



**TURUN
YLIOPISTO**

Matemaattis-luonnontieteellinen
tiedekunta

Spatial modelling of salmonid microhabitats in regulated rivers

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Maantiede (Maantieteen linja)

Pro gradu -tutkielma

Laajuus: 30 op

8.11.2024

Turku

The originality of this thesis has been checked in accordance with the University of Turku quality assurance system using the Turnitin OriginalityCheck service.

Master's thesis

Subject: Geography

Author: Katriina Eskola

Title: Spatial modelling of salmonid microhabitats in regulated rivers

Supervisors: Petteri Alho, Tua Nylén

Number of pages: 101 pages

Date: 8.11.2024

Rivers and streams create important habitats for fish species of the Salmonidae family. Their natural habitats are threatened in many places since they are often affected by dams and other human-induced disturbance. Salmonid species have complex life cycles, and their habitat requirements vary by the life stage. Geospatial methods together with accurate field data allow modelling of real-world environments. Habitat modelling aims to map the potential habitat of a species based on different environmental variables. It also helps the restoration planning in regulated rivers.

A methodology for microhabitat modeling in river environments was developed and tested. The source material was a two-dimensional hydraulic model point cloud. The workflow was tested with data from two regulated rivers, river Vuoksi in Finland and river Gullspång in Sweden. Two different study sites provided an opportunity to evaluate the model's functionality and the impact of parameter changes on model outputs. Habitat rules were defined for two target species, juvenile Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*). The flow velocity and water depth conditions what are considered as suitable habitat for the two target species were identified based on literature. The habitat suitability values form a habitat rule for both species and their two juvenile life stages (young of the year and parr), four rules in total.

The aim of this research was to define and test a geospatial methodology for modelling microhabitat dynamics in rivers. The effect of different cell sizes and minimum habitat patch sizes on the predicted habitat area were analyzed. The hydraulic model was rasterized to three different cell sizes, 0.5, 1 and 2 m, to see the effect of the cell size. The impact of the analysis cell size on the predicted total area of habitat depended on study site and discharge, however compared to the total study area, the effect of different cell sizes was small. The effect of limiting the smallest habitat patches of the results was tested since fish need a large enough area of habitat to survive. The effect of patch size limitation on the predicted habitat area depended on the study site and the used cell size.

Also, the quality and stability of habitats were analyzed statistically and visually. Different habitat rules significantly affected the predicted habitat extent. The suitability range was divided to the range of optimal and suitable habitat to visually analyze the quality. The analysis of overlapping habitat areas in different discharge conditions was determined to better understand where suitable conditions for juvenile salmonids persist in in complex and constantly changing river environments, since the amount of habitat varies based on discharge. The results showed that channel morphology affects the distribution and stability of habitats in varying discharges. The shift of habitat patch location is usually gradual when the discharge grows.

The habitat modelling workflow resulted in a useful tool for future habitat analysis. The habitat modelling methodology which uses raster data about environmental conditions allows the user to choose different parameters, including the habitat rules, enabling an examination of their impact on the results. The same methodology can be utilized in different river environments, with different source data, and alternatively different habitat suitability rules. It was noted as part of this study that the modeler's knowledge of the local environment is important when interpreting the results, since the results may vary significantly based on the study site. The developed methodology offers a flexible and useful tool for assessing fish habitats, with potential applications in restoration planning and environmental management, also in regulated rivers.

Key words: Habitat analysis, ecohydraulic modelling, hydropower, *Salmo salar*, *Salmo trutta*

Pro gradu -tutkielma

Pääaine: Maantiede

Tekijä: Katriina Eskola

Otsikko: Lohikalojen mikrohabitaattien spatiaalinen mallinnus säännöstelyissä joissa

Ohjaajat: Petteri Alho, Tua Nylén

Sivumäärä: 101 sivua

Päivämäärä: 8.11.2024

Joet ja purot luovat tärkeitä elinympäristöjä lohikaloille (Salmonidae). Niiden luonnolliset elinympäristöt ovat monin paikoin uhattuina, sillä ne altistuvat usein patojen ja muiden ihmisen aiheuttamien vaikutuksille. Lohikaloilla on monivaiheinen elinkierto ja niiden elinympäristövaatimukset muuttuvat niiden elinkierron vaiheen mukaan. Geospaatialiset menetelmät yhdessä ajantasaisen kenttäaineiston kanssa mahdollistavat elinympäristöjen (habitaatti) mallintamisen. Habitaattimallinnuksen tavoitteena on kartoittaa lajin mahdollinen elinympäristö erilaisten ympäristömuuttujien perusteella. Sitä voidaan hyödyntää myös säänneltyjen jokien kunnostamisessa.

Tutkielmassa kehitettiin ja testattiin menetelmä mikrohabitaattien mallintamiseen jokiympäristöissä. Lähdeaineistona oli kaksiulotteinen hydraulinen pistepilvimalli. Menetelmää testattiin kahden säännöstellyn joen, Suomen Vuoksi- ja Ruotsin Gullspång-joen, aineistoilla. Kaksi eri tutkimuspaikkaa tarjosivat mahdollisuuden arvioida mallin toimivuutta ja parametrien muutosten vaikutusta mallinnuksen tuloksiin. Habitaattisäännöt määriteltiin kahdelle kohdelajille, nuorille lohille (*Salmo salar*) ja taimenille (*Salmo trutta*). Veden virtausnopeus- ja syvyysolosuhteet, joita pidetään sopivina kohdelajeille, tunnistettiin kirjallisuuden perusteella. Habitaattien soveltuvuusarvot muodostavat habitaattisäännön molemmille lajeille ja niiden kahdelle nuorelle elämänvaiheelle (0+ ja 1+ 2+), eli yhteensä mallinnettiin neljä eri habitaattisääntöä.

Tämän tutkimuksen tavoitteena oli määritellä ja testata geospaatialinen menetelmä mikrohabitaattien dynamiikan mallintamiseen joissa. Aineiston rasteroinnin eri solukokojen ja pienimpien habitaattilaikkujen rajaamisen vaikutusta ennustettuun elinympäristöön analysoitiin. Hydraulinen malli rasteroitiin kolmeen eri solukokoon, 0,5, 1 ja 2 m. Solukoon vaikutus mallin ennustamaan elinympäristön kokonaispinta-alaan riippui tutkimuspaikasta ja virtaamasta, mutta verrattuna koko tutkimusalueeseen kokoon eri solukokojen vaikutus ennustettuun habitaatin määrään oli pieni. Tulosten pienimpien habitaattilaikkujen rajoittamisen vaikutusta testattiin, sillä kalat tarvitsevat riittävän suuren habitaattialueen selviytyäkseen. Habitaattilaikun kokorajoituksen vaikutus ennustettuun habitaatin kokonaisuuteen riippui tutkimuspaikasta ja käytetystä solukoosta.

Lisäksi elinympäristöjen laatua ja pysyvyyttä analysoitiin tilastollisesti ja visuaalisesti. Eri habitaattisäännöt vaikuttivat merkittävästi ennustettuun habitaatin laajuuteen. Habitaatin soveltuvuus kohdelajille jaettiin optimaalisen ja sopivaan habitaattiin habitaatin laadun visuaalista analysointia varten. Habitaattilaikkujen päällekkäisyyttä eri virtaamisolosuhteissa analysoitiin, jotta voitaisiin paremmin ymmärtää, missä lohikalojen sopivat olosuhteet pysyvät riippumatta jatkuvasti muuttuvista jokiympäristön virtaamaolosuhteista. Tulokset osoittivat, että jokiuoman morfologia vaikuttaa habitaatin levinneisyyteen ja vakauteen. Habitaatin sijainnin siirtyminen tapahtuu yleensä asteittain virtaaman kasvaessa.

Habitaattimallinnuksen menetelmä tuotti hyödyllisen työkalun tulevia elinympäristöanalyysiä varten. Ympäristöolosuhteiden rasteridataa käyttävän elinympäristömallinnuksen menetelmän avulla käyttäjä voi valita erilaisia parametreja, mukaan lukien elinympäristösäännöt, jolloin voidaan tarkastella niiden vaikutusta tuloksiin. Samaa metodologiaa voidaan hyödyntää eri jokiympäristöissä eri lähdetiedoilla ja vaihtoehtoisesti erilaisilla elinympäristön soveltuvuusäännöillä. Osana tätä tutkimusta todettiin, että mallintajan paikallisen ympäristön tuntemus on tärkeää tuloksia tulkittaessa, koska tulokset voivat vaihdella merkittävästi tutkimuspaikan mukaan. Kehitetty metodologia tarjoaa joustavan ja hyödyllisen työkalun kalojen elinympäristöjen arviointiin, jolla on potentiaalisia sovelluksia ennallistamissuunnittelussa ja ympäristönhoidossa, myös säänneltyissä joissa.

Avainsanat: Habitaattianalyysi, ekohydraulinen mallinnus, vesivoima, *Salmo salar*, *Salmo trutta*

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1 Introduction

40 % of the freshwater fish species in Europe are threatened (European parliament, 2021). Humans are altering the freshwater systems in many ways. To mention a few, hydropower production scatters the suitable habitats of fish, and other human activities, such as dredging and pollution, do also harm the riverine ecosystems (Juttila, 1985). Especially salmonids, the fish from Salmonidae family, are in threat if the river is blocked by a dam and they are not able to migrate to the spawning areas and reproduce.

At the same time hydroelectric power is an important part of the energy production in the Nordics. In Finland approximately 19 % (Energiateollisuus ry, n.d.) and in Sweden 35-45 % (Lindholm, 2023) of the energy production is produced by hydropower. Hydropower has many advantages, and it is an essential part of the green transition (U.S. Department of energy, n.d.). It is a renewable source of energy; it does not emit greenhouse gases and has an important role in balancing the energy system with its flexibility. The significance of balancing will increase while the proportion of weather dependent solar and wind production globally is increasing rapidly.

Due to the unique life cycle of salmonid species, they require different microhabitats at different life stages. The interest in this thesis is to develop spatial methods for analyzing dynamic changes in abiotic microhabitat conditions in regulated rivers. Two study sites, river Gullspång in Sweden and river Vuoksi in Finland, have been selected to test the methodology. Both rivers are regulated by hydropower production. In these sites, the summertime habitats of juvenile landlocked brown trout (*Salmo trutta*) and Atlantic salmon (*Salmo salar*) are modelled. The habitats of these populations are influenced by altered hydrology in regulated rivers and their free movement to upstream part of the rivers are constrained by dams.

The populations are endangered or threatened in both sites (Urho et al., 2019, p. 555; Brockmark & Persson, 2021). To mitigate the human effects, many conservation measures are taken to enhance the living condition of these species. For example, the Swedish Agency for Marine and Water Management has set fishing regulations in lake Vänern to conserve the unique population of Gullspång salmon (Brockmark & Persson, 2021). Conservation measures are also made in river Vuoksi, e.g., by building the Imatra City Brook which works as built nature-like spawning and rearing habitat for trout or restoring habitats in the main channel (Koljonen et al., 2022). Successful conservation requires knowledge of both the condition of a

population and its habitat. Population studies of the salmonids are performed for example by electrofishing. To restore and maintain suitable habitat for the population, the abiotic conditions of the environment must be studied.

Hydropower and dams can alter the discharge of rivers which can rapidly change the state of abiotic conditions and therefore fluvial habitats. Consequently, to support the natural lifecycle of salmonids in hydro-regulated rivers it is important to know how the habitats are changing with different discharges (Heggenes et al., 1996). Habitat restoration planning requires information of the environment's current state to support positive environmental measures. Utilizing modern geographic information systems (GIS) together with accurate field data can help understanding the current state of the habitats and also to plan different measures and their impact via habitat modelling (Žagar, 2021). Habitat modelling aims to model the habitat conditions of a species with different environmental variables (Heggenes et al., 1996). For salmon and trout in rivers the most important habitat variables are water depth, flow velocity and bottom substrate (Armstrong et al., 2003).

One important aspect in this thesis is the temporal connectivity and stability of microhabitats in habitat models, since modified flow regimes can alter the availability and suitability of fluvial habitats with consequences for freshwater ecology and especially fish population (Anderson et al., 2006). Connectivity is a measure of the spatial distribution of habitat patches (Carnie et al., 2016). Connectivity is important since organisms are moving among patches to satisfy their needs (Wiens, 2000). More research is needed to understand the effect of habitat spatial distribution at the microhabitat scale (Carnie et al., 2016). For a species to thrive it is important that there is sufficient amount of suitable habitat present in the river system available for all life stages, that they are large enough and connected. The role of habitat size and connectivity is also recognized in the field of habitat restoration (Isaak et al. 2007).

The main objective of this thesis is to define and test a geospatial methodology for modelling microhabitat dynamics in rivers. In this study the river channels are regulated by dams and hydropower production, where discharges are altered by humans. In some regulated rivers the discharges vary frequently even within a day. The sometimes fast varying discharge exposes the fish to strongly changing habitat conditions which requires understanding of the habitat of different species. The same methodology can be applied also to natural, non-altered channels.

Two-dimensional hydraulic model point clouds are used as the source data for the habitat modelling which makes it possible to be utilized in different rivers and for different species and

their life stages. The methodology allows the user to choose which habitat rules to use and multiple modelled discharge conditions can be used as a source data for the modelling. The utilized water depth and flow velocity habitat preference parameters, which form the habitat rules, used in this thesis are decided based on literature.

The functionality of the model is tested on four different habitat suitability rules (two species and their two life stages), study sites, and flow scenarios. The impact of analysis cell size and minimum habitat patch size on the predicted are tested statistically. The cell size is tested to see how the results change based on the decided raster cell size in the point cloud rasterization in beginning of the habitat modelling workflow. Since having large enough patches of habitat is vital for salmonids, the effect of limiting the smallest habitat patches of the results is tested. The spatial distribution, quality, and stability are analyzed based on the habitat model results. The goal is to gain broader knowledge of the survival and vitality of the salmonid populations in dynamic environments, such as regulated rivers. Analyzing microhabitat behavior in dynamic flow conditions provides new information on the impacts of abiotic conditions fish habitat and supports preserving and improving aquatic habitats in regulated rivers.

The research questions are:

1. What is the impact of analysis cell size and minimum habitat patch size on the predicted habitat area?
2. What do the habitat modelling results tell about salmonid habitat quality and connectivity in the two regulated rivers?

1 Fluvial environments

1.1 Physical characteristics of rivers

A river is a naturally downstream flowing waterbody that usually empties into an ocean, lake or another river (Ji, 2017: 307). Rivers are complex, dynamic, and highly diversified. They vary widely by morphological characteristics including river slope, width, and depth. River slope is the elevation difference between two points of the river divided by the river length between the points.

The main hydrological characteristics of rivers are flow rate and velocity, water temperature and sediment transport and contaminants deposition. The river flow can be generally divided into two components, which are base flow and storm flow. Baseflow consists mostly of groundwater, and it sustains river flow also through dry weather periods. Storm flow on the other hand originates from the runoff during or shortly after a precipitation event. Rivers can also gain water from point sources, such as wastewater treatment plant discharges or tributaries to the river. Thus, the source of all flows at some point is precipitation. (Ji, 2017: 307).

The water flowing within a channel is subject to two principal forces: the force of gravity and frictional forces. Overall, the size, shape, roughness of the boundary and bed slope determine the velocity and amount of water a channel is able to carry. Channel velocity and discharge can be observed through cross-sections. Discharge (Q) is a measure of the volume of the water passing through a particular cross-section during one second, e.g., $m^3 s^{-1}$. The water velocity and flow characteristics, however, can vary considerably within a cross-section. Generally, in a straight channel water velocities are greatest in the middle part of the channel and lower closer to the channel bed and margins, whereas in bended rivers the area of maximum velocity, known as thalweg, moves towards the outer bank. At river bends centrifugal forces add fluid pressure on the outer bank and a deficit on the inner bank. That leads to surface water gradient between the inner and outer bank. The channel is deeper on the outer bend, and it has a greater hydraulic head and the water falls to the bottom of the so called pool and then moves up towards to the inner bend. This spiral kind of movement of water downstream is called helicoidal flow path. These patterns of velocity differences can be visualized by isovels, lines of constant velocity (figure 1). (Gilvear & Jefferies, 2017: 493-501)

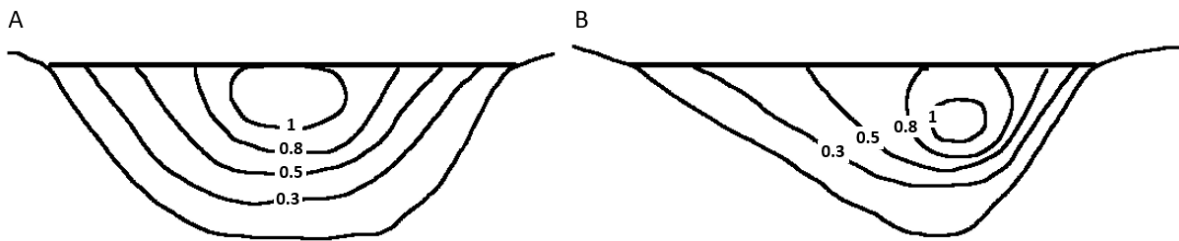


Figure 1. Isovle lines representing the equal velocity (m s^{-1}) at a (A) straight channel and (B) river bend cross-sections. Adapted from Aldefae et al. (2020).

Also, the ecological characteristics, such as nutrient inflows and eutrophication processes vary widely between rivers. Rivers can also change significantly over time not only in response to human activities but also affected by changing climate and hydrologic conditions (Ji, 2017: 307-310).

The longitudinal profile of a river can be split into three zones, which are headwater zone, transfer zone and depositional zone (Ji, 2017: 307). The headwater zone is the area from which water originates within a channel network (Gomi et al., 2002). It is often in steep and mountainous area with rapidly flowing cold water (Ji, 2017: 307-308). The streambeds are usually made of rocks and boulders and sometimes of gravel and sand. The spatial extent of headwater system makes up a major portion of the total catchment area, usually 70–80 % (Gomi et al., 2002). Headwaters are geographically isolated, thus they support genetically isolated species and have an important role in the biodiversity of watersheds.

The headwater zone features vertical erosion and weathering, leading to V-shaped valleys, potholes, waterfalls, rapids and canyons (Ji, 2017: 307), and processes are tightly linked between hillslopes and channels and from terrestrial to aquatic environments (Gomi et al., 2002). The headwater tributaries are an important source of sediment, water, nutrients and organic matters for the downstream systems affecting the material transport within whole watershed system.

As a river continues downstream the surrounding terrain flattens out and the river turns wider, forming the transfer zone (Ji, 2017: 308). It is characterized by wider floodplains and slower flow velocities and the river starts to meander. The transfer zone receives eroded material and nutrients from the headwater zone.

The end of the river, where it flows into an ocean, lake or another river, is called the river mouth (Ji, 2017: 308). The depositional zone is characterized with even lower slope, increased

sediment deposition and broader floodplains, through which the river meanders slowly across a broad nearly flat valley. The sediment carried throughout the river system is mostly deposited creating a large alluvial area. The new land, which forms at the river mouth that usually is formed as a triangular shape, is called delta. In the lower depositional zone and delta the river may divide into different slow-flowing channels. The larger floodplain and slower flow velocities allow also more fluvial vegetation.

As demonstrated above, the movement of sediment in streams is a key process affecting the fluvial environments. Sediment includes particles of all sizes that are derived from rocks or biological material. Sediment transport consists of three main steps: 1) erosion, 2) transport, and 3) deposition. (Ji, 2017: 73). Sediment processes are strongly depended on the flow hydrodynamic conditions and on the sediment properties, such as particle size, shape, density and composition (Ji, 2017: 77; Gilvear & Jefferies, 2017: 501). Sediments are divided to cohesive (e.g. clay) and noncohesive (e.g. sand and gravel) sediments and they have different properties in the sediment processes (Ji, 2017: 85-98). The diagram originally presented by Hjulström (1935) presents the relationships between the size of sediment and the average flow velocity required to erode, transport and deposit it (figure 2). For cohesive sediments, the erosion velocity increases with decreasing grain size, but the critical velocity for deposition depends on the settling velocity. For noncohesive particles the required erosion velocity increases with particle size and the curves follow each other closely. According to the diagram (figure 2), the particles of a size around 0.1 mm (sand) erode at the slowest flow velocity.

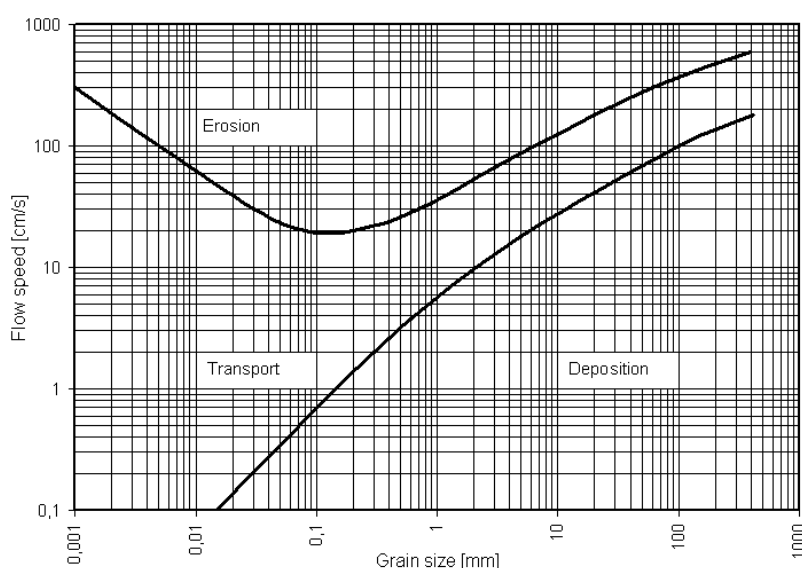


Figure 2. Hjulström diagram, describing the transport, deposition and erosion of sediments in streams in relation to flow velocity and grain size. The scales are logarithmic. (Wikimedia Commons, 2009).

Erosion occurs when the shear stress applied to the sediment bed exceeds a critical value of the shear stress (Ji, 2017: 77). The sediment is transferred to the river system through multiple erosional processes, including surface erosion, rill and gully erosion and landslides (Gilvear & Jefferies, 2017: 494-495). The sediment delivery to the river system occurs often during or following precipitation events, and therefore it is pulsed in nature. In Nordic countries the runoff regime is dominated by snow and ice melt which produce a major peak of streamflow during the late spring due to snow melt, or in in early summer due to glacial ablation. Sediment can be also eroded directly in the river channel, when river banks erode floodplain materials or valley sides.

A sediment particle can be mobilized if the forces applied to it are greater than the resisting forces. In fluvial environments, sediment can either be suspended in a water column or accumulated on the bottom of a waterbody. The movement of suspended sediment is called wash load and the movement along the bed is called bed load. Coarse sediment, such as gravels and cobbles, which are typically eroded from river bank, river bed or hillslopes are dominantly transported as bedload by rolling, hopping or bouncing. Finer sediment particles, such as silt and clay, are usually sourced from soil erosion and river bank erosion, and carried downstream as wash load, suspended in the water. (Gilvear & Jefferies, 2017: 500-501).

Suspended sediment particles in the water column are brought to the bottom by settling (Ji, 2017: 78). Deposition takes place when the transport capacity of the flow is exceeded (Ji, 2017: 73) or when the velocity falls below the critical conditions in bed load movement (Gilvear & Jefferies, 2017: 501). The deposition and accumulation of sediment in a waterbody is called siltation (Ji, 2017: 309-310).

The process of sediment exchange between the sediment bed and water column, deposition and resuspension, is very complex. It is dependent on the water column processes and the sediment properties of the bed (Ji, 2017: 77). If the net erosion and deposition are equal within a river channel, the river bed will sustain at approximately the same elevation (Gilvear & Jefferies, 2017: 501). However, these channels will probably still undergo lateral changes as the river migrates naturally across the floodplain. The size and shape of a river can be transformed even overnight by a single large flood, when strong erosional forces get sediment to transported to different areas than in a steadier flow situation (Gilvear & Jefferies, 2017: 493). The riverbed

material however determines the likelihood of quick alterations in river shape (Gilvear & Jefferies, 2017: 501). Especially bed rock channels are really stable.

1.2 Human induced disturbances

1.2.1 River regulation

River regulation means controlling river water level or the variability of river discharge to meet human needs (Petts, 1999). Rivers are regulated for multiple purposes, such as agricultural irrigation, hydroelectric power generation, flood control and for domestic and industrial water supplies. Today, the regulation can cover entire river basins and large-scale water transfer from wet to dry regions. According to Petts (1999), river regulation can be achieved in four ways, however in many catchments combination of multiple ways may be in use.

Firstly, the river may be regulated by channelization or canalization, which refers to river channel engineering aiming to regulate rivers (Petts, 1999). Rivers have been channeled to desired position usually by regulating channel width so that the water may flow freely without disturbance and concentrating the flow to maintain a single, deep, uniform channel. Channelization and dredging have been performed also for the purpose of navigation and timber floating (Jutila, 1985). For example in Finland, nearly all rivers in the northern and eastern part of the country were dredged either by manpower or bulldozers for timber floating.

The three following regulation types are achieved with some kind of damming of rivers. A dam is a structure is a structure that blocks the flow of a river or other waterways to form a basin and holds water back and usually creates a reservoir (Ji, 2017: 313–314). Usually, dams have structures that control the release of impounded waters. Dams range from small temporary structures constructed of sediment to massive multipurpose structures (The Federal Interagency Stream Restoration Working Group [FIRSWG], 1998). They can have a significant impact on the river system. The extent and impact largely depend on the purpose and the size of the dam. Rivers are dammed for the purpose of, e.g., water supply, flood control, navigation and the generation of hydroelectric power (Ji, 2017: 313–314).

The second type of river regulation is flow regulation achieved by building large dams, which are often located in the headwaters of rivers. Large dams typically alter the hydrology, particularly by regulating discharge. Large dams are designed to regulate the discharge of a river to reduce flood, to store water and to increase flows during the dry season. (Petts, 1999).

Thirdly, many rivers are regulated by a chain of major dams. A chain of dams offers the possibility to optimize the use of river's water resources. The aim of the regulation is often to maximize the production of hydroelectric power. Having more than one dam also increases the ability to control floods and allows the electricity production at more than one site. (Petts, 1999).

Lastly, water levels can be controlled by series of run-of-river structures. They can be weirs that control the water levels, or locks that enable navigation in channels and rivers. Often these smaller structures also include low-head hydroelectric power plants. (Petts, 1999).

When dams are present in rivers, the river can be considered to consist of different reaches separated by the dams. Dams alter not only the hydrodynamic processes of a river, but also they can greatly affect the sediment processes. Dams slow down the natural flow of the river which causes suspended sediment settling below the dams. The release of sediment free water below the dam increases the degradation of the channel bed, clearwater erosion, since sediment is lost from the reach but not replaced. In time, the degradation process moves downstream, and the process can be seen along the whole course of the river below the dam. (Ji, 2017:313-14).

Other types of physical disturbances also affect the river systems on a broader scale. Different land use activities such as flood control, forest management, road building, agricultural tillage, irrigation and urban encroachment may possibly have substantial effects on the morphology and therefore hydrology of a watershed and the stream corridor morphology within it. Also, altering the structure of plant communities and soils can possible effect the infiltration and movement of water and therefore alter the timing and magnitude of runoff events. The modification of stream hydraulics directly affects the system, which can increase the intensity of disturbances caused by floods. (FIRSWG, 1998: ch. 3)

Often, several pollutants and stressors caused by unnatural regulation impact a single river reach (Ji, 2017: 310). For example, dredging of rivers has caused extensive damage in the spawning areas of salmonid fish species and dams typically disconnect river habitats by preventing, e.g., the upstream migration of the migratory fish. After all, growing awareness and expanding scientific research of river ecosystems and the environmental impact of river ecosystems is leading to new, more environmentally sensitive, regulatory approaches, more environmental assessment, and more considered selection of rivers for development (Petts, 1999).

1.2.2 Chemical disturbances

Chemical disturbances caused by different land use practices are present in many rivers (FIRSWG, 1998). Human induced chemical pollution has the potential to disturb natural chemical cycles in streams and degrade the water quality. The pollutants in rivers can flow to lakes and estuaries and impair water qualities largely in waterbodies (Ji, 2017: 309-310). The disturbances can be either from point-sources or nonpoint sources (FIRSWG, 1998). Main sources of chemical disturbances are agriculture, urban activity and mining. Major sources of sediment siltation are runoff from agriculturally and forestry intensive areas as well as urban areas (Ji, 2017: 309-314). Also dams can cause sediment siltation and greatly affect water quality and hydraulic processes. Siltation can cause pollution problems in rivers and affect aquatic habitats. It can suffocate fish eggs and other bottom dwelling organisms. The suspended material also blocks sunlight leading to depressing the growth of aquatic vegetation.

