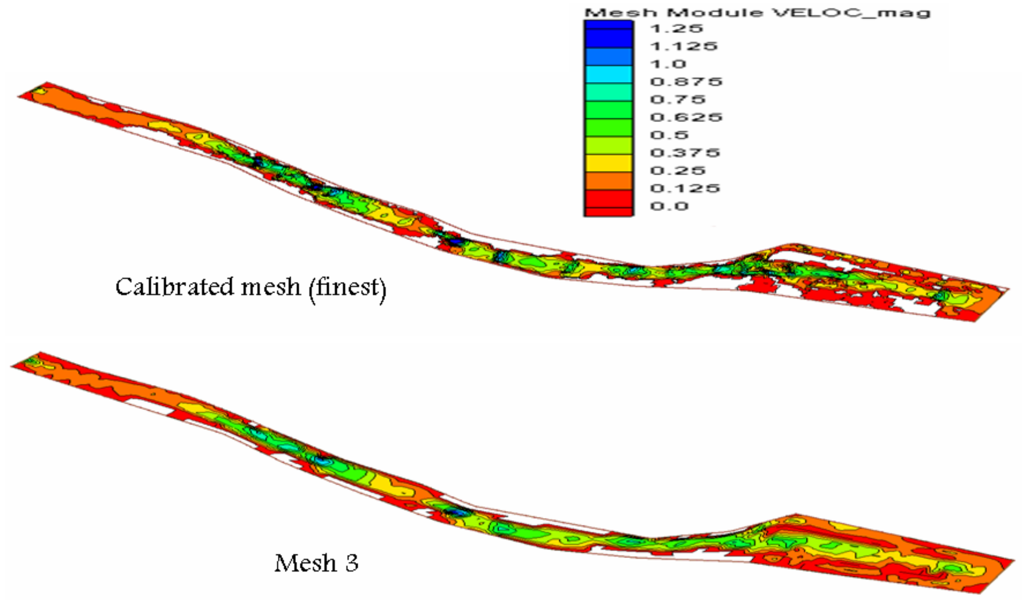

Figure 4.11: Velocity contours from Hydro_As-2D for schnaitbach (m/s).

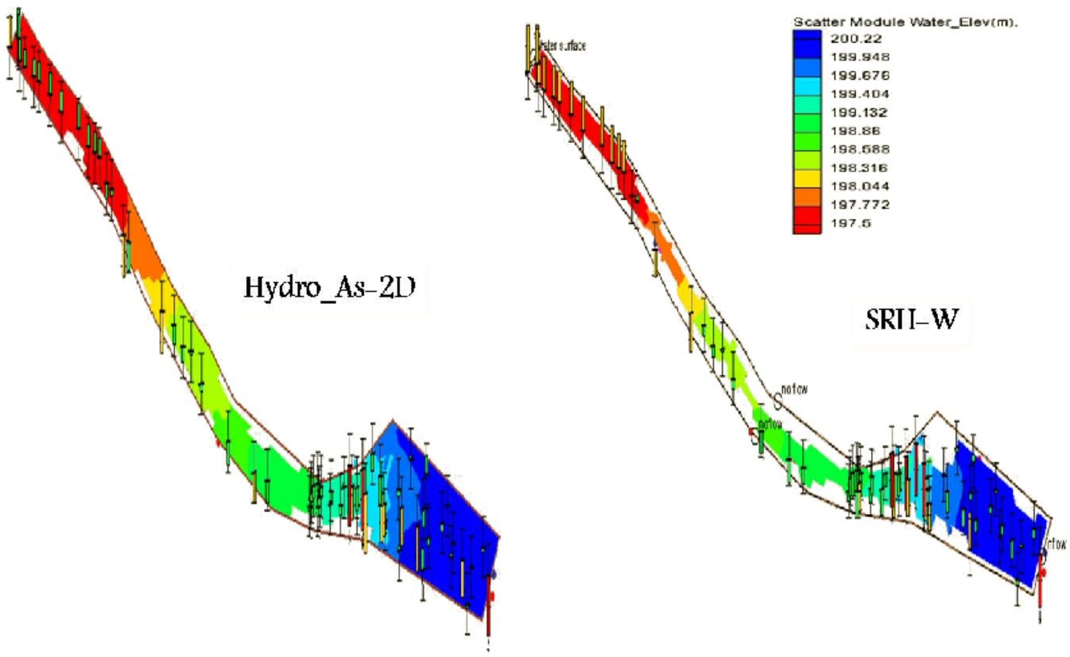

Figure 4.12: Water surface elevation outputs from Mesh 3.

Figure 4.12 shows that the drying and wetting of elements cannot be simulated accurately with coarse meshes. Hydro_As-2D under estimted and SRH-W over estimated the dry elements compared to the calibrated fine mesh.

Effects of Excluding Boulders from Bathymetery Data

Analysis of how the absence of boulders from the bathymetry data affects model outputs is given here. Model outputs from the finest mesh with boulders are compared to model outputs of the same mesh without boulders in the bathymetry. Interpolating different data sets to a specific mesh assigns different elevations to the nodes in the mesh, but keeps the number and position of the elements the same. Therefore, when two meshes with the same resolution are compared, any differences in model outputs are a result of the difference in bathymetry data. In the previous section, all the available bathymetry data was used for modeling of the reach. The bathymetry data used in this section includes only the xyz coordinates of the scatter data for the river bed. All the other model parameters of the two models remained the same as in section 4.2.3 and 4.2.4.

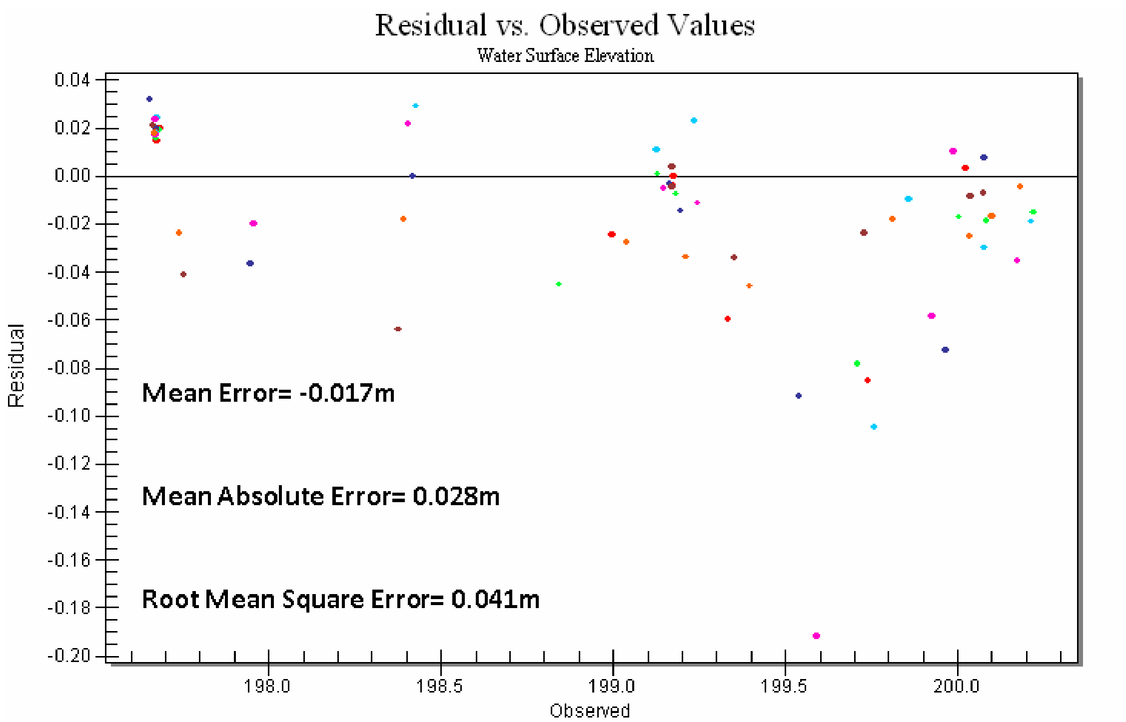

Figure 4.13: Error summary of WSE without boulders from Hydro_As-2D .

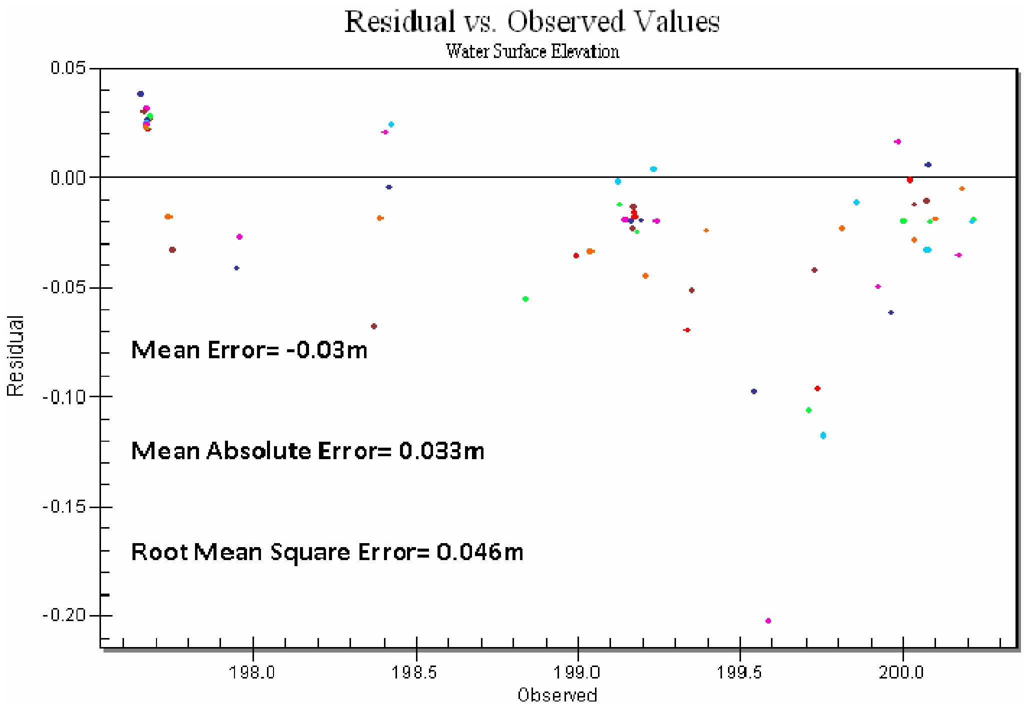

Figure 4.14: Error summary of WSE without boulders from SRH-W .

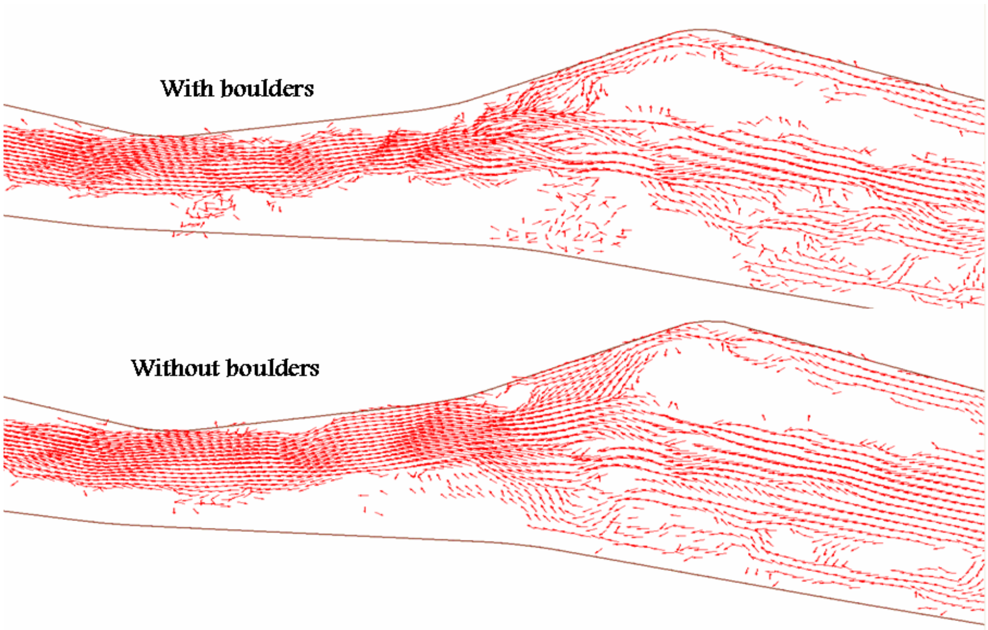

Figure 4.15: Velocity vectors with and without boulders in the bathymetry data.

Both Hydro_As-2D and SRH-W predicted the water surface elevations well even in the absence of boulders from the bathymetry data (figures 4.13 and 4.14). The presence of increased measurement density bathymetry including the boulders will result in better predictions. In studies where only the water surface elevation is the main interesting parameter (flooding), including some representative information about boulders and increasing channel bed roughness coefficients are sufficient to get reasonable model outputs.

Figure 4.15 shows that he velocity vectors predicted with and without boulders are not remotely the same. In the absence of boulders the flow remains largely parallel to the channel banks. The maximum velocity predicted in the reach is less than the maximum velocity obtained when all the bathymetry data including the boulders was used (table 4.5). Including boulders in the scatter data is important for accurate prediction of velocities and the complex flow patterns around the boulders. The steep velocity gradients, velocity shelters, and other complex flow patterns found in the immediate vicinity of the boulders cannot be modeled without incorporating boulder geometry into model's bathymetry data. Model outputs from the mesh including bathymetry data with the boulders were found to be much more representative to the flow patterns visually observed at the model site.

Table 4.5: Maximum velocity with and without boulders (m/s)

Model	Maximum Velocity With boulders	Maximum velocity without boulders
Hydro_As-2D	1.86	1.47
SRH-W	1.80	1.41

4.3 Case Study 2: Neumagen

This subchapter deals with the hydrodynamic modeling of the second case study reach. This reach was calibrated first for the SRH-W model and then the same mesh and roughness parameters were used to model the reach with Hydro_As-2D.

