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Microhabitat Modelling as a Tool for Instream Flow Assessment - A Case-Study for the River Rällsälven

Mikrohabitatmodellering för bedömning av ekologiskt flöde - Fallstudie för Rällsälven

Karin Pehrson

ABSTRACT

Microhabitat Modelling as a Tool for Instream Flow Assessment
- A Case-Study for the River Rällsälven
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Many rivers in Sweden have been regulated for the purpose of electricity production, and the natural flow regime is replaced by a regime that will optimize the economical profits. Due to the implementation of the EU Water Framework Directive in 2000, all major rivers are to be investigated and classified, and their ecological status may have to be improved. Many of Sweden's hydropower stations will have to be re-licensed, and the new regulation limits should be set so that the minimum discharge is sufficient for the riverine life, yet the economical losses should be limited.

In this study, the microhabitat model PHABSIM has been tested in Rällsälven in Örebro County to investigate whether PHABSIM may be a useful tool in assessing instream flow requirement. The river is 7 kilometres long and the studied area totals 350 metres of the river length, divided into three reaches. The area is almost dry due to diversion of water to Stjernfors hydropower station. Data of water surface elevation, discharge, depth, velocity, and substratum was collected at two occasions during the summer of 2007. The hydraulics was simulated using the three different water surface profile models MANSQ, STGQ, and WSP, and the velocity model VELSIM. Habitat suitability for different lifestages of brown trout was calculated using HABTAE and habitat suitability criteria (HSC) curves for velocity, depth, and substratum.

It was found that, of the different water surface elevation models, only the MANSQ model could be applied to all three reaches. STGQ and WSP would not work at the reach with the steepest slope and the roughest substrate, presumably because the head losses between adjacent cross sections were too great to be handled by the models. The magnitude of the weighted usable area (WUA) differed greatly depending on which set of HSC curves that was used, but the shapes of the WUA curves were similar in most cases. The discharge giving the maximum WUA in the studied area varied between 0.4 and 1.0 m^3/s depending on reach and lifestage.

It was concluded that the microhabitat model PHABSIM may be used as a reliable and objective tool in recommending a flow regime that is favourable both to the riverine life and the power companies. However, much work remains before a model of this type may be efficiently used in Sweden. HSC curves have to be developed for Swedish conditions, and standards on how to carry out the modelling have to be agreed upon. The performance of other habitat models should also be tested to investigate whether the hydraulics may be more accurately simulated for the kind of steep slopes and rough substratum that are common in Sweden.

Key words: Brown trout, habitat model, habitat suitability, habitat suitability curves, instream flow, PHABSIM, Rällsälven, Water Framework Directive.

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SAMMANFATTNING

Mikrohabitatmodellering för bedömning av ekologiskt flöde
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En stor del av Sveriges älvar är reglerade, och i dessa älvar är det naturliga flödets storlek och variabilitet ersatt med en flödesregim som ska optimera vattenkraftföretagens vinster. Det finns idag vattendomar som reglerar vilket minsta flöde kraftverken måste släppa, men många domar är gamla och kommer att behöva revideras. I och med att EU:s ramvattendirektiv implementerades år 2000 ska alla större vattendrag undersökas och klassificeras, och åtgärder kan behöva sättas in för att förbättra vattendragens ekologiska status. När de nya vattendomarna fastslås ska det göras med ökad hänsyn till de ekologiska funktionerna så att livet i älven inte skadas. Förhoppningen är att djur- och växtlivets krav ska kunna tillgodoses utan att kraftbolagens inkomster ska behöva minska nämnvärt.

I denna studie är mikrohabitatmodellen PHABSIM testad i Rällsälven i Örebro län för att undersöka hur PHABSIM kan användas för att bestämma ekologiskt hållbart flöde. Rällsälven är 6,9 kilometer lång och det studerade området innefattar 349 meter fördelat på tre delsträckor. Älvsträckan är nästan helt torrlagd eftersom vattnet avleds till Stjernfors kraftverk. Fältdata på flöde, vattenytans lutning, djup, flödeshastighet och substrat samlades in vid två tillfällen sommaren 2007. Hydrauliken simulerades med tre olika modeller för att bestämma vattenyteprofilen, MANSQ, STGQ samt WSP och hastigheten simulerades med VELSIM. Habitatlämplighet för bäcköringens olika åldersintervall beräknades med HABTAE i kombination med preferenskurvor för flödeshastighet, djup och substrat.

Den enda modell för vattenyteprofil som klarade simulering av samtliga tre delsträckor var MANSQ. Modellerna STGQ och WSP fungerade inte för den delsträcka med brantast lutning och grövst substrat, antagligen för att fallförlusterna mellan två närliggande transekter var för stor för att kunna hanteras av modellerna. Storleken på WUA för en viss delsträcka varierade mycket beroende på vilka preferenskurvor som användes, medan formen på WUA-kurvorna var liknande i de flesta fall. Det simulerade flöde som gav maximal WUA i det undersökta området låg mellan 0,4 och 1,0 m^3/s beroende på delsträcka och fiskens ålder.

PHABSIM har visat sig kunna användas som verktyg för att på ett objektivt sätt ta fram en flödesregim som är gynnsam både för livet i älven och för kraftföretagen. Mycket arbete återstår dock innan modellen kan användas som beslutsunderlag fullt ut. Preferenskurvor måste anpassas till svenska förhållanden, och man måste utveckla standarder för hur modelleringen och tolkningen av resultatet ska gå till. Andra habitatmodeller bör också testas för att undersöka om hydrauliken kan modelleras bättre för de vanliga svenska förhållandena med brant lutning och grovt substrat.

Nyckelord: Bäcköring, ekologiskt flöde, habitatlämplighet, habitatmodellering, PHABSIM, preferenskurvor, ramvattendirektivet, Rällsälven.

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PREFACE

This master thesis was done for IVL Swedish Environmental Research Institute as part of the TWINLATIN project. The master thesis is part of the M.Sc. in Aquatic and Environmental Engineering Programme at Uppsala University, and the thesis covers 20 Swedish academic credits, 30 ECTS. My supervisor at IVL was Dr. Tony Persson and the thesis has been reviewed by Ass. Prof. Lars Hylander, Department of Earth Sciences at Uppsala University.

I would like to thank IVL for making it possible for me to in depth study such an interesting and important topic. Thank you Tony for your time, support, and never-ending enthusiasm for the subject. Thanks also to Annika Martinsson at IVL for the hard work in the river, to the Department of Earth Sciences for lending me the field equipment, to the Scottish electrician that managed to fix the broken current-meter, and to Lars for important suggestions regarding the report.

And thank you Dad, for the invaluable support and encouragement you have given me.

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POPULÄRVETENSKAPLIG SAMMANFATTNING

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En stor del av Sveriges älvar är utbyggda med dammar och vattenkraftverk, något som naturligtvis påverkar djur och växter i vattendragen. Regleringen kan påverka flödet i älven på flera sätt; flödet kan bli för litet när kraftverken sparar på vattnet och den naturliga variationen av hög- och lågflöde uteblir ofta, vattnet kan också bitvis vara helt avlett från den naturliga fåran för att skapa en högre fallhöjd där kraftverket är beläget.

När EU:s ramvattendirektiv infördes i svensk lag år 2000 kom krav på att alla större vattendrag ska studeras och klassificeras i grupper beroende på deras ekologiska status. Kriterierna för klassningen utgår från hur biologin, kemin och de fysiska förhållandena ser ut i vattendragen. De vattendrag som bedöms ha dålig status ska restaureras så att de kan anses ha god ekologisk status till år 2015. Utbyggda älvar kommer aldrig att helt kunna efterlikna naturliga fritt flödande vattendrag, därför bedöms de enligt särskilda kriterier för kraftigt modifierade ytvattenförekomster. Verksamheten ska få fortgå i älven, men vattendomar kan behöva skrivas om och åtgärder vidtas för att den negativa påverkan ska minimeras.

Det är ännu inte helt klarlagt hur klassningen ska gå till rent praktiskt i älvar som inte är så väl studerade sedan tidigare, det skulle bli kostsamt att göra biologisk inventering i de många och otillgängliga norrlandsälvarna. I detta examensarbete testas mikrohabitatmodellen PHABSIM för att undersöka om den kan användas i klassificeringen av vattendrag och för att rekommendera gränser för lägsta och högsta flöde i reglerade älvar. Habitatmodellering är vanligt i många andra länder, särskilt i USA, men i Sverige har det tidigare inte utförts några större publicerade studier av detta slag. Studien har utförts för Rällsälven som ligger nära Kopparberg i Örebro län. Älvsträckan är nära sju kilometer lång och där ligger tre kraftverk. Modelleringen är gjord för den övre biten av älven, en sträcka på en kilometer som är nästan helt torrlagd på grund av avledning av vattnet från den naturliga fåran till Stjernfors kraftverk. I dagsläget släpper man ca 50 l/s i torrsträckan. Med hjälp av habitatsmodellering bör man kunna beräkna hur mycket vatten som skulle behöva släppas i fåran för att åstadkomma acceptabla förhållanden för vattenlevande organismer.

Modellen PHABSIM är uppbyggd i två delar. Först görs fältmätningar av flöde, djup, flödeshastighet och bottensubstrat, baserat på detta simuleras sedan djup och hastighet för ett antal önskade flöden. Sedan studerar man hur lämpligt det studerade området är som habitat för en fiskart vid de flöden man simulerat i modellen. I detta arbete studerades bäcköring som är den vanligaste arten i habitatmodelleringsstudier. Om bäcköringen trivs tas det som tecken på att vattendragets kvalitet är bra även för andra arter. Den biologiska modelleringen grundar sig på så kallade preferenskurvor som hämtats från fyra olika studier. Preferenskurvorna beskriver på en skala noll till ett hur väl bottensubstrat, det simulerade djupet och flödeshastigheten överensstämmer med fiskens krav. Det finns olika kurvor beroende på fiskens ålder: för yngel, fisk mellan ett och två år, vuxen fisk samt för lekperioden. Den hydrauliska modelleringen i kombination med den biologiska resulterar i 2- eller 3-dimensionell grafik över älven med habitatets storlek och ett värde förr dess lämplighet samt grafer över ”viktad användbar area”, WUA. Med hjälp av grafiken kan man identifiera habitatets kvalitet på en skala från noll till ett samt se hur kvaliteten ändras med storleken på det simulerade flödet. WUA-graferna visar hur många kvadratmeter habitat som finns tillgångligt per kilometer älvsträcka, och hur detta värde varierar med varierande flöde. Vanligtvis är WUA litet vid ett litet flöde, sedan ökar det med ökat flöde och vid riktigt höga flöden avtar WUA mot noll. Genom att studera WUA kan man rekommendera vilket lägsta och högsta flöde som kraftverken ska tillåtas släppa och även se om fisken är särskilt känslig under någon period, till exempel under lekperioden. Om vattendomar ska baseras på modelleringen måste man naturligtvis även se till vilket flöde som är praktiskt möjligt att åstadkomma i den aktuella älven eftersom det kan hända att maximalt WUA är beräknat för ett flöde som är högre än vad som är normalt förekommande i älven.

I denna studie simulerades det högsta WUA för flöden mellan 0,4 och 1,0 m^3/s, vilket är väldigt högt att rekommendera att släppa i torrsträckan eftersom medelvattenföringen i älven bara är 3,8 m^3/s. WUA-graferna visar dock även att en stor ökning av habitatarean kan skapas bara genom att öka flödet från 0,1 till 0,2 m^3/s, vilket skulle kunna vara möjligt att genomföra. Dock återstår problemet med dammarna som utgör vandringshinder. Omlöp skulle behöva anläggas för att höja hela älvsträckan till en bättre ekologisk status.

Slutsatser som kunnat dras av arbetet är att PHABSIM skulle kunna användas som hjälpmedel i arbetet med att klassificera och restaurera älvar, men att mycket arbete återstår innan modellen kan utnyttjas fullt ut. Det måste skapas standarder för hur modelleringen ska gå till och vilka preferenskurvor som ska användas, så att olika studier går att jämföra. Det är också möjligt att det finns andra habitatmodeller som fungerar bättre i svenska förhållanden. Innan det slutgiltiga valet faller på PHABSIM borde fler modeller testas för att se vilken som skulle passa bäst att använda i arbetet med vattendirektivet.

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1 INTRODUCTION

Rivers regulated for power generation purposes have lost their natural regime of flooding and drought, and instead artificial flow regimes that are economically efficient for the power companies are maintained in such rivers. During periods with large water supply, such as during spring flood, water is stored in the reservoirs to be used for power generation throughout the year. The large hydroelectric power stations make daily or even hourly changes in their release of water to match the current power demand. Water may also be diverted from the original reach to increase the hydraulic head at the site of the turbines, and the resulting dry reaches are conspicuous interferences in the landscape (Figure 1).

The artificial flow regime has a large impact upon the flora and fauna in the river and a complete diversion of water obviously eliminates the aquatic life in the former water course. If only a small amount of the diverted water was allowed to run in the original course, or an optimal flow regime was found, the damage to the ecosystem could be reduced while the economical loss to the power companies would be limited.

Figure 1 Photo from River Rällsälven taken in the channel approximately 100 metres downstream the dam at Ljusnaren in April 2007. The river channel is almost completely dry due to diversion of water and may be classified as a heavily modified water body.

The EU Water Framework Directive, WFD, with the aim to improve the ecological status of surface water bodies in the European Union member states was implemented in year 2000. The status of the water bodies is to be classified according to the biological, chemical, and hydromorphological conditions, and by 2015 the water bodies should have reached “good ecological status”. Rivers that have been altered for irrigation purposes, dammed for flood control or hydropower, etc may be classified according to the WFD as being “heavily modified”. For such rivers the ecological status goal is slightly more lax; it is sufficient to reach “good ecological potential”. In a preliminary classification including 1000 of Sweden’s lakes and rivers, 8-10 percent of the investigated water bodies were found to fall into the category “preliminary heavily modified water bodies”. In this preliminary classification only the main channels of the major regulated rivers were classified as heavily modified, but more rivers will probably be included in the near future as more detailed information of the dams and rivers is collected. The classification is based on information regarding the dam size, the catchment area, the degree of flow regulation, and the installed efficiency of the hydropower station. (Naturvårdsverket, 2005)

Methods for the classification of ecological status are currently under development by The National Environment Protection Board (Naturvårdsverket). The emphasis of the classification system will be on measurements of biological variables. However, the biological status is heavily dependent on the physical conditions in the river. Therefore there is need for methods to predict how the status of flora and fauna will be influenced by restoration measures of the physical environment, such as changes of flow regime or river morphology.

An important measure to improve the status of regulated rivers is to revise the regulation limits that govern the flow regime of the hydroelectric power stations. A large amount of the Swedish regulation limits were set in the first half of the 20th century and at that time not enough consideration was taken to the ecology of the river (personal com. Gyllenhammar, 2007). Some power stations do not even have any definite limits at all, and the minimum flow is dependent only on oral agreements between the power companies and the county administration.

As the WFD now is to be implemented and the regulation limits revised, there is increased concern about how care for the ecology shall be combined with the demand for electrical energy and need for cost effectiveness of the hydropower plants. The new regulation limits have to ensure the best compromise between the power companies' interests and the ecology of the river (Löwgren, 2003). In order to in an objective way determine the instream flow, i.e. the magnitude of flow that is necessary to enable a satisfactory ecological status in a river, a model may be set up to calculate how the riverine life responds to changes in flow. A microhabitat model combines hydraulic and biological data to calculate the amount of living space available to fish or benthic fauna in relation to the river discharge.

In this study the microhabitat model, PHABSIM (Physical HABitat SImulation Model) was used to study habitat availability to brown trout. The model is widely used in many parts of the world, especially the U.S., but so far no major case-studies seem to have been carried out in Sweden. In PHABSIM, the size and quality of fish habitat was calculated for a range of simulated flows in the river Rällsälven located in Örebro County. The upper part of the river is dry due to diversion of water during large parts of the year, which makes it an interesting study area for modelling and restoration measures.

The aim is primarily to test the applicability of the microhabitat model PHABSIM for Swedish conditions. The model will be evaluated in terms of its applicability, the data requirements, and its performance for hydraulic and habitat modelling. If the model is found to work well it could be recommended to be used as a tool for classification of current ecological status and to predict the outcome of planned restoration measures by reason of the implementation of the WFD.

In addition the modelling will be a case study of the reach with the aim to recommend a site specific instream flow requirement for the upper part of Rällsälven. The ecological potential could possibly be enhanced by increasing the flow through one of the confluences to the dry river reach, or by letting water through the currently closed dam that is located upstream the dry river reach.

2 METHODS FOR ASSESSMENT OF INSTREAM FLOW

Through the years several methods using different approaches have been developed to calculate the amount of water needed to maintain a sustainable ecological status in rivers. The methods may be based on statistical data, experts' judgements or simulation with different kinds of models. A brief review of some of the most common types of methods is given below. The methods are listed in order of increasing complexity.

When choosing a model one has to consider at which scale it is going to be used, the data requirement and availability, user friendliness, and possible licence fees. Several methods require an extensive amount of field work and it is desirable that the knowledge gained by the field workers is put forth to those evaluating the results. If the output is shown as maps or graphics of the area the interpretation may be easier than if the result is presented as tables. PHABSIM was chosen for this study rather early in the process since it is well known, there is no licence fee, and the output of graphs and graphics is simple and clear.

2.1 HYDROLOGICAL METHODS

These are the simplest methods, and they are based on statistics of hydrological observations in the area. The most well-known of these is the Tennant method (Tennant, 1976 cited by Naturvårdsverket, 2003). When using the method the yearly average flow, as it would have been if the river was unaffected, is calculated and a certain percentage of that flow is recommended as the minimum flow for the regulated river. A flow of at least 30 percent of the yearly average was found to give satisfactory velocity, depth, and width to maintain the ecological status when it was calibrated for several North American rivers. The recommended percentage of the natural flow may also be varied according to season to increase the model validity during sensitive times such as while the fish is spawning. (Naturvårdsverket, 2003)

An advantage of the hydrological methods is that once the statistical data for an area has been collected, the application on the study site is easy. The method is reported to work well for large rivers where the variability of flow is small, but would probably not be suitable for the small river used in this study. (Naturvårdsverket, 2003)

Though simplicity is often desirable, Acreman & Dunbar (2004) claim in *Defining environmental flow requirement -a review* that models of this type are often too simplified and that they have low ecological validity. Hydraulic data is often readily available, but the ecological data for calibration is time consuming and expensive to collect. Even if ecological data is collected, it is often site specific and can not easily be transferred. The models may be appropriate to use as guiding tool in low controversy situations, but often more complex methods are necessary.

2.2 STATISTICAL ANALYSIS OF HYDROLOGICAL DATA

In addition to the magnitude of flow, the statistical analysis also takes into account the duration, frequency and the timing of the high and low flow events. Different theoretical flow regimes may be generated, and with knowledge about the biological needs, the influence upon the living conditions in the river can be tested. (Naturvårdsverket, 2003)

One method belonging to this group is the Range of Variability Approach (RVA) (Richter *et al.,* 1997 cited by Richter *et al.,* 1998). Long term records from before and after dam construction are used in a statistical analysis of several ecological and hydrological parameters. The natural (pre-construction) variability of the parameters such as duration of high and low flow events, rate of change of flow and frequency of flow events is compared to the variability observed after the construction to calculate the degree of alteration. A large degree of alteration due to hydropower regulation indicates harsher living conditions for the animals and plants in the river. The values of alteration are illustrated in GIS-systems to show where the management efforts should be focused. (Shoeller, 2005)

The application of RVA may be problematic, if not impossible, if there are no long term flow records available for the river. The method needs data from both before and after construction, which is not always recorded (Richter *et al.,* 1998). In Rällsälven, for example, the first dam was constructed in the end of the 19th century, and there is no reliable flow data available of the natural regime before dam construction. In the case of Rällsälven there is need for a predictive tool to find the flow regime changes needed to improve the ecological status, but with the lack of pre-construction flow records RVA is not a suitable method. A short or defective flow record may be repaired by using statistical analysis or hydrologic modelling, but the validity must be carefully considered (Richter *et al.,* 1998).

As is the case with the hydrological methods discussed above, there seem to be different opinions about the ecological validity of the model. R. E. Tharme (2003) states that she questions the ecological relevance of RVA, but she also admits that several researchers are of contrary opinion.

If sufficient hydrological data is available, RVA can be a good source of information for river maintenance or restoration. The method may find hydrological irregularities of the river system or point out problematic reaches that disrupt connectivity of the river, and find the human activities that causes the problems. Once the problem sites have been identified, a new improved flow regime can be recommended to the hydroelectric power plants. (Richter *et al.,* 1998)

2.3 HYDRAULIC RATING METHODS

The hydraulic methods require a hydromorphological survey of cross sections similar to that used in the physical habitat models, and they include some simple modelling of width and wetted perimeter.

