Master Thesis
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Optimal Discharge from a Hydropower Plant for Fish Reproduction

An Aquatic Habitat Model

Hugo Lindbäck

Division of Water Resources Engineering
Department of Building and Environmental Technology
Lund University

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By:
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Division of Water Resources Engineering
Department of Building & Environmental Technology
Lund University
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221 00 Lund, Sweden

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Author(s):	Hugo Lindbäck
Supervisor:	Magnus Persson
Assistant supervisor:	Fainaz Inamdeen
Examiner:	Magnus Larson
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This report is a master's degree project in environmental engineering at LTH, the faculty of engineering at Lund University in Sweden. It was written during the spring and summer of 2023 at the Division of Water Resources Engineering.

The idea for the project was inspired by the European Water Framework Directive, which in Sweden has been implemented partly through The National Strategy for Review of Hydropower (Den nationella planen för omprövning av vattenkraft, NAP). The strategy, NAP, outlines a plan to review the operational permits of hydropower plants that were issued 40 years ago or more. Genastorp hydropower plant was chosen as a case study because concerns had been raised about the 5 km long dry run of the river from which flow is diverted to the turbine of the hydropowerplant. With this project, my intention was twofold. The primary goal was to provide a basis for future decisionmakers reviewing the Genastorp's operational permits. The second goal was more for personal education: to learn how to build an aquatic habitat model from the ground up.

That brings me to the people who I would like to thank for their roles in making this project come to fruition. First, I would like to give a major thank you to my supervisor Magnus Persson for believing in my vision and providing support when I doubted myself. My assistant supervisor Fainaz Inamdeen also deserves a big thank you for giving me a 101 course on hydraulic modelling in HEC-RAS. I also want to thank my examiner Magnus Larsson for continually demonstrating his interest throughout the project by providing valuable contact information and historical maps.

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Finally, I would like to give thanks to my friends and family who have pushed me to continue throughout this spring and summer. This degree project has been one of the most difficult and rewarding challenges I have ever faced, and it would never have been completed were it not for the love and support I have been given. Thank you all!

Hugo Lindbäck
August 24th, 2023

Abstract

Hydropower is the dominant source of electricity in Sweden, constituting 45% of the national supply. While pivotal for decarbonization and climate goals, its environmental impact on freshwater biodiversity is concerning. In this case study of a hydropower plant in Helge River, Sweden, the aim was to find a flow suitable for trout (*Salmo trutta*) and salmon (*Salmo salar*) reproduction. A terrain model was constructed with bathymetric data gathered in a field study. Then, seven flow scenarios were simulated in 2D space in this order: 0.5, 1, 2, 3, 4, 5 and 6 m^3/s. The resulting hydraulic maps were classified in a rule-based habitat model based on preference curves for salmon and trout in Finnish and Norwegian rivers, and the Weighted Usable Area (WUA) was calculated. The habitat model suggests that more flow is better, as WUA increased all the way up to the highest flow scenario of 6 m^3/s. The greatest benefit to habitat area by increasing flow was observed up to 2 m^3/s, and slowing after, particularly for ‘good’ quality habitat. In conclusion, there is great potential for improvements to fish conditions with the implementation of a minimum discharge requirement in future operational permits for the hydropower plant.

Sammanfattning

Vattenkraft är den dominerande källan till elektricitet i Sverige, med ett bidrag på 45% av den nationella produktionen. Samtidigt som vattenkraften är avgörande för utfasningen av fossila bränslen och för klimatmålen, är dess miljöpåverkan på den biologiska mångfalden i sötvatten oroande. I denna fallstudie av ett vattenkraftverk i Helge å, var syftet att hitta ett lämpligt flöde för reproduktion av öring (*Salmo trutta*) och lax (*Salmo salar*). En terrängmodell konstruerades med batymetriska data insamlade i en fältstudie. Sedan simulerades sju flödesscenarier i 2D i rummet i denna ordning: 0,5, 1, 2, 3, 4, 5 och 6 m^3/s. De resulterande hydrauliska kartorna klassificerades i en regelbaserad habitatmodell baserad på preferenskurvor för lax och öring i finska och norska floder, och ett viktat mått för habitatarean (WUA) beräknades. Habitatmodellen indikerar att ju högre flöde, desto bättre effekt. WUA ökar genom alla scenarier, upp till det högsta studerade flödet 6 m^3/s. Den största nyttan av att öka flödet observerades upp till 2 m^3/s, efter vilket den avtog, särskilt för habitat av ”god” kvalitet. Sammanfattningsvis finns det en stor potential för att förbättra förutsättningarna för fisk genom implementering av ett krav på minimitappning i framtida miljötillstånd.

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Introduction

Background

Hydropower plays a leading role in global energy supply. It accounted for around 17% of the global electricity generation in 2020 (IEA 2022). In Sweden, hydropower is by far the dominant source of electricity, contributing 45% (around 72 TWh) of the total production in 2020 (Energimyndigheten 2023). As a renewable energy source that can reliably manage increasingly fluctuating supply–demand balances, it is vital for the decarbonization of the power sector (IRENA 2023). In the Paris Agreement's scenario for a global average temperature increase limited to 1.5°C relative to pre-industrial levels, hydropower capacity relative to 2020 is predicted to increase by 30% in 2030 and to be doubled in 2050 (IRENA 2022). While these numbers illustrate the importance of hydropower for electric and climate sustainability, the opposite argument can be made regarding its ecological sustainability.

Hydropower projects—new and old—can pose a threat to freshwater biodiversity. They cause changes to natural hydraulic and thermal regimes, decrease river–floodplain connectivity, aquatic productivity and fish access to spawning and nursery habitats, all of which fundamentally alter riverine systems (Reid et al. 2019). The capability of hydropower to manage grid fluctuations requires corresponding fluctuations in discharge, which can have devastating consequences for aquatic ecology (Rosenberg et al. 1995). Naturally, rivers have a seasonal variability in flow that fish are well adapted to, and natural high and low flow periods can be important in a natural life strategy of certain species (Everard 1996 and Humphries et al. 1999). However, fish are generally less resistant and resilient to unpredictable disturbances to the natural seasonality of river discharge and certain species are more vulnerable than others (Lake 2003).

Two species which are highly sensitive to unpredictable changes to hydraulic regime are salmon (*Salmo salar*) and trout (*Salmo trutta*). Broadly speaking, these species share common life histories. The female parent deposits the eggs in gravel, and when an egg hatches, an alevin emerges. After having subsided on their yolk sacs in the shelter of the substrate, they emerge from the gravel as fry seeking nursery habitats. There they grow into parr, which migrate to different habitats where they feed actively and grow into maturity. They then return to their site of oviposition to spawn and close the life cycle (Crisp 2008). During reproduction migration, a relatively high steady flow should be maintained in order to facilitate upstream movement (Malcolm et al. 2012). Egg and alevin life stages are sensitive to dewatering, which calls for adequate minimum flows with minimal periods of drawdown. Emerging fry are especially sensitive to fluctuating flows, while parr are less sensitive (Hayes et al. 2019).

Finding the balance between the production of fossil free electricity and sustainable conditions for fish entails temporally variable flow regulation for hydropower plants (Degerman et al. 2001). This is the express purpose of the Swedish review strategy for hydropower which is defined in the 11th Ch. 28 § of the Swedish Environmental Code (SFS 1998:808), as an implementation of the European Water Framework Directive. The review strategy outlines a plan of updating the operational permits of hydropower plants with permits older than 40 years (Havs och Vattenmyndigheten [HaV] et al. 2019).

In parallel with the review strategy, an action plan has been produced by the County Administrative Boards for each river basin that is affected by hydropower. That includes the river basin of Helge River, which contains Genastorp, the biggest hydropower plant in Scania County. In the Helge River action plan, two measures are proposed to increase the ecological and morphological status of the river with respect to Genastorp: to facilitate up- and downstream passage for fish (Vatteninformationssystem Sverige [VISS] 2019), and to restore or improve the hydrological regime (VISS 2021). Having been postponed by one year, Helge River is currently scheduled for review in 2028 according to the appendix to the regulation (SFS 1998:1388) on waterworks, and with operational permits from the 1960s, Genastorp will be among the eligible for review.

Aim

The aim of this degree project is to investigate the potential of improving the hydrological regime of Helge River by prescribing a minimum flow requirement for the Genastorp hydropower plant to the study area, i.e., the 5 km long natural reach of Helge River that lies between the sluice gates and the discharge outlet for the turbine. This aim will be achieved by constructing a computer model of the study area. The terrain will be modelled using topographic maps and in-situ measurements. Then the hydraulics will be modelled in 2D space for seven constant flow scenarios: 0.5, 1, 2, 3, 4, 5, and 6 m^3/s. Finally, these scenarios will be categorized in terms of trout and salmon habitat area and quality, using Weighted Usable Area (WUA) classification. Specifically, the following questions will be addressed:

- How does WUA change depending on flow scenario?
- What is the optimal minimum flow requirement for the Genastorp hydropower plant with regards to salmon and trout habitat?

Methodology

This degree project comprises a field study and modelling of terrain, hydraulics, and fish habitat (specifically salmon and trout). These parts will be described in further detail in this section. and an overview of how the models are interconnected is provided in Figure 1.

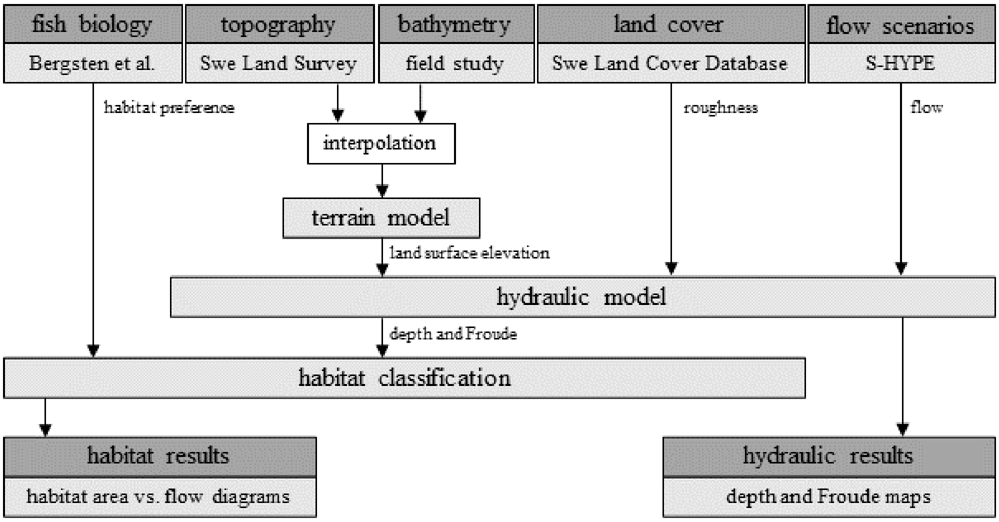

Figure 1. Schematic overview of the methodology used in this project.

This section will first give a qualitative introduction to the study area, with emphasis on hydraulics and hydrology. Following that, the three models outlined above will be described in detail.

The study area

The aim was to study the 5 km reach of Helge River that is defined from the sluice gates of the Genastorp hydropower plant to the discharge outlet from the turbine. However, due to limitations to the field study methodology (see section Field study (p. 16), the final habitat model was reduced to two smaller areas (Hönjarum and Göta bruk). In the current section however, the entire 5 km reach is considered as study area.

To replicate the river morphology as closely as possible, the area was surveyed both remotely and on foot. Hydraulic structures are documented qualitatively in this section, and later compiled quantitatively into the terrain model, as will be explained in the section Terrain model (p. 19).

The most obvious anthropogenic alterations to the river reach originate from the 1960s and forward, with the construction of the hydropower plant. But the river has had a long history of exploitation before modern times, which has left a lasting mark on the river morphology.

Modern structures

The Genastorp hydropower plant is located in the south of Sweden, in Osby Municipality (Figure 2). It is the biggest hydropower plant in the county of Scania, both in terms of hydraulic head and mean annual production, at 16 m and 24 GWh respectively. A storage type of hydropower plant, it uses lake Osby as a natural reservoir. Using a sluice gate dam, it diverts Helge river's discharge through a turbine. Söderbygdens Vattendomstol found among other things in partial ruling 45/1963 of the court case AD 66/1962, that the power plant may divert 100% of the flow to its turbines for electricity production at flows lower than 45 m^3/s. Moreover, partial ruling 57/1968 found that for the months December and January, the power plant may divert an extra 5 m^3/s for a total of 100 hours. The natural reach of Helge River that stretches from the sluice gates down to the turbine discharge point is thereby deprived of the diverted flow. Along the reach, however, are three smaller dams that, in combination with base flow and the tributary Hönjarum Creek, prevent the stream from drying out completely in periods of high electricity demand and low flow (Figure 3).

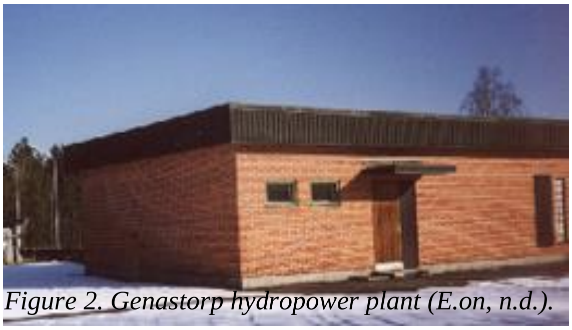

Figure 2. Genastorp hydropower plant (E.on, n.d.).

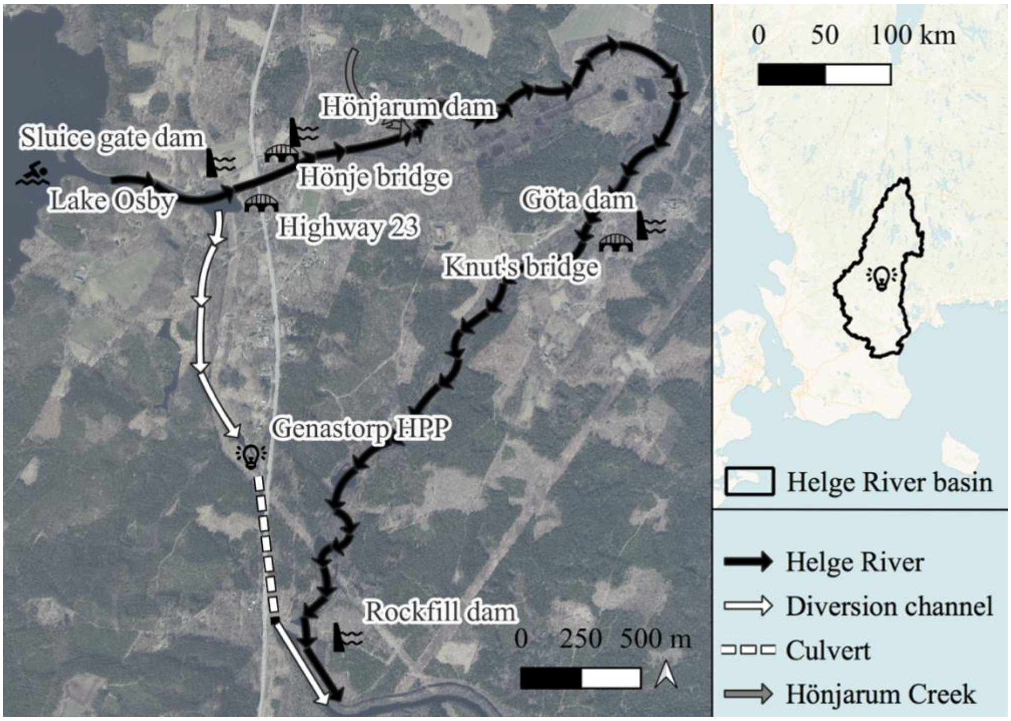

Figure 3. Map indicating the major flows and dams around Genastorp hydropower plant (HPP).

The upstream boundary to the study area is the Genastorp dam. It has three sluice gates and is situated just west of the Road 23 bridge (Figure 4).

Figure 4. The most upstream dam in the study area (Google Street View, 2022).

Just 370 m downstream from the first dam, lies Hönjarum dam (Figure 5). This is a smaller dam, which was built simultaneously with the power plant. The purpose of this dam was both esthetical and environmental. It would avoid draining the river completely and retain water for vegetation around the river reach. To avoid freezing at the upstream sluice gate however, the pond is drained from November 15 until April 15 (Söderbygdens Vattendomstol 45/1963).

Figure 5. Northward view of the Hönjarum dam, filled to capacity (Rosandra Nilsson, n.d.).

The Hönjarum dam can be drained using two small sluice gates (Figure 6).

Figure 6. Downstream-facing (eastward) view of the northern sluice gate at Hönjarum dam during dry conditions.

Next, 2.5 km downstream of Hönjarum Dam and just upstream of Göta Bruk, lies another dam built with the same purpose as the former, which—for lack of a better name—here will be called Göta Dam. A simpler dam than Hönjarum, this one is only a rubble embankment designed to retain water in the upstream bend of the river reach (Figure 7).

Figure 7. Göta dam, i.e., the rubble embankment dam upstream of Göta Bruk.

The final dam, a rockfill dam, constitutes the downstream boundary of the Genastorp study area. It is located just upstream of the junction between the diversion culvert and the natural channel (Figure 3). There, water is diverted through a weir into a spillway running in parallel with the main channel. They converge at a junction ca 1.5 km downstream (Figure 8).

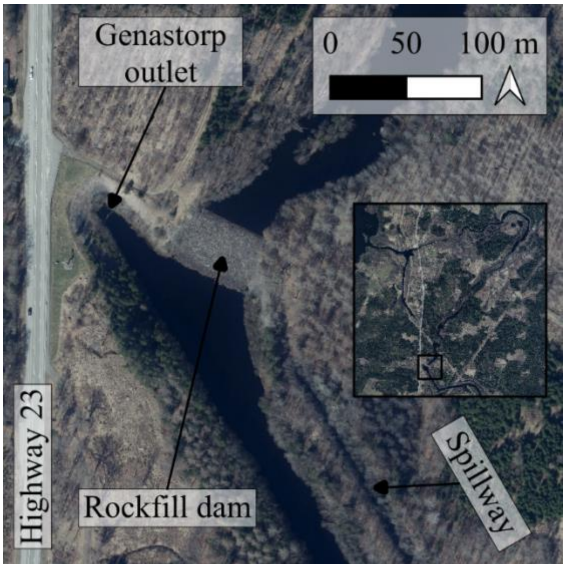

Figure 8. Rockfill dam and spillway.

Historical structures

The current dams are the most recent alterations to the morphology of the river reach in the study area, but there is a long history of industry that has employed hydraulic heads for different purposes, some of which has a lasting effect on the river today. There is evidence from the Swedish Land Survey from as long ago as 1721, when the surveyor Zacharias Almgren indicated several mills along the river (Appendix D). Interestingly, it appears on this map as though there is a dam in roughly the same location as today's Genastorp dam.

Most of the historical structures that remain around the river today originate from the 1800s. This includes the two stone bridges Hönjebro bridge and Knut's bridge (Figure 9 and Figure 10).

Figure 9. Photo of Hönjebro bridge, facing upstream. Highway 23 and a sluice gate of the Genastorp dam are visible through the rightmost arch.

Figure 10. Photo of Knut's bridge, facing downstream. It has four arches, one outside the left side of the frame.

There are smaller manmade channels that were built during this period as well. Immediately downstream of the Hönjarum dam lie two decommissioned mills: Östra Genastorp Mill on the southern bank and Duvemölla Mill on the northern bank. The former is in relatively good repair, with a wooden dam and waterwheel still in place inside a reinforced rock channel (Figure 11).

Figure 11. Downstream-facing view of the wooden dam and waterwheel of Östra Genastorp Mill.

On the other hand, the only remaining sign of the latter today is a decrepit channel and a stone monument. (Figure 12).