4.3.1 Site Description

Neumagen is a river reach in southwestern Germany. It is a 26 km long tributary of the river Moehlin and is the steepest river on the west side of the southern Black Forest. A reach of about 69 m in length was selected for this case study. The selected reach has a relatively simple bed morphology compared to the Schnaitbach. It is a straight and channelized reach with few obstructions like boulders and has two locations with man made drops. The width of the selected reach is 8.3 m at the upstream end and 8.5 m at its exit.

Figure 4.16: The Neumagen reach.

4.3.2 Data Available

Bathymetry data

Bathymetry data in the form of xyz coordinates surveyed with Lecia L-7945 total station was available both for the river bed and for the boulders and obstructions. A total of 3214 xyz coordinates were available as bathymetry data. 2775 of the bathymetry data were for the river bed and 439 point coordinates were for the boulders. Since the number of boulders in this reach was relatively few, the number of surveyed coordinates representing them was also few.

Discharge and water level

A discharge of 0.486 m^3/s was measured at the entrance as the upstream boundary condition. A water surface elevation of 999.32 m was surveyed at the exit for the downstream boundary condition. One hundred fifty (150) water surface elevation measurements were taken at different points in the reach and were used for calibration.

4.3.3 Mesh Preparation

Mesh for this reach was prepared using SMS. The path method was used for generating mesh with linear elements exactly as for the Schnaitbach. The average size of the mesh used with highest resolution was 0.237 m. Table 4.6 summarizes the statistics of the generated mesh for this reach.

Table 4.6: Statistics of mesh used to model the Neumagen reach

Number of elements	Number of nodes	Average Grid size(m)
16163	16570	0.237m

4.3.4 Modeling with SRH-W

This reach was first modeled using SRH-W. The model was calibrated by changing the Manning's roughness values so that the predicted and observed values of the water surface elevations match well. The same mesh calibrated with SRH-W was also used for modeling the reach with Hydro_As-2D.

Boundary Conditions

Total discharge through the inlet was specified as the upstream boundary condition. A discharge of 0.486 m^3/s was defined for the upstream boundary condition. The uniform-q approach was chosen for the velocity distribution at the inlet. A constant water surface elevation of 999.32 m was defined at the exit for the downstream boundary condition.

Figure 4.17: Mesh for the Neumagen.

Model Parameters

The distribution of bed roughness and viscosity has to be specified for the model area before running the model. Channel bed roughness was assigned for every element with Manning's bed roughness coefficient. The main important model parameter is the Manning's roughness coefficient. Additional input parameters used are summarized below:

- The dynamic wave solver (Type 3) was chosen as a flow solver as this deals with modeling of river reaches

- At present, unsteady simulation is used to simulate even steady state conditions and the following values were specified as unsteady simulation parameters:

  TSTART=0, for the simulation starting time in seconds

  DT (time step in seconds) =1

  NTSTEP (total number of time steps to be simulated) =5000

- A constant kinematic viscosity with a default value of 1.0e-6 was used for the molecular viscosity of water

- A depth averaged parabolic turbulence model was selected. The default value α =0.7 was used for the eddy viscosity coefficient.
- The dry bed setup was selected for the initial condition.
- No special properties within mesh zones were considered.

Model Calibration and Simulation Outputs

For this reach, 150 measured water surface elevation values were used to calibrate the model. The trial and error procedure was used where bed roughness coefficients were changed for calibration. Three roughness zones with Manning's values of n_1=0.065, n_2=0.15 and n_3=0.2 were identified as suitable final roughness values after calibrating the SRH-W model.

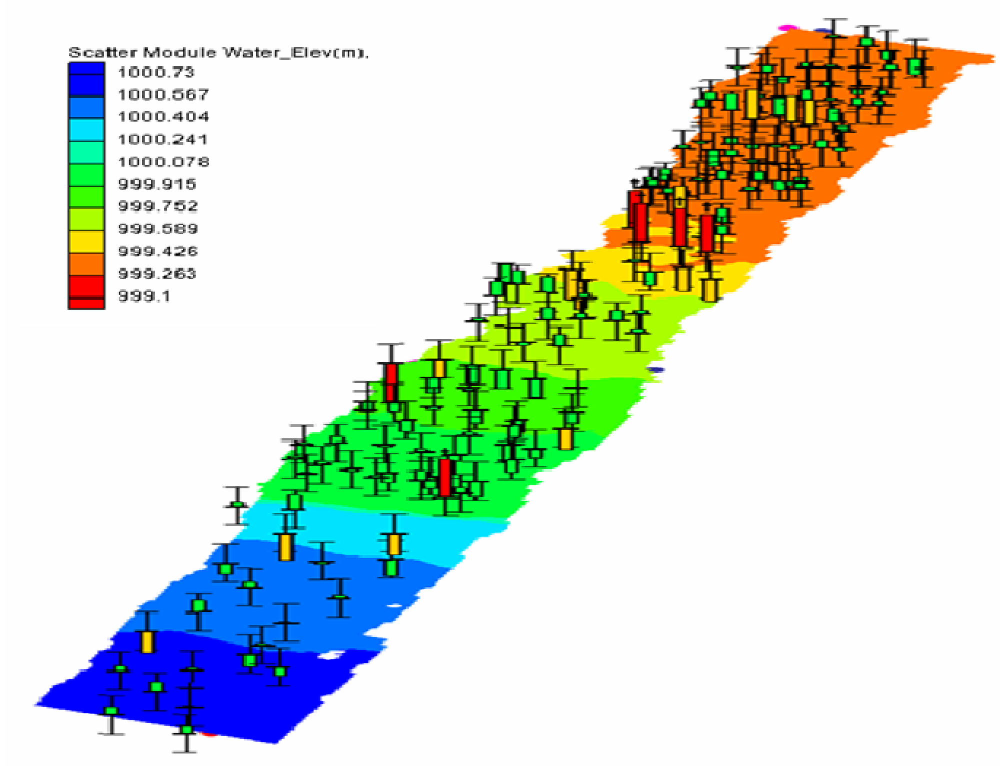

Figure 4.18: Calibration output of water surface elevation for the Neumagen with SRH-W.

Figures 4.18 and 4.19 show that SRH-W predicted the observed water surface elevations quite satisfactorily.

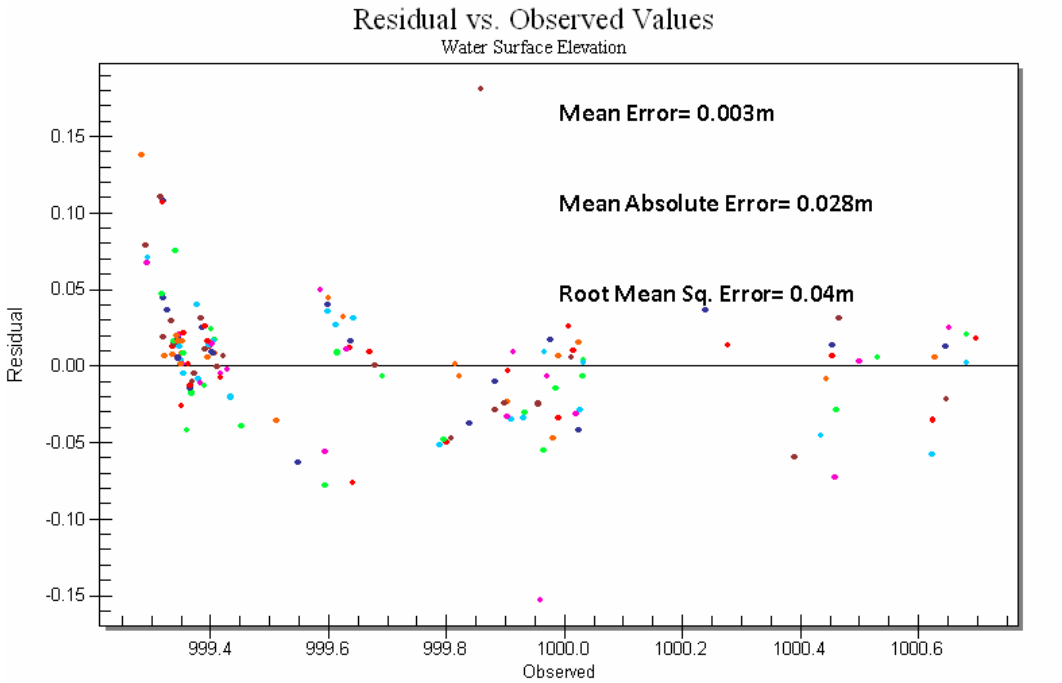

Figure 4.19: Error summary of water surface elevation for SRH-W.

Other model outputs include: water depth, velocity magnitude, Froude number, bottom shear stress, bed elevation of each mesh node.

4.3.5 Modeling Using Hydro_As-2D

Boundary Conditions

A discharge of q=0.486m^3/s was defined for the upstream boundary condition. A rating curve was given for the downstream boundary condition.

Model Parameters

Channel bed roughness value expressed as Strickler coefficient is the main important model parameter. Additional model parameters for Hydro_As-2D were taken to be the same as for the Schnaitbach reach :

- Total time = 5000 seconds with a time step of 500 seconds.

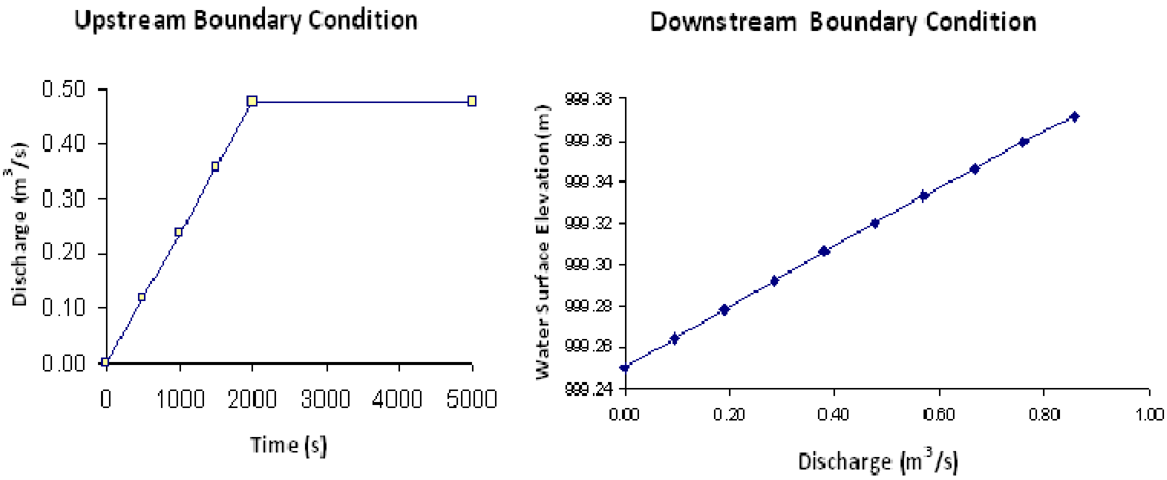

Figure 4.20: Upstream and downstream boundary conditions for the Neumagen.

- A default value of c_{μ} =0.6 for the eddy viscosity constant coefficient.
- Minimum water depth (Hmin) = 0.01 m.
- Maximum admissible magnitude of velocity (VELMAX) = 15 m^3/s.
- Minimum allowable control volume area (Amin) =1.0e-15 m^2.

Model Calibration and Simulation Outputs

The same mesh, the same bed roughness zones and bed roughness values obtained from calibration using SRH-W were used. The bed roughness coefficients obtained from SRH-W are in terms of manning's values and theses have to be converted in to strickler values. The final Strickler values used for the three roughness zones identified after calibrating the model with SRH-W are Kst_1=15.38, Kst_2=6.67 and Kst_3=5.

From the results in figures 4.21 and 4.22 it can be concluded that both SRH-W and Hydro_-As-2D predicted the observed water surface elevations quite well. The results of the two models are better and more similar than for the Schnaitbach reach. This is because the river bed morphology for this reach is not as complicated as that of the Schnaitbach reach.
The mean absolute error of simulation for the observed water surface elevations was less

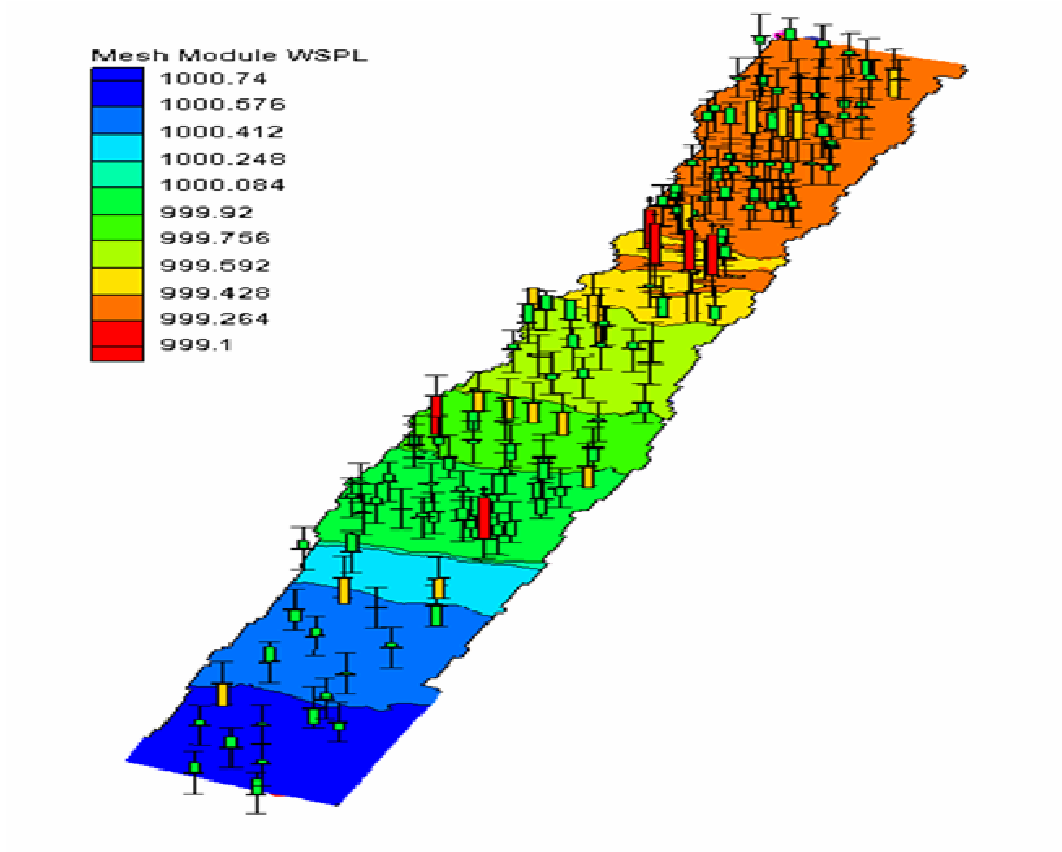

Figure 4.21: Water surface elevation output for the Neumagen with Hydro_As-2D.

than 3 cm for both models which is a good result.