The most common hydraulic method is the wetted perimeter method in which it is assumed that size of habitat is related to the ratio of wetted perimeter to flow (Gippel & Stewardson, 1966 cited by Naturvårdsverket, 2003; Jowett, 1997). Ideally, as the flow increases, the length of wetted perimeter will increase rapidly at the beginning and later level out (Figure 2). The increase of available habitat area with an increase of flow will be small beyond this break point; therefore the minimum flow of a regulated river is set to the break point discharge. (Naturvårdsverket, 2003)

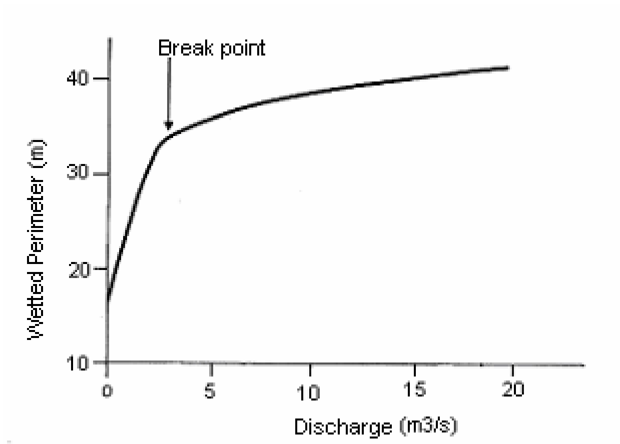


Figure 2 Example of wetted perimeter curve (modified from Collings, 1974).

The wetted perimeter method will not work for all types of rivers. If the banks are smooth and poorly defined there will be no clear break point of the slope, and rivers with well defined banks may have two or more break points. The area of habitat is related to the wetted perimeter, but the quality of the habitat is not considered. In uniform channels a very shallow flow may be enough to cover a large bottom surface area, while the velocity and depth is unsuitable. In such extreme cases the wetted perimeter method and other hydraulic rating methods should be avoided, but the methods may be useful for instream flow assessment of “normal” rivers. (Jowett, 1997)

Though hydraulic methods are still in use today, few advances have been made since the development of them more than 30 years ago. R. E. Tharme (2003) claims that the hydraulic methods have fulfilled their key roles as tools for instream flow assessment, and that more sophisticated methodologies are needed.

2.4 PHYSICAL HABITAT MODELS

These methods combine hydrological modelling with habitat preferences for different species of fish and benthic fauna to calculate how the size and quality of habitat area vary depending on the magnitude of flow. It may be used to estimate the effects of future changes in flow magnitude and regime due to water abstraction or dam construction, or the improvement of habitat quality resulting from rehabilitation efforts. (Acreman & Dunbar, 2004)

Habitats may be modelled on different spatial scales, from macro habitats which include whole catchments, mesoscale that consider reaches up to a few hundred meters of similar habitat type, down to microscale that deal with the living space of an individual animal at the size of a few square meters. When discussing habitat models, it is generally the microscale models that are intended. (Harby *et al.,* 2004)

The use of microhabitat models of the type that is tested in this study is close to non-existent in Sweden although the use is widespread in many other parts of the world. In the U.S., institutions and companies such as for example the U.S. Geological Survey and Golder Associates frequently use PHABSIM to establish levels for minimum flow in rivers (Clipperton *et al.,* 2003; Krstolic *et al.*, 2006). Australia along with several Central European countries also have been using habitat models for decades (Naturvårdsverket, 2003; Acreman & Dunbar, 2004; Harby *et al.,* 2004). No extensive case studies seem to have been made in Sweden, and in the other Nordic countries microhabitat models have been used only sparsely, and mainly for academic research purposes. (Heggenes, 1996; Thorn & Conallin, 2006)

The hydraulics of the river may be computed using either 1-, 2-, or 3-dimensional modelling. In using 1-dimensional modelling, the most commonly used physical habitat modelling type, the river hydraulics is computed as extrapolations of measured cross sections that are spaced about 10–100 metres apart. The cross sections are preferably laid in the transition between different habitat types; runs, riffles, pools, etc. As the flow is rather uniform within each short reach, the hydraulics may be properly represented with a 1-dimensional model. The advantages are that few measurements are needed and the model is easy to calibrate manually. 2- or 3-dimensional models do not extrapolate between cross sections, instead they rely on large amounts of topographical data and calculate velocity and depth at every grid point. Accurate computational results may be received if the density of the mesh of the grid is high enough, but the high cost of collecting the data might overshadow the benefits. (Hydropower Reform Coalition, 2005)

The hydraulic conditions at simulated flows are combined with habitat suitability criteria (HSC) curves to calculate the habitat area. The HSC curves describe different species' preferences regarding the physical environment; velocity, depth, substratum, and sometimes temperature. The target species in this study is brown trout *Salmo trutta* (Linnaeus, 1758) which is one of the most commonly used species in studies of this type. Brown trout is found in large parts of the world, and a healthy stock is often used as an indicator that the overall status of the river is good. Brown trout has been used as target species for example by Greenberg *et al.* (1996), Heggenes (1996), Vismara *et al.* (2001), and Thorn and Conallin (2006). Other species used for the same purpose include Chinook salmon *Oncorhynchus tshawytscha* (Walbaum, 1792), rainbow trout *Oncorhynchus mykiss* (Walbaum, 1792), Atlantic salmon *Salmo salar* (Linnaeus, 1758), and grayling *Thymallus thymallus* (Linnaeus, 1758) (Greenberg *et al,.* 1996; Heggenes, 1996; Clipperton *et al.,* 2003).

A general assumption for all the physical habitat models is that the quality of habitat depends on the physical characteristics of the river. The models normally do not consider chemical variables such as pH, oxygen, sediment transport or polluting substances, and only a few of the models include temperature in the habitat modelling. The output from this kind of models is usually given as weighted usable area (WUA) curves that illustrate the size of suitable habitat area at different simulated flows.

A selection of the most commonly used physical habitat models is presented below.

PHABSIM (Physical HABitat SImulation Model). PHABSIM is a collection of several sub-models that are developed by U.S. Fish and Wildlife Service. The development of PHABSIM started in the 1970's, and in 1984 the model was made into a computer simulation model similar to that used today. The program has been updated several times since then, and the current version was released in year 2000 (Midcontinent Ecological Science Center, 2001).

The hydraulic modelling is 1-dimensional and there is a choice of three sub-models to simulate water surface elevation. The models rely on a stage-discharge relationship, Manning's equation, or the energy equation. When water surface elevation has been simulated, the velocity can be simulated. The simulated velocity distribution is based on the distribution across the cross sections that was measured in the field.

When the hydraulic part of the modelling is concluded, the size and quality of habitat is calculated using univariate HSC curves.

A more detailed description of PHABSIM is given in Section 3.3.

EVHA (ÉValuation de l'HAbitat) (Ginot, 1995 cited by Booker & Acreman 2007). EVHA is a French model developed in the mid-1980 by Cemagref, Laboratoire d'Hydroécologie Quantitative, Lyon, to study how the fish stock is affected by variations in flow. EVHA is derived from PHABSIM, and the models are similar in most respects (Capra *et al.,* 2003). There are a few differences, though:

One major distinction between EVHA and PHABSIM is the way substratum and cover is described. In EVHA the channel index is denoted by three numbers representing dominant and sub-dominant substratum, and the coverage of these, instead of merging these values into one number as in PHABSIM. (Scruton *et al.,* 1998; Naturvårdsverket, 2003)

The calculation of water surface elevation is also slightly different; it has similarities with the WSP model in PHABSIM but uses the Limerinos equation instead of Manning's equation to estimate the bed hydraulic roughness (Capra *et al., 2003*). Limerinos equation takes into account the proportion of the water depth occupied by bed particles, and is said to more accurately represent the hydraulics of rivers with steep gradient and coarse substratum (Naturvårdsverket, 2003).

Limerinos equation for Manning's *n* (1):

$$n = \frac{0.133R^{1/6}}{1.16 + 2.00 * \log_{10}\left(\frac{R}{D_{84}}\right)} \qquad (1)$$

n = Manning's n
R = hydraulic radius
D_{84} = maximum size of 84% of the elements of the substratum

RHABSIM (Riverine HABitat SIMulation) is a model very similar to PHABSIM. It was developed in the 1990's by Thomas R. Payne and Associates, based on PHABSIM but rewritten to be more user-friendly. As in PHABSIM, there are several options for the hydraulic modelling, and the representation of habitat preferences is also similar to the RHABSIM's predecessor. (Caldwell & Shredd, 2002)

RHYHABSIM (River HYdraulics HABitat SIMulation) is a model developed in the early 1990's in New Zealand by Ian Jowett at the National Institute of Water and Atmospheric Research, Hamilton. The model is based on the same concepts as PHABSIM and the difference is that RHYHABSIM contain a lower number of variable inputs in order to simplify the modelling process. According to Gordon *et al.* (2004)

quoted by Thorn and Conallin (2006) the model is easier to use than PHABSIM, yet it produces results that are accurate and reproducible.

FISU is a Finnish habitat model developed in the end of the 1990's for Fortum Engineering, Helsinki. Unlike most other habitat models, FISU is based on 2-dimensional hydraulic modelling, and the preference curves may be either univariate or multivariate (Harby *et al.,* 2004). The use of a 2-dimensional hydraulic model increases the accuracy of the modelling compared to 1-dimensional models (European Aquatic Modelling Network, 2000).

The number of studies in which FISU has been used as an assessment tool is quite small to this date, but there are some studies made in Finland. T. Yrjänä evaluated the results from restoration efforts in the Finnish river Oulojoki using FISU. The river had previously been dredged, and now reefs and side channels had been created to improve the riverine habitat. A differential GPS was used in the mapping of river topography, and the 2-dimensional flow model RMA2 was used to simulate the hydraulics. Yrjänä used FISU to evaluate the achieved habitat quality using data measured before and after the restoration, but the model may also be used as a predictive tool. (Yrjänä, 1999 cited by Harby *et al.,* 2004).

RSS (River System Simulator) (Killingtveit & Harby, 1994 cited by Booker & Acreman, 2007). RSS is a Norwegian model that integrates thirteen different sub-models into a river managing tool. The hydraulics of the investigated river is modelled 1-dimensionally in HEC-RAS, or 2- or 3-dimensionally in SSIIM, and there are models to handle technical and hydrological data from the power plants, ice cover, temperature, and chemical parameters of the river. The habitat suitability is modelled in HABITAT that can handle the 1-, 2-, or 3- dimensional hydraulic data. The outputs from HABITAT are WUA, habitat duration curves, and various maps showing distribution of habitat and the hydraulic variables. (Harby *et al.,* 2004)

RSS does not seem very widely used and the published studies that have been found are all from Norway. The model has for example been used in the river Maana, Norway, in which five hydropower plants are located. The impacts of the hydropower and possible rehabilitation efforts were assessed as hydropower plants were to be re-licensed. The authors of the study report that RSS has been a useful tool in handling the extensive quantities of data. Some models share the same input data, and output from one sub-model may be used as input in other, and RSS makes the data handling more efficient and reliable. (Harby *et al.,* unpublished)

CASiMiR (Computer Aided SImulation Model for Instream flow Requirements) (Jorde 1996, cited by Harby *et al.,* 2004)**.** The development of CASiMiR started in the early 1990's by the Institute of Water Sciences at University of Stuttgart, and the model is still being developed (Giesecke *et al.,* unpublished). Unlike the previously described models, CASiMiR is a toolbox for GIS which may rationalize the input of data, and the output is presented as GIS layers.

The way habitat suitability is presented in CASiMiR is different from other habitat models; instead of HSC curves, CASiMiR make use of fuzzy-logic to produce membership functions that divide the parameters of velocity, depth, substratum, and cover into three or four different classes with smooth transitions between them (Figure 3).

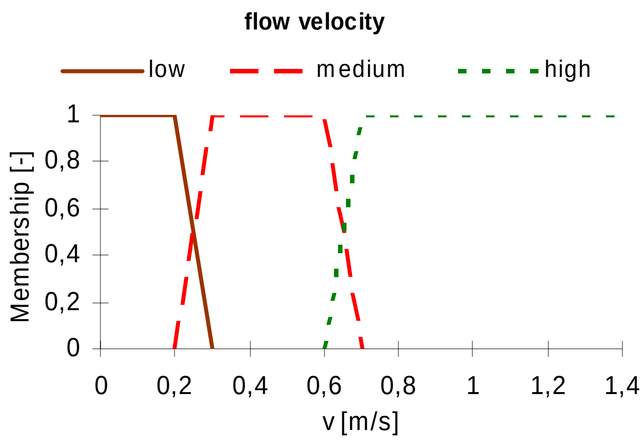


Figure 3 Example of a membership function for flow velocity used in CASiMiR modelling (IVL Svenska Miljöinstitutet, 2007).

The habitat values for the different combinations of the variables are calculated by using fuzzy rules. Each combination of depth, velocity, substratum, and cover is given a combined suitability ranging from low to high. For example "IF flow velocity is high AND water depth is high AND substratum is gravel AND vegetation cover is high THEN habitat suitability is medium."(Kerle *et al.,* unpublished)

Logic statements are made for every combination of variables and for every life stage of the fish. In case a parameter belongs between two classes, and the logic statement does not perfectly fit, the degree of fulfilment is calculated. After a final transformation, the habitat suitability is represented on a scale between 0 (unsuitable) and 1 (suitable). WUA for every simulated flow is calculated and presented on maps generated from GIS. (Kerle *et al.,* unpublished)

The use of fuzzy-logic is by some considered the solution to the difficulties in development and usage of preference curves in PHABSIM and similar models. CASiMiR does not deal with exact numbers, but rather with imprecise and "fuzzy" information directly transferred from experts in the field (IVL Svenska Miljöinstitutet, 2007). On the other hand, the number of logic statements will be large and difficult to handle if several variables are to be considered.

Some attempts of using CASiMiR for this study were made; it could have been a suitable continuation to the MesoCASiMiR study that was done by IVL at the mesoscale of the river in 2006. However, the model is currently being developed and the studies evaluating it are very sparse. The material about the model is mainly unpublished and written by, or in cooperation, with the developers at Schneider & Jorde Ecological Engineering GmbH. The user-guide material is quite insufficient so far, and written in German, though the developers are currently working on a manual in English language. The uncertain status of the development process and the lack of documentation contributed to the decision not to use CASiMiR.

2.5 EXPERT JUDGEMENT

Expert judgement is a method that is often mentioned when discussing the WFD. If there is not enough data available to set up a model, or if modelling is considered unsuitable, an expert may be employed. The current status of a river may be classified by an experts' judgement, or remedial measures for a modified river may be proposed by an expert. (Naturvårdsverket 2007)

The concept of expert judgement is quite vague; it is not specified who may be considered to be an expert, or how they are supposed to come to their conclusions. The studies may be made by one single person, or by a group of experts that reach consensus on the question. The method is simple and flexible, but in lack of guiding standards expert judgement may be subjective.

3 STUDY AREA AND METHOD USED

Data of discharge, velocity, depth, and river bed geometry was collected in Rällsälven at two occasions, June 26th – 29th and August 15th – 16th 2007. The data was applied in the PHABSIM microhabitat model to simulate habitat size for brown trout.

3.1 RÄLLSÄLVEN AND ITS CATCHMENT

The river Rällsälven, in which the study was performed, is a 7 kilometres long river that runs between the lakes Ljusnaren and Rällen near Kopparberg in Örebro County (Figure 4). The total change in elevation along the stretch is 53 meters. There are three hydropower dams located in the river, and all the three dams are definite barriers to migrating fish. At the outlet of Ljusnaren, there has been a dam ever since the 17th century when Stjärnfors Iron Works was located there, and the current dam was built in 1872 (Länsstyrelsen Örebro län, 2007a). In the early 20th century, the works was shut down and Stjernfors hydropower station was built (Wikipedia, 2007). Soon thereafter, the river was cleared and widened and Dammen power station was built downstream, close to the outlet in Rällen (Sundén, unpublished). Rällsälv power station is located between Dammen and Stjernfors. The installed capacities of Stjernfors, Rällsälv, and Dammen are 1030, 500, and 190 kW respectively (Länsstyrelsen Örebro län, 2007a). The upper part of the river is rather steep and the river is surrounded by mixed forest on both sides, further downstream the water is more slow-flowing and agricultural land frames the river. There are eleven confluences with small brooks along the course (IVL Svenska Miljöinstitutet, 2007). The catchment of Stjernfors hydropower station is 291 km^2, and the yearly average precipitation in the area is 700-800 mm (Länsstyrelsen Örebro län, 2007a; SMHI, 2007).

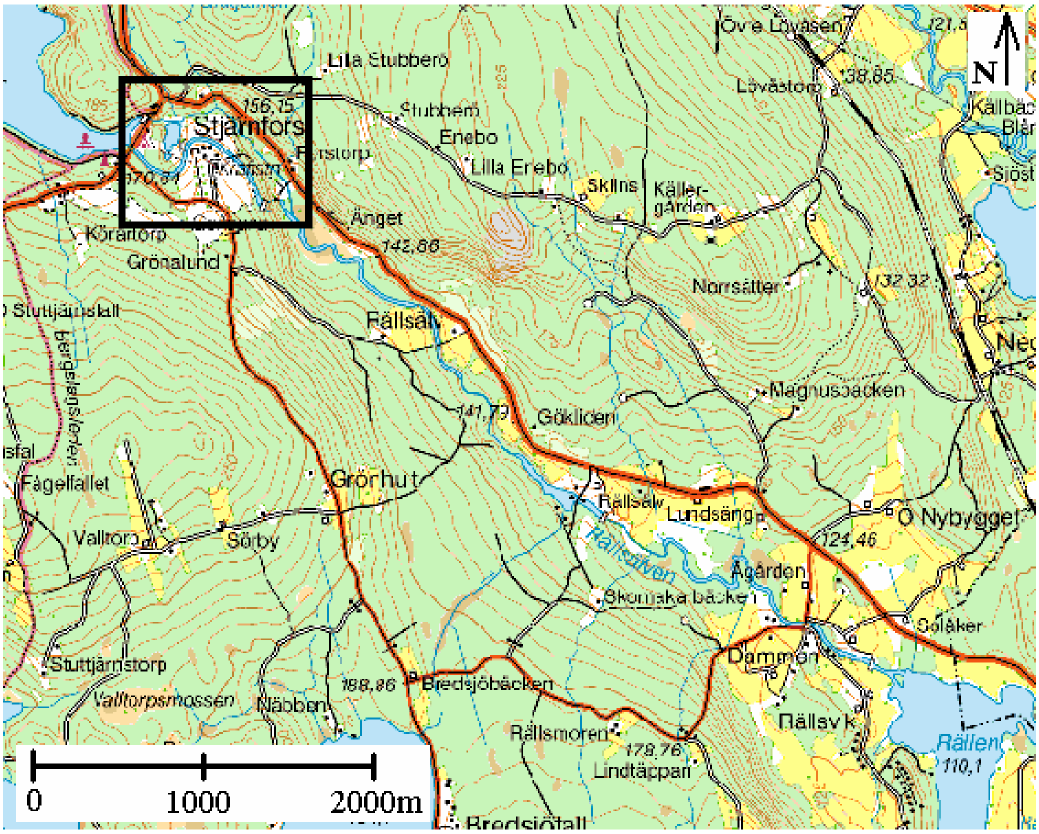


Figure 4 Rällsälven runs from the lake Ljusnaren in north-west to Rällen in south-east. The framed part is the area in which the study took place (Lantmäteriet KartSök, 2007).

The study was performed in the uppermost kilometre of the river which is normally almost completely dry due to diversion of water to Stjernfors power station. Some water seeps through the dam wall into the original course of the river, and there are a few confluences with small creeks along the reach gradually increasing the flow. Only during spring flood, the dam is opened to let water out into the original course. During the time of the first set of data collection, however, Stjernfors power station was shut off due to maintenance work of the turbines. During that time only a small amount of water, about 0.1 m^3/s, was diverted and led through the turbines while the rest of the water ran in the original water course. The water level of the lake Ljusnaren was kept lower than usual due to repair work of the dam at Rällsälv power station during the summer months. This was to keep the flow in the river at a steady level even in case of large amounts of precipitation (Mälarenergi, 2007).

The average flow of Rällsälven at Stjernfors hydropower station is 3.8 m^3/s, with lows down to about 0.3 m^3/s during the summer months and a few high flows of 15-20 m^3/s (Länsstyrelsen Örebro län, 2007a; SMHI, 2006). The regulation limit from 1919 sets the minimum flow at Stjernfors to between 0 and 1.3 m^3/s depending on the current stage at the reservoir lake Ljusnaren (Länsstyrelsen Örebro län, 2007b). A later agreement between the power companies and the county administration recommends that the flow should be no less than 0.4-0.5 m^3/s, an agreement that is not legally binding. Bruno Johansson, the private owner of Dammen hydroelectric power station which is located downstream Stjernfors and Rällsälv, states that the river flow has been as low as 0.18 m^3/s due to the regulation upstream. There has also been an occasion during winter time when the flow was so low that parts of the river froze; this left hundreds of mussels dead on the bottom and may also have damaged the fish stock. The last four years, however, the situation has been improving, and the power stations try to always release at least 1 m^3/s.

