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Simo Tammela

ENHANCING MIGRATION AND REPRODUCTION OF SALMONID FISHES

METHOD DEVELOPMENT AND RESEARCH USING PHYSICAL AND NUMERICAL MODELLING

UNIVERSITY OF OULU GRADUATE SCHOOL;
UNIVERSITY OF OULU,
FACULTY OF TECHNOLOGY,
DEPARTMENT OF PROCESS AND ENVIRONMENTAL ENGINEERING

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Method development and research using physical and numerical modelling

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Abstract

Dam building for hydropower production, dredging for log floating and drainage of peatlands have massively affected migrating salmonid populations in Finland. Increased sedimentation and changes in hydraulic conditions have destroyed the majority of spawning and rearing habitats in freshwater brooks and dam building has stopped migration upstream at river mouths.

This thesis examines the current state of drained forest brooks, possibilities for restoration and methods to assist migration in rivers used for hydropower. Drainage down to the mineral soil has caused massive erosion and sedimentation in headwater brooks. The surface layer of a sand bed is constantly moving, preventing vegetation growth, while shortcuts created during drainage increase flow velocity and reduce retention time. The cross-sectional and longitudinal profiles become homogeneous and biodiversity is severely reduced. A simple wooden brook restoration structure was developed in laboratory experiments.

Fish migration problems past a hydropower dam and reproduction possibilities offered by a natural-like bypass channel were studied in the river Oulujoki, the mouth of which was blocked by a hydropower dam in the late 1940s. Public pressure for remedial structures has grown since then and was given a boost after a fishway was opened at Merikoski, in the river mouth, in 2003. This thesis examined the next dam upstream, Montta at Muhos, which was studied separately as a partial and sole natural-like bypass. A natural-like bypass can offer stable conditions for spawning and rearing and can be designed precisely, through water flow and habitat modelling, to match desired conditions. The most important section in a fishway is ultimately the entrance. Fishway discharge is often merely a fraction of whole river discharge and the attractivity of the entrance can be increased by pumping additional discharge to the lowest part of the fishway. The hydraulics of a twin-slot vertical slot fishway were studied here by laboratory flume testing and 2D water flow modelling. Water flow and habitat modelling proved to be good tools in designing partly natural-like bypasses. However, fish behaviour should be closely monitored in any natural-like fishways already built, in order to verify the results of habitat modelling.

Keywords: fishway, habitat, migration, modelling, natural-like, restoration, spawning, vertical slot

Tammela, Simo, Lohen ja taimenen vaelluksen ja lisääntymisen edistäminen. Menetelmien kehittäminen ja tutkimus fysikaalisen ja numeerisen mallinnuksen avulla
Oulun yliopiston tutkijakoulu; Oulun yliopisto, Teknillinen tiedekunta, Prosessi- ja ympäristötekniikan osasto
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Tiivistelmä

Jokien patoaminen vesivoiman tuotantoon, ruoppaaminen puunuiton helpottamiseksi sekä latvapurojen ojitukset metsän kasvun edistämiseksi ovat voimakkaasti vaikuttaneet vaeltavien lohikalakantojen vaellus- ja lisääntymismahdollisuuksiin. Muuttuneet hydrauliset olosuhteet ja lisääntynyt sedimentaatio ovat tuhonneet lohikalojen lisääntymisalueet ja patoaminen on katkaissut ylösvaelluksen lisääntymispaikoille. Väitöstyö koostuu viidestä artikkelista, joissa esitellään uusia menetelmiä ja ratkaisuja lohikalojen vaelluksen ja lisääntymisen ennallistamiseksi.

Kaksi artikkelia keskittyy ojituksesta kärsivien latvapurojen nykytilaan, kunnostusmahdollisuuksiin sekä kunnostusrakenteen kehittämiseen. Paikoin ojituksen seurauksena on ollut massiivinen mineraalimaan eroosio ja hienon hiekan sedimentoituminen puroihin. Puroihin on kertynyt paksuja hiekkakerroksia, joiden pintakerros on jatkuvassa liikkeessä. Pintakerroksen jatkuva liike estää kasvillisuuden kasvamisen. Osittain ojitus on myös oikaissut puroja, jolloin virtausnopeudet ovat kasvaneet ja veden viipymä lyhentynyt. Purojen pituus- ja poikkileikkauksen vaihtelu ja biodiversiteetti ovat on vähentyneet huomattavasti. Laboratoriokokeissa kehitettiin yksinkertainen puusta rakennettava kunnostusrakenne hiekoittuneiden purojen kunnostamiseksi.

Kolme artikkelia käsittelee Oulujokea, kalateiden suunnittelua ja kalatierakenteita. Vuonna 2003 rakennettu Merikosken kalatie kasvatti paineita kalatierakentamiseen Oulujoen muille voimalaitoksille. Erityisesti väitöstyö keskittyi Montan voimalaitoksen ohitukseen suunniteltuun kalatiehen, jota tutkittiin virtausmallinnuksen avulla kokonaan ja osittain luonnonmukaisena ohitusuomana. Luonnonmukainen ohitusuoma voidaan suunnitella toimimaan kutukanavan tyyppisenä uomana, jonka tarkoitus on tarjota vakaat virtausolosuhteet lohikalojen lisääntymistä varten. Virtaus- ja habitaattimallinnuksen avulla uoma voidaan suunnitella tarkasti haluttujen virtausolosuhteiden mukaisesti. Kalatien toimivuuden kannalta tärkeintä on että kalat löytävät kalatien sisäänkäynnin. Kalatien virtaama on usein vain murto-osa koko joen virtaamasta, joten sisäänkäynnin houkuttavuutta voidaan lisätä lisävettä pumppaamalla. Kaksirakoisen pystyrakokalatien hydrauliikkaa tutkittiin sekä laboratorio- että virtausmallilla.

Asiasanat: habitaatti, kalatie, kunnostus, kuteminen, luonnonmukainen, mallinnus, pystyrako, vaellus

To my grandfather

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List of symbols and abbreviations

b	Real slot width
b_0	Characteristic slot width
$c_{\mu1}$, $c_{\mu2}$	Kinematic eddy viscosity coefficients
g	Gravitational acceleration
L	Pool length
Q	Discharge
Q_*	Dimensionless discharge
S_0	Channel slope
WUA	Weighted usable area
y_0	Mean water depth in the pool
ν_{t0}	Base kinematic eddy viscosity

List of original articles

This thesis is based on five original publications, which are referred to in the text by their Roman numerals:

I Tammela S & Kløve B (2013) Design of twin-slot vertical slot fishways based on flume tests and numerical modeling. