DIPLOMARBEIT

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Improvements of salmon habitats at the Nausta river

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Finally I would like to thank my dear Lisa for correcting my thesis and always raising a smile.

Zusammenfassung

Die Diplomarbeit wurde in Zusammenarbeit mit SINTEF Energy Research in Trondheim durchgeführt. Sie dient als Teil eines Programms zur Erhöhung der Lachspopulation im Fluss Nausta. Zu diesem Zweck wurde ein Flussabschnitt topografisch vermessen und ein 3-dimensionales Geländemodell erstellt. Dieses Geländemodell war die Grundlage für ein 2-dimensionales (River2D) und ein 3-dimensionales (SSIIM) hydraulisches Modell. Mittels Simulierung von Einbauten im Modell wurde eine Änderung hinsichtlich Habitate für den atlantischen Lachs und der Bachforelle untersucht.

Während einer Woche vor Ort wurden die Topographie und drei verschiedene Abflüsse gemessen. Die Topographie sowie die Wasseranschlagslinien der einzelnen Abflüsse wurden mittels DGPS (Differential Global Positioning System) vermessen. Die Fließgeschwindigkeiten und Abflüsse wurden mittels ADVP (akustisches Doppler Verfahren) gemessen.

Die Topographie wurde mittels der Software Surfer 8 für die hydraulischen Modelle interpoliert. Mit den vor Ort gemessenen Werten wurden mit der Software River2D und SSIIM für die drei Abflüsse jeweils ein hydraulisches Modell erstellt und kalibriert. Aufgrund dieser Modelle wurden zwei weitere Abflussmengen simuliert (Situation bei Niederwasser, 1-jähriges Hochwasser).

Weiters wurden die hydraulischen Modelle mit Einbauten (Steinblöcke, Steinbuhnen, inklinante Buhnen, künstliche Insel,…) versehen und auf eine etwaige Veränderung der Habitateigenschaften des geänderten Fließgewässerabschnittes hin untersucht.

Abstract

In collaboration with SINTEF Energy Research this thesis was a part of a project to increase Atlantic salmon production in the river Nausta. The main goal of this thesis was to collect, systematize, analyse and prepare field data. Two hydraulic models, the two dimensional model River2D and the three dimensional hydraulic model SSIIM, were established for a 400 m reach just upstream of Naustdalsfossen in the lower part of the Nausta River.

The models were calibrated with the use of verifying data of three different discharges. Furthermore the model was adapted for a low flow condition and a one-year-flood. Analysis and adjustments of various habitat improvements were carried out with the hydraulic model. Combinations of different adjustments such as adding larger rocks, velocity concentrators, rock thresholds, deeper pools in addition to other enhancements were tested on the reach of interest.

The results were evaluated by SINTEF Energy research in co-operation with NINA (Norwegian Institute for Nature Research). Furthermore the results were analysed with the use of biological preferences from the literature and from expert opinions in order to find the most optimal habitat improvements.

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1 Preface

1.1 The overall goal

As a part of a project to increase salmon production in the Nausta river, mitigation efforts like constructing improved habitats in the river was carried out. A two and three dimensional hydraulic model was established for a 400 m reach just upstream of Naustdalsfossen in the lower part of the Nausta River. The models were calibrated with the use of verifying data of three different discharges.

Analysis and adjustments of various habitat improvements was carried out with the hydraulic model. Changed bed topography, discharge and velocities, substrate composition (erosion and sedimentation) and other related factors were simulated. Combinations of different adjustments such as adding larger rocks, groynes, velocity concentrators, rock thresholds, deeper pools in addition to other enhancements were tested on the reach of interest.

The results were evaluated by SINTEF Energy research in co-operation with NINA (Norwegian Institute for Nature Research) and presented as a habitat enhancement suggestion for “Stiftelsen Villaksens framtid”.

1.2 The main goals

As a part of the project to increase the salmon population in the Nausta river the mean goal of this thesis is to collect, systematize, analyse and prepare field data. This field data was further used establishing a distributed topographical basis for two hydraulic models, the two dimensional model River2D and the three dimensional hydraulic model SSIIM.

The hydraulic models were calibrated with the use of measured and observed data of three different discharges. Furthermore the model was adapted for a low flow condition and a one-year-flood. Different adjustment were made and added into the two dimensional hydraulic model River2D. The adjustments were boulders, groynes and man-made islands.

The results were analysed with the use of biological preferences from the literature and from expert opinions (NINA scientists) in order to find the most optimal habitat improvements.

The adjustments should also be added into the three dimensional model SSIIM but several problems with this program occurred. Problems were amongst other things the very heterogeneous topography and the handling of the program. Furthermore the measured topography was too inaccurate for a three dimensional hydraulic model.

Furthermore these and other problems are discussed in the chapter 8 “Discussion and Conclusion“.

2 Introduction

2.1 Sogn og Fjordane, Norway

Sogn og Fjordane is a county of Norway. It has three traditional districts: Sogn in the south, Sunnfjord in the center and Nordfjord in the north. The three largest fjords are Sognefjord Nordfjord and Sunnfjord.

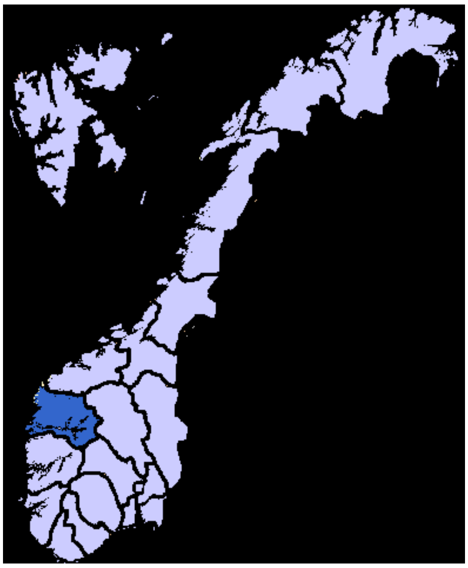

Figure 2.1 Norway (www.wikipedia.org)

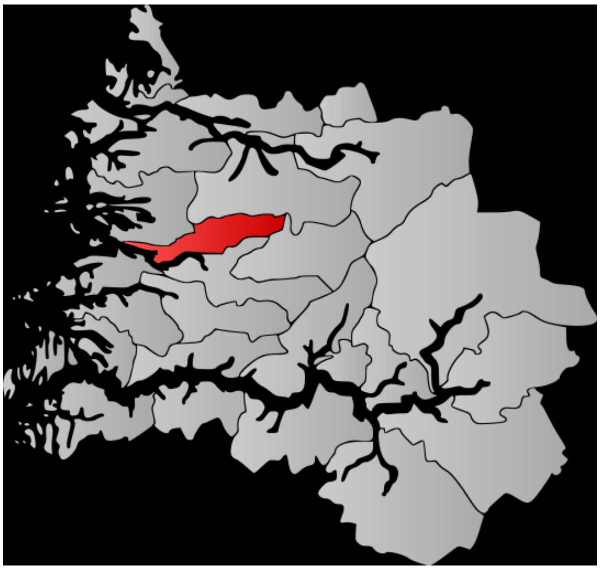

Figure 2.2 Sogn og Fjordane (www.wikipedia.org)

2.2 Naustdal

In figure 2.2 Naustdal is shown as the red area. It is a municipality in the county of Sogn og Fjordane and in the traditional district of Sunnfjord. The municipality is located to the northern coastline of the Førdefjord, moreover it has 40km of shoreline bordering the fjord.

Typical for the climate in Naustdal is a short summer and a mild winter near by the fjord, but a long winter with a lot of snow up in the valley. Naustdal has a yearly precipitation of 2335 mm with the maximum in September and October with 299 mm and 290 mm and the minimum in May with 96 mm.

2.3 The River Nausta

Next to Naustdal the river Nausta flows into the Førdefjord.

The river has a rich fish fauna containing amongst other things the Atlantic salmon, the brown trout and the char. The river is known as one of the best rivers for fishing Atlantic salmon in the county. The part between the river mouth and the waterfall "hovefoss" is also good for sea trout fishing. The River is unregulated and protected against the use of hydropower.

Figure 2.3 River Nausta

2.3.1 Hydrology

The regime of river Nausta is a complex "nival transition". Caused by thaw the first maximum takes place in May in spite of minimum precipitate. The second maximum in September is a result of maximum precipitate. The minimum discharge in February and March is caused by precipitation in form of snow and frozen underground.

The river rises to a peak flow after each precipitation event, then falls in a recession. The characteristic about the river Nausta is the rapid increase of the discharge at a heavy rain and a fast fall in a recession. An active example is given in figure 2.6, when discharge increased 40 times larger over a few hours. The rapid increase of discharge is a result of the sparely storing soils and the alpine character with steep mountain sides in the catchment area.

The mean flow of the river Nausta averages 22 m^3/s. Furthermore, the amount of the mean flow is caused by numerous short flood waters. As a result the discharge is lower during 255 days per year. The average of low water is 5,8 m^3/s every month. In addition the Q_{95} (=discharge which is exceeded 95% of the year) is 2,1 m^3/s which is about yearly low water. The 1-year-flood of Nausta averages 208 m^3/s and the 50-years-flood is 395 m^3/s.

MQ	22,0	m^3/s
Q_{95}	2,1	m^3/s
NNQ	0,16	m^3/s
HQ_1	208	m^3/s
HQ_{50}	395	m^3/s
$HHQ_{1964-2005}$	449	m^3/s

Table 2.1 Nausta discharge statistic

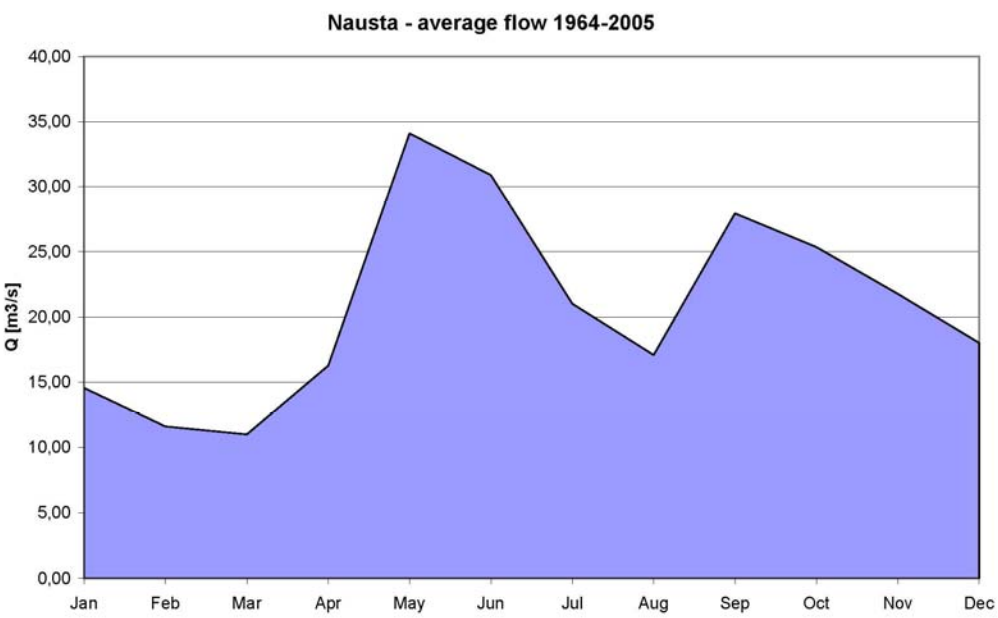

Figure 2.4 Average flow

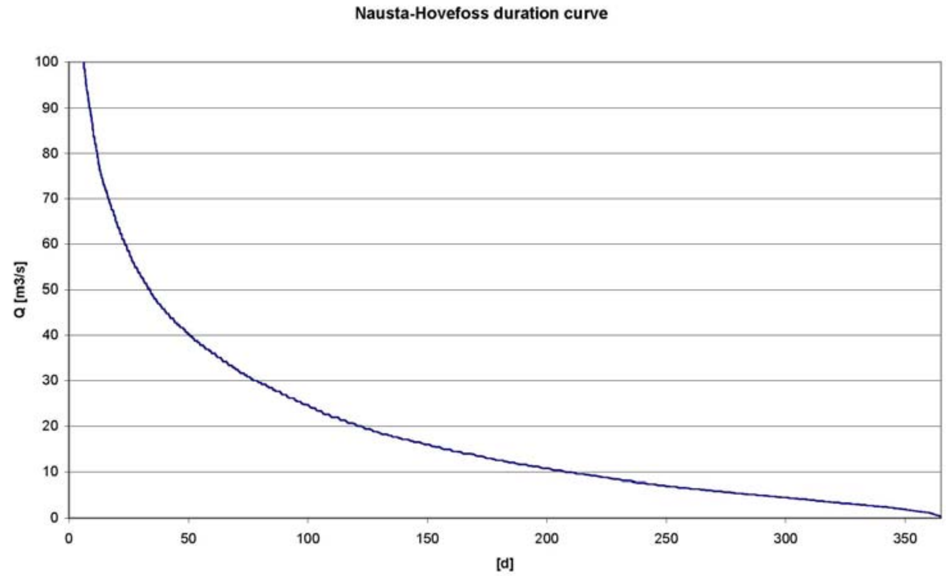

Figure 2.5 duration curve

The lowest discharge ever measured at gauging station hovefoss amounted a total of 0,16 m^3/s in December 1963. In the last decade the lowest discharge amounted a total of 0,54 m^3/s in September 1996 caused by low precipitation. The highest discharge ever measured since 1963 was 448,9 m^3/s in January 1971. The statistic about the yearly flood waters demonstrates a linear distribution with two outliers during the observation period from 1964 until 2005 (figure 2.7).

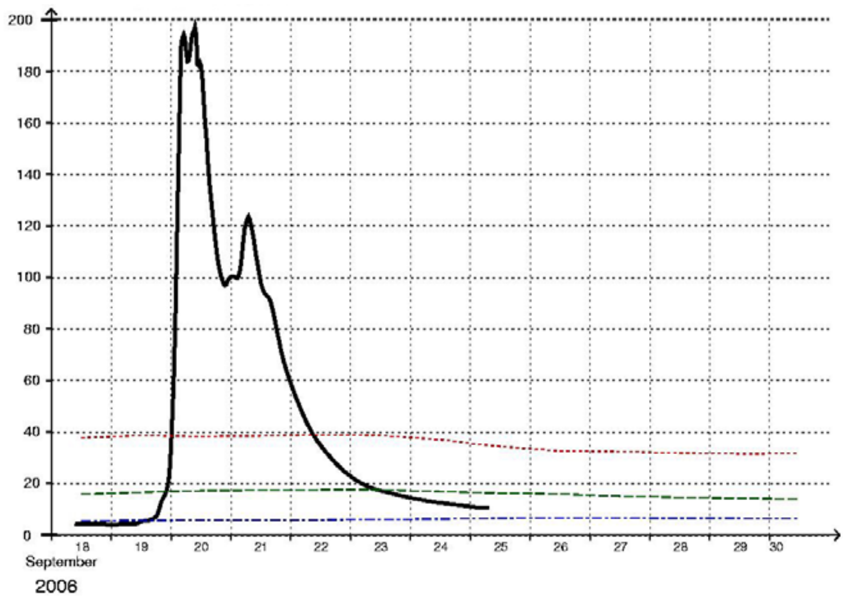

Figure 2.6 peak of discharge

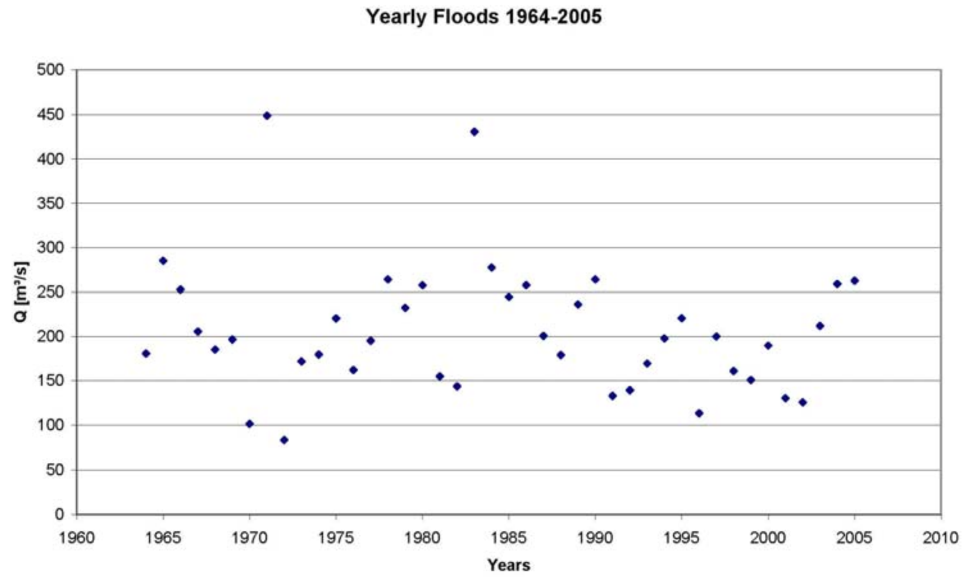

Figure 2.7 Yearly flood statistic since 1964

2.3.2 Catchment

The catchment of a river above a certain gauging station is determined by the surface area of all terrain which drains toward the river from above that station. The river's discharge at that location depends on the precipitation on the catchment area and the inflow or outflow of groundwater to or from the area. Furthermore stream modifications for instance dams, as well as evaporation and evapotranspiration from the area's land and plant surfaces play an important role.