4.3.6 Sensitivity Analysis for the Two Models

Effects of Different Mesh Resolutions on Model Outcomes

Three additional coarser meshes were prepared using SMS to compare the effect of mesh size on the outputs of the two models for this reach. The same roughness zones and roughness coefficients as the calibrated model were applied for all the meshes.
Table 4.7 summarizes the properties of the different meshes prepared.

Here it is worth noticing that the size of the optimal mesh depends on the complexity of the reach to be modeled and the nature of the problem at hand required to be solved.

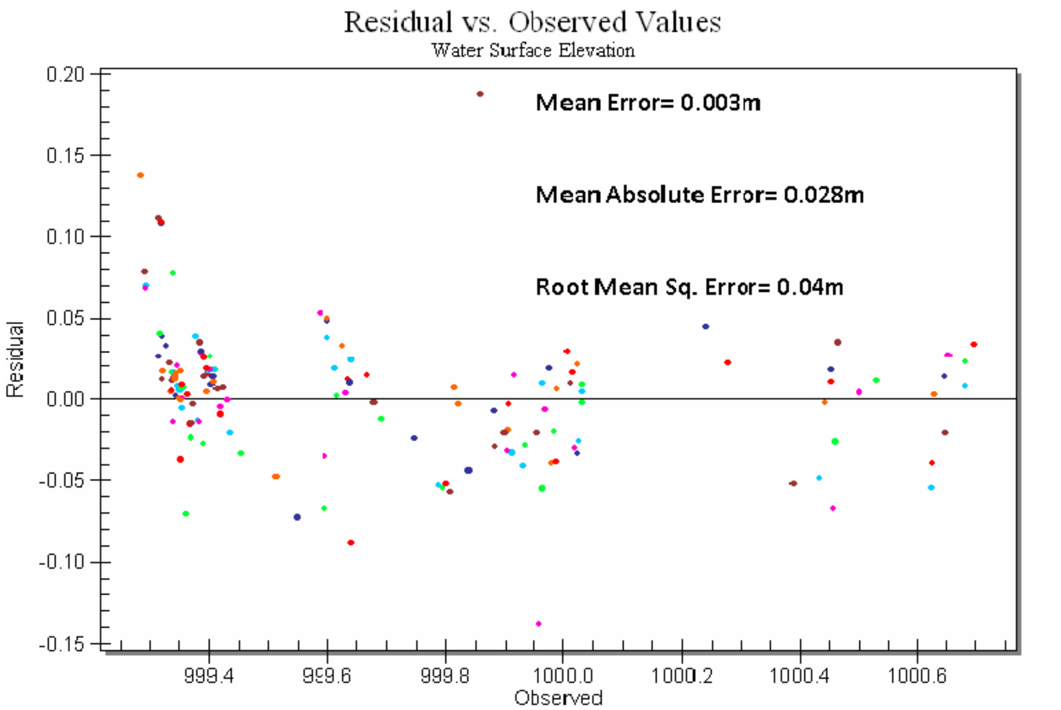

Figure 4.22: Error summary of water surface elevation for Hydro_As-2D.

Table 4.7: Different mesh resolutions used for the Neumagen

Mesh	Calibrated Mesh	Mesh 1	Mesh 2	Mesh 3
Total number of elements	16163	3940	1793	985
Total number of nodes	16570	4140	1928	1086
Average distance between vertices (m)	0.237	0.478	0.708	0.952
Minimum distance between vertices (m)	0.206	0.414	0.613	0.892
Maximum distance between vertices (m)	0.267	0.523	0.776	1.046

Table 4.8: Error summary for water surface elevations for Neumagen

Meshes	Mean Absolute Error (m)		R.M Square Error (m)		# of points not estimated	
	SRH-W	Hydro_As-2D	SRH-W	Hydro_As-2D	SRH-W	Hydro_As-2D
Calibrated	0.028	0.028	0.04	0.04	3	0
Mesh 1	0.027	0.027	0.04	0.041	4	1
Mesh 2	0.03	0.029	0.042	0.045	9	1
Mesh 3	0.034	0.031	0.046	0.044	12	1

The results in table 4.8 and figure 4.24 show that both SRH-W and Hydro_As-2D predicted the observed water surface elevations reasonably. SRH-W is more sensitive to mesh resolution than Hydro_As-2D and requires a finer mesh. Additionally, looking at the number of observed

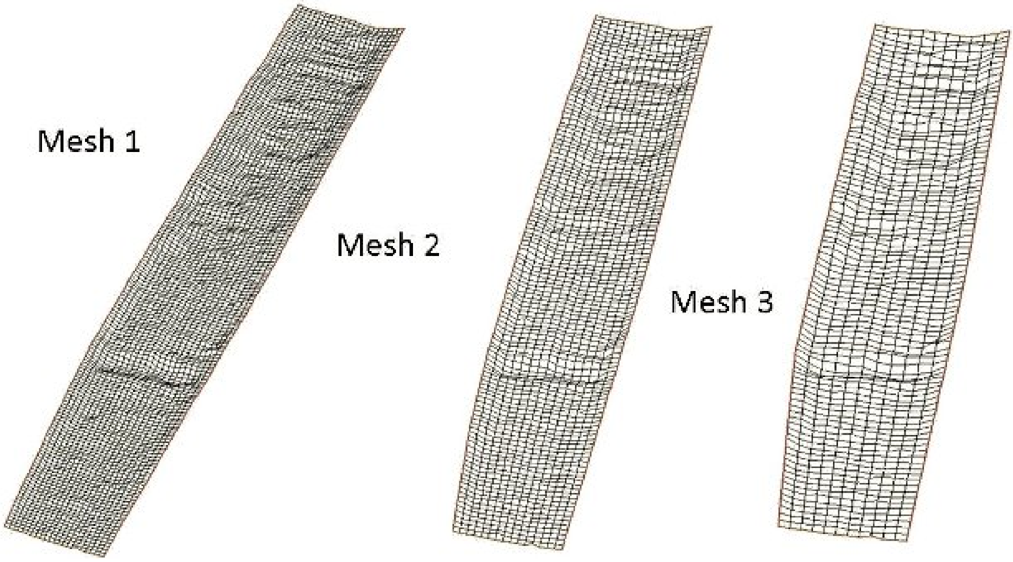

Figure 4.23: Meshes used for sensetivity analysis for the Neumagen.

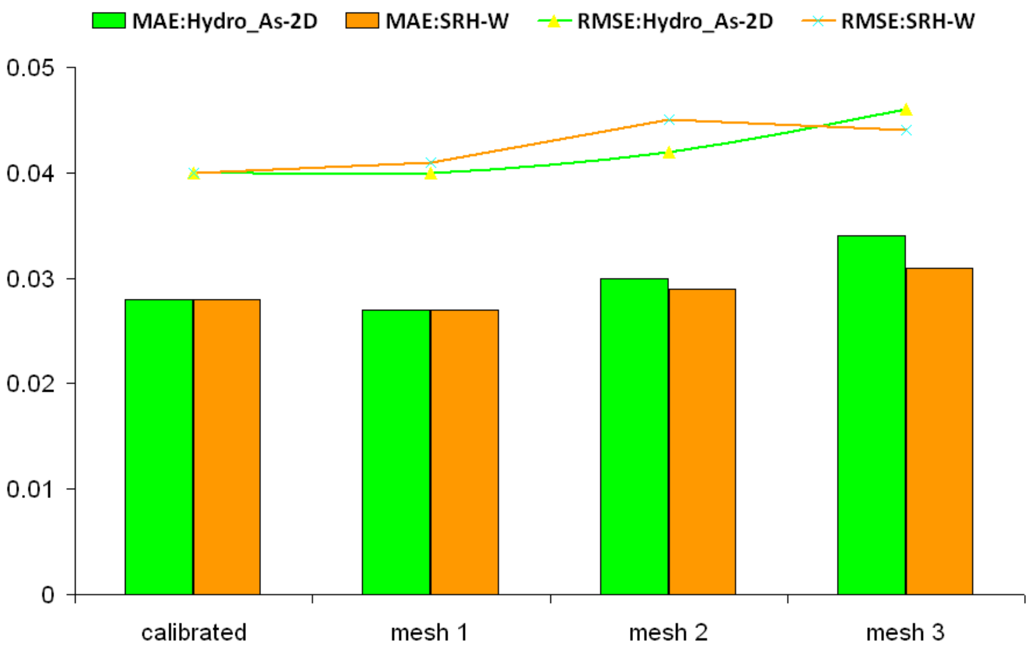

Figure 4.24: Mean Absolute Error(MAE)and Root Mean Square Error for WSE (m).

water surface elevations which were not estimated by the two models under different mesh sizes Hydro_As-2D was more consistent in representing the dry and wet areas than SRH-W. The results of the two models are more similar for this reach than the Schnaitbach reach.

This is because of the less complex bed morphology the few boulders.

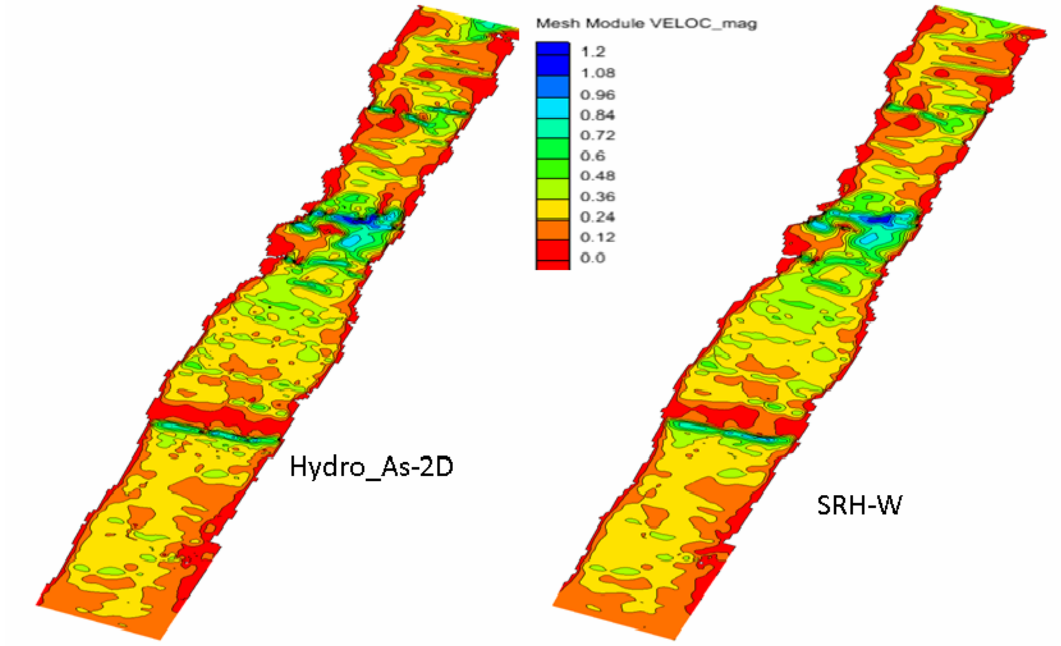

Figure 4.25: Velocity contours for the finest mesh (m/s).

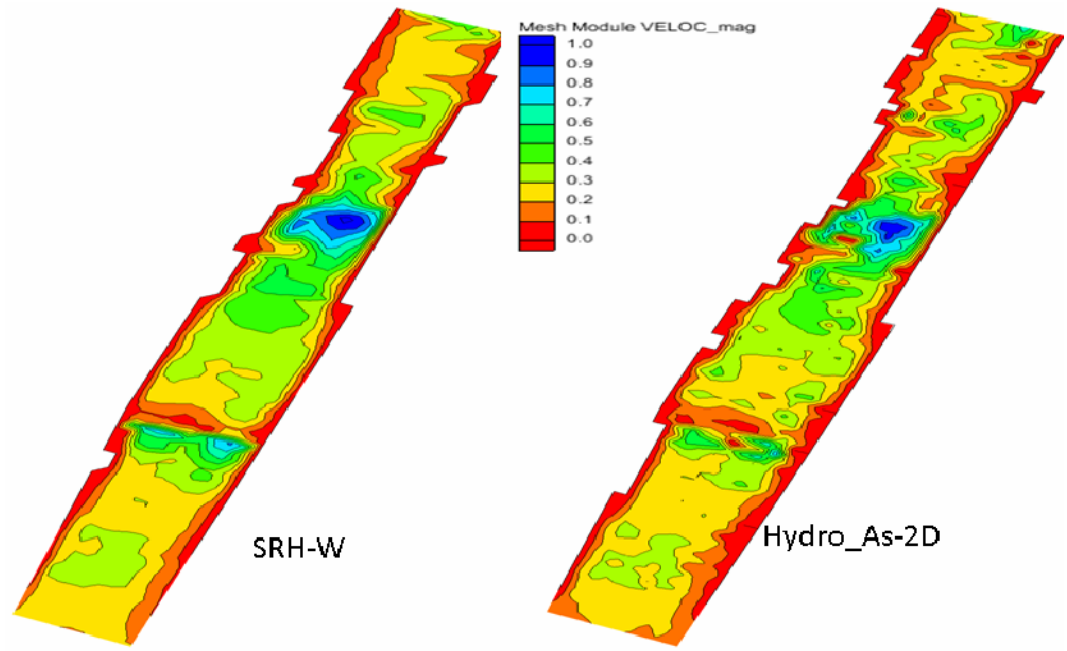

Figure 4.26: Velocity contours for mesh 3 (m/s).

Velocity Outputs

The finer meshes were able to reproduce the complex velocity patterns (figure 4.25). But for coarser meshes, there is the effect of averaging and the velocity heterogeneities cannot be simulated as shown in figure 4.26. The responses of the two models were more or less similar for varying mesh resolutions. There was no measured velocity data for this reach and thus only a qualitative comparison could be carried out for the velocity outputs. Since this reach has a relatively simple morphology, the results for the coarser meshes were not far off from the fine mesh results.
It was found that Mesh 2 gave reasonable model output, and thus a similar resoluton is recommended when modeling rivers having similar properties as this reach.

Table 4.9: Maximum velocities predicted by the two models for the Neumagen reach (m/s)

Mesh	Hydro_As-2D	SRH-W
Calibrated	1.170	1.299
Mesh 1	1.139	1.191
Mesh 2	1.069	1.093
Mesh 3	1.043	0.942

SRH-W computed slightly higher velocities than Hydro_As-2D for the for the calibrated mesh, however there is no trend for either model regarding higher or lower velocities for the other meshes. Table 4.9 summarizes the maximum velocities computed by the two models for the different meshes.

Effects of Excluding Boulders from Bathymetery Data

In this subsection, the effect of excluding boulders from the bathymetry data on model outputs was investigated. The finest calibrated mesh was used. The predicted water surface elevations for the two models are shown in the figures 4.27 and 4.28.

The results in figures 4.27 and 4.28 show that the water surface elevations were underesti-

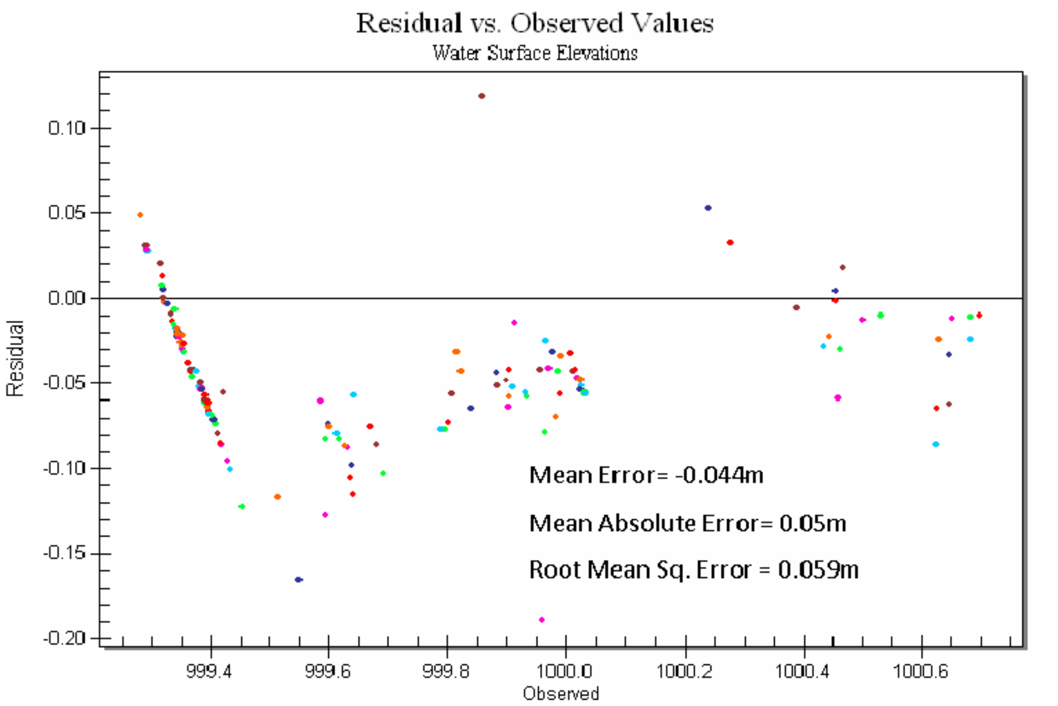

Figure 4.27: Error summary of WSE without boulders from SRH-W for the Neumagen.

mated by the two models when the boulders were excluded from the bathymetry data even if there were only very few boulders in this reach. The water surface elevations can be approximated relatively well by increasing the roughness of the bed. If the interest of the problem at hand is determining accurately only water surface elevations but not velocity patterns, including only some of the boulders and increasing the bed roughness would result in good model agreement with observed water surface data.

But for accurate determination of the complex flow patterns around the boulders which is crucial for aquatic habitat studies, including the boulders is required. The maximum velocities predicted by the two models without the boulders were greater than the maximum velocities predicted with the boulders. The reverse was true for the first case study reach. This is probably because of the two drops which exist in this reach.

The velocity vectors are a bit different (figure 4.29). The difference is not as pronounced as in the case of the Schnaitbach reach because the number of boulders for this reach is quite few.

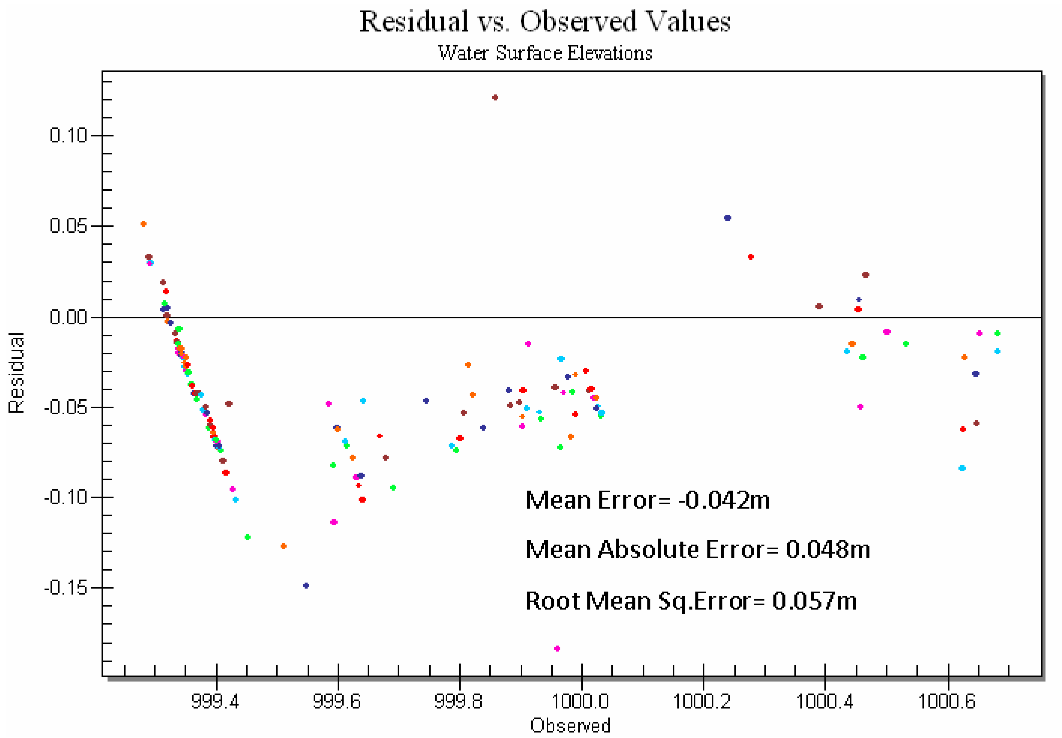

Figure 4.28: Error summary of WSE without boulders from Hydro_As-2D for the Neumagen .

Table 4.10: Maximum velocity with and without boulders (m/s)

Model	Maximum velocity with the boulders	Maximum velocity without the boulders
Hydro_As-2D	1.17	1.26
SRH-W	1.3	1.37

4.4 Case Study Three: Gurgler Ache

4.4.1 Site Description

The third case study was carried out on the Gurgler Ache. It is an alpine reach located in Austria with complicated bed morphology. It is a relatively wide reach with pimarily gravel substrate and includes a large number of boulders. The modeled reach has a length of 39 m and a width of 15.4 m at upstream and 13.7 m downstream. This reach was difficult to calibrate because of the low number of surveyed bathymetry data.

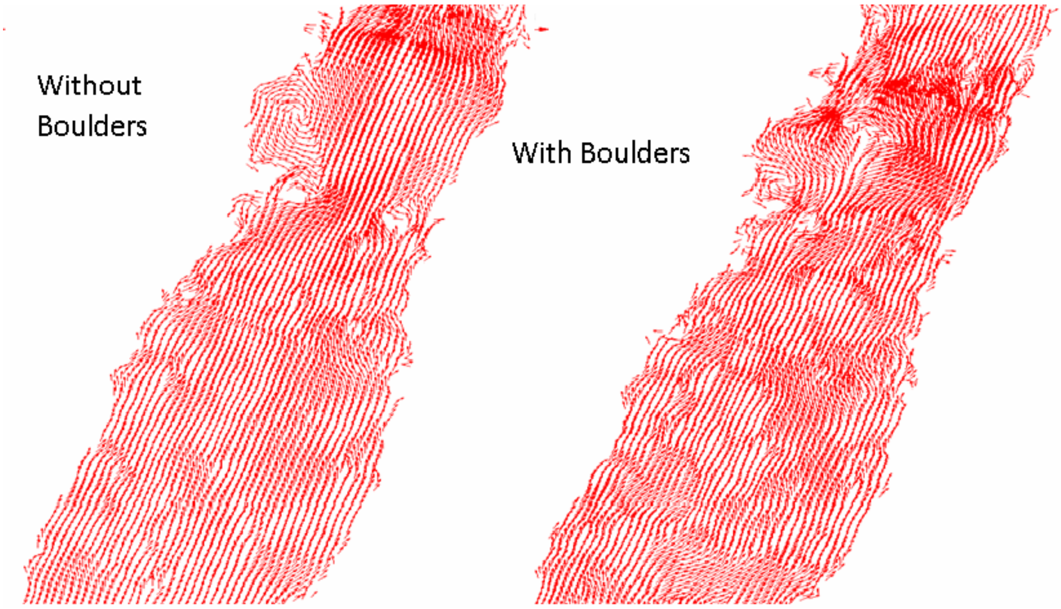

Figure 4.29: Velocity vectors with and without boulders for the Neumagen.

Figure 4.30: The Gurgler Ache investigation reach.

4.4.2 Data Available

Bathymetry data for the river bed and for the boulders in the form of xyz coordinates were provided. Measured discharge and water surface elevations were also available.

Bathymetry data

1474 xyz coordinates describing the river bed and 55 xyz coordinates for the boulders were available. The number of surveyed coordinates for the boulders was quite few and this created difficulty for accurate representation of the river morphology.

Discharge and water level

This reach was modeled for a discharge of 3 m^3/s. The average water surface elevation measured at exit for the same discharge was 97.05 m. Seventy seven (77) water surface elevations taken at different points in the reach were available as calibration data.

4.4.3 Mesh Preparation

SMS was used for mesh generation. The patch method was utilized for the element type. The mean grid size for the calibrated mesh was 0.229 m.

Table 4.11: Mesh used to model Gurgler Ache

Number of elements	Number of nodes	Average grid size (m)
19737	20001	0.229

4.4.4 Modeling Using SRH-W

This reach was first calibrated for SRH-W model. Then the same mesh was used to model the reach with Hydro_As-2D.

Boundary Conditions and Model Parameters

A discharge of 3 m^3/s with constant-q method for velocity distribution was specified at inlet for upstream boundary condition. A constant water surface elevation of 97.05 m was defined at exit for the downstream boundary condition. Channel bed roughness coefficient was changed to calibrate the model. All the other model parameters were set the same as the previous two reaches.

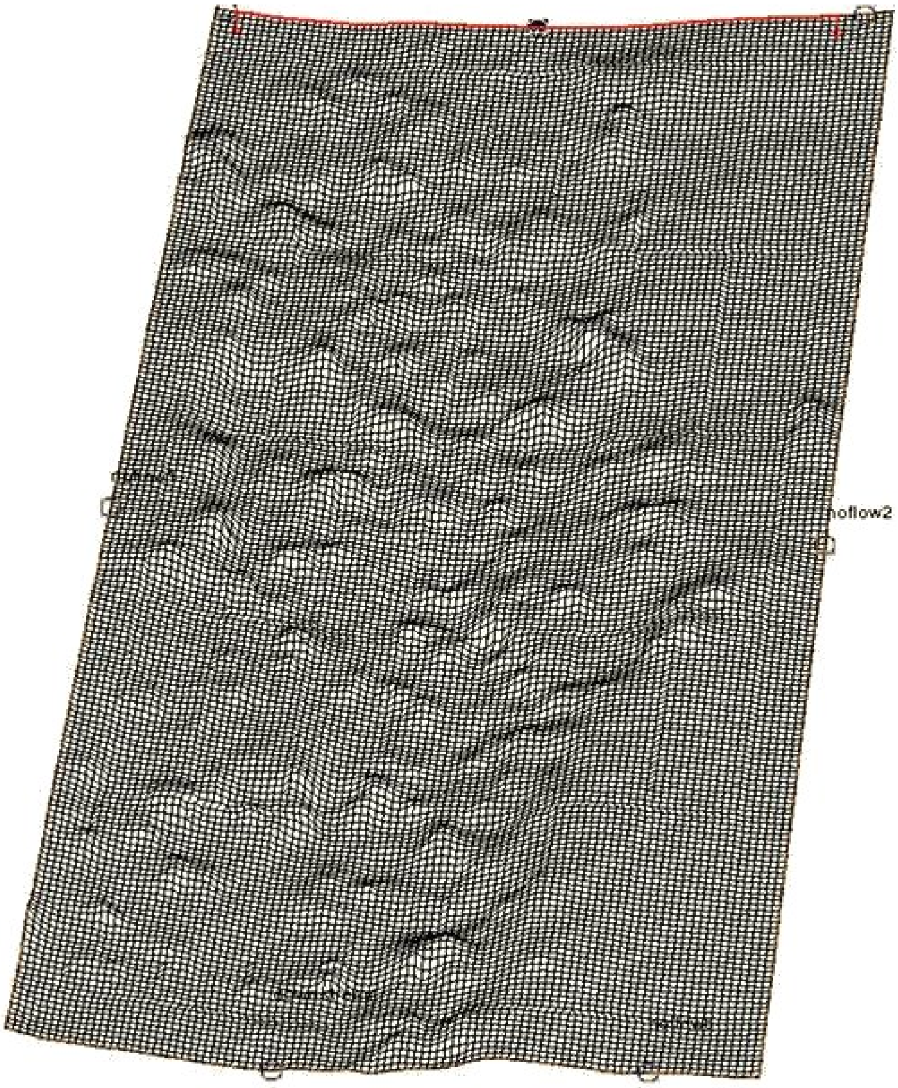

Figure 4.31: Mesh for the Gurgler Ache.