Electro fishing has been carried out in 1989, 1994 and 2006. The stock of brown trout, which was the target species in this study, seems to be demonstrating a declining trend; in 1989, the trout population was calculated to 8 trout per 100 m^3, in 1994 the density was 0.3 trout per 100 m^3, and in 2006 no trout at all were registered from the electro fishing (Fiskeriverket, 2007a). However, according to Mikael Nyberg (personal com., 2007), the statistics are not to be taken too seriously; the reason to why no trout was found in 2006 may have been, except for an actual decline of the stock, the extremely high flow in Rällsälven that year. High flows make electro fishing problematic since fish are often swept by without being registered. The electro fishing was carried out at a site between Stjernfors and Rällsälv power stations, and since the dams are definite migration barriers the calculated densities of fish may not be extrapolated to other areas of the river. (Personal com. Nyberg, 2007)

Brown trout is being hatched and released into the river in order to enable the fry of the river pearl mussel *Margaritifera margaritifera* (Linnaeus, 1758) to spread. Last time it was done was in 2001, when the County Administration released 250 kg of 2-year old fish in the river (personal com., Wallin, 2007). However, it seems unclear if the contribution of trout has had any effect upon the mussels; Rällsälven has the largest population of river pearl mussel of Örebro County but the population consists of older individuals, and reproduction has not been confirmed lately (Holst & Tapper, 2005). No angling is being made for brown trout, and according to Bruno Johansson, the overall fish stock of the river has been improving during the last five years. Crayfish, perch, and large pike have been observed.

In November 2006 the river Rällsälven was surveyed by staff from IVL and a group of researchers from Germany with respect to velocity, depth, substratum, cover, and migration barriers. The data was processed in the mesohabitat model MesoCASiMiR which is being developed by University of Stuttgart. According to MesoCASiMiR there was only one site along the whole river reach that was a suitable spawning ground for brown trout. This site is a 300 metres long section located in the middle of the river reach, just upstream Rällsälv power station. In the upper kilometre of the river two areas with suitable substratum were found, but these had a much to low flow to be used by the fish (IVL Svenska Miljöinstitutet, 2007). Attempts were made to use the data collected for the mesohabitat modelling also at the microscale. However, it was soon found that the data could not be reused; the variables were sampled as broad intervals rather than the more exact numbers needed for microhabitat modelling.

3.2 FIELD WORK AND DATA COLLECTION

At the first sampling occasion, data of river bed elevation were collected with a total station for the uppermost 750 metres of the river reach. Within that distance, one part of 74 metres (C-reach) and one part of 184 metres (B-reach) were chosen for further study. These stretches were located in areas indicated as potential spawning grounds in the MesoCASiMiR modelling (IVL Svenska Miljöinstitutet, 2007). At the second occasion of data collection, elevation data of the remaining 500 metres was collected with a levelling instrument. A final stretch of 91 metres (A-reach) was chosen for microhabitat modelling. See Figure 5 for location of the reaches. A local coordinate system for the elevation was established starting at 100 metres at the foot of the Ljusnaren dam. The starting point of 100 metres corresponds to about 160 metres above sea level. The elevation data in the following report are given as local elevation coordinates.

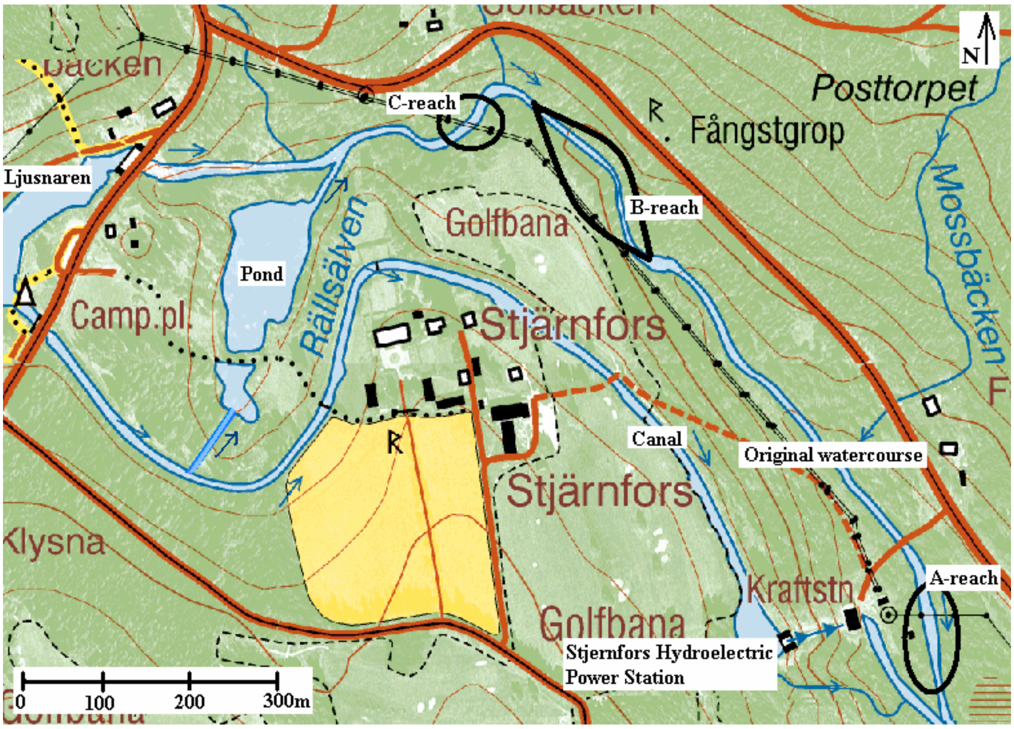


Figure 5 The uppermost section of Rällsälven in which the study was carried out. The northern course from the lake is normally dry, and water is diverted through the canal that runs south of the original course at a higher elevation (modified from Digital Miljöatlas, 2007).

The A-reach area is quite narrow, three to six metres, with well defined banks on both sides (Figure 6). Dense forest frames the river reach, the slope is small, and the substratum is mainly pebbles. At the beginning and end of the area are wide pools with substratum of dead organic matter. The photo was taken during low flow in August.

Figure 6 Photo taken in the upstream direction in the middle of the A-reach, August 2007.

The B-reach is located in a steeper area with substratum of mainly small and medium boulders (Figure 7). The river is framed by steep forested hillsides and the channel is wider than at the A-reach, the rod in the foreground is 2.4 metres long. The boulders cause turbulence, and there are a few small white water rapids. The photo was taken during high flow, when the dam was opened in June.

Figure 7 A representative piece of the long B-reach. Photo taken in the downstream direction in June 2007.

The C-reach is of similar slope as the A-reach but a bit wider, five to seven metres (Figure 8). The substratum is mainly pebbles, but slightly larger than at the A-reach. A gravel bank runs along one side of the river, and the other side is forested. The water is shallow and slowly flowing at the side of the gravel bank. Along the other bank there is a deep furrow with rapidly flowing water.

Figure 8 Photo taken in the upstream direction from the downstream-most cross section of the C-reach in June 2007.

In the three chosen reaches, transects were laid across the river, and data on water surface elevation, channel geometry, depth, velocity, and substratum size were collected according to the PHABSIM manual recommendations (Midcontinent Ecological Science Center, 2001). The water surface elevation was measured using a total station or levelling instrument. The best achievable accuracy of the water surface was about +/- 15 millimetres, though the manual recommends accuracy of a few millimetres for better modelling results. Depth was measured with a folding rule and flow velocity with a Söderlund current-meter. The substratum was measured with the folding rule and classified according to the system of soil classification used in Sweden, see classes in Table 2. The distance between each transect varied from 10 to 56 metres, and data were sampled at verticals every metre across the transects. Every transect was photographed and marked with an identification number at both banks of the river to enable further measurements at the exact spot.

At the B- and C-reaches, the water surface elevation, channel geometry, depth, velocity, and substratum was sampled in June, and an additional set of measurements of the water surface elevation for calibration of the model was made in August. At the A-reach, the basic measurements were made in August and no additional measurement of water surface elevation was made.

The river discharge was measured in two ways; with a Söderlund current-meter and with the salt-dilution method. The former method was considered to give a more reliable result, so the value derived from the current-meter calculation was used in the modelling. The inflows from tributaries along the reach were estimated by simply measuring or estimating depth, width, and surface flow velocity. See flow data in Appendix 2. The tributaries caused a gradual increase of flow in the main channel, and the discharge differences of the reaches have been accounted for in the modelling.

3.3 PHABSIM MICROHABITAT MODEL

The methods and sub-models listed here are the default options in PHABSIM, and these are the ones that have been used in this project. There are several other options within PHABSIM to further refine the modelling. However, the more complex models used, the more experienced the modeller has to be.

Figure 9 below shows the different modelling components in PHABSIM and the order in which they are to be carried out. Solid lines indicate the path followed and the sub-models used in the modelling process of this project. Several other options are available within the PHABSIM model, those options are indicated by dashed lines.

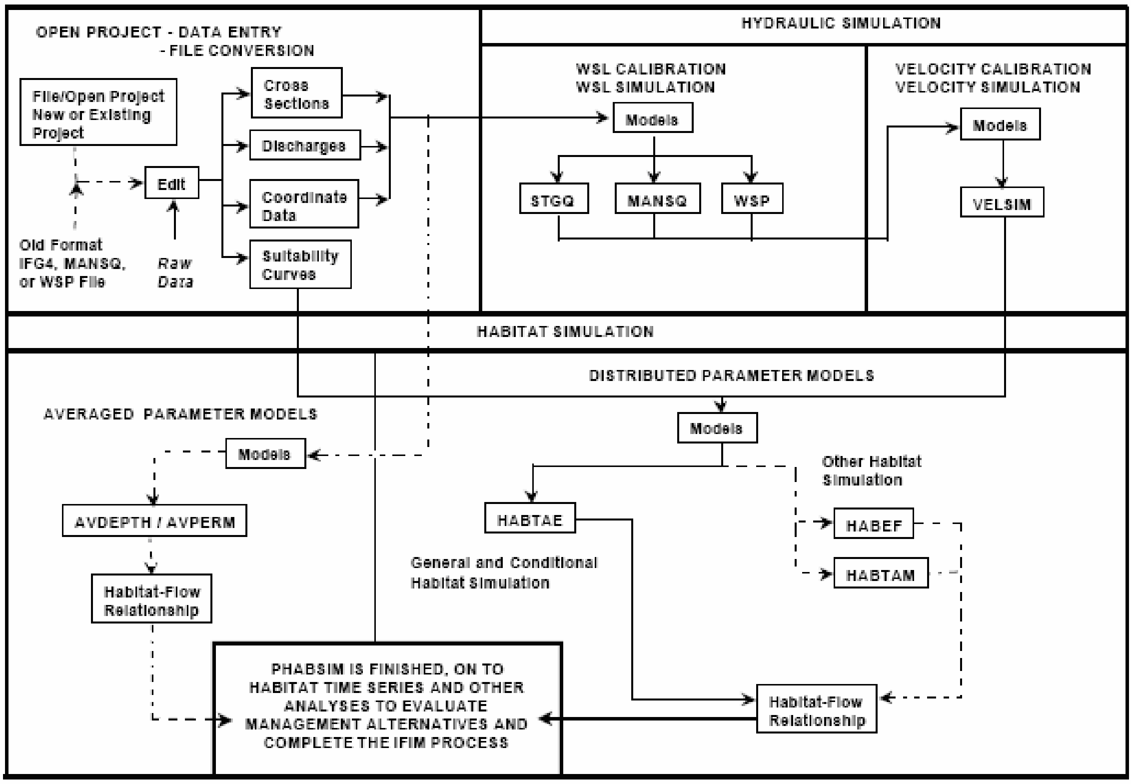


Figure 9 Flow chart of the PHABSIM modelling process (modified from Midcontinent Ecological Science Center, 2001).

3.3.1 Theory about PHABSIM hydraulic modelling

Within PHABSIM, there is a choice of three sub-models to carry out the water surface elevation modelling; STGQ, WSP and MANSQ. The velocity simulation is made in VELSIM. The following information collected from the PHABSIM manual supplied by the developers of PHABSIM, Midcontinent Ecological Science Center.

A general assumption for all the models is the equation of continuity. The study site is chosen so that no inflows or outflows occur along the reach, and the stage needs to be constant during the time of data collection.

Equation of continuity (2):

$$Q = VA \qquad (2)$$

Q = discharge
V = cross section mean velocity
A = cross section area

The flow in the channel between two adjacent transects is assumed to be uniform so that bed slope, hydraulic slope, and energy slope may be considered to be equal. Figure 10 shows the relationship.

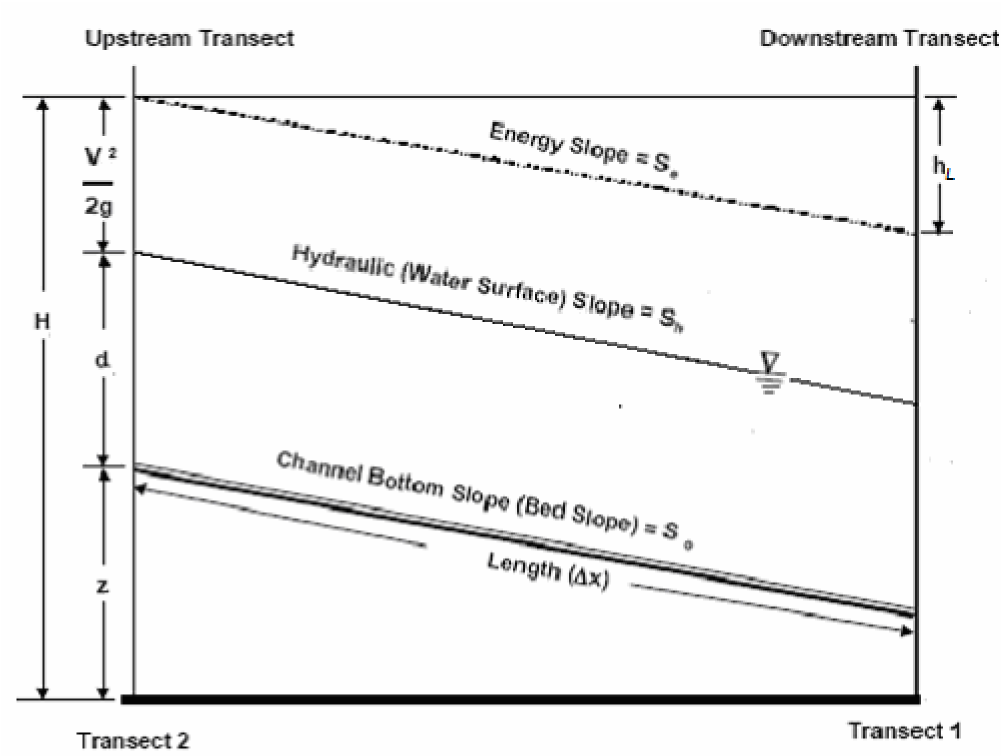


Figure 10 Energy relationships between transects at uniform flow.

V = velocity
g = acceleration of gravity
$\frac{v^2}{2g}$ = velocity head
z = river bed elevation above datum
d = water depth
H = total head
h_L = head loss
S_e = energy slope
S_h = hydraulic slope
S_0 = bed slope
Δx = distance between transects

(Modified from Midcontinent Ecological Science Center, 2001).

Water surface elevation model using regression (STGQ)
The STGQ sub-model is based upon an empirical relation between discharge and the stage at every cross section. It is recommended to use at least three sets of stage and discharge to develop a reliable regression. In case only two calibration flows are used extrapolation shall be done with caution. Each transect is treated individually, so the length of the reach between two transects is unimportant. When the channel shape is regular, the relation between the stage and discharge at a transect follows the relationship of the normal rating curve.

Normal rating curve (3):

$$(W_{SL} - S_{SF}) = aQ^b \qquad (3)$$

W_{SL} = water surface elevation
S_{SF} = stage of zero flow
Q = discharge
a = constant derived from measured values of discharge and stage
b = constant derived from measured values of discharge and stage

Equation 3 may be transformed into Equation 4 to form a linear relationship:

$$\log(W_{SL} - S_{SF}) = \log(a) + b * \log(Q) \qquad (4)$$

A linear regression is performed to find the constants a and b, and from the received equation the stage may be computed for a given discharge.

In cases of very irregular channel shape, the linear regression will not hold true, nor will this method work if the stage at the transect is influenced by back-water effects from a downstream hydraulic control such as in a pool.

Water surface elevation model using Manning's equation (MANSQ)
The backbone of the MANSQ model is Manning's equation in the form (5) which is applied to each cross section.

Manning's equation (5):

$$Q = \left[\frac{1}{n} S_e^{1/2}\right] A R^{2/3} \qquad (5)$$

Q = discharge
n = Manning's n
S_e = energy slope
A = cross sectional area
R = hydraulic radius

The assumption of uniform flow makes it possible to use the measured hydraulic slope instead of the energy slope.

The variable K is introduced for $\frac{1}{n} S_e^{1/2}$ and Equation 5 is rearranged to Equation 6:

$$K = \frac{Q}{AR^{2/3}} \tag{6}$$

The measured stage and cross section geometry is utilized by the model to give cross sectional area and hydraulic radius. A and R together with the measured discharge is used in Equation 6 to give K for one of the measured calibration discharges.

The calibration values for K and Q are used in Equation 7 and the remaining measured discharges are inserted one at the time.

$$K = K_0 \left(\frac{Q}{Q_0} \right)^{\beta} \tag{7}$$

K = the variable from which the simulated water surface elevation is found
Q = simulation discharge
K_0 = calibration value of K
Q_0 = calibration value of discharge
β = calibration coefficient

The calibration coefficient β is adjusted by the modeller so that the errors between the simulated water surface elevations derived from K and the observed water surface for the measured discharges are minimized. The coefficient β is a measure of how the roughness decreases with increasing discharge. A high β implies that the roughness decreases rapidly with increasing discharge. When a β-value has been found for every cross section, the chosen simulation discharges are applied to Equation 7. Every simulation discharge will give a K from which the cross sectional area and hydraulic radius may be found through Equation 6. From the cross sectional area, the hydraulic radius and the known cross section geometry, MANSQ can find the stage.

As in the STGQ model, each cross section is treated independently in MANSQ. It makes the calibration process easy, but it may cause problems when applying the model in pool areas.

Water surface elevation model using the water surface profile model (WSP)
WSP uses a step-backwater method to calculate the sequence of connected water surface elevations, starting at the downstream-most cross section and continuing upstream. The equation of continuity (2) is applied and the losses between two adjacent cross sections are calculated in the energy equation (8).

Energy equation (8):

$$z_1 + d_1 + \frac{v_1^2}{2g} = z_2 + d_2 + \frac{v_2^2}{2g} + h_L \qquad (8)$$

z = elevation of channel bottom
d = water depth
$\frac{v^2}{2g}$ = velocity head
v = mean velocity of water
g = gravitational constant
h_L = head loss due to friction, turbulence and viscous effects.

In addition to the energy equation, Manning's equation in the form (9) is used at every cross section to cross-check between the flow and energy balances by defining the energy slope, S_e.

Manning's equation (9):

$$S_e = \left[\frac{Q}{R^{2/3} A} n \right]^2 \qquad (9)$$

Q = discharge
n = Manning's n
A = cross sectional area
R = hydraulic radius
S_e = energy slope

The roughness coefficient Manning's *n* is used to indicate the factors that contribute to the resistance to flow in the channel. The higher the resistance due to friction, turbulence, and viscous effects, the higher the value of *n*. In calibrating the model, the modeller assigns a value of *n* for every cross section. Guidelines for expected Manning's *n* values are listed in Table 1.

Table 1 Expected values of Manning's *n* in natural channels (Crowe *et al.,* 2001; Midcontinent Ecological Science Center, 2001).

Channel type	**Ranges of Manning's *n***
Gravel substratum, clean and straight,	0.025 to 0.030
Winding, with pools and sandbars	0.033 to 0.040
Gravel beds with large boulders	0.035 to 0.045
Earth, very weedy and overgrown	0.075 to 0.150

The resistance to flow decreases with increasing discharge, and this is accounted for in the calibration process by setting roughness modifiers, RMODs, that scales the Manning's *n* up or down at every simulation flow.

The WSP model requires an initial water surface elevation value at the first cross section for every simulation discharge. This may either be supplied manually, or by running the STGQ or MANSQ model before the WSP model is run.

Velocity simulation (VELSIM)
Lacking reliable theoretical formulas to compute velocity distribution, PHABSIM velocity modelling relies on empirical relations. Velocity distribution may be simulated without previous velocity measurements, but more reliable results will be given if VELSIM is supplied with one or several sets of measured velocity distributions as a template for the simulations. VELSIM calculates roughness coefficient, *n*, values for each vertical across the transects and these *n* govern the velocity distribution.