The river Nausta drains a catchment area of 278 km^2. The gage-station “Hovefoss”, which is the nearest station for permanent discharge-measuring, has a catchment area of 232 km^2.

Figure 2.8 Naustdal and catchment area of the River Nausta

2.4 Salmon (salmo salar) and trout (salmo trutta)

The family Salmonidae includes the Atlantic and Pacific salmon, the trout and the char. For this project the Atlantic salmon and the brown trout are more important.

2.4.1 Salmon (salmo salar)

The Atlantic salmon originally occurred in every country whose rivers flowed into the North Atlantic and Baltic Sea. Salmon have disappeared from nearly every river of these countries due to the erection of navigation locks, the construction of dams and pollution. This is one reason why the river Nausta is so important for salmon population and protection.

2.4.1.1 <u>Juvenile phase</u>

Salmon spawn in whole or in part of the river wherever there is a suitable substrate of clean, silt-free and well aerated gravel. Spawning therefore tends to be in the riffles or faster flowing areas at the head and tail of pools. The greatest proportion of this kind of substrate occurs in the upper reaches of the rivers, where the flow is more turbulent. Spawning can also occur in the main river channel above tide level. A permeability of more than 1 m/h appeared to be necessary for successful emergence of fry [2].

Spawning usually takes place from late October to December. A mean depth of 38 cm and the mean water velocity of 93 cm/s 12 cm above the substrate were observated.. The eggs deposited may be under 15 – 30 cm of gravel and the time required for their hatching ranges from 70 to 160 days depending on water temperature [2].

Figure 2.9 Alevin

On hatching, the fish is called an alevin and is about 2 cm long. By the time the alevin have emerged from the gravel the yolk sac has been absorbed. Now they are ready to start feeding and are known as fry.

The young salmon is territorial and its rearing habitat has been defined as any part of a river accessible to adult salmon. This habitat contains a combination of gravel, rubble, cobble or boulder substrate or where at least 10% of the substrate is of particle size greater than 10 cm. The habitat preference of juvenile salmon shows a seasonal change. In the summer months shallow and riffle habitat is preferred while in the colder months, when feeding activity is reduced or stops, the juvenile salmon move into deeper water of pools. This behaviour occurs when the temperature of the water fell below 7 °C [2].

Figure 2.10 Young salmon

In very cold rivers, such as those on the western and northern coasts of Norway, the water temperatures may never exceed 10 °C. In such cold rivers salmon do not react to river temperatures in the same way as in “warmer” rivers.

2.4.1.2 Adult phase

Figure 2.11 Adult Atlantic salmon

Once the smolts have entered the sea little is known of their movements. For the thesis, this part of life circle of salmon is less important, therefore it will not be pursued.

One of the most interesting aspects of salmon’s life is its homing instinct. Many theories have been put forward. Probably the theory which has most acceptances is the importance of stream odours in the orientation of fish. This implies that the fish are guided by odour trails back to their spawning grounds. The substances responsible for these trails emanate amongst other things from the plants and minerals characteristic of the home-stream water [2].

Many factors are claimed to be responsible for the time of entry of salmon into rivers. Salmon do not travel in dry water. Before they ascend a river they require a ‘leading water’. They persist, hovering over the estuary mouth, unless there is a flood in the river. During a flood they rush up in shoals. A salmon is able to take many miles from the sea in the course of a few hours. The time of entry of the main runs of fish varies from river to river. The length of a river may be responsible for the time of year at which fish return. Fish returning to short rivers need not return as early in the season as those entering long river systems [2].

As soon as entering fresh water, salmon don’t eat anymore. The adult male and female change in appearance after entering fresh water and as spawning time approaches. As the salmon does not feed during the time it is in fresh water the only energy available is from other parts of the body. After spawning both male and female are known as kelts. The death rate after spawning is high, especially among male fish. The loss of approximately 40% in weight brings the salmon close to death. As a result it is so weak on its return to the ocean that it is hardly able to undergo normal recuperation [2].

2.4.2 Trout (salmo trutta)

The brown trout is essentially a European species. The brown trout and the sea trout are fish of the same species. Brown trout is largely a freshwater fish. Sea trout shows anadromous reproduction. The sea trout occur in Western Europe from latitude 42° northwards and are found in rivers flowing into the sea. In the beginning of the 20th Century brown trout became a global species because of anthropogenic propagation [3].

Figure 2.12 Adult Brown Trout

The spawning behaviour is similar to that of the Atlantic salmon. The usual time for breeding in the northern hemisphere is November and December. Spawning usually takes place in clean gravel in running water. A female digs a depression in the gravel bed at an average water depth of 30 cm. The female moves into the depression and lays her eggs. The male alongside her sheds synchronous his sperm. Afterwards the female moves slightly upstream and cover the eggs with gravel. This act usually repeats several times until all eggs are laid [3].

Brown trout usually spawn over several years. 5-8 years being recorded in many populations. It can live to ages of 20 years, but like the Atlantic salmon, there is a high proportion of death of anadromous males after spawning.

Eggs laid in October to December usually hatch in February or early March. The small alevins remain in the nest for 5-6 weeks before they leave the gravel. Feeding of invertebrates mostly commences before all the yolk is exhausted. Afterwards they enter as fry a critical period of the life circle. The mortality is high whilst the fries establish feeding territories. After a few weeks the young trout become a parr with 9-10 black stripes down the sides of the body and the characteristic red or orange tip to the adipose fin [3].

The fist year of life cycle of the young trout is nearly always spent in the natal stream. Sometimes the trout remain in their natal stream for the rest of their life. The most variable of the life cycle of brown trout is to migrate to an estuary or the sea (sea-trout) [3].

2.5 Habitat

2.5.1 Habitat of Atlantic Salmon

Young salmon of all age classes occupies a wide range of water depths during summer. They are concentrated mainly in depths of 24-36 cm, in autumn exclusively in these depths. Summer focal velocity at the fish's snout was predominantly 10-30 cm/s for 0+ fish, 10-40 cm/s for 1+ fish, 30-50 cm/s for 2+ fish and during the autumn it was always less than 10 cm/s for all ages [2].

Juvenile rearing habitat has been defined as any part of the river accessible to adult salmon. The habitat contains a combination of gravel, rubble, cobble or boulder substrate or where at least 10% of the substrate is of particle size greater than 10cm. The size of 'home' stones selected increased with the fish age. In summer the individual position of the juvenile fish of all ages is most closely associated with the stream-bed stones, which were always less than 20 cm. In autumn, all ages were associated with these 'home' stones up to 40 cm in diameter [2].

2.5.2 Habitat of Brown Trout

Brown trout requires suitable spawning gravels which are well oxygenated trough a constant flow of high quality water. The optimal gravel size varies between 1 cm and 7 cm. The mean velocity averages 40 cm/s [3].

The water temperature is a very important factor. The limits for growth in this species are 4-19.5 °C. The lower limit for survival is 0 °C and the upper limit varies between 25-30 °C. Limits for egg development are narrower, it ranges from 0°C to 13 °C where at least 50 per cent of the eggs hatch [4].

The second most important factor is the oxygen content of the water. A minimum concentration of 5 mg/l can be tolerated (at least 80 per cent of saturation). Minimum oxygen content for the eggs is suggested from 1 mg/l at 5 °C to 7-10 mg/l at 10-17 °C. These factors assume an adequate flow through the riverbed [3] [4].

2.5.3 Habitat conditions of the investigated area

One major goal of this project is to increase salmon population by adjusting the area to the preferred habitat conditions of 20-50 cm/s and a water depth of 30-80 cm [1].

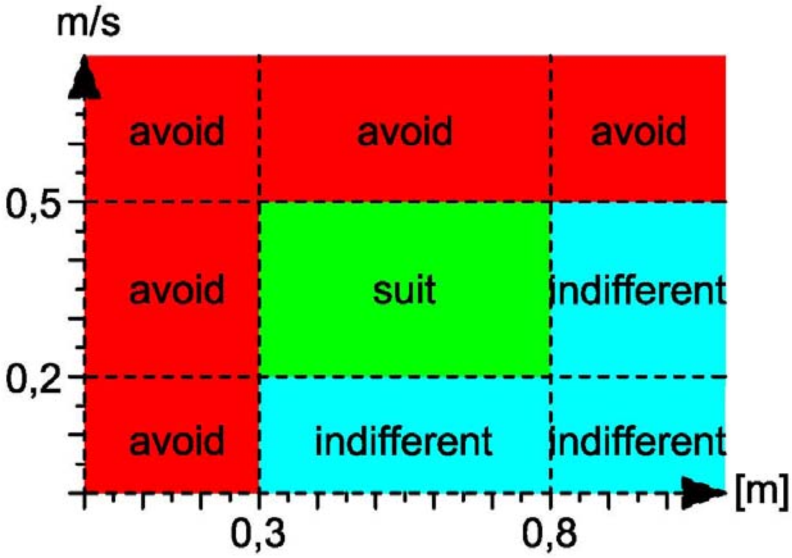

Figure 2.13 Preferred habitat conditions of young salmon [1]

The habitat conditions in the investigated area are neither perfect for the Atlantic salmon, nor for the trout. During mean flow at 22 m^3/s flow velocity about 50% reach of the river flows faster than 50 cm/s. Therefore the range with good habitat conditions is less than 20% of the whole area. For spawning salmon the areas with higher flow velocity are too deep. In times with lower discharge the water depth becomes too little whereas in areas of deeper water the flow velocity becomes too slow.

For example the figure 2.14 illustrates a shallow area during a discharge of 10 m^3/s.

Figure 2.14 River Nausta at 10 m³/s

Nearly the total riverbank is fixed with boulders. Nearby the growth of algae alongside of the bank is above average, especial in zones of slow flow velocity. Most likely the overgrowth is caused by agriculture. Furthermore algae partial overgrow the substrate.

Pebble, gravel and sand dominate the embedded substrate. Stream-bed stones alternatively home stones, which are important for the young salmon, are missing.

3 Measurements

For this thesis two kind of grid-based models are used, a 2D-model (River 2D) and a 3D-model (SSIMM). The 2D- especial the 3D-model requires point method measurements from the topography to simulate the natural processes. In average cross sections were measured about every 10 m. Programs like surfer (chapter 4.1) can be used to interpolate between the measured points.

To calibrate and validate the models discharge, the water level was measured at the discharge of 10 m^3/s, 15 m^3/s and 20 m^3/s. Also the flow velocity was measured in several random points.

The measurements took place between the 1^{st} and the 6^{th} of October 2006.

3.1 Topography

At the investigated area land survey could hardly be used. With its several overgrown islands in addition the wide width a horizontal view from one riverbank to the opposite side was barely possible. To obtain the topography of the river bed furthermore the elevation of the waterline during different discharges, Differential Global Positioning System (DGPS) was used at Nausta.

3.1.1 Differential Global Positioning System (DGPS)

The degradation of the point positioning accuracy by selective availability has led to the development of Differential Global Positioning System (DGPS). This technique is based on the use of two ore more receivers, where one stationary reference or base receiver is located at a known point and the position of the moving remote receiver is to be determined.

At least four common satellites must be tracked at the same time at both sides. The known position of the reference receiver is used to calculate corrections to the GPS derived position or to the observed pseudo ranges. These corrections are then transmitted via telemetry to the roving receiver and allow the computation of the rover position with far more accuracy than for the single-point positioning mode [5].

The special equipment (Topcon GPS) for this measurement is able to receive the signals from the American GPS satellites furthermore also from the Russian GLONASS satellites. Together they build the Global Navigation Satellite System GNSS. GNSS is the standard generic term for satellite navigation systems that provide autonomous geo-spatial positioning with global coverage. It allows small electronic receivers to determine their location to within a few metres using time signals transmitted along a line-of-sight by radio from satellites.

The satellites send out a code on two hyper frequency waves. Unlike the usual GPS instruments, the Topcon GPS processes the phase of the wave instead of the code. Considering the wavelength is only 90 cm instead of 300 km for the length of the code, as a result accuracy is much higher. The Topcon Legacy-E receiver uses 40 universal channels that can each track all signals of either L1 or L2 GPS and GLONASS frequencies and up to 20 GPS+ satellites at once, which is the maximum available at any one time (Topcon, 2004)

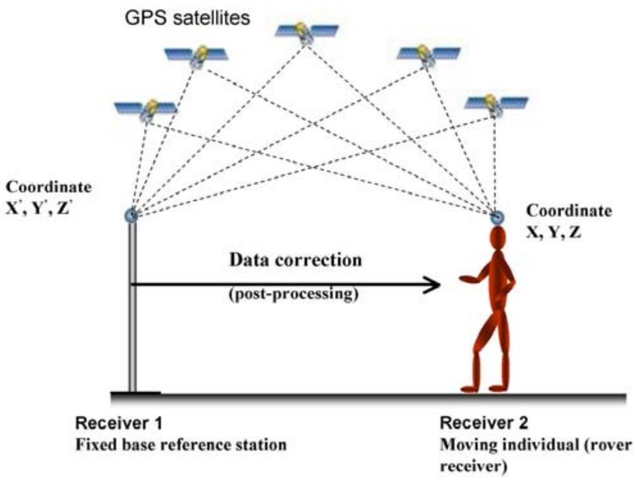

Figure 3.1 Principle of DGPS

Figure 3.2 DGPS field equipment

Problems with DGPS

Expectedly the accuracy of measurement nearby for example trees got worse. The accuracy depended on satellites available and the form of the crown. During daytime the available satellites changed their position thus different areas could be measured. Nevertheless in some areas it was hardly possible to get good measurement results even on different times of the day. In that case a quick note was written if the area is able to get interpolated from measured points nearby.

3.2 Discharge and Velocity

Beside geodetic data hydraulic models require information about the hydraulic as an input, especially the discharge and velocity.

Discharge is the volume rate of water flow per time unit which is transported through a given cross-sectional area. There are several methods to measure the discharge of a river. A stream gauging station provides continuous flow over time at one location for water resource and environmental management or other purposes. If a continuous measurement of stream flow over time is not required, current meters or acoustic Doppler velocity profilers can be used.

During field work at river Nausta, the velocity and discharge measurements were done with an Acoustic Doppler velocimeter (Sontek FlowTracker, www.sontek.com).

Figure 3.3 Sontek FlowTracker (www.sontek.com)

3.2.1 Acoustic Doppler Velocimeter (ADV)

The FlowTracker Handheld-ADV (Sontek) is used to measure the flow velocity in a single point. It uses acoustic Doppler technology to measure 2D and 3D flow in a small sampling volume located a fixed distance from the probe. Sound generated by the transmitter bounces off suspended particles in the water. The water itself does not reflect the sound, but small particles in the water for example suspended sediment, zooplankton and small air bubbles. This reflected sound returns to the receivers, is averaged together by the processor, and results in water velocity measurements that are recorded at a rate of once per second [19].

One sensor sends out a signal and three sensors measure the shift in the frequency of the receiving signal. The shift in the frequency is proportional to the flow velocity [19].

$$F_{Doppler} = -2*F_{Source}*(V/C)$$

$F_{Doppler}$ … change in the received frequency at the receiver

F_{Source} … frequency of the transmitted sound

V … velocity between the source and the receiver

C … speed of sound

The disadvantage of this measuring method is, if the water is very clear the returning signal may not be strong enough. Without enough signal strength, the velocimeter is not able to gauging accurate velocity measurements.

Flow Tracker is capable of measuring velocities from 0,001 m/s to 4 m/s and in water as shallow as 2 cm. The actual measurement height depends on the water depth. If the water depth is below 75 cm the point of velocity measurement has to be at 40% of the actually height. If the water depth is above 75 cm two points of velocity measuring are necessary, one point at 20% of the actually height, the other at 80% [19].

During field work every 2 m along the inflow cross section velocity and the water depth was measured. Furthermore at several random points velocity was measured for the calibration of the hydraulic models. The collected data is transferred via cable to a computer, which saves the data and calculates the discharge trough the cross section.

Figure 3.4 Flow tracker in use

3.3 Investigation Area

The area under investigation is located close to the Førdefjorden above the waterfall “Naustdalsfossen” nearby the town Naustdal. The area is about 400m in longitudinal direction and 100m in cross direction. Two big islands and, depending on the water depth, numerous smaller overgrown islands are remarkable for this river section. During medium flood the smaller islands compared to the bigger islands are under water. While dry spells several gravel banks occur.

Nearly the entire riverbank in addition the bank of the bigger islands is fixed with boulders as well as the banks of two big islands. Bordering to the river section agriculture area is in use.

Upstream of the investigated area is an even bigger island with an agriculture area in use, which divides the river in two streams. For this reason the inflow area is divided in two inflow sections.