Model Calibration and Simulation Outputs

The model was calibrated by changing the bed roughness coefficients. The trial and error procedure was applied for calibration. Two roughness zones with Manning's bed roughness coefficients n_1=0.07 and n_2=0.09 were obtained as final roughness values.

Figures 4.32 and 4.33 show the calibration outputs of the SRH-W model. The results of calibration for this reach were not as good as the other two reaches. The error was high especially near the upstream end. This might be because there was not sufficient bathymetry data describing the river bed morphology well especially the boulders and other flow obstructions. The flow pattern is also complex in this which made calibration difficult. The other reason might be the accuracy of measurement during surveying.

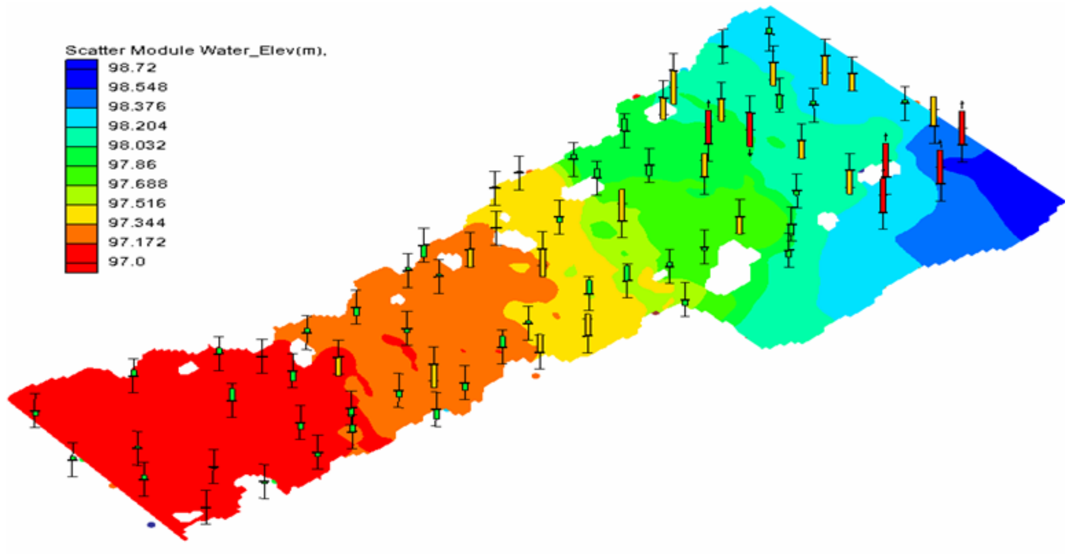

Figure 4.32: Calibration output of water surface elevation for the Gurgler Ache using SRH-W.

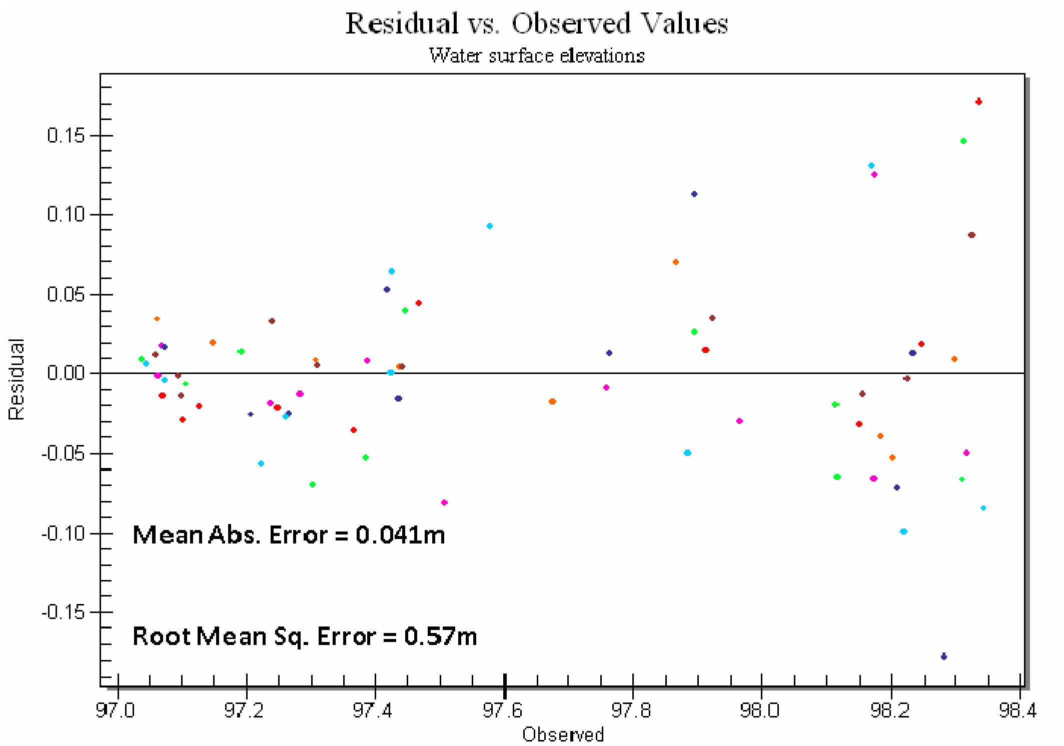

Figure 4.33: Error summary for water surface elevation outputs from SRH-W.

4.4.5 Modeling Using Hydro_As-2D

The same mesh and bed roughness coefficients obtained after calibrating using SRH-W model was used for modeling of the reach with Hydro_As-2D.

Boundary Conditions and Model Parameters

The upstream boundary condition was specified as the discharge versus time and a rating curve was specified for the downstream boundary condition. Channel bed roughness was expressed in terms of Strickler values. All the other model parameters were set the same as the previous two case study reaches.

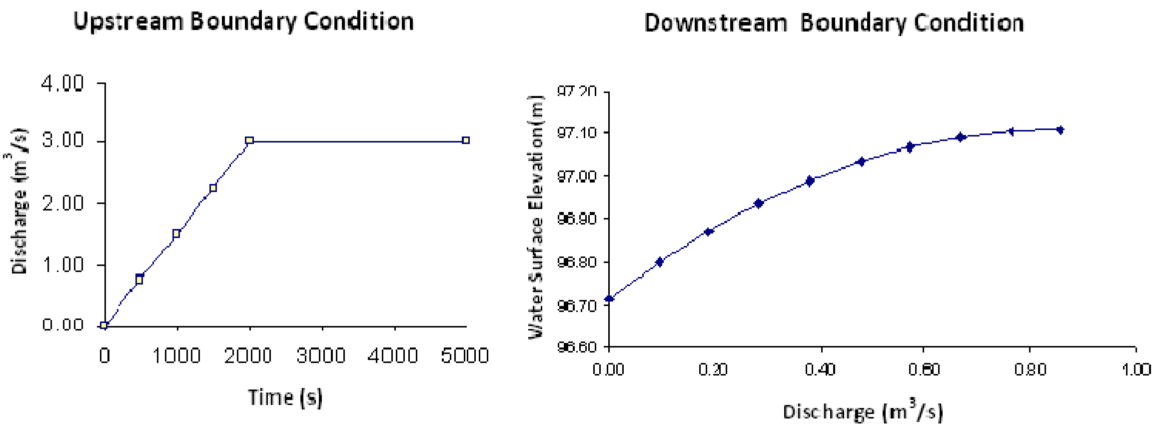

Figure 4.34: Upstream and downstream boundary conditions for the Gurgler Ache.

Model Calibration and Simulation Outputs

The final Strickler values used for the two roughness zones identified after calibrating the model with SRH-W were Kst_1=14.28 and Kst_2=11.11.

The results show that the performance of the two models is more or less the same in predicting the observed water surface elevations (figures 435 and 4.36). The mean absolute error of calibration was about 5 cm for the water surface elevations.

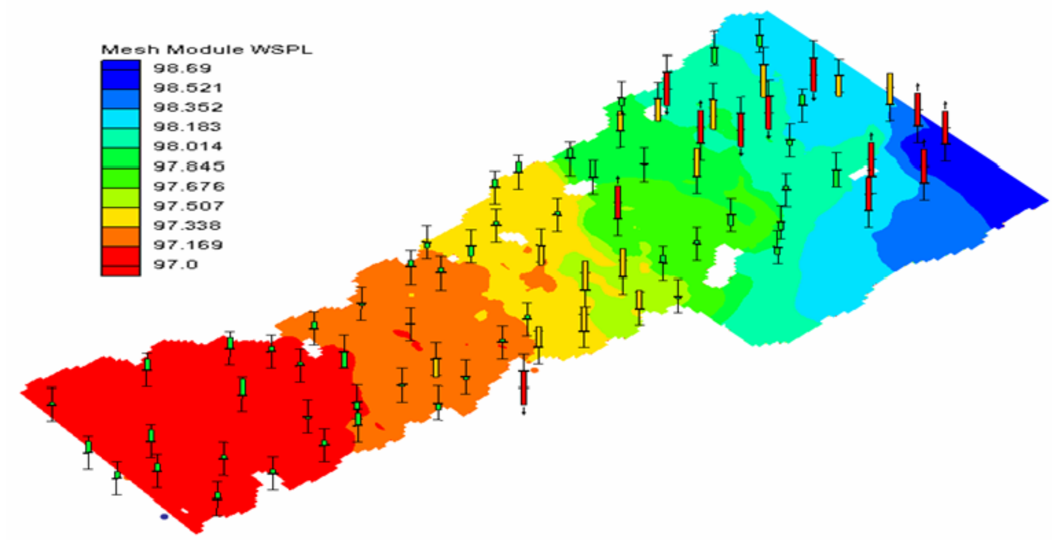

Figure 4.35: Water surface elevation output for the Gurgler with Hydro_As-2D.

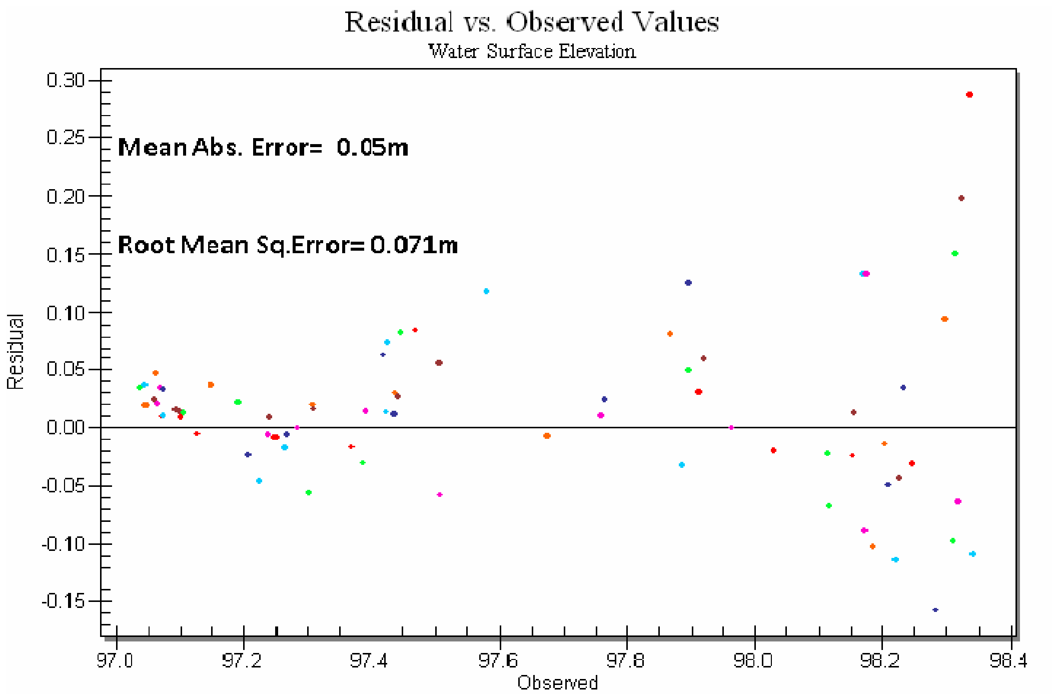

Figure 4.36: Error summary for water surface elevation outputs from Hydro_As-2D.

4.4.6 Sensitivity Analysis

For this reach, the sensitivity analysis was done to investigate the effects of different mesh resolutions on model outcomes. Since the number of bathymetry data identified as boulder was very few, no investigation was done on the effect of excluding boulders from the bathymetry data.

Effects of Mesh Resolutions on Model Outcomes

Three additional coarse meshes were prepared using SMS for this reach. Table 4.12 summarizes the statistics of all the meshes prepared for this reach.

Table 4.12: Different mesh resolutions used for the Gurgler Ache

Mesh	Calibrated Mesh	Mesh 1	Mesh 2	Mesh 3
Total number of elements	19737	5160	2442	1290
Total number of nodes	20001	5305	2541	1365
Average distance between vertices (m)	0.229	0.447	0.650	0.892
Minimum distance between vertices (m)	0.199	0.361	0.564	0.763
Maximum distance between vertices (m)	0.265	0.494	0.708	0.980

The same roughness coefficients and other model parameters as the finest mesh (calibrated mesh) were specified for all the three additional meshes.