Figure 12. Upstream-facing view of the remains of the Duvemölla mill channel. The photo was taken at the confluence of the Hönjarum Creek and Helge River. The inscription on the stone monument in the inset image top right corner reads: "Dufwe mill and stamp mill founded year 1807 by Lars L. Dufwa, Christina I. Berg".

Further downstream, by Knut's bridge, lies the decommissioned Göta bruk. While the industrial wing of the compound was demolished in 1922 (Greater Copenhagen Skåne 2023), today the channel remains in good repair (Figure 13 and Figure 14).

Figure 13. Upstream-facing view of the Göta bruk channel from Knut's bridge.

Figure 14. Upstream-facing view of Göta bruk channel, seen through the westernmost arch of Knut's Bridge.

There is a small waterfall at the upstream end of the Göta bruk channel, which could be an obstacle for migratory fish traveling upstream (Figure 15).

Figure 15. A small waterfall at the top of Göta bruk channel; potentially an obstacle for migratory fish.

Hydrology

Helge River is the biggest catchment by area in Scania, at 4699 km^2 (Vattenatlas 2023). Genastorp is situated close to the midpoint of the catchment, where the river has a mean low-, mean-, and mean high flow (MLQ, MQ and MHQ) of 5.35, 23.7 and 67.4 m^3/s respectively according to the Swedish Meteorological and Hydrological Institute's (SMHI) hydrological model S-HYPE (SMHI 2016).

Study area in summary

There are many structures—big and small, old and new—that alter the hydraulics of the river in the study area. Naturally, the most important of these is the Genastorp sluice gate dam. It controls the inflow of water to the entire reach, which is why it is the focus for this report. However, the impact of the minor dams on the hydraulics in the reach can also play a decisive role for fish habitat. When the sluice gates of the Genastorp dam are completely close, they may have a positive effect by preventing a complete drought, but when the gates are open, the reduction in velocity and increased depth may have a detrimental impact on fish. Besides the potential migratory obstacle that they constitute, trout (*Salmo trutta*) prefer more rapidly streaming water, and at lower depths (Degerman et al. 2001), as will be explained in more detail in section Habitat model (p. 31).

Field study

The purpose of the field study was to measure the bathymetry of the river in the study area. This data was later used to complement the DTM used in the terrain model, as it was missing bathymetric data. The process of merging the two data sets will be described in the Terrain model section (p. 19), as the present section focuses on the field study alone.

As time constraints made it impossible to measure the bathymetry of the entire river, two smaller areas were chosen for detailed study, which henceforth will be called *Hönjarum* and *Göta bruk*. The areas were chosen under the assumption that they were potentially high-quality habitat for fish, and that maximizing the habitat area for these areas would therefore give a similar optimum flow as considering the entirety of the river reach would. The potential for high-quality habitat was identified through orthophotos: a recent one from 2022 and one from ca 1960, before the construction of the hydropower plant (Figure 16). The turbulence visible as white spots in the 1960s is not visible in the 2022 photos. Turbulence indicates riffle-pool areas that are the ideal conditions for spawning trout (Degerman et al. 2001). A promising goal for future regulation of the river would be to recreate these habitats. The final extent of the study area was defined as two areas, shown in Figure 16.

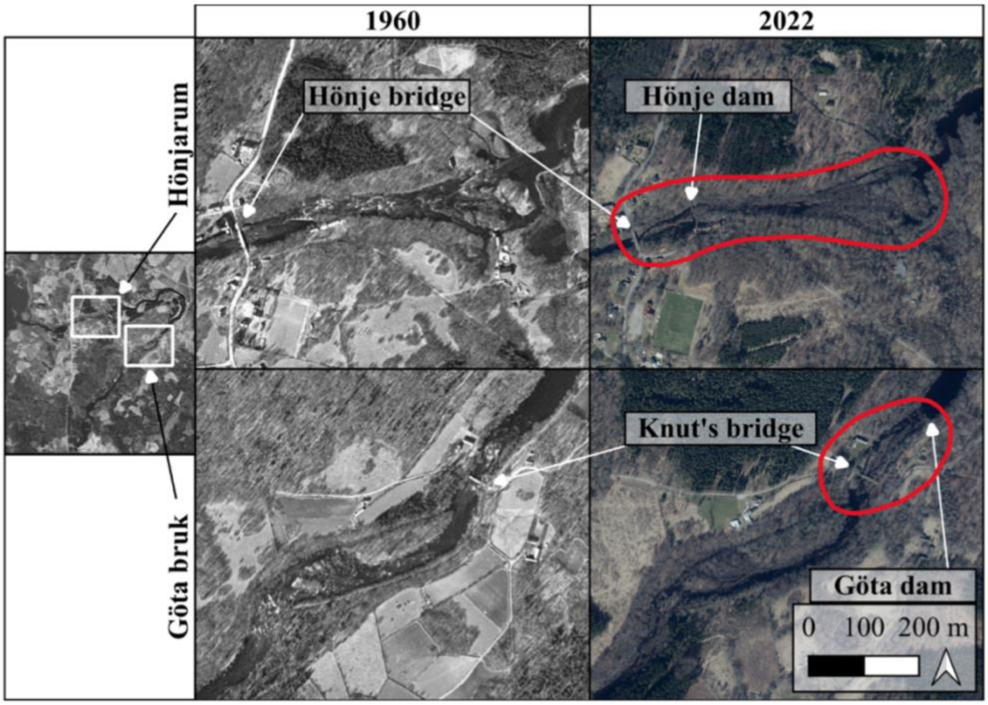

Figure 16. Comparison between orthophotos of areas with potential for fish habitat, taken ca 1960 vs. 2022. The bridges exist in both pictures, but the dams were built after the first photograph was taken. The areas marked in red represent the extents of the final two study locations.

The field study was conducted on April 25, 2023. March was a wet month, with SMHI modelled flows above 45 m^3/s (Figure 17). As stated in the Study Area section (p. 4), that is the limit for when the power plant must open the sluice gates to allow the additional discharge into Helge River. Thus, the sluice gates of the hydropower plant were open until the middle of April. This meant that the system had been drained for about a week before the field study, and much of the river was dry enough to be waded through and manually measured with a handheld DGPS (Figure 18). The DGPS used was an NCGeo S4, which records elevation with a precision of 0.1 mm using geoid WGS 84, and latitudinal and longitudinal coordinates at 0.01 mm precision in the coordinate system SWEREF 13°30'E, aka. ESPG 3008.

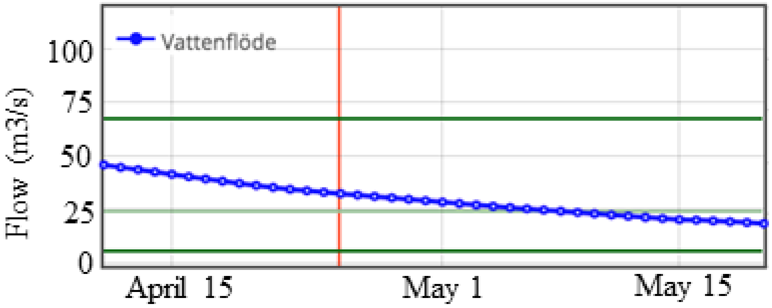

Figure 17. The flow at the study site (S-HYPE SUBID 645) according to the SMHI. The green lines indicate MHQ, MQ and MLQ, at 67, 24 and 5.5 m3/s respectively. The day of the field study, April 25, is marked with a red vertical line (SMHI 2023).

Within the two field study areas, point measurements were taken in a manner analogous to filling in a coloring book. A shapefile representing the areas where bathymetric data was missing from the DTM had been prepared and visualized in the DGPS GUI. Accessible areas were then traversed in waders with the goal to "fill" the shapefile with measurement points in as much detail as possible. In certain cases, like for manmade channels with square geometries, measurements were taken outside of the boundaries of the shapefile.

Figure 18. Bathymetric measurements were gathered in situ with a handheld DGPS.

The exact extents and density of the field study measurements was a product of as a combination of the following factors:

- Assumptions made from Figure 16
- Depth of the water needed to be shallow enough to wade in
- Time constraints

Terrain model

A good terrain model is essential for any hydraulic model. It should represent the geometry of the river well in places that control the movement of water. Especially in areas with pronounced elevation changes and localized flow dynamics, the resolution and accuracy of the terrain model is of greatest importance (US Army Corps of Engineers 2023).

The terrain model was the result of an interpolation between the Swedish Land Survey’s 1 m resolution DTM, and bathymetric data from the field study. First, the missing bathymetric data in the DTM raster were defined as no data regions

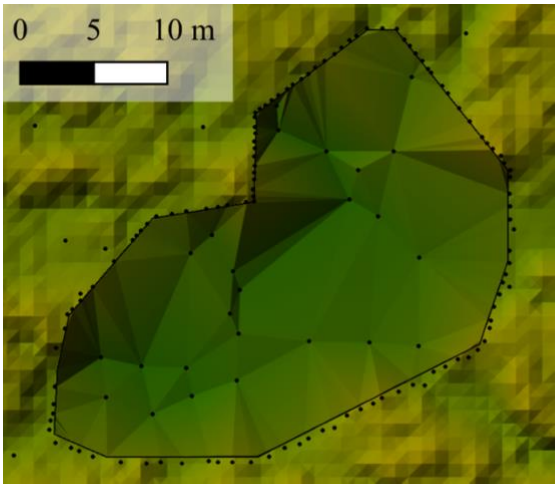

Figure 19. HEC-RAS Mapper terrain modification triangulates the terrain surface inside of the polygon (black line) using the elevation of the control points (black dots). Note the points dotted along the border, which have been added in order to smooth out the interpolation between field measurements and Land Survey data. The color of the interpolated surface represents the elevation, where high and low points are colored yellow and dark green respectively. The snapping tolerance of this shape is 1 m.

in QGIS. Then, the raster was imported into HEC-RAS Mapper, which is the GIS component of HEC-RAS (HEC-RAS will be introduced in the

Hydraulic model section (p. 23). The two data sources were assembled in RAS Mapper using the terrain modification feature, with the priority of patching no data regions of the DTM with field study data. After the data sources were combined, some fine tuning of the terrain model was performed, which is outlined in the rest of this section.