In this project one set of velocity measurements was collected, and since slope, velocities, and depths for each vertical are known, *n* may be solved for from Equation 10:

$$n_i = \frac{S_e^{1/2} d_i^{2/3}}{v_i} \qquad (10)$$

n_i = Manning's *n* at vertical *i*
S_e = energy slope
d_i = depth at vertical *i* at calibration discharge
v_i = velocity at vertical *i* at calibration discharge
The subscript *i* denotes the verticals across the cross section.

Using the Manning's *n* derived from the calibration discharge, simulation discharge velocities may be calculated with Equation 11 from the known variables:

$$v_i = \frac{S_e^{1/2} d_i^{2/3}}{n_i} \qquad (11)$$

n_i = Manning's *n* at vertical *i*
S_e = energy slope
d_i = depth at vertical *i* received from water surface elevation simulation
v_i = simulated velocity at vertical *i*
The subscript *i* denotes the verticals across the cross section.

The Manning's *n* derived with Equation 10 will not be correct for discharges that are higher or lower than the calibration discharge. Manning's *n* has to be scaled in a similar way as is done by RMODs in the WSP modelling to account for the varying resistance depending on the magnitude of discharge. This is done automatically by VELSIM using the so-called velocity adjustment factors, VAF.

3.3.2 Theory about PHABSIM habitat modelling

When the hydraulic modelling is completed, habitat modelling with the HABTAE model is applied to the simulated depth and flow velocity. Habitat preferences of velocity, depth, and substratum for the target species is represented by a set of three curves showing the degree of suitability in a range of zero to one (Figure 11).

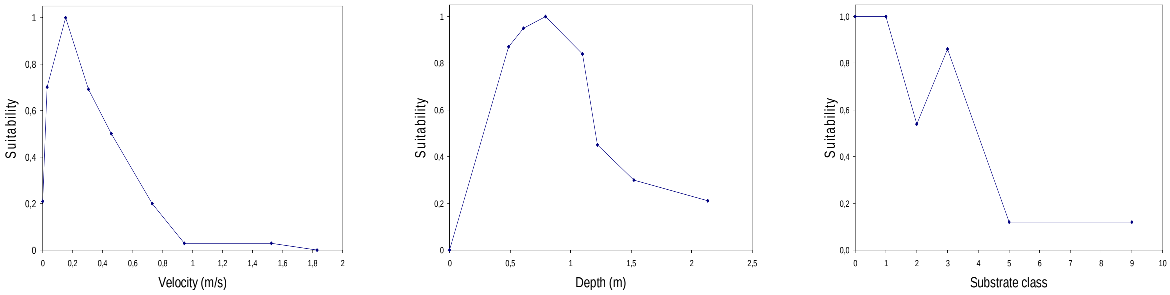


Figure 11 Example of a set of HSC curves. Velocity, depth, and substratum HSC curves for adult brown trout (Raleigh *et al*., 1986).

HSC curves are developed by studying the fish in their natural environment. The availability of certain physical conditions and the fish's usage of those conditions is studied, and HSC curves are developed from the data. The curves should preferably have been developed in the same, or in a similar river, as the PHABSIM study is being conducted (Heggenes *et al.,* 1996; Greenberg *et al.,* 1996 cited by Vismara *et al*., 2001).

There are no suitability curves developed in Sweden; the curves used in this study are collected from various scientific papers, and are produced in the U.S., Norway, Denmark, and transferred from fuzzy-sets for MesoCASiMiR developed in Germany (Raleigh *et al*., 1986; Heggenes, 1996; Lund, 1996 used by Thorn and Conallin, 2006; IVL Svenska Miljöinstitutet, 2007). The substratum classes were defined in different ways in the different papers. Some authors named the classes as gravel, pebbles, cobbles et cetera, classes that may belong to different classification systems. Other authors stated definite size ranges of the substratum. The substratum fractions were transferred to the system of soil classification used in Sweden (Table 2). The collection of HSC curves used in this study is supplied in the form of tables in Appendix 3.

Table 2 Size ranges for classification of substratum.

Code	Abbrev.	Definition (Swe.)	Definition (Eng.)	Particle diam. (m)
0	FIN	Finsediment	Fine sediments	<0.0002
1	SAND	Sand	Sand	0.0002-0.002
2	GRUS	Grus	Gravel	0.002-0.02
3	ST1	Mindre sten	Small pebble	0.02-0.1
4	ST2	Större sten	Large pebble	0.1-0.2
5	BL1	Mindre block	Small boulder	0.2-0.3
6	BL2	Medelstor block	Medium boulder	0.3-0.4
7	BL3	Större block	Large boulder	0.4-2
8	HÄLL	Häll	Bedrock	>2
9	VEG	Undervattensveg.	Vegetation	-

The computed velocity, depth, and substratum at every computational cell in the river correspond to a value on the three HSC curves, respectively. These values are combined to give a value between zero and one that represents the overall suitability at that site. There are three ways to combine the values:

Standard calculation
The suitability values are multiplied according to Equation 12 to give the overall suitability at every computational cell:

$$\textit{Combined suitability} = v\ d\ s \qquad (12)$$

v = preference value for velocity
d = preference value for depth
s = preference value for substratum

Using this way of calculating suitability it is assumed that the variables are independent and have a synergistic effect on the combined suitability.

Geometric mean
Equation 13 calculates combined suitability using the geometric mean**:**

$$\textit{Combined suitability} = \sqrt[3]{vds} \qquad (13)$$

v = preference value for velocity
d = preference value for depth
s = preference value for substratum

Using the geometric mean calculation implies that parameters with high suitability values can compensate for a parameter that has a lower value. The parameter with the low value will have small effect on the total suitability unless the value is zero.

Lowest limiting factor
The parameter with the lowest value sets the value of the combined suitability according to Equation 14:

$$\textit{Combined suitability} = Min(v, d, s) \qquad (14)$$

v = preference value for velocity
d = preference value for depth
s = preference value for substratum

It is assumed that other parameters with high suitability values cannot compensate for the inconvenience caused by the “worst” parameter.

Output
The final output given from the habitat modelling are graphs showing the suitability values of the different parts of the river, and the weighted usable area (WUA).

The maps may be viewed either as a 2-dimensional colour pattern indicating the suitability at different areas, or as a 3-dimensional picture that also shows the geometry and slope of the river bed. The suitability may be viewed separately one at the time, or as the combined suitability.

The WUA is the output that is most commonly referred to when evaluating a microhabitat model. WUA is given as the area of usable habitat in square metres per 1000 metres of river reach, and is calculated according to Equation 15:

$$W_{UA} = \frac{\sum_{i=1}^{n} A_i C_i}{1000L} \qquad (15)$$

W_{UA} = weighted usable area
n = number of computational cells
A_i = area of cell i
C_i = combined suitability of cell i
L = reach length
The subscript i denotes the number of computational cells of the reach

Calculating WUA in this way implies that a large area of low suitability is as desired as a small area of high suitability. An option in the HABTAE program allows the user to exclude areas of low suitability from the WUA sum.

4 RESULTS

Attempts were made to apply all three water surface elevation models to all three reaches, but several obstacles were encountered. Only for the C-reach, which had a simple morphology, it was possible to apply all models. The models were applied as listed in Table 3.

Table 3 Summary of the characteristics of the reaches and the water surface elevation models applied to each reach.

	General characteristics	Applied models
A-reach	Water flowing from a pool through a narrow outlet Small slope Straight reach Narrow channel, ends in a wide pool Substratum mainly pebbles, finer material in the pool	MANSQ WSP with MANSQ as initializer
B-reach	Steep slope Straight reach Wide channel Substratum large pebbles and boulders	MANSQ
C-reach	Small slope Straight reach Wide channel Substratum mainly pebbles, some sand and boulders	STGQ MANSQ WSP with STGQ as initializer WSP with MANSQ as initializer

After finishing the water surface elevation modelling, velocity modelling and habitat modelling was carried out. The simulated flows were 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, and 1.4 m^3/s.

Based on the results in the hydraulic and habitat modelling, the model performance of PHABSIM is evaluated in Section 5.

4.1 RESULTS FROM THE HYDRAULIC MODELLING

4.1.1 STGQ modelling

It is recommended to use at least three different observed discharges to find the regression equation that will compute the simulated water surface elevation. However, if the simulation flows are not extrapolated too far from the calibration discharges, the model will also give reasonable results with only two calibration discharges. In this study, the highest simulation discharge was 0.54 m^3/s higher than the highest calibration discharge, a small extrapolation that is assumed to be valid.

A-reach

Only one calibration flow is available for the A-reach, and this is insufficient to run the STGQ-model.

B-reach

The STGQ-model would not run for this reach. A sufficient amount of calibration flows were available, but probably the geometry of the reach was too complex to be handled by the model.

C-reach

The model runs without problems. The reach is short, with only three transects, it has an even slope, and evenly sloping banks. The regular shape of the reach makes the stage-discharge regression reliable and the modelling results more valid than if the shape would have been irregular. Extrapolation above the calibration flows is also more reliable if the geometry of the channel is regular. An example of longitudinal view of the reach with its simulated water surface elevations is given in Figure 12. The simulated discharges 0.1 and 0.8 m^3/s are calibrated to coincide with the corresponding observed flows. An intermediate simulated discharge of 0.4 m^3/s is also shown on the graph.

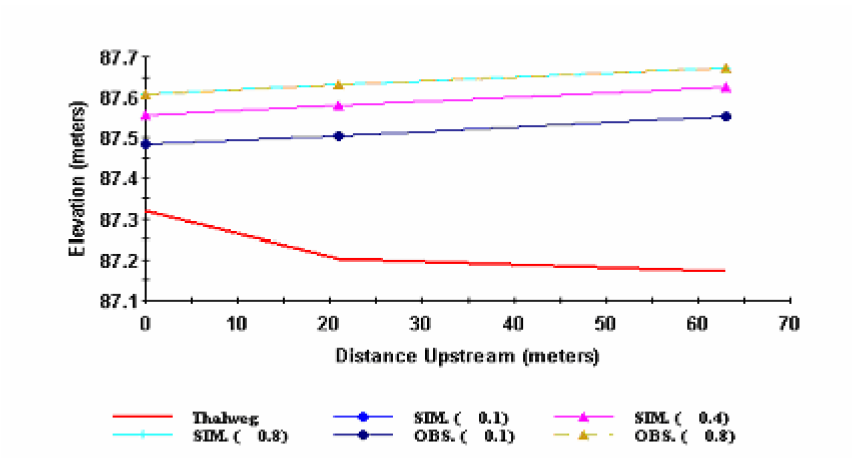


Figure 12 Water surface elevation profile simulated for C-reach with STGQ.

4.1.2 MANSQ modelling

A-reach

At least two calibration flows are needed, but only one is measured at this reach. In order to run the MANSQ model, an extra flow is made up; the same increase of water depth at high flow noted in the field at the C-reach, 0.23 metres, is used at the A-reach. The A- and C-reaches have similar slope and substratum. Using water surface elevation data from another reach is a crude way to estimate the missing data, and the result from the WSP modelling is probably more reliable than the result from this modelling.

Reasonable results are given along the reach, except at the uppermost transects where a pool flows into the narrow channel. At discharges greater than 1.5 m^3/s the simulated water surface profile shows water flowing the opposite direction. In the final calculations the maximum discharge is 1.4 m^3/s.

B-reach

MANSQ is the only model that simulates this reach. However, the agreement between modelled and simulated water surface is not satisfactory at all parts of the reach. The β-coefficient is maximized, but should have been further increased at some cross sections to further improve calibration.

C-reach

The model is easy to calibrate and runs without problems. The substratum is mainly consisting of rather small cobbles, the reach is straight, and the channel bottom is even so the resistance to flow is small. The β-coefficient is therefore kept reasonably low, and all cross sections can be calibrated.

4.1.3 WSP modelling

WSP would not run for discharges less than 0.1 m^3/s. Even though the smallest discharge in this study was 0.079 m^3/s, 0.1 m^3/s had to be used in the WSP modelling and also in the other models to enable comparison of the results.

A-reach

The WSP-modelling of the A-reach is unreliable due to several assumptions whose validity has not been verified.

The WSP-model starts water surface calculations at the transect furthest downstream, and works its way upstream. In this area the calculations stopped before it reached the top end of the river reach. To solve this, extra transects were added at the problem sites in order to decrease the head difference (Equation 8) between adjacent transects. The extra transects were constructed as the average with respect to elevation, velocity, and substratum of the two transects it was inserted between. With three extra transects inserted, the WSP model would calculate the whole reach.

Water surface elevations were measured only at one discharge, which makes the calibration less reliable than if more flows had been measured. The WSP model needs initializers, the water surface elevation at the transect furthest downstream, in order to start the simulations. The initializers are supplied either manually or by modelling the initial stage with MANSQ or STGQ. In this case the initializers were supplied by MANSQ.

Two calibration flows are needed to find the RMOD relationship, the RMODs needed for the WSP-modelling are taken from the C-reach.

At the uppermost transects, just downstream a pool, unrealistically high water surface elevations are simulated. This area is removed in the final calculations.

B-reach

The model will not run at all for this reach, even though several extra transects are added in the problematic areas. The distance between the transects was decreased down to three metres, but still the problems persisted. Figure 13 shows the observed water surface elevation and the result from the attempts to simulate the B-reach using WSP. The model managed the higher discharges slightly better than the lower ones. The high discharge is modelled a short distance further upstream than the lower, but the overall modelling is clearly not satisfactory.

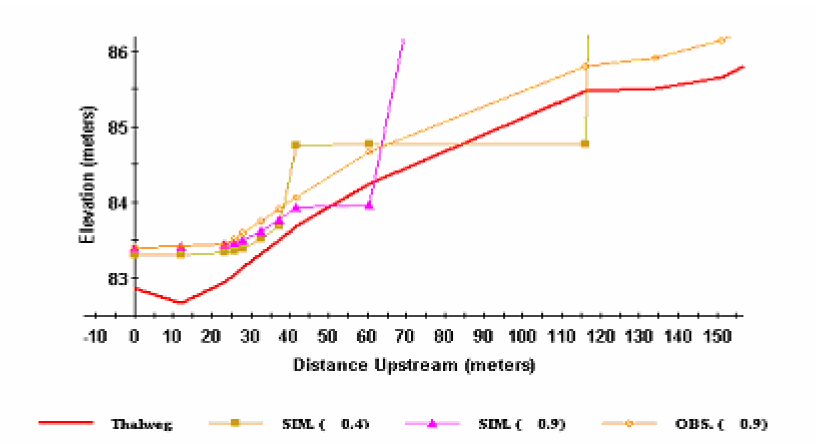


Figure 13 Water surface elevation simulated for B-reach with WSP. Thalweg elevation, observed water surface elevation, and simulated water surface elevations.

C-reach

The model runs without problems. Manning's *n* is easily found for all three transects. The resistance to flow is rather small due to the small substratum size and simple morphology of the reach so Manning's *n* is within the range that is recommended in the PHABSIM manual (Midcontinent Ecological Science Center, 2001). Water surface elevation was modelled using initializers supplied by either STGQ or MANSQ, and the two resulting water surface elevation profiles were almost identical. The differences were well within the margin of error of the field measurements.

4.1.4 VELSIM modelling

No evident problems were encountered in the VELSIM modelling, though it is difficult to evaluate how realistic the simulated output is; a water surface sloping the wrong way is visually more apparent than an erratic velocity distribution. With the default options chosen, the process is automated with PHABSIM automatically calibrating the Manning's *n* used in velocity simulation. The simulated velocity distribution is very much dependent on the measured distribution; the measured distribution is used as a template, and the simulated value is shifted up or down depending on the simulated water surface elevation. The velocity distribution along with the river bed geometry may be viewed for cross sections of the river at every measured transect (Figure 14).

Observed velocity for 0.1 m^3/s is zero because no measurements were made at that discharge.

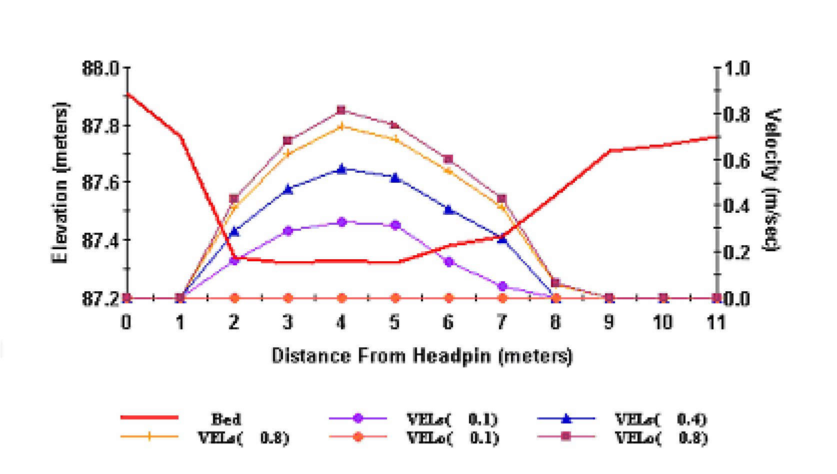


Figure 14 Measured and simulated velocity profiles and river bed geometry at the C-transect furthest downstream.

4.2 SENSITIVITY ANALYSIS OF HYDRAULIC RESULTS

A sensitivity analysis of the hydraulics was made in order to see the influence of small changes of the input data and calibration values on the simulated water surface elevation results. The final modelling result of the middle transect in the C-reach was taken as reference value, and parameters in the calibration process that could influence the result were varied one at the time with 10 percent each. The parameters were the discharge, β-coefficient, Manning’s *n*, and RMOD. In this sensitivity analysis, the default options recommended in the PHABSIM manual are used, and variation of parameters measured in the field or changed in the calibration process is investigated. The result is presented for three simulated flows; 0.2, 0.8, and 1.2 m^3/s, chosen to represent low, medium, and high discharges (Appendix 5 Table 1). The C-reach was chosen because it was the only one for which all models worked properly.

The change that had the most influence on the water surface elevation result was the increase of the parameter high calibration flow when using the MANSQ model. The newly simulated water surface elevation differed more than 0.1 m from the reference value. The other simulated water surface elevations differed less than 0.01 m from the reference value when changing calibration flow and calibration constants, a value that is within the margin of error of the field measurements.

4.3 RESULTS FROM THE HABITAT MODELLING

The final output from the hydraulic and habitat modelling are the WUA graphs that show the discharge needed to enable maximum habitat area, and colour coded 2- or 3-dimensional graphs showing the suitability values in different areas of the river. The full set of WUA graphs for all reaches and lifestages are supplied in Appendix 4. The habitat modelling was performed using the standard calculation method for habitat suitability.

An example of a 3-dimensional habitat graph is shown in Figure 15. These may be useful to identify specific problematic areas, and to see how the suitability at specific sites varies with varying flow. However, an overview of all simulated flows would require a large amount of graphs, and the final output is most commonly presented as WUA graphs.

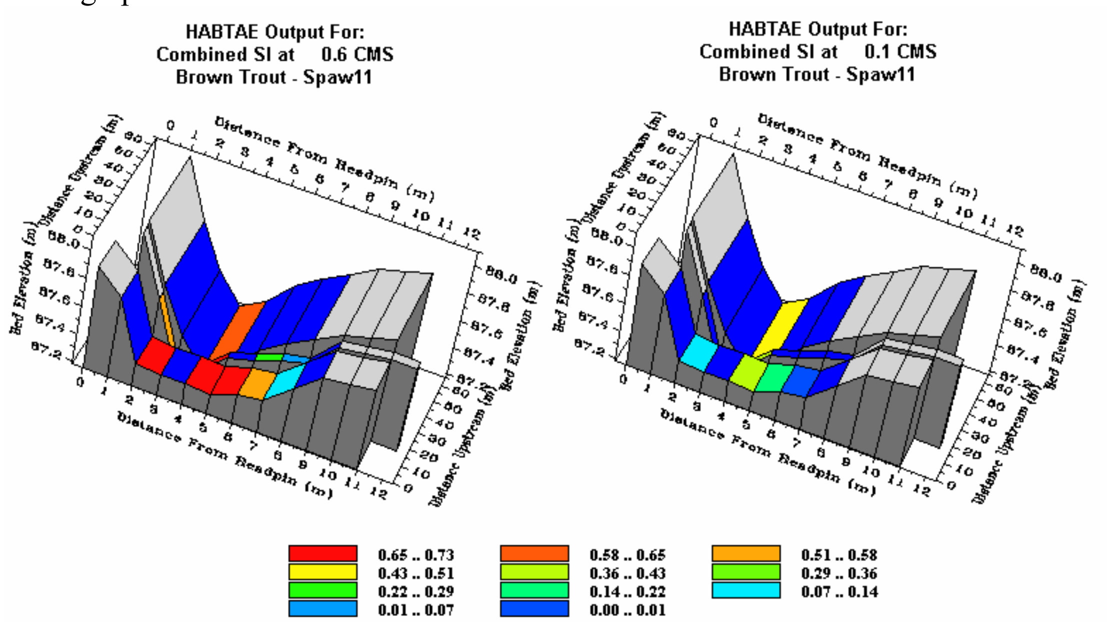


Figure 15 3-dimensional view of habitat simulation results from C-reach. Discharges 0.6 and 0.1 m^3/s, water surface elevation simulated with STGQ. Spawning lifestage, standard calculation.