Figure 3.5 shows the investigated area during low flow with numerous Islands and gravel banks.

Figure 3.5 Investigation area

3.4 Meso-scale habitat classification

Habitat modellers have to look at complex systems, where problems inherent in applying models developed for small scales applied for larger scales need to be overcome. Meso-scale classification of rivers has been used for decades in Norway, mainly to study minimum flow, impacts of hydro regulations and ecology. The riffle-run-pool is widely applied.

The use of meso-scale habitat classes allows the up scaling of results from more detailed models, in addition data collected from meso scales should be adaptive to macro and micro scale models.

The Norwegian University of Science and Technology (NTNU) and SINTEF Energy Research have developed a method for middle and smal sized streams. The meso scale physical habitat classification method is first applied to a river by visual observation from walking along the river bank either by boat. At least one representative station must be chosen within each meso habitat class to carry out micro scale habitat conditions. The micro scale habitat conditions are assessed either by direct measurements of physical variables or by using microhabitat models. The relationship between flow and habitat conditions from the representative stations can then be transferred to the entire river by the meso scale classification [12].

3.4.1 Methodology

The method is using meso scale physical habitat classification as the first step. The developers have established a method for classification based on observations or estimations of four physical variables: surface pattern, surface gradient, surface velocity and water depth, thereby ten different classes are obtained (table 3.1). Some combinations are practically impossible, either they are natural non-appearing or very rare and therefore neglected [13].

<table>
<tr><th>Criteria</th><th>surface pattern</th><th>surface gradient</th><th>surface velocity</th><th>water depth</th><th>Code</th><th>Common name</th></tr>
<tr><td rowspan="15">Decision</td><td rowspan="7">smooth / rippled</td><td rowspan="3">steep</td><td rowspan="2">fast</td><td>deep</td><td>A</td><td>Run</td></tr>
<tr><td>shallow</td><td colspan="2" rowspan="2">Non existing combination</td></tr>
<tr><td>slow</td><td>deep/shallow</td></tr>
<tr><td rowspan="4">moderate</td><td rowspan="2">fast</td><td>deep</td><td>B1</td><td>Deep glide</td></tr>
<tr><td>shallow</td><td>B2</td><td>Shallow glide</td></tr>
<tr><td rowspan="2">slow</td><td>deep</td><td>C</td><td>Pool</td></tr>
<tr><td>shallow</td><td>D</td><td>Walk</td></tr>
<tr><td rowspan="8">Broken / unbroken standing waves</td><td rowspan="4">steep</td><td rowspan="2">fast</td><td>deep</td><td>E</td><td>Rapid</td></tr>
<tr><td>shallow</td><td>F</td><td>Cascade</td></tr>
<tr><td rowspan="2">slow</td><td>deep</td><td colspan="2" rowspan="2">Non existing combination</td></tr>
<tr><td>shallow</td></tr>
<tr><td rowspan="4">moderate</td><td rowspan="2">fast</td><td>deep</td><td>G1</td><td>Deep splash</td></tr>
<tr><td>shallow</td><td>G2</td><td>Shallow splash</td></tr>
<tr><td rowspan="2">slow</td><td>deep</td><td colspan="2">Non existing combination</td></tr>
<tr><td>shallow</td><td>H</td><td>Rill</td></tr>
</table>

Table 3.1 Classification decision tree

<table>
<tr><td rowspan="2">surface pattern</td><td>smooth / rippled</td><td>wave height <0,05m</td></tr>
<tr><td>broken / unbroken standing waves</td><td>wave height <0,05m</td></tr>
<tr><td rowspan="2">surface gradient</td><td>steep</td><td>>0,4%</td></tr>
<tr><td>moderate</td><td><0,4%</td></tr>
<tr><td rowspan="2">surface velocity</td><td>fast</td><td>>0,5 m/s</td></tr>
<tr><td>slow</td><td><0,5 m/s</td></tr>
<tr><td rowspan="2">water depth</td><td>deep</td><td>>0,7 m</td></tr>
<tr><td>shallow</td><td><0,7 m</td></tr>
</table>

Table 3.2 Decision criteria

The method has a flexible structure, therefore it can be adapted to different situations. The surface of the river is divided into triangular and quadratic units considering the four physical variables: surface pattern, surface gradient, surface velocity and water depth. A maximum of three units between cross sections are allowed (Figure 3.6). These are identified and are drawn to the paper or digital map [14].

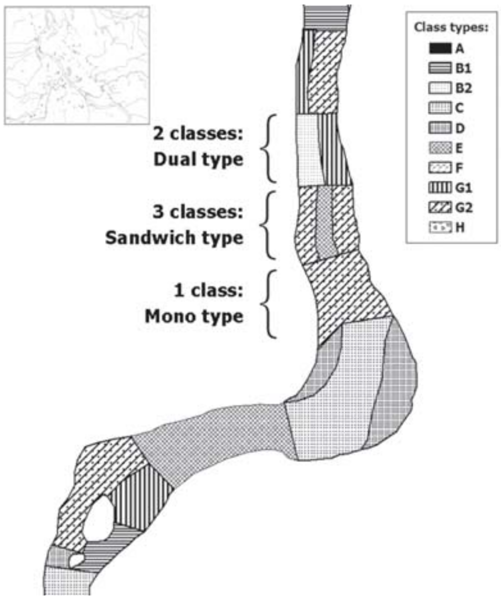

Figure 3.6 Explanation of classification layout [14]

When microhabitat conditions are direct measured, water depth, mean column velocity and substrate size are measured in 40 randomly selected points within a meso habitat. Additionally roughness, embeddedness and other velocities are measured [12].

4 Models

Hydraulic modelling is a form of physical modelling widely used to investigate design and operation issues in hydraulic engineering. It entails, with a degree of sophistication that varies with the objective of the investigation, the use of a scaled model for replicating flow and fluid-transport processes in diverse natural flow systems and for evaluating the performance of hydraulic structures and hydraulic machines [15].

Modelling river systems, using computers, is a powerful tool for instance river engineering, habitat evaluation and flood forecasting. Accordingly modifications can be tested on the model before they are constructed.

Two-dimensional furthermore three-dimensional hydraulic modelling allows investigators to calculate a depth and mean column water velocity for anywhere, and everywhere, on a river and under any flow conditions chosen. For instance depths and water velocities taken from the hydraulic model can be used to analyze habitat conditions.

Two- and three-dimensional models are based on detailed topography survey, data on bed roughness and boundary conditions like for example water level and discharge. Water level, furthermore flow velocity measurements are required for validation of the model.

To get a regular spaced or refined grid as an input for the hydraulic model a graphic program like surfer can be used.

4.1 Surfer

For this thesis Surfer version 8.02 was used. Surfer is a grid-based graphics programs. It transforms XYZ data to create contour maps, 3D surface maps, 3D wire frame maps, shaded relief maps, rainbow colour "image" maps, post maps, classed post maps, vector maps, and base maps. It can calculate cross sections, areas, and volumes.

Surfer provides twelve gridding methods: inverse distance, kriging, minimum curvature, modified Shepard's method, natural neighbour, nearest neighbour, polynomial regression, radial basis function, triangulation with linear interpolation, moving average, data metrics and local polynomial. Surfer interpolates irregularly or regularly spaced data into a useful, functional map. Each gridding method provides complete control over an abundant number of gridding parameters to generate an accurate map for representing the data.

The Surfer 8 manual commends the interpolation method depending on the number of measured points (table 4.1).

Number of xyz data points	Interpolation method
<250	*Kriging* or *Radial basis function* produce good represantations
250-1000	*Triangulation with Linear Interpolation* creates a good represantation of the data, *Kriging* and the *radial basis function* also create a good represantation, but they need more time
>1000	*Minimum curvature* and *Triangulation with Linear Interpolation* are fast and produce good representations. *Kriging* and the *Radial basis function* produce good maps, but are slow

Table 4.1 Interpolation method based on number of data (Surfer 8.0 manual)

The Surfer manual commends for instance over 1000 measured xyz point's minimum curvature or triangulation with linear interpolation was to be used. Nowadays computational capability is high-capacity enough to use kriging or the radial basis function.

To smooth the data measured at Nausta, kriging was used as the gridding method for creating a functional map (figure 4.1). The results are illustrated in chapter 7.1.

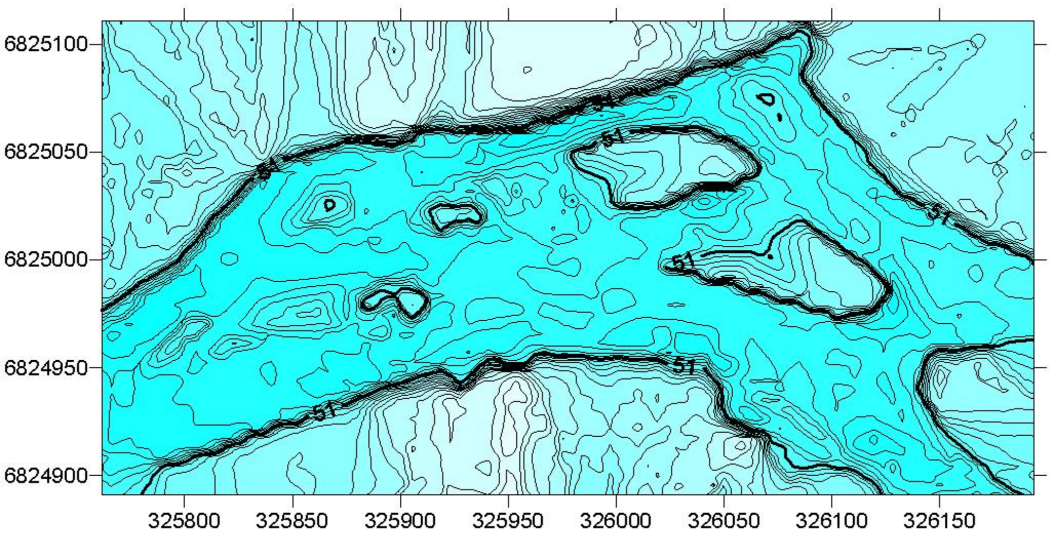

Figure 4.1 Surfer created topography

4.2 River2D

The following chapter is mainly a summary of ”R2D_Bed - User’s Manual” (University of Alberta, 2002), “R2D_Mesh – Introduction to Mesh Generation and User’s Manual” (U.S. Geological Survey, 2002) and “River2D – Introduction to Depth Averaged Modelling and User’s Manual” (University of Alberta, 2002). The summary is amended with own results and own experiences during the modelling process. The shown examples and figures are only extracts from the models created for this thesis (except figure 4.4).

River 2D is a two dimensional depth averaged finite element hydrodynamic model that has been customized for fish habitat evaluation studies. The River 2D model suite actually consists of four programs: River 2D Bed, River 2D Ice, River 2D Mesh and River 2D. All four programs have graphical user interfaces that are supported by any 32 bit version of Windows. The Bed, Ice and Mesh program are graphical file editors. River 2D Bed was designed for editing bed topography data while River 2D Ice is intended for developing ice topographies to be used in the modelling of ice-covered domains. The Mesh program is used for the development of computational meshes that will ultimately be input for River 2D [7].

These programs are typically used in succession. The normal modelling process would involve creating a preliminary bed topography file from the raw field data, then editing and refining it using the Bed program. If an ice-covered domain were being modelled, the Ice program would be used to develop ice topography. The resulting bed topography file is used (in conjunction with an ice topography file where relevant) in the Mesh program to develop a computational discretization as input to the River2D model. The hydrodynamic model is then used to solve for the water depths and velocities throughout the discretization. Finally, the model may be used to visualize and interpret the results and perform PHABSIM type fish habitat analyses. An iterative approach at various stages, including modification of the bed topography (and ice topography), is usual [7].

4.2.1 River2D Bed

River2D Bed is a utility program intended for use with the River2D river modelling system. The bed program is an interactive and graphical bed topography file editor. The relevant physical characteristics of the channel bed necessary for flow modelling are the bed elevation and the bed roughness height. The bed program allows these values to be edited on an individual point basis or over irregular polygonal regions. It is also useful for editing channel index files, used in habitat analyses, with channel index replacing roughness height as the second nodal parameter [7].

The modelling process begins creating a preliminary bed topography file from the raw field data. Before the XYZ data can be imported to the bed program the coordinates has to get changed in a text file.

Every single XYZ data point is represented by a line in the text file and consists of a point number, x-coordinate, y- coordinate, bed elevation, bed roughness height and an optional code (up to twenty alphanumeric characters), all separated by any number of spaces or tabs. An example of the text file is shown below. Ordinary plain text output (tab or space delimited) from a text editor, word processor, or spreadsheet is entirely suitable. The end of the list of data points should be indicated with a period, which may be part of a comment, such as "end of data points [8].

```
n      y      x      z      k      Code
1      326125.9585 6824879.8755      50.9635     0.1   CS-inflow
2      326126.9295 6824884.1195      50.9855     0.1   CS-inflow
3      326125.7275 6824887.7055      50.9995     0.1   CS-inflow
4      326121.2975 6824891.7585      50.9935     0.1   CS-inflow
5      326120.4985 6824895.8895      50.9775     0.1   CS-inflow
```

no more nodes.

no more breakline segments.

no more boundary segments.

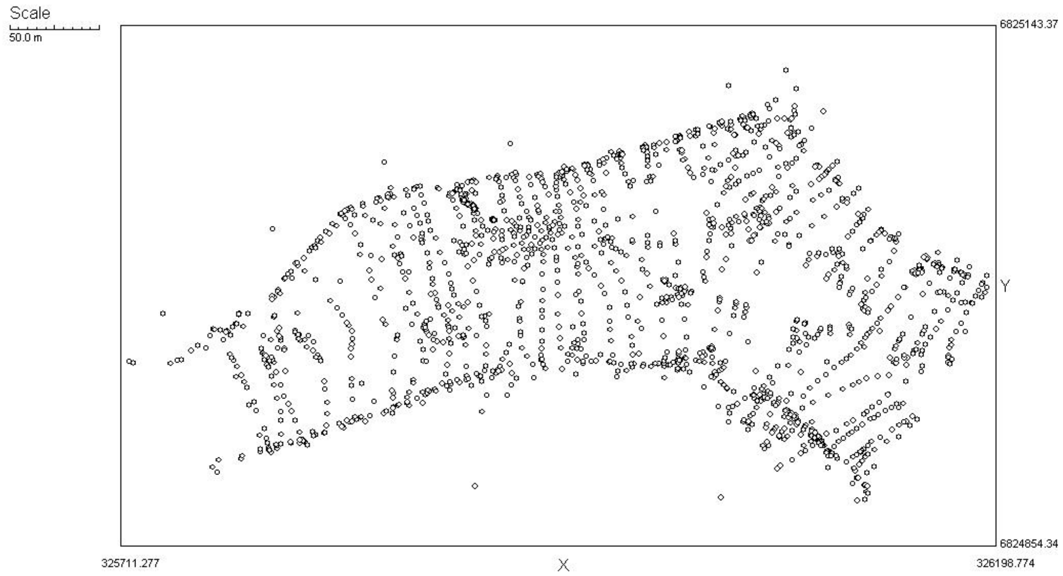

Figure 4.2 XYZ data

River2D Bed interpolates the raw field data and shows a premature topography from the measured area. The first visualised topography requires to be checked accurately. Many mistakes happened because of incorrect interpolation or erroneous data, however every node can get changed manually afterwards.

After creating a preliminary bed topography file from the raw field data the bed program is used to refine and edit the data. The River2D model is based on the Triangulated Irregular Network methodology, including breaklines, for spatial interpolation of nodal parameters. The nodal values are usually measured points, but the breakline locations are judgemental. The bed program allows interactive setting and deleting of breakline segments. An example of the breakline written into the .bed file is shown below.

```
41          14          42
41          42          72
41          72          71
41          71          44
41          44          13
```

```
no more breakline segments.
```

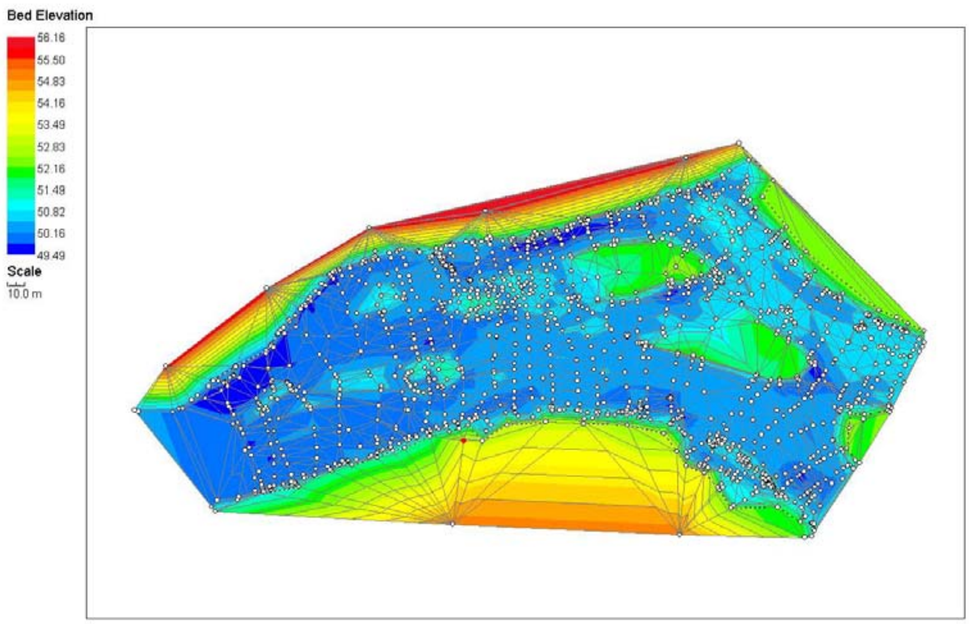

Figure 4.3 Bed Elevation

Finally according to the triangulation the topography, the bed roughness, the breaklines and boundaries are written to a .bed file. Points and sections can be extracted to .csv file. Furthermore the .bed file is used as an input file for the mesh program.