The RAS Mapper terrain modification feature triangulates the terrain surface between points both inside of a defined polygon as well as outside of the polygon at a user defined ’snapping tolerance’ distance. To smooth out the border between the field study data and the Swedish Land Survey data, additional points with the elevation of the Swedish Land Survey DTM were added along the border (Figure 19).

Additional terrain modification was performed to mould the terrain into a shape that could be verified using satellite imagery or field study experience.

Figure 20 illustrates several examples of this. Elevation points were added just downstream of Hönje bridge so that the triangulation algorithm would create a continuous channel leading to the northernmost sluice in Hönje dam, which can be verified with satellite imagery or the field study photograph in Figure 21. Note that the terrain model does not reflect the pillars of the Hönje bridge, a source of error that will be addressed in the discussion (p. 39).

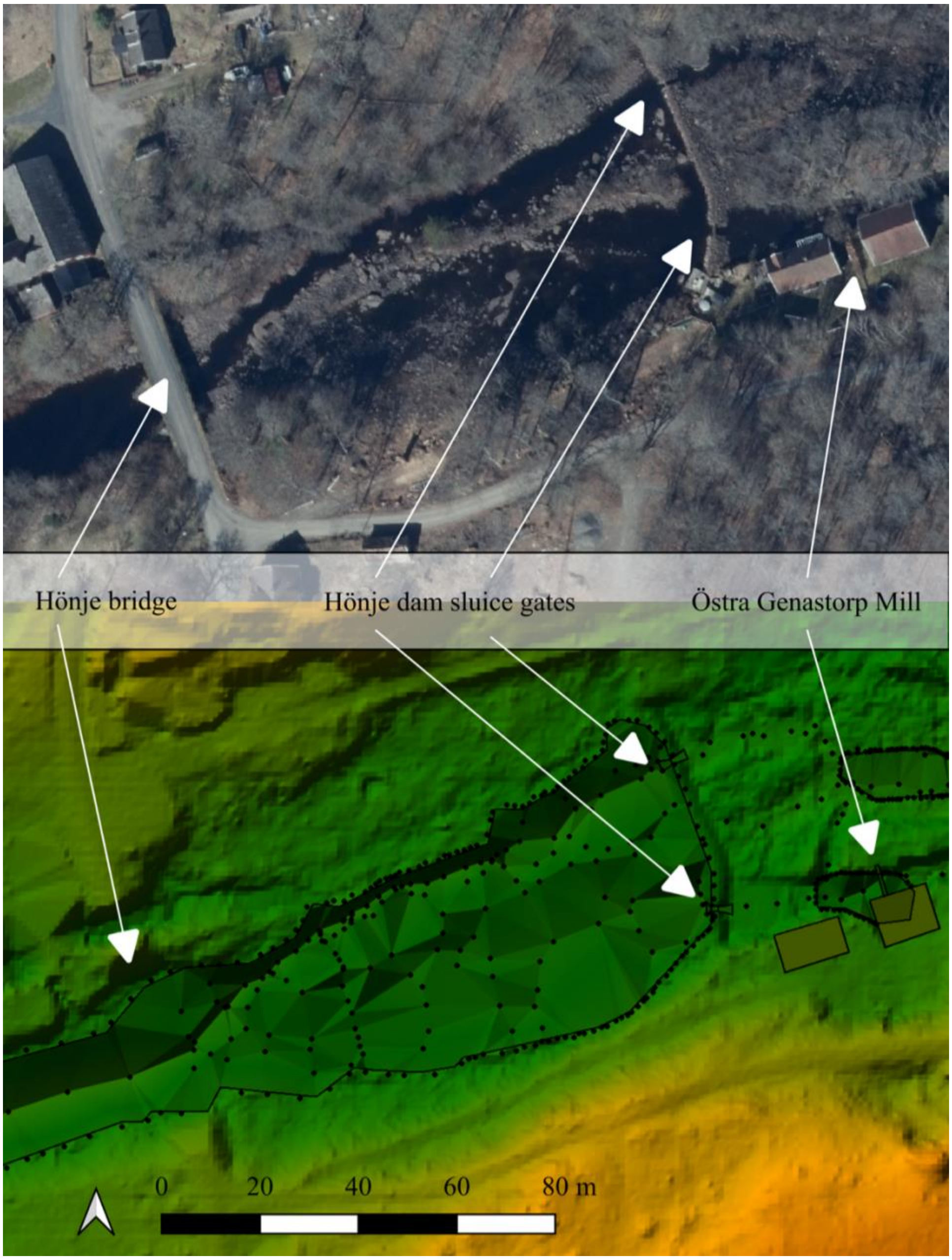

Figure 20. Comparison between satellite imagery and terrain model in Hönjarum.

Figure 21. View from Hönje bridge. A continuous channel stretches from the bridge's central arch to the northern sluice gate of Hönje dam.

Hydraulic model

With the terrain model assembled, next comes the hydraulic modelling. Building a good hydraulic model comprises the following key points:

1. Describing the flow characteristics with sufficiently accurate governing equations
2. Constructing a good computational mesh and selecting an appropriate time step
3. Providing appropriate initial- and boundary conditions
4. Describing the roughness of the land surface
5. Calibration (missing from this study)

In this section, these points will be described with respect to choices made for the hydraulic model used in this project.

Governing equations

The hydraulic model was run in HEC-RAS. HEC-RAS (Hydrologic Engineering Center - River Analysis System) is a hydraulic modelling software with many applications in water resources engineering. In addition to its capabilities for 1D space river modelling, it also provides functionality for simulating 2D space flow areas. For this project, the 2D modelling component was chosen in order to accurately capture the branching flows observed in the study area (Figure 16). The 2D space component simulates unsteady flow conditions, which means that an additional dimension of time is also being studied (p. 26).

HEC-RAS uses a finite volume approach to simulate 2D flow areas. The flow area is divided into a grid of cells, and the equations for conservation of mass and momentum are solved for each cell. The most fundamental description of these equations is given by the Navier-Stokes equation set. Numerically solving these equations requires highly sophisticated computational methods, and in the context of channel and flood modelling, it can be appropriate to make some assumptions, e.g., assuming shallow flow conditions.

The Shallow Water Equations (SWE) assume that the vertical flow direction is less important than the horizontal. Consequently, vertical velocity is small, and pressure is hydrostatic. Additional assumptions include incompressible flow, uniform density and negligible wind forcing. Furthermore, eddy viscosity (i.e., turbulence) is modelled as a gradient diffusion process. Because the conservation of momentum is directionally invariant, momentum may be computed orthogonally to the cell faces in the computational mesh (in the N direction). Depth averaged and in cartesian coordinates; the SWE for mass conservation and momentum can be written as follows:

$$\frac{\partial h}{\partial t} + \boldsymbol{\nabla} \cdot (h\mathbf{V}) = q \tag{1}$$

$$\frac{\partial u_N}{\partial t} + (\boldsymbol{V} \cdot \boldsymbol{\nabla})u_N + f_c u_N = -g\frac{\partial z_s}{\partial N} + \frac{1}{h}\boldsymbol{\nabla} \cdot (\boldsymbol{v_t} h \boldsymbol{\nabla} u_N) - \frac{\tau_{b,N}}{\rho R} - \frac{1}{\rho}\boldsymbol{\nabla} p_a \tag{2}$$

Where

h : water depth [L]
t : time [T]
$\boldsymbol{\nabla}$: gradient operator [-]
$\mathbf{V}$: velocity vector [L/T]
u_N : velocity component normal to the cell face [L/T]
q : source/sink flux term [L^3/T]
f_c : Coriolis parameter [1/T]
g : gravitational acceleration [L/T^2]
z_s : water surface elevation [L]
$\mathbf{v_t}$: eddy viscosity tensor [L^2/T]
$\tau_{b,N}$: bottom shear stress tensor normal to the cell face [M/L/T^2]
ρ : water density [M/L^2]
R : hydraulic radius [L]
p_a : atmospheric pressure [M/L/T^2]

Bottom shear stress is computed using Manning’s roughness coefficient n as follows:

$$\boldsymbol{\tau_b} = \frac{\rho n^2 g}{R^{1/3}} |\mathbf{V}|\mathbf{V} \tag{3}$$

There are two methods of solving the momentum equations of the SWE available in HEC-RAS: the Eulerian and the Eulerian-Lagrangian methods. The Eulerian method is the most momentum conservative approach and is recommended for lab scale simulations. The Eulerian-Lagrangian method is more stable for larger time steps, which is why it was chosen for the simulations in this degree project.

The SWE requires the solution of a system of differential equations, which is computationally demanding. Under the assumptions of the Diffusion Wave Equation (DWE), however, the system reduces into a single equation. The DWE approach assumes that gravity and frictional forces are dominant, while disregarding the effects of advection, turbulence, and Coriolis forces. The DWE is classically written as follows:

$$\frac{dh}{dt} = \boldsymbol{\nabla} \cdot (\beta \boldsymbol{\nabla} z_s + S + q) \tag{4}$$

Where

$$\beta = \frac{hR^{2/3}}{n} \left| \boldsymbol{\nabla} z_s + \frac{1}{\rho g} \boldsymbol{\nabla} p_a - \frac{\boldsymbol{\tau_s}}{\rho g h} \right|^{-1/2}$$

$$S = \boldsymbol{\nabla} \cdot \left[\beta \left(\frac{1}{\rho g} \boldsymbol{\nabla} p_a - \frac{\boldsymbol{\tau_s}}{\rho g h} \right) \right]$$

τ_s : wind shear stress tensor [M/L/T^2]

The DWE allow for faster and more stable computations, which is useful for generating initial conditions for further simulations with more physically rigorous equations, like the SWE.

To summarize, the SWE Eulerian-Lagrangian approach was used consistently throughout the simulations, except for when generating the initial conditions for the first model run, when the DWE were employed for stability reasons.