Common for all spawning curves is that the greatest increase of WUA per increased flow is modelled for an increase of flow from 0.1 to 0.2 m^3/s. Depending on which set of HSC curves has been used, the increase of WUA may be two-fold to ten-fold for the small increase of discharge. One set of HSC curves even give an increase from 0 to 500 $m^2/1000$ m at the C-reach.

At the A-reach, the WUA for spawning continues to increase with increased discharge, and reaches its maximum around 1.0 m^3/s. The shapes of the three WUA curves are quite similar; two of curves coincide while the third is of similar shape but lower (Figure 16). The curves derived from water surface elevations computed with WSP-MANSQ are a lot lower than those derived with MANSQ; the MANSQ curves show almost twice the habitat area.

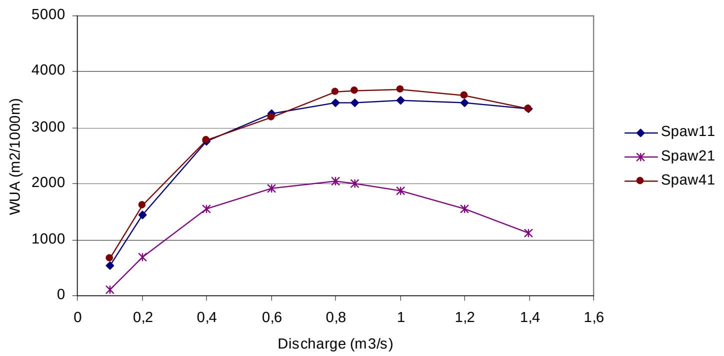


Figure 16 A representative WUA curve for the spawning lifestage. A-reach with water surface elevation modelled with MANSQ.

The WUA spawning curves computed for the B-reach have similar shape as those for the A-reach; there is a moderate increase of WUA with increased flow up to a maximum WUA of 2000- 2500 m^2/1000m at a discharge of 0.8 m^3/s.

The spawning curves for the C-reach have a somewhat different shape; the increase of WUA is more rapid, and the peak WUA is reached at a discharge of 0.5 m^3/s. The magnitude of WUA rapidly declines at higher discharges.

The WUA curves for Fry12 and Juv13 have the same shape as the spawning curves but are consistently lower, while the curves for Juv33 show an irregular shape and reach surprisingly high values. At the A-reach the Juv33 curve shows a decrease of available habitat for increased discharge, contrary to the pattern of the other curves. At the B- and C-reaches the Juv33 curve reaches WUA values three times higher than the other juvenile curve (Figure 17).

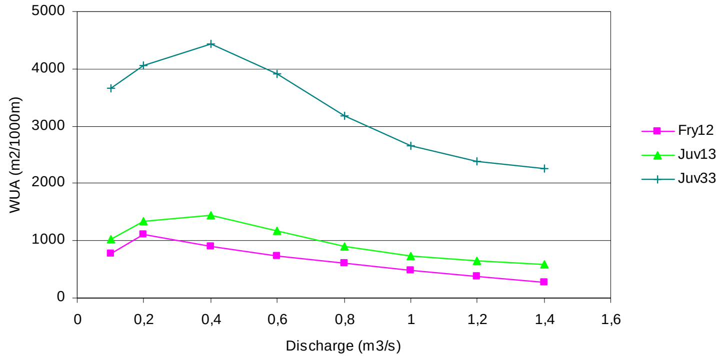


Figure 17 The Juv33 curve is surprisingly high compared to the curve for fries and the other juvenile curve. C-reach with water surface elevation modelled with MANSQ.

The WUA curves for the adult lifestage do not show the characteristic pattern of a distinct peak WUA at a certain discharge. The highest WUA for adult individuals is quite low, just above 1500 m^2/1000 m at all of the reaches (Figure 18).

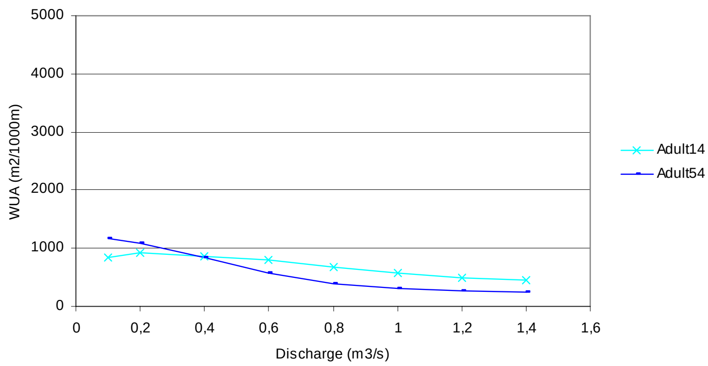


Figure 18 Representative WUA curves for the adult lifestage. The curves do not show a peak value for any certain discharge. C-reach with water surface elevation modelled with MANSQ.

For the adult lifestages at the A- and B-reaches there is a relatively small increase of WUA, 25- 30 percent, with an increase of discharge from 0.1- 0.2 m^3/s. At the C-reach, the curve for Adult54 shows a constant decrease of available habitat with an increase of flow, while Adult14 shows a small initial increase, and then decreases. The WUA for adults is low at all reaches and a minimum WUA of 240 m^2/1000 m is calculated for the C-reach at a discharge of 1.4 m^3/s.

4.4 SENSITIVITY ANALYSIS OF HABITAT RESULTS

A sensitivity analysis of the WUA output was performed in order to investigate the influence of small increases and decreases in slope, substratum size, and the β-coefficient upon the value of WUA. The analysis was performed for the C-reach with one of the suitability curves for spawning, Spaw11. The water surface elevations were calculated with MANSQ. The result is presented for three simulated flows, chosen to represent the range of simulated discharges (Appendix 5 Table 2). The sensitivity analysis is only presented for the C-reach and MANSQ since it was realized that the variability of the output was of similar pattern irrespectively of model used and reach modelled.

When changing slope by 10 percent or changing β by 10 percent, the change of the resulting WUA is small. The maximum change of WUA, 3.32 percent, is found when β is decreased by 10 percent. Otherwise the change of WUA is 1.71 percent or less. On the other hand, when changing the substratum classes, the change of WUA is very large. By decreasing the substratum sizes given for the reach to the class below, the WUA could be increased by 263 percent. By increasing the classes one level the habitat area was almost completely erased. If the habitat size increases or decreases due to changes is of course dependent on the original condition.

A sensitivity test of the HSC curves was also made. The three sets of HSC curves for spawning were laid in the same diagram and two new sets were produced by following the curve that gave the highest and the lowest suitability, respectively. As the original HSC curves crossed occasionally, the new ones were made up from sections of one, two, or three HSC curves. The resulting HSC curves are shown in Figure 19.

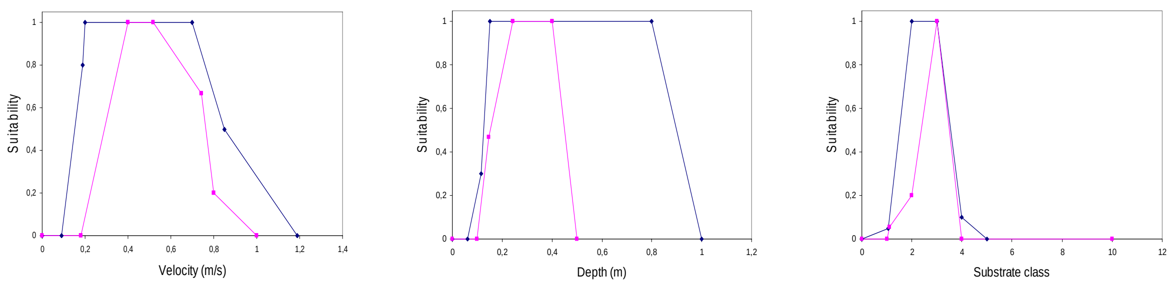


Figure 19 Maximum (upper) and minimum (lower) HSC curves for spawning brown trout. Velocity, depth, and substratum class.

The two new sets of HSC curves were run with the MANSQ model at all three reaches, and the output is presented in Appendix 6.

The difference in the magnitude of WUA is very large depending on if the area is calculated with an allowing set of HSC curves giving high suitability, or if the stricter limits are used. The shape of the curves are about the same within each reach, but the WUA calculated with the maximum HSC is twice the magnitude of the minimum curve at some discharges.

5 DISCUSSION

The performance of the various hydraulic and biologic sub-models of PHABSIM has been tested in Rällsälven. The reliability and usability of the model is discussed, based upon the results obtained. The hydraulic and habitat modelling are discussed separately. Possible remedial measures for the dry reach in Rällsälven are proposed and the usability of PHABSIM as a decision making tool is finally discussed.

5.1 HYDRAULIC MODELLING

The modelling in this study has been made with the default options chosen from the multitude of options in PHABSIM. Different assumptions may be made regarding friction computations, velocity distribution, the fish's behaviour, etc. There are also additional habitat sub-models available within PHABSIM that have not been discussed in this paper. The different options have not been tested but the choice of options would certainly influence the result.

It requires a large amount of knowledge to choose the right ones among all the options available, but a more experienced modeller can probably get a better agreement with reality. However, the result is difficult to validate, especially the habitat simulations. The output from the hydraulic model could quite easily be verified by measuring depth and velocity at the simulation flows, but inventorying the fish stock in order to see how it has recovered due to restoration is a very difficult task.

The build-up and calibration of the hydraulic models was easy for the C-reach, which had a simple morphology and a small number of cross sections. For the other two areas, however, several problems were encountered in the calibration of the reaches.

At the A- and B-reaches, the WSP modelling "gets stuck" as it is supposed to work its way upstream from the transects further downstream. This is possibly due to a too large head difference between adjacent cross sections and the model looses track when the calculations do not converge. The head losses are due to friction and turbulence which are increased by rough substratum, and the influence of friction is larger at shallow, rapid waters than in deep, slowly flowing waters. The modelling problem could be solved for the A-reach by adding extra cross sections to decrease the gap between adjacent cross sections. The problems with the WSP-model persisted at the B-reach, which is both steeper and have rougher substratum than the A- and C-reaches.

The poor modelling results for high-gradient rivers have been noticed previously, for example by Azzillino and Vismara (2001) who state "high-gradient (>1%), low-order streams, characterized by hydraulically non-uniform and heterogeneous channels, represent a problem for the most widely employed habitat-based in-stream flow methods (IFIM-PHABSIM)". The WSP model problems at the B-reach were looked closer at to find a threshold value for when the model calculations break down. See Appendix 7 for a detailed description. It seems as if the WSP model is sensitive to steep river bed slopes, and has problems properly calculating water surface elevations at a slope greater than about 1 percent. The model is also more sensitive to steep slopes when the simulated discharge is small, and the discharge 0.1 m^3/s is the smallest flow that WSP allows to be simulated at all.

The sensitivity analysis results for the C-reach listed in Appendix 5 Table 1 show that the differences in calculated water surface elevation due to small changes in slope, calibration flow, and calibration constants are in most cases very small. Only in one case the change was notably large. When the calibration flow for MANSQ was increased by 10 percent, the modelled elevation deviated from the previously modelled elevation by -0.107 m. This happened because the water surface elevation could not be properly calibrated. In the calibration process the simulated water surface elevation deviated from the observed, but the calibration constant β was maximized and thus no better fit could be achieved. This made the water surface elevation of the subsequently modelled discharges deviate greatly from the originally modelled elevations. The calibration problem illustrates the need for accurate flow measurements, but also how close to the boundary of the model's working range the modelled reach is. The β is a measure of slope and Manning's *n*, and the slope is too steep and the substratum too rough to be properly modelled with MANSQ. The same kind of problem is encountered in the modelling of the B-reach (Paragraph 4.1.2); the simulated water surface elevation for 0.1 m^3/s is about five centimetres below the observed water surface elevation for the same discharge. The β is maximized and the water surface elevation cannot be properly calibrated because the slope is too large and the substratum too rough to be represented by the model.

The morphology of the simulated reaches with their rather steep slopes and rough substratum is typical for Swedish rivers, especially in the northern part of the country. It is also mainly this kind of rivers in the mountainous areas that are regulated for hydropower and for which there is a need for habitat modelling. A hydraulic model that shows such a poor performance in such a common environment should interpreted with great caution. For all the areas in this study, it is possible to find at least one water surface elevation simulation method that seems to give a reasonable output, but it is time-consuming to go through the methods by trial and error.

5.2 HABITAT MODELLING

The concept of HSC curves is a questioned part of the microhabitat modelling. In PHABSIM and other habitat models it is assumed that the suitability is dependent only on a few physical parameters of the river. The interactions between these are assumed to follow relations represented by simple mathematical formulas, which might be too much of a simplification. Other parameters that also influence the production, such as pollutants, oxygenation, pH, food supply, and competition with other species are omitted. (Hudson *et al*., 2003)

While studying the WUA output (Appendix 4), it is obvious that the result within each life stage varies greatly depending on which HSC curve is being used. There are differences both in the absolute values of the curves and in the shapes of the curves. This indicates that one has to interpret the results with great caution. Especially the WUA curve for Juv33 shows an odd shape and an unexpectedly high value. The curve was retrieved from a Danish study using the habitat model RHYHABSIM. It was assumed that HSC curves were transferable between the models since models are based on the same concept, but possibly there is some difference in how the curves are used that causes the deviating output. On the other hand, the Spaw41 curve is taken from the same study, and the WUA curve produced with that HSC curve follows perfectly the WUA curve for Spaw11, which is produced with American PHABSIM data.

Another reason to question the habitat output is that these curves may not apply perfectly to Swedish trout. Brown trout living in the Swedish rivers are smaller than other brown trout due to the cold and nutrient-poor waters, and the habitat preferences may be slightly shifted towards lower values (IVL Svenska Miljöinstitutet, 2007). The two sets of HSC curves developed in Denmark are supposedly adjusted for rather slow-flowing low-land rivers. The other curves were developed in Norway and the U.S., but it was not specified for which type of environment the curves had been calibrated. Applying HSC curves to an area they were not made for may give misleading results.

The sensitivity analysis in which the input parameters for the habitat modelling were varied shows that the model is very sensitive to the substratum class used. This is especially true for the spawning life stage, which is very specific in its choice of substratum size. The sensitivity analysis emphasizes how important it is to conduct the substratum classification in a correct manner and also highlights a shortcoming of the model; it is sometimes impossible to classify the substratum clearly into one class, and choosing the higher or lower class may largely affect the WUA result. If the substratum was classified into smaller intervals this problem could be reduced, but then the HSC curves would have to be remade as well. In this study, an additional problem regarding substratum classification is that the HSC curves were taken from several sources. The different classification systems had to be merged into one, and in the transfer some of the accuracy of the substratum size and the corresponding suitability may have been lost.

The WUA curves produced from the sensitivity analysis with the max and min HSC curves clearly show the great span of modelled WUA (Appendix 6). Ideally the HSC curves, and thus WUA curves within each reach, should coincide to show consensus and increase the credibility of the curves. But instead, by choosing either the maximum or the minimum HSC curve, the output may differ by as much as 2000 m^2/ 1000 m. The modelling does not give a reliable answer to the magnitude of WUA. The WUA may be used for a simple comparison, for example to investigate if the habitat area will change due to a project. However, one should not put too much trust in the exact numbers; the magnitude is too dependent on which HSC curve has been used.

5.3 INTERPRETING THE MODELLING RESULTS FOR RÄLLSÄLVEN

This study does not claim to give an answer to the specific magnitude of the discharge needed to ensure the best ecological conditions in Rällsälven, because the calibration data and HSC curves are much too insufficient to give a reliable clear-cut number. However, the results may give a hint on the order of magnitude at which the most suitable flow could be expected.

The peak WUA occurs at different discharges at the different reaches, which makes it difficult to recommend one optimal flow for the whole reach. Looking at the spawning life stage, the maximum WUA is calculated for discharges about 0.8 m^3/s at the A-reach, above 1.0 m^3/s at the B-reach, and 0.5 m^3/s at the C-reach. This should be compared with the yearly average discharge at Stjernfors, which is 3.8 m^3/s. In order to maximize the WUA, 15-25 percent of the yearly discharge would be used to improve the ecological status of the dry reach instead of being led through the turbines

To demand Mälarenergi, the owner Stjernfors, to give up one fourth of the discharge would probably be to ask for more drastic measures than is required by the WFD. The highest status class a heavily modified water body may reach according to the WFD is "maximum ecologic potential". The waters belonging to that class are those that show the "best approximation to a natural aquatic ecosystem that could be achieved given the hydromorphological characteristics that cannot be changed without significant adverse effects on the specified use /…/" (European Communities, 2003). This may require an overview and adjustment of minimum flow, removal of migration barriers or construction of fish ways (Naturvårdsverket, 2005). The man-made hydromorphological characteristics in the case of Rällsälven are the dam and the hydropower station. According to the WFD, they should be allowed to remain where they are and also make use of a reasonable amount of the water resource but migration barriers may have to be removed.

The discharge giving the maximum WUA for fries, juveniles, and adults is considerably lower than for spawning; about 0.3- 0.5 m^3/s. This is a more realistic amount to lead past the hydropower station. That is also close to the discharge of 0.4- 0.5 m^3/s that is recommended by the county administration to keep an acceptable ecological status in the river downstream Stjernfors hydropower station (personal com. Johansson, 2007). The fact that the modelled values and experts' judgement coincide increases the models' credibility. As discussed above, the most rapid increase of WUA with increased discharge occurs when the discharge is up from 0.1 to 0.2 m^3/s. Even if the WUA of the reach is not maximized, a large gain of habitat area may be the result of a small additional flow allowed in the channel.

The extra water to increase the flow may either be let through the dam at Ljusnaren directly into the original river reach, or drawn from the canal to discharge into the river reach just upstream the C-reach (Figure 5). An increased flow will quite easily improve the habitat value of the reach, but it will not immediately make the area passable for trout migrating towards or from Ljusnaren. The dam at Ljusnaren is high and the surrounding terrain is steep, so it would be difficult to build a fish way in that area. There are also some smaller dams upstream the pond effectively stopping any fish from passing.

It is not only the magnitude of flow that is important to habitat quality; the timing also plays a role. Spawning, which is a sensitive period, occurs during a limited time in October to December and the eggs are hatched in late winter or early spring (Fiskeriverket, 2007b). With knowledge about the exact time for spawning, the discharge may be increased and adjusted to suit the fish at that certain time period. Too large amounts of water may also be a problem; spring flood is normally the only time when the dam at Ljusnaren is opened and large amounts of excess water, up to 15 m^3/s is not uncommon, fills the dry reach. These high flows have not been modelled, but certainly they are disturbing to the aquatic life, and especially the sensitive fries. Better forecasts of the water stage in Ljusnaren and better planning of water releases could possibly decrease the magnitude of the high flows.

5.4 THE USABILITY OF PHABSIM AS A DECISION-MAKING TOOL

In order for a model to be useful as a tool for decision-making, the cost for a site-specific study has to be reasonable and the model output reliable and objective. PHABSIM has the potential to be a powerful tool used in Swedish conditions, but as all microhabitat modelling it is a rather laborious method.

Setting up the hydraulic part of a microhabitat model requires large amounts of manually measured data, which makes the data collection time-consuming and costly. The data should preferably be accurate at the scale of a few millimetres, and will probably not be available from previous investigations of rivers. The data should be collected at least at two, preferably three or more separate flows, and at as a wide range of discharges as possible to make the hydraulic modelling reliable. The field data for this study was collected in eight man-days. With some training and experience the same amount of data could probably be collected in less time, maybe four-five days. However, Rällsälven is very small compared to other Swedish rivers used for hydro-power, and a greater discharge will certainly complicate the field work. In such cases more refined equipment will improve the efficiency of the data collection, for example echo sounder could be used for survey of bottom morphology and an acoustic Doppler device for water velocity measurements, as in the study by Yrjänä (1999). A differential GPS would enable accurate positioning in both horizontal and vertical direction.

To reduce the time spent on mapping the river, the studied areas should be chosen with care. Suppose the aim of the study is to find an instream flow suitable for spawning, the substratum will be an important factor. A quick survey of the substratum may be done by walking along the river or viewing aerial photos, or the substratum could be estimated by studying topographical maps. By immediately excluding unsuitable areas, focus may be laid upon a few short interesting reaches that may give a result representative for the whole river.

Before any further microhabitat modelling of Swedish rivers can be done, proper HSC curves have to be developed for Swedish conditions. This is a long and costly process; Vismara *et al.* (2001) covered 10 000 m^2 and made more than 500 fish observations in order to develop HSC curves for an Italian river. Possibly, data for development of HSC curves may be collected as electro fishing is performed in monitored rivers. The extra cost for data collection would probably be comparably small if there is already a monitoring programme running.

Once the hydraulic modelling has been completed, and if HSC curves are available, the habitat modelling is quick and easy. The curves can easily be exchanged to produce WUA calculated with curves from different sources or for different target species.

Trying to simply use the value of WUA to classify the current status of a river will not be a useable method. This is partly due to the uncertainty among the HSC curves, it has been shown that the output varies greatly depending on which set of curves has been used. Different types of rivers also have different basic conditions that determine habitat suitability, a river may be untouched by humans yet have a low WUA. The WUA should never be seen as an absolute truth, rather a tool to plan how to carry out restoration measures and to compare the habitat situation before and after.

One question needed to address is whether it is necessary to use a model at all to plan restoration measures and to classify the achieved river status. Is it worth the time and money spent? In remote areas that are poorly studied, and in areas where there is lack of long-term records to conduct a statistical analysis, expert judgement is often the first choice. Expert judgements are certainly faster and cheaper than habitat modelling. However, the objectivity of the experts' judgements may be questioned. As the new regulation limits are to be settled, the power companies will lobby for regulations as soft as possible, because every cubic metre of water through the turbines is a valuable income. The public and environmentalists on the other hand, will probably ask for a higher minimum discharge and low variability of the flow throughout the year. Habitat modelling may be an objective method that produces recommendations of a flow regime that all parties can agree upon. Once standards are set for choice of model, models settings, and HSC curves, habitat modelling may give reliable and reproducible results.

6 CONCLUSIONS

PHABSIM may very well become a suitable tool in the classification of waters according to the WFD and in the planning of rehabilitation measures, but much work is required before microhabitat modelling can be widely used in Sweden.

As has been shown, the resulting WUA curves are much dependent on the hydraulic model that has been used for water surface elevation simulation and the HSC curves that have been applied. Standards have to be developed on how to collect the data, which model to use, and how to proceed in the calibration. HSC curves have to be developed for Swedish conditions, either site specific of or applying to certain types of rivers, and these have to be agreed upon by all parties concerned.

In this study some hydraulic models would not work for specific reaches, and areas that can not be modelled at all might be encountered as PHABSIM becomes more widely used. Other physical habitat models such as RSS and FISU that are developed in Northern countries may possibly be more suited to represent the type of high gradient rivers that are common in Sweden. The Italian model EVHA that uses Limerinos equation instead of Manning's is also said to better represent high gradient rivers. If habitat modelling is to be recommended as a tool for instream flow assessment, the performance of these models should be tested and evaluated before any definite choice of model is made.

Well conducted habitat modelling may give objective answers to issues regarding instream flow; classification and recommended magnitude and timing of flow. If standards are set for which model to use, and if HSC curves are developed for Swedish conditions, the method may produce results that are acknowledged by all parties.

7 REFERENCES

7.1 PRINTED SOURCES

Acreman, M. & Dunbar, M. J. (2004). “Defining environmental flow requirements – a review”. *Hydrology and Earth System Sciences,* 8(5), 861-871.

Booker, D. J. & Acreman M. C. (2007). “Generalization of physical habitat-discharge relationships”. *Hydrology and Earth System Sciences,* 11(1), 141-157.

Bovee, K. D. (1986). *Development and evaluation of habitat suitability criteria for use in the instream flow incremental methodology.* Instream Flow Information Paper 21, Report 86 (7), U.S. Fish and Wildlife Service.

Caldwell, B. & Shedd, J. (2002). *Walla Walla River Fish Habitat Analysis Using the Instream Flow Incremental Methodology.* Washington State Department of Ecology and Department of Fish and Wildlife, Open File Technical Report No. 02-11-009.

Capra, H., Sabaton, C., Gouraud, V., Souchon, Y., & Lim, P. (2003). “A Population Dynamics Model and Habitat as a Tool to Predict Brown Trout Demography in Natural and Bypassed Stream Reaches”. *River Research and Applications,* 19, 551-568.

Clipperton, K, Vaughn, L. & DeFranscesco, D. (2003). *Little Spokane River Watershed Planning Instream Flow Needs Assessment.* Golder Associates Inc., Report No. 013-1372.2400.

Collings, M. R. (1974). *Generalization of Spawning and Rearing Discharges for Several Pacific Salmon Species in Western Washington.* USGS, open-file report.

Crowe, C.T., Elger, D. F. & Robertson, J. A. (2001). *Engineering Fluid Mechanics.* John Wiley & Sons, Inc., New York.

European Aquatic Modelling Network (2000). Proposal for a new Cost Action.

European Communities (2003). *Common Implementation Strategy for the Water Framework Directive (2000/60/EC). Overall Approach to the Classification of Ecological Status and Ecological Potential.* Office for Official Publications of the European Communities, Guidance Document No 13.

Giesecke, J., Schneider, M. & Jorde, K. (unpublished). *Analysis of Minimum Flow Streches Based on the Simulation Model CASIMIR.* Institute for Hydraulic Engineering, University of Stuttgart.

Ginot, V. (1995). “EVHA, Un logiciel d’evaluation de l’habitat du poission sous Windows” *Bull. Fr. Peche Pisic.,* 337/338/338, 303-308.

Gippel, C. G. & Stewardson, M. J. (1966). *Use of wetted perimeter in defining minimum environmental flows.* 2nd International Symposium in Habitat Hydraulics, Ecohydraulics 2000, Quebec City.

Greenberg, L., Svendsen, P. & Harby, A. (1996). "Availability of microhabitats and their use by brown trout (Salmo trutta) and grayling (Thymallus thymallus) in the river Vojmån, Sweden". *Regulated Rivers: Research and Management*, 12, 287-303.

Gordon, N. D., McMahon, T.A., Finlayson, B.L., Gipper, C.J., & Nathan, R.J. (2004). *Stream Hydrology: An Introduction for Ecologists.* Second Edition John Wiley and Sons, Chichester.

Harby, A., Baptist, M., Dunbar, M. J. & Schmutz, S. (2004). *State-of-the-art in Data Sampling, Modelling, Analysis and Model Applications of Riverine Habitats.* European Aquatic Modelling Network, COST Action 626 Report.

Harby, A., Bjerke, P. L., Halleraker, J. O., Tjomsland, T., Vaskinn, K. A & Osthus, N. (unpublished). "Application of The River System Simulator for optimising environmental flow in a Norwegian regulated river".

Heggenes, J. (1996). "Habitat selection by brown trout (*Salmo trutta*) and young Atlantic salmon (*S. salar*) in streams: static and dynamic hydraulic modelling" *Regulated Rivers: Reasearch and Management, 12, 150-169.*

Heggenes, J., Saltveit, J. & Lingaas, O. (1996). "Predicting fish habitat use to changes in water flow: modelling critical minimum flows for Atlantic salmon, *Salmo salar,* and brown trout, *S. trutta" Regulated Rivers: Research and Management,* 12, 331-344.

Holst, I. & Tapper, J. (2005). *Flodpärlmussla och tjockskalig målarmussla i Örebro län 2004. Resultat från översiktlig kartering efter nya vatten med förekomst av flodpärlmussla.* Länsstyrelsen i Örebro län, publ. nr 2005:3.

Hudson, H. R., Byrom, A. E. & Chadderton, W. L. (2003). "A Critique of IFIM-Instream Habitat Simulation in the New Zealand Context" *Science for Conservation* 231.

IVL Svenska Miljöinstitutet (2007). *Applying habitat model MesoCASiMiR in river Rällsälven in Sweden.* Report for TWINLATIN.

Jorde, K. (1996). *Ecological evaluation of instream flow regulations based on temporal and spatial variability of bottom shear stress and hydraulic habitat quality.* Proceedings of the 2nd IAHR Symposium on Habitat Hydraulics, Ecohydraulics 2000, Quebec City.

Jowett, I.G. (1997). "Instream flow methods: a comparison of approaches" *Regulated Rivers: Research and Management,* 13, 115-127.

Kerle, F., Zöllner, F., Schneider, M., Böhmer, J., Kappus, B. & Baptist, M. J. (unpublished). "Modelling of long-term fish habitat changes in restored secondary floodplain channels on the river Rhine".

Killingtveit, Å. & Harby, A. (1994). "Multi purpose planning with the River System Simulator- a decision system for water resources planning and operation". *Proceedings of the First International Symposium on Habitat Hydraulics,* Norwegian Institute of Technology, Trondheim, Norway.

Krstolic, J. L., Hayes, D. C. & Ruhl, P. M. (2006). *Physical habitat classification and instream flow modeling to determine habitat availability during low-flow periods, North Fork Shenandoah River, Virginia.* U.S. Department of the Interior, U.S. Geological Survey, Scientific investigations report 2006-5025.

Linnaeus, C. (1758). *Systema naturae per regna tria naturae, secundum classes, ordines, genera, species, cum characteribus, differentiis, synonymis.*

Lund, T. (1996). *Elverdamsaaen. Hydraulikkens og vandfoeringens betydning for oerredbestandens fysiske vilkaar.* Final Master Thesis. Geography institute, Aarhus University.

Länsstyrelsen Örebro län (2007a). Kraftverksinformation och damminformation.

Länsstyrelsen Örebro län (2007b). Vattendom för Stjernfors vattenkraftverk.

Löwren, M. (2003). *Den ekonomiska analysen i Vattendirektivet. Ett pilotprojekt i Motala Ströms avrinningsområde.* Tema vatten i natur och samhälle, Linköpings universitet.

Midcontinent Ecological Science Center (2001). *PHABSIM for Windows.* U.S. Department of the Interior, U.S. Geological Survey, Open File Report 01-340.

Naturvårdsverket (2003). *Flöden i vattendrag. Bakgrundsrapport till: Miljökvalitetsnormer för flöden/nivåer i rinnande vatten.* Naturvårdsverket, rapport 5293.

Naturvårdsverket (2005). *Beskrivning, kartläggning och analys av Sveriges ytvatten. Sammanfattande rapport den 22 mars 2005 enligt artikel 5 i EU:s ramdirektiv för vatten (2000/60/EG).*

Naturvårdsverket (2007). *Status, potential och normer för sjöar, vattendrag, kustvatten och vatten i övergångszon. En handbok om hur kvalitetskrav för ytvattenförekomster kan fastställas och följas upp*. Remissversion 2007-04-02.

Raleigh, R. F., Zuckerman, L. D. & Nelson, P. C. (1986). *Habitat Suitability Index Models and Instream Flow Suitability Curves: Brown Trout.* U.S. Department of the Interior, Fish and Wildlife Service, Biological Report 82(10.124), revised 1986.

Richter, B. D., Baumgartner, J. V., Wigington, R., & Braun, D. P. (1997). "How much water does a river need?" *Freshwater Biology*, 37, 231-249.

Richter, B. D., Baumgartner, J. V., Braun, D. P. & Powell, J. (1998). "A Spatial Assessment of Hydrologic Alteration within a River Network". *Regulated Rivers: Research and Management,* 14, 329-340.

Scruton, D. A., Heggenes, J., Valentin, S., Harby, A. & Bakken T. H. (1998). ”Field sampling design and spatial scale in habitat-hydraulic modelling: comparison of three models” *Fisheries Management and Ecology,* 5, 225-240.

Shoeller, S. (2005). *Determining instream flow, analysis of methods and their application to the river Ebro in Spain.*Universitat Politècnica de Catalunya, Spain.

SMHI (2006). Flödesdata för Rällsälven 1978-2001.

Sundén, H. (unpublished). *MKB för arbetsplan och tillståndsprövning. Bro över Rällsälven vid Dammen, Ljusnarsbergs kommun.* Vägverket Region Mälardalen.

Tharme, R. E. (2003). "A Global Perspective on Environmental Flow Assessment: Emerging Trends in the Development and Application of Environmental Flow Methodologies for Rivers". *River Research and Applications,* 19, 397-441.

Thorn, P. & Conallin, J. (2006). "RHYHABSIM as a Stream Management Tool: Case Study in the River Kornerup Catchment, Denmark". *The Journal of Transdiscipinary Environmental Studies,* 5, no. 1-2.

Tennant, D. L. (1976). "Instream flow regimes for fish, wildlife, recreation and related environmental resources". *Fisheries*, 1 (4), 6-10.

Vismara, R., Azzelino, A., Bosi, R., Crosa, G. & Gentili, G. (2001). "Habitat suitablity curves for brown trout (*Salmo trutta fario* L.) in the river Adda, northern Italy: comparing univariate and multivariate approaches" *Regulated Rivers: Research and Management,* 17, 27-50.

Walbaum, J. J. (1792). *Genera Piscium.*

Yrjänä, T, Lahti, M., Kamula, R. (1999). *Effects of a habitat enhancement experiment in the Laukka area of the river Oulujoki, Finland.* University of Oulo. Publications of Water Resources and Environmental Engineering Laboratory. A5. pp. 35. (In Finnish, with English summary).

7.2 INTERNET SOURCES

Digital Miljöatlas (2007). www.gis.lst.se/ivl Accessed June to September, 2007.

Fiskeriverket (2007a). Elfiskeregistret. http://www2.fiskeriverket.se/databas/el_bas.htm Accessed 23 May, 2007.

Fiskeriverket (2007b). Arter: öring. www.fiskeriverket.se/vanstermeny/fiskochskaldjur/arter.4.70e0ced410e4101406780002450.html Accessed 11 October, 2007.

Hydropower Reform Coalition (2005). Citizen Toolkit for Effective Participation in Hydropower Licensing. www.hydroreform.org/book/export/html/7 Accessed 25 May, 2007.

Lantmäteriet KartSök (2007). Rällsälven. http://www2.lantmateriet.se/ksos/index.html Accessed 4 August, 2007.

Mälarenergi (2007). Vattenflöden vid våra vattenkraftstationer. Ljusnaren och Rällsälven. www.malarenergi.se/t1log/waterflow.aspx Accessed 7 July, 2007.

SMHI (2007). Verklig årsnederbörd. Uppskattat medelvärde 1961-1990. www.smhi.se/sgn0102/images/p118.gif Accessed 10 October, 2007.

Wikipedia (2007). Stjärnfors. www.wikipedia.se Accessed 4 August, 2007.

7.3 PERSONAL COMMUNICATION

Gyllenhammar, Andreas. Seminar “Ekologiska flöden. Hur mycket vatten behöver ett vattendrag”, Geocentrum, Uppsala, September 24, 2007.

Johansson, Bruno. Owner of Dammen hydropower plant, 21 September, 2007.

Nyberg, Mikael. Länsstyrelsen Örebro län, 3 July, 2007.

Wallin, Anne-Marie. Länsstyrelsen Örebro län, 9 October, 2007.

APPENDIX 1 LIST OF ABBREVIATIONS

AdultXX	Adult HSC curve with identification number
CASiMiR	Computer Aided SImulation Model for Instream flow Requirements
ECTS	European Credit Transfer System
EU	European Union
EVHA	ÉValuation de l'HAbitat
FryXX	Fry HSC curve with identification number
GIS	Geographical Information System
GPS	Global Positioning System
HABITAT	Habitat simulation model
HEC-RAS	Hydrologic Engineering Center- River Analysis System
HSC	Habitat Suitability Criteria
IFIM	Instream Flow Incremental Methodology
JuvXX	Juvenile HSC curve with identification number
MANSQ	Manning's-discharge model
PHABSIM	Physical Habitat Simulation Model
RHABSIM	Riverine HABitat SIMulation
RMA2	Resource Management Associates
RMOD	Roughness MODifier
RSS	River System Simulator
RVA	Range of Variability Approach
SpawXX	Spawning HSC curve with identification number
SSIIM	Sediment Simulation In Intakes with Multiblock option
STGQ	Stage-discharge model
SZF	Stage of Zero Flow
TWINLATIN	Twinning European and Latin-American river basins for research enabling sustainable water resources management
VAF	Velocity Adjustment Factor
VELSIM	VELocity SIMulation
WFD	Water Framework Directive
WSL	Water Surface Elevation
WSP	Water Surface Profile model
WUA	Weighted Usable Area.

APPENDIX 2 FLOW MEASUREMENTS

Table 1 Sites of flow measurements. The site numbers refer to sites marked at the map, Appendix 2 Figure 1.

	Site number	Discharge June 27, 2007 (m^3/s)	Discharge August 15-16, 2007 (m^3/s)
Total river discharge (current-meter)	1 and 2	0.86 (site 1)	0.098 (site 2)
Total river flow (salt-Q method)	2	0.45	-
Brook, 50 m upstream the bridge	3	0.010	0.010
Brook between the B- and C-reaches	4	0.005	0.003
Confluence from pond	5	0.048	0.069
Brook opposite fish pond confluence	6	0.003	0.003
Seepage through dam at Ljusnaren	7	-	0.001

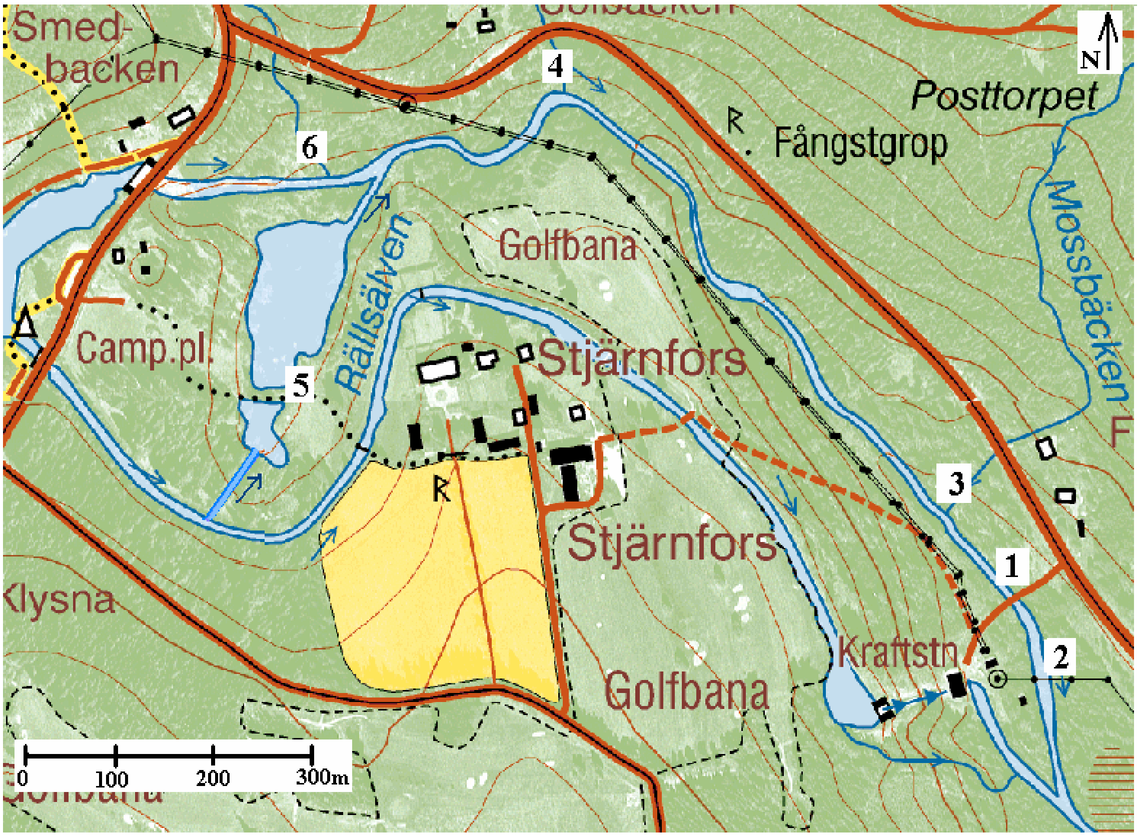


Figure 1 Sites of flow measurements marked (modified from Digital Miljöatlas, 2007).