4.2.2 River2D Mesh

The mesh program is a computational mesh generating environment for two-dimensional depth average finite element hydrodynamic modelling [7].

The mesh program is not a fully self-contained data pre-processor. There is no facility for modifying the input topography, for instance deleting an erroneous data point. The interpolation of the topographic input data to the finite element mesh is on the basis of a constrained Delauney triangulated irregular network. Therefore it is usually desirable that the raw field data be processed through the bed program or a GIS application to the point where an adequate bed topography model is achieved [9].

The Mesh program generates data files exclusively for the River2D hydrodynamic model. The functionality of the generator is basic, but adequate for effective mesh generation. The generated mesh should be saved often to minimize the impact of program crashes [9].

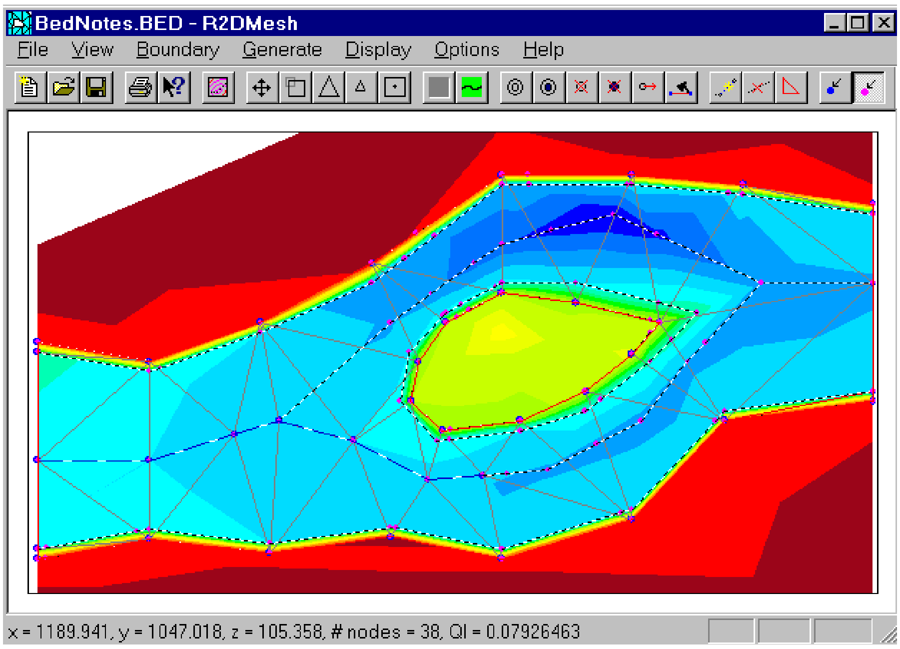

Figure 4.4 River2D Mesh [9]

The basic procedure is to input a bed topography file which appears in the mesh generation window as a contour map. Afterwards the user draws a boundary outline within the map to delineate the modelled region. Breaklines or featurelines can be specified in the input topography file as well. The effect of defining a breakline is that the resulting triangulation is constrained to interpolate linearly along the breakline.

The boundary geometry consists of an enclosing polygon in addition if necessary any number of internal polygons representing islands. Discharge and stage boundary conditions are defined as desired.

Now that the boundary is defined and the boundary conditions are specified, the actual discretization points can be inserted. The boundary conditions are automatically transferred from the boundary definition and the topography data to the new points and segments. Boundary nodes should be generated only once.

Then the interior of the modelled region is filled with nodes by various means. The key feature of the mesh program is its ability to triangulate any arbitrary distribution of input nodes into a usable mesh. Any combination of uniform, radial, area, and region fills can be used as well as inserting individual fixed or floating nodes. Each inserted node takes its bed elevation and roughness values by linearly interpolating from the underlying topography model.

Depending on the computational capability a limit number of nodes are given. If the number of nodes is exceed the Simulation will not start considering of too much nodes to calculate, therefore it is better to start with less nodes and refine the mesh if it runs.

When the density pattern is achieved, the overall mesh is smoothed by adjusting nodal positions, elevations and roughness change simultaneous. The mesh is smoothed one or several times to regularize the triangle shape and give more gradual transitions between areas of different node density.

Furthermore the user has to specify the boundary conditions. A specified total discharge across a boundary segment is defined using the inflow condition. It is simplest if the boundary has been defined so that a single boundary segment covers the complete inflow section. A fixed downstream water surface elevation boundary condition is specified using an outflow condition. Any segment defined to be inflow or outflow can be changed back to a no flow boundary by selecting the “Set Noflow” command.

Finally the user creates from the generated mesh an input data file for the River2D hydrodynamic model program. Before the input file is saved, a dialog box appears requesting an estimate of the inflow water surface elevation. Since the inflow boundary condition is usually discharge, the inflow elevation is an unknown which the program must solve for [9].

Finally the generated mesh should be saved.

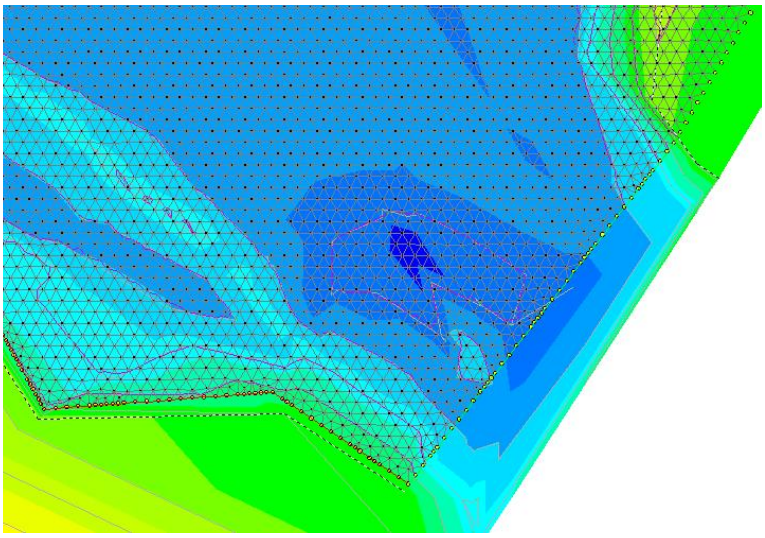

Figure 4.5 Detail of the uniform filled mesh file in Nausta

4.2.3 River2D 0.90

The River 2D model is a two-dimensional, depth averaged finite element model. It is intended for use on natural streams and rivers and has special features for accommodating supercritical / subcritical flow transitions and variable wetted area. It is basically a transient model but provides for an accelerated convergence to steady-state conditions. The River 2D environment has a number of options to aid the user in visualizing the progression and/or final results of the hydrodynamic computations including colour maps, contour maps and velocity vector fields [7].

A model is only as good as its input data. As input data, River2D require channel bed topography, roughness, boundary conditions and initial flow conditions. In addition, some kind of discrete mesh or grid must be designed to capture the flow variations.

The basic procedure is to input the River2D input file from the mesh program in addition the bed topography file. To identify problem points every node gets a number. The node numbers are also useful when editing boundary conditions.

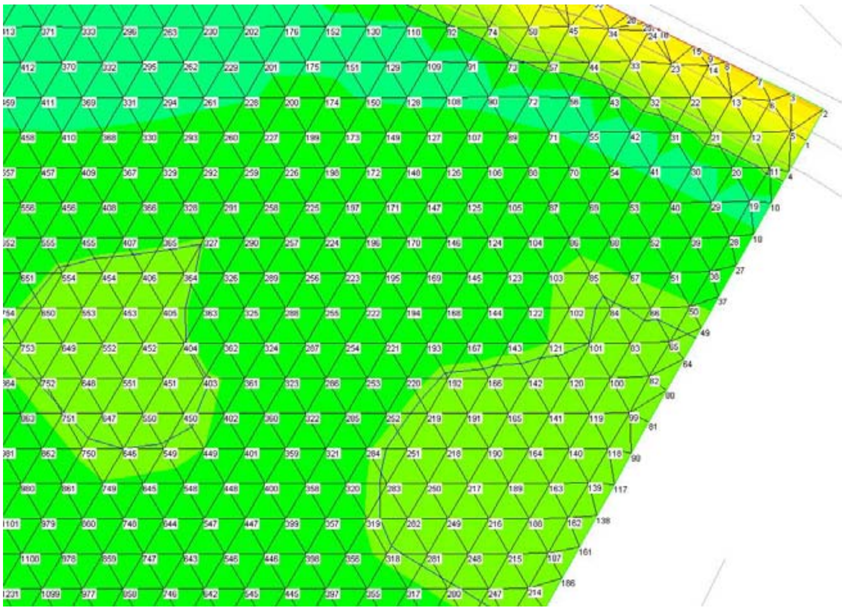

Figure 4.6 River2D input file (.cdg) with mesh and node numbers

The River2D model is in fact a transient one, at any given time. The model can be run in two different modes: steady and transient. The steady mode is actually a pseudo-transient one. Therefore the iterations are moderated by time increments and a final time is used to end the simulation. The model time required to reach steady state varies from problem to problem. A useful scale is to estimate the time for a fluid particle to flow the length of the reach (Δt figure 4.7.). Doubling or tripling this time will usually provide a reasonable estimate of the model time to steady state [10].

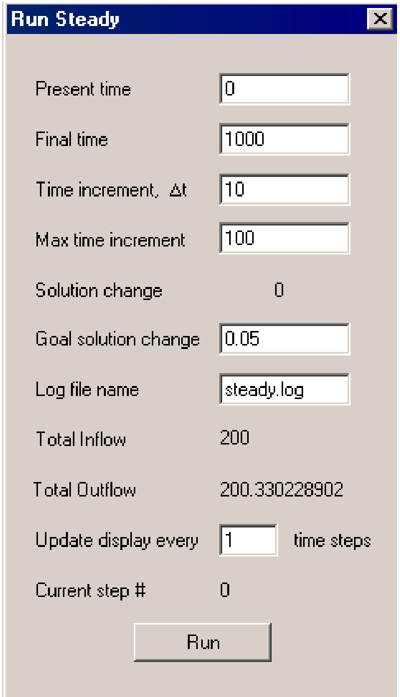

Figure 4.7 The run steady dialog box

The *Present time* value is the point in model time at which the solution is currently running or has stopped at. It can be reset before the start of a subsequent run.

Final time is the time at which execution of the hydrodynamic model will be stopped. If the final time is achieved before the goal solution, the time should be increased.

Time increment is the size of the current time step. It may be set at the start of a run. If it is too long the program will automatically adjust it downward. During computation the iterations this value normally increases steadily. If the number decreases dramatically and gradually grow again, there may be a problem with the boundary conditions and/or the mesh.

Max time increment is a user specified setting for the largest time step allowed.

Solution change is the relative overall change in the solution variables over the latest time step. If the number becomes small enough, the solution can be considered converged.

Goal Solution change is the user specified target relative overall solution change.

Log file name is the name of the text file to which a record of the program execution is written. This record includes the time, time increment and solution change for each iteration.

Total Inflow and *Total Outflow* display the total discharge flowing through inflow and outflow boundaries. In steady mode these two values should become equal.

Update display every … time steps is used to set how often the display updates.

Current step … keeps track of the number of time step iterations since the start of the latest run.

In a transient simulation, the purpose is to receive accurate spatial results throughout the duration of a specific temporal event. This requires an accurate solution of the governing *non-linear* system of equations at every time step in a simulation. For further information on the transient mode solution process see River2D User's manual [10].

After successful simulation the results can be displayed graphically (figure 4.8), dump as nodal alternative grid csv file or extract points either sections as csv file.

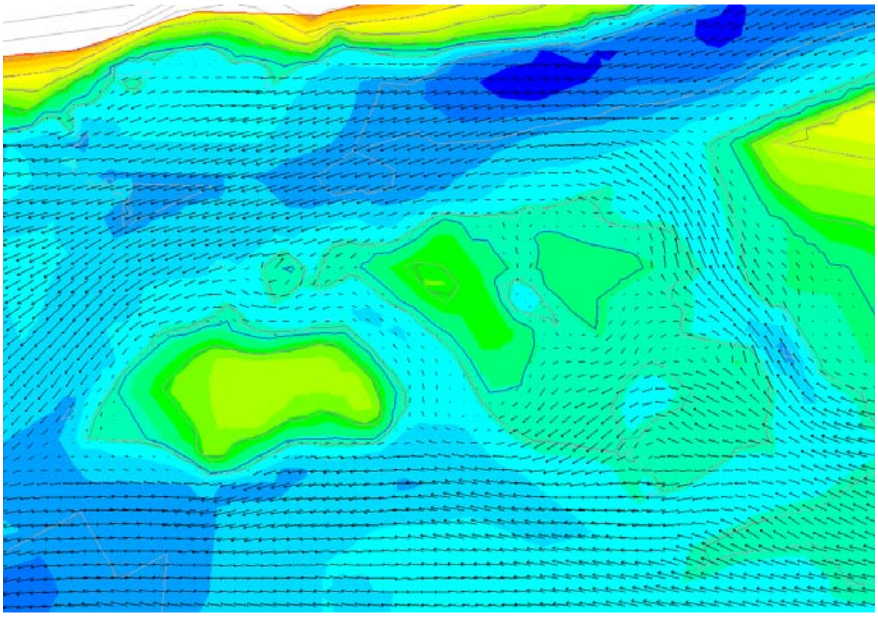

Figure 4.8 Velocity vectors as result of River 2D

4.3 SSIIM

The following chapter is mainly a summary of the User's manual of SSIIM Version 1.1 and 2.0, written and published in the year 2005 by N.R.B Olsen (Department of Hydraulic and Environmental Engineering, NTNU Trondheim, Norway). The shown examples and figures are only extracts from the models created for this thesis.

The abbreviation SSIIM stands for Sediment Simulation In Intakes with Multiblock option. The program is made for use mainly in research for hydraulic, river, sedimentation and enviromental engineering.

The main strength of SSIIM is the capability of modelling sediment transport with movable bed in a complex geometry. It is also be used for habitat studies in rivers, mainly for Atlantic salmon, furthermore for modelling free-flowing algae. Two different versions are available: SSIIM 1 and SSIIM 2. For this thesis SSIIM 1.1 was used.

SSIIM 1.x uses a structured grid compared to SSIIM 2 which uses an unstructured grid. Both solve the Navier-Stokes equations using the control volume method with the SIMPLE algorithm and the k–ε turbulence model. The Navier-Stokes equations for turbulent flow in a general three-dimensional geometry are solved to obtain the flow velocity. The k–ε turbulence model is used for calculation the turbulent shear stress. It also solves the convection-diffusion equation for sediment transport, using van Rijn's formula for the bed boundary.

The Navier-Stokes equations for non-compressible and constant density flow can be modelled as [17]:

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

The program has an interactive graphical grid editor creating a structured grid. The post-processor includes vector graphics, contour plots, profiles etc. which can run simultaneously with the solver, enabling viewing of intermediate result [17].

A SSIIM run should be started by reading input files or generating the grid first using the grid editor.

4.3.1 The grid editor

If the Grid editor is started without reading a previously generated grid, a rectangular grid is shown as default. At the beginning the dimension moreover the accuracy of the grid were defined by the number of cross sections and the number of points per cross section. The left side of the grid is preset as the water inflow, the right side as water outflow. When generating a grid for a natural geometry, the inflow and outflow of water are often not as preset. Before modelling the grid it should be changed into the correct direction.

Furthermore the external borders of the grid were modelled. Since SSIIM does not work very well with dry cells the grid should be generated with the measured waterline from the particular discharge to model the external borders of the grid. To fix the borderline ’no-move points’ were generated and dragged to characteristic points along the waterline.

When the external borders are defined the detailed topography survey are carried out by writing a new geodata file moreover it should be import into the model. The xyz data's are shown as circles, the different colours indicate different vertical levels (figure 4.9).

The z values of the grid are interpolated from a set of geometrical data read from the new geodata file. Before proceeding in this matter it is very important to write a new koordina file manually to save the new values of the grid from the interpolation. If SSIIM is closed without saving the modification is lost and the process has to be repeated.

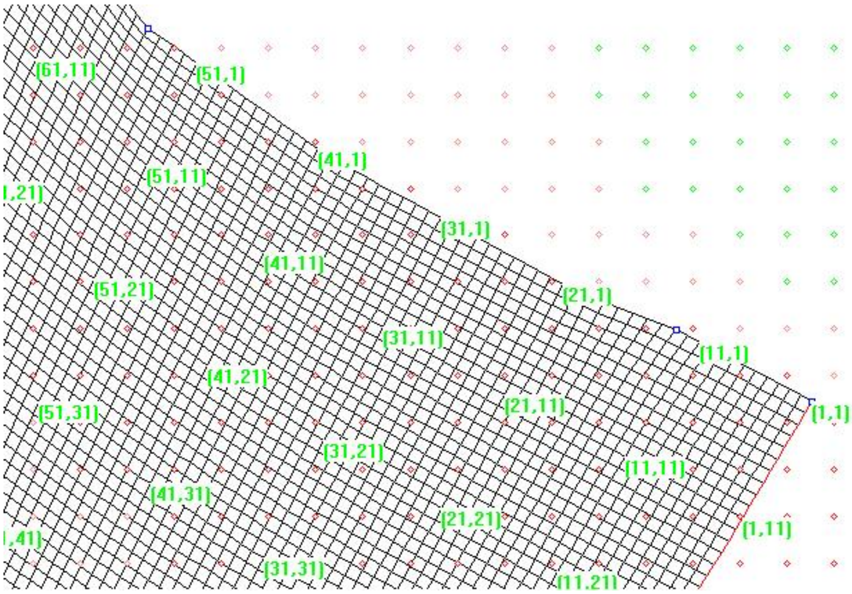

Figure 4.9 Grid editor with geodata points and structured grid

4.3.2 Input files

The program can produce many of the input files by itself. Most of the files are only used for special purposes and they are normally not required. Two main input files have to be present when the program starts. If not, the program then generates default files. All the input files can be edited using a standard editor.

In the following, some important input files are shortly described.

4.3.2.1 <u>The geodata file</u>

This file contains a number of xyz coordinates in meter. An example is given below:

```
E     26.4512    0.2894     50.9792
E     30.8931    0.2894     51.1315
```

```
E     35.3351    0.2894     51.2626
E     39.7770    0.2894     51.3027
E     44.2190    0.2894     51.6015
E     48.6609    0.2894     51.7443
```

Every xyz data point is shown in the grid editor when generating the grid. It is also used in the interpolations to generate the z values for the bed of the grid.

To achieve a smooth grid, making the interpolation of the detailed topography survey with an graphic program like surfer (chapter 4.1) is recommended.

4.3.2.2 The koordina file

The koordina file contains the grid geometry, describing the bed of the geometry with a structured grid. The grid can be made using a map, a spreadsheet or the grid editor. After each modification in the grid editor it is very important to write a new koordina file, especially after the interpolation.

It contains the necessary input data, the x, y and z coordinates of the points where the grid lines crosses. The first two numbers are integers including the number of the cross section and the point on the cross section followed by the xyz coordinates in meter. An example is given below:

```
1 1 441.524 121.161 50.904
1 2 441.087 120.300 50.699
1 3 440.649 119.440 50.628
1 4 440.212 118.579 50.609
1 5 439.774 117.719 50.651
```

4.3.2.3 The bedrough file

The bedrough file is used to give a roughness height in meter to individual bed cells. The roughness heights in the bedrough file overwrite the information about the roughness given in the control file. The first character is a B followed by two integers as indexes for the bed cell. An example is given below:

```
B     1     1     0.035
B     1     2     0.035
B     1     3     0.035
B     1     4     0.035
B     1     5     0.035
```

4.3.2.4 The innflow file

This file is used for the upstream boundary condition and includes the flow velocity in xyz direction. If the inflow file exists in the subdirectory, the program searches and uses it automatically, otherwise the program proceeds normally.

The first character is a E followed by two indexes for the horizontal and vertical position. Then the flow velocity components in the x, y and z directions are given in meter per second. An example is given below:

```
E     61    2     -0.2233    0.1249     0
E     61    3     -0.4013    0.2245     0
E     61    4     -0.4996    0.2794     0
E     61    5     -0.5702    0.3189     0
```

4.3.2.5 The control file

The control file is the core of SSIIM giving the most of the parameters the model needs, for instance the downstream waterlevel, the water discharge furthermore the Manning-Strickler's friction factor. If a control file does not exist the program then generates a default file. In addition after modifications in the program according to the user's needs can write a new control file (as control.new).

Some parameters which affect the accuracy and the convergence of the solution can be modified while the water flow field is being calculated. The program does not need every data set, default values are given when a non-required data set is missing. It checks the data sets top down, furthermore if an error is found the program is terminated and a message is written to the boogie file.

An example for necessary and non-necessary data sets is given below:

```
F 16 0.0330000   roughness in meters
F 53 100 100 1 1
G 1 200 100 5 1    grid and array sizes
G  3  0.000000  20.000000  40.000000  70.000000  100.000000
vertical grid distribution
G 8 1 1 48 53 1 5 0.000000 0.000000 0.000000
G 13 3 2 12 49 53 2 5
G 13 3 39 131 38 42 2 5
W 1 30.000000 20.000000 50.660000
W 2 5 1 50 100 150 200
W 6 1 100
```

```
W 6 1 1
```

The F 16 data set gives the roughness coefficient which is used on the side walls and the bed. If not set, the coefficient is calculated from the Manning-Strickler's friction coefficient (W1). Values in the bedrough file overwrite this value.

The F 53 data set generates print iterations. Four integers are read, which gives the interval for when printout to files are done.

The G 1 data set gives the number of cross-sections, grid lines in the stream wise direction in addition vertical direction, furthermore the number of sediment sizes. This data set must be present in the control file

The G 3 data set must also be present in the control file. It gives the vertical distributions of grid cells.

The G 8 data set gives values for initial velocities.

The G 13 data set is used when a region of the geometry is blocked out by a solid object, for example an island.

The W 1 data set define Strickler's number, discharge and downstream waterlevel. This data set must be present in the control file. It is used to generate the water level for the calculations using a standard backwater calculation.

The W 2 data set identify the integers which cross section are used in the initial backwater surface computation.

The W 6 data set gives the 'no-move points' which is used in the grid editor

4.3.3 Result files

The boogie file and the result file are result files which are automatically and simultaneously generated by the program during a calculation.

4.3.3.1 <u>The boogie file</u>

Print-outs of intermediate results from the calculations, furthermore parameters as average water velocity, shear stress and water depth are shown in the boogie file. If in SSIIM an error occurs, an explanation is written in this file. Examples are given below:

Initial water level calculation:

```
In initial - velocity
```

```
Loop1,iter,area,radius,velocity,waterlevel:  8  4.081160e+001
2.909344e-001 4.900568e-001 5.083233e+001
Loop1,iter,area,radius,velocity,waterlevel:  8  3.922239e+001
3.080801e-001 5.099129e-001 5.099339e+001
Waterlevel = 50.661823 meters for cross-section i = 199
Waterlevel = 50.663642 meters for cross-section i = 198
Waterlevel = 50.665456 meters for cross-section i = 197
...
```

Information about input files:

```
Have read 19701 roughness points from file 'bedrough'
File 'innflow' not used
```

Error solution diverged:

```
Iter: 91, Large residual for f(171,10,3,6) : 1.016966e+006
f = 8.677439e-005, source = 1.016969e+006, wap =
1.541025e+006
flow3 = 6.993444e+003, flow2 = -1.853878e+003, flow1 = -
1.065982e+004
xvel = 1.046687e+002, yvel = 2.166910e+001, zvel = 3.345663e-
001
Solution diverged
```

After the word Iter an integer follows, which shows the number of the iteration. Then the residuals for the six equations are shown, all these must be under 10-3 before the solution has converged.

4.3.3.2 The result file

In the result file the results from the water flow calculations are shown for all grid cells. The results are flow velocities in x, y, and z direction, k, ε, pressure and the fluxes on all the walls of the cell. An example of a result file is given below:

```
Results from SSIIM - flow, iter = 18667
Residuals:  0.000091  0.000085  0.000446  0.000820  0.000983
0.000113
Roughness : 0.100000
C 200 100 5
 i  j  k    u    v    w    k   e   f1   f2   f3   p
```

```
F   1   1   0 0.00000000e+000  0.00000000e+000  0.00000000e+000
0.00000000e+000         1.00000000e-014         0.00000000e+000
0.00000000e+000 0.00000000e+000 0.00000000e+000
F   1   1   1 0.00000000e+000  0.00000000e+000  0.00000000e+000
0.00000000e+000         1.00000000e-014         0.00000000e+000
0.00000000e+000 0.00000000e+000 0.00000000e+000
F   1   1   2 0.00000000e+000  0.00000000e+000  0.00000000e+000
0.00000000e+000         1.00000000e-014         0.00000000e+000
0.00000000e+000 0.00000000e+000 0.00000000e+000
```

The first result lines give the residuals, the roughness and the grid size. Furthermore the next lines give the nine values for one cell. After the letter F the three indexes of the cell are followed by the flow velocities in x, y, and z direction, k, e, the fluxes in the three directions and finally the pressure.

In the program the result file can also be shown graphically. An example of a cross section with velocity vectors is given below:

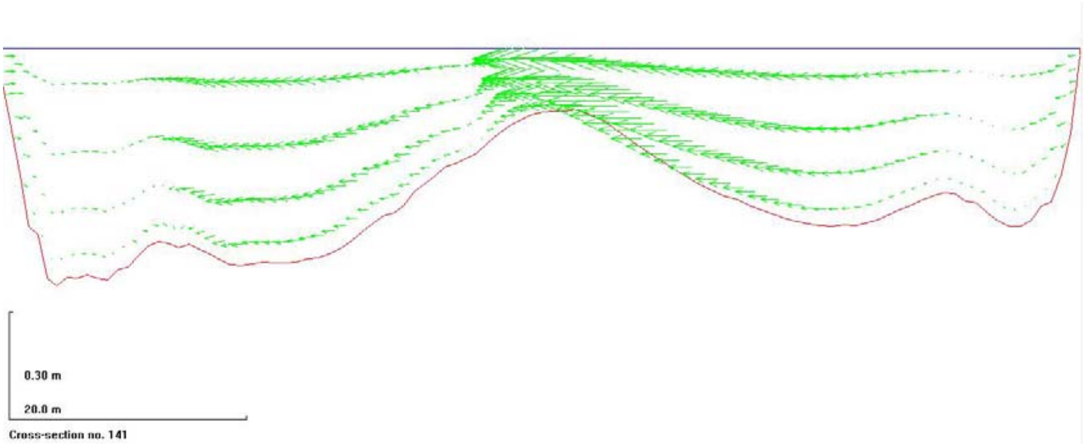

Figure 4.10 cross section with velocity vectors

5 Calibration of the Models

Calibration is the validation of models with specific measurement. A basic calibration is a comparison between measurements and another measurement made in a similar way as possible with a second device.

In case of calibration of a hydraulic model it is the process of modifying the input parameters (for example roughness height or inflow velocities) to a hydraulic model until the output from the model (for example flow velocity furthermore water level) matches an observed set of data.

Once the model is calibrated at a certain discharge, other discharges are able to be calculated. Primarily the modelling process should have been carried out for at least three different discharges, about mean flow (22 m³/s) and two lower discharges. In the end the discharges 20 m³/s, 15 m³/s and 10 m³/s were measured moreover have been used for further calculations.

The parameter roughness height requires an accurate survey of the substrate covering the river bed. As a result a substrate map (figure 5.1) was made defining the different substrate regions.

Figure 5.1 Substrate map

5.1 River 2D

The calibration of the model in River2D was done by changing the roughness height in the River2D Bed program by comparing the water levels exported from the model with the measured water levels in real.

Changing the roughness is much easier compared to the bedrough file for SSIIM caused by the possibility of graphically modification. Every Node a roughness height is dedicated, accordingly the bed program interpolates the values. Alongside on the riverbank in addition outside from the water level the roughness height was set very high. This was made only for graphically reasons, furthermore it has no stake in the calculation. The result of the interpolation is given below:

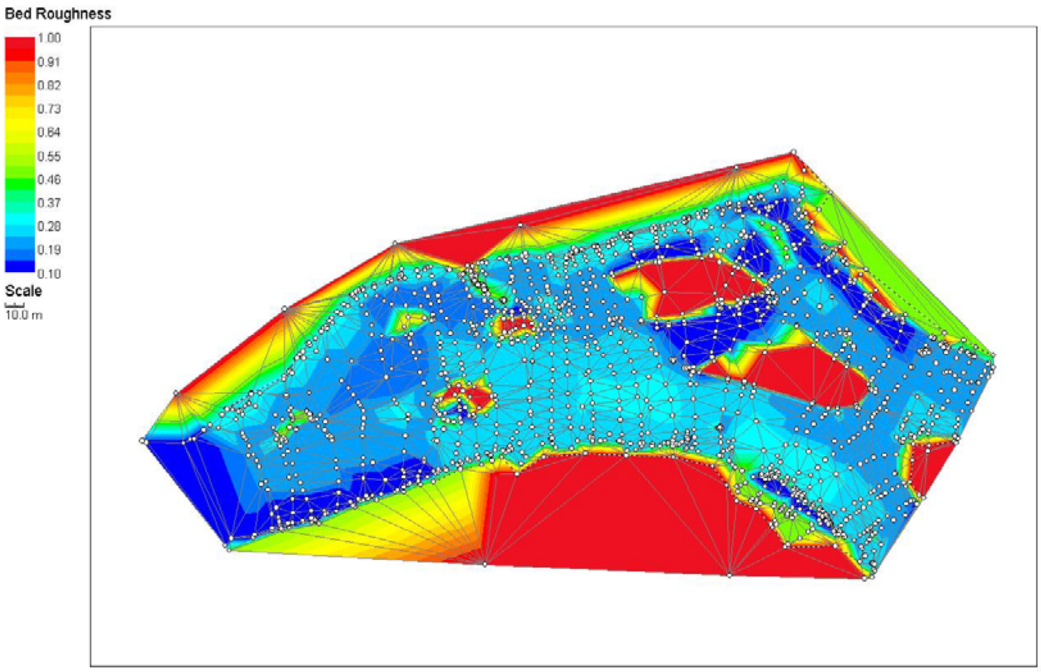

Figure 5.2 Bed roughness displayed with River2D Bed program

5.2 SSIIM

The calibration of the model was only done by changing the roughness in the control file or in the bedrough file. Further the roughness is essential for the calculation of the flow velocity furthermore the water level. Changing the bedrough file is very extensive by reason that the file is a simple text file and had to be changed in every cell of 40.000 all over the riverbed.

The measured flow velocities could not be used to calibrate the model. Every run with given flow velocities diverged the solution. This problem is discussed amongst other things in chapter 8.

Once the model is calibrated at a certain discharge, other discharges are able to be modelled by changing the water level downstream in the control file. If lower discharges are modelled, it is possible that the calculation diverges caused by dry cells. For this purpose the grid has to be changed in these areas, another opportunity is to block out the dry cells. In the G 13 data set of the control file 49 blocks can be used.

An improvement of the model can be achieved by using the innflow file (chapter 4.3.2.4). It forces the flow velocities in x, y, and z direction in the inflow section. During field work this measurement was done during a discharge of 20 m^3/s. As a result an innflow file was written, nevertheless the calculation diverged fast immediately after the inflow section. There are many reasons possible why this improvement did not work. Maybe this was caused by the two inflow sections which are given in Nausta or the flow velocity measurement was not accurate enough. The transect of the inflow section in Nausta is about 100 meter wide furthermore every 2 meter a flow velocity measurement in x, y and z direction normal to the transect was made. As a result numerous data's had to be convert into the coordinate system. No matter what was the mistake, the calculation with the innflow file diverged every run.

6 Changes in the Riverbed

The objectives of river improvement works are to aid navigation, to prevent flooding, to reclaim or protect land or to provide water supply for irrigation, hydropower development or domestic and industrial use [11].

The improvements at the river Nausta are arrangements at a small scale initiating of new natural habitat for the Atlantic salmon and the brown trout. Adjusting and analyzing various habitat improvements is one of the sub goals of the project increasing salmon production in this investigation area. Combinations of different adjustments, to increase areas with good habitat for the Atlantic salmon, will be tested with the hydraulic models.

For this project nature orientated structuring is demanded. Using constructions with natural materials like larger rocks or wood is a condition of the adjustments in the riverbed. Also the adjustments should not look like human engineered, moreover they have to be under the water surface of mean flow and do not change the natural scenery [1].

Generally discharges around mean flow causes areas where the flow velocity is too high or water depth is too shallow. With lower discharge shallow areas in addition avoided habitat conditions are increasing. Accordingly at higher discharge, regions with avoided flow velocities are dominating. As a result, adjustments should be generated which reduces the velocity and increases the water depth.

To fulfil the conditions groynes and boulders should be integrated strategically. The structures have to resist a 50-years-flood furthermore the shear stress should be as high that the sediments are able to rebuild.