Agriculture is often widespread, nonpoint source of chemical disturbance (FIRSWG, 1998). Cultivation and soil compaction effect soil's capacity to infiltrate water. Surface runoffs are increased and the water holding capacity of agricultural land is decreased. Agricultural practices using pesticides and nutrients generates runoff which is rich in polluted sediment. Nutrients are mainly nitrogen (N) and phosphorus (P), and they can leach into ground water or flow to streams. They are either dissolved to the water or absorbed to soil particles. The excessive levels of N and P can cause eutrophication in rivers, exhausting the dissolved oxygen concentration needed for many fish and plant species (Ji, 2017: 309-310). Pesticides and nutrients are sometimes applied aerially from where they can also drift into stream corridors (FIRSWG, 1998). Also, improper storage and use of animal waste are potential sources of chemical and bacterial pollution.

Both surface water and aquifers are utilized for irrigation causing major changes in the natural hydrology. Soil salinity is a naturally occurring phenomenon especially in floodplains but irrigation can import salts into drainage basins. Irrigation has not only chemical effects, but it has led to the diminishing of ground water supplies in some parts of the world. (FIRSWG, 1998).

Besides agricultural practices, other kinds of development in urban areas can increase erosion, which results in higher sediment loads to rivers. Urban areas have often point-source pollution. Power plant cooling waters discharges can elevate river temperature and have impact on river

ecosystem. Also discharges from waste water treatment plants can contain toxic chemicals and metals. (FIRSWG, 1998).

Mining changes the stream geomorphology and changes the hydrologic conditions. The vegetation removal at the mining site can aggravate the changes. Mining activities often lead to contaminants, such as acid mining drainage (AMD), leaking to waters. AMD is formed from the oxidation of sulfite minerals and its runoff adds sulfide acid to the water and lowers the pH, which can be toxic and kill aquatic life. The poor water quality has many consequences for the species, such as loss of cover, food, or reproduction. (FIRSWG, 1998).

2 Methods for studying fluvial habitats

2.1 LiDAR

Light detection and ranging (LiDAR), commonly known as laser scanning, is an art of active, non-imaging remote sensing (e.g., Hohenthal et al., 2011). It is currently the most accurate method to produce digital elevation models (DEM) or digital terrain models (DTM) (Hohenthal et al., 2011). DEM, is a numerical presentation of the Earth's surface points and DTM is a model that represents the Earth's surface together with other topographic information, such as land cover (Oksanen, 2021).

In LiDAR mapping technology, the sensor transmits laser pulses and precisely measures the time it takes for the laser pulse to travel from the surface back to the sensor and the orientation of the pulse (e.g., Kinzel et al. 2006; Hohenthal et al., 2011). Typically, short laser pulses are emitted at a high frequency (50-400 kHz). Commercial laser scanners typically measure multiple pulse (about 4-5) and that way the scanners are able to separate different objects within the travel of the laser pulse. On a vegetated cover the scanner obtains multiple pulses, where one may assume that the first pulse is from the top of the canopy and the last one from the ground (Andrew and Heritage, 2009). On a flat surface only a single pulse is obtained. The measurements are used together with the information of the position of the aircraft, which is determined with an onboard GPS, and with the inertial measurement unit (IMU) to map the elevation of the ground surface (Kinzel et al. 2006).

Several types of laser scanning methods are used in fluvial studies (Hohenthal et al., 2011). The LiDAR data used on in this thesis is acquired through airborne laser scanning (ALS), where the LiDAR system is mounted in an aircraft. The airborne approach is most suitable when long reaches are being studied. Topography could also be measured with terrestrial laser scanning (TLS) or mobile laser scanning (MLS) (Hohenthal et al., 2011). In TLS laser scanners are mounted on a tripod situated on a riverbank, and they can provide more accurate description of the topography. To tackle some spatial limitations of the static TLS in river environments, boat-based mobile mapping system (BoMMS) can be used, where the mobile laser scanner is mounted on boat. It can map larger spatial areas and give better data coverage of the riverbanks. According to Hohenthal et al. (2011), topographical data from laser scanning surveys have also been increasingly applied for river habitat classification and modelling.

In addition to the topography measurements, aerial LiDAR can be applied for bathymetric mapping purposes with the newest technology. Airborne laser bathymetry (ALB) is a remote sensing system which allows to observe the riverbed from the air using the LiDAR system (Hohenthal et al., 2011). ALB operates similarly to ALS, but the travel time of the return signals and the known speed of light is also calculated to water in addition to air (Hohenthal et al., 2011). According to Szafarczyk & Tós (2023), all modern LiDAR bathymetric sensors can also measure topography. ALB was developed in the late 1960s but the improvements of the GPS in the late 1990's overcame accuracy problems (Hickman & Hogg, 1969). It was originally developed for the purpose of coastal bathymetry mapping (Guenther et al., 2000), but nowadays it is also used in fluvial studies. Also, novel UAV-borne topo-bathymetric laser profiler has been presented by Mandlbürger et al. (2016).

Since objects reflect different wavelengths differently, right wavelengths of the laser beam are used for different surveying purposes. Topographical measurements are acquired with short infrared laser pulses (1064 nm) whereas the bathymetric LiDAR is based on the use of blue-green wavelengths (532 nm), which can better penetrate water than the wavelengths used in topographical LiDAR (e.g., Hildale & Raff, 2008; Kinzel et al., 2013; Szafarczyk & Tós, 2023). Longer wavelengths are absorbed by water whereas shorter would be scattered and absorbed by water-borne particles, decreasing the penetration depth (Wang & Philpot, 2007). Bathymetric scanners differ from topographic scanners also in much greater power, lower frequency of laser pulses, and in lower operation flight altitudes (Szafarczyk & Tós, 2023).

The water depth can be calculated based on the backscatter between water surface and the bottom (Wang & Philpot, 2007). The whole time-history of the LiDAR return signal, the waveform (figure 3), must be recorded in order to detect the surface and bottom backscatters and the distance between them. This waveform contains information about both the change in water transmission with depth and bottom reflectance. Broadly the backscattered pulses can be separated to surface return, water column backscatter, and bottom return. The surface return is the first signal of the waveform and it is usually the strongest backscatter. The water column signal starts as the pulse enters the water, increases until the pulse is entirely within the water and once the pulse is fully submerged into water, it abates towards the bottom. The bottom return is the last signal of the waveform. The amplitude of the bottom reflection contains information on the reflectance of the bottom and that information can be applied also to detect different bottom materials.

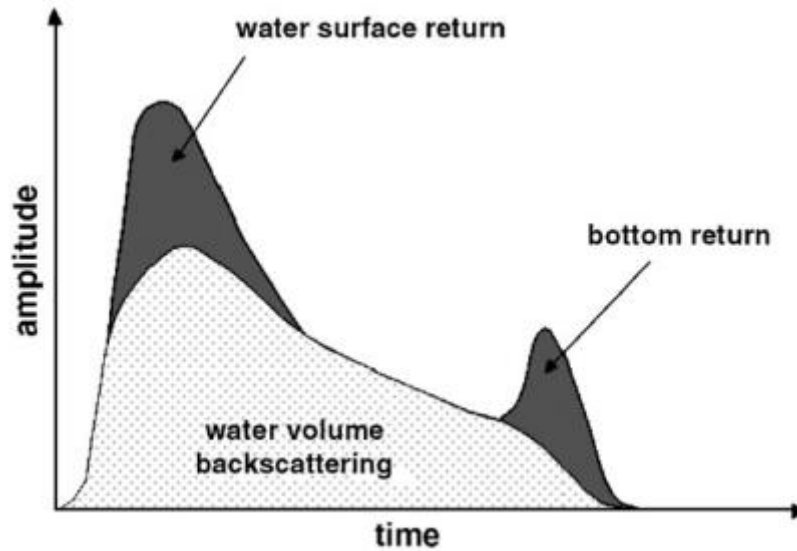


Figure 3. Example of ALB waveform. (Wang & Philpot, 2007).

There are different limitations and advantages in LiDAR bathymetric measurements. The transparency of water and the density of the point cloud significantly affect the amount of detail of detecting underwater objects (Szafarczyk & Tós, 2023). The maximum detectable depth is an important limitation for fluvial remote sensing, especially for LiDAR due to a lack of deep bottom returns (Legleiter & Harrison, 2019). The depth limit of ALB is somewhere around two to three times the Secchi depth, which is however deeper than with passive optical systems (Wang & Philpot, 2007). The penetration depth depends on the laser power. The laser power correlates with the pulse duration in a way that deeper water column penetration means lower measurement frequency (Szafarczyk & Tos, 2023). Also, the large volume of data and high acquisition and processing costs may limit the usage of LiDAR.

Even though ALB has its limitation in fluvial mapping it has also advantages compared to other bathymetric mapping methods. It can map deeper areas than optical imaging, detect changes in substrate material, and surface waves does not cause as much trouble (Hilldale & Raff, 2008). It is especially useful when mapping long reaches and it is a safer method in deep water areas or in rapid discharges. With ALB it is possible to measure non-navigable watersheds and remote locations (Szafarczyk & Toś, 2023). The technology allows fast tracking of large areas and is particularly suitable for the detection of shallow waters, which are hard to reach with traditional boat-based measuring systems. Therefore, other time-consuming ground surveys can be prevented with topo-bathy sensors (Hildale & Raff, 2008). Compared to underwater echo sounding, ALB can map vast and shallow areas in high resolution (Szafarczyk & Toś, 2023).

ALB has filled the gap of shallow water measurements at a depth of 0–2 m which have been difficult to measure with other systems accurately. To sum up, bathymetric and topographic LiDAR systems together can provide a seamless, accurate and dense topo-bathymetric data of ground and shallow waters and thus support change detection analysis.

The recorded range, beam deflection, sensor position and orientation can be converted into a georeferenced three-dimensional (3D) point cloud representing the geometry of surface targets. However, the data need some pre-processing before it can be used in fluvial applications (Hohenthal et al., 2011). The processing of ALB data consist of georeferencing raw data, noise removal, point classification, and refraction correction (Szafarczyk & Toś, 2023). The high spatial resolution compared to traditional survey methods decreases the need for interpolation (Hohenthal et al., 2011).

2.2 MBES

Echo-sounding is an active remote sensing method. Bathymetry has been traditionally measured via shipboard echo sounding (Gao, 2009) and larger scale bathymetric surveying still relies on it (Tomsett & Leyland, 2019). MBES is predominantly used to map the bathymetry, but it has also been used in different applications, such as investigating the bed roughness (Tomsett & Leyland, 2019), flow structures (Best et al., 2010), or supporting underwater habitat mapping (Brown & Blondel, 2009).

The sub-surface MBES instrument emits sound pulses, covering a wide swath on each side of the vessel's track (e.g. Brown & Blondel, 2009; Hughes Clarke, 2018). The sensor consists of orthogonally mounted linear acoustic arrays (Hughes Clarke, 2018). The projector array sends a broad acoustic fan shaped pulse at a known frequency (Wu et al., 2021). The pulse has a narrow along-track opening angle ($\sim 1^\circ$) and a wide across-track angle ($\sim 150^\circ$), known as swath. The hydrophone array records the echoes of the pulse and forms multiple received beams that are much narrower in the across-track direction. The position and depth of the measurement points can be calculated using the incident angle and two-way travel time of each narrow beam. In addition, the water depth is calculated also based on the speed of sound in water, and the distance of the sensor from the water surface must be known in the calculations.

The angle of the instrument can be adjusted and the rate of the areal coverage of the sound pulses is mainly dependent on the angular sector (Hughes Clarke, 2018). A wider sector provides larger coverage but at the same time the projected beam grows nonlinearly with

obliquity. That results in larger footprints and higher bottom detection noise, since as a beam covers a larger area, it detects more signals from the bottom including unwanted noise in addition to the actual signals. Also, integration errors generally grow with increased obliquity. With wider sector the beam spacing is sparser with less footprint overlapping decreasing the resolution. MBES measurements are therefore a compromise between areal extent (angular sector) and desired resolution. Data accuracy is important especially in geomorphological change detection.

Echosounders and the processing software have greatly evolved in the last 30 years (Brown & Blondel, 2009). One key constraint of MBES systems, especially in fluvial environments, is still the inability to measure very shallow waters (Kasvi et al., 2019). Therefore, the ALB measurements with a good coverage in shallow waters can complement the gaps that are unavailable to measure with MBES. Echo-sounding is difficult to apply to sites with limited access.

2.3 Two-dimensional hydraulic model

A hydraulic model is a collection of mathematical equations that give a simple representation of real-world hydraulic system, such as rivers and streams, in a way that the models can be used to support water management and decision making (Ji, 2017: 5). There are three main types of hydraulic models: 1D, 2D, and 3D. An important difference of these models is the spatial resolution. A 1D model predicts the depth and mean vertical velocity at points across the river, whereas a 2D model predicts the depth, magnitude, and direction (x, y) of mean vertical velocity at points. A 3D model is most complex and it predicts the depth and magnitude, direction and vertical distribution (x, y, z) of velocity in a three dimensional space. The minimum data requirements increase with the complexity of the hydraulic model. (Jowett & Duncan, 2012).

The fundamental physics of hydrodynamic models are based on three conservation laws. The laws governing hydrodynamic processes include the conservation of mass, the conservation of energy, and the conservation of momentum (Ji, 2017: 13). Two-dimensional models solve the basic mass conservation equation and two horizontal components of momentum conservation (Steffler & Blackburn, 2002). Two-dimensional model outputs are two velocity components (direction and magnitude) and a depth at each point or node. Vertical velocity distributions and other three-dimensional effects are assumed to be uniform. Two-dimensional models are needed, when lateral variation is an important feature of the river (Ji, 2017: 319).

Generally hydraulic modelling consists of model setup, model calibration, model verification, and model applications (Ji, 2017: 301). As input, a two-dimensional model requires channel bed topography, roughness and transverse eddy viscosity distributions, boundary conditions, and initial flow conditions (Steffler & Blackburn, 2002). A vital part in the model setup is the gathering and processing of the input field data (Ji, 2017: 301). The data measured at the field must be validated and pre-processed before the hydraulic modelling.

Spatial and temporal resolutions are important characteristics of the hydraulic model, and they affect the construction of the model's grid (Ji, 2017: 291). Both resolutions are related to each other, and they should be adjusted in a way that computational stability, accuracy, and efficiency is achieved. The critical factors of spatial resolution are the extent to which spatial gradients occur and the extent to which these variations need to be considered from the model application perspective. The decision of proper spatial resolution is often a tradeoff between model accuracy and study costs. The temporal resolution is determined as the model time steps. It varies widely based on the usage of the model. The simulated time should be long enough to eliminate the model's initial conditions. In addition, the model should have time steps frequently enough to ensure computational stability and convergence. With small time steps the model can be utilized for different applications, such as sediment transport modelling.

The constructed hydraulic model must be calibrated (Ji, 2017: 291). In calibration, the model result is compared against the field data. The model parameters are adjusted in a way that the model results and measured data are within acceptable ranges of accuracy. Technically, the calibrated model is valid only for the particular flow scenario in which the calibration data have been collected. Model calibration is dependent on the quality of measured data and the skills of the modeler. Quality of the model can be improved by utilizing several calibration points with good spatial distribution, and representative flow distribution. A hydraulic models's reliability and accuracy is best in the designated calibration range for the model. Applications outside the range or a model with unknown range is less reliable to use for hydraulic simulations.

After calibration, the model is verified by comparing the results produced by the calibrated model to yet another independent dataset (Ji, 2017: 305). Usually, the model is verified against different flow conditions. Verification is done to find out if the model also works in other conditions, in addition to just the one calibration data. The reliability of the model grows when it is verified also with different scenario. In addition to verification the credibility of the model can be still validated with a third dataset. After calibration, verification, and validation the

model can be seen as ready and the results can be analyzed, and it can be used for further applications, such as fish habitat modelling. However, it is important to notice that in any hydraulic model, the quality of the results will depend on the quality of the topographic and hydrographic fieldwork, and on the calibration, verification, and validation processes (Jowett & Duncan, 2012). Especially in two-dimensional models, the accuracy of the DEM plays a crucial role in the model accuracy.

3 Salmonid habitats

3.1 Atlantic salmon & brown trout

The modelled species in this thesis are Atlantic salmon (*Salmo salar*) (hereafter salmon) and brown trout (*Salmo trutta*) (hereafter trout) (figure 4). Salmon is distributed on the coast of northern Atlantic Sea, and they can be roughly separated to three groups: (1) North American, (2) European, and (3) Baltic sea (NOAA Fisheries, 2023). Brown trout is native to Europe, northern Africa, and western Asia, but today it is distributed worldwide as a result of stockings (Fly Fisherman, 2021). According to Youngson et al. (1993), low rates of hybridization between the two species are common in the wild throughout Europe where the species are sympatric, meaning they co-exists in same streams. In Europe allopatric populations of salmon do not occur under natural conditions, due to the distributional overlap of brown trout (Thorstad et al., 2011). The study sites of this thesis are located in southern Sweden and Finland (see chapter 4). In the Swedish Gullspång study site habitat of both salmon and trout habitats are modelled, whilst in Finland at Vuoksi study site only trout habitats are modelled.



Figure 4. Adult Atlantic salmon (above) (Wikimedia commons, 2008) and brown trout (Wikimedia commons, 2018).

Salmon has undergone historical declines and localized extinctions within its European range (Nieto et al., 2015). Primary causes have been over-fishing, pollution, sedimentation of especially spawning habitats, and damming. Salmon are vulnerable to many stressors and threats, therefore they can be considered as an indicator species telling about the health of its

ecosystem. Salmon can thrive when the river ecosystem is clean and well-connected but when it is not clean or well-connected, its salmon population will usually decline. (NOAA Fisheries, 2023). The population sizes of salmon vary globally among individual rivers, from single individuals to hundreds of thousands. There are also clear differences in the status of individual populations from individual rivers (Nieto et al., 2015). Some populations are extinct or in serious decline, whilst other populations are steady or on the rise benefitting from successful conservation and restoration acts.

In the European Red List of Marine Fishes “salmon was assessed as Vulnerable (VU A2ace) based on levels of exploitation, declining habitat quality, reduced extent of occurrence, and the impacts of pollution, climate change, and introduced taxa” (Nieto et al., 2015: 24). Salmon does not have an assessment in the red list of Sweden even though their amount has declined sharply as a result of the expansion of waterways (Florin & Svensson, 2013). It is seen that the species is not in imminent risk of extinction since the decrease of these fish happened long ago and the stocks are now stable. However, single populations can be threatened, like the salmon population of Gullspång (Brockmark & Persson, 2021).

Brown trout vary greatly in shape, size and colouring depending on their habitat, therefore they were once divided into three sub-species based on their habitat: (1) sea trout (*salmo trutta m. trutta*), (2) lake brown trout (*Salmo trutta m. lacustris*), and (3) the small resident trout of stream (*Salmo trutta m. fario*) (Koli 1998: 81–89; NatureGate, n.d.-b). However, the current thinking is that the brown trout is a single species exhibiting much variation (NatureGate, n.d.-b). Resident and migrating trout can breed with each other (Koli 1998: 81–82). The small resident stream trout are hard to distinguish from young trout preparing to leave their natal stream to migrate to a lake or sea (NatureGate, n.d.-b). The sea and lake migrating trout are fairly similar throughout their lives.

In the European Red List the status of trout is least concern (LC) (European Environment Agency, n.d.). However, similarly to salmon, some populations can thrive while others are threatened. According to the 2019 Red List of Finnish Species brown trout is classified as an endangered species in Finland south of 67N latitude (Urho et al., 2019: 555). There are also multiple causes of threat: construction of waterways, trapping, hunting, fishing, peatland drainage for forestry and peat harvesting, chemical disturbances, random factors, and extreme fluctuations in population size. The status for trout in Sweden is same as for the salmon. It is

not imminent risk of extinction (Florin & Svensson, 2013), but it can be locally protected, like at the study site of Gullspång (Brockmark & Persson, 2021).

Trout and salmon are closely related and share many physiological similarities. Both species have the small adipose fin in front of the tail, which is typical for the species of *salmonidae* family. Also, the anal fin of both species has maximum of 12 rays. Even though the two species are very similar, they can be distinguished by their coloring and other physical properties. Salmon has a narrower “wrist” to the tail and the caudal fin is forked, compared to the square or convex shaped caudal fin of the trout. Teeth vomerine teeth of trout point both left and right while salmon has those in a single straight row. The upper jaw’s maxillary bone of salmon extends back only at the level of the eye, while for brown trout it extends further back. (NatureGate, n.d.-a; NatureGate, n.d.-b).

Trout and salmon parrs may be hard to distinguish from each other, but salmon parr have longer and sharper pectoral fins (NatureGate, n.d.-b). Both species have vertical bars along their sides as parr; salmon has usually 8–10 and trout 10–12 (NatureGate, n.d.-a; NatureGate, n.d.-b). Trout have numerous redd spots surrounded by paler halos and the adipose fin is reddish yellow, whilst salmon have only a few red spots and the adipose fin is grey or black.

In adulthood, sea brown trout are silver in color with a dark back, and there are numerous black spots on the gill cover and sides (NatureGate, n.d.-a; NatureGate, n.d.-b). Compared to salmon, trout have more spots and they are extended lower on the sides, whilst salmon have fewer dots majority of them located above the lateral line. The trout living in lakes may also be silver in color, though they are usually brownish with numerous spots surrounded by paler halos. The coloring of both species darkens for spawning. Salmon tend to have more spots especially at the forebody, whereas the spots on trout are more prominent and cover the entire body. The most significant difference is between the female landlocked salmon, which are nearly black when spawning, and female landlocked trout, with numerous well defined spots. In addition, male salmon develop a kype (Witten & Hall, 2001). The bones and teeth of salmon undergoes drastic changes during the upstream spawning migration and males develop hook-like distal tip to the lower jaw. The purpose of the kype is yet poorly understood, but it could be a feature in males that is attractive to females.

3.2 Life cycle of salmon and trout

The life cycle is similar both for salmon and trout. Salmonids are mostly anadromous, meaning they spend their adult life in sea and return to spawn to freshwater streams (NatureGate, n.d.-a). However, some populations are landlocked and spend their whole life in freshwaters, like the populations studied in this thesis. In streams, the juvenile salmon and trout compete over same resources, but the competition in marine or lake environments has been difficult to determine since the fish exploit a vast scale of habitat (OECD, 2017).

The life cycle of new generation starts when the adult fish migrate to spawn at their natal stream (NatureGate, n.d.-a). The migration happens usually in autumn, however the time of entry of the main spawning migration varies from river to river (OECD, 2017). Adult salmonids use olfactory clues when they start their migration into their natal streams to spawn, thus sufficient water flow is important (HELCOM, 2011). The exact mechanism how the fish find the stream where they hatched is not yet fully understood (Limburg et al., 2001; Hasler, 1971). The fish must reach spawning grounds at the proper time and with sufficient energy reserves to complete their life cycles (Bjornn & Reiser, 1991). The native stocks have often developed behaviors which helps the fish to survive the migration despite the occurrence of temporarily unfavorable conditions. Salmonids usually reserve extra time in their migration and spawning to accommodate delays which can be caused by, e.g., low flows, high turbidities or unsuitable temperatures. Salmon and trout also respond to temperature during their upstream migration. Some stocks that migrate long distances arrive in the spawning areas 1-3 months before they spawn, while stocks with shorter distances may not move to the spawning spots until shortly before spawning. Salmon and trout can jump over barriers many times their size during the upstream migration (Powers & Orsborn, 1985). The jumping abilities of the fish depends on their swimming velocity, the horizontal and vertical distances to be jumped, and the angle to the top of the barrier.

The environmental factors for anadromous salmonids differ greatly between marine and fresh water environments (HELCOM, 2011). The fish have to adapt physiologically to the changes in salinity but also adjust their swimming to the faster and more turbulent current and shallower water. Salmon has observed to feed and spend time in so called holding pools (Bardonnet & Bagliniere, 2000). They offer shelter for the fish during upstream migration.

Atlantic salmon and brown trout usually spawn during the autumn and winter months (Armstrong et al, 2003; HELCOM, 2011). When the environmental conditions are suitable, the

female digs a pitch in the gravel with her tail, called ‘redd’. Redds can consist of multiple nests and be several square meters in size (HELCOM, 2011). Females excavate nests around 20 cm deep in the substrate where they lay the eggs (figure 5), and the male fertilizes the eggs by releasing milt. The number of spawners that can be accommodated in a stream is according to Bjornn & Reiser (1991) a function of the area suitable for spawning (suitable substrate, water depth, and velocity), area required for each redd, suitability of cover for the fish, and behavior of the spawners.

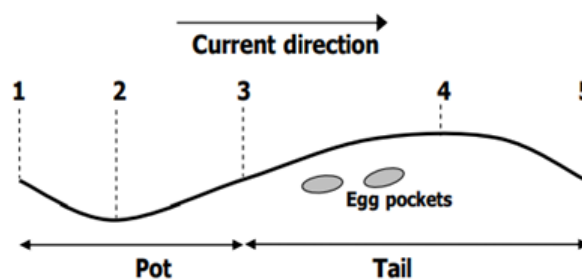


Figure 5. Side-view illustration of salmonid redd. 1 = upstream edge of pot, 2 = deepest point in pot, 3 = border between pot and tail, 4 = highest point in tail, and 5 = downstream edge of tail (Syrjänen et al., 2014).

Eggs incubate in the gravel and the embryos develop within redds for several months (HELCOM, 2011). The embryos hatch and develop into alevins during the following spring. Alevins still remain in the gravel and they feed off their yolk sac attached to their body for several weeks. The yolk sac eventually disappears and the alevins grow into ‘fry’. Frys emerge from the gravel and start feeding plankton from the stream at their hatching site. The period during emergence is a critical period, when mortality can be very high (Armstrong et al., 2003). The juveniles of the first summer after hatching are called young of the year (yoy) or 0+. For most salmon and trout the spreading of the yoy from the redd can be very limited, therefore the early development appears to occur mostly in the habitat in which the fish settle (Egglisshaw & Shackley, 1977; Egglisshaw & Shackley, 1980).

When the offspring leaves their hatching site they are called ‘parrs’ or ‘juvenile’ (HELCOM, 2011). Parrs remain in the natal streams from one year up to more than four years before they start migrating, except the trout populations that are residential to their natal streams (Koli 1998: 81-89; NatureGate, n.d.-b). The salmon of river Gullspång usually spend 1 to 2 years growing in the river before migration (SLU Artdatabanken, 2019). Yoy and parr can be recognized from

their total length. In literature, the usual size used to separate the two age groups are either 7 cm (e.g. Gibson, 1993), 9 cm (e.g. Mäki-Petäys et al., 2002), or 10 cm (e.g. Huusko et al., 2003).

The abundance of juveniles in streams is a function of abundance of newly emerged fry, quantity and quality of suitable habitat, abundance and composition of food, and interaction with other fish, birds and mammals (Bjornn & Reiser, 1991). Density-independent environmental factors set the upper limit on the abundance of juveniles, but the population is held to a certain level together with competition and some types of predation. The carrying capacity and fish production may vary both yearly and seasonally.

The downstream migrating young fish is called smolt. In the spring, the older parr undergoes ‘smoltification’ or ‘smolting’, when they prepare for the migration to a lake, or a transition from fresh water to salt water (HELCOM, 2011; OECD, 2017). Hormones are responsible for the physiological and morphological changes during the smolting. The coloring of the fish often changes to a silvery color. The smolt run is controlled by temperature and the increase in day length (HELCOM, 2011).

The post-molt stage at lake or sea is believed to be high in mortality (HELCOM, 2011). The distance fish travel and the time spent in sea or lake varies greatly (OECD, 2017). The sea migrating salmon of the Baltic Sea catchment stay at the Baltic Sea whereas other European Atlantic populations spread over large areas of the northern Atlantic ocean and even Northeast towards the Barents Sea. The North American populations tend to stay in the western Atlantic. Adult sea trout usually reside in coastal waters within a few hundred kilometers range from their home stream, although some populations migrate longer distance to the open sea (ICES, 2020). Adults remain at the feeding areas from one to a few years until they begin their spawning migration (HELCOM, 2011).