Table 4.13: Error summary for water surface elevations for the Gurgler Ache

Meshes	Mean Absolute Error(m)		R.M Square Error(m)		# of points not predicted	
	SRH-W	Hydro_As-2D	SRH-W	Hydro_As-2D	SRH-W	Hydro_As-2D
Calibrated	0.041	0.05	0.057	0.071	5	1
Mesh 1	0.044	0.049	0.061	0.072	9	3
Mesh 2	0.055	0.053	0.070	0.075	17	3
Mesh 3	0.058	0.055	0.073	0.077	19	5

The results of the sensitivity analysis show that as mesh resolution decreases model outputs deteriorate as indicated in table 4.13 and figure 4.38. SRH-W requires finer meshes than Hydro_As-2D. To get accurate predictions of the water surface elevations using SRH-W,

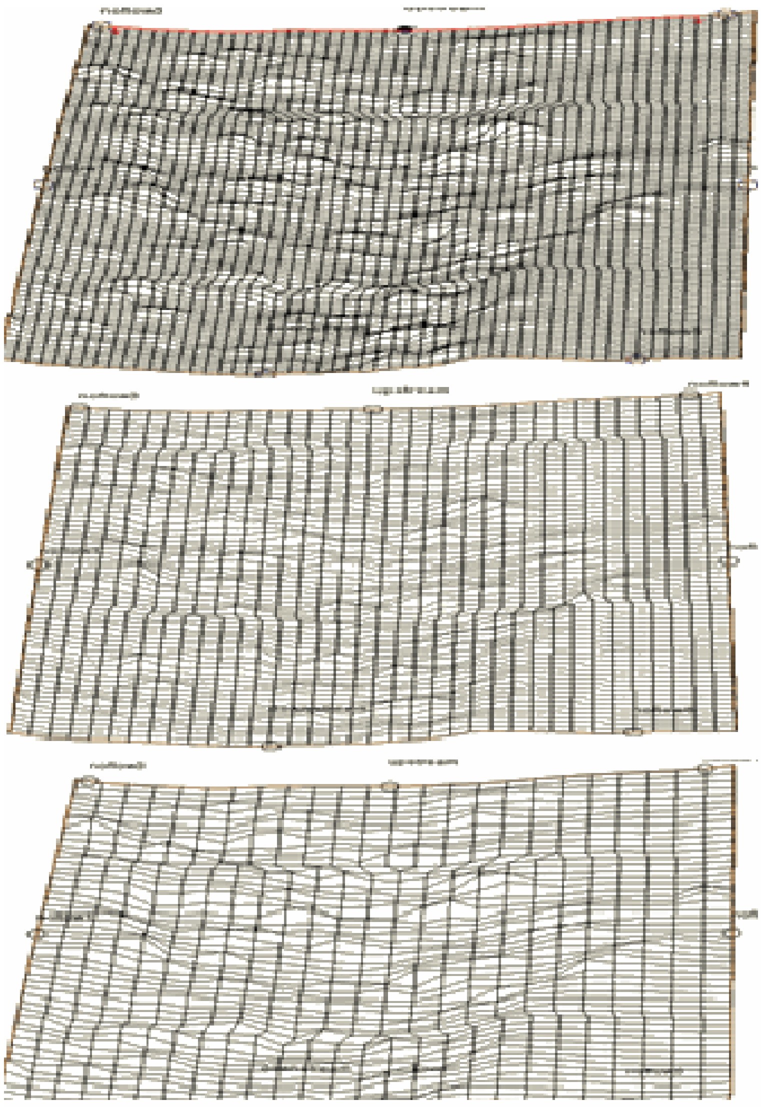

Figure 4.37: Figure of meshes used for sensetivity analysis for Gurgler Ache .

meshes coarser than Mesh 1 are not recommended for reaches with similar bed morphology and flow characteristics as the Gurgler Ache. Additionally, for coarser meshes the numbers of observed but unpredicted water surface elevations from SRH-W are quite significant for Meshes two and three. Nineteen observed water surface elevations out of seventy seven were not predicted for Mesh 3 by SRH-W. This also shows that fine meshes are required for accurate modeling of dry and wet cells.

Computed patterns of flow velocities were also found to be heavily dependent on mesh size

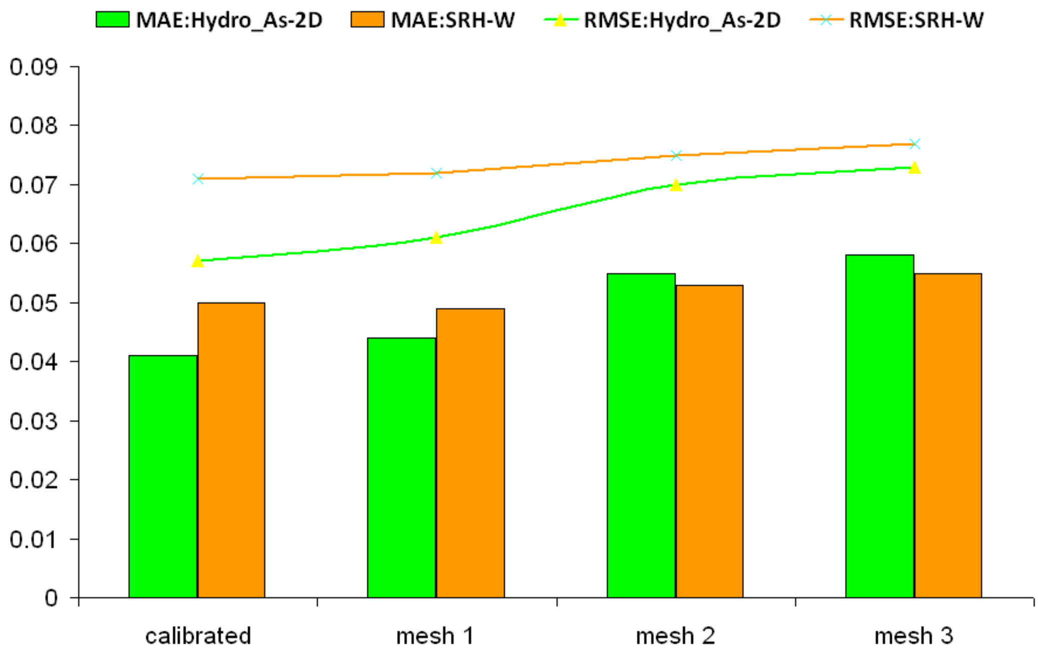

Figure 4.38: Mean absolute error and root mean square error for WSE for all meshes (m).

as shown in figures 4.39 and 4.40. For habitat studies, the flow velocity is an important parameter. The maximum velocities computed using coarse meshes are less than those computed by the finer meshes (table 4.14). To get accurate spatial resolution of flow velocities and to determine the drying and wetting of elements accurately fine meshes are required.

Table 4.14: Maximum velocities predicted by the two models for Gurgler Ache reach (m/s)

Mesh	SRH-W	Hydro_As-2D
Calibrated	1.95	2.193
Mesh 1	1.87	2.040
Mesh 2	1.92	1.74
Mesh 3	1.84	1.68

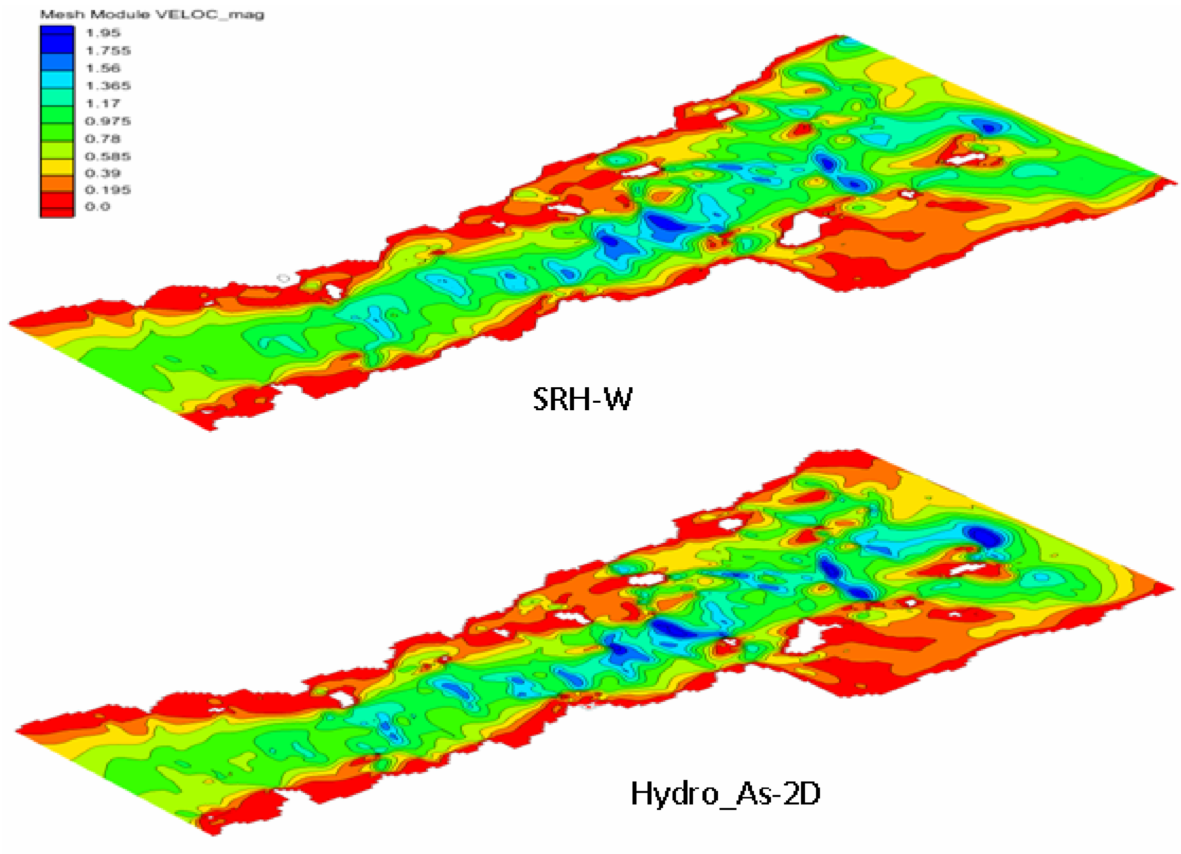

Figure 4.39: Velocity contours for the finest Mesh for the Gurgler Ache (m/s).

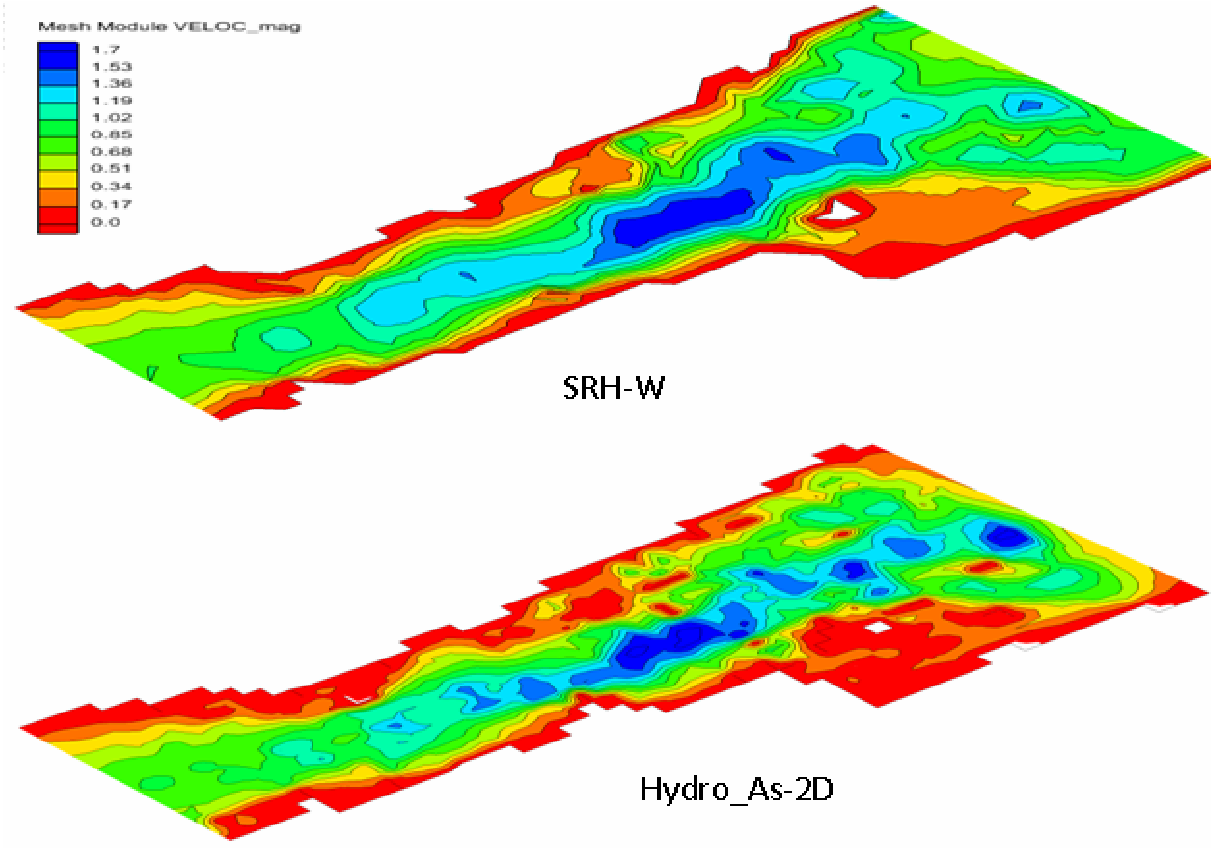

Figure 4.40: Velocity contours for Mesh 3 for the Gurgler Ache (m/s).

5 Comparison of the Two Models

5.1 Introduction

In this chapter the comparison of all simulation outputs of the two models for the three case study reaches is performed. Model outputs of the finest mesh for each reach which gave best results were used. The two models were compared with respect to their water surface elevation, water depth, velocity, number of dry and wet cells and Froude number distribution. Additionally, the computation time required, cost and user friendliness of the models were considered as comparison criteria.

5.2 Water Surface Elevation and Water Depth Outputs

In the previous chapter, it was seen that both Hydro_As-2D and SRH-W predicted the observed water surface elevations quite well. The computation error was less for the Schnaitbach reach where there was enough bathymetry data and the Neumagen reach where there were enough bathymetry data and the bed morphology was relatively simple. Accuracy of Gurgler Ache reach was less than for the other two. Figure 5.1 below shows the water surface elevation estimated by Hydro_As-2D minus the water surface elevation computed by SRH-W.

Figure 5.1 shows the difference between the water surface elevations computed by the two models. The sorted deviations were used so that the maximum and minimum differences

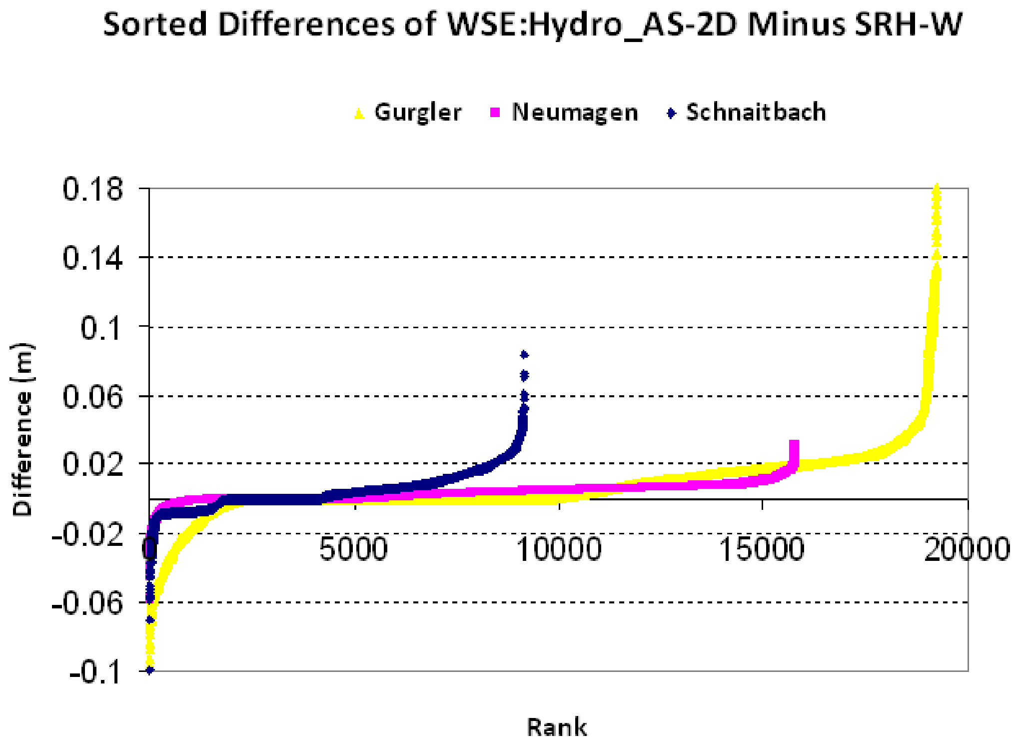

Figure 5.1: Differences between the water surface elevations computed by the two models.

could be clearly seen. From the graph it can be seen than the simulation outputs of the water surface elevations of the two models are quite comparable. There was a difference in the number of computed dry cells and those cells were not taken in to account for this comparison. No general trend of over or under estimation of the water surface elevations by one of the models was observed for all the three reaches. Hydro_As-2D computed a bit higher water surface elevations for most elements. The difference is less for Neumagen reach and high for the Gurgler Ache reach.

The percentage of cells where Hydro_As-2D computed higher or lower values of the water surface elevations is summarized for all the reaches in table 5.1.

Water Depth

Water depth is water surface elevation minus river bed elevation. To compare the water depths computed by the two models, the frequency and the cumulative frequency distributions of the water depths predicted by the two models for the Schnaitbach and Gurgler

Table 5.1: Percentage of elements where the water surface elevations computed by Hydro_As-2D as compared to SRH-W

Reach	higher	equal	lower
Schnaitbach	50.1	21.9	19.8
Neumagen	64.9	23.9	8.9
Gurgler Ache	48.9	46.1	12.1

reaches were drawn. A frequency analysis is usually done to obtain insight into how often a certain depth occurs. The frequency of a particular observation is the number of times the observation occurs in the data. A frequency distribution shows the number of observations falling into each of several ranges of values. The cumulative frequency distribution is the sum of the frequencies of all points below and including the current point. It is a summary set of data showing the frequency (or number) of values or equal to the upper class limit of each class. From figures 5.2 and 5.3 it can be concluded that the distributions of the water depths computed by the two models are reasonably identical for both reaches. The frequency distributions of the computed water depth for the Neumagen reach were also very comparable. This implies that the water depths predicted by the two models are quite similar.

5.3 Computed dry and wet cells

The number of dry cells computed by the two models was different for all the three reaches. In Hydro_As-2D a minimum water depth is specified to determine whether a particular cell is dry or wet. If the water depth in an element is less than 1cm then the cell is assumed to be dry. There was no criterion available to be specified by the user in SRH-W for drying and wetting. SRH-W computed more dry cells than Hydro_As-2D in all the three reaches (table 5.2). This might be because it uses a more conservative approach for drying and wetting. The result for the Schnaitbach reach from SRH-W resembles more the situation visually observed on the field during surveying.

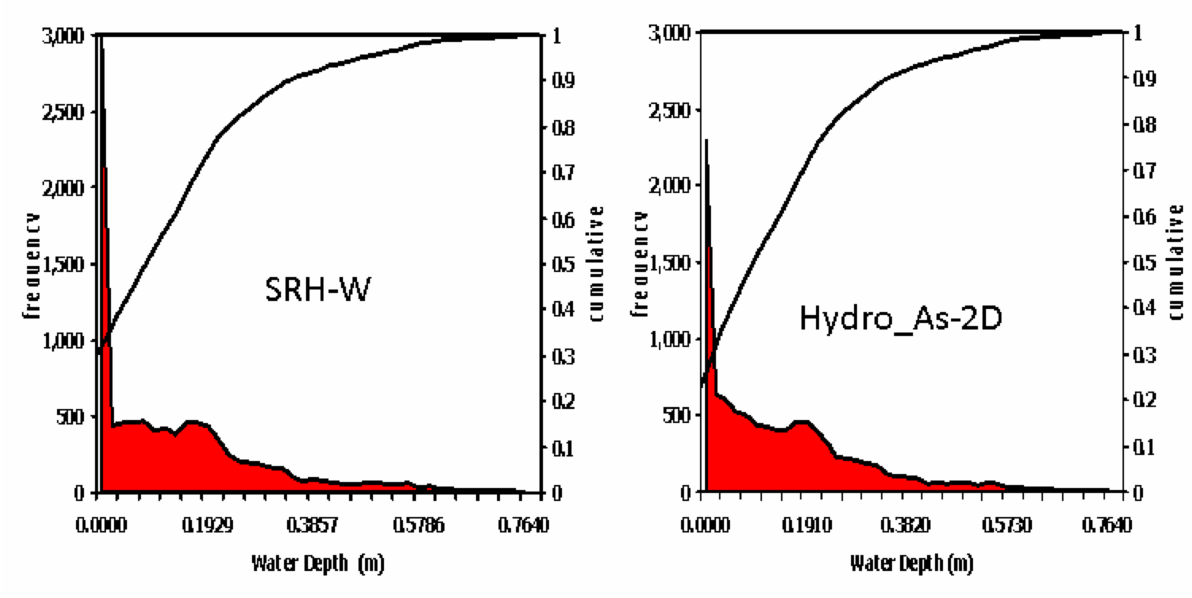

Figure 5.2: Depth distribution for the Schnaitbach.

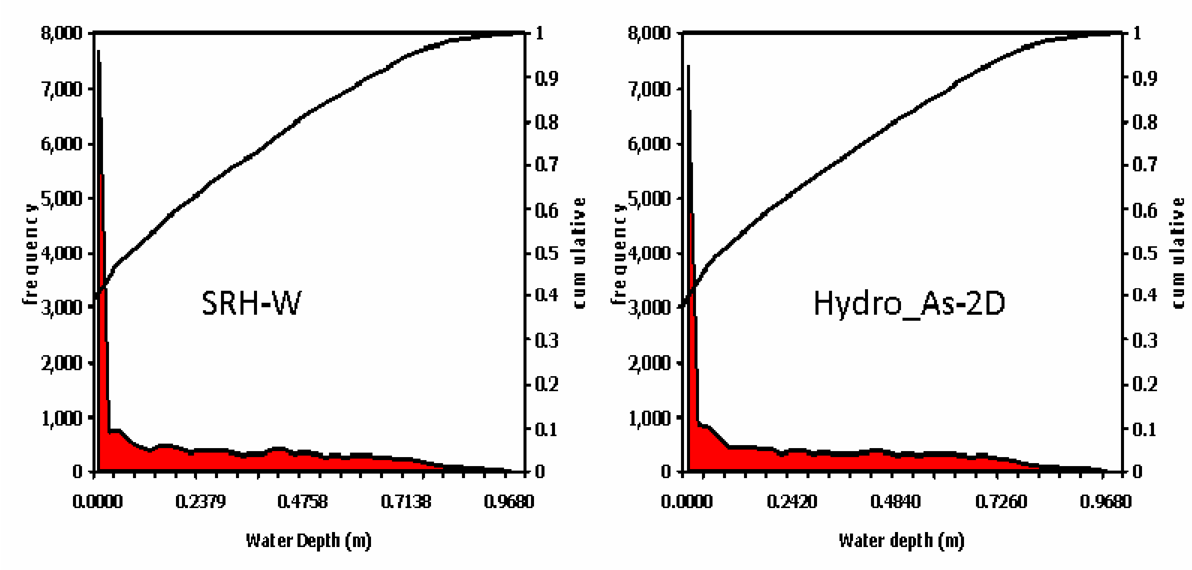

Figure 5.3: Depth distribution for the Gurgler Ache.

Table 5.2: Number of dry and wet elements from the two models

Reach	Number of dry cells		Number of wet cells	
	SRH-W	Hydro_As-2D	SRH-W	Hydro_As-2D
Schnaitbach	2985	2196	6980	7769
Neumagen	3504	3125	12659	13038
Gurgler Ache	7681	7378	12056	12359

5.4 Velocity Comparison

This section compares the velocities computed by the two models. There was not any measured velocity data for all the reaches. Only comparison of velocity magnitudes computed by the two models was done. The sorted velocity differences are drawn for the Schnaitbach reach in showing the maximum deviations between the two models. The spatial distribution of the velocity output of Hydro_As-2D minus the velocity output of SRH-W are also shown for Schnaitbach and Gurgler Ache reaches with figures 5.5 and 5.6.

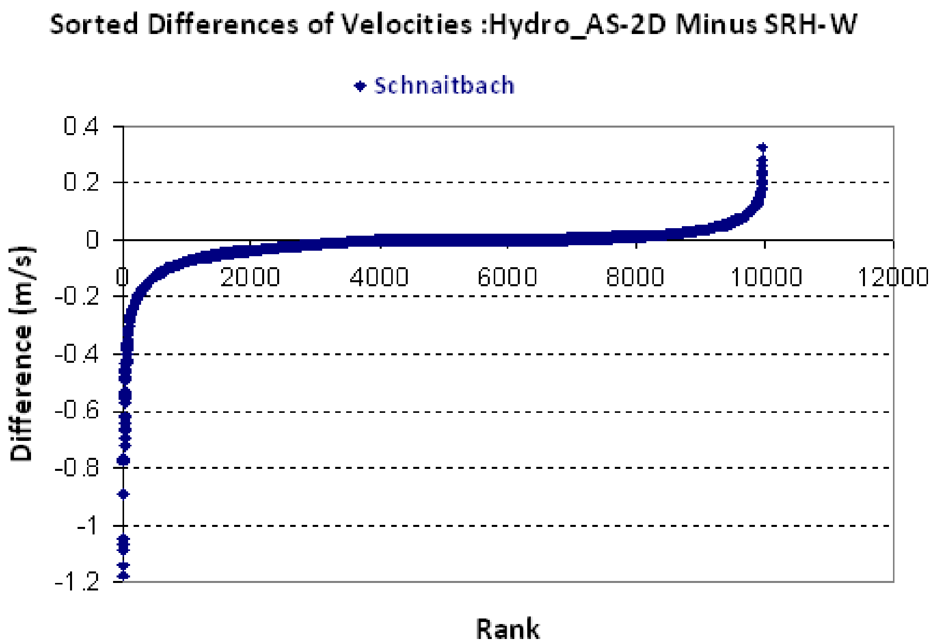

Figure 5.4: Sorted deviation of velocity for Schnaitbach (m/s).

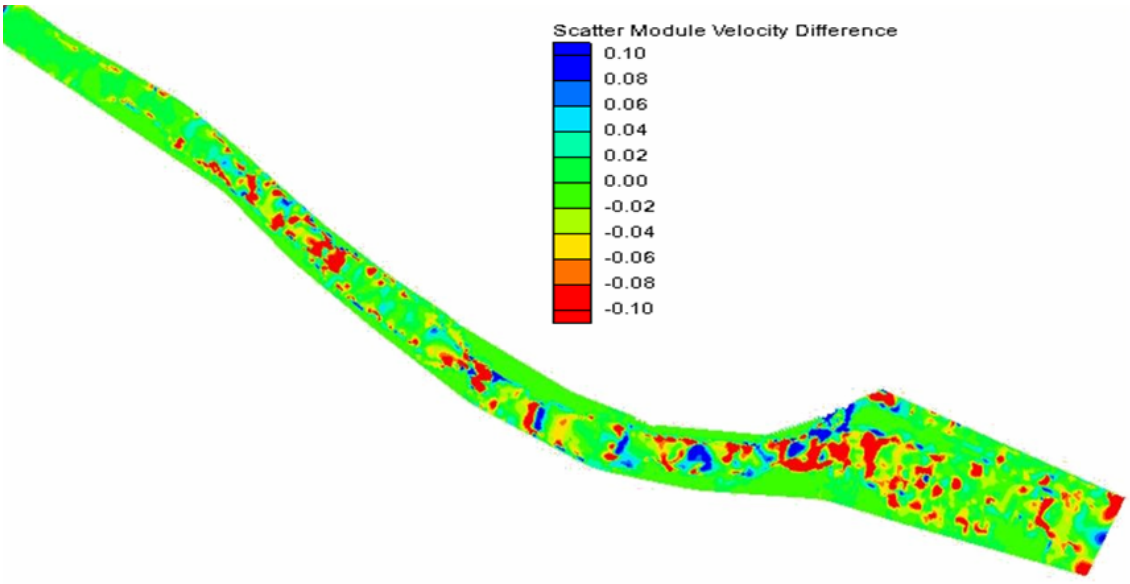

Figure 5.5: Spatial distribution of the difference in velocities between the two models for the Schnaitbach (m/s).