APPENDIX 3 HSC CURVES FOR BROWN TROUT

Table 1 HSC curve for brown trout spawning. Velocity, depth, and substrate class. Curve ID: Spaw11. (Raleigh *et al.*, 1986)

v (m/s)	Suitability	d (m)	Suitability	Substr. cl.	Suitability
0.00	0.00	0.00	0.00	0	0.00
0.09	0.00	0.06	0.00	1	0.00
0.21	1.00	0.24	1.00	2	1.00
0.52	1.00			3	1.00
1.19	0.00			4	0.00
				9	0.00

Table 2 HSC curve for brown trout spawning. Curve ID: Spaw 21. (IVL Svenska Miljöinstitutet, 2007)

v (m/s)	Suitability	d (m)	Suitability	Substr. cl.	Suitability
0.00	0.00	0.00	0.00	0	0.00
0.18	0.00	0.10	0.00	2	0.10
0.40	1.00	0.20	1.00	3	1.00
0.70	1.00	0.40	1.00	4	0.10
0.80	0.20	0.50	0.00	5	0.00
1.00	0.00			9	0.00

Table 3 HSC curve for brown trout spawning. Curve ID: Spaw41. (Lund 1996 used by Thorn and Conallin, 2006)

v (m/s)	Suitability	d (m)	Suitability	Substr. cl.	Suitability
0.00	0.00	0.00	0.00	0	0.00
0.15	0.00	0.10	0.00	1	0.00
0.20	1.00	0.15	1.00	2	0.50
0.70	1.00	0.80	1.00	3	1.00
1.00	0.00	1.00	0.00	4	0.00
				9	0.00

Table 4 HSC curve for brown trout fry. Curve ID: Fry12. (Raleigh *et al.*, 1986)

v (m/s)	Suitability	d (m)	Suitability	Substr. cl.	Suitability
0.00	0.00	0.00	0.00	0	0.76
0.03	0.38	0.20	0.19	2	1.00
0.18	1.00	0.40	1.00	3	1.00
0.27	0.94	0.49	1.00	5	0.35
0.37	0.47	0.70	0.82	8	0.04
0.88	0.00	1.40	0.00	9	0.00

Table 5 HSC curve for brown trout juvenile. Curve ID: Juv13. (Raleigh *et al*., 1986)

v (m/s)	Suitability	d (m)	Suitability	Substr. cl.	Suitability
0.00	0.58	0.00	0.00	0	0.66
0.03	0.88	0.15	0.12	1	0.66
0.15	1.00	0.30	0.61	2	1.00
0.30	0.92	0.61	0.84	3	0.97
0.46	0.70	0.91	1.00	5	0.12
0.61	0.26	1.22	0.27	8	0.12
1.07	0.05	2.13	0.24	9	0.00
1.31	0.00	2.44	0.08		

Table 6 HSC curve for brown trout juvenile. Curve ID: Juv33. (Lund, 1996 used by Thorn and Conallin, 2006)

v (m/s)	Suitability	d (m)	Suitability	Substr. cl.	Suitability
0.00	1.00	0.00	0.00	0	0.40
0.40	1.00	0.10	1.00	2	0.80
0.70	0.20	0.40	1.00	3	0.90
1.00	0.00	0.50	0.00	4	1.00
				5	0.20
				6	0.20
				7	0.20
				8	0.00
				9	0.70

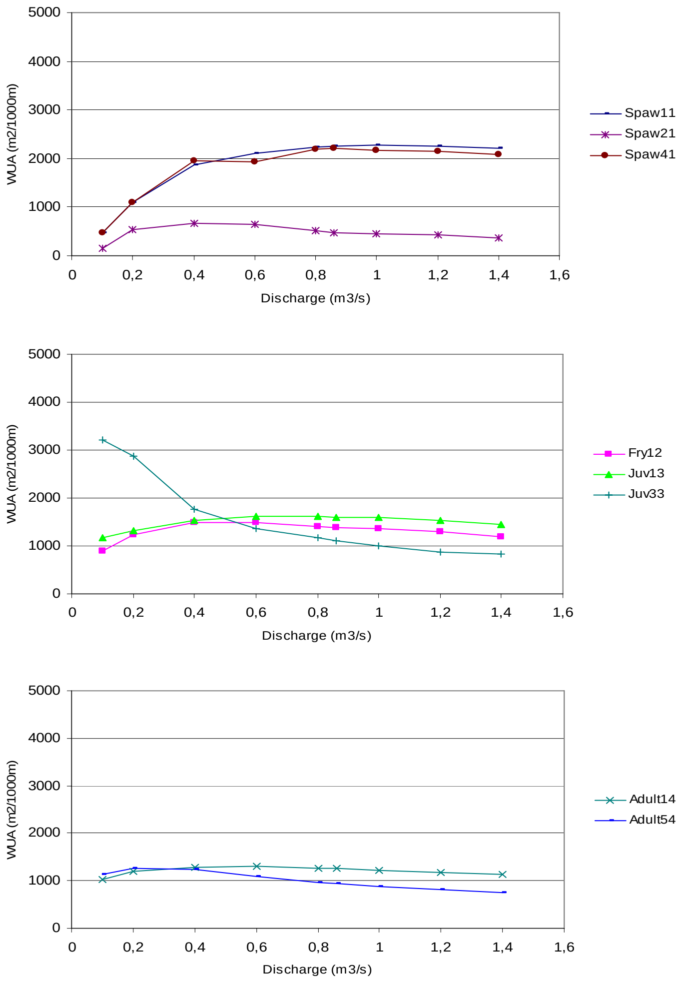
Table 7 HSC curve for brown trout adult. Curve ID: Adult14. (Raleigh *et al*., 1986)

v (m/s)	Suitability	d (m)	Suitability	Substr. cl.	Suitability
0.00	0.21	0.00	0.00	0	1.00
0.03	0.70	0.49	0.87	1	1.00
0.15	1.00	0.61	0.95	2	0.54
0.30	0.69	0.79	1.00	3	0.86
0.46	0.50	1.10	0.84	5	0.12
0.73	0.20	1.22	0.45	8	0.12
0.94	0.03	1.52	0.30	9	0.00
1.52	0.03	2.13	0.21		
1.83	0.00				

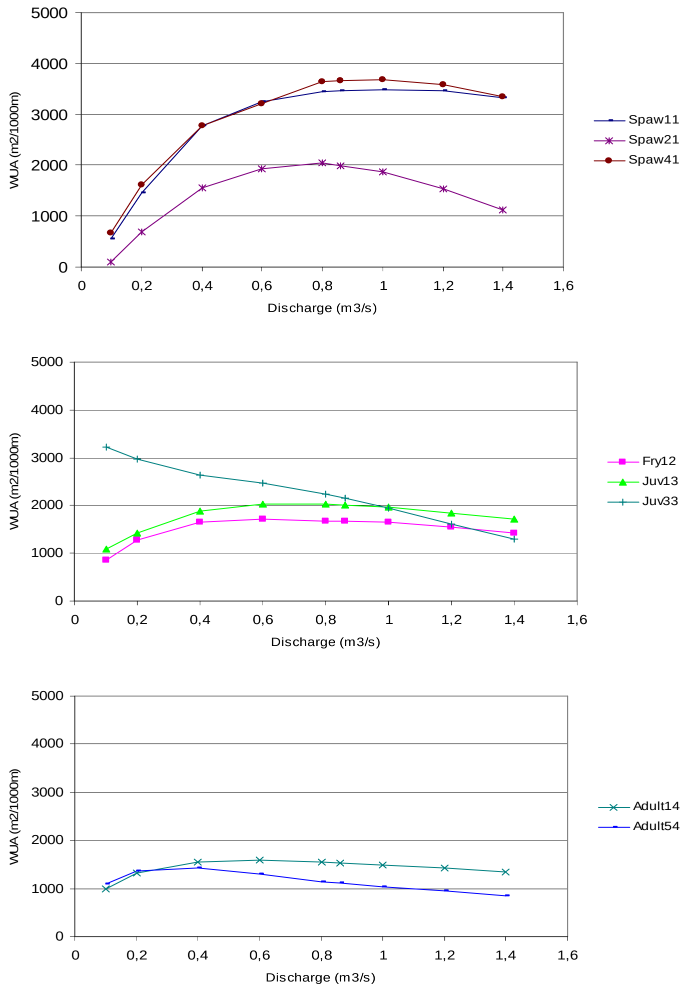
Table 8 HSC curve for brown trout adult. Curve ID: Adult54. (Heggenes, 1996)

v (m/s)	Suitability	d (m)	Suitability	Substr. cl.	Suitability
0.00	0.40	0.00	0.00	0	0.00
0.03	0.60	0.10	0.10	1	0.03
0.05	0.70	0.20	0.30	2	0.06
0.08	0.90	0.30	0.70	3	1.00
0.11	1.00	0.40	0.90	4	1.00
0.15	0.90	0.50	1.00	5	0.50
0.20	0.70	0.72	1.00	6	0.25
0.25	0.60	0.90	0.80	7	0.27
0.34	0.40	1.00	0.40	8	0.30
0.48	0.20	1.15	0.20	9	0.00
0.60	0.05	1.30	0.10		
0.70	0.03	1.45	0.10		
0.85	0.02	1.55	0.05		
1.00	0.01	2.00	0.00		
1.50	0.00				

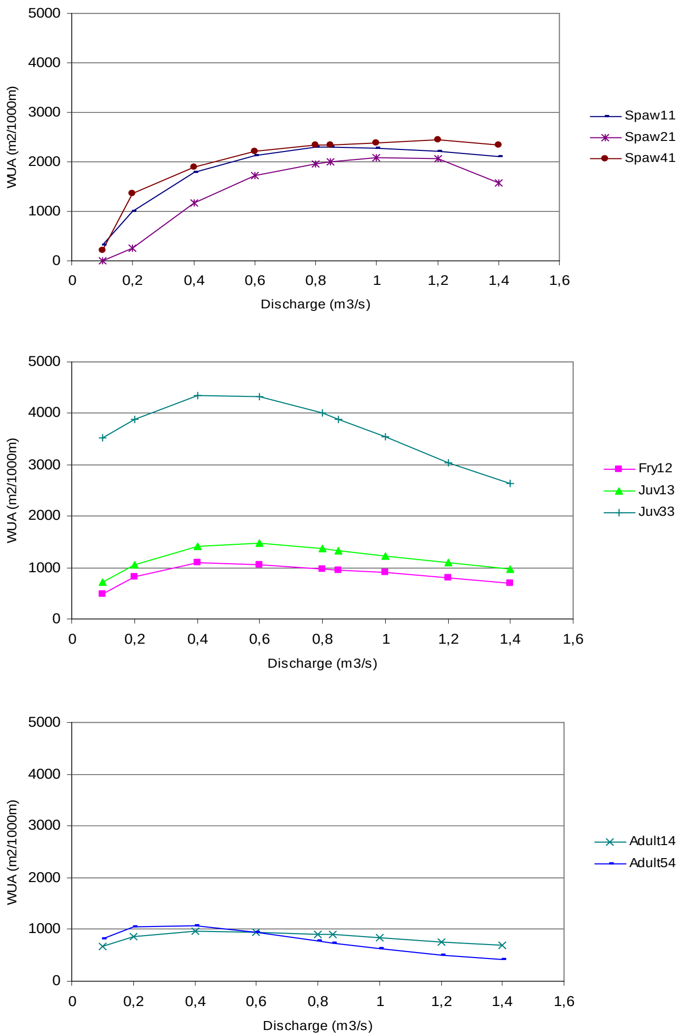
APPENDIX 4 WUA CURVES



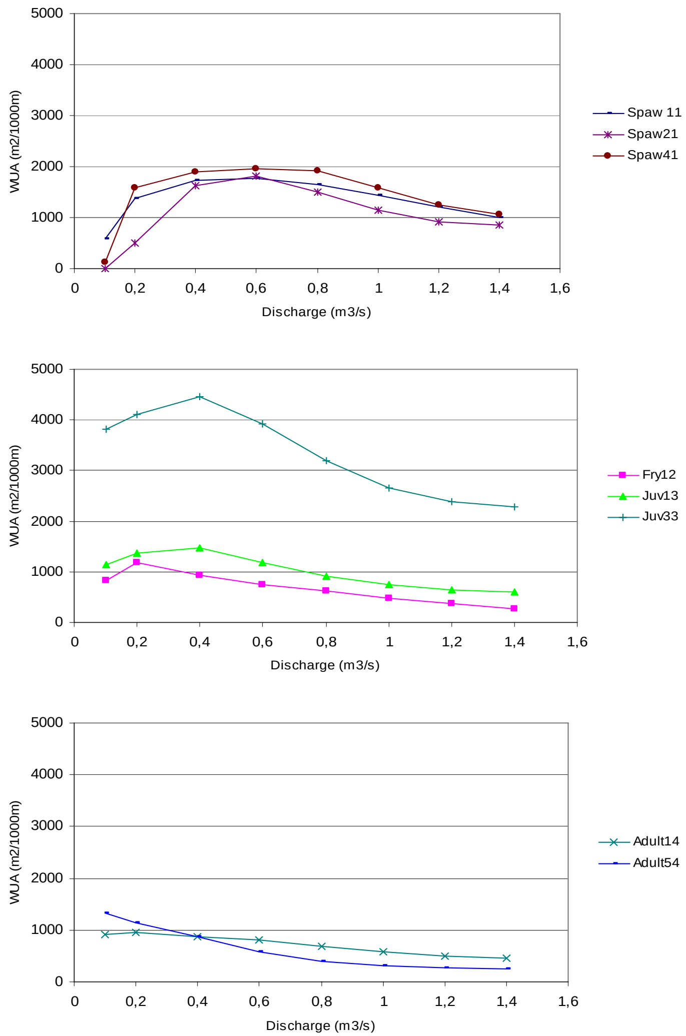
Figures 1-3 A-reach. WSP- MANSQ.



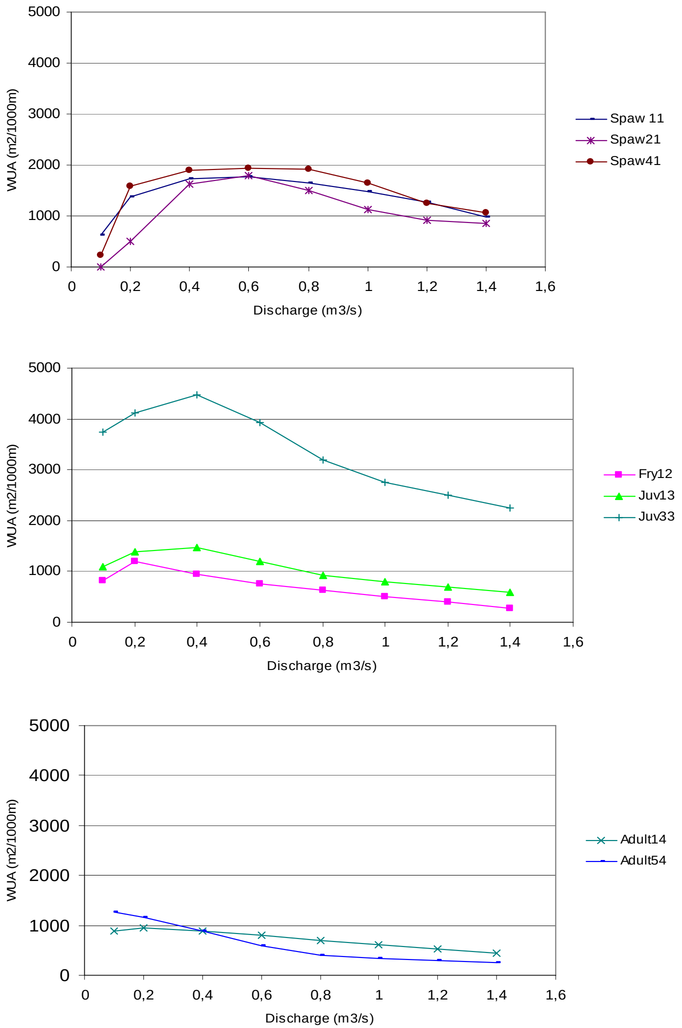
Figures 4-6 A-reach. MANSQ.



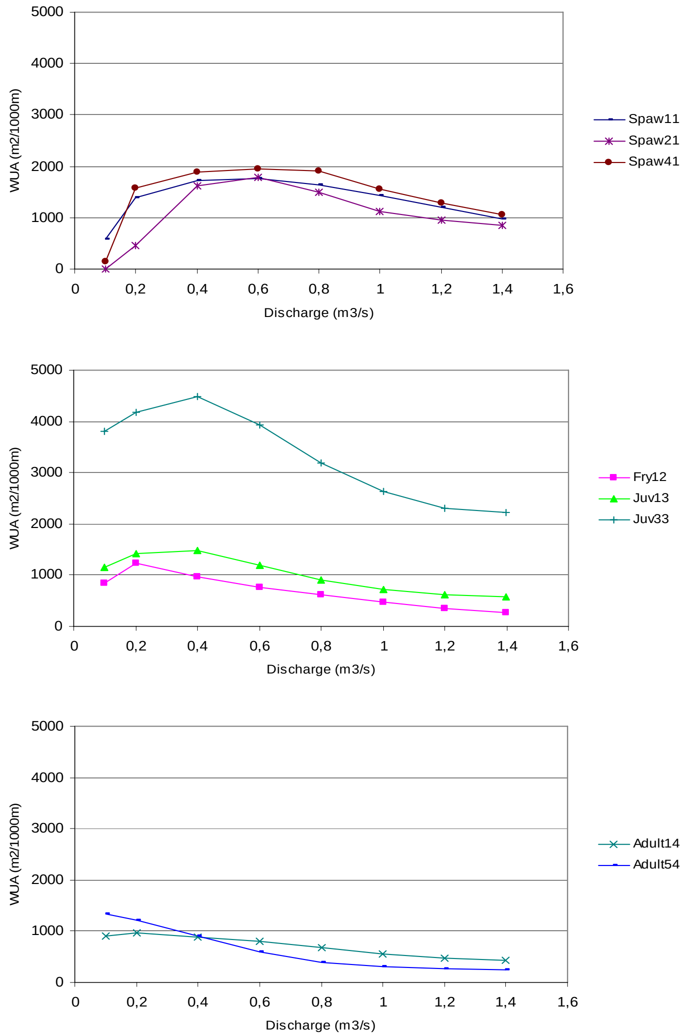
Figures 7-9 B-reach. MANSQ.



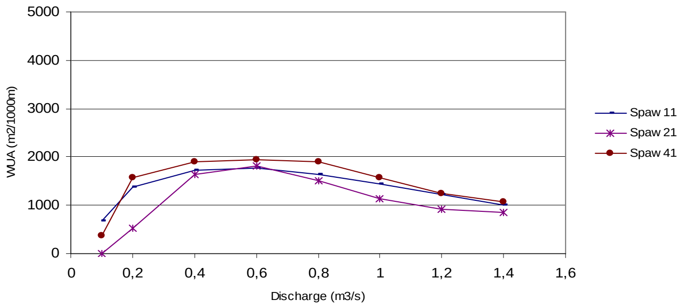
Figures 10-12 C-reach. WSP-MANSQ.

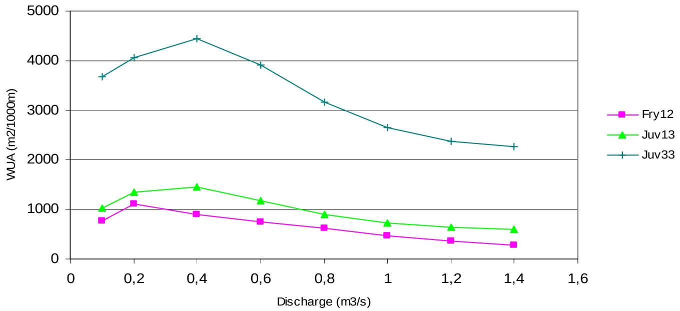


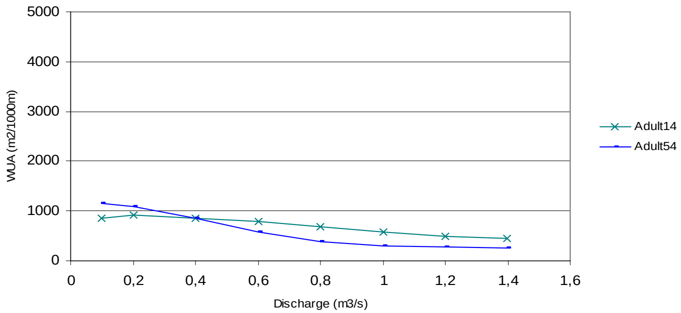
Figures 13-15 C-reach. WSP-STGQ.



Figures 16-18 C-reach. STGQ.







Figures 19-21 C-reach. MANSQ.

APPENDIX 5 SENSITIVITY ANALYSIS OF SELECTED INPUT PARAMETERS

Table 1 Sensitivity analysis of simulated water surface elevations at the C1-transect.

Model	Parameter	Simulated discharge (m^3/s)	Original water surface elevation (m)	New water surface elevation (m)	Change (m)
MANSQ	High cal. flow +10%	0.2	87.547	87.440	-0.107
		0.8	87.629	87.611	-0.018
		1.2	87.659	87.676	0.017
STGQ	High cal. flow +10%	0.2	87.539	87.537	-0.002
		0.8	87.629	87.622	-0.007
		1.2	87.662	87.653	-0.009
WSP, STGQ as initializer	High cal. flow +10%	0.2	87.542	87.545	0.002
		0.8	87.628	87.622	-0.006
		1.2	87.663	87.655	-0.008
MANSQ	β-coefficient +10%	0.2	87.547	87.555	0.008
		0.8	87.629	87.629	0.000
		1.2	87.659	87.656	-0.003
WSP, MANSQ as initializer	Manning's *n* +10%	0.2	87.541	87.546	0.004
		0.8	87.628	87.633	0.004
		1.2	87.659	87.664	0.005
	RMOD +10%	0.2	87.541	87.546	0.004
		0.8	87.628	87.633	0.004
		1.2	87.659	87.670	0.011

Table 2 Sensitivity analysis of WUA for Spaw11 at the C-reach. Water surface elevations modelled with MANSQ.

Parameter	Simulated discharge (m^3/s)	Original WUA (m^2/1000m)	New WUA (m^2/1000m)	Change (%)
Slope +10%	0.2	1024	1019	-0.49
	0.8	1591	1582	-0.54
	1.2	1622	1611	-0.64
Slope -10%	0.2	1024	1029	0.49
	0.8	1591	1599	0.52
	1.2	1622	1632	0.66
Substratum one class larger	0.2	2092	11	-99.17
	0.8	3994	122	-92.52
	1.2	4419	188	-84.51
Substratum one class smaller	0.2	2092	1379	51.76
	0.8	3994	1638	143.86
	1.2	4419	1216	263.38
Beta +10%	0.2	1395	1377	1.28
	0.8	1635	1633	0.16
	1.2	1195	1216	-1.71
Beta -10%	0.2	1395	1360	-1.29
	0.8	1635	1628	-0.25
	1.2	1195	1256	3.32

APPENDIX 6 SENSITIVITY ANALYSIS OF HSC CURVES

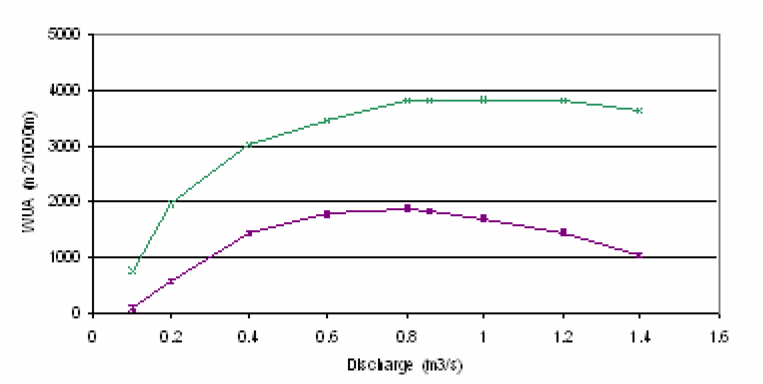


Figure 1 WUA for spawning calculated with maximum and minimum HSC curves. A-reach.

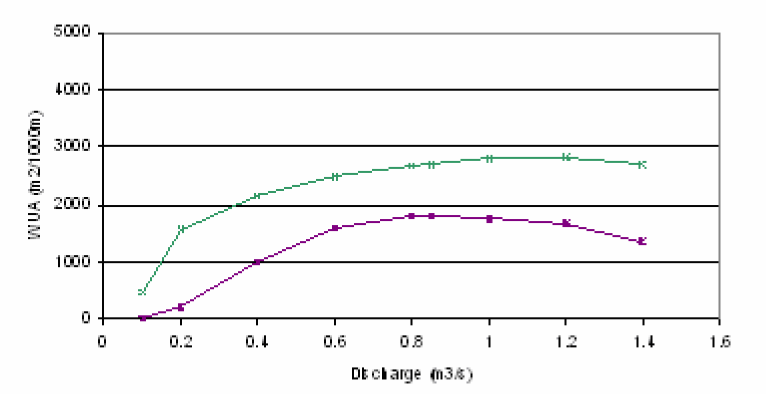


Figure 2 WUA for spawning calculated with maximum and minimum HSC curves. B-reach.

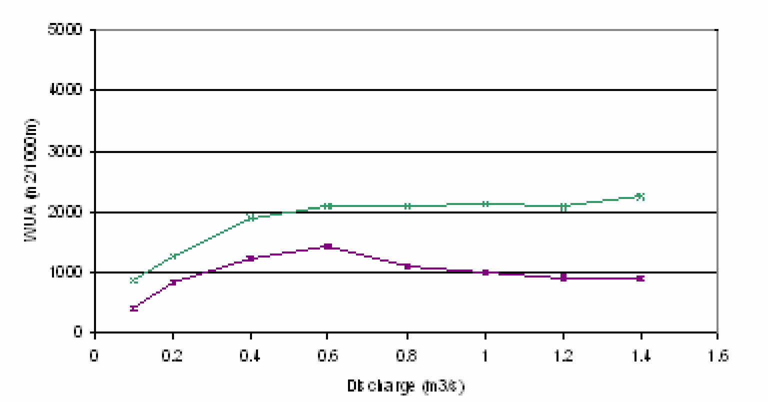


Figure 3 WUA for spawning calculated with maximum and minimum HSC curves. A-reach.

APPENDIX 7 MODELLING OF B-REACH

The reach length is 184 m, and total change in elevation is 3.5 m, which gives an average slope of 1.9 percent. The water surface elevation was closely reproduced at the three first cross sections in the downstream area which had pool-like appearance, but at the next upstream cross section the model got off the track. The distance between transect B2 and B3 is 37 m and the slope is 3.5 percent. Instead of the simulated water surface following roughly 0.2 – 0.5 m above the river bed as expected, the model simulates a water surface elevation that is a horizontal line between the two transects, thus ending up below thalweg elevation. The thalweg slope was gradually lowered to find the threshold value for when the model manages to give a reasonable output. The river bed elevation at cross section B3 and above was decreased in steps of 0.1 m, and at a slope of 1.09 percent when the elevation was modelled as 0.9 m below the actual measured elevation, a change in the model output was noticed. For the highest modelled flow, 0.86 m^3/s, the WSP model now managed to calculate the WSL one step further upstream, making it reach transect B3 before the same problem as previously was encountered. The calculations were interrupted between transects B3 and B4 where the slope was 2.2 percent. The lower flows still were only simulated up to transect B2. The river bed elevation was further decreased until the simulated water surface elevations of all flows, including the lowest simulated flow of 0.1 m^3/s, showed a somewhat reasonable result for the next upstream step. That occurred when the river bed of the transects B3 and above had been lowered by 1.1 m and the slope between B2 and 3 was 0.55 percent. Calculating the next step upstream leads to the same problem as before with the model giving unreasonable water surface elevations.

APPENDIX 8 LONGITUDINAL PROFILE OF THE DRY REACH

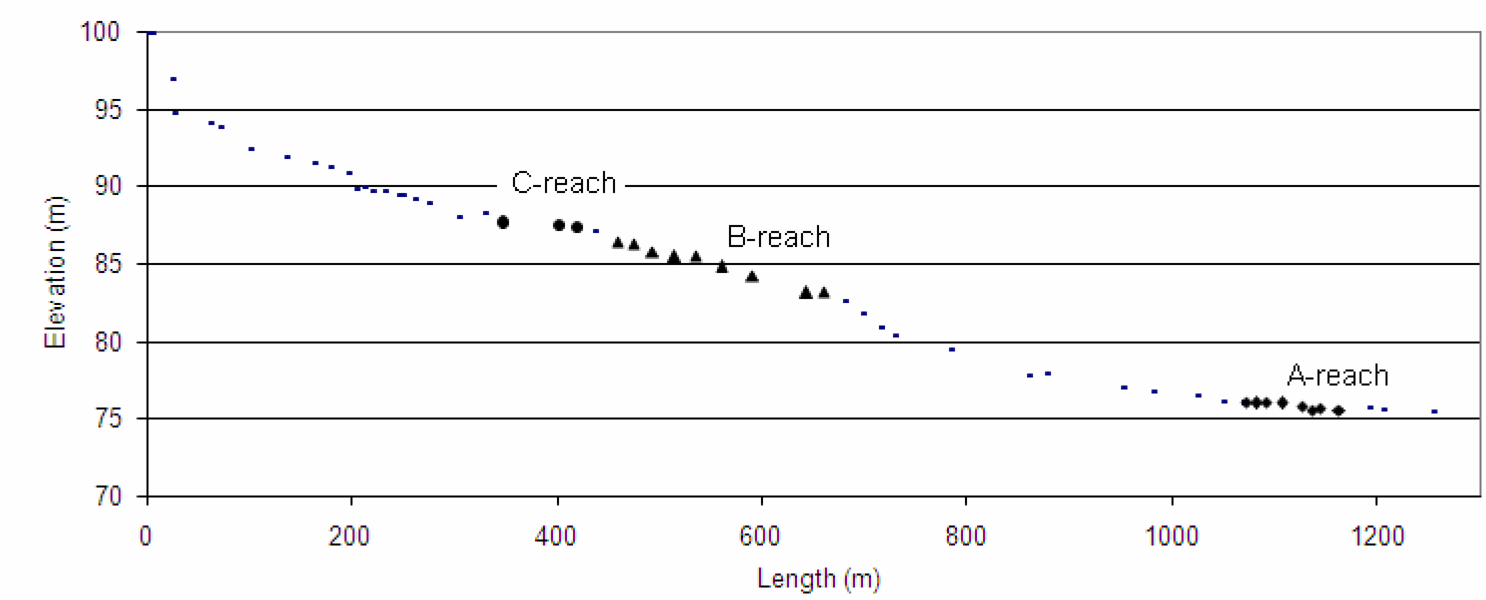


Figure 1 Longitudinal profile of the river reach between the foot of the dam at Ljusnaren and the confluence with the diverted water downstream the hydropower station. The location and elevation of the three modelled reaches are marked. The foot of the dam is assigned the elevation 100 m, which corresponds to about 160 m above sea level.

APPENDIX 9 CROSS SECTION DATA

A 0 = reach and cross section number
x = distance across the cross section
y = distance from the cross section furthest downstream
z = cross section bottom elevation. Where z is given with one decimal, field data was missing and the elevation is estimated by the modeller.
vel = velocity measured during low or high discharge
sub. cl.= substrate class
+ or - = substrate size in the upper or lower end of the class interval
WSL = water surface elevation for low or high discharge
Upstr. WF = upstream weighting factor for habitat type

Table 1 Cross section data for A-reach. WSL2 was estimated as 0.23 m above WSL1. Discharge 1: 0.098 m^3/s, discharge 2: 0.86 m^3/s.

		x (m)	y (m)	z (m)	sub. cl.	vel1 (m/s)
A 0		0	0	76.411	6	
WSL1 (m):	75.911	0.8	0	75.911	2	0
Length (m):	0	1.0	0	75.801	2	0
		2.0	0	75.711	2	0
		3.0	0	75.611	3	0
		4.0	0	75.591	-3	0.03
		5.0	0	75.601	+3	0.05
		6.0	0	75.671	-3	0.09
		7.0	0	75.701	-3	0.12
		8.0	0	75.751	-3	0.13
		8.8	0	75.911	3	0
		9.0	0	76.111	9	
		10.0	0	76.311		
A 1		2.8	18.5	76.216	6	
WSL1:	75.916	2.9	18.5	75.916	3	
Length (m):	18.5	3.0	18.5	75.616	3	0.02
		4.0	18.5	75.436	3	0.07
		5.0	18.5	75.426	3	0.12
		6.0	18.5	75.516	-3	0.08
		7.0	18.5	75.626	-3	0.02
		8.0	18.5	75.806	2	0
		8.2	18.5	76.061	3	
		8.4	18.5	76.316	3	

A 2		1.5	26	76.4		
WSL1:	75.924	2.0	26	76.224	9	
Length (m):	7.5	2.2	26	75.614	2	0.02
		3.0	26	75.464	1	0.04
		4.0	26	75.504	2	0.11
		5.0	26	75.464	-3	0.09
		6.0	26	75.684	3	0.01
		7.0	26	75.884	3	0
		7.7	26	75.924	3	0
		8.0	26	76.074	3	
		9.0	26	76.224		
		9.5	26	76.4		
A 3		0.5	36	76.456	0	
WSL1:	75.926	1.0	36	76.326	9	
Length (m):	10.0	1.5	36	76.196	9	
		2.0	36	76.066	2	
		2.3	36	75.916	+2	0
		3.0	36	75.826	+3	0.30
		4.0	36	75.796	-3	0.58
		5.0	36	75.816	3	0.33
		6.0	36	75.796	+3	0.18
		7.0	36	75.896	3	0
		7.5	36	76.106	9	
		8.0	36	76.316	9	
		8.5	36	76.526	9	
A 4		1.0	56	76.6		
WSL1:	76.129	1.6	56	76.429	6	
Length (m):	20.0	2.0	56	76.099	2	0
		3.0	56	76.009	-3	0.19
		4.0	56	75.999	+3	0.21
		5.0	56	75.929	3	0.38
		6.0	56	76.049	+3	0.17
		6.3	56	76.129	+3	0
		7.0	56	76.229	-3	
		8.0	56	76.6		
A 5		2.0	71.5	76.671	9	
WSL1:	76.171	3.0	71.5	76.471	4	
Length (m):	15.5	3.8	71.5	76.171	4	
		4.0	71.5	76.071	4	0.04
		5.0	71.5	76.061	+3	0.25
		6.0	71.5	76.111	4	0.14
		6.3	71.5	76.171	+3	
		7.0	71.5	76.271	-3	
		7.8	71.5	76.321	+3	
		8.0	71.5	76.571	9	

A 6		1.5	81.5	76.7		
WSL1:	76.221	2.0	81.5	76.521	9	
Length (m):	10.0	3.0	81.5	76.101	-3	0.18
		4.0	81.5	76.181	-3	0
		5.0	81.5	76.031	-3	0.34
		6.0	81.5	76.001	3	0.44
		6.8	81.5	76.221	+3	0
		7.0	81.5	76.521	-3	
		8.0	81.5	76.6		
A 7		3.7	91	76.6	9	
WSL1:	76.231	3.9	91	76.431	9	
Length (m):	9.5	4.0	91	76.041	-3	1.23
		5.0	91	76.131	-3	0.50
		5.3	91	76.231	+3	0
		6.0	91	76.281	-3	
		7.0	91	76.4	3	
		8.0	91	76.5	3	
		9.0	91	76.6		

Table 2 Cross section data for B-reach. Discharge 1: 0.088 m^3/s, discharge 2: 0.76 m^3/s.

		x (m)	y (m)	z (m)	sub. cl.	vel2 (m/s)
B 0		0.0	0	83.907	6	
WSL1:	83.197	1.0	0	83.207	2	0
WSL2:	83.407	2.0	0	83.107	2	0.07
Length (m):	0	3.0	0	83.177	6	0.45
		4.0	0	83.207	7	0.13
		5.0	0	82.857	4	0.46
		6.0	0	83.057	7	0.26
		7.0	0	82.967	7	0.34
		8.0	0	82.907	3	0.48
		9.0	0	83.037	4	0.35
		10.0	0	83.107	6	0.30
		11.0	0	83.277	6	0.30
		12.0	0	83.402	6	0.24
		13.0	0	83.397	-3	0.35
		14.0	0	83.407	-3	0
		15.0	0	83.557	3	
B 1		2.0	12	84.417	7	
WSL1:	83.277	3.0	12	83.217	2	0.20
WSL2:	83.417	4.0	12	82.757	4	0.11
Length (m):	12.0	5.0	12	82.667	3	0.34
		6.0	12	82.967	4	0.42
		7.0	12	82.917	4	0.35
		8.0	12	82.997	6	0.22
		9.0	12	83.037	+3	0.19
		10.0	12	83.217	+3	0.13
		11.0	12	83.317	+3	0.04
		12.0	12	83.417	-3	0
		13.0	12	83.517	-3	
		14.0	12	83.617	3	
B 2		2.0	23.3	83.648	5	
WSL1:	83.266	3.0	23.3	83.448	5	0
WSL2:	83.448	4.0	23.3	83.248	6	0.07
Length (m):	11.3	5.0	23.3	83.048	7	0.46
		6.0	23.3	83.048	6	0.20
		7.0	23.3	82.948	7	0.96
		8.0	23.3	82.948	7	0.30
		9.0	23.3	83.178	7	0.76
		10.0	23.3	83.348	4	0.49
		11.0	23.3	83.298	3	0.59
		12.0	23.3	83.648	2	

B 3		2.0	60.3	85.070	6	
WSL1:	84.600	3.0	60.3	84.670	2	0
WSL2:	84.670	4.0	60.3	84.420	4	0.07
Length (m):	37.0	5.0	60.3	84.320	5	0.73
		6.0	60.3	84.330	6	0.52
		7.0	60.3	84.570	7	0.10
		8.0	60.3	84.440	6	0.47
		9.0	60.3	84.250	6	0.18
		10.0	60.3	84.320	6	0.58
		11.0	60.3	84.520	2	0.13
		12.0	60.3	84.870	5	
B 4		0.0	116.3	86.000	3	
WSL1:	85.683	1.0	116.3	85.900	3	
WSL2:	85.800	2.0	116.3	85.700	-3	0
Length (m):	56.0	3.0	116.3	85.730	-3	0.08
		4.0	116.3	85.610	6	0.17
		5.0	116.3	85.550	5	0.71
		6.0	116.3	85.480	+3	0.28
		7.0	116.3	85.600	+3	0.86
		8.0	116.3	85.520	3	0.80
		9.0	116.3	85.560	+3	0.28
		10.0	116.3	85.700	3	0.45
		11.0	116.3	86.000	2	
B 5		0.0	134.3	86.623	4	
WSL1:	85.813	1.0	134.3	86.423	4	
WSL2:	85.923	2.0	134.3	85.923	-3	0
Length (m):	18.0	3.0	134.3	85.773	-3	0.36
		4.0	134.3	85.793	6	0.48
		5.0	134.3	85.793	6	0.46
		6.0	134.3	85.513	+3	0.48
		7.0	134.3	85.573	4	0.61
		8.0	134.3	85.573	5	0.49
		9.0	134.3	85.873	6	0.07
		10.0	134.3	85.693	2	0.03
		11.0	134.3	86.323	4	
B 6		2.0	151.3	86.554	4	
WSL1:	86.044	3.0	151.3	86.004	3	0.07
WSL2:	86.154	4.0	151.3	85.904	4	0.17
Length (m):	17.0	5.0	151.3	85.654	6	0.69
		6.0	151.3	85.684	7	0.52
		7.0	151.3	85.804	5	0.35
		8.0	151.3	85.854	+3	0.33
		9.0	151.3	86.034	3	0.12
		10.0	151.3	86.104	+3	0.12
		11.0	151.3	86.554	4	

B 7		1.0	169.3	86.746	-3	
WSL1:	86.436	2.0	169.3	86.546	3	0
WSL2:	86.546	3.0	169.3	86.376	3	0.35
Length (m):	18.0	4.0	169.3	86.246	4	0.94
		5.0	169.3	86.166	4	0.67
		6.0	169.3	86.196	4	0.73
		7.0	169.3	86.146	5	0.76
		8.0	169.3	86.216	4	0.14
		9.0	169.3	86.316	3	0.16
		10.0	169.3	86.746	5	
		11.0	169.3	86.846	5	
B 8		1.0	184.1	86.83	3	
WSL1:	86.603	2.0	184.1	86.78	3	
WSL2:	86.680	3.0	184.1	86.53	+3	1.20
Length (m):	14.8	4.0	184.1	86.36	+3	1.14
		5.0	184.1	86.4	4	0.56
		6.0	184.1	86.43	4	0.37
		7.0	184.1	86.48	4	0.33
		8.0	184.1	86.51	6	0.10
		9.0	184.1	86.53	-3	0.30
		10.0	184.1	86.88	6	

Table 3 Cross section data for C-reach. Discharge 1: 0.088 m^3/s, discharge 2: 0.76 m^3/s.

		x (m)	y (m)	z (m)	sub. cl.	vel2(m/s)
C 0		0.0	0	87.909	5	
WSL 1:	87.484	1.0	0	87.759	5	
WSL 2:	87.609	2.0	0	87.339	1	0.43
Length (m):	0	3.0	0	87.319	3	0.68
Upstr. WF:	0.8	4.0	0	87.329	4	0.81
		5.0	0	87.319	3	0.75
		6.0	0	87.379	3	0.60
		7.0	0	87.409	+3	0.43
		8.0	0	87.559	+3	0.06
		9.0	0	87.709	+3	
		10.0	0	87.729	+3	
		11.0	0	87.759	+3	
C 1		1.0	21	88.033	4	
WSL1:	87.504	2.0	21	87.623	1	0
WSL2:	87.633	3.0	21	87.203	2	0.72
Length (m):	21.0	4.0	21	87.213	+3	0.86
		5.0	21	87.383	3	0.60
		6.0	21	87.433	4	0.34
		7.0	21	87.503	3	0.17
		8.0	21	87.543	3	0.30
		9.0	21	87.733	3	
		10.0	21	87.753	3	
		11.0	21	87.783	3	
		12.0	21	87.783	3	
C 2		1.0	74	88.073	6	
WSL1:	87.551	2.0	74	87.673	6	0
WSL2:	87.673	3.0	74	87.373	6	0.43
Length (m):	53.0	4.0	74	87.173	4	1.06
		5.0	74	87.273	3	0.86
		6.0	74	87.453	4	0.40
		7.0	74	87.573	4	0.14
		8.0	74	87.673	3	0
		9.0	74	87.773	3	
		10.0	74	87.823	9	
		11.0	74	87.873	9	