3.3 Habitat

According to Armstrong et al. (2003) “habitat is usually understood to be the range of physical and chemical factors that affect an animal”. The different biotic and abiotic environmental factors interact in complex webs and have direct and indirect effects on the growth and chances of survival of species. For example, the changes in the physical and chemical factors may not have a direct effect on salmonids, but they may have indirect effect to the favor of the prey and therefore negatively affect the survival of salmonids. During population bottlenecks, when stock approaches the carrying capacity of the environment, habitat probably has strongest

effects. Habitat may be fully occupied at some times of the year, e.g., during winter. It is important to distinguish between habitat preference and utilization when interpreting the spatio-temporal patterns of fish (OECD, 2017). Habitat preference refers to the habitat requirements of microhabitat that an individual is looking for, whereas habitat utilization is a compromise (trade-off) between the requirements and how these can be met by availability within the habitat.

Habitat preference curves are plots of the number of organisms found in relation to the habitat variable (e.g., flow velocity or water depth) biased by the availability of the habitat variable. They are often presented as a habitat suitability index (HSI), where suitability of the habitat variable is given a value between 0 and 1 (e.g. Huusko et al. 2003). It can be challenging to quantify the optimum level for each habitat factor (Armstrong et al., 2003). Habitat models use habitat indices to predict the fish abundance or to predict the consequences of habitat manipulation. Since the habitat-fish relationships are extremely complex and dynamic, it must be kept in mind that the models are just simplifications of complex ecological processes and caution should be used when applying them. Fish habitat preference curves are created for stable flow environments. However, they are useful for the purposes of predicting the abundance, classifying river habitat, and impact assessment.

According to Fausch et al. (2002), a continuous view of the river is needed to understand how processes interacting among scales set the context for stream fishes and their habitat. Research must be conducted at appropriate scales for the questions of interest (Wiens, 1989). There are different approaches to scale classification. Labbe & Fausch (2000) divides the habitat to four scales; Watershed (100 km), Segment (10 km), Reach (1 km), and pool (0,1 km). Another way to describe the salmonid habitats is the classification to microhabitat and mesohabitat scales (Boessow et al., 2020). Mesohabitat describes short sections of rivers, which have unique physical characteristics that make them distinct from one another, whereas microhabitat is generally shorter than one channel width and constitutes a relatively homogenous area which can be used by an individual fish. In habitat models, the microhabitat can be performed at a meter resolution (Carnie et al., 2016).

Areas with similar habitat conditions are often considered discrete habitat patches that offer different ecological functions and are used by different species and life stages of those species (Carnie et al. 2016). The connectivity of habitats is a key concept in landscape ecology (Baudry & Merriam, 1988). The concept of connectivity consist of structural and functional habitat

connectivity. Structural habitat connectivity reflects the physical structure of the landscape, which are for example the size, shape and relative location of the habitat patches, or the presence of natural and artificial barriers. The functional connectivity, on the other hand, refers to the way organisms respond to the physical structure of a river as they move between habitats. It explains how the environment facilitates or restricts dispersal or migration of organism between habitat patches (Taylor et al., 1993). Habitat connectivity can be assessed in different spatial and temporal scales.

According to Carnie et al. (2016), habitat connectivity, quality and patch size are important on the microhabitat scale. In this paper the habitats of salmon and trout are observed on a microhabitat scale in two reaches. The cell size used in the model can be as small as 0.5 m. The temporal and spatial connectivity of the habitat patches are analyzed visually. The temporal connectivity in this research lies in the discharge variation over time.

3.4 Habitat requirements of salmon and trout

3.4.1 General factors

The distributions and abundances of trout and salmon are strongly influenced by their habitat (Armstrong et al. 2003). Salmon and trout are closely related to one another and there is abundant evidence that both species prefer similar habitat conditions (Armstrong et al. 2003; OECD, 2017). The more the habitats are overlapping, the more there can be competition over same resources (Huusko et al., 2003). Competition is the negative effect which one organism has upon another by consuming or controlling access to a resource, such as food or space, that is limited in availability (Tilman 1982). Trout have been reported to mostly out compete salmon, they dominate especially in headwaters and creeks, whereas salmon tend to dominate in fast flows and large rivers (Armstrong et al., 2003; Sutela et al. 2020). High swimming skills of salmonids may be valuable, so that the fish are able to react on changing environmental conditions, such as refuging downstream from small creeks during drought periods.

The potential limiting habitat factors may be of a physical (e.g., water temperature, turbidity, substrate type, and flow), chemical (e.g., pH, dissolved oxygen, salinity, and contaminants) or biological (e.g., food availability, competition, predators, and pathogens) in nature (OECD, 2017). The variables affecting the habitat are different in different scales (Bjornn & Reiser, 1991). Temperature, productivity, suitable space, and water quality are examples of variables that regulate the general distribution and abundance of fish within a stream or drainage,

corresponding to the meso-scale habitat factors. At micro-scale, the factors to which fish respond are velocity, depth, substrate, cover, predators, and competitors.

All of the habitat factors must be within suitable ranges for salmonids during the time they use a stream segment; otherwise, no fish will be present and there will be no concern about site-specific factors (Bjornn & Reiser, 1991). Rarely, if ever, all factors are optimum for salmonid production. Often some factors may be near optimum while others are suboptimum but still in a suitable range.

Salmonids in natural streams have evolved to use the diversity of habitats for different life stages and at different seasons (Gibson, 1993). Therefore, one way to understand the habitat requirements of salmon and trout is to consider these at each life stage (HELCOM, 2011). The stream fluvial habitats can be classified generally for spawning, for feeding during the major growing period, and for overwintering. Fish often spawn in limited parts of drainage but the juveniles spread out and occupy most of the areas that are suitable and accessible (Bjornn & Reiser, 1991). Therefore, juveniles have broader habitat criteria than those for spawning sites (Louhi et al., 2008). Winter generally affects the spatial distribution of salmonids in streams. A common criterion to all life stages is the need of refuge to hide from predators (HELCOM, 2011).

The results of salmon and trout habitat preferences have a great variation within the results (Armstrong et al., 2003). In the review Armstrong et al. (2003) identifies four factors that can explain the variation. Fish may be genetically adapted to local habitats. Salmon and trout also tolerate a wide range of habitat conditions. Therefore, the habitats in the study regions affect the results of a habitat study. Also, the density of the population has an effect on the use of habitat. At low densities the fish tend to use the best habitat, whereas at high densities with more competition, fish may have to use sub-optimal habitat more often. In nature the fish also choose the habitat based on combination of variables, not by independent variable.

River regulation has often severe impacts on salmon populations (Thorstad et al, 2021). The changes caused by damming may alter the extent of wetted area and thermal regimes in rivers, which may alter fish physiology, growth and timing of the life cycle events. Migration barriers, such as hydropower dams and weirs, can affect the distribution both of juveniles and adult spawners in the river, as well as increase the mortality of downstream migrants depending on the turbine type. Also, studies show increased trout smolt predation in reservoirs compared to natural lakes, probably due to the changed physical environment and introduced predators, such

as pike and pikeperch (Jepsen et al., 2000). As a response removing such migratory barriers or constructing and improving road crossings and fishways would improve the connectivity and free movement of fish to the varied habitats salmonids need to survive. The removal of barriers often facilitates increased production of salmon juveniles, by creating rearing habitats with faster flow (Thorstad et al, 2021).

In this thesis, the analysis is limited to the summertime juvenile habitat of salmon and trout in terms of abiotic factors flow velocity and water depth criteria. These habitat characteristics and requirements are described in the following chapter.

3.4.2 Summertime juvenile microhabitat

The juvenile habitat in streams can be broken down by different age groups (e.g. Armstrong et al., 2003; Huusko et al., 2003). Here, we separate the habitat requirements of juvenile salmon and trout, according to the year of age of the juvenile, to nursery and rearing habitats. Referring to Armstrong et al. (2003), nursery habitat is the area used during the first summer after hatching (0+ or yoy) and after the summer parr move to rearing habitat to grow (1+ 2+).

Young of the year salmon are most common in shallow pebbly riffles with broken water surface (Gibson, 1993). The preferred depth increases with body size and larger salmon parr prefers deeper (>20 cm) riffles. Deep habitats (>1 m depth) of large rivers, which have not been traditionally considered in salmon production estimations, are showed to be important for juvenile salmon (Linnansaari et al., 2010). The previous habitat studies have typically reported the habitat use in smaller nursery streams, but juvenile salmon, both fry and parr, have been identified using habitats deeper than 1 m in large rivers. Therefore, Linnansaari et al. (2010) concludes that the use of suitability curves examined from shallow nursery streams may lead to significantly bias interpretation of habitat suitability studies in deep, large rivers. The deep habitats have been proven to be used throughout the summer season indicating these habitats provide steady supply of both shelter and food necessary for juvenile salmon. Juvenile salmon can also use deep habitats in fast flowing water if they hold their positions at sheltered bottom locations and their energetic costs are minimized. The salmon in deep habitats remained mostly near to the bottom substratum and made only short bursts to capture prey in the study of Linnansaari et.al. (2010) in large Finnish rivers.

Sympatric juvenile salmon and trout compete over critical resources, such as feeding places, which leads to the segregation of their used habitat in rivers and streams (Berg et al., 2013;

Heggenes et al., 1999). Juvenile trout tend to mostly hold positions in slow-flowing areas close to the riverbank (Heggberget, 1991). Salmon are found in deeper areas at longer distances from the riverbank and at places with swifter currents closer to the bottom of the river (e.g., Heggberget, 1991; Linnansaari, 2003; Linnansaari et al., 2010; Bremset & Heggenes, 2001). Since young trout grow faster than salmon, it is likely that trout hold a stronger dominance in the wild (Gibson, 1993).

According to Lahti (2009: 232) in the two-dimensional modelling of aquatic habitats, the selection of habitat preference curves and the density of field measurements were found to have the greatest effect on results. Since there are no detailed habitat studies for juvenile trout and salmon from either study site available, the habitat preferences for this study are combination of different habitat curves presented in salmon and trout habitat studies. Common patterns and boundary values are identified, and the preference curves are carefully decided. Due to the findings of deep habitat use by salmon (Linnansaari et al., 2010), the habitat suitability criteria chosen for this thesis are weighted towards deeper values found in the literature. To simplify the habitat criteria, the velocity and depth values are classified into two classes based on their suitability for the life stage of a species, which are suitable, and optimal (tables 1–2).

The curves used to define the trout habitat are based on the studies from Heggenes & Saltveit (1990), Armstrong et al. (2003), and Huusko et al. (2003) (table 1). In these studies, the velocity preferences for 0+ life stage varies from a minimum of 0 cm/s to a maximum of 60 cm/s and for 1+ 2+ life stage from 0-70 cm/s. The depth preferences vary between 5–40 cm for 0+ trout and 5–120 cm for 1+ 2+ trout.

For salmon, in addition to the three studies (Heggenes & Saltveit, 1990; Armstrong et al., 2003; Huusko et al., 2003), also the studies from Heggenes (1990), and Mäki-Petäys et al. (2000), are used to compose the habitat suitability preferences (table 2). In these studies, the velocity preferences for 0+ life stage varies from a minimum of 5 cm/s to a maximum of 100 cm/s and for 1+ 2+ life stage from 5-80 cm/s. The depth preferences vary between 5–100 cm for 0+ trout and 20–70 cm for 1+ 2+ trout.

Table 1. The habitat preferences for juvenile brown trout in terms of mean column velocity and water depth. Combined from multiple studies (Heggenes & Saltveit, 1990; Armstrong et al., 2013; Huusko et al., 2003).

Life stage	Preference	Mean column velocity (cm/s)	Depth (cm)
yoy / 0+	suitable	0–50	5–40
	optimal	10–30	20–30
1+ 2+	suitable	10–70	20–70
	optimal	30–50	40–50

Table 2. The habitat preferences for juvenile Atlantic salmon in terms of mean column velocity and water depth. Combined from multiple studies (Heggenes & Saltveit, 1990; Heggenes, 1990; Mäki-Petäys et al., 2000; Armstrong et al., 2003; Huusko et al., 2003).

Life stage	Preference	Mean column velocity (cm/s)	Depth (cm)
yoy / 0+	suitable	5–75	15–60
	optimal	30–50	30–40
1+ 2+	suitable	10–70	20–70
	optimal	20–60	30–50

4 Study sites

4.1 River Gullspång

The river Gullspång (Gullspångsälven) (58°59' N, 14°7' E) in Västra Götaland County, Southern Sweden, is part of the largest watershed in Sweden, Göta älv watershed (figure 6) (Swedish Meteorological and Hydrological Institute, 2023). The river itself is 8 km long and drains from lake Skagern to lake Vänern. Gullspång is the second largest river entering Vänern (Piccolo et al., 2012).

The river has been regulated for hydroelectric power production since the completion of the Gullspång hydropower plant in 1906 (Fortum, 2023). According to the latest environmental verdict, the discharge is regulated on a weekly basis between April 20 and August 19 and the rest of the year short term regulation is allowed (Väneborgs Tingsrätt Miljödomstolen, 2005). The hydropower plant has two outlets feeding water to river Gullspång. Water is flowing from the spillway to Gullspång rapids, which create an important habitat for salmon and trout, and the water through the hydropower turbines is flowing out from the southern, man-made channel. The discharge varies between the minimum of 9 m³/s and the maximum production capacity of 230 m³/s (Watz et al., 2023), from which ca. 3 m³/s is diverted through the spillways to the Gullspång rapids (Gullspångsforsen) (Väneborgs Tingsrätt Miljödomstolen, 2005).

Ca. 5,5 km downstream from the dam, the river divides into two channels that flow into lake Vänern (figure 6). There is a built regulating dam (“divergeringsdamm” in Swedish), which lets water to flow towards north to a diversion channel during high flows. The purpose of the dam is to stabilize the discharge variation in the lower main channel in a way that water flows over the dam when the discharge exceeds 9 m³/s. At the maximum flow situation about 154 m³/s of water flow through the side channel to Vänern (Väneborgs Tingsrätt Miljödomstolen, 2005), and around 80 m³/s flows through the main channel (Watz et al., 2023). In the lower main channel there are two Årås rapids, Lilla Åråsforsen and Stora Åråsforsen, which are important habitats for salmon and trout (Piccolo et al., 2012).

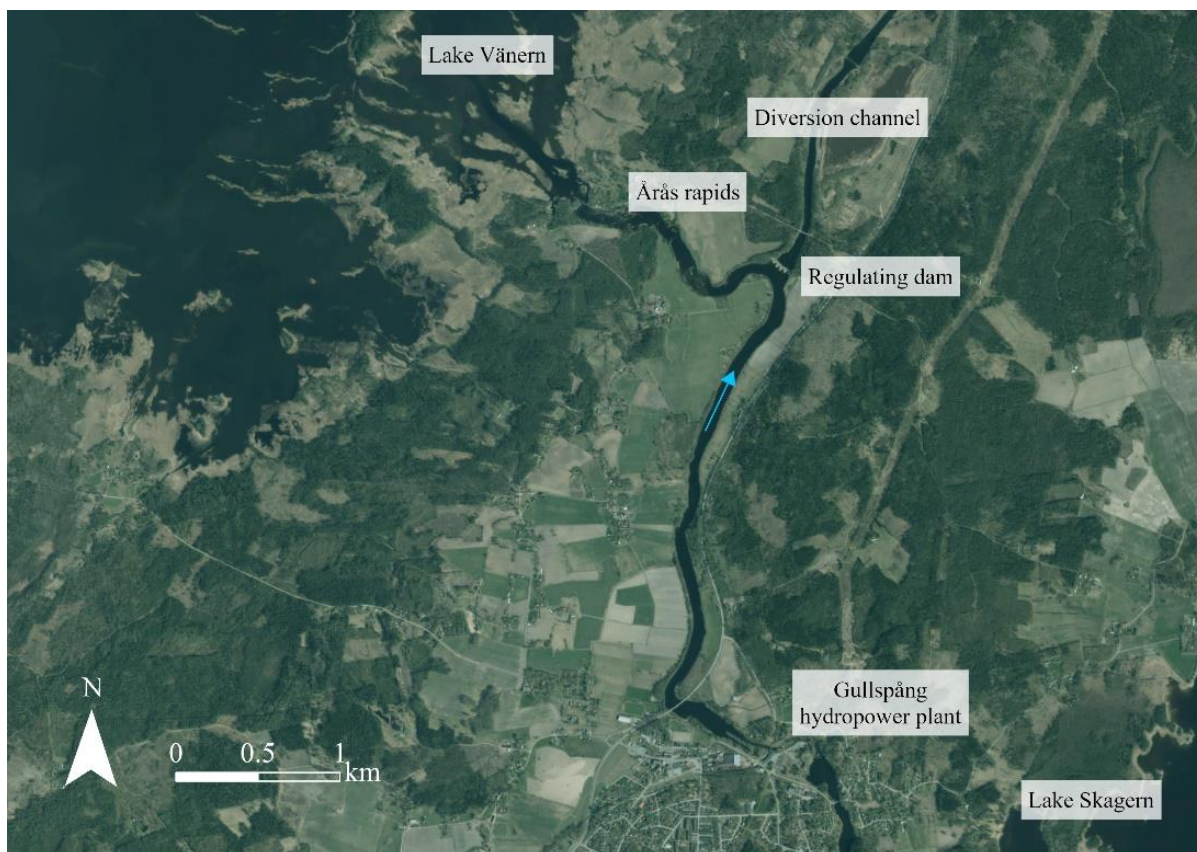


Figure 6. River Gullspång flows from lake Skagern to lake Vänern. Gullspång hydropower plant at the upstream regulates the flow. Part of the discharge flows over a regulating dam towards the diversion channel and the main channel flows towards west, where the Årås rapids are located. (Base map: Metria Maps Orthophoto, 2019).

The habitats of landlocked salmon and trout population in river Gullspång are studied in this thesis. The salmon and trout populations of Gullspång are the only wild migratory fish populations in Vänern that reproduce naturally. The three rapids in the river Gullspång constitute the main spawning and rearing habitats for salmon. The recent restoring efforts in the lower parts of the river for spawning and rearing have resulted in both salmon and trout redds sights (Christensen, 2009; Syrjänen & Norrgård, 2021).

The study area used in this thesis covers the Lilla and Stora Åråsforsen rapids in the lower part of the river (figure 7). The reach is ca. 1400 m long and the width is ca. 65–160 m. Its total size is ca. 12,7 ha. The land cover around the reach is mostly agricultural with forest patches and few buildings.

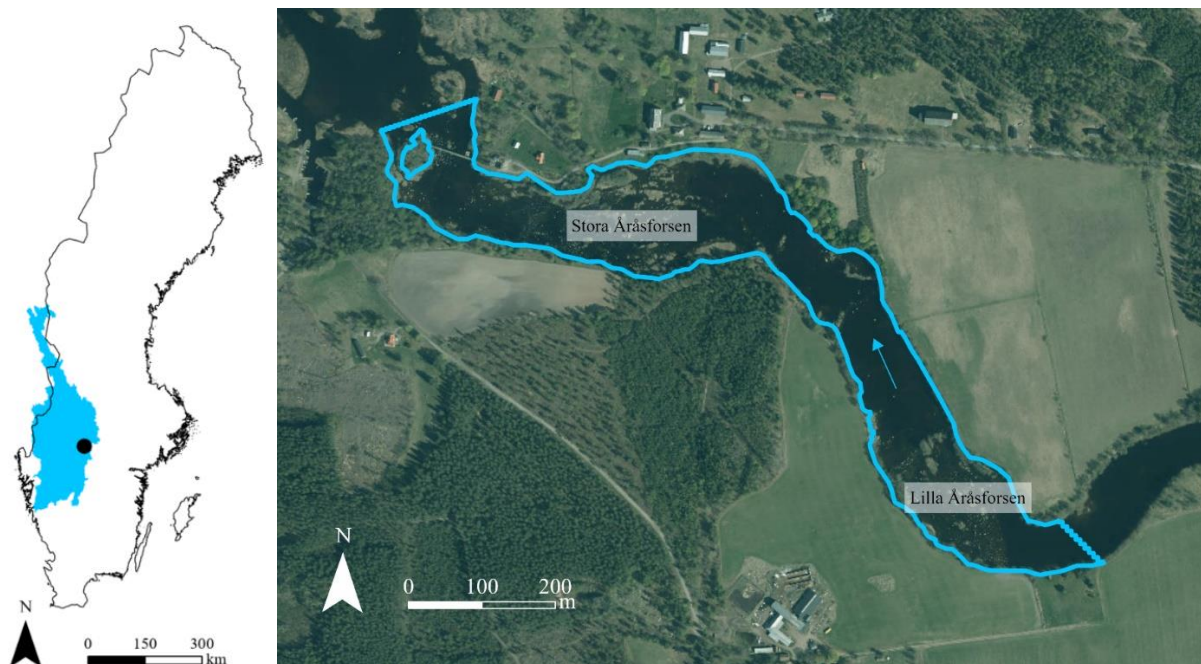


Figure 7. River Gullspång is in Southern Sweden in the Göta Älv watershed (left). Two rapids, Lilla and Stora Åråsforsten, are within the study area boundaries. Water flows from Lilla Åråsforsten towards Stora Åråsforsten and flows to lake Vänern. (Base map: Metria Maps Orthophoto, 2019).

4.2 River Vuoksi

River Vuoksi is located in the Southwestern Finland (figure 8). It drains from the lake Saimaa, the largest lake of Finland, to the lake Ladoga in Russia, which is the largest lake of Europe that is located entirely within Europe. The river is 153 kilometers long, of which only ca. 15 kilometers flows within Finland. The average natural discharge is considered to be approximately 600 m³/s (Korjonen-Kuusipuro, 2017) (figure 9).

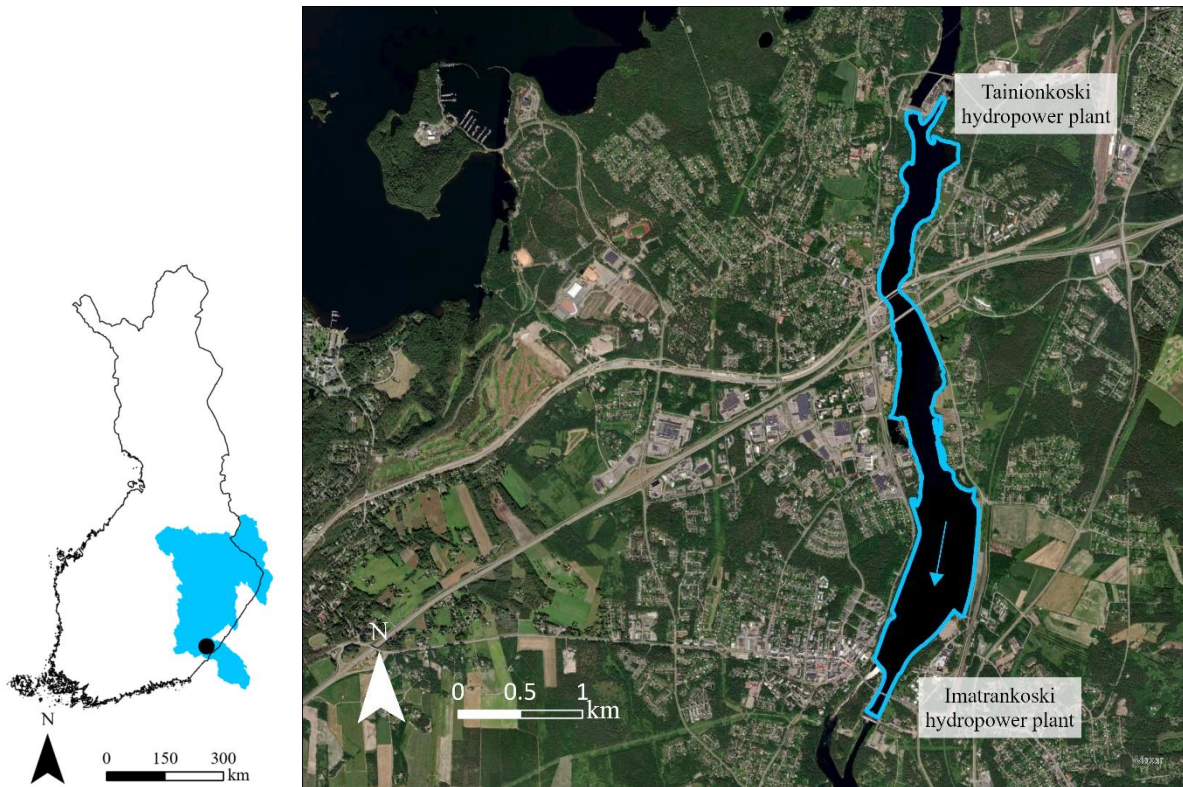


Figure 8. River Vuoksi study site is located between Tainionkoski and Imatrankoski hydropower plants in Imatra, Southeastern Finland (left). The study area is the main channel between Tainionkoski and Imatrankoski hydropower plants. The river flows from lake Saimaa from north towards south. (Base map: Esri World Imagery, 2021).

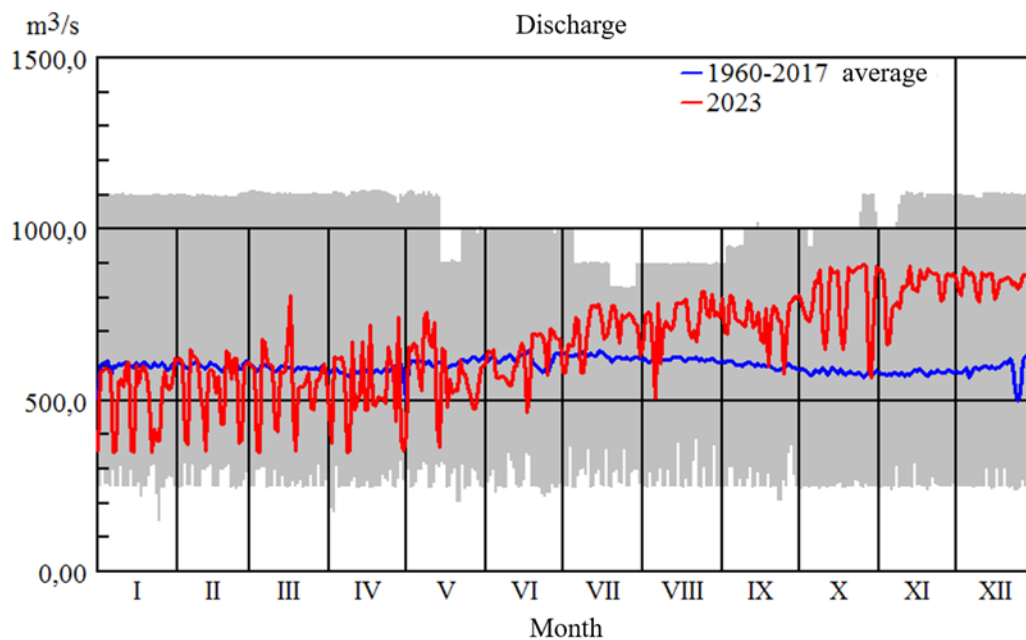


Figure 9. Vuoksi discharge average 1960-2017 and daily values 01.01.-23.10.2023 (red line). The grey area presents the daily range of variation in the 1960-2017 period. (Finnish Environment Institute, 2024).

There are two hydropower plants in the Finnish part of the river (figure 8). The Tainionkoski power plant, completed in 1949, is located 1,5 km from lake Saimaa, the starting point of river Vuoksi (Fortum, n.d.). 4,8 km downstream from Tainionkoski is the next hydropower plant, Imatrankoski, completed in 1929, which is the largest hydropower plant in Finland. On the Russian side of Vuoksi, there are two more power plants: Svetogorsk and Lesogorsk as well as remaining free flowing rapids (Korjonen-Kuusipuro, 2017).

The regulatory authority for the power plants in Finland is the Southeast Finland's Centre for Economic Development, Transport and the Environment (Kaakkois-Suomen ELY-keskus) (Fortum, n.d.). Tainionkoski is the first hydropower plant in Vuoksi, which regulates the water level of lake Saimaa, and the regulation decisions are made by the regulatory authority. The regulation follows legal decrees and long-term natural averages. The 1960-2017 average is 609 m³/s (Finnish Environment Institute, 2024). In normal circumstances, the water level of lake Saimaa and the discharge of river Vuoksi is kept normal when possible (Asetus Neuvostoliiton kanssa..., 1991). The water level is considered to be normal when the water level is within 50 cm from the long-term average water level. The discharge may be altered from the normal levels only if heavy floods or droughts are expected. The water level between Tainionkoski and Imatrankoski power plants are pretty much stable since the two power plants are operated simultaneously, with same discharge flowing either through the turbines or flood gateways.