Hydraulic model grid and time step

The total time of each flow scenario was chosen to 24 hour in order to approximate steady state conditions. In order to increase model stability and reduce computation time, a variable time step was used. The variable time step adapts based on Courant numbers calculated in each cell. The Courant number (Cr) is dimensionless and represents the number of mesh cells travelled by a particle at a given time step, and is calculated according to the following equation:

$$Cr = \frac{v \cdot dt}{dl} \tag{5}$$

Where

v : flow velocity [L/T]

dt : time step [T]

dl : cell length [L]

If the Courant number is higher than 1 ($Cr > 1$), then the particle may skip entire cells in the mesh, which can lead to model instability. The courant number should therefore preferably be less than or equal to 1 ($Cr \leq 1$). Reducing the time step reduces the Courant number, i.e., increases model stability. However, the model is able to stay stable with Courant numbers that are somewhat higher than 1. In this project, the target Courant range was set to $0.5 \leq Cr \leq 1.5$. If any cell in the mesh violated this condition, the time step was automatically either halved or doubled, to compensate. As a limit to this compensation, the doubling or halving of the time step could be done at most four times in each direction. Starting at a time step of 10 s, this meant that the time steps available to the model were as is shown in Table 1.

Table 1. Values available for the variable time step algorithm. 10 s is the initial time step.

x	**$10 / 2^x$**	**$10 \cdot 2^x$**
1	5 s	20 s
2	2.5 s	40 s
3	1.25 s	80 s
4	0.625 s	160 s
5	0.3125 s	320 s

The computational mesh was created in RAS Mapper and is shown in Figure 22. It comprised two 2D flow areas with a maximal mesh resolution of 20 m inside the outer perimeter. The mesh was refined to a 1 m resolution inside the refinement regions. To avoid unintended leakage across barriers to flow, like embankments or walls, breaklines were drawn so that cell faces were aligned with the crest of the barriers. Breaklines were also added at the interface between the Swedish Land Survey DTM and the field study regions to increase the stability of the model.

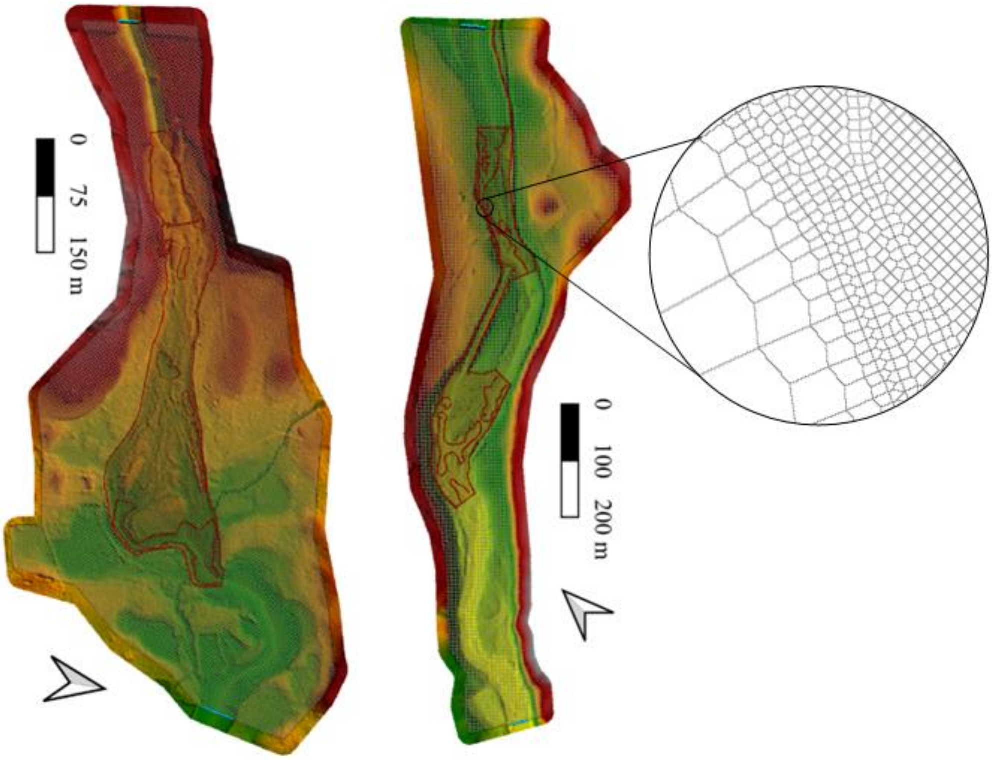

Figure 22. HEC-RAS geometries of the two study areas: Hönjarum (right) and Göta bruk (left). They have been rotated so that the upstream boundary conditions (blue lines) are at the top. The red lines indicate refinement regions and breaklines. The color of the terrain surface represents surface elevation, where surfaces are shown on a spectrum from high to low as red to green respectively.

Initial- and boundary conditions

The upstream and downstream boundary conditions were defined as lines orthogonal to the flow direction. The flow released from the boundary condition line was distributed across the cells it overlapped based on the proportion of overlap for each cell. They were placed at a distance of at least 100 m from the shallow flow areas, so that any error caused by their configuration would be negligible.

Seven scenarios with different constant flows were analysed, listed in Table 2. The scenarios were chosen so that the flow was roughly less than the MLQ of 5.35 m^3/s, so that hydrology wouldn't be considered a limiting factor. For each flow scenario, the upstream boundary conditions were assigned an idealized hydrograph with constant flow over the full 24 hours. The downstream boundary condition lines were assigned a corresponding negative flow hydrograph.

Table 2. Constant flow scenarios analyzed.

Scenario order	**Flow (m^3/s)**
1st	0.5
2nd	1
3rd	2
4th	3
5th	4
6th	5
7th	6

The scenarios were run in series, going from lowest flow to highest. The flow conditions obtained at the end of each scenario were used as initial conditions for the next scenario. For the first scenario (0.5 m^3/s), initial conditions were derived from a model run with dry initial conditions and the simpler DWE approach. This was the only time the DWE approach was used, and it was chosen here for its robustness with regards to the higher hydraulic gradients that arise when propagating a flood wave onto a dry 2D flow area. For all subsequent model runs, from scenario 0.5 to 6 m^3/s the SWE approach was used.

Surface roughness

In hydraulic modelling, the surface roughness is described with Manning's roughness coefficient n (Equation (3)). The value of this coefficient depends on the land cover type and in river hydraulics it can vary by a factor of 10 (HEC 2023). This means that assigning an appropriate Manning's n to each computational cell is of great importance. However, land cover maps rarely have sufficiently high resolution for hydraulic modelling, and it can be difficult to find studies of Manning's n values with perfectly matching land cover. This makes Manning's n the subject for model calibration and sensitivity analysis in state-of-the-art hydraulic modelling.

In this project, however, a fixed Manning's n has been prescribed for each land cover type since there was no calibration data available. The values lie in the range specified in the HEC-RAS 2D User's Manual (2023b). Open water surfaces were set to $n = 0.028$, and roughness of other land uses are specified in Appendix A. These were applied to the 10 m resolution Swedish National Land Cover Dataset classification raster, which is based on mapping conducted during 2017–2019 (Swedish Environmental Protection Agency [EPA] 2020).

Calibration (missing in this study)

The hydraulic model was not calibrated in this study. Sample flow data for calibration was not available, and so an alternative approach had to be adopted. The results were visually validated using aerial photography to make sure that they were realistic. This runs the risk of producing realistic looking results without accurately reflecting real-life conditions. Thus, a model should preferably be calibrated using sampled flow data, e.g., of water surface elevation in several locations along the river that correspond to the flow rates that are being studied. The model can then be fine-tuned, e.g., by changing the Manning's n values until the model results match the calibration dataset. Consequently, the detailed hydrodynamics produced by the model should be viewed with scepticism, but conclusions may still be drawn from observing how flow scenarios relate to each other.

Habitat model

The aim of the habitat model was to evaluate how the flow conditions (depth, velocity, etc.) that were found for the different flow scenarios would relate to fish habitat in the river. In contemporary river restoration projects, two different fish modelling methods are used. The state-of-the-art method for this is individual-based modelling, where model fish make fitness-oriented decisions based on a range of ecological factors (Piccolo and Watz 2017). This method has the benefit of yielding nuanced results regarding substrate, flow conditions, and all life-stages of fish, but requires multifaceted data (Watz et al. 2022). In contrast, the most common method, which has been used in river restoration projects since the 1970s, is the correlative method (Frank et al. 2011). Here, areas of the river with hydrodynamics that correspond with fish habitat preferences are matched and classified in terms of quality (Booker and Dunbar 2004). Correlative models are easier to use and can be predict flow effects on younger life stages well but may underestimate the flow requirements of larger fish (Watz et al. 2022).

In this project, a relatively simple correlative method was used, following the same basic methodology which has been used for several river restoration projects in Sweden (Bergsten et al. 2014 and Nordblom 2018). The model builds on habitat preference curves, which are relationships based on empirical observations of at which depths and flows reproduction occurs. Specifically, studies of salmon (*Salmo salar*) and trout (*Salmo trutta*) reproduction in Finnish and Norwegian rivers were used, which indicate that these species prefer flow velocities and depths in the ranges 0.1–0.9 m/s and 0.1–0.6 m for reproduction (Lahti 2009). Bed substrate is not considered in this model, which implies that bed substrate is assumed to be of perfect quality everywhere, i.e., a sort of best-case-scenario.

Fish preference for velocity can be different at high and low flows, as was described by Moir et al. (2002), making habitat classification difficult. However, in their study, the authors found that the Froude number (*Fr*) was a more constant variable for describing habitat quality. A unitless number defined by the ratio of inertial to gravitational forces, it is defined as follows:

$$Fr = \frac{v}{\sqrt{gh}} \tag{6}$$

where v is flow velocity [L/T], g is gravitational acceleration [L/T^2] and h is depth [L]. Thus, Froude number indirectly accounts for velocity. Therefore, habitat classification in this study is based on depth and Froude number.