6.1 Groynes

Groynes are small jetties, solid or permeable, constructed for example of timber, stone rubble or vegetation. They are generally project into the stream upright to the riverbank. Sometimes the groynes are inclined in the upstream or downstream direction.

The main determination of groynes is to reduce channel width and removing the danger of erosion from the banks. In the model they are mainly used to change the direction of the water flow and increase the variation of flow velocity differences.

Like their effect is generally local, the spacing between two groynes should not exceed around five lengths, usually the length is smaller. The larger the ratio of spacing between groynes and the river width is, the stronger is the local acceleration and retardation. To reduce channel width longitudinal dykes are generally more economical than groynes, furthermore equally or even more effective. In the case of this thesis reducing the channel is not the requirement. As a result no dykes are modelled [11].

Figure 6.1 Groyne

6.2 Boulders

Boulders are head-sized cobbles and coarse blocks. If they extend over the riverbed they are literally rocks, moreover therefore they can dominate habitat conditions. Furthermore, isolated boulders alternatively rocks are a micro habitat of their own.

As stream-bed stones alternatively home stones boulders are very important for the young salmon. Depending of its age Atlantic salmon prefers stream-bed stones with a diameter up to 40cm (chapter 2.5.1). For hydraulic constructions river boulders are often sized 60 cm and larger. They are furthermore used for landscaping and water features.

In several areas with a suited water depth but high flow velocity boulders should be used to achieve places where fishes are able to rest.

Figure 6.2 Boulders at a landscaping materials concern

7 Results

This chapter shows the different working steps which achieved the results. They then will serve as an input for the future work.

Therefore the results of

- the refined grid with Surfer
- the hydraulic simulation with River2D
- the hydraulic simulation with SSIIM
- the Meso-scale habitat Classification

are presented in this chapter.

7.1 Surfer

Smoothing the grid for the hydraulic models, data from the land survey were inserted into surfer. For the SSIIM program the kriging method was used to interpolate a regular grid of 1 meter in x- and y-direction (figure 7.1). At areas where the riverbank has a disadvantageous angle according to the grid points additional smoothing had to be done. This was done in the koordina file by avoiding up and down of the bed elevation. An alternative is to interpolate the raw field data in another angle or with another interpolation method.

In comparison the River2D bed program interpolates the raw field data itself and shows a premature topography from the measured area. To avoid mistakes caused by incorrect interpolation surfer was used to interpolate at complicated areas. This was done where enough points were missing to get a smooth grid. The triangulation with linear interpolation was used to smooth the data for the River2D model (figure 7.2).

The following figures give an overview about surfer-made results. The 3D surface was made with the kriging method. It was only made to get a fast optical conclusion about the successful interpolation. If one measured point has a wrong height (bed elevation) it could be seen here relatively quickly.

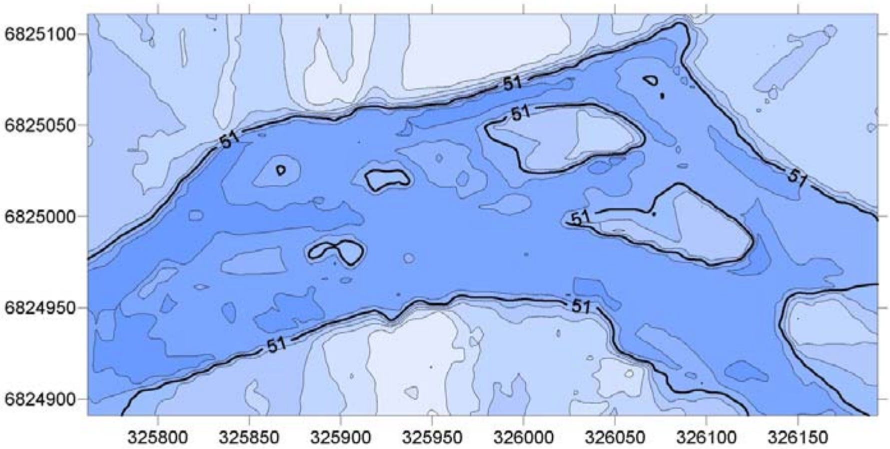

Figure 7.1 Surfer Contour Map (Kriging)

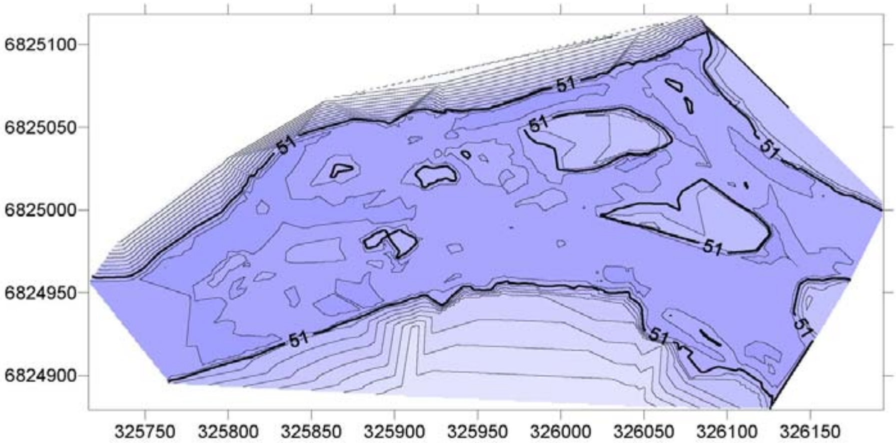

Figure 7.2 Surfer Contour Map (Triangulation with linear Interpolation)

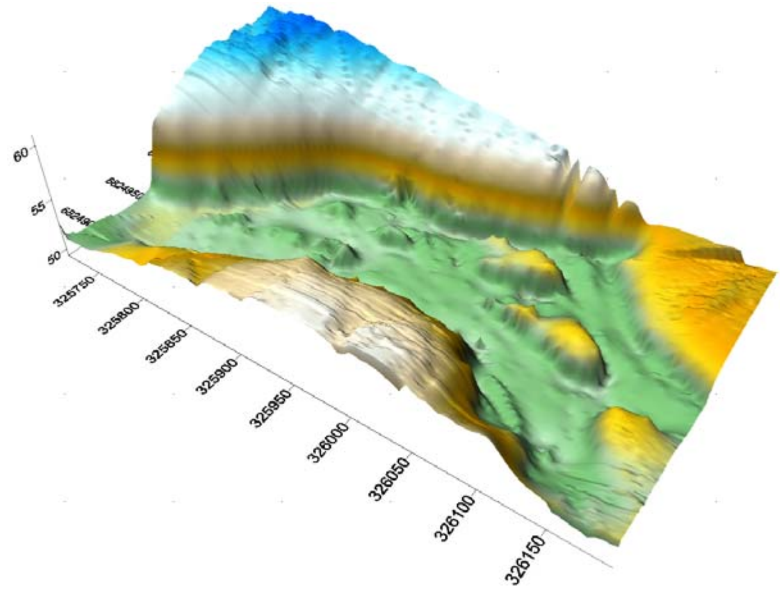

Figure 7.3 Surfer 3D surface (Kriging)

7.2 River 2D

Knowing that a two-dimensional model cannot be compared with a three-dimensional model, the length of the calculations between SSIIM and River2D differed enormously. For example SSIIM required at the same grid size at least 2 days while River2D spend not even 2 hours. As a result River2D was used to check changes in the riverbed first before a SSIIM-run was started.

The sampling of the date was carried out from 1st to 6th October 2006 at river Nausta for three different discharges: 20 m^3/s, 15 m^3/s and 10 m^3/s. The hydraulic model was calibrated for all of these three discharges. In addition it was adapted to the 1-year-flood of 208 m^3/s and to a low flow condition of 5 m^3/s by calculating the waterline downstream. Furthermore the borders were adapted to the new waterlines of the model.

On average 255 days per year are below mean flow of 22 m^3/s, the average of low water every month is 5,8 m^3/s. The Q_{95} (=discharge which is exceeded 95% of the year) is 2,1 m^3/s which is about yearly low water.

Modelling the discharge of 5 m^3/s was chosen because of unavailable data at yearly low water (for example water level and inflow and outflow conditions).

Q = 20 m³/s

The measurements started with the discharge of 20 m^3/s close below mean flow. The discharge was measured with the flow tracker (chapter 3.2.1) and compared with the data at the next gauging station Hovefoss.

In general the flow velocity of the main stream is high, in almost the same manner for the branches. Exceptions are the deeper pools between the bigger islands, where the flow velocity is slower. The results of the flow velocity and the water depth are given below (figure 7.4, 7.5).

Northwards of the big islands right after the inflow area the riverbed is nearly planar moreover the substrate is smooth. This branch turns westwards alongside a fixed riverbank where some smaller branches are discharged into it. However it discharges in the end again into the main stream.

At the downstream area the river furcates between several smaller islands. Those are overgrown with reed and smaller shrubs.

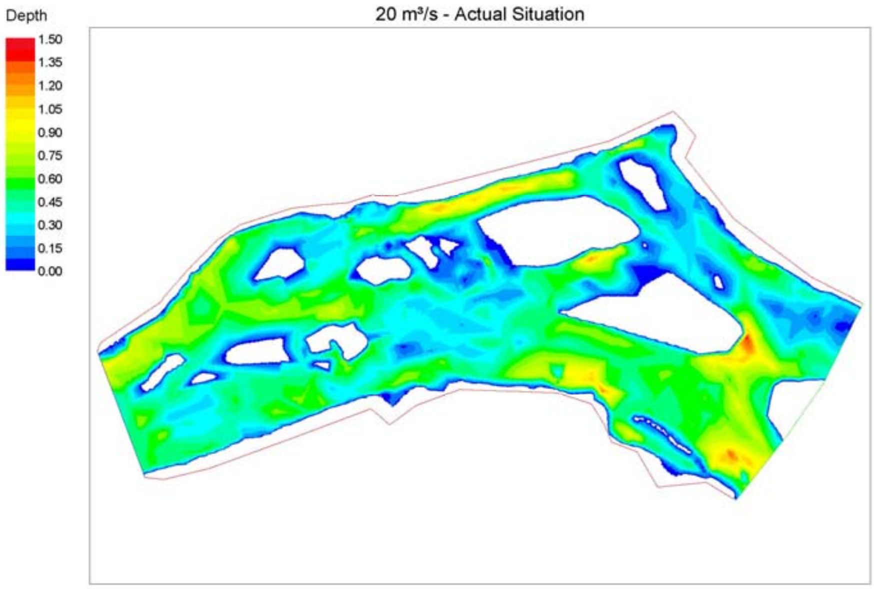

Figure 7.4 Water depth distribution at 20 m³/s

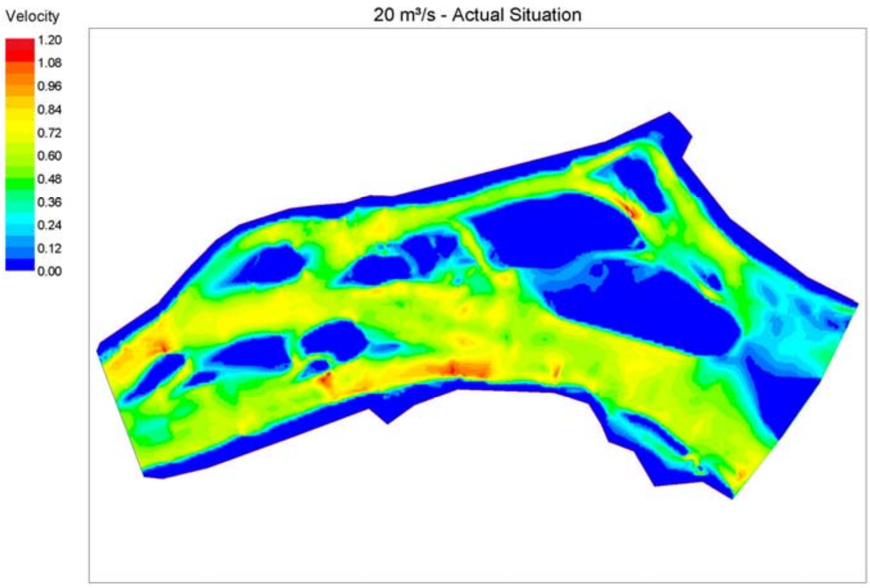

Figure 7.5 Flow velocity distribution at 20 m³/s

Q = 10 m³/s

Even more islands appear at the discharge of 10 m³/s, or rather the existing ones are getting bigger. It is the lowest discharge which could be measured during the observation period. Nevertheless it is the discharge with the highest amount of suitable habitat for the Atlantic salmon (table 7.1). This result is caused by lower velocities with still enough water depth.

The results of the flow velocity and the water depth are given below (figure 7.6, 7.7).

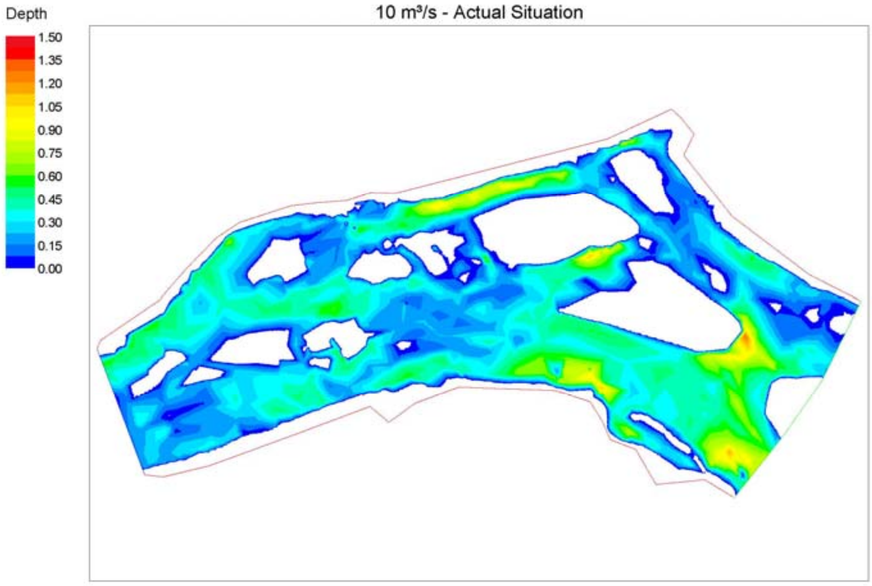

Figure 7.6 Water depth distribution at 10 m³/s

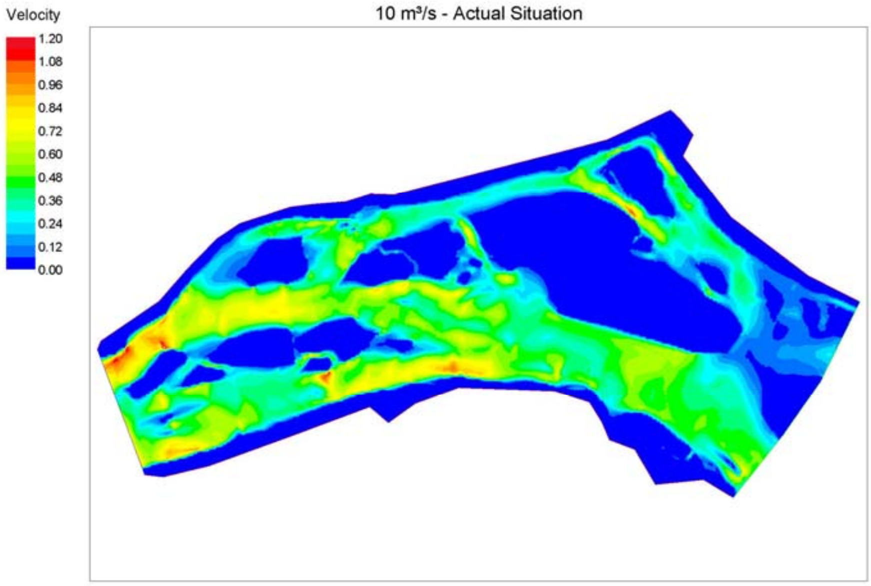

Figure 7.7 Flow velocity distribution at 10 m³/s

Q = 5 m³/s

This model was adapted from the calibrated model with a discharge of 10 m³/s. Modelling the discharge of 5 m³/s was chosen due to the fact that at lower discharges several branches fall dry. Furthermore the observation especially of the flow directions of the data is missing.

At this discharge even more islands occur or rather getting bigger. Suitable habitat regions decrease, similarly deeper pools as retreat areas are hardly available. The water depth of the northern nearly planar branch becomes too shallow. As a result at even less discharge the branch falls almost dry. A bigger retreat area is situated alongside of the fixed northern river bank (oblong green till yellow area at figure 7.8). Furthermore this retreat area still exists at lower discharges.

The results of the flow velocity and the water depth are given below (figure 7.8, 7.9).