Today, trout are known to breed in some parts of the main channel, but the stocks are mostly maintained by stocking (Menna et al., 2022). There have been also observations of salmon that have an adipose fin, which indicates that salmon could also breed in river Vuoksi, or they could be also downstream migrating individuals from lake Saimaa. Since there is no certainty of breeding population in Vuoksi main channel, only trout habitats of Vuoksi will be studied in this paper.

The study area of this thesis covers the 5 km long reach between the Tainionkoski and Imatrankoski power plants (figure 8). The widest part of the channel is more than 500 meters wide, and it is at its narrowest in the channel above the Imatrankoski power plant, at ca. 85 m. The total study area is ca. 151 ha. It is located in the city of Imatra, which has a population of approximately 25 000 people. The land use around the reach is mostly urban.

5 Materials & Methods

5.1 Materials

The source materials for the analysis were outputs of two-dimensional hydraulic models which had been processed by Fortum Power and Heat Oy. The modelling resulted in point clouds describing water depth and velocity data of the studied rivers (figure 10 & 11). The file types were text files containing the x-coordinate, y-coordinate and a z-value representing either the water depth or the water velocity. Therefore, there were two files for each flow scenario; flow velocity and water depth. The modelling had been conducted in MIKE 21 software.

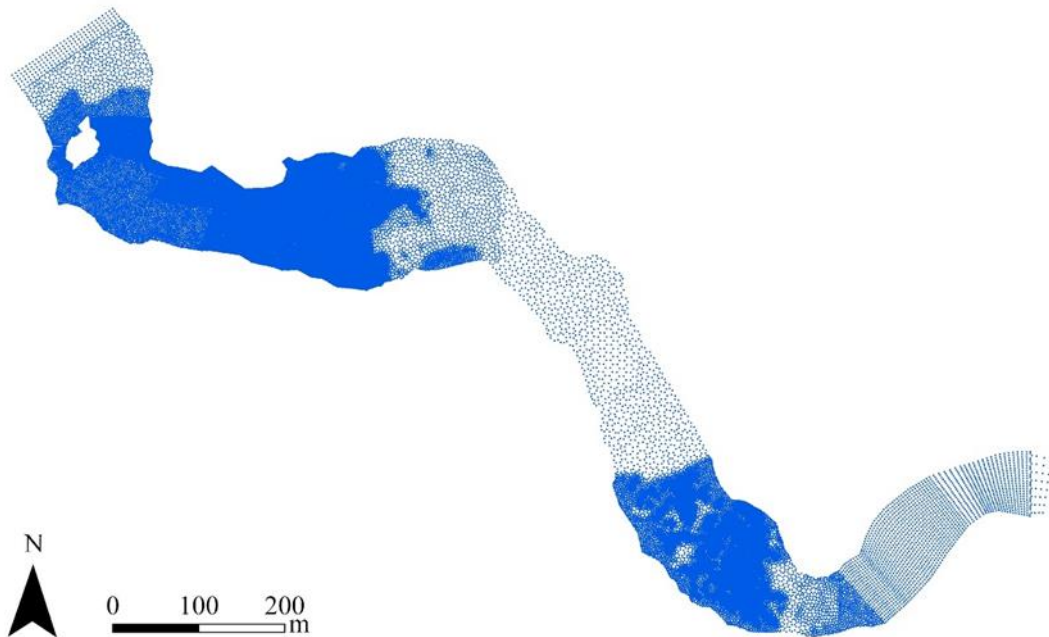


Figure 10. Hydraulic model output point cloud from Gullspång study site. The points represent the two-dimensional hydraulic model mesh, where each point has a flow velocity (m/s) and water depth (m) value.

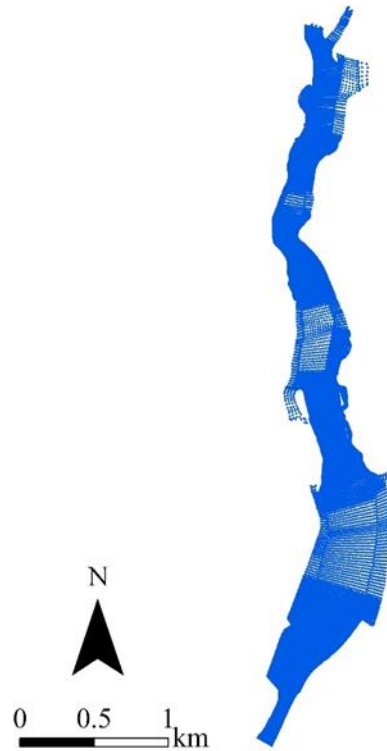


Figure 11. Hydraulic model output point cloud from Vuoksi study site. The points represent the two-dimensional hydraulic model mesh, where each point has a flow velocity (m/s) and water depth (m) value.

The hydraulic models for the two study sites have been created by Fortum based on topographic and bathymetric field measurements acquired with remote sensing methods: light detecting and ranging (LiDAR) and multi beam echo sounding (MBES) (figure 12). The topographic and bathymetric measurements have been processed by Fortum to a uniform digital elevation model (DEM).

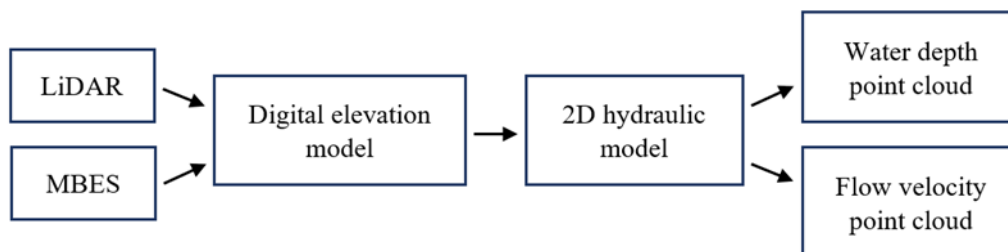


Figure 12. The source data for this study were water depth and flow velocity point clouds supplied by Fortum. In both study sites, they were outputs of a two-dimensional hydraulic model which had been constructed from digital elevation model created from LiDAR and MBES field measurements.

In river Vuoksi, the elevation and bathymetric data were collected for Fortum in 2020 and in river Gullspång in 2021. In both rivers the measurements were conducted by Arctia Meritaito Oy. The aerial LiDAR had been collected with Chiroptera 4X bathymetric LiDAR system manufactured by Leica. The system had been installed to an aircraft and it comprises a digital camera and two sensors: DragonEye II Topographic LiDAR, and Chiroptera II Shallow Water Bathymetric LiDAR.

Since the bathymetric LiDAR is not able to penetrate the bottom of the river in deeper areas and areas with white water, the aerial measurements were supplemented with MBES, surveyed with 400 kHz frequency. The system was placed to a boat in the way that the scan lines were perpendicular to the water surface in deeper areas, but in shallower areas the angle of the system was tilted in order to get data also from the areas where it was too shallow for the vessel to operate.

The field measurements had coordinates allowing the data to be used in GIS software. National coordinate and height systems were used in data processing to get accurate results. The field measurement from Finland were processed in ETRS-TM35FIN coordinate system and N2000 height system, whereas the field measurements from Sweden were in SWEREF 99 TM coordinate system and RH2000 height system.

5.2 Methods

For this study, I used the hydraulic model which had been processed by Fortum as the source data. The point cloud must be pre-processed in a way that it can be used for the habitat modelling. The point cloud data was rasterized. To test how different raster cell sizes effect the result, the data was interpolated and rasterized with three different cell sizes, 0.5, 1 and 2 meters. The flow velocity and water depth layers were calculated with habitat suitability values based on the habitat rules. The corresponding cells of depth and velocity suitability raster layers were multiplied to generate a layer which represents the habitat suitability, that takes into account the suitability of both variables. The outputs were processed to polygons for further analysis. The amount of habitat and the effect of minimum patch sizes were analyzed statistically. Habitat quality and connectivity were done by visual map analysis. The results present the spatio-temporal connectivity of habitat patches. All analysis were performed for the four habitat rules, one rule for each species and age group.

Raster and vector data processing and analyzing were done in ArcGIS Pro 3.1. software. ArcGIS Pro is a full-featured professional desktop GIS application, produced by Esri Inc. (Esri, 2023c).

5.2.1 Creating depth and flow velocity surfaces

To perform cell-based analysis, the point clouds containing depth and velocity information were rasterized. To compare the results between different raster sizes, the points were rasterized in three different cell sizes: 0.5, 1 and 2 m. Rather small cell sizes were chosen, since I was analyzing microhabitats that are generally in this size range.

To create a uniform surface and fill any gaps in the data, the layers were rasterized and interpolated. The interpolation was performed with inverse distance weighting (IDW) method, which is available in the ArcGIS Pro software. The method determines cell values using a linearly weighted combination of a set of sample points, where the weight is a function of inverse distance (Esri, 2023b). In this method the sampled points closer to the predicted points have more on value given to the predicted cell than the sample points farther apart (Shepard, 1968; Philip & Watson, 1982).

In IDW the user can define two parameters. The power parameter is a positive real number. It controls the significance of known points on the interpolated values based on their distance from the output point. I used the ArcGIS Pro default value 2. The number of points used for interpolation is an adjustable parameter. Points far away may have poor or no spatial correlation, therefore only closer input points were used in the calculation. In this thesis, I used three closest points in the interpolation, thus taking into account only the closest points. Since the number of points is used in the calculation of the value for interpolated cell, the search radius distance varies for each interpolated cell. The search radius depends on the density of the measured points near the interpolated cell. Another method would be to use a constant search radius which requires a neighborhood distance and a minimum number of points.

The interpolation method can in some areas also create water depth and velocity values for areas that are known to be dry land. That can occur in islands and peninsulas, where the search radius crosses the shoreline. Therefore, the output layers were clipped with the actual study area (figure 13). The polygon was created following the outer boundaries of the hydraulic model output extent. Also, areas at the upstream and downstream of the study areas were clipped, since they were mostly created to stabilize the hydraulic model. Those areas have a poor spatial

resolution which would demand a lot of interpolation thus they do not present the velocity and depth conditions as accurately.

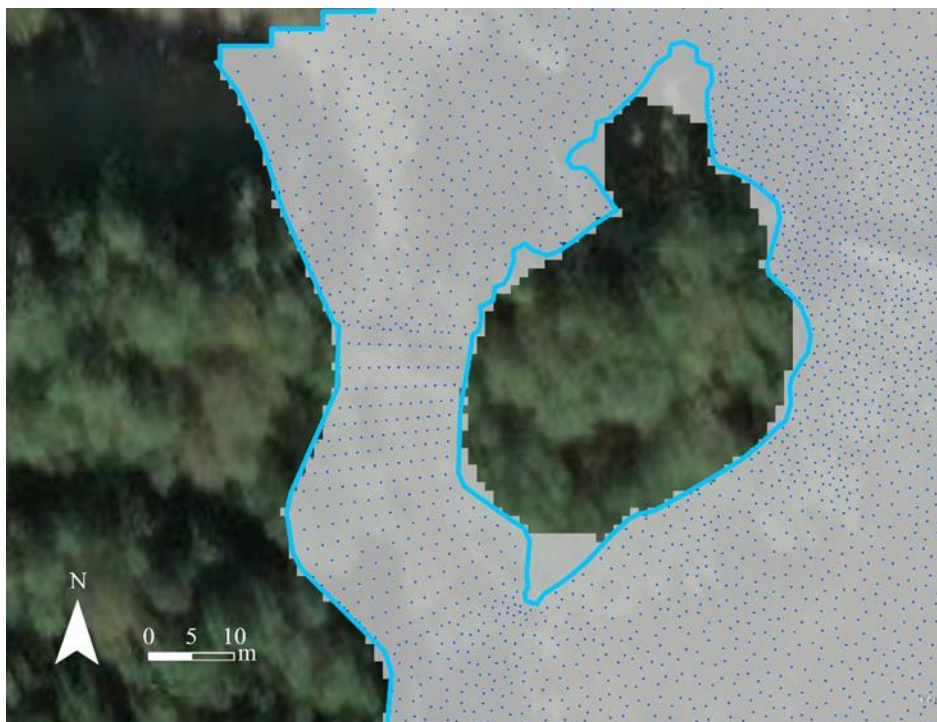


Figure 13. Interpolation can create unwanted values across the shoreline. In this case, the interpolated raster layer (gray) covers part of an island in river Gullspång, even though the hydraulic model point cloud (blue points) does not cover the location. The raster outputs were clipped with the extent of the hydraulic model point cloud, and the actual study area is formed (blue line). (Base map: Metria Maps Orthophoto, 2019).

5.2.2 Habitat modelling

After the flow velocity and water depth layers were converted to raster layers, habitat modelling can be performed. Habitat modelling aims to predict habitat distribution of a species with different environmental variables (e.g., Heggenes et al., 1996). There are four main steps in habitat modelling: 1) determine and prepare the habitat suitability criteria data, 2) transform the values of each criterion to a common suitability scale (habitat rule), 3) weight criteria relative to one another and combine them to create a suitability map, and 4) locate the suitable areas (Esri, 2023a). The habitat modelling in this paper follows these four general steps (figure 14).

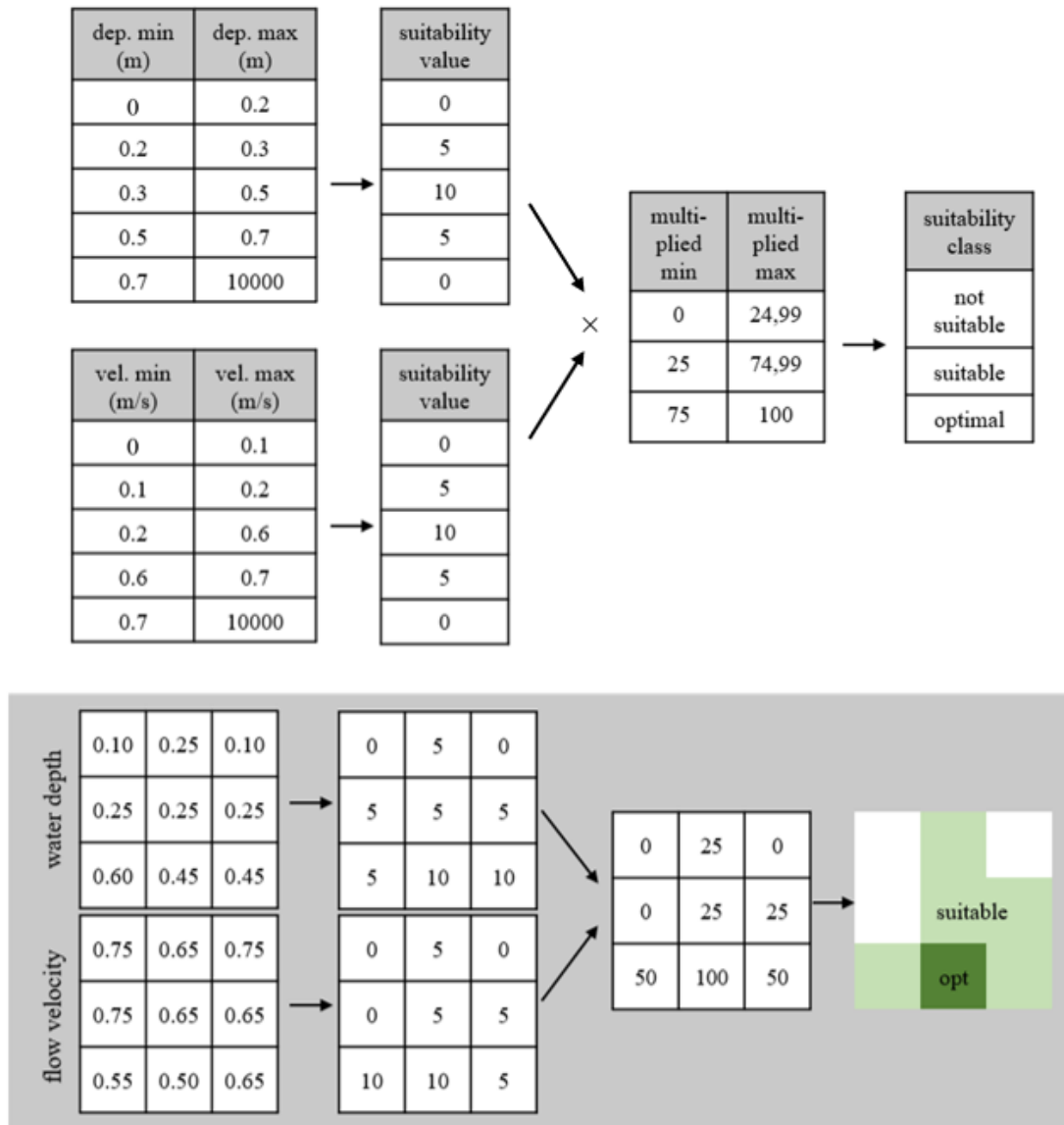


Figure 14. Flow chart of the habitat modelling procedure. Example workflow with Atlantic salmon parr (1+ 2+) habitat suitability rule. The output of the model is a polygon layer representing the suitable and optimal habitat patches.

Firstly, the habitat suitability criteria were defined for the two examined fish species of different ages. The age groups were young of the year (0+) and parr (1+ 2+). The habitat suitability parameters for juvenile salmon and trout presented in chapter 3.6.2 (tables 1–2) were utilized. The interpolated water depth and flow velocity raster layers will be reclassified and assigned habitat suitability values from 0 to 10 based on the suitability functions, where 0 is not suitable, 5 is suitable and 10 an optimal habitat (figures 15–16). The habitat suitability criteria and classification are referred as ‘habitat rules’ in this thesis. In total four habitat rules are modelled, one for both species and both life stages (figures 15–16).

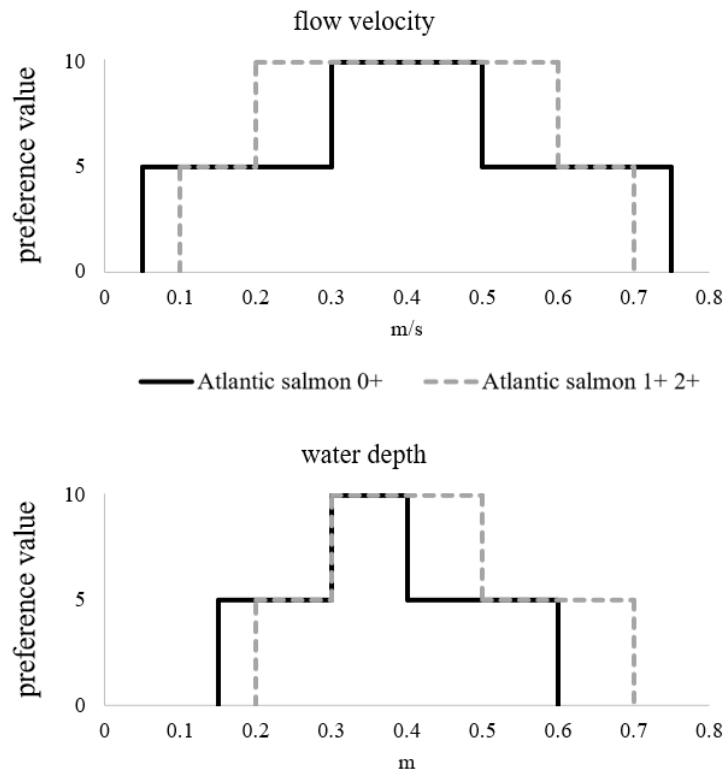


Figure 15. Habitat suitability rules for Atlantic salmon individuals of young of the year (0+) and parr (1+2+) age groups used for water depth and flow velocity variables. Values are derived from tables 1 and 2.

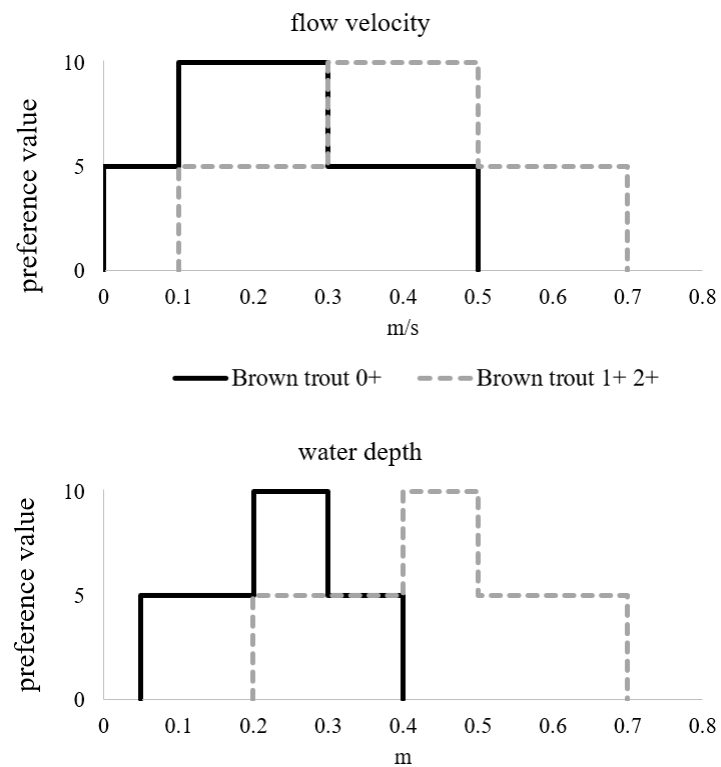


Figure 16. Habitat suitability values for Brown trout individuals of young of the year (0+) and parr (1+2+) age groups used for water depth and flow velocity variables. Values are derived from tables 1 and 2.

Next, the values of each criterion for water depth and flow velocity values of each five discharge conditions in both study sites were reclassified to habitat suitability values 0, 5 or 10 using the habitat suitability criteria, separately for each species and age group (figure 14). As a result, new flow velocity and water depth raster layers were created with the suitability values. To generate a raster layer which combines the habitat suitability of both two parameters, the corresponding cells of depth and velocity raster layer values (0, 5 or 10) were multiplied. The output represents the habitat suitability, that takes into account the suitability of both variables. The habitat suitability raster has values of 0, 25, 50 or 100, with value 100 indicating optimal water depth and flow velocity conditions for the fish species and age group in question. This process (figure 14) was performed for each species and life stages at each discharge condition selected for this study.

Based on the reclassified raster layer a new polygon layer is created, where the suitability numbers were given names by a set of rules (figure 14). If the cell value is 25 or 50 the polygon is given a value 'suitable', and if the cell value is 100, the polygon is given a value 'optimal'. The cells which had a value of 0 were not converted to the polygon layer since they are not suitable habitat and were not considered in further analyses. The cells of the same suitability class and connected to each other from their sides or corners form a habitat 'patch'. These habitat patches were detected and converted into polygons. This output shows the amount of suitable and optimal habitat based on a certain habitat rule and discharge. The habitat model results can be used for further analysis and visualizations directly, or the smallest habitat patches can be filtered out in the next steps. Filtering out the smallest patches can help presenting only the areas where there is enough suitable habitat for the species to thrive.

5.2.3 Analyses of habitat model outputs

To see how the habitats change over time in different discharge conditions, modelling was performed for the five modelled discharge conditions in both study sites. Habitat analyses were performed from raster data, that was rasterized to 0.5 m, 1 m, and 2 m cell sizes. The total habitat area for each cell size is compared per study area, habitat rule and discharge. In Gullspång the modelled discharge conditions were 9, 15, 20, 25, and 30 m³/s. The smallest discharge condition in Gullspång (9 m³/s) represents a minimum discharge condition whereas 30 m³/s is a high discharge condition in the channel. In Vuoksi the modelled discharges were

significantly higher: 200, 300, 500, 800, and 1000 m³/s. There, 200 m³/s represents extremely low discharge condition and 1000 m³/s a high discharge condition.

The effect of different cell sizes and minimum patch sizes on the predicted habitat area was analyzed to answer the first research question. The tests are performed for overall suitability (table 1 and 2), where the suitability range also includes the optimal variable values. Suitable and optimal habitats are not separated, to see the effect on the overall habitat areas that are created by the model. The separation of suitable habitats into two classes would create smaller habitat patches than the combined rule, and that would affect the results when testing the model's sensitivity for minimum habitat patch size. The different cell sizes were produced in a previous phase where the point clouds were rasterized. I separately calculated the distribution of habitat using water depth and flow velocity data of three cell sizes, 0.5, 1 and 2 meters.

The last step of the habitat modelling is to filter the predicted patches to only those that were larger than a selected minimum patch size. This is relevant, because it is important that there is enough suitable habitat present in the river system available for all life stages and that the patches are large enough. I tested the impact of varying minimum patch size since it can be argued that the smallest patches may not offer enough suitable habitat for the fish species to thrive, and it can help to assess the current state of habitats and support restoration planning by identifying the largest uniform habitat areas. The used minimum patch sizes were 0.25, 0.5, 1, 2, 4, 8, 16, and 32 m². The smallest possible patch size with the 1 m cell size is 1 m² and with 2 m cell size 4 m². The results were analyzed statistically and the changes between different combinations were visually located.

Third, to answer the second research question about habitat quality and connectivity, I examined the predicted habitats in different discharge conditions and calculated the number of overlapping habitats with ArcGIS 'calculate overlapping features' geoprocessing tool. The shift and overlap of habitat patches in different discharge conditions is analyzed by calculating the overlapping features at five different discharge conditions with the different habitat rules. As a result, all possible habitat areas within one rule are divided into five classes (1, 2, 3, 4, 5) based on in how many discharge conditions habitats overlap in the same location. The analysis shows how the habitats are shifting in altering discharges and where the habitats are stable even in changing discharge conditions. It presents the spatio-temporal connectivity of habitat patches. This was also examined for the four different habitat rules (both species and age groups), using

a 1-meter cell size results without patch size filtering. 1-meter cell size was used because it was the median cell size examined.

6 Results

6.1 Impact of analysis cell size on the predicted habitat area

The impact of the analysis cell size (0.5, 1 or 2 meters) on the predicted total area of habitat depended on study site and discharge. However, the dependency was similar for the two species and their two age groups. In Gullspång, 2 m cell size produced the largest and 1 m cell size produced the smallest habitat areas in most cases (figure 17). In Vuoksi, 0.5 m cell size produced mostly the largest habitat areas and 2 m mostly the smallest (figure 18). Even though different cell sizes produced different total areas, the results of cell size between discharge conditions followed the same trends. It is seen in both study sites with all rules, that all cell sizes provided the same ascending or descending trend in growing discharges.