Cells in the hydraulic mesh were classified into three levels of habitat quality: poor (class 1), middling (class 2) and good (class 3) quality, as illustrated in Figure 23 and Table 3. Note that class 3 is a subset of class 2, which in turn is a subset of class 1. The usable area of each class was calculated as the cumulative area of all cells belonging to that class. A weighted average, commonly referred to in the literature as the Weighted Usable Area (WUA), was calculated according to the following formula:

$$WUA = 0.2 \cdot Area_{class\ 1} + 0.3 \cdot Area_{class\ 2} + 0.5 \cdot Area_{class\ 3} \tag{7}$$

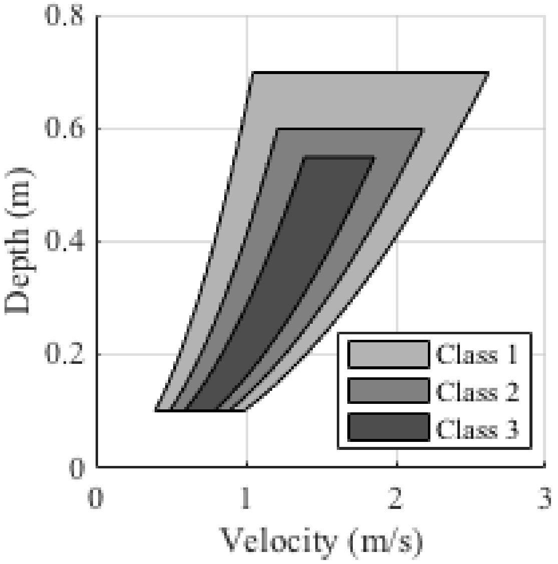

Figure 23. Classification of habitat quality for anadromous fish. Class 1, 2 and 3 represent poor, middling, and good quality habitat respectively (from Bergsten et al. 2014).

Table 3. Classification of habitat quality for growth and reproduction of anadromous fish (from Bergsten et al. 2014).

Habitat class	**Froude number (-)**	**Depth (m)**
1: poor	0.4–1.0	0.10–0.70
2: middling	0.5–0.9	0.10–0.60
3: good	0.6–0.8	0.10–0.55

The classification analysis was performed in the Python interface of QGIS, PyQGIS 3.28, using the code shown in Appendix B. The code is structured around for-loops that cycle through the flow scenarios (Table 2) and classes (Table 3) iteratively. For each scenario and class, the following operations were performed:

A. Raster calculator performs binary classification of the Froude and depth rasters produced by the habitat model based on the class rules. A value of 1 is assigned to cells that fulfill the logical expression defined by the current class’ rule, and 0 to those that do not match.
B. The classified rasters are polygonised into vector shape files and bordering cells are merged if they belong to the current class.
C. The vectors that do not belong to the current class are removed.
D. The area of each vector is calculated.
E. The vectors are disaggregated according their geographic location: Hönjarum or Göta bruk. The mask layers defining the extents of the two locations is largely based on the extents of the field study (as shown in red in Figure 16).
F. The cumulative area of the vectors in each location is calculated.

Finally, these cumulative areas were compiled in Matlab and the WUA was calculated for both areas, as well as the sum of the two. To summarize the results of the flow scenarios, diagrams were plotted of the area of each class in m^2 vs. flow in m^3/s.

Results

Here, the results of the hydraulic and habitat models will be presented. Furthermore, some statistics from the field study data that was used to construct the terrain model (Figure 22) will be provided.

Hydraulic results

Maps detailing the inundation and water depth in different scenarios are displayed in Appendix C. The use of these maps is twofold. Firstly, the inundation extents can be compared to satellite imagery in order to qualitatively validate the hydraulic model. Secondly, they can be used to check for potential barriers to connectivity at low flows. That is, if one assumes that fish require a water depth at least equal to their own body height in order to swim through, then passage may be hindered at locations of shallow water depth.

Habitat results

The results of the habitat model indicated that the usable area generally increased as a function of flow (Figure 24). In all locations, the WUA curve increased monotonously up to the highest flow scenario of 6 m^3/s, in a manner that appears nearly logarithmic up to that point. The highest quality habitat (habitat class 3), increased faster in the flow range 0.5–2 m^3/s. After that, the rate of increase slowed, until it reached a plateau of ca 1000 m^2 after 4 m^3/s. At higher flow rates however (> 4 m^3/s), the two different study locations trend in opposite directions. The lower quality habitat curves (class 1 and 2) for Hönjarum trend upwards, while the same curves for Göta bruk seem to flatten out. Conversely, class 3 habitat begin to dip in Hönjarum and rise in Göta bruk at higher flow rates.

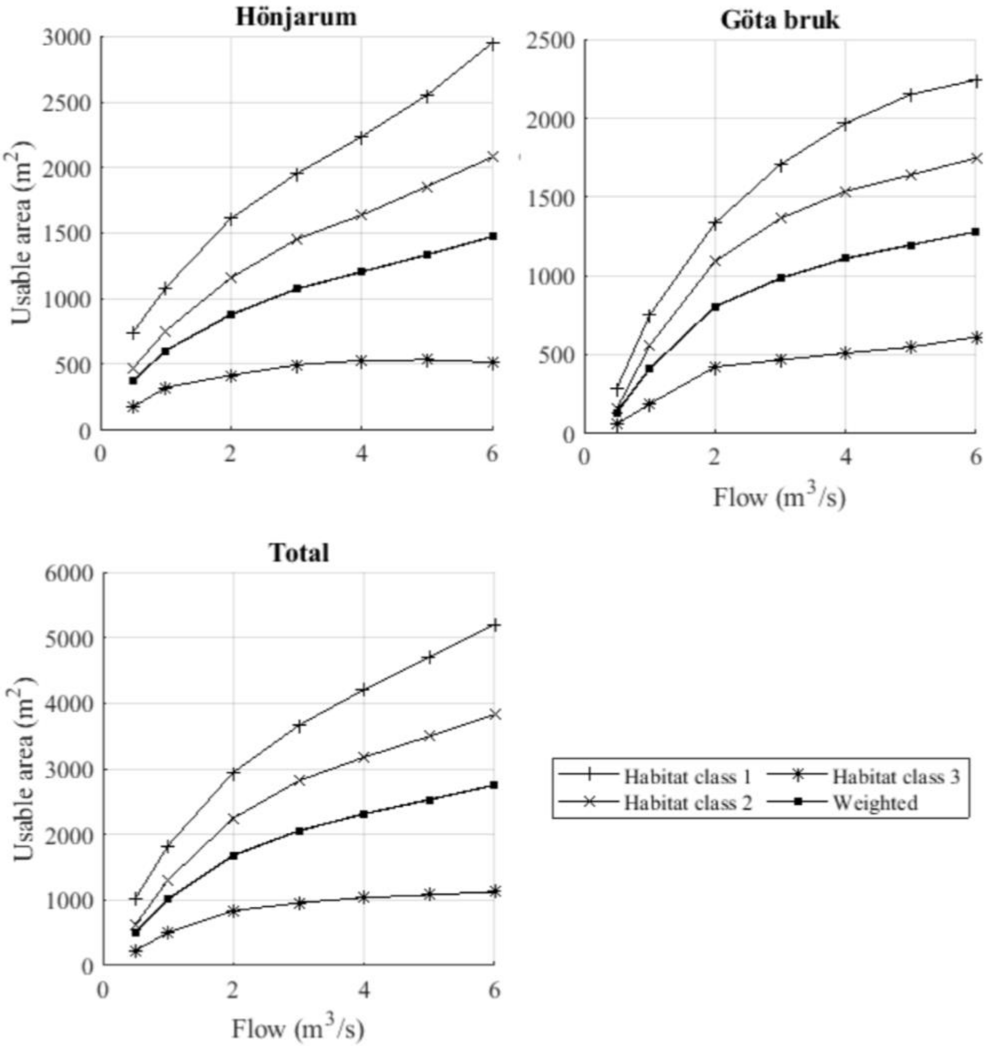

Figure 24. Effect of variable flow on usable area of different quality (quality increases with class number), as well as a weighted measurement which accounts for all three classes. Note that the scales of the y-axes in the plots are not the same.

Field Study statistics

A total of 582 elevation measurements were taken during the field study: 345 in Hönjarum and 237 in Göta bruk. The average distance between measurement points was calculated to 2.8 m in total, 3.3 m in Hönjarum and 2.1 m in Göta bruk (Figure 25). The density of the control points for the bathymetry in terrain model was therefore lower than the 1-meter grid in the hydraulic model.

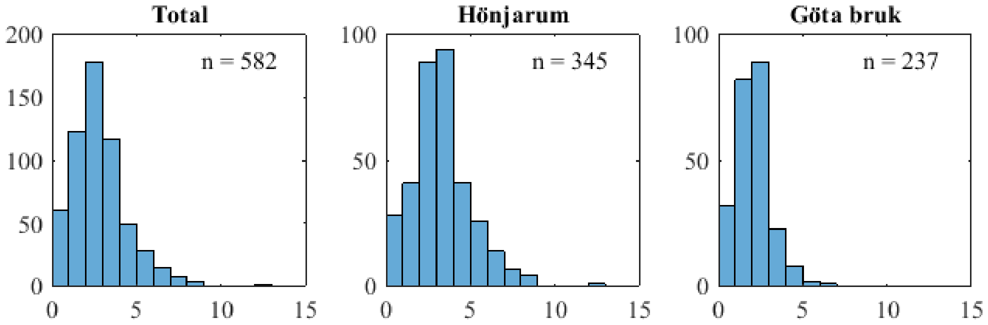

Figure 25. Histograms of the distance to the nearest neighbor of the measurement points in the field study. The x-axis represents distance (m) and the y-axis represents frequency.

Discussion

The results from the habitat model indicate that the optimum flow with regards to habitat area was 6 m^3/s. That corresponds to the hydrological mean low flow for the area (SMHI 2023), and it is the highest flow scenario for this study. In other words, the WUA curve increased steadily for all flow scenarios studied (Figure 24). However, the benefit of increasing the flow is greatest up to 2 m^3/s, as area of all three habitat classes increases fastest under that point. The class 3 habitat ("good" quality) increases the slowest of the three classes, and more or less reaches a plateau of 1000 m^2 around 3–4 m^3/s. Further study is needed to determine how the WUA–flow relationship behaves at higher flows.