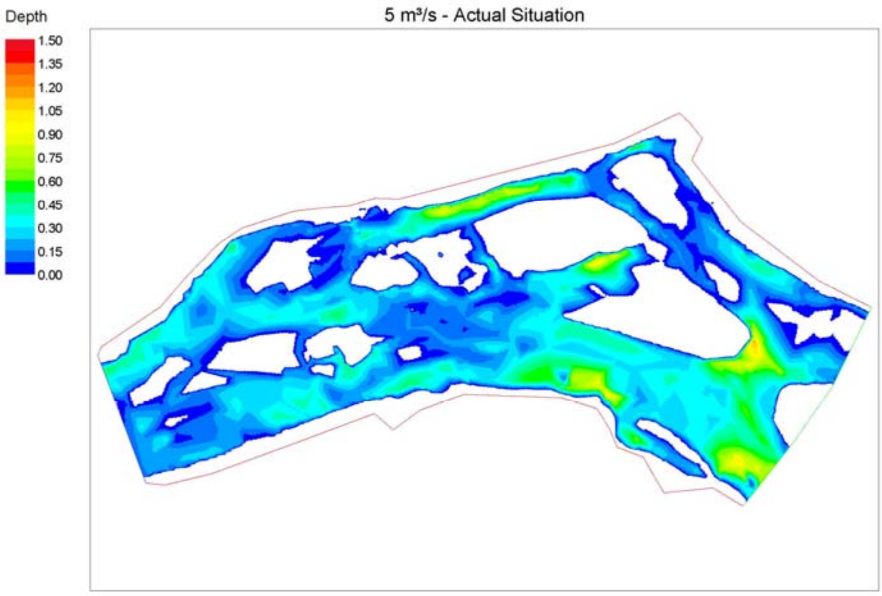

Figure 7.8 Water depth distribution at 5 m³/s

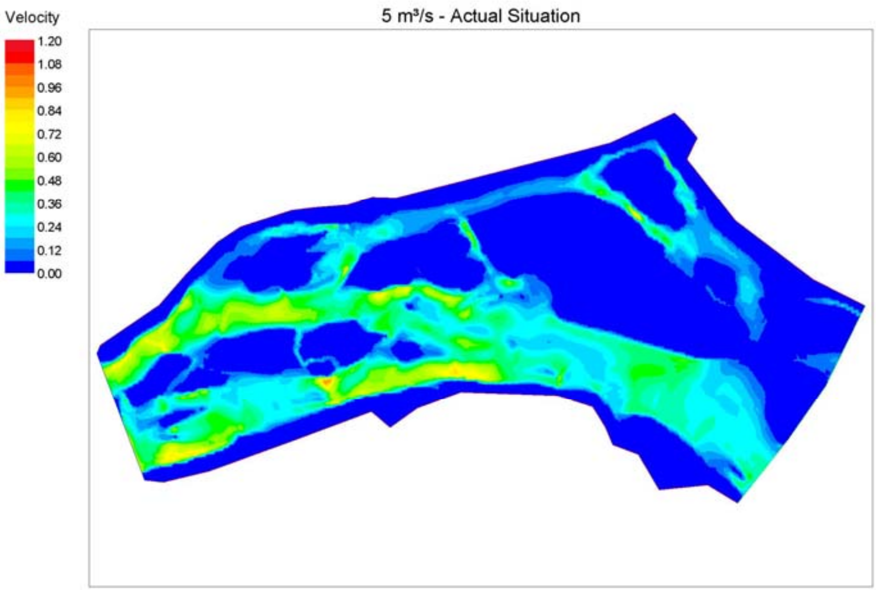

Figure 7.9 Water depth distribution at 5m³/s

After comparing the discharges in the actual situation preferred habitat conditions are most suitable for the discharge-range between 10 m³/s and 15 m³/s, which appears one-seventh of the year. Three-seventh of the year the discharge is below this range, in almost the same manner three-seventh of the year are above this range.

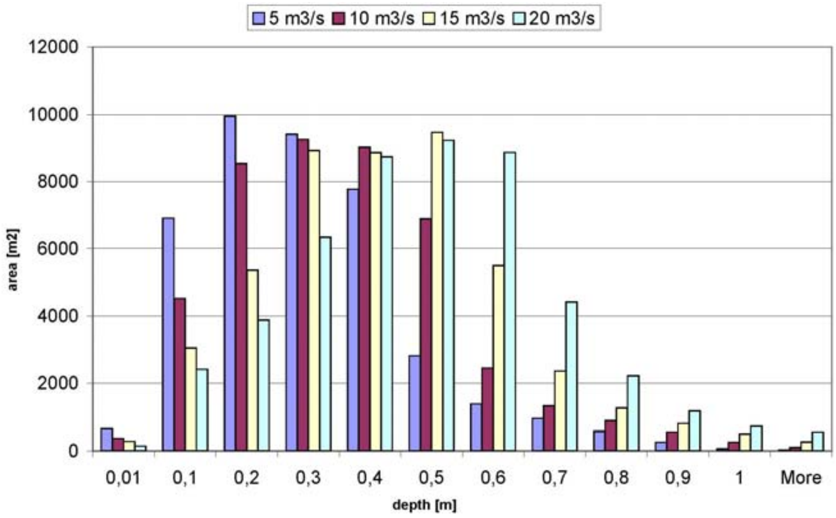

Figure 7.10 Comparison water depth distribution

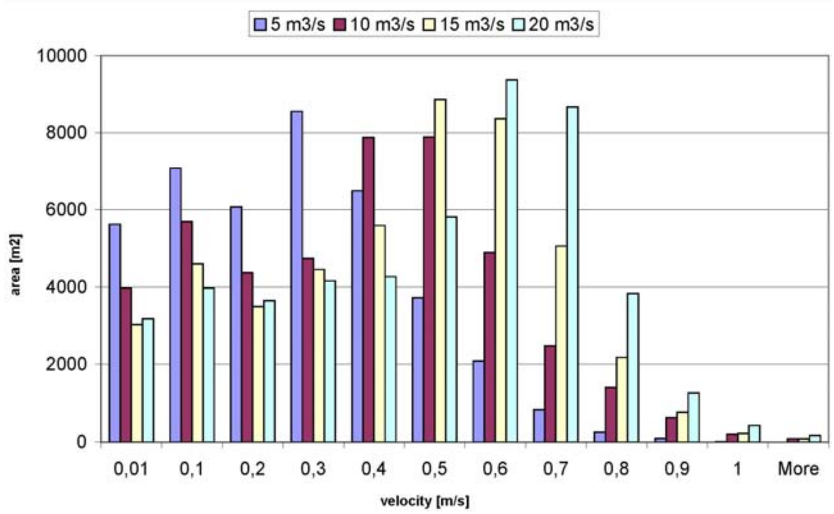

Figure 7.11 Comparison flow velocity distribution

During higher discharges more area is flooded, accordingly more area can be used as habitat. As a result changes in the river bed have to be done for low flow.

After several runs with the River2D model a combination between groynes and boulders seem to yield good results in terms of increasing suitable habitat conditions. With the results of the meso scale habitat classification it would be possible to transmit the changes to other areas in the same class.

River2D can not model changes of the substrate, therefore some positive effects for habitat caused by the groynes and boulders are missing. Downstream of the changes in the riverbed boulders, especially groynes create pools. In the actual situation areas of pools are rare which Atlantic salmon needs in general during autumn and winter.

The Comparisons of the flow velocity and the water depth in the actual and modified situation in order to the preferred habitat conditions of young salmon are given below (table 7.1). The preferred habitat conditions for young salmon are shown in figure 2.12.

		Actual Situation				Modified Situation			
		suit	indifferent	avoid	sum	suit	indifferent	avoid	sum
5 m³/s	m²	7184	5420	28188	40792	6599	6487	28053	41139
	%	**17,6**	13,3	69,1	100	**16,0**	15,8	68,2	100
10 m³/s	m²	10980	4982	28240	44201	12247	4905	27477	44629
	%	**24,8**	11,3	63,9	100	**27,4**	11,0	61,6	100
15 m³/s	m²	11354	5112	30211	46676	12746	5288	28789	46823
	%	**24,3**	11,0	64,7	100	**27,2**	11,3	61,5	100
20 m³/s	m²	9540	5100	34084	48724	11572	4880	31943	48395
	%	**19,6**	10,5	70,0	100	**23,9**	10,1	66,0	100

Table 7.1 Comparison actual situation to modified situation for young Atlantic salmon

A result of a modified situation is given below (figure 7.12, 7.13)

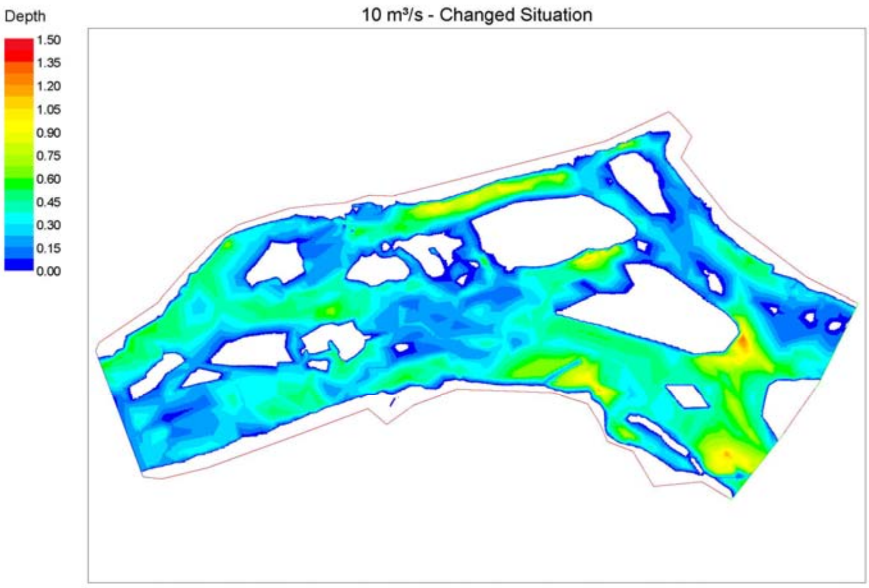

Figure 7.12 Water depth distribution at 10 m³/s (modified situation)

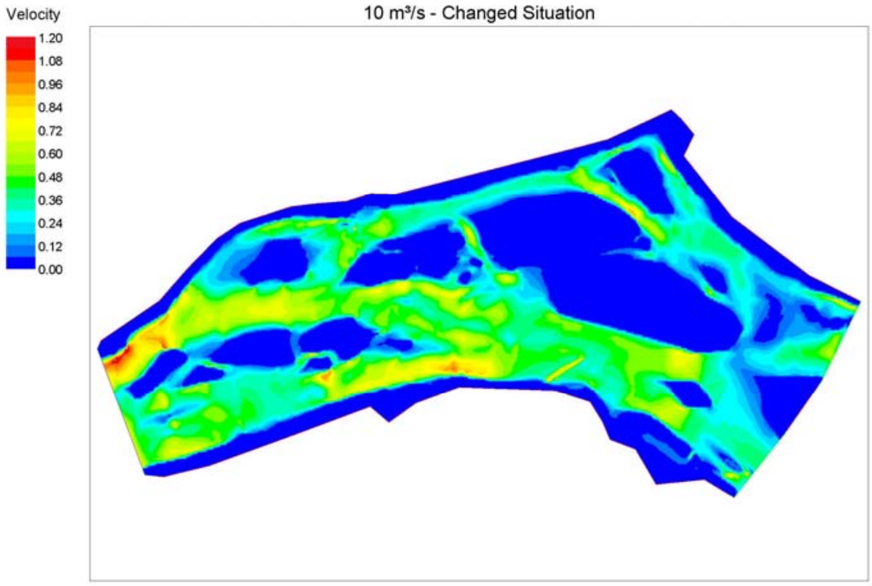

Figure 7.13 Flow velocity distribution at 10 m^3/s (modified situation)

7.3 SSIIM

First of all the SSIIM results are difficult to compare with the River2D results. While River2D generates one column per grid cell, SSIIM generates seven columns, five layers and the upper and lower wall condition. As a result 40.000 grid cells generate a result file with 280.000 columns. Microsoft Office Excel 2003, which was used to interpret the River2D results, is limited to 65.536 columns. Therefore Excel could not be used, even the splitting into two models did not help. A grid size of more than 2m in x and y direction would solve this problem but would not be accurate enough. Amongst other things this problem is discussed in chapter 8.

As described above the result file from SSIIM could not be interpreted with Excel, consequently only the graphic results are shown in this chapter. Also the model was split into two regions whereas the outflow of the upper region was used as inflow file for the lower region.

Sampling the data was carried out in autumn 2006 at river Nausta for three different discharges: 20 m^3/s, 15 m^3/s and 10 m^3/s. The hydraulic model was calibrated for all of these three discharges by adjusting the roughness. An adaptation to the 1-year-flood of 208 m^3/s and a low flow condition at 5 m^3/s did not converged in several runs.

Q = 20 m³/s

The measurements started with the discharge of 20 m³/s close below mean flow. The discharge was measured like the other discharges with the flow tracker (chapter 3.2.1) and compared with the data at the next gauging station Hovefoss.

In general the flow velocity of the main stream is high, as well as for the branches. Exceptions are the deeper pools between the bigger islands, where the flow velocity is slower. The results of the flow velocity are given below (figure 7.14, 7.15).

Northwards of the big islands right after the inflow area the riverbed of the branch is nearly planar moreover the substrate is smooth. The branch turns westwards alongside a fixed riverbank where it discharges in the end again into the main stream. At the downstream area the river furcates between several smaller islands. Those are overgrown with reed and smaller shrubs.

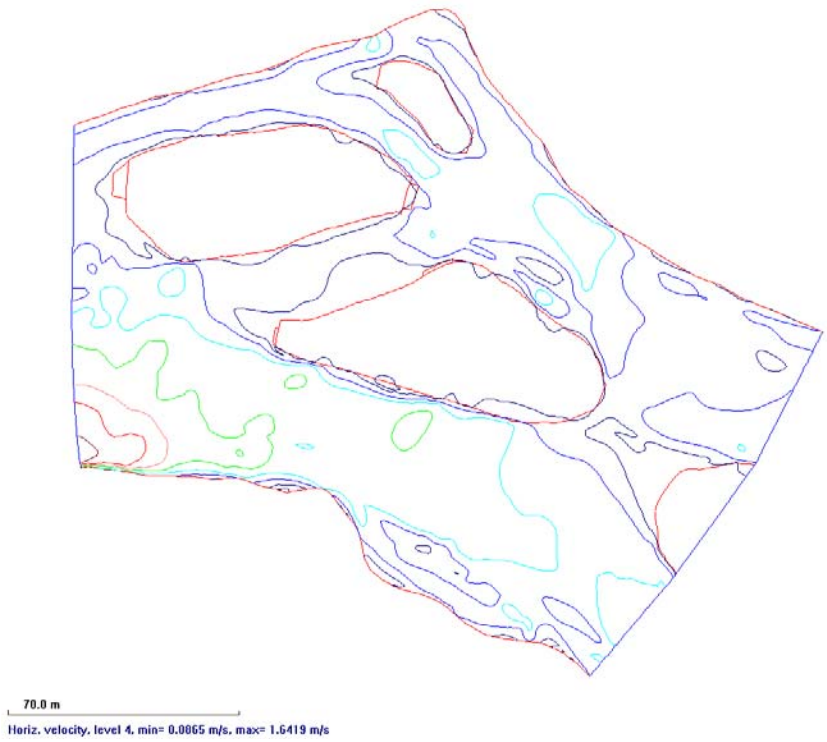

Figure 7.14 Horizontal velocity at 20 m³/s (upper region)

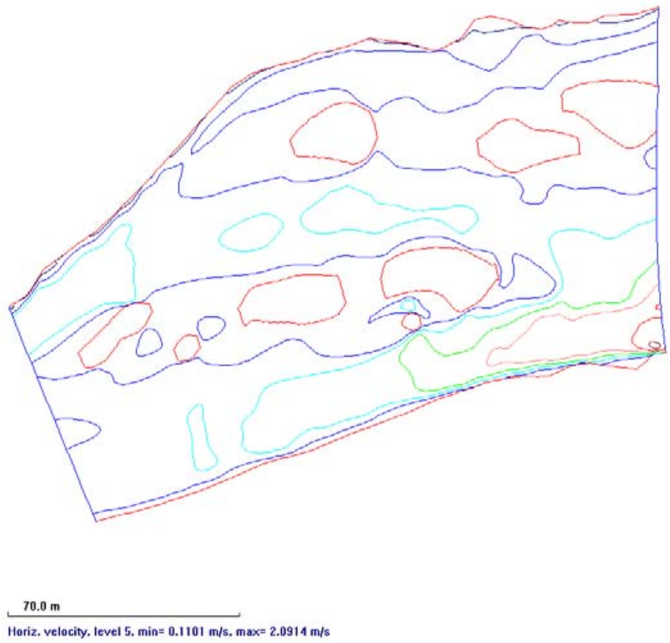

Figure 7.15 Horizontal velocity at 20 m³/s (lower region)

Compared to the results of the River2D model and the real situation the velocity vectors in the SSIIM model show a wrong direction in some areas. Furthermore, the modelled flow velocity differ more from the current situation. An example is given below (figure 7.16, 7.17) where downstream of the island the flow direction is in a complete wrong direction. The drawn arrow in figure 7.17 shows the real direction. The white areas inside the vector field are the blocked out cells from the islands.