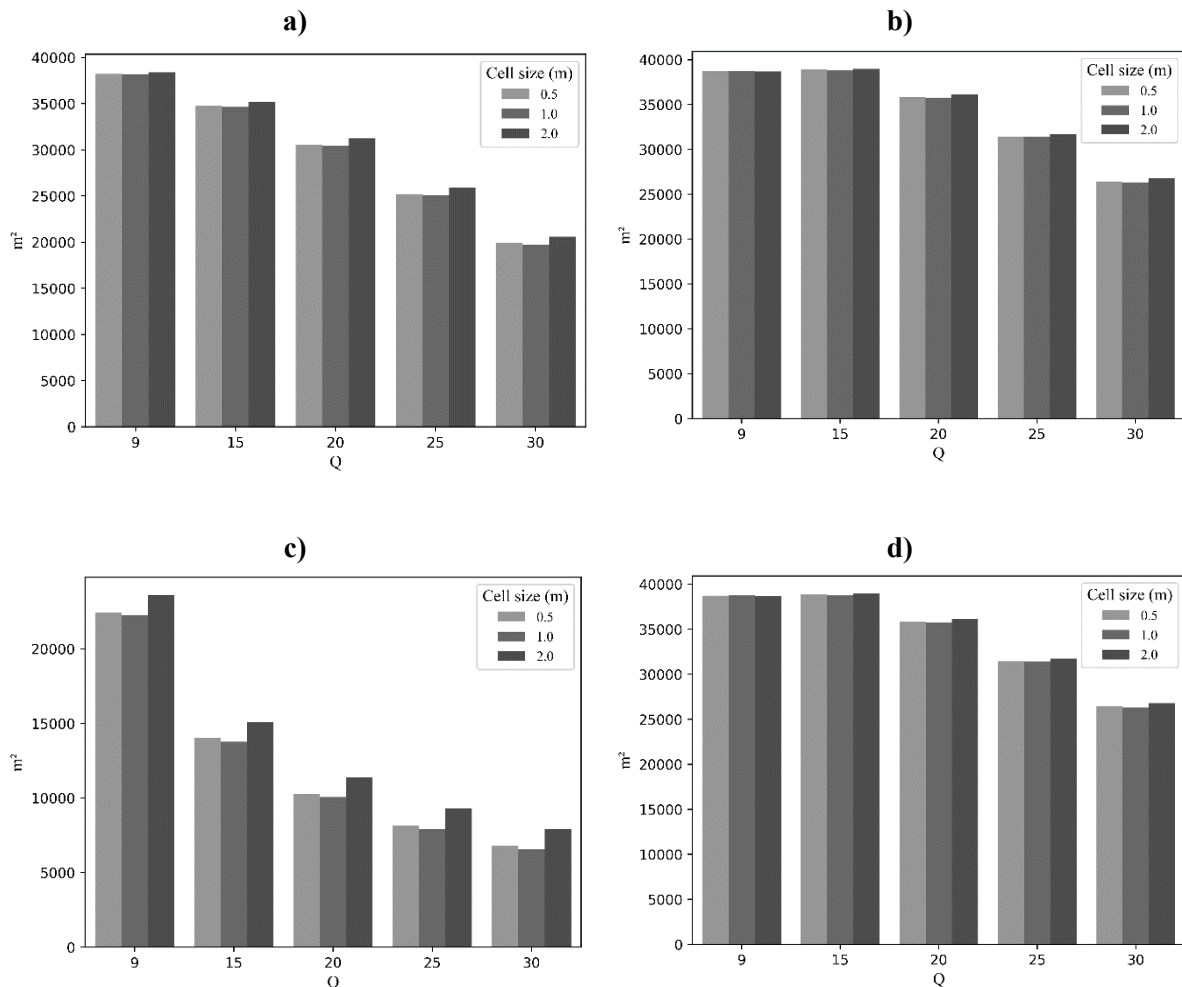


Figure 17. The effect of cell size on the amount of suitable habitat area (m²) at Gullspång study site with the habitat rules for a) 0+ Atlantic salmon, b) 1+ 2+ Atlantic salmon, c) 0+ brown trout, and d) 1+ 2+ brown trout, in discharge (Q) conditions of 9, 15, 20, 25 and 30 m³/s.

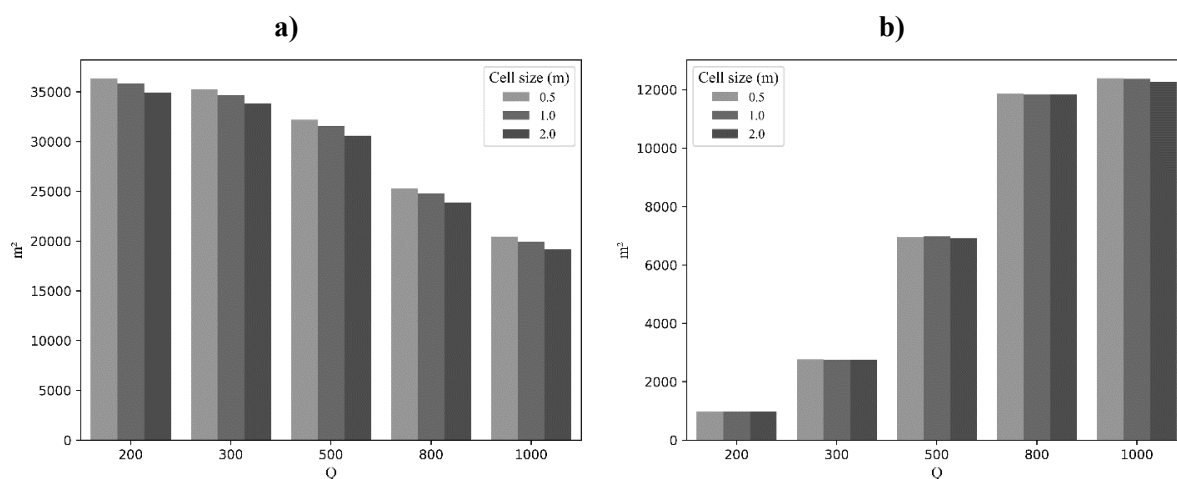


Figure 18. The effect of cell size on the amount of suitable habitat area (m^2) at Vuoksi study site with the habitat rules for a) 0+ brown trout, and b) 1+2+ brown trout, in discharge (Q) conditions of (Q) 200, 300, 500, 800 and 1000 m^3/s .

The impact which cell size (0.5, 1 or meters) predicted the largest or the smallest amount of suitable habitat (m^2) was mainly dependent on the study site (figure 17 and 18). What was common in both study sites was a phenomenon that the relative difference between the smallest and largest produced area by cell size increased as the discharge increased.

In Gullspång, almost in every case the 1-meter cell size predicted the smallest amount of habitat, and 2 meters produced the largest total area (figure 19). Only with Atlantic salmon and brown trout parrs (1+ 2+) 2 meters cell size predicted the smallest amount of habitat and 1 meter predicted the largest amount with the smallest modelled discharge condition ($9 \text{ m}^3/\text{s}$). The 0.5-meter cell size predicted the median amount of habitat in all habitat rule and discharge combinations.

In Gullspång the relative difference of the smallest and largest predicted habitat area (m^2) based on the used cell size varied from almost no change (0.2 %) to a larger variation of 20.3 % (figure 19). The variation was different between the habitat rules. For 1+ 2+ Atlantic salmon and brown trout, which had the same suitability values, the effect of cell size was smallest, ranging from 0.2 to 1.8 % growth from the smallest compared to the largest predicted area. The variation was greatest with the habitat rule for brown trout 0+ with 6,2–20,3 % growth in the total habitat area.

Predicted habitat area		Gullspång Atlantic salmon 0+					Gullspång brown trout 0+				
		Q (m ³ /s)	0.5 m	1 m	2 m	Largest – smallest %	Q (m ³ /s)	0.5 m	1 m	2 m	Largest – smallest %
Smallest		9				+ 0.7	9				+ 6.2
Median		15				+ 1.7	15				+ 9.5
Largest		20				+ 2.7	20				+ 13.4
		25				+ 3.4	25				+ 17.6
		30				+ 4.4	30				+ 20.3
Predicted habitat area		Gullspång Atlantic salmon 1+ 2+					Gullspång brown trout 1+ 2+				
		Q (m ³ /s)	0.5 m	1 m	2 m	Largest – smallest %	Q (m ³ /s)	0.5 m	1 m	2 m	Largest – smallest %
Smallest		9				+ 0.2	9				+ 0.2
Median		15				+ 0.4	15				+ 0.4
Largest		20				+ 1.0	20				+ 1.0
		25				+ 1.0	25				+ 1.0
		30				+ 1.8	30				+ 1.8

Figure 19. Comparison of the effect on cell size on the predicted habitat area at Gullspång study site. In the right columns the growth from the smallest formed area to the largest area per discharge condition was calculated.

In Vuoksi the habitat modelling was done for Brown trout 0+ and 1+ 2+ age groups, and 1 meter cell size predicted the smallest amount of habitat, and 0.5 meter produced the largest total area (figure 20). The only anomaly was with brown trout parr (1+ 2+) rule, in which 1-meter cell size predicted the largest amount of habitat with the 500 m³/s discharge condition. The 2 meters cell size predicted the smallest amount of habitat in all habitat rule and discharge combinations.

In Vuoksi, the relative difference of the smallest and largest predicted habitat area (m²) was modest with both habitat rules (brown trout 0+ and 1+ 2+). Compared to Gullspång, where the relative difference of the predicted area for brown trout 0+ was up to 20.3 %, in Vuoksi the difference was only 4.3–6.9 %. The effect of cell size was small with the brown trout 1+ 2+ rule in Vuoksi, only up to 1.2 %.

Predicted habitat area		Vuoksi brown trout 0+					Vuoksi brown trout 1+ 2+				
		Q (m ³ /s)	0.5 m	1 m	2 m	Largest – smallest %	Q (m ³ /s)	0.5 m	1 m	2 m	Largest – smallest %
Smallest		9				+4,3	9				+ 0.9
Median		15				+ 4.3	15				+ 0.9
Largest		20				+ 5.3	20				+ 1.0
		25				+ 6.2	25				+ 0.2
		30				+ 6.9	30				+ 1.2

Figure 20. Comparison of the effect on cell size on the total habitat area at Vuoksi study site. In the right columns the growth from the smallest formed area to the largest area per discharge condition was calculated.

The difference between the cell sizes was however quite small when the predicted habitat areas were compared to the whole study area. In Vuoksi the habitat areas per rule and discharge condition were 0.1–2.4 % of the total study area. In Gullspång more habitat was predicted and the corresponding proportions were 5.2–30.3 %.

6.2 Impact of minimum habitat patch size on predicted habitat area

The results were filtered based on minimum habitat patch size. Selected minimum patch sizes were 0.25, 0.5, 1, 2, 4, 8, 16, and 32 m² to test the effect of different values to the total area of predicted habitat (m²).

As expected, increasing the minimum patch size uniformly decreased the area of predicted habitat in both study sites, and for both species and age groups (tables 3–8). The impact of the minimum patch size on habitat area depended on analysis cell size. The relative decline of the total habitat area is calculated from the smallest possible patch size to the largest minimum patch size, which is for all cell sizes 32 m². The smallest possible patch size is dependent on the cell size of the habitat analysis. The smallest possible patch size with the 1 m cell size is 1 m² and with 2 m cell size 4 m².

In Gullspång, the relative decline was largest with the 1 m cell size with all habitat rules and discharge conditions (tables 3–6). There was no consistent pattern where a single cell size consistently predicted the smallest relative decline; it varied depending on the habitat rule. It varied based on the habitat rule. In Vuoksi, the largest relative declines occurred with 2 m cell size and smallest declines with 0.5 m cell size in all combinations.

The results indicate that when the total habitat is predicted to be small, the impact of minimum patch size is largest. For example, the habitat of the youngest brown trout individuals was predicted to be the smallest in the Gullspång study site, and its size was most sensitive to the selected minimum patch size (table 5). A similar pattern was found in the Vuoksi study site for the brown trout 1+ 2+, that were predicted to have smallest habitat (table 8).

As increasing discharge generally decreased the size of the predicted habitat, the relative impact of the selected minimum patch size on total habitat area was largest with highest discharges (tables 3–8). In Gullspång there is a decreasing trend with habitat areas with rising discharges. There, the limitation of small patch sizes has a larger effect on total habitat area with increasing discharges. In Vuoksi, the increasing discharges also increase the habitat areas with the brown

trout 1+2+ rule (table 8) but with the rule brown trout 0+ (table 7) the habitat decreases with the increasing discharge.

Table 3. The effect of patch size limitation to the total area of predicted habitat (m²) in Gullspång study site for Atlantic salmon juveniles (0+).

Dis-charge	Cell size	Minimum habitat patch size (m ²)								% decline
		0.25	0.5	1	2	4	8	16	32	
9	0.5	38231	38222	38215	38202	38164	38085	37941	37729	-1.3%
	1			38166	38140	38105	38027	37890	37620	-1.4%
	2					38425	38361	38213	37917	-1.3%
15	0.5	34774	34765	34751	34731	34693	34638	34465	34281	-1.4%
	1			34638	34602	34562	34481	34294	34030	-1.8%
	2					35197	35097	34925	34667	-1.5%
20	0.5	30552	30541	30524	30491	30448	30337	30103	29728	-2.7%
	1			30406	30365	30287	30174	29941	29547	-2.8%
	2					31218	31123	30939	30593	-2.0%
25	0.5	25211	25193	25172	25140	25078	24901	24591	24237	-3.9%
	1			25072	25022	24935	24747	24408	24079	-4.0%
	2					25909	25729	25367	24984	-3.6%
30	0.5	19909	19888	19861	19811	19738	19541	19212	18562	-6.8%
	1			19721	19641	19547	19315	18955	18219	-7.6%
	2					20591	20379	20029	19438	-5.6%
Average decline										-3.2%

Table 4. The effect of patch size limitation to the total area of predicted habitat (m²) in Gullspång study site for Atlantic salmon parrs (1+ 2+).

Dis-charge	Cell size	Minimum habitat patch size (m ²)								% decline
		0.25	0.5	1	2	4	8	16	32	
9	0.5	38724	38715	38710	38699	38665	38634	38531	38260	-1.2%
	1			38761	38743	38716	38685	38575	38197	-1.5%
	2					38681	38637	38493	38301	-1.0%
15	0.5	38887	38878	38871	38852	38808	38743	38607	38425	-1.2%
	1			38819	38795	38749	38680	38540	38341	-1.2%
	2					38974	38897	38749	38521	-1.2%
20	0.5	35838	35825	35810	35796	35755	35672	35514	35350	-1.4%
	1			35772	35738	35680	35607	35405	35204	-1.6%
	2					36112	36056	35872	35656	-1.3%
25	0.5	31431	31418	31398	31376	31304	31224	31038	30735	-2.2%
	1			31395	31357	31277	31184	31020	30652	-2.4%
	2					31710	31614	31474	31102	-1.9%
30	0.5	26424	26403	26382	26363	26297	26163	25988	25591	-3.2%
	1			26309	26266	26199	26077	25844	25441	-3.3%
	2					26789	26659	26475	26169	-2.3%
Average decline										-1.8%

Table 5. The effect of patch size limitation to the total area of predicted habitat (m²) in Gullspång study site for brown trout juveniles (0+).

Dis-charge	Cell size	Minimum habitat patch size (m ²)								% decline
		0.25	0.5	1	2	4	8	16	32	
9	0.5	22452	22446	22437	22414	22358	22239	21948	21555	-4.0%
	1			22246	22199	22081	21907	21495	20950	-5.8%
	2					23602	23458	23143	22580	-4.3%
15	0.5	14030	14022	14012	13985	13894	13725	13435	12850	-8.4%
	1			13769	13702	13549	13250	12705	11987	-12.9%
	2					15053	14880	14356	13574	-9.8%
20	0.5	10273	10262	10247	10207	10118	9933	9632	8829	-14.1%
	1			10059	9982	9785	9359	8829	7886	-21.6%
	2					11372	11143	10509	9701	-14.7%
25	0.5	8166	8157	8138	8097	8000	7778	7442	6835	-16.3%
	1			7913	7821	7604	7209	6653	5701	-27.9%
	2					9273	8956	8287	7508	-19.0%
30	0.5	6794	6784	6761	6729	6644	6426	5963	5313	-21.8%
	1			6577	6482	6214	5795	5139	4268	-35.1%
	2					7891	7563	6917	6133	-22.3%
Average decline										-15.9%

Table 6. The effect of patch size limitation to the total area of predicted habitat (m²) in Gullspång study site for brown trout parrs (1+ 2+).

Dis-charge	Cell size	Minimum habitat patch size (m ²)								% decline
		0.25	0.5	1	2	4	8	16	32	
9	0.5	38724	38715	38710	38699	38665	38634	38531	38260	-1.2%
	1			38761	38743	38716	38685	38575	38197	-1.5%
	2					38681	38637	38493	38301	-1.0%
15	0.5	38887	38878	38871	38852	38808	38743	38607	38425	-1.2%
	1			38819	38795	38749	38680	38540	38341	-1.2%
	2					38974	38897	38749	38521	-1.2%
20	0.5	35838	35825	35810	35796	35755	35672	35514	35350	-1.4%
	1			35772	35738	35680	35607	35405	35204	-1.6%
	2					36112	36056	35872	35656	-1.3%
25	0.5	31431	31418	31398	31376	31304	31224	31038	30735	-2.2%
	1			31395	31357	31277	31184	31020	30652	-2.4%
	2					31710	31614	31474	31102	-1.9%
30	0.5	26424	26403	26382	26363	26297	26163	25988	25591	-3.2%
	1			26309	26266	26199	26077	25844	25441	-3.3%
	2					26789	26659	26475	26169	-2.3%
Average decline										-1.8%

Table 7. The effect of patch size limitation to the total area of predicted habitat (m²) in Vuoksi study site for brown trout juveniles (0+).

Dis-charge	Cell size	Minimum habitat patch size (m ²)								% decline
		0.25	0.5	1	2	4	8	16	32	
200	0.5	36375	36370	36364	36340	36297	36174	35929	35526	-2.3%
	1			35785	35737	35615	35373	34855	33958	-5.1%
	2					34669	34044	32934	31253	-9.9%
300	0.5	35271	35268	35260	35234	35188	35066	34823	34455	-2.3%
	1			34686	34642	34525	34252	33636	32901	-5.1%
	2					33632	33021	31875	30357	-9.7%
500	0.5	32191	32188	32181	32155	32098	31951	31772	31395	-2.5%
	1			31566	31514	31393	31094	30585	29770	-5.7%
	2					30343	29733	28623	26909	-11.3%
800	0.5	25322	25317	25303	25273	25210	25060	24875	24313	-4.0%
	1			24745	24668	24532	24223	23775	22958	-7.2%
	2					23557	23020	22009	20290	-13.9%
1000	0.5	20439	20436	20424	20384	20309	20170	19906	19377	-5.2%
	1			19893	19801	19648	19295	18800	17985	-9.6%
	2					18710	18188	17154	15662	-16.3%
Average decline									-7.3%	

Table 8. The effect of patch size limitation to the total area of predicted habitat (m²) in Vuoksi study site for brown trout parrs (1+ 2+).

Dis-charge	Cell size	Minimum habitat patch size (m ²)								% decline
		0.25	0.5	1	2	4	8	16	32	
200	0.5	984	970	945	912	864	727	527	260	-73.6%
	1			977	916	831	695	480	177	-81.9%
	2					968	697	444	80	-91.7%
300	0.5	2767	2758	2741	2694	2646	2542	2284	1853	-33.0%
	1			2754	2687	2583	2366	2025	1586	-42.4%
	2					2734	2391	1770	1242	-54.6%
500	0.5	6961	6947	6926	6904	6847	6771	6486	5873	-15.6%
	1			6983	6913	6797	6600	6263	5580	-20.1%
	2					6889	6478	5782	4792	-30.4%
800	0.5	11862	11848	11835	11798	11733	11582	11367	10847	-8.6%
	1			11841	11776	11674	11467	11094	10431	-11.9%
	2					11750	11261	10571	9226	-21.5%
1000	0.5	12397	12384	12368	12331	12277	12139	11876	11213	-9.6%
	1			12365	12310	12202	12043	11541	10827	-12.4%
	2					12103	11642	10818	9427	-22.1%
Average decline									-35.3%	

To better visualize the effect of minimum patch size for the different habitat rules, discharge conditions and cell size, scatter plots with regression lines were created. I examined the linear relationship between the selected minimum patch size and the suitable habitat predicted (figures 21–26). The three used cell sizes (0.5, 1 and 2 meters) and different discharge conditions are displayed in the plots.

In Gullspång, there is no noticeable trend that one cell size always has the steepest slope (figures 21–24). Generally, the impact of minimum habitat patch size on predicted habitat area is independent of analysis cell size. Also, the total habitat area produced by different cell sizes stays in the same order in most scenarios when the minimum patch sizes are limited. However, in Vuoksi, the predicted habitat area is sensitive to the combination of minimum patch size and analysis cell size (figures 25–26). With a 2-meter cell size, increasing the minimum patch size has a dramatic impact on the predicted habitat area, whereas the 0.5 m cell size has the gentlest slope. That leads to a result, that in the largest minimum patch size limitation of 36 m², the 2 m cell size has the smallest total habitat area and the 0.5 cell size the largest.

The discharges scenarios that predicted the smallest amount of habitat in the first place tend to be more sensitive to minimum patch size limitations. However, the cell size which is most sensitive to minimum patch size limitations is different between the study sites. In Vuoksi study site, the largest cell size (2 m) is most sensitive to the limitation of minimum habitat patch size whereas in Gullspång the 1 m cell size is most sensitive. These trends are seen with all habitat rules and discharge conditions in the study sites. This leads to the conclusion that the local environment and channel morphology affects the size of habitat patches and their location in the channel.

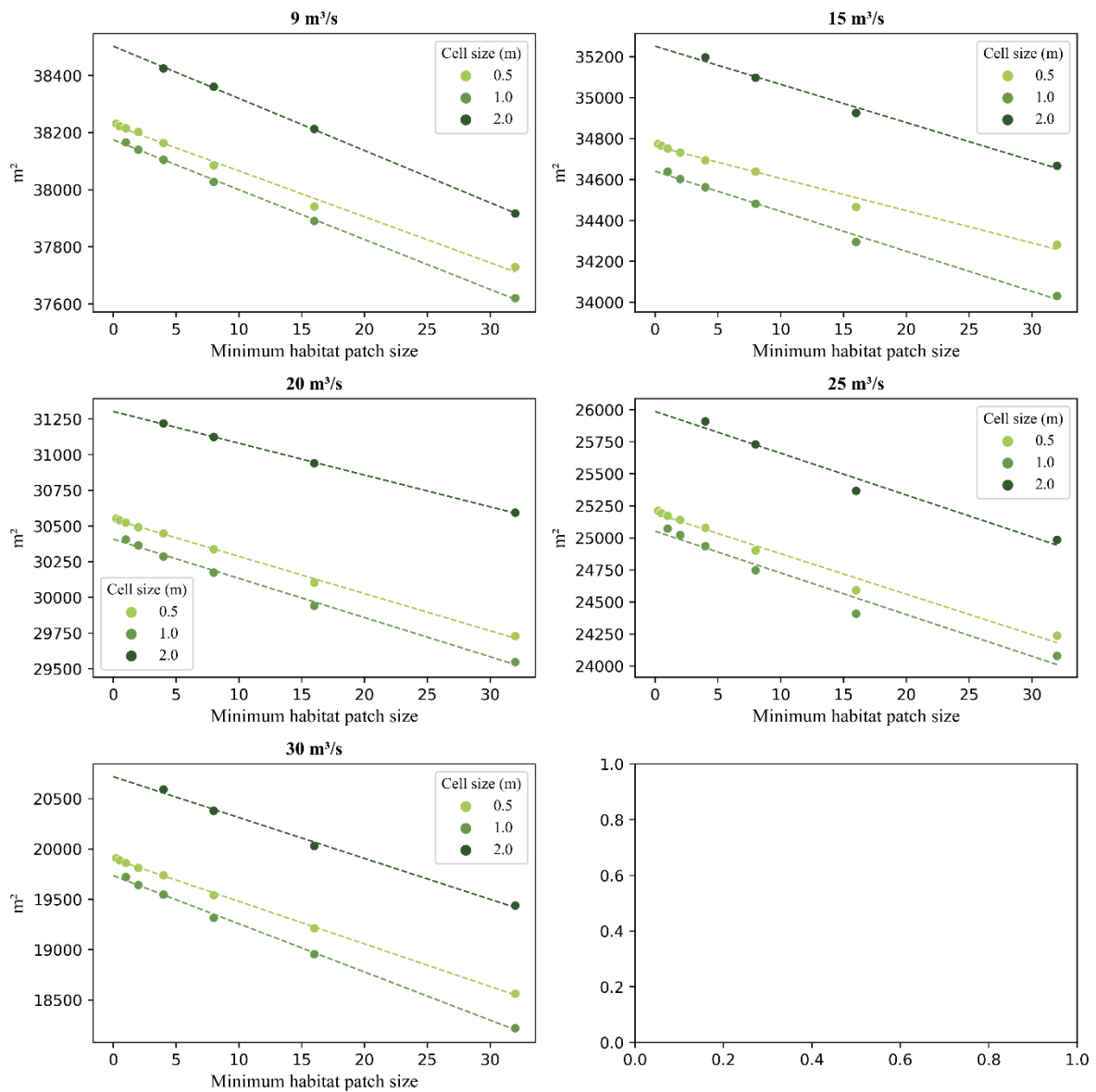


Figure 21. Linear relationship between the selected minimum patch size and the amount (m²) of predicted suitable habitat with three modelled cell sizes (0.5, 1 and 2 meters) and different discharge conditions, at Gullspång study site with Atlantic salmon 0+ habitat rule.

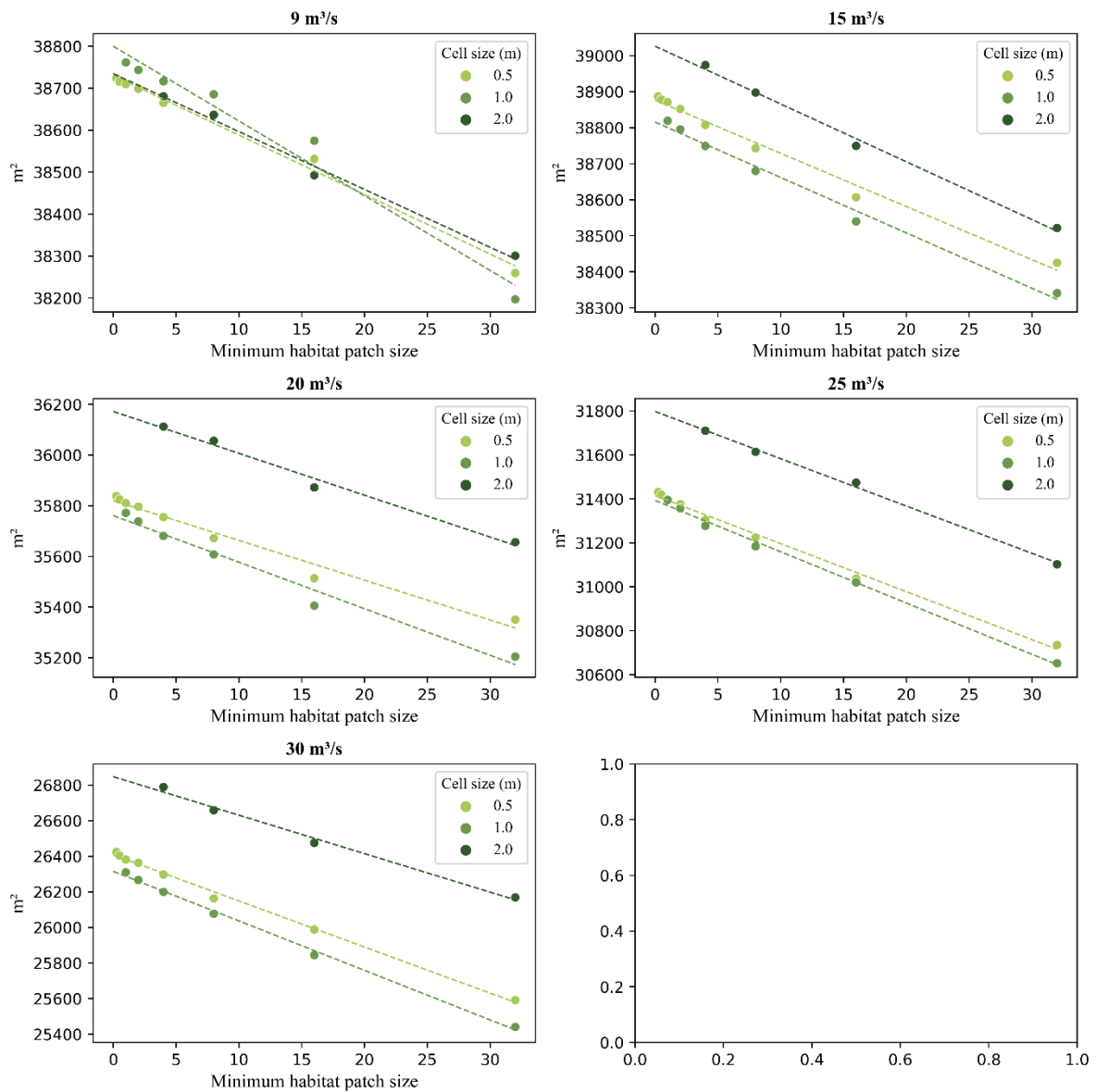


Figure 22. Linear relationship between the selected minimum patch size and the amount (m²) of predicted suitable habitat with three modelled cell sizes (0.5, 1 and 2 meters) and different discharge conditions, at Gullspång study site with Atlantic salmon 1+ 2+ habitat rule.