In a future river restoration plan, the minimum flow requirement should not be the lone measure under consideration as means to improve the ecological status of the river. For instance, an upstream fish passage past the hydropower dam may be considered. Additionally, it may be considered for the small dams and obstacles in Hönjarum and Göta bruk to be demolished or altered in some way to facilitate fish migration, although this must be done in concert with a constant flow through the area in order to avoid complete drainage of the river.

There are a number of sources of error that contribute to uncertainty in this study. Here they are listed in the order they will be discussed below, i.e., not in order of importance:

1. Limited geographical extent of the study
2. Resolution of field study terrain elevation data
3. Uncertainty in Swedish Land Survey data under tree canopy
4. User error in terrain modification
5. Lack of calibration and validation data for hydraulic model
6. Riverbed sediment quality disregarded in habitat model

The first two items in the list above relate to limitations in the field study methodology.

Firstly, the full geographic extent of the study area was narrowed down to two sub-areas due to the limitations of the field study. These areas were chosen based on the assumption that they would have good potential for fish habitat, which in turn was based on aerial photography where turbulence was visible.

Therefore, it could be argued that optimizing the WUA for these areas will be the most efficient method. However, a more detailed survey of the bathymetry of the entire reach using e.g., an airborne drone equipped with green lidar would eliminate this source of uncertainty.

Secondly, the resolution of the elevation data collected in the field, where the average nearest neighbour distance was 2.8 meters, was generally courser than the 1-meter grid resolution in the hydraulic model. The distribution of the distances was however skewed towards the smaller distances, as is visible in Figure 25. This is because an effort was made during the field study to gather data in higher density in areas that were assumed to be of higher hydraulic importance, i.e., where the terrain changed more dramatically over short distances. While this difference in resolution makes detailed analysis of small-scale hydraulics impossible, aggregate analysis is more well suited.

The third and fourth items in the list of limitations relate to sources of error in the terrain model.

The Swedish Land Survey elevation data was used extensively in the terrain model, to model the banks of the river, as well as shallow flow areas where the lidar had been able to penetrate the water surface and capture the terrain. This was especially useful to model the terrain in Hönjarum, where the river branches out into a forested wetland that would have been very time consuming to survey with DGPS. However, the positional accuracy of the lidar data can be impaired in low lying areas with a dense canopy cover (Figure 26).

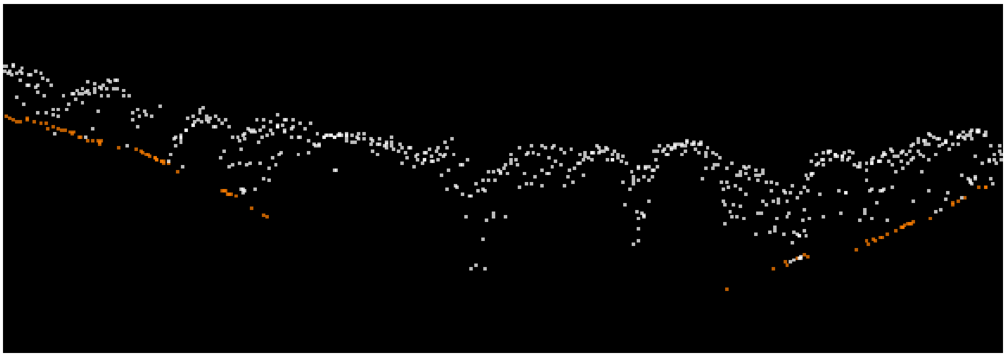

Figure 26. A dense canopy cover can block the laser from reaching the ground. Due to the shortage of ground points in the depression, the surface will be interpolated. White points are unclassified, and brown are ground (Swedish Land Survey [Lantmäteriet] 2020).

Therefore, the terrain in these areas is likely rougher in reality than what the Swedish Land Survey data indicates.

Next, user input played a major part in the terrain modification, when the hydraulic structures were digitized and incorporated into the model. Their geometries were based on satellite imagery and field study observations, and so any structures that were hidden from view or simply missed at the field study will not have been incorporated properly into the model. A known example of this is Hönje bridge, where the pillars of the bridge were forgotten, but there can be other examples of this that are unknown.

The fifth limitation in the list relates to the hydraulic model. This study lacks qualitative calibration data for the hydraulic model. The results can only be validated by comparing the modelled extents of the inundation (as shown in Appendix C) to satellite imagery. From this simple analysis it is clear that the modelled hydraulics look realistic and should therefore share a lot of the characteristics of the real-world river. It cannot be expected that the model is perfect however, as for instance the fixed values of surface roughness defined in Appendix A should ideally be calibrated. The ideal calibration data set would be produced by performing test spills from the sluice gates that match the studied scenario and measuring the flow depth in chosen locations. Therefore, the results cannot be considered as absolute representations of the flow dynamics in the river. Relating the results between different scenarios, however, can give an indication of how the habitat-flow relationship behaves for the morphology of the river, which is one of the aims of this study.

The final limitation that will be addressed here relate to the methodology of the habitat model. Since the model does not account for sediment quality, it effectively assumes a best-case scenario, i.e., that the sediment quality is perfect. As observed in the field however, this is not in fact true. Much of the riverbed is rocky, not gravely, which is not a preferred substrate for a female to deposit her eggs. While the natural sediment quality of the river is unknown, it is likely to have been affected by both short-term regulation of the flow, causing erosion, and by sediment trapping in Lake Osby by the sluice gates. In order to improve the riverbed sediment quality, it could therefore be considered if the sediment that is likely trapped upstream of the sluice gates could be dredged, and—following a toxicological analysis determining them safe—

deposited downstream of the dam. Moreover, limiting short-term regulation of the river not only reduces erosion, but is also important for ecological reasons (e.g., Degerman 2001).

Conclusions

In conclusion, the results from this study highlight the potential of implementing a minimum discharge requirement for the Genastorp hydropower plant. Even small levels of discharge can have a positive impact on fish in the downstream river, although no upper limit to the benefits were found in the scenarios studied here. Increased WUA was observed at least up to 6 m^3/s, corresponding to the hydrological mean low flow. Future studies should include scenarios with even higher flows in order to find the theoretical optimum in the WUA curve.

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Appendices

Appendix A. Land Cover roughness Classification

Table 4. Manning's roughness coefficient (n) values assigned to different land cover types in the hydraulic model (from HEC 2023b).

ID	Name	Manning's n
0	NoData	99
1	Inland water	0.028
2	Open wetland	0.08
3	Arable land	0.035
4	Mixed forest not on wetland	0.19
5	Vegetated other open land	0.01
6	Pine forest not on wetland	0.16
7	Mixed coniferous not on wetland	0.19
8	Pine forest on wetland	0.08
9	Deciduous forest not on wetland	0.08
10	Deciduous hardwood forest not on wetland	0.18
11	Artificial surfaces, road, railway	0.025
12	Mixed coniferous on wetland	0.08
13	Spruce forest on wetland	0.08
14	Mixed forest on wetland	0.08
15	Spruce forest not on wetland	0.16
16	Deciduous forest on wetland	0.08
17	Temporarily non-forest on wetland	0.07
18	Artificial surfaces, building	0.055
19	Deciduous forest with deciduous hardwood forest not on wetland	0.18
20	Temporarily non-forest not on wetland	0.1
21	Artificial surfaces, not building or road, railway	0.055
22	Deciduous hardwood forest on wetland	0.08
23	Non-vegetated other open land	0.03
24	Deciduous forest with deciduous hardwood forest on wetland	0.08

Appendix B. Habitat quality classification

The code for the habitat model was written in PyQGIS 3.28. The code below can be copied and pasted into the QGIS Python console and run after the four directories in the beginning of the code – “input”, “output”, “honjarum” and “gota_bruk” – have been set up correctly, with the output rasters for Froude and Depth from the HEC-RAS model as inputs.