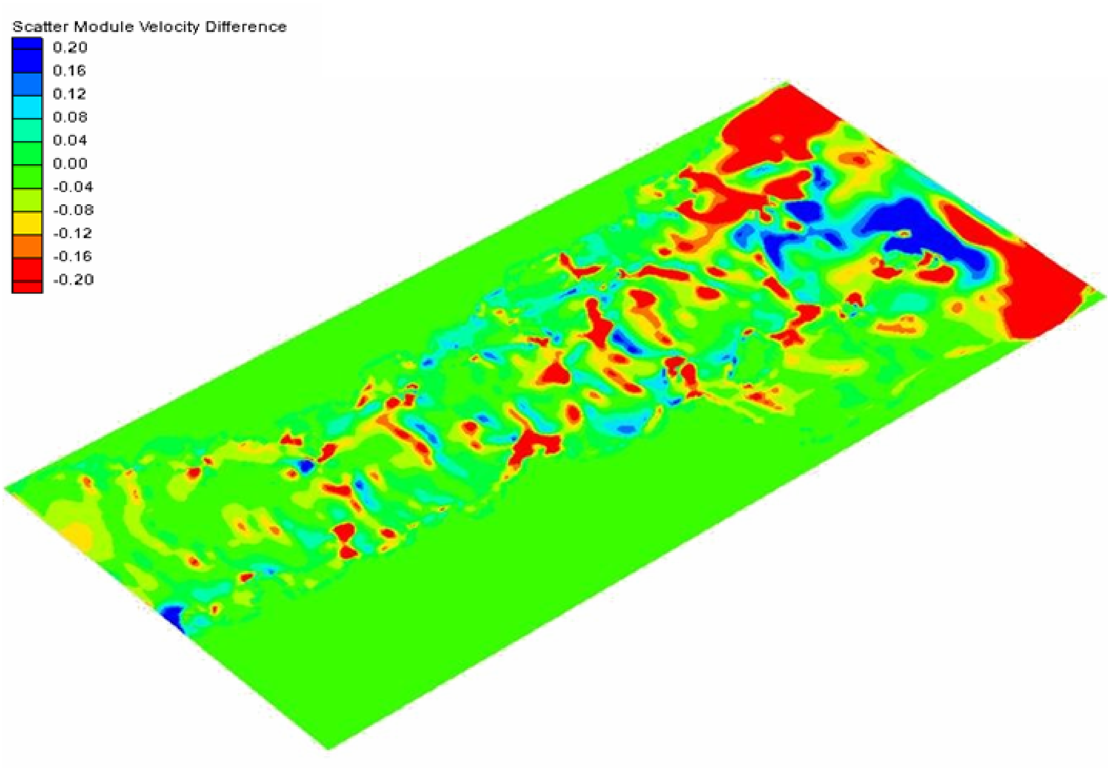

Figure 5.6: Spatial distribution of the difference in velocities between the two models for the Gurgler Ache (m/s).

Velocity outputs of the two models were also reasonably the same. No general trend of over or under estimation by one of the models was seen. The maximum difference seen is because of the difference in computing the dry cells especially near boulders. For more than 90% of the cells, the velocities match quite well. The maximum difference was observed for the Gurgler Ache reach where there was not sufficient data for the river bed morphology. As in the case of the water surface elevation, results were more similar for the Neumagen reach. Therefore, it was not included in this report.

5.5 Froude Number Distribution

The Froude number distribution is helpful to see how the two models capture places where the flow is subcritical or supercritical and transitions from subcritical to supercritical state which are normally accompanied by hydraulic jumps. If the Froude number is less than one the flow is subcritical and if it is greater than one the flow is supercritical. Hydro_As-2D computed higher maximum Froude number in all of the reaches.

Table 5.3: Maximium Froude numbers computed by the two models

Reach	Hydro_As-2D	SRH-W
Schnaitbach	2.32	1.94
Neumagen	1.99	1.49
Gurgler Ache	3.10	2.10

The spatial distribution of the Froude number showed that (figures 5.7 and 5.8). The Froude numbers computed by the two models are more or less similar and the two models captured the places where there was a transition of the state of flow and formation of hydraulic jumps identically.

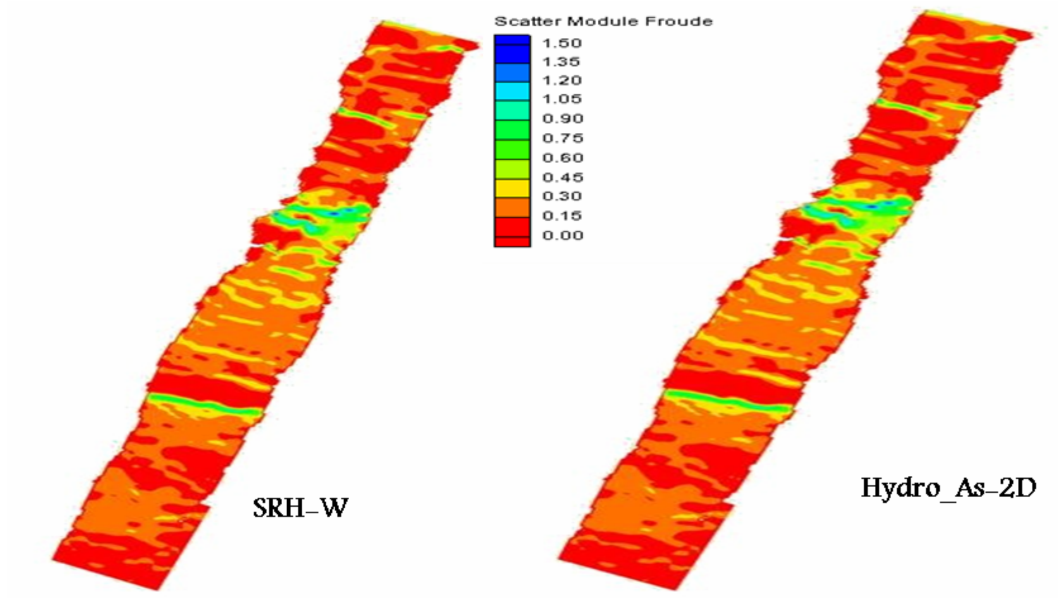

Figure 5.7: Froude number spatial distribution for the Neumagen.

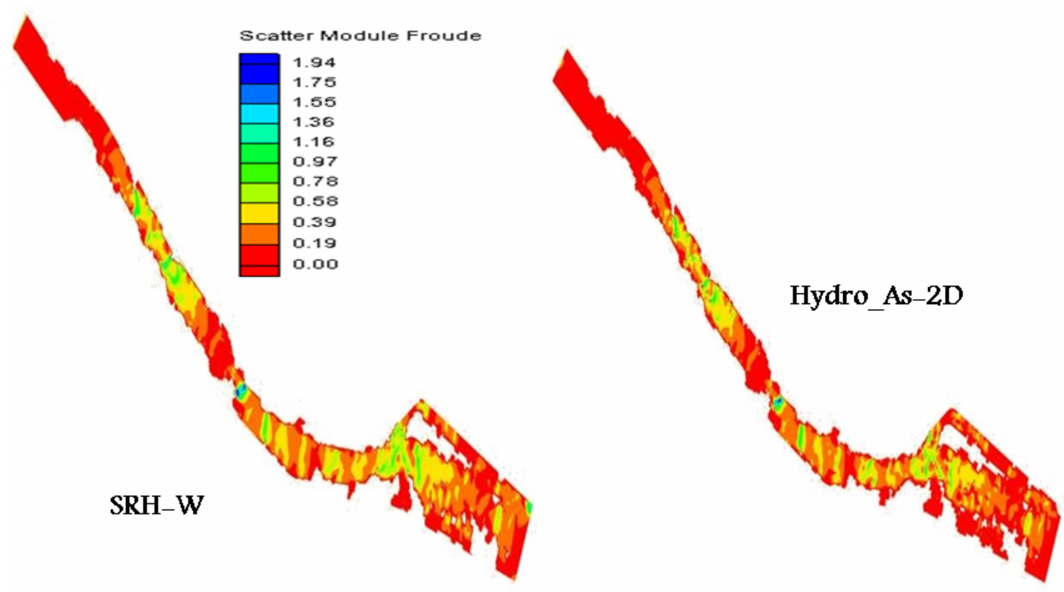

Figure 5.8: Froude number spatial distribution for the Schnaitbach.

5.6 Computation Time, Cost and User Friendliness

Another important consideration in model selection is the labour and computational costs involved and the simplicity of the model for users.

Computation time

A comparison of computation time requirements for the two models was carried out. The models were run with the same computer for all the reaches. SRH-W was on average about five times faster for all conditions than Hydro_As-2D.

Table 5.4: Computation time needed by the two models for the calibrated meshes

Reach	Hydro_As-2D	SRH-W
Schnaitbach	1 hour	9 minutes
Neumagen	1.28 hours	17 minutes
Gurgler Ache	1.67 hours	20 minutes

Cost

Both of these models require SMS for pre- and post-processing which can be bought at a reasonable price.

The mesh, map and scatter modules of SMS cost 2050 $.

Hydro_As-2D is commercial software which costs 7875 Euro.

SRH-W is freely available and anyone can download and use it.

(*http://www.usbr.gov/pmts/sediment/model/srh2d*).

User friendliness

Both SRH-W and Hydro_As-2D are quite user friendly and simple to use. SRH-W has a text output file which can be easily edited for varying the model parameters and boundary conditions. This makes model calibration and sensitivity analysis very simple.

6 Conclusions and Recommendations

The main advantage of using 2D-Models in habitat studies is their ability to sufficiently reproduce spatial variations that 1D-Models cannot adequately capture. An important step in performing a hydraulic modeling study is determining the relevant flow parameters to the study and what type of model is needed to obtain this information. For example, the most important parameter in flood plain analysis is river stage. The river stage will determine how much area is inundated. Accurate description of velocity gradients and spatial variation of flow is not of a primary concern and a 1D-Model is sufficient for obtaining river stage (depending on the heterogeneity of the river bed, a 2D-Model may also needed sometimes).

In aquatic habitat studies, selecting the appropriate model is not so simple. Factors such as the species and life stage of the aquatic organisms being studied dictate to what degree and accuracy depth, velocity, velocity gradients and localized flow patterns need to be described. A 1D-Model may suffice for a habitat study requiring only accurate description of the river's macro-scale flow patterns. Alternatively, a 2D-Model excluding information on topographic features could be used to describe the macro-scale flow features. However, a 2D-Model that incorporates obstructions in to the bathymetry may be necessary for a habitat study requiring an accurate description of both macro- and meso-scale flow patterns. Such information may also provide new and improved habitat metrics based on better defined local and spatial parameters (Using two-dimensional hydrodynamic models at scales of ecological importance; D.W. Crowder and P. Diplas, 2000).
The extension of hydrodynamic modeling to ecological habitat design and appraisal in rivers is a recent area of study. The potential to predict the detail of changing locations of depth,

velocity and substrate at scales of commensurate with the occurrence, abundance and life stage of aquatic habitat is of enormous benefit. Habitat modeling and using 2D hydrodynamic modeling are important research areas for the future as mankind tries to restore the degraded environment.

The main aim of this master thesis was to compare two 2D hydrodynamic models with respect to their outputs, accuracy, computation time, etc. and to perform sensitivity analysis of the two models to investigate the effects of mesh resolution and exclusion of boulders from the scatter data on model outputs. Comparison of two spatial interpolation methods (Krigging and triangulation with linear interpolation) was also carried out. Three case study reaches with different flow characteristics and bed morphologies were selected for modeling. Both models require the surface water modeling system (SMS) for pre- and post-processing. Computed and measured water surface levels for the three reaches were compared. In general it can be said that the water surface levels predicted by the two models were quite satisfactory. From the results of the three case study reaches the following conclusions can be drawn:

- There is no significant difference between the two spatial interpolation methods Krigging and triangulation with linear interpolation. Both of them predicted important spatial features such as location of pools and boulders quite similarly. Krigging performed slightly better in the studied reaches.

- The quality and quantity of bathymetry data representing the river bed and other spatial features like boulders determine quality of model outputs. Regardless of the study area, the proper description of the channel and mesh development are crucial to obtaining accurate numerical results. The approximate density of surveyed bathymetry data required to obtain a reasonable model accuracy are: 6 points/m^2 for the Schnaitbach, 3 points/m^2 for the Neumagen and 5 points/m^2 for the Gurguler Ache reaches. These densities of bathymetry data are recommended for modeling river reaches having similar morphological characterstics as the three reaches studied.

- Both Hydro_As-2D and SRH-W can be used for 2D hydrodynamic modeling of river reaches with various bed morphology and flow characteristics. Both models predicted observed water surface elevations well and velocity outputs of the two models are also comparable.

- SRH-W computed more dry cells than Hydro_As-2D for all the three case study reaches.
- Sensitivity analyses plays an important role in 2-D hydrodynamic modeling. SRH-W is more sensitive to mesh resolution than Hydro_As- 2D and finer meshes are required to get model outputs having similar agreement to measured data as for Hydro_As-2D. However, due to the difference in computational speed, using finer meshes is not a problem.
- Boulders influence the velocity more than the water surface elevation. To capture complex velocity patterns around boulders including sufficient bathymetry data describing the location of boulders is important. Accurate prediction of velocity patterns and velocity gradients are very important for habitat modeling.

In this thesis, model calibrations were done using only measured water surface elevations. There was not any measured velocity data for all the three case study reaches. It is necessary to calibrate the models using velocity data too. Therefore, in the future velocity measurements should be included for model calibration and to get a quantitative assessment of velocity outputs of the two models. Additionally, only steady state simulations were performed in this paper because of lack of data. Unsteady simulations can be performed in more or less similar way for the two models and comparison of the two models for unsteady flow simulations should also be done for example for hydropeaking investigations.

Sediment transport modeling is one of the very challenging issues facing sustainable water resources management. The new version of SRH-W can perform sediment transport modeling and this should also be investigated. Sediment transport modeling is important for instance for studies of temporal variation of habitats.

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