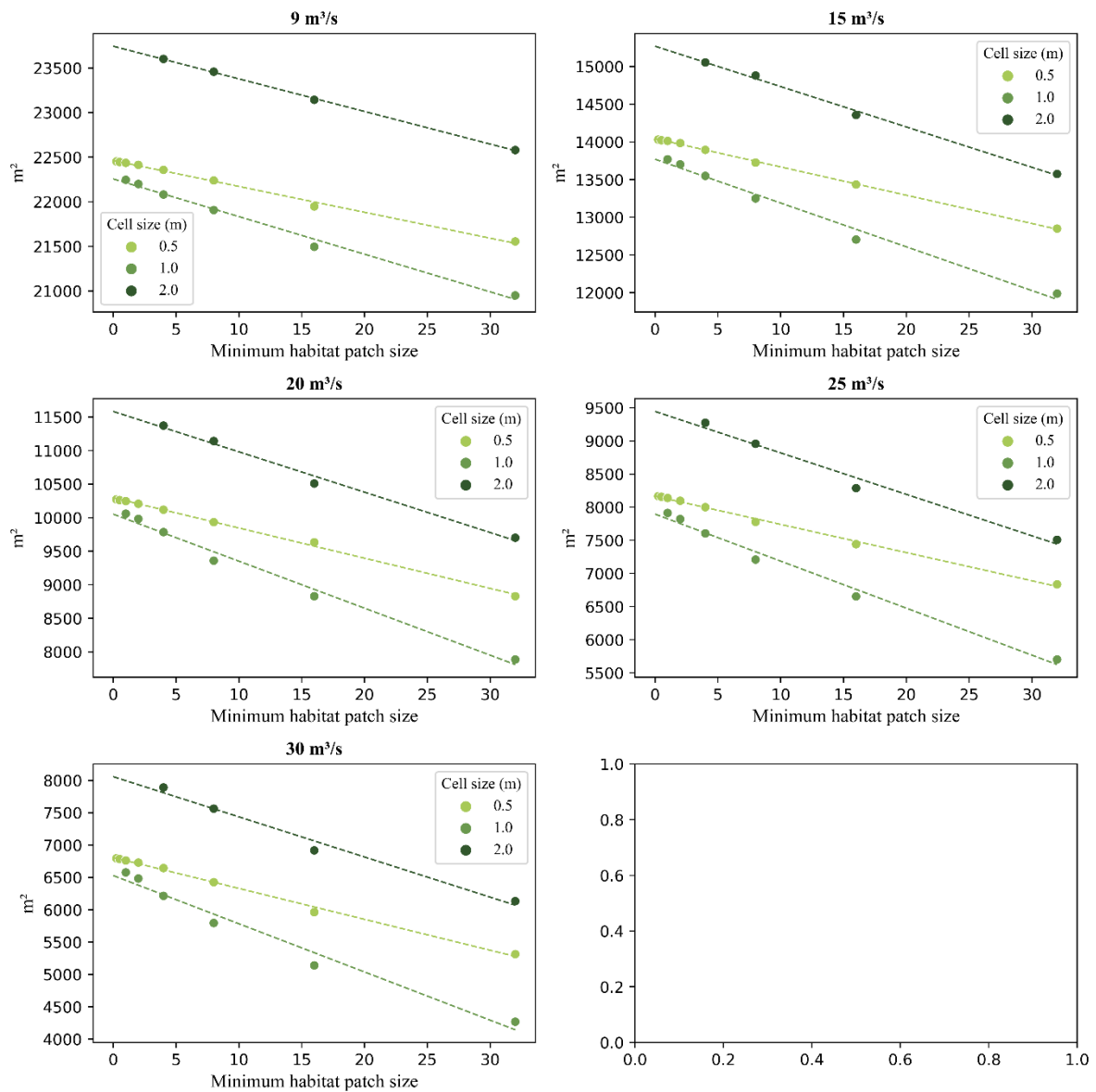


Figure 23. Linear relationship between the selected minimum patch size and the amount (m²) of predicted suitable habitat with three modelled cell sizes (0.5, 1 and 2 meters) and different discharge conditions, at Gullspång study site with brown trout 0+ habitat rule.

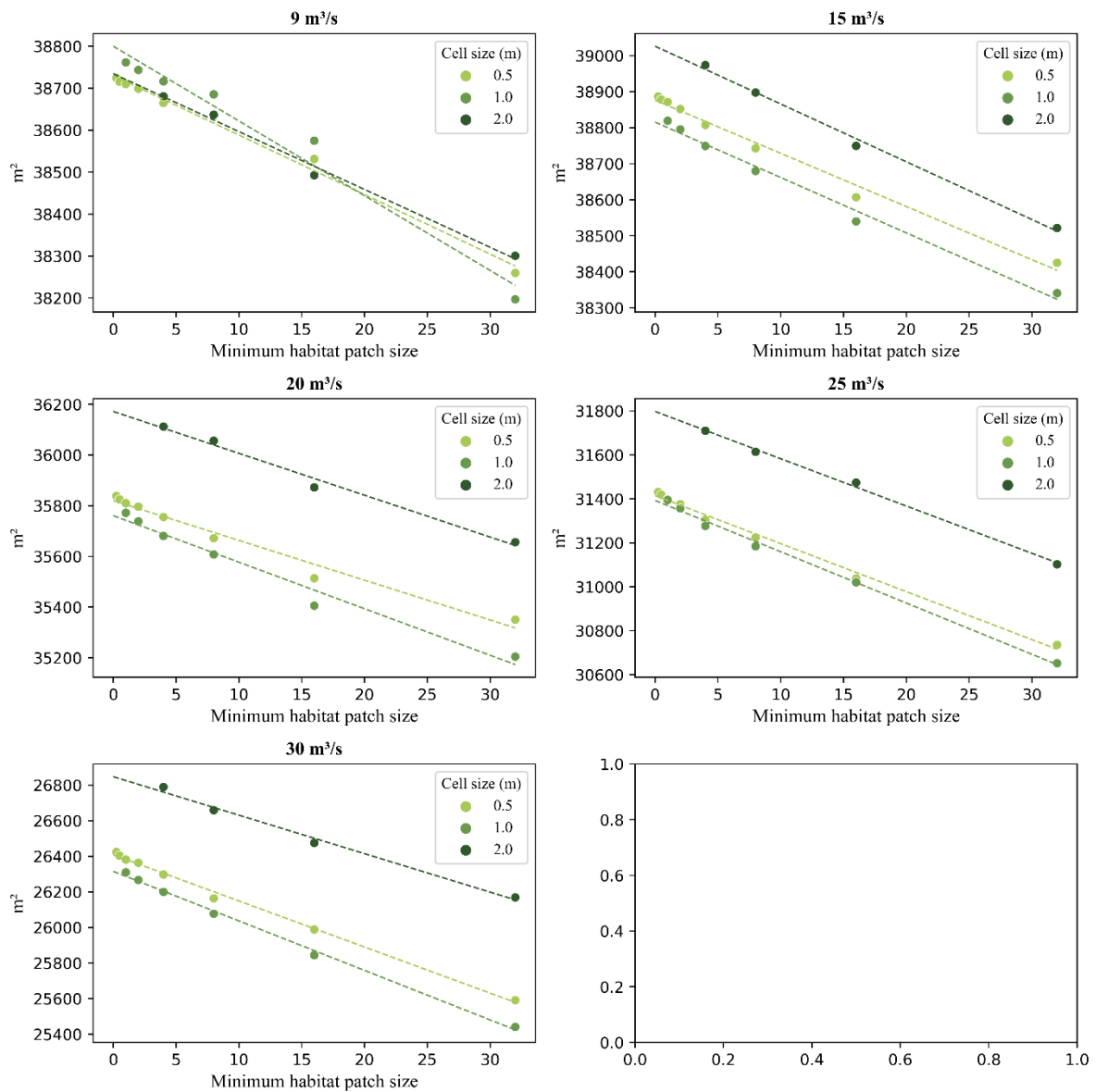


Figure 24. Linear relationship between the selected minimum patch size and the amount (m²) of predicted suitable habitat with three modelled cell sizes (0.5, 1 and 2 meters) and different discharge conditions, at Gullspång study site with brown trout 1+ 2+ habitat rule.

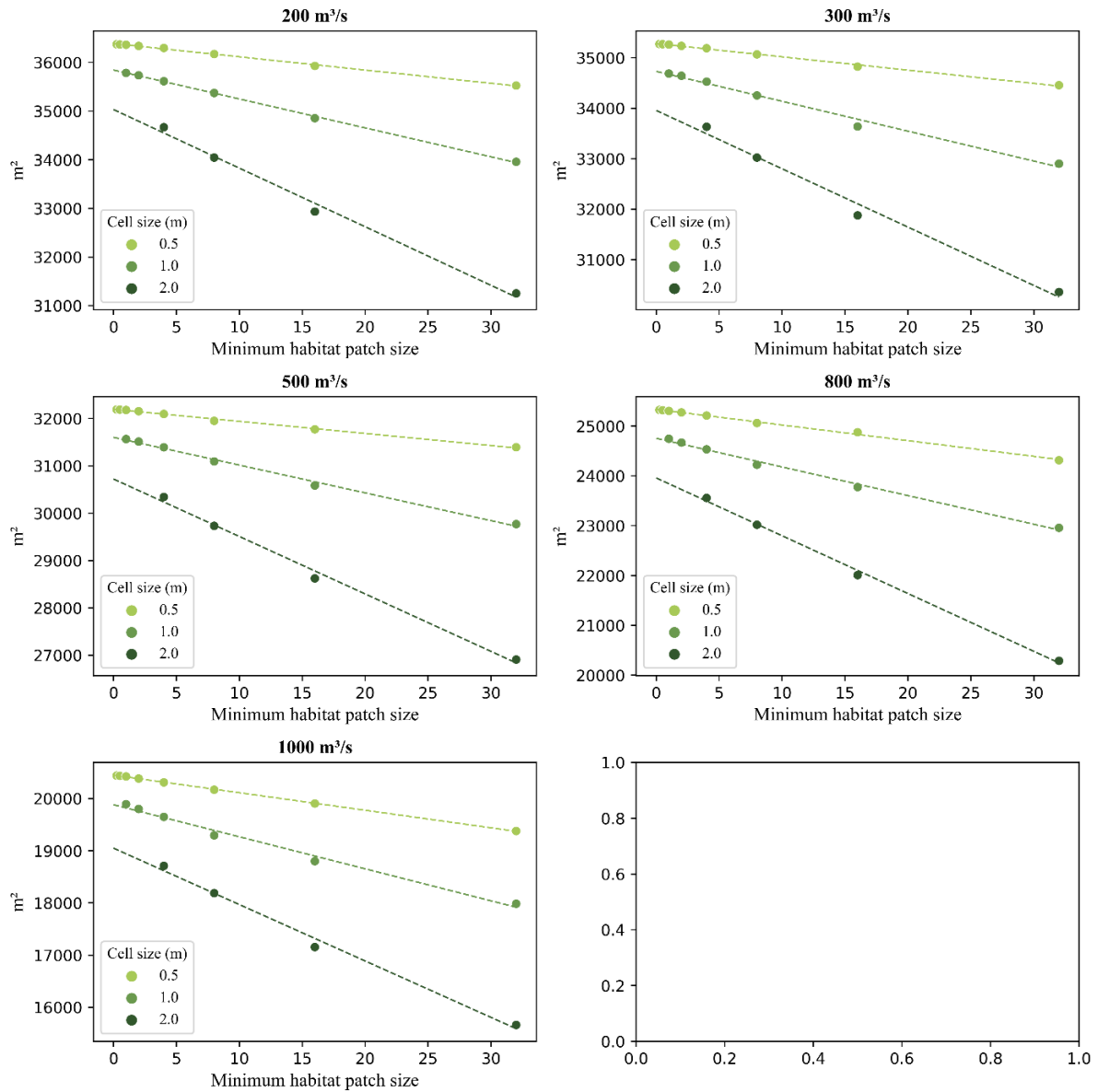


Figure 25. Linear relationship between the selected minimum patch size and the amount (m²) of predicted suitable habitat with three modelled cell sizes (0.5, 1 and 2 meters) and different discharge conditions, at Vuoksi study site with brown trout 0+ habitat rule.

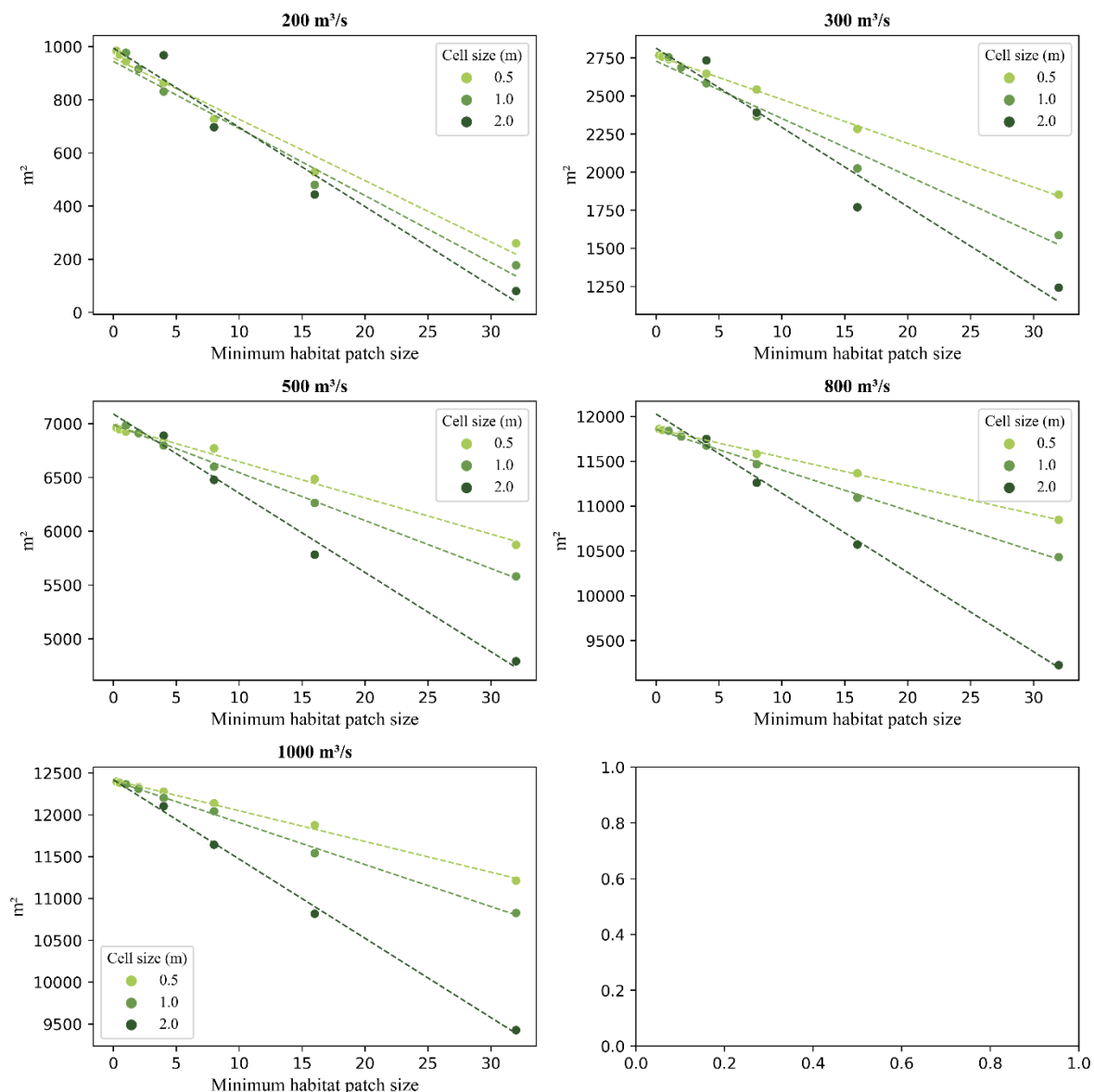


Figure 26. Linear relationship between the selected minimum patch size and the amount (m²) of predicted suitable habitat with three modelled cell sizes (0.5, 1 and 2 meters) and different discharge conditions, at Vuoksi study site with brown trout 1+ 2+ habitat rule.

6.3 Habitat quality and stability

I exemplified ways to interpret the quality and stability of habitats from the habitat model outputs. All results in this chapter were created with 1 m cell size and without patch size limitations.

The quality of the habitat can be analyzed by dividing suitability into multiple classes or using a suitability curve. In this thesis, I divided habitat suitability into two classes: ‘suitable’ and ‘optimal’ habitat (tables 1–2) and examined the distribution of these classes numerically (tables

9–10) and visually on maps (figures 27–32). The maps describe the spatial distribution of habitat quality in different discharge conditions.

As expected, the area of suitable habitat was larger than optimal habitat for both species and age groups in both study sites (tables 1–2). In the Vuoksi study site the proportion of optimal habitat was only 0.1–5.1 % of total habitat (table 10). In Gullspång, the amounts of optimal habitat were higher but similarly the suitable class dominates, and the largest amount of optimal habitat was only 36.6 %, with the habitat rule for Atlantic salmon parrs (salmon 1+ 2+) in discharge condition of 15 m³/s (table 9). Optimal habitats were often surrounded by suitable habitat and the patch sizes were smaller than patches in the suitable class (figures 27–32).

Table 9. Proportions of optimal habitat in Gullspång study site.

Q (m³/s)	Atlantic salmon 0+	Atlantic salmon 1+ 2+	Brown trout 0+	Brown trout 1+ 2+
9	5.9 %	31.1 %	15.0 %	6.6 %
15	7.4 %	36.6 %	10.5 %	12.1 %
20	7.2 %	30.7 %	9.4 %	11.3 %
25	5.2 %	26.1 %	8.6 %	10.0 %
30	4.4 %	22.5 %	8.4 %	9.6 %

Table 10. Proportions of optimal habitat in Vuoksi study site.

Q (m³/s)	Brown trout 1+ 2+	Brown trout 1+ 2+
200	0.4 %	0.1 %
300	1.3 %	0.6 %
500	2.4 %	1.3 %
800	4.4 %	3.1 %
1000	5.1 %	3.4 %

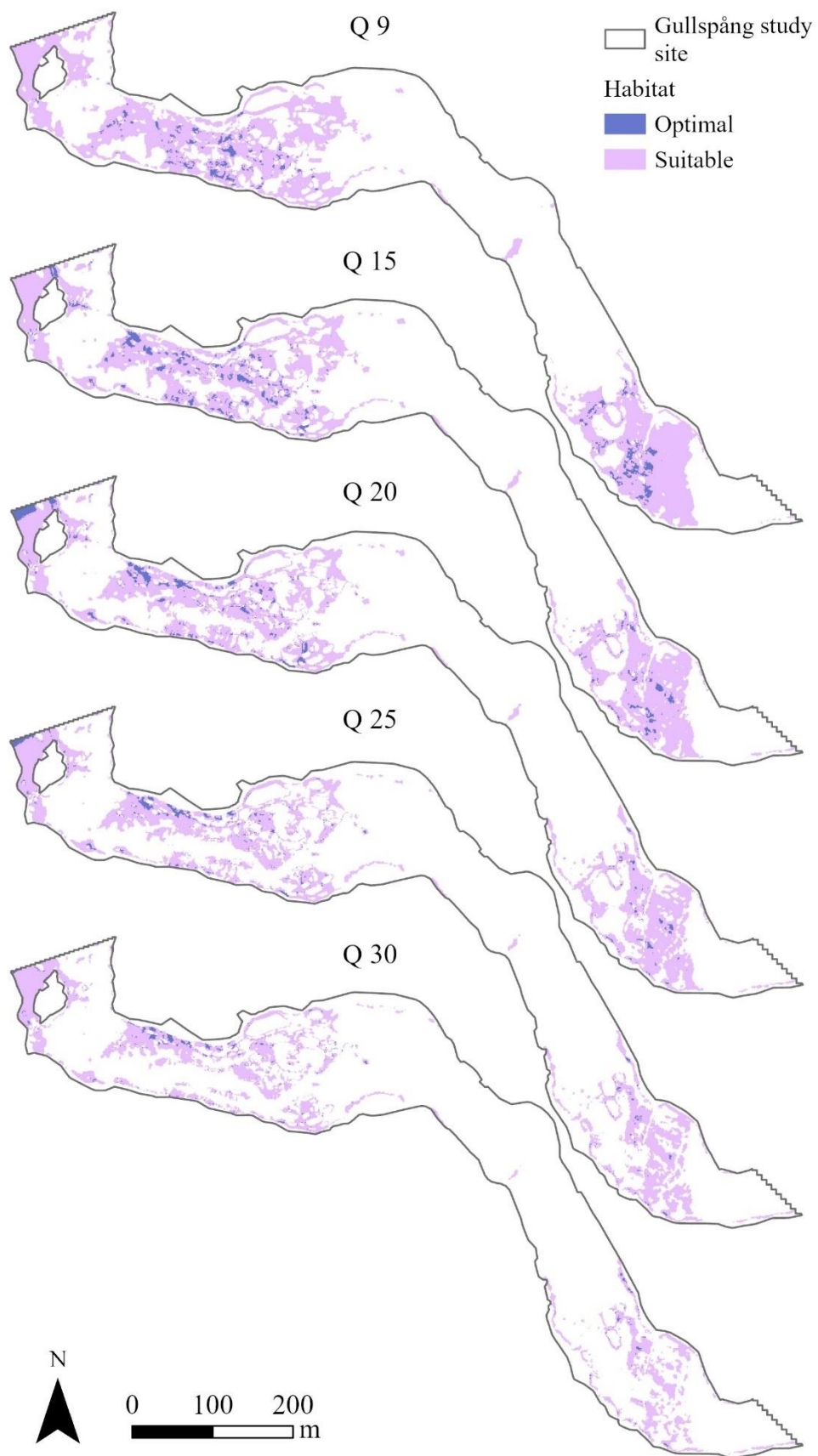


Figure 27. Optimal and suitable habitat displayed with Atlantic salmon 0+ habitat rule and 1 meter cell size at Gullspång study site.

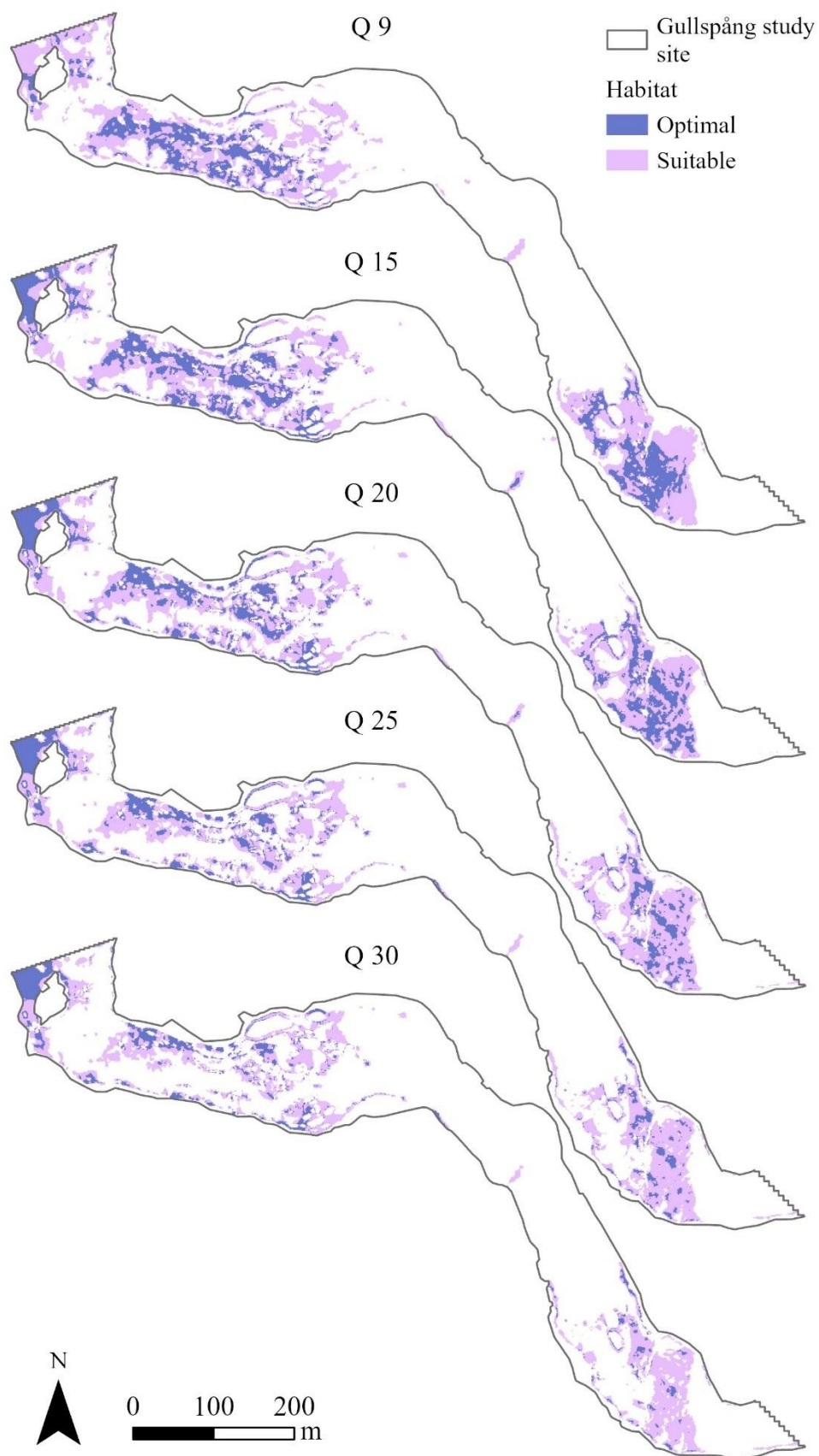


Figure 28. Optimal and suitable habitat displayed with Atlantic salmon 1+ 2+ habitat rule and 1meter cell size at Gullspång study site.

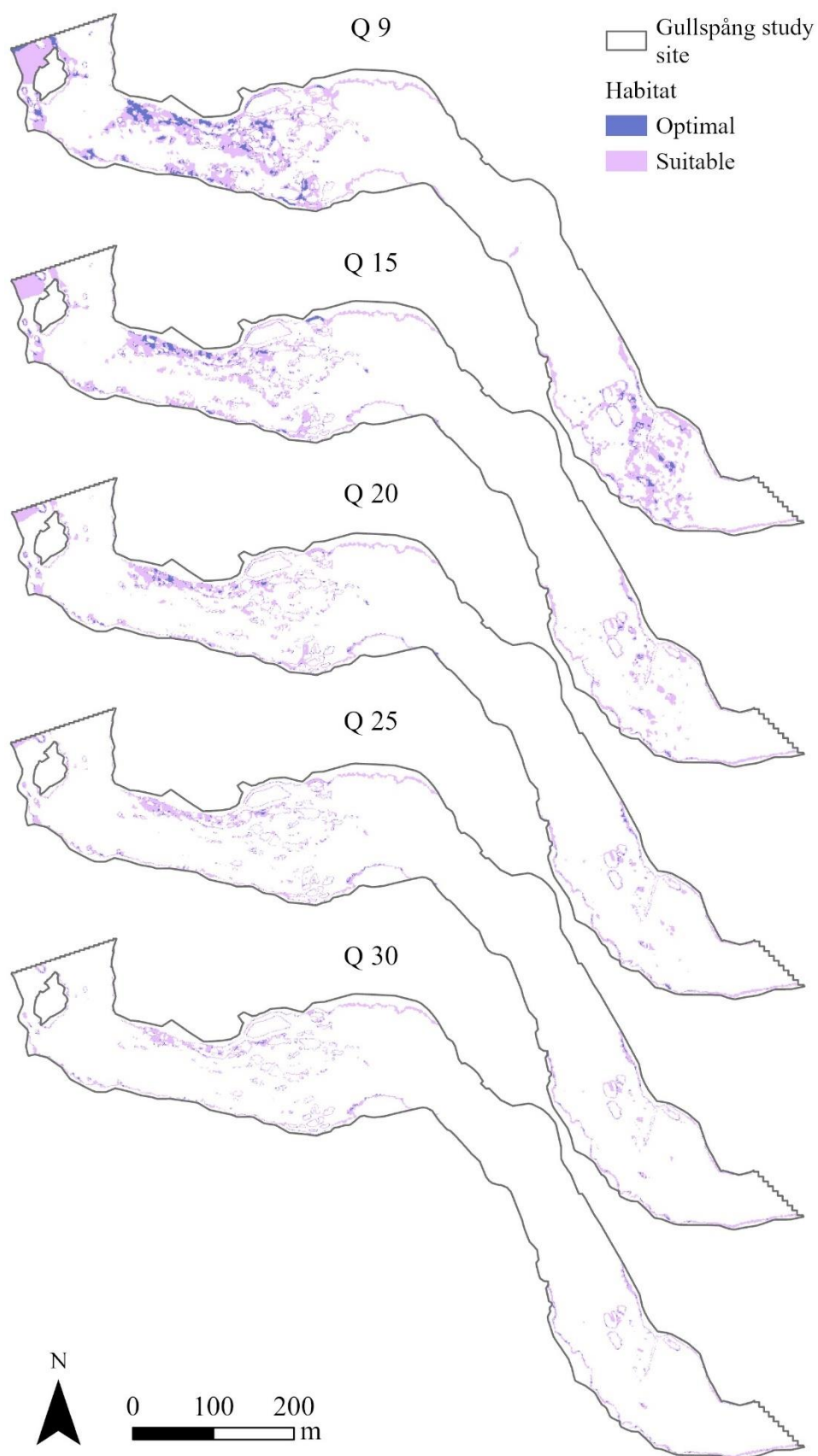


Figure 29. Optimal and suitable habitat displayed with brown trout 0+ habitat rule and 1meter cell size at Gullspång study site.