Alterations of the innflow file in addition the bedrough file were tested. This could not change the situation because the problem was the height of the water level in the downstream section. In current situation the water level in the area northwards is lower, but the model generates a horizontal water level in the outflow cross-section as input data.

Consequently the results of the model can hardly be used compared to the results of the River2D Model as well as to the current situation. In addition it is questionable to use this model for simulations of changes in the riverbed.

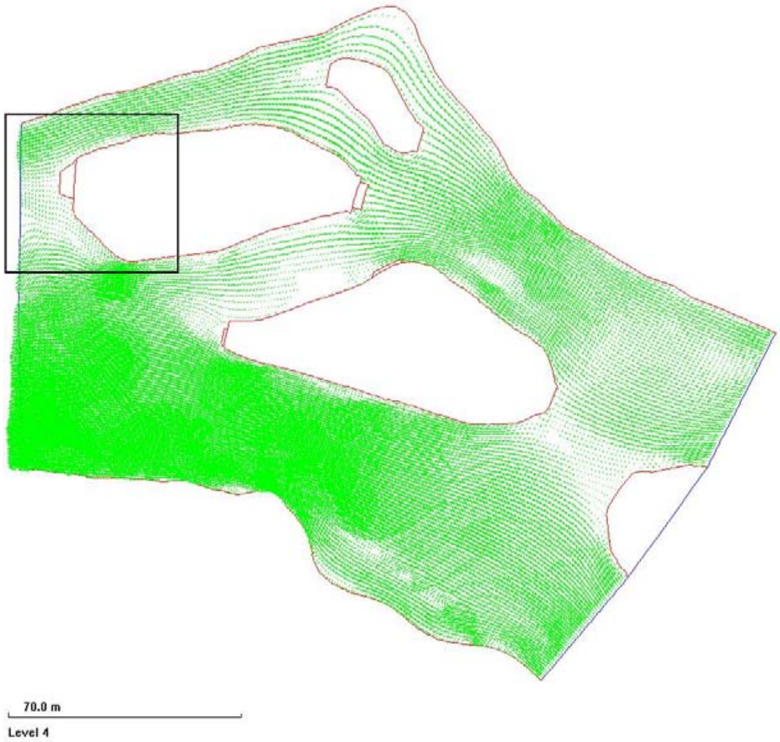

Figure 7.16 Vector field at 20 m³/s (upper region)

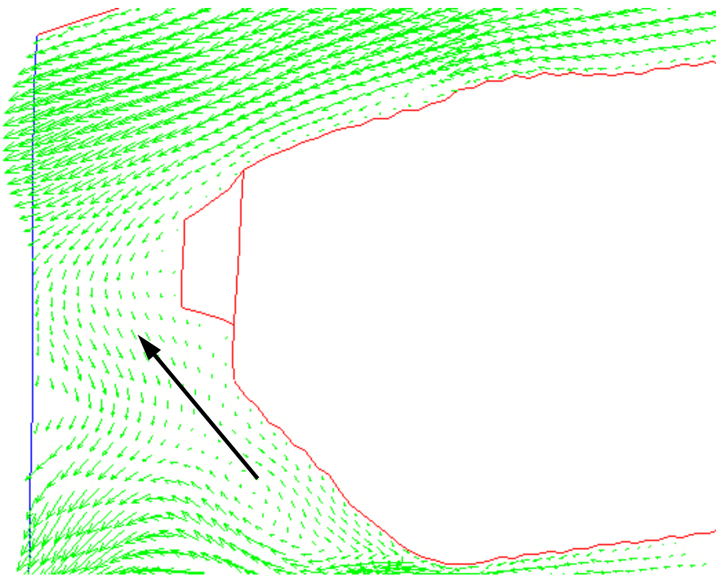

Figure 7.17 Wrong Vector field at 20 m³/s (end of the upper region)

Q = 10 m³/s

Even more islands appear at the discharge of 10 m³/, or rather the existing ones are getting bigger. As a result more cells from the islands had to be blocked out. Moreover it is the lowest discharge which could be measured during the observation period. Nevertheless it is the discharge with the highest amount of suitable habitat for the Atlantic salmon. This result is caused by lower velocities with still enough water depth.

The results of the flow velocity are given below (figure 7.18, 7.19)).

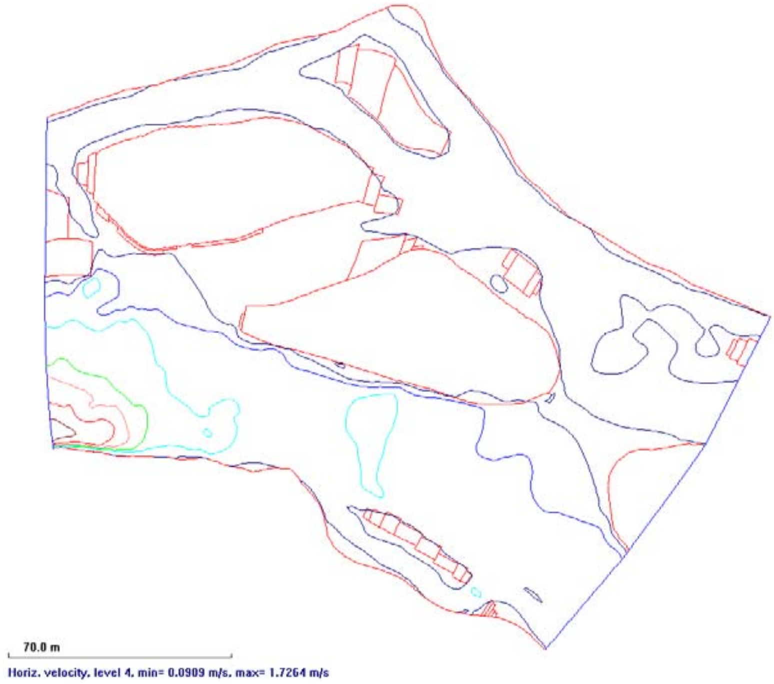

Figure 7.18 Horizontal velocity at 10 m³/s (upper region)

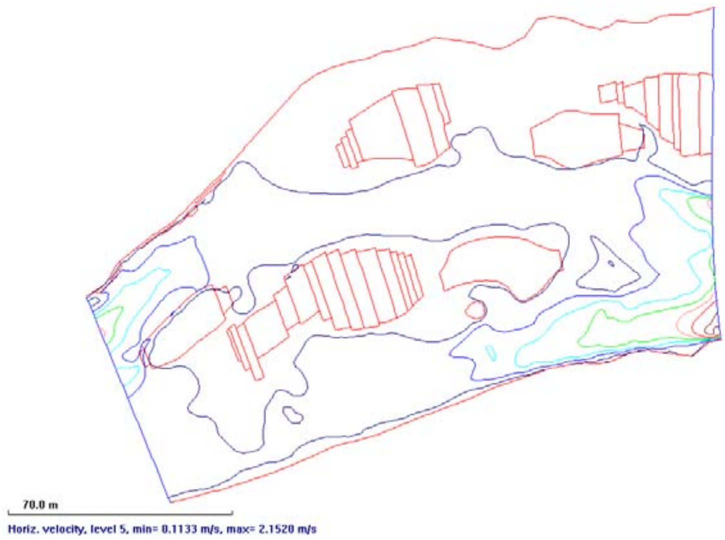

Figure 7.19 Horizontal velocity at 10 m³/s (lower region)

Similar to the problems at the discharge of 20 m³/s the same problems occur at the discharge of 10 m³/s. The velocity vectors in the SSIIM model have the wrong direction in some areas. Furthermore, the modelled flow velocities differ greater from the current situation. An example is given below (figure 7.20, 7.21) where downstream of the island the flow direction is in a complete wrong direction notwithstanding the several blocked out cells from the islands. The drawn arrow in figure 7.21 shows the real direction.

Figure 7.20 Vector field at 10 m³/s (upper region)

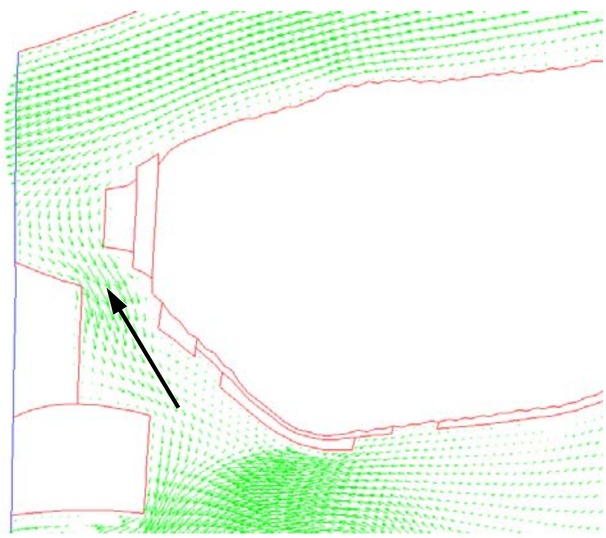

Figure 7.21 Wrong Vector field at 10 m³/s (end of the upper region)

7.4 Mesohabitat classification

The meso habitat mapping was made at Nausta with the discharges during the field work. As described in chapter 3.4 a river is divided into ten classes. Caused by the smooth surface pattern and the moderate surface gradient in the investigated area during field work four classes were left to specify.

At the discharge of 20 m³/s almost the whole area is dominated by the classes B1 and B2. Accordingly the velocity in those areas is higher than 0,5 m/s, which is neither good for the Atlantic salmon, nor for the trout. The areas with good habitat conditions are areas with the classes C and D. Nevertheless class D can also be an avoided habitat area. The water depth in the class D is just below 0,7 m, consequently it cannot be seen how shallow the area is.

To ameliorate the habitat conditions in the areas of class B2 several boulders would create resting places. Caused by the higher water depth in the areas of class B1 boulders would not help. Therefore groynes or man-made islands would create pools and areas with reverse flow. As a result the flow conditions would vary more which creates more suitable microhabitats.

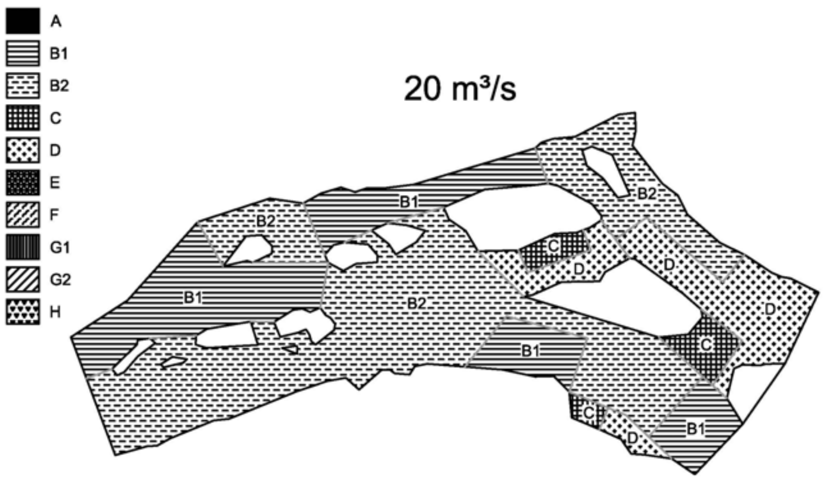

Figure 7.22 Mesohabitats of investigated area at 20 m³/s

Compared to the discharge of 20 m³/s at the discharge of 10 m³/s the class B1 decreases and the class D increases. Almost the whole area is dominated by the classes B2 and D caused by the low water depth. Apart from the shallow parts on the class D the habitat conditions here are good. In the class B2 the velocity is higher than 0,5 m/s, which is neither good for the Atlantic salmon, nor for the trout. To ameliorate the habitat conditions in the areas of class B2 as described above several boulders would create resting places. Accordingly man-made constructions like groynes or islands can decrease the flow velocity and increase the water depth also in shallow areas of class D.

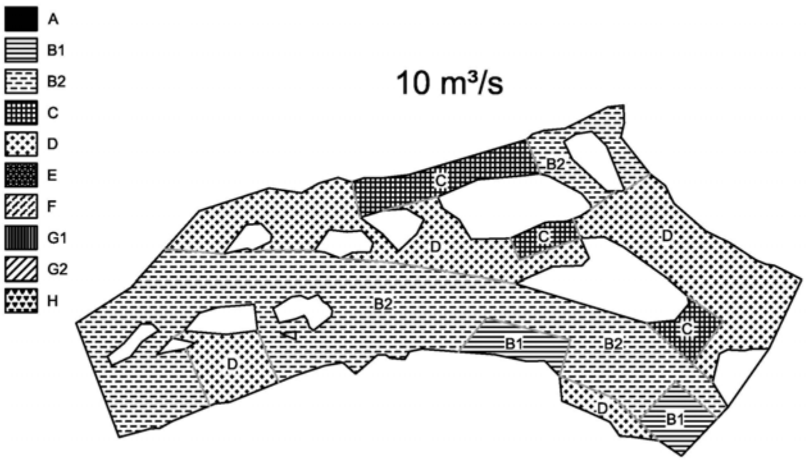

Figure 7.23 Mesohabitats of investigated area at 10 m³/s

8 Discussion and Conclusion

The mean goal of this thesis was first of all to collect, systematize, analyse and prepare field data for further use. Beside of the establishment of a topographic survey, the data of three different discharges were measured. In this chapter the results, solutions and the problems are shortly discussed.

8.1 Improvements of the models

The calibration and validation of the two dimensional model River2D could be set up without any problems. Compared to the SSIIM model River2D did not manage a grid size of 1m because of too much cells. Therefore a grid size with 1,5 m was chosen. In contrast to River2D, SSIIM has as a limit the capacity of the computer. Nevertheless above a definitive model-size the results were too excessive to handle the data with Office Excel. Other programs had to be used to handle the enormous amount of data. Therefore the results of SSIIM with about 280.000 columns were unable to work with. Microsoft Office Excel 2003, which was used to interpret the River2D results, is limited to 65.536 columns. As a result Excel could not be used, even the splitting into two models did not help. A grid size of more than 2m in x and y direction would solve this problem but would not be accurate enough to model the changes in the riverbed.

In the end the topographic survey was accurate enough for the two dimensional hydraulic model but not for SSIIM. Measuring a cross-section every ten meters would be enough at an elongate stream course. However at the river Nausta with its several islands it was not accurate enough. Consequently the survey of the numerous islands and the water level at each island should have been more accurate. After several diverged simulations during the modelling process the interpolated grid was smoothed by hand.

Caused among other things by the complex topography and the inaccurate measurements for the three dimensional hydraulic model, SSIIM was calibrated only by adjusting the bed roughness. The flow velocity was measured at several points. Furthermore at the inflow cross-section the flow velocity was measured to create an innflow file. However using the innflow file the solution diverged immediately. A solution can be a grid width of 2 m, caused by the fact that the velocity in the cross-section was also measured every 2 m.

Furthermore while River2D has no problems simulating low flow conditions, SSIIM requires the amount of dry cells to block them out. Due to the fact that observation data of lower flow conditions are missing it was not possible to get a converged solution. Also the amount of cells, which SSIIM is able to block out, is limited.

In order to receive more exact results for low flow conditions, further measurements at low flow should be done. Especial the water line of the several islands should be measured accurately.

It is leading nowhere when the topography for a three dimensional hydraulic model is not accurate enough. Furthermore SSIIM is not the most user-friendly hydraulic model moreover with its several text files and data sets at the control file it is not easy to handle.

Due to the fact that the most literature about the habitat conditions for Atlantic salmon and Brown trout correspond to average water depth and average flow velocity, it is questionable if a three dimensional hydraulic model is the right way to go. For example with River2D a fast and usable result is possible.

8.2 Habitat improvements

Adjusting and analyzing various habitat improvements is one of the sub goals of the project increasing salmon production in this investigation area. For this project nature orientated structuring is demanded.

In shallow areas with higher flow velocity boulders create resting places and vary the flow conditions. In deeper areas with higher flow velocity groynes and a man-made island decrease in average the flow velocity, create pools and vary the flow conditions.

Accordingly the results of the hydraulic model should be imported into habitat models. Furthermore fish observations have to be made. Comparison of the results of the hydraulic models with the results of habitat models and fish observations would show the usability and correctness of the habitat improvements. Furthermore an experienced ecologist should also interpret the results.

With the results of the meso-scale habitat classification it would be possible to transmit the changes of the riverbed to other areas at the same class. An extra class for areas which are too shallow would be reasonable.

8.3 Future Work

As a part of a project to increase salmon production in the Nausta river further work has to be done. Building the changes in the riverbed compared with fish observations are the primary work. Furthermore developing preference curves of local fishes would yield exact habitat model results.

A longer stretch of the River should be classified with the meso-scale habitat classification. After a successful reconstruction of habitats and observation in these areas, the changes in the riverbed are able to transmit to another area in the same habitat class. Accordingly the changes in the new areas should be observed. If the transmittion is successful, the changes are able to get implemented in other areas.

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