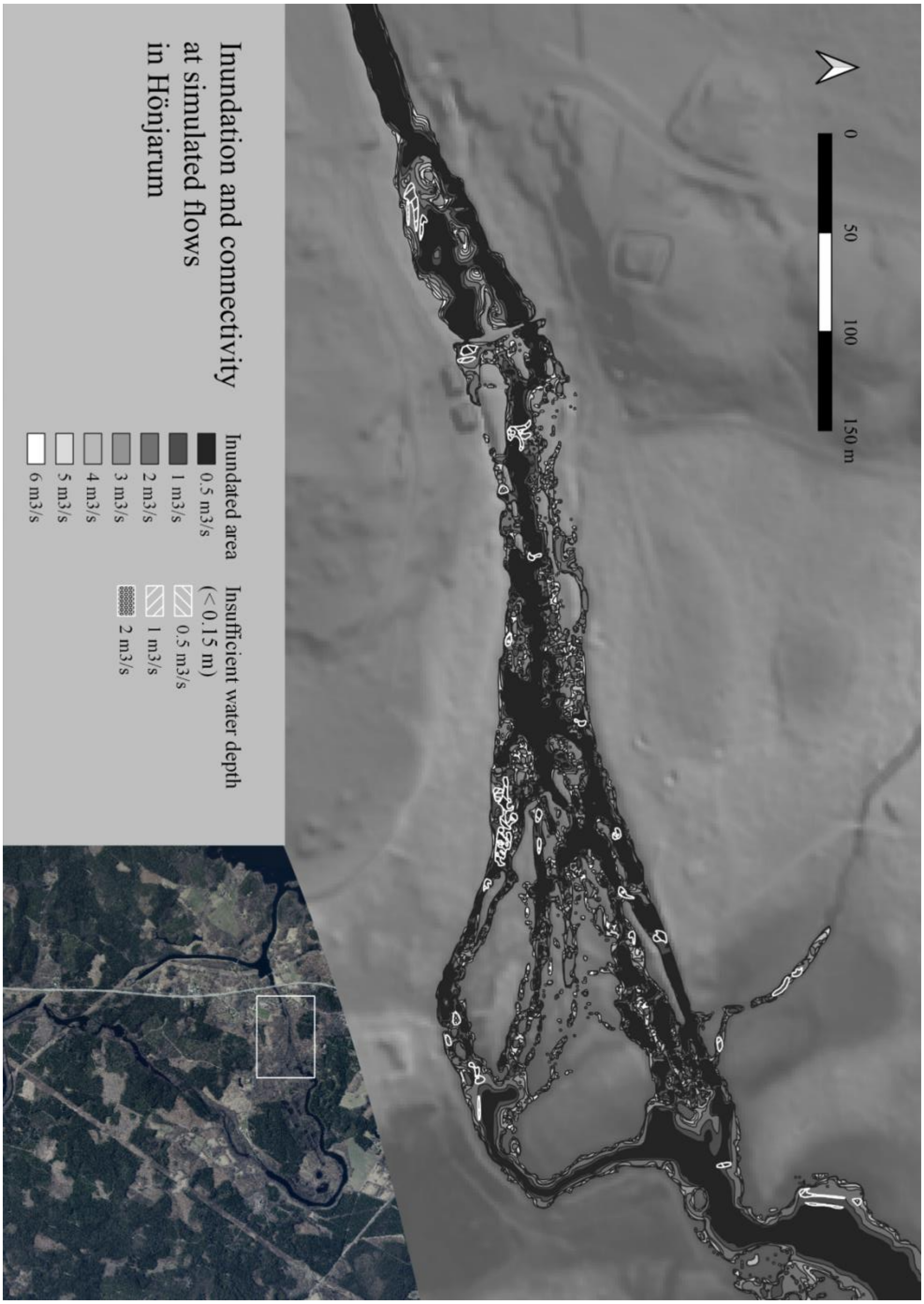
```
import os
import processing

# input = (string) directory to output folder for
HEC-RAS model
# output = (string) directory to output folder for
habitat model
# honjarum = (string) directory to Hönjarum study
area mask layer
# gota_bruk = (string) directory to Göta bruk study
area mask layer

scenarios = ['05', '1', '2', '3', '4', '5', '6']
classes = [1, 2, 3]
rules = ['a@1 >= 0.4 and a@1 <= 1 and b@1 >= 0.1
and b@1 <= 0.7', \
'a@1 >= 0.5 and b@1 <= 0.9 and b@1 >= 0.1 and b@1
<= 0.6', \
'a@1 >= 0.6 and a@1 <= 0.8 and b@1 >= 0.1 and b@1
<= 0.55']

for sc in scenarios:
    # Raw hydraulic data input
    input_AA = QgsRasterLayer(input + '\\Froude ' +
sc + '.tif')    # Froude
    input_AB = QgsRasterLayer(input + '\\Depth ' +
sc + '.tif')     # Depth
    for cl in classes:
        # Output file name for the current scenario
```

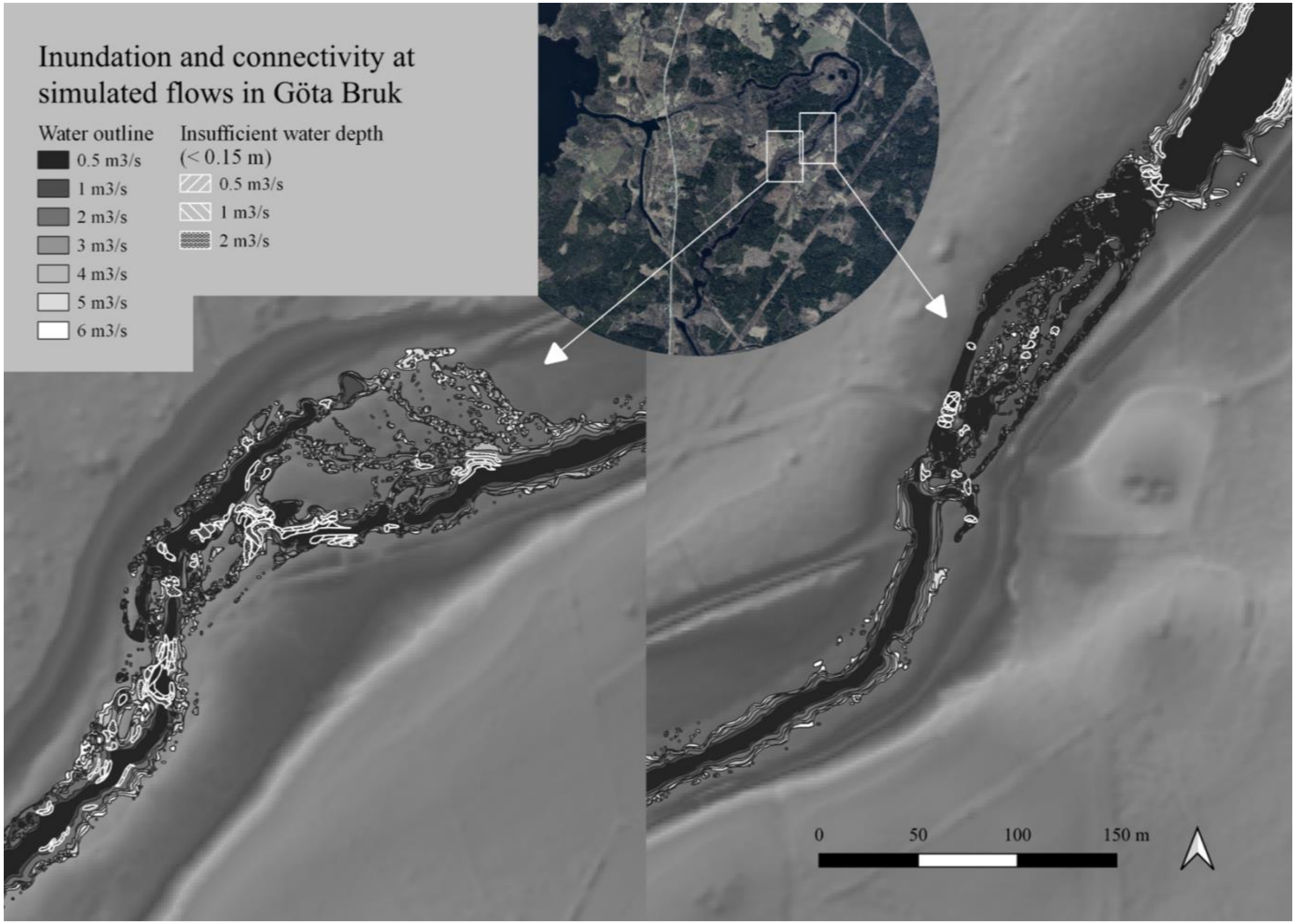
```
and class
        # (should be formated and given appropriate
suffix)
        output_ = f'{output} {sc} {cl}'

        # A. Raster calculator
        output_A = output_.format('calculated') +
'.tif'
        entries = []
        a = QgsRasterCalculatorEntry()
        a.ref = 'a@1'
        a.raster = input_AA
        a.bandNumber = 1
        entries.append(a)
        b = QgsRasterCalculatorEntry()
        b.ref = 'b@1'
        b.raster = input_AB
        b.bandNumber = 1
        entries.append(b)
        calc = QgsRasterCalculator(rules[cl-1],
output_A,'GTiff', \
        input_AA.extent(), input_AA.width(),
input_AA.height(), entries)
        calc.processCalculation()

        # B. Polygonize (raster to vector)
        input_B = output_A
        output_B = output_.format('vectorized') +
'.shp'
        parameters_B = {'INPUT' : output_A,
        'BAND' : 1,
        'FIELD' : 'Habitat',
        'EIGHT_CONNECTEDNESS' : bool(False),
        'OUTPUT' : output_B}

processing.run('gdal:polygonize',parameters_B)
```

```
        # C. Extract classified habitat
        input_C = output_B
        output_C = output_.format('extracted') +
'.shp'
        parameters_C = {'INPUT' : input_C,
        'FIELD' : 'Habitat',
        'OPERATOR' : 0,
        'VALUE' : '1',
        'OUTPUT' : output_C}
        processing.run("native:extractbyattribute",
parameters_C)

        # D. Add geometrical info (area
specifically)
        input_D = output_C
        output_D = output_.format('geomericalized')
+ '.shp'
        parameters_D = {'INPUT' : input_D,
        'CALC_METHOD' : 0,
        'OUTPUT' : output_D}

processing.run("qgis:exportaddgeometrycolumns",
parameters_D)

        # E. Disaggregate by field study location
        input_E = output_D
        output_EA = output_.format('honjarum') +
'.shp'
        output_EB = output_.format('gota bruk') +
'.shp'
        parameters_EA = {'INPUT' : input_E,
        'OVERLAY' : honjarum,
        'OUTPUT' : output_EA}
        parameters_EB = {'INPUT' : input_E,
        'OVERLAY' : gota_bruk,
```

```
        'OUTPUT' : output_EB}
        processing.run("native:clip",
parameters_EA)
        processing.run("native:clip",
parameters_EB)

        # F. Summarize geometrical info (aggregate
area)
        input_FA = output_EA
        input_FB = output_EB
        output_FA = output_.format('honjarum
stats') + '.html'
        output_FB = output_.format('gota bruk
stats') + '.html'
        parameters_FA = {'INPUT_LAYER' : input_FA,
        'FIELD_NAME' : 'area',
        'OUTPUT_HTML_FILE' : output_FA}
        parameters_FB = {'INPUT_LAYER' : input_FB,
        'FIELD_NAME' : 'area',
        'OUTPUT_HTML_FILE' : output_FB}

processing.run("qgis:basicstatisticsforfields",
parameters_FA)

processing.run("qgis:basicstatisticsforfields",
parameters_FB)
```

Appendix C. Inundation maps from hydraulic modelling




Inundation and connectivity at simulated flows in Göta Bruk
Water outline
0.5 m3/s
1 m3/s
2 m3/s
3 m3/s
4 m3/s
5 m3/s
6 m3/s
Insufficient water depth (< 0.15 m)
0.5 m3/s
1 m3/s
2 m3/s
0
50
100
150 m

Appendix D. Map of Östra Genastorp dated 1721