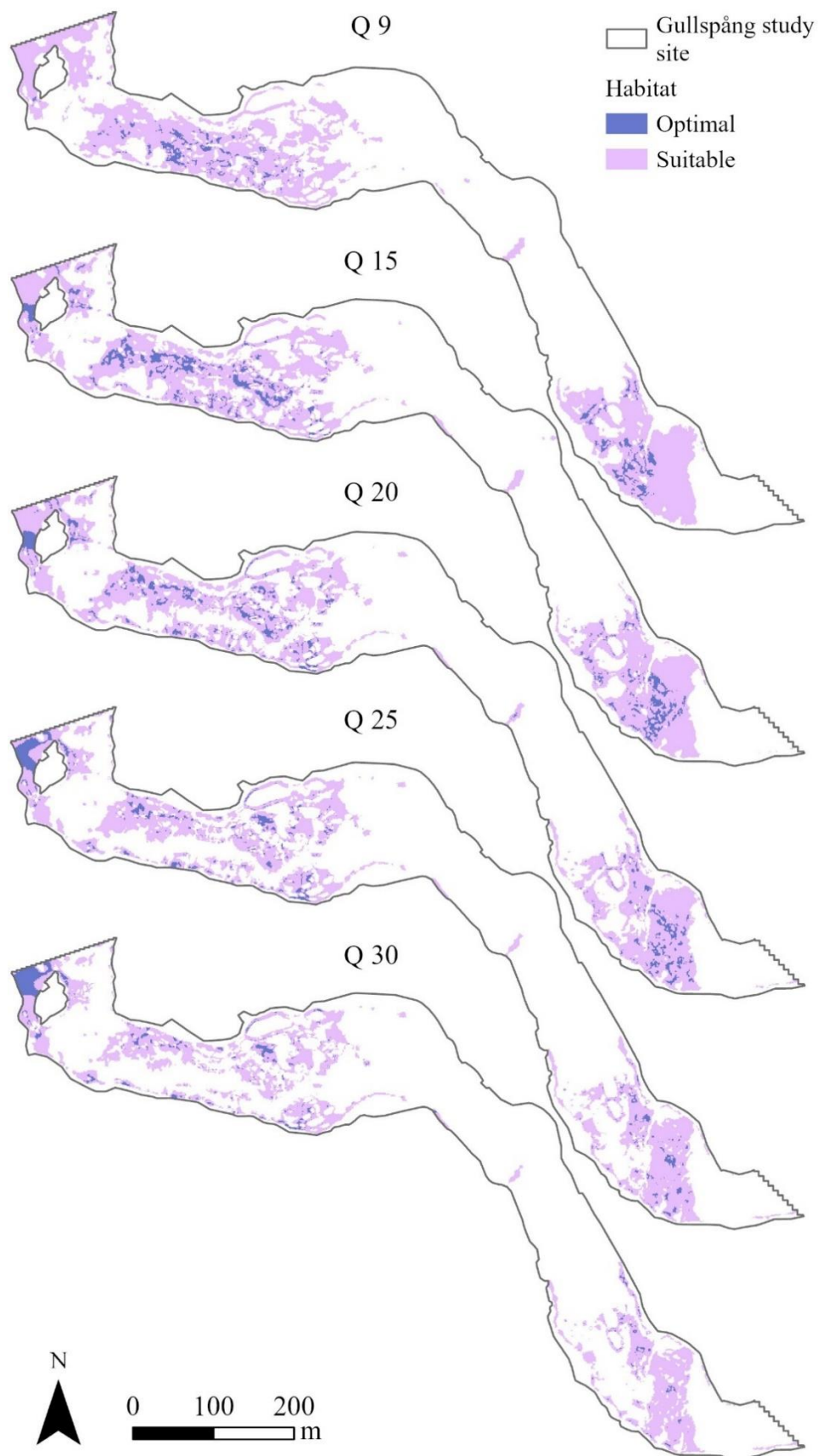


Figure 30. Optimal and suitable habitat displayed with brown trout 1+ 2+ habitat rule and 1meter cell size at Gullspång study site.

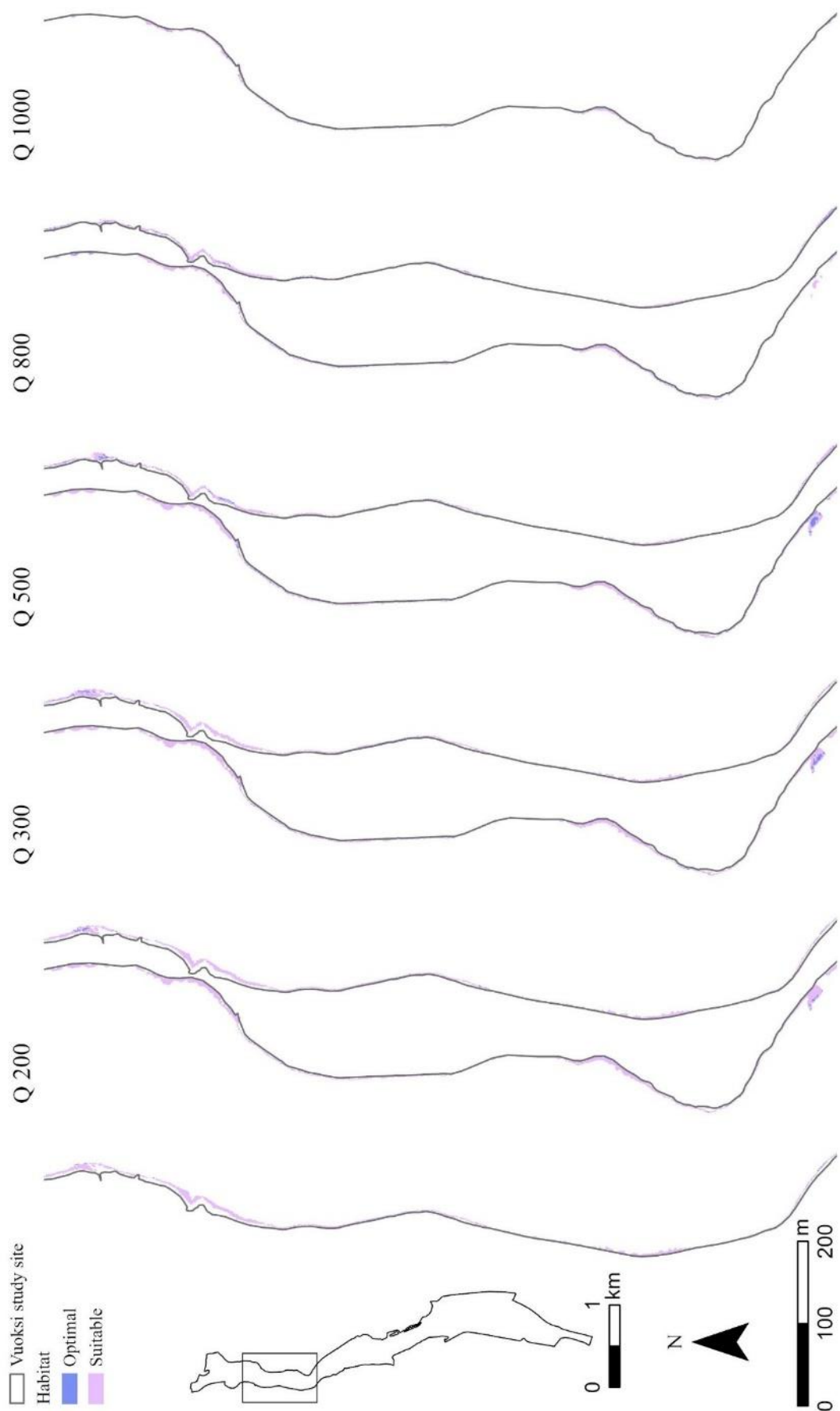


Figure 31. Optimal and suitable habitat displayed with brown trout 0+ habitat rule and 1meter cell size at Vuoksistudy site.

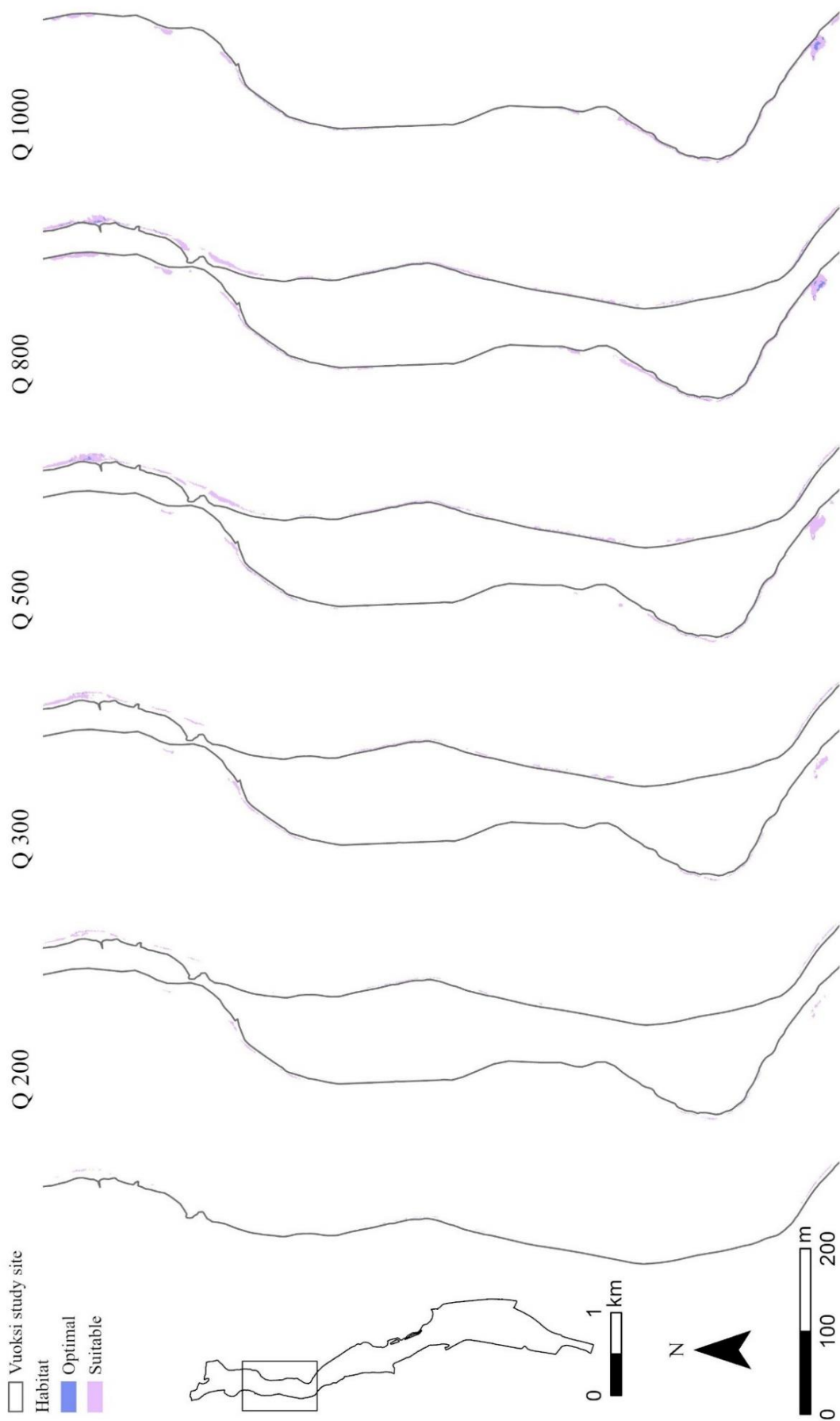


Figure 32. Optimal and suitable habitat displayed with brown trout 1+ 2+ habitat rule and 1meter cell size at Vuoksi study site.

The habitat quality of individual patches within specific discharge conditions cannot adequately represent overall river habitat quality, especially in systems with naturally fluctuating or hydropower-regulated discharges. As the discharge varies in the channel, shifts in water depth and flow velocity cause suitable habitat areas to relocate, resulting in different habitat positions for each scenario. Therefore, understanding the habitat quality in altering discharge conditions is important.

In both study sites and with all rules, there were habitat areas falling into all five categories of overlap (tables 11–13; figures 33–38). That means that suitable some areas had higher tolerance for discharge variations, and there was suitable habitat available even with all five scenarios, whereas some habitat patches were formed only at one discharge condition. If the number of overlapping features is only one, it means that habitat disappears from the location if discharge increases or decreases to another modelled discharge condition. It is valuable to see where such scenarios occur, and which were the discharge conditions that produce habitat in new places. If no habitat was predicted, it means that either flow velocity value, water depth value or both values of the cell were not within the suitability range of the habitat rule.

There were clear differences in the distribution of overlaying features between the rules and study sites (tables 11–13; figures 33–38). In Gullspång study site both Atlantic salmon rules and brown trout 1+ 2+ rule had a lot of overlapping habitats in different discharge conditions (tables 11–12). The largest proportion of habitats (36–42 %) overlapped in all five scenarios, other classes were quite evenly distributed (13–18 %). Brown trout 0+ rule (table 12) was the opposite compared to the other three rules in Gullspång study site since the brown trout 0+ rule the largest proportion of habitat was predicted with no habitat overlap (41 %) and other classes were quite evenly distributed (12–19 %). The least overlap was in Vuoksi study site with habitat rule for brown trout 1+ 2+, where only 1 % of the suitable habitats occurred with all five discharges, and 43 % of the areas occurred in only one scenario (table 13). With the habitat rule for brown trout 0+ no class was dominating with all classes covering 10–28 % (table 13).

Table 11. Overlapping habitat areas with Atlantic salmon rules at Gullspång with Q 9, 15, 20, 25 and 30 m³/s. With 1 meter cell size and without minimum patch size requirements.

Number of overlapping features	Atlantic salmon 0+		Atlantic salmon 1+ 2+	
	Area (m ²)	%	Area (m ²)	%
1	6 995	16	6 289	13
2	5 985	14	5 915	13
3	6 888	16	6 937	15
4	7 678	18	8 266	18
5	15 533	36	19 813	42
Total	43 079	100	47 219	100

Table 12. Overlapping habitat areas with brown trout rules at Gullspång with Q 9, 15, 20, 25 and 30 m³/s. With 1 meter cell size and without minimum patch size requirements.

Number of overlapping features	Brown trout 0+		Brown trout 1+ 2+	
	Area (m ²)	%	Area (m ²)	%
1	10 294	41	6 289	13
2	4 896	19	5 915	13
3	3 274	13	6 937	15
4	2 898	12	8 266	18
5	3 817	15	19 813	42
total	25 180	100	47 219	100

Table 13. Overlapping habitat areas with brown trout rules at Vuoksi with Q 200, 300, 500, 800 and 1000 m³/s. Cell size is 1 m, no minimum patch size requirements.

Number of overlapping features	Brown trout 0+		Brown trout 1+ 2+	
	Area (m ²)	%	Area (m ²)	%
1	4 607	10	8 101	43
2	9 020	20	6 876	36
3	12 456	28	2 707	14
4	7 095	16	913	5
5	11 679	26	263	1
total	44 858	100	18 860	100

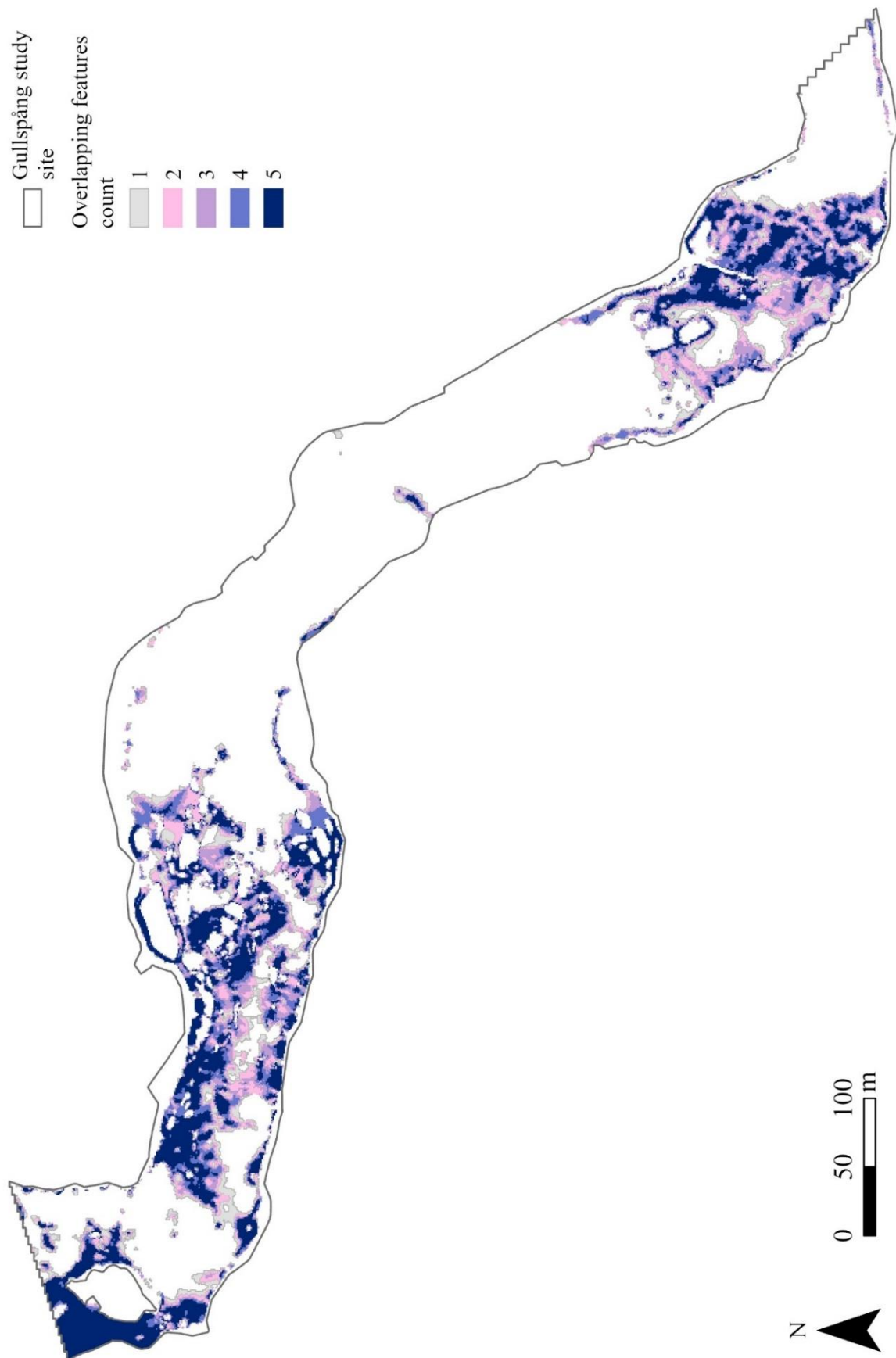


Figure 33. Overlapping habitat prediction in varying discharge conditions in Gullspång study site with Atlantic salmon 0+ habitat rule.

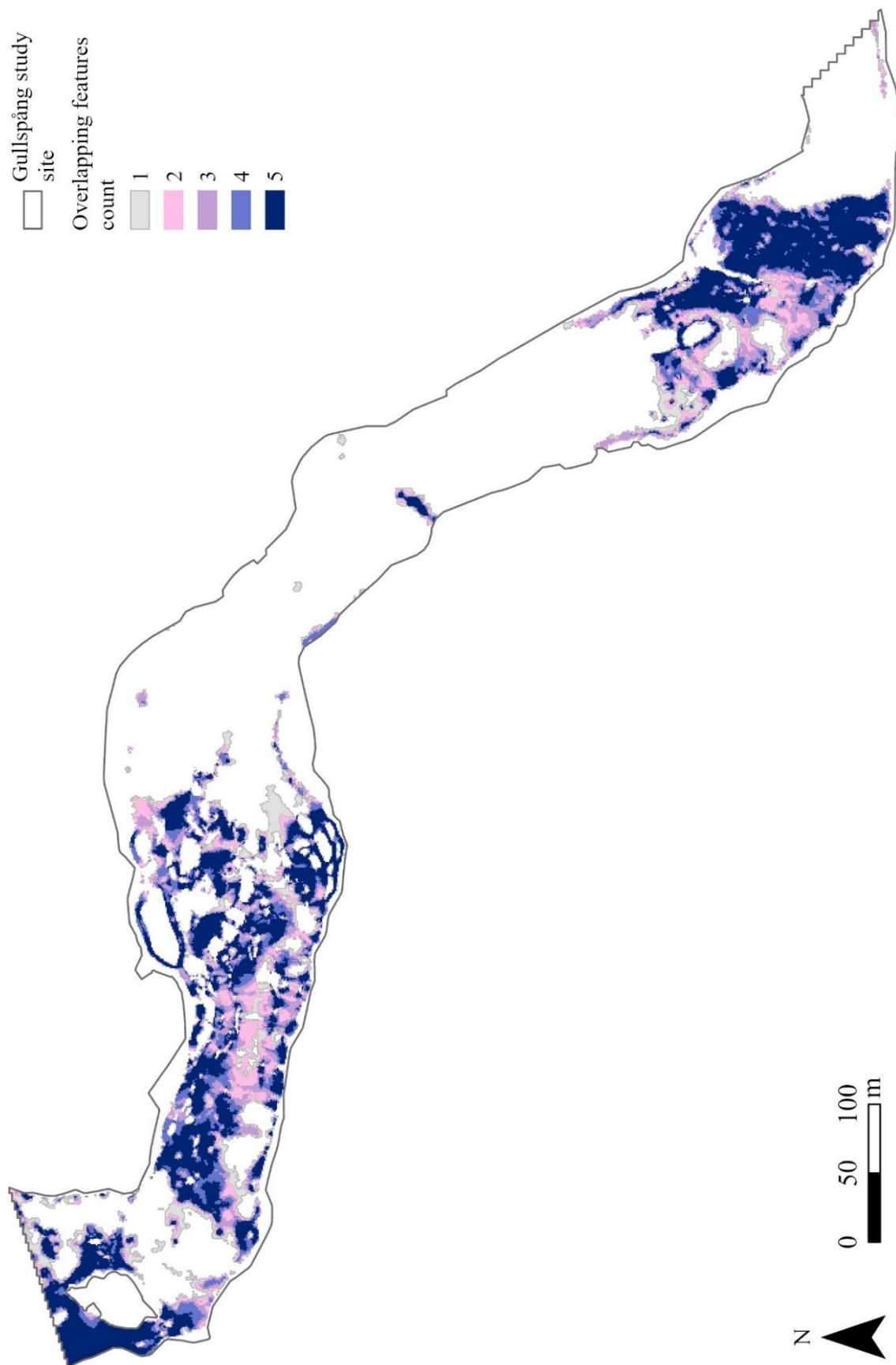


Figure 34. Overlapping habitat prediction in varying discharge conditions in Gullspång study site with Atlantic salmon 1+ 2+ habitat rule.

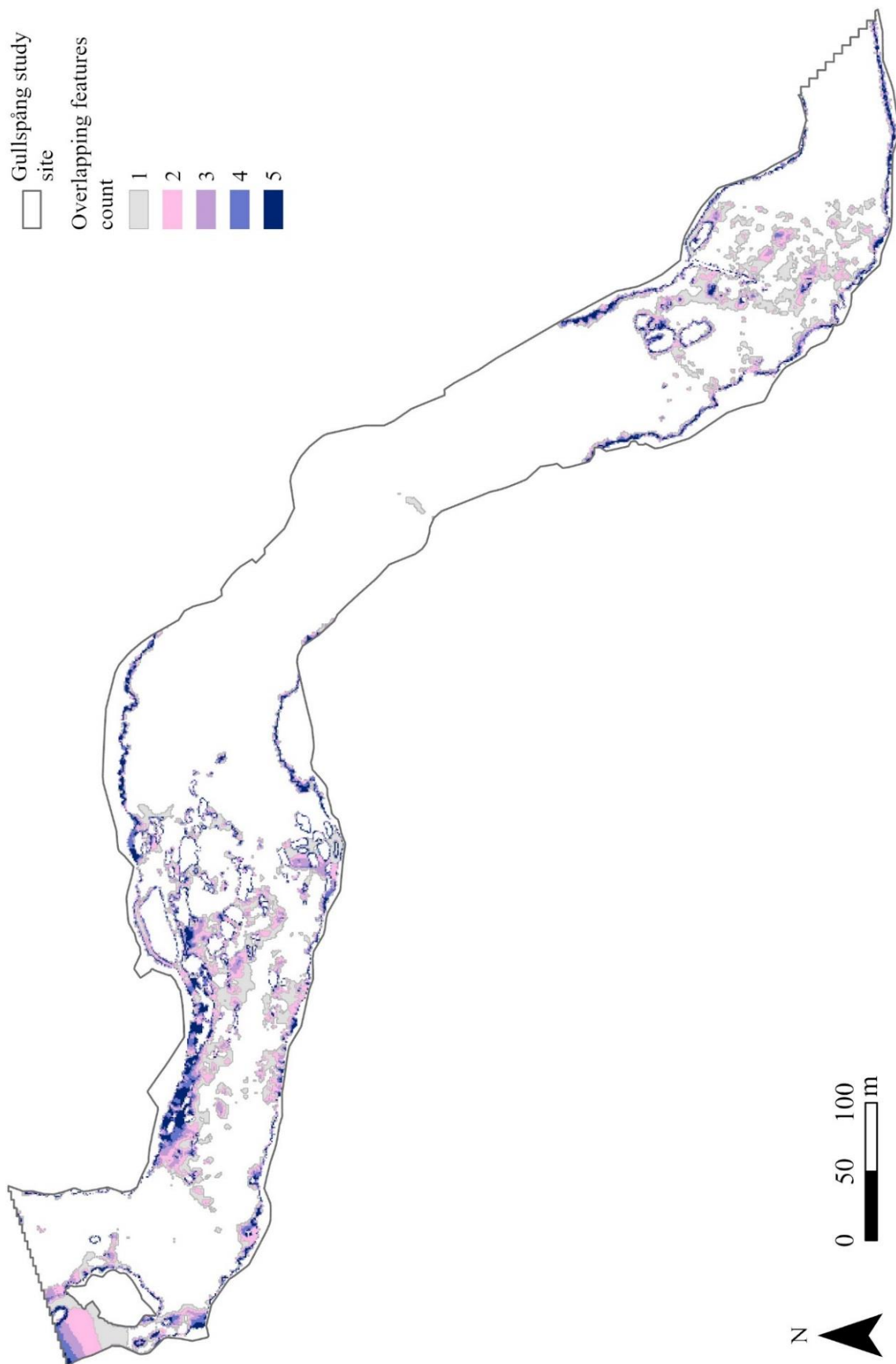


Figure 35. Overlapping habitat prediction in varying discharge conditions in Gullspång study site with brown trout 0+ habitat rule.

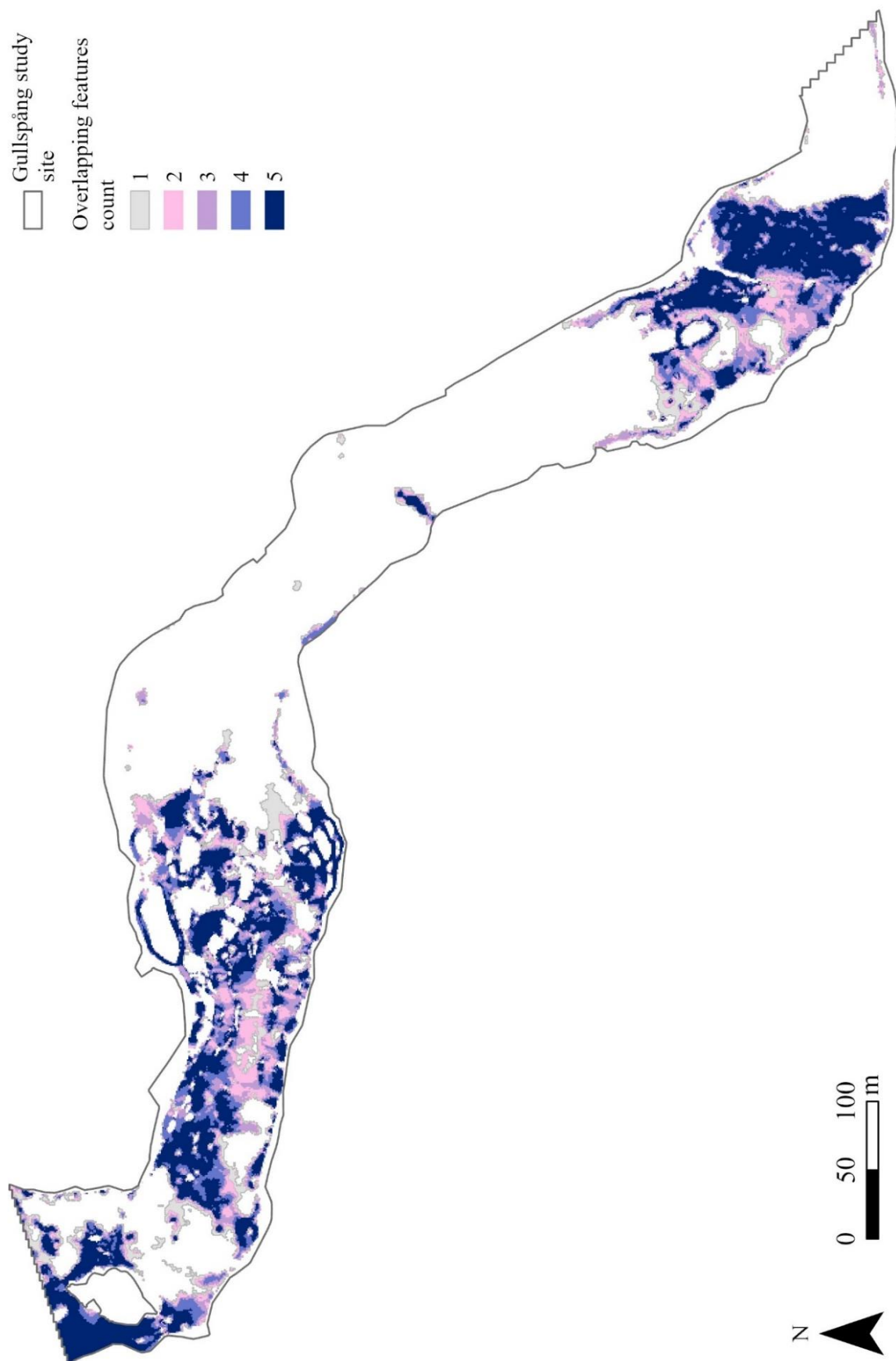


Figure 36. Overlapping habitat prediction in varying discharge conditions in Gullspång study site with brown trout 1+ 2+ habitat rule.

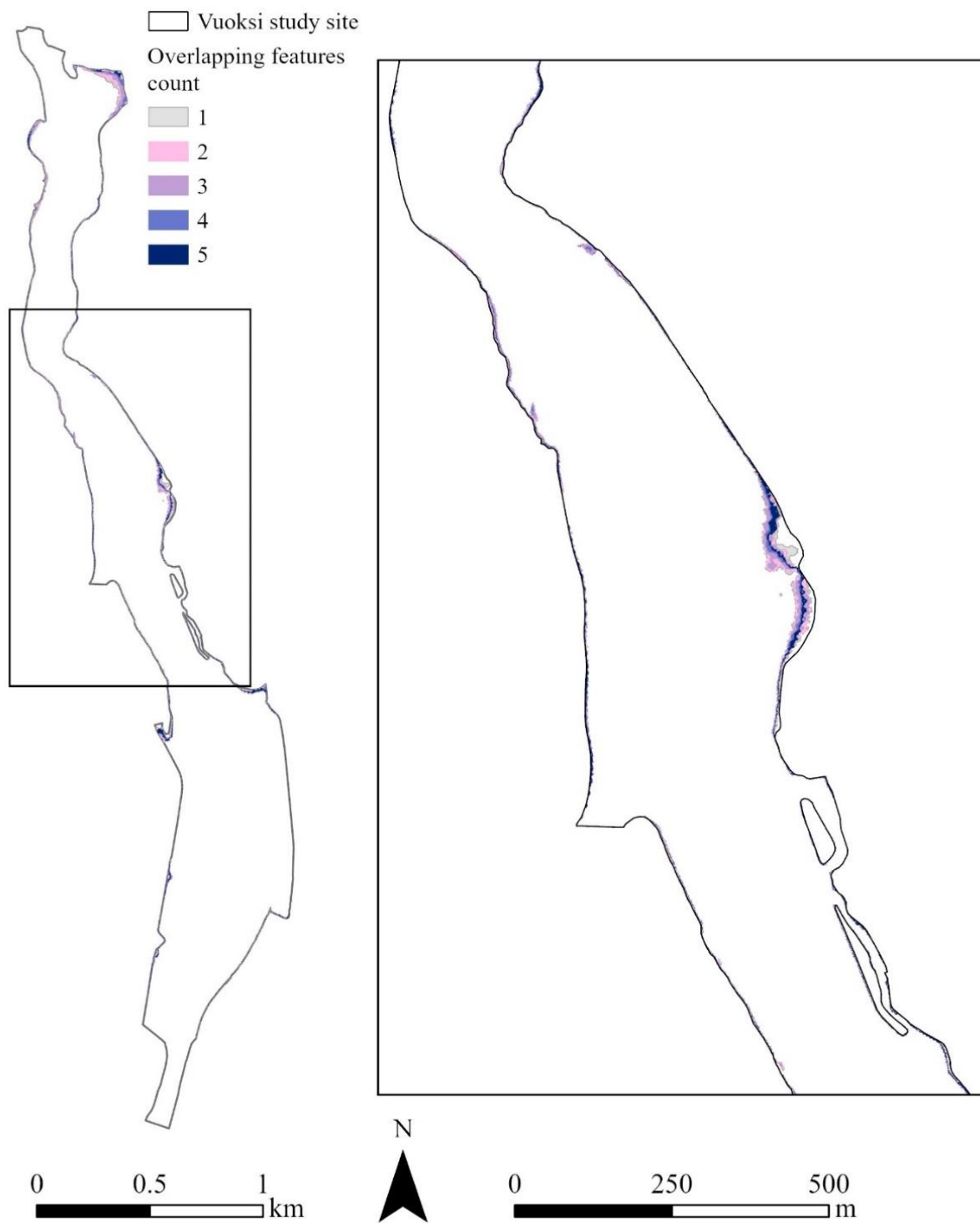


Figure 37. Overlapping habitat prediction in varying discharge conditions in Vuoksi study site with brown trout 0+ habitat rule.

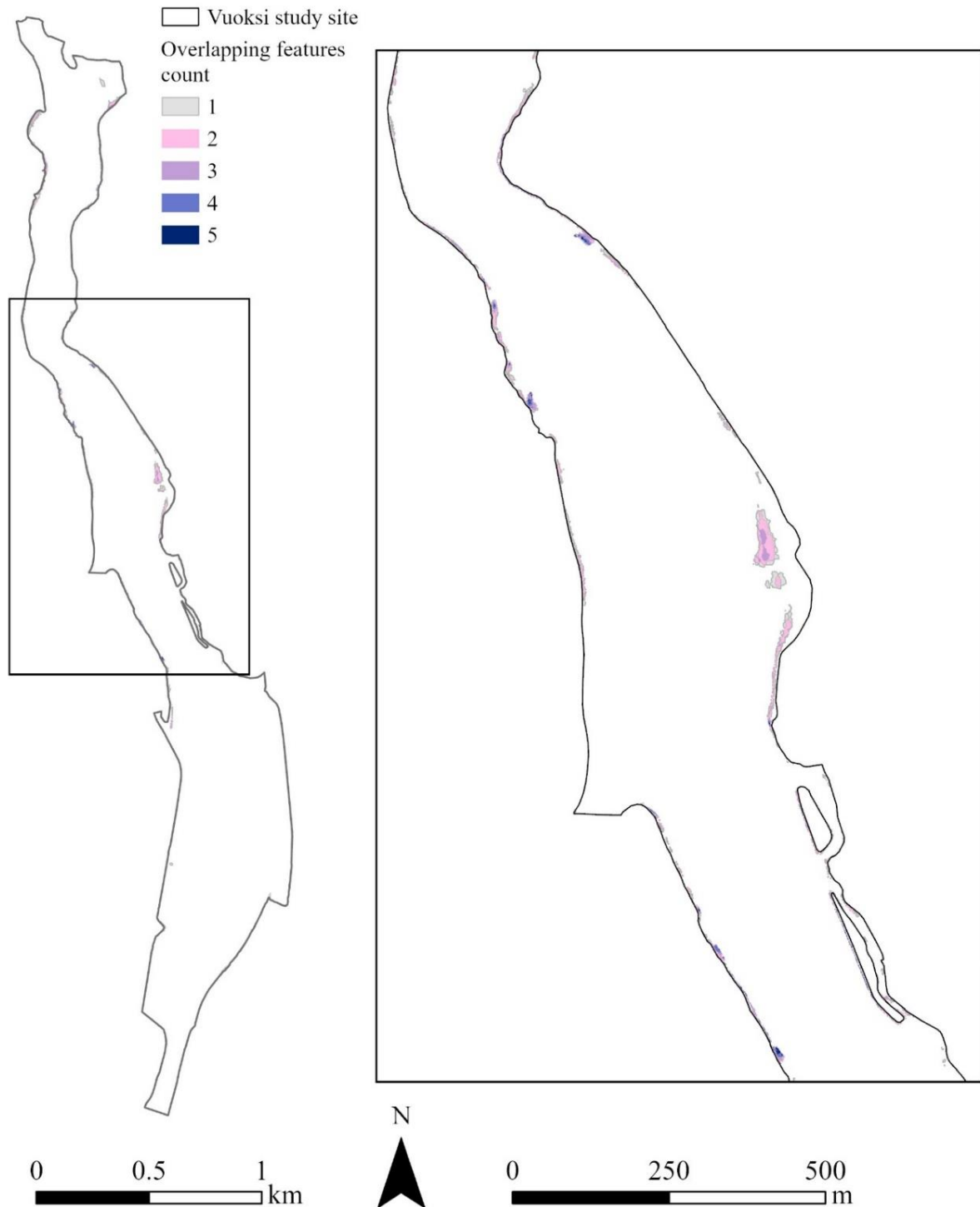


Figure 38. Overlapping habitat prediction in varying discharge conditions in Vuoksi study site with brown trout 1+ 2+ habitat rule.

I analyzed further the areas and discharge conditions, where predicted habitat occurred in only one discharge condition (tables 14–15). In Gullspång, the trends were similar with both species and age groups (table 14). Largest proportions of only one overlapping habitat feature were with the smallest discharge condition ($9 \text{ m}^3/\text{s}$) (74.8–94.6 %). If discharges drop from $15 \text{ m}^3/\text{s}$

to 9 m³/s, new habitat is formed and vice versa if discharges increase from 9 m³/s, some habitats were lost. The second largest proportion is with Q 30 m³/s, which indicates that in the highest discharge condition, new habitat areas were still formed.

Table 14. The proportion (m² %) of discharges scenarios from the areas where habitat appears only at one discharge condition, per habitat rule in Gullspång study site.

Q (m³/s)	Atlantic salmon 0+	Atlantic salmon 1+ 2+	Brown trout 0+	Brown trout 1+ 2+
9	86.2 %	74.8 %	94.6 %	74.8 %
15	2.6 %	9.1 %	0.3 %	9.1 %
20	0.8 %	2.1 %	0.2 %	2.1 %
25	0.7 %	1.5 %	0.2 %	1.5 %
30	9.6 %	12.5 %	4.8 %	12.5 %

In Vuoksi study site, the largest proportions (51,1–51,6 %) of only one overlapping habitat feature with both brown trout life stages were with the highest discharge (1000 m³/s) (table 15). The proportions with other discharges however varied significantly between the rules. With the brown trout 1+ 2+ rule the proportion decreased gradually with the decreasing discharge, and the smallest discharge condition counts only 0,6 % of the area. The gradual change indicates that the habitats areas predicted with the smallest discharge condition (200 m³/s) were stable and persisted also the growing discharge, while also new habitat areas were formed with growing discharges. With the brown trout 0+ rule the area of only one overlapping habitat feature with smallest discharge (200 m³/s) counted (45.3 %) for nearly as much as with the largest discharge (1000 m³/s) and the three middle scenarios counted only a very small share (0.0–2.9 %). The stability was high in the habitats predicted with the mid-discharges and new habitat areas were formed with the smallest and highest discharge conditions.

Table 15. The proportion (m² %) of discharges scenarios from the areas where only habitat appears only at one discharge condition, per habitat rule in Vuoksi study site.

Q (m³/s)	Brown trout 0+	Brown trout 1+ 2+
200	45.3 %	0.6 %
300	0.0 %	3.0 %
500	0.7 %	19.9 %
800	2.9 %	24.8 %
1000	51.1 %	51.6 %

It is logical that the largest proportions of such habitat areas where habitat was predicted only with one discharge condition were with the smallest and largest modelled discharges, since they were the limits of the modelled discharge range. Especially in the Gullspång study site the dominance of smallest modelled discharge ($Q\ 9\ \text{m}^3/\text{s}$) was significant (table 14). That indicates that the habitat rules chosen for the species preferred shallower water and lower velocities, which were provided with the smallest discharge. Overall, most habitat was predicted with $9\ \text{m}^3/\text{s}$ discharge condition in Gullspång with all rules (figure 17). In Vuoksi, there was a drastic growth of habitat area with increasing discharges with the rule brown trout 1+ 2+ (figure 18 b), which was also seen in the high proportion of newly formed habitat in higher discharge conditions (table 15).

The habitat stability was analyzed also visually. While the numbers showed poor temporal connectivity of habitat patches in terms of habitat overlap in Vuoksi (table 13) and the maps (figures 37–38) of overlapping features also provides information on the location of the habitat patches. In the Vuoksi study site, it was seen that even with poor overlapping, the habitat patches of different discharge conditions were located close to each other in the shallow depths in the sides of the channel. The chosen discharge conditions had large $100\text{--}300\ \text{m}^3/\text{s}$ difference, which may have caused the poor stability. In real environment, it takes time for the discharge alterations to happen. Therefore, it can be argued that the habitats might have good connectivity because the changes take time and the habitat areas in different conditions were located right next to each other in clusters, even it does not seem so in the light of statistics.

In Gullspång study site, the visual analysis supported the finding of the overlapping habitat feature statistics (tables 11–12). It was observed from the maps (figure 33–36) that the habitat patches that do not overlap in other discharge conditions were mostly located next to better overlapping areas. Larger areas without habitat overlapping with other discharge conditions were mostly located in the mid-channel. Also, there was some instances where smaller patches without habitat overlap were quite isolated from the other suitable areas. There, the connectivity to other patches was poor and based on this model these areas do not provide suitable habitat to survive, since they exist only in one discharge condition.

As a result, the visual analysis can provide more information of the habitat than statistics alone. They can be used together to gain a better understanding of the quality and stability of habitats. Habitat quality can be observed as the quality in one discharge environment, or as the stability between suitable habitat patches between in multiple discharge environments. The two different

study sites which produced different results show that also knowledge of the local environment is always needed in the interpretation of the modelling results.

7 Discussion

Microhabitat modelling was performed in two regulated rivers. Having two study sites with very different physical characteristics offered a good opportunity to examine the functioning of a habitat model and how different parameter changes affect the results. Different environmental characteristics also offered different perspectives on the interpretation of habitat quality and stability.

A common result from all analysis was that there was great variation of predicted habitat area and the effect of parameter changes between the two study sites. It would require more study sites and hydraulic models for comparison to draw better conclusions on how the model reacts to different parameter changes and environments. Different results from two areas highlighted the importance of knowledge of the local environment when choosing parameters and analyzing the model results.

The effect of analysis cell size and the impact of minimum patch size on the predicted habitat area was tested. The impact of the analysis cell size (0.5, 1 or 2 meters) on the predicted total area of habitat depended on study site and discharge. Compared to the total study area, the effect of cell size on the predicted total habitat area was small. I suggest that the final decision of the cell size should be decided based on the desired resolution of the habitat analysis, whether a high-resolution micro-scale analysis is wanted or if the target is to do a larger meso-scale analysis, even larger cell sizes than tested in this thesis can be selected. Also the study site plays a role in the selection of the correct cell size. If the bathymetric of the channel is very steep, like the channel of Vuoksi which has steep rapidly changing bathymetry on the sides of the channel, it is recommended to use smaller cell size to avoid excess interpolation which would result in losing important water depth information.

Also, the resolution of the field data and hydraulic model grid density should be kept in mind to avoid too much interpolation. If the source data has a high spatial resolution, also small cell size can be used. However, in some cases time and computation power can be saved by choosing a larger cell size. That way also excess interpolation can be avoided. It was seen in the Gullspång study site that the largest (2 m) cell size produced largest predicted fish habitat area. This might indicate that larger cell size might overestimate the area of fish habitat. Also, information about small habitat patches can be lost with larger cell sizes. In case very small

predicted habitat patches are not considered suitable for the species, they can be later filtered out from the model result using a minimum patch size threshold.

Using a minimum patch size threshold was tested in order to see how it affects the results. As expected, using the threshold has a minor impact on predicted total habitat area if the habitat is widespread and comprised of large patches, such as seen in the Gullspång study site. In cases where the habitat patches are small and scattered, using the patch size threshold has a larger effect on predicted total habitat area. Based on the result, the effect of applying the patch size threshold on the predicted total habitat area depends on factors that influence the size of individual patches, i.e., species, age group, study site, discharge and analysis cell size.

Minimum patch size affects the total habitat area that is formed, but the concept of limiting too small patches is closely tied to the idea of habitat quality and connectivity. The limitation can be used in analysis if a modeler thinks that too small individual patches should be limited from the end results. Naturally, if there is a larger habitat patch the fish have more area to live in which also offers more flexibility for the fish to move in case of changes in the environment or a threat occurs. Also sufficient amount of habitat is needed for spawning (Bjornn & Reiser, 1991).

I do not suggest that always a certain minimum patch size should be used, since it should be decided based on the examined species and its known habitat requirements. To take the habitat connectivity into consideration I would set some limit for habitat patches, especially if using the smallest cell size of less than one meter. Having larger patch size already sets the minimum patch size automatically to be larger, for example with 2 m cell size the minimum patch size is 4 m². Limiting the minimum patch size can be also considered as an unnecessary step. In natural environments there can be in fact more and larger patches of suitable habitat than the model produces, and even the smallest habitat patches can be considered as indicators of habitat suitability. The two-dimensional model does not take into account the vertical differences in flow conditions. In reality, there can be suitable habitat available for example closer to the bottom, but the suitable habitat patch was not predicted based on the two-dimensional model. Two-dimensional model is a simplification of a three-dimensional environment, which provides only one value for the flow velocity (usually presenting the value in the middle of the water column) and does not take into account vertical the vertical variation in flow velocities. Even if the flow value based on the two-dimensional model is considered to be too fast for suitable habitat the velocity can be suitable close to the bottom of water column, since generally

velocities are greatest in the middle part of the channel and lower closer to the channel bed and margins (Gilvear & Jefferies, 2017: 493-501) as presented in figure 1. Therefore, even smaller predicted habitat patches can be considered as indicators of suitable habitat, and they don't have to be necessarily filtered from the results.

The habitat quality in different discharge conditions was analyzed. By dividing the suitability range, the spatial distribution of habitat areas and their quality can be analyzed visually from maps. Already with the tested two classes (optimal and suitable) it is seen that the quality of habitats is often spatially continuous, where the optimal habitat patches are surrounded by suitable habitat, which is surrounded by areas that are not suitable for the species.

The stability of habitat in varying discharges can be observed by analyzing the overlapping of habitat patches in changing discharge conditions. It can be analyzed, in what kind of discharge conditions new habitat patches are created and when they are lost. For example, in Gullspång it was seen with all rules, that there is most habitat when the discharge is very low ($9 \text{ m}^3/\text{s}$), and a great proportion of the habitat is lost when the discharge grows to $12 \text{ m}^3/\text{s}$.

The overlay analysis provides information of the stability. Visual interpretation of the overlay analysis is also needed since only the statistics of overlapping habitat features do not tell the whole reality of habitat stability. That was especially visible in Vuoksi, where most of the suitable habitat is located on the sides of the channel as narrow strips, since the channel is deep, and the banks are steep. This environment did not produce much overlapping in different discharges since there was no habitat in cross-channel direction, like in Gullspång. However, the visual analysis of the results showed that habitats were still located really close to each other even though they did not overlap. One reason for poor overlap can also be the modelled discharge conditions which have large differences ($200\text{--}300 \text{ m}^3/\text{s}$). Therefore, also visual analysis of the habitat stability should be performed.

When considering the real discharge variation, the temporal resolution of this study is limited. Examining individual discharge conditions does not represent the connectivity in real environment, where the change is gradual, and the fish have time to relocate from increasing flow velocity into calmer areas. Especially in the Vuoksi study site, the steps between discharge conditions examined in this thesis are notable. To examine the connectivity aspect of habitats more thoroughly, I suggest aiming for a more dynamic approach that was tested in this thesis. Examining smaller discharge steps, could provide insights into the rate of spatial habitat shift and the real connectivity of habitats at various discharge levels. Taking temporality into account

by knowing how fast the flow conditions react to discharge alterations would provide tools to analyze whether fish have adequate time to adapt to changing discharges. In that way the effects of hydropeaking, i.e., the impact of rapidly rising and falling water levels due to hydropower production, on habitats could also be better analyzed and understood. The impact of hydropeaking on fish habitats might be notably different from the impacts of gradual changes in discharge.

There are many uncertainties in the results, since they are based on mathematical models, which are always simplifications of the real world (Ji, 2017: 285). Especially when modeling highly dynamic river environments where direct measurements are challenging, simplifications e.g. by using a hydraulic model are necessary. Measurement errors can occur in the data acquisition, which affects the creation of the digital elevation and bathymetric models. Especially in the two-dimensional hydraulic models, the accuracy of the DEM plays a crucial role in the model accuracy (Jowett & Duncan, 2012). The two-dimensional hydraulic model simplifies the river processes heavily, since vertical velocity distributions and other three-dimensional effects are assumed to be uniform (Steffler & Blackburn, 2002). Also, any environmental changes, e.g., restorations that alter the bathymetry, affect the flow conditions and water depth. Therefore, up to date measurement data should be used as the source data.

The habitat suitability criteria are assumptions of population's habitat preferences. The habitat rules for each species and age group in this thesis were chosen from literature, where preference values are formed through observations in different rivers, which does not perfectly translate to the study sites. Habitat rules have also other limitations, e.g., they don't take predation into account. For example, with the rule brown trout 0+ still and very slowly flowing water are within the suitable range, which might be also favorable for pike, which is a natural predator of trout. The rules used were examples, and the geospatial tool allows the user to decide which suitability rules to use. Habitat suitability rules have the largest impact on the results of the habitat modelling, and the decision of habitat rule can have a great effect on the results. Also, in the research of Lahti (2009: 232) in the two-dimensional modelling of aquatic habitats, the selection of habitat preference curves and the density of field measurements were found to have the greatest effect on results.

It should be kept in mind that habitat preference is different than habitat utilization when analyzing the spatio-temporal patterns of fish habitats (OECD, 2017). Habitat preference refers to the habitat requirements of microhabitat that an individual is looking for. In real

environments habitat utilization is a trade-off between the requirements and how these can be met by availability within the habitat. In Gullspång both juvenile salmon and trout were studied within the same study area, but the relationships between different habitat rules was not analyzed. Juvenile salmon and trout are reported to compete over the same resources (e.g., Berg et al., 2013; Heggenes et al., 1999), which might affect their habitat utilization.

The two-dimensional hydraulic model does not take into account the vertical velocity distribution in the river, which is assumed to be uniform. That is a limitation in microhabitat modelling, since the vertical velocities seems to have importance for salmonids (Steffler & Blackburn, 2002). Juvenile salmon and trout are often found close to the river bottom which provides shelter especially in swift currents and deeper parts of the river (e.g., Heggberget, 1991; Linnansaari, 2003; Linnansaari et al., 2010; Bremset & Heggenes, 2001). Therefore, habitat models based on a two-dimensional hydraulic model should not be considered as the exact representation of real-world environments. Due to the uncertainties mentioned above, it is important to highlight that the results of this thesis provide a simple test of the sensitivity of the predicted habitat to parameter changes and the methodology also provides tools to present habitat durability in changing discharge conditions.

Since habitat modelling is performed using the hydraulic model, getting desired result might require iteration in both modules by performing the habitat model for the first version of hydraulic model, information is gained where the habitat patches are located. Then, the hydraulic model grid density can be increased based on the collected field measurements in the areas of interest to get more accurate model from these areas, after which habitat modelling can be performed again with enriched information. Also, more field data can be gathered from the areas of interests. Through this kind of iteration high spatial resolution can be targeted to desired locations.

In the future use of the habitat modelling methodology, the user can add more variables, e.g., bottom substrate, to the suitability rules to improve the analysis. Salmonids prefer gravel substrate for spawning, and the suitability of the substrate depends mostly on fish size, but salmon and trout prefer a range from 1.3 to 10.2 cm in diameter (Bjornn & Reiser, 1991). Substrate suitability modelling can be complex, as when the flow velocity increases, some grain sizes are more prone to erosion. However, the results using flow velocity and depth only can provide important information on the habitat conditions for juvenile salmon and brown trout. Millidine et al. (2016) suggest avoiding complex hydraulic habitat models for juvenile Atlantic

salmon, and those containing hydraulic variables alone should be considered if predictions of habitat quality are to be made at new sites.

The presented habitat modelling methodology Provides new tools for analyzing dynamic habitat changes, their spatial connectivity and temporal durability in changing flow conditions. The tool is flexible and enables users to define different parameters that affect the result. Suitable parameter values can be decided based on the scope of the study and the characteristics of the modelled environment. Therefore, it can be also applied in rivers and streams of different sizes and on meso- and microscale in regulated rivers.

Finding a balance between parameter settings in habitat modelling requires user's knowledge of the target species and its habitat requirements as well as hydraulic modelling and GIS analyzes. It is important for the user to acknowledge the limits and simplifications of geospatial models.

The habitat modelling methodology can be helpful in restoration planning to create more suitable habitat for fish species in rivers. An automated tool which derives habitat modelling results from bathymetric and flow velocity point clouds saves time and multiple scenarios can be quickly compared. The parameters should be however always decided based on the study site, available field data and the scope of the study. It is important to have the right tools and methodology to provide different modelling scenarios. Especially for the salmonid species, like Atlantic salmon and brown trout, which have complex life cycle and different habitat requirements in different life stages. Testing the methodology and parameters with different habitat rules showed the result variation with different combinations. Habitat modelling should be used to improve the habitat conditions of fish species, especially in regulated rivers where the fluvial environments are modified by humans.

Acknowledgements

I am thankful to my supervisors, Professor Petteri Alho and Associate Professor Tua Nylén, for insightful comments and support in completing this thesis.

Thank you to Fortum Power and Heat for providing the source data and offering me the invaluable opportunity to deepen my understanding of hydropower production in the Nordics and the environmental management and technological development surrounding renewable energy. I am truly grateful to have been part of this project. Special thanks goes to Heini Auvinen for the mentorship, trust, and support throughout the thesis process and other projects I had the privilege to be involved in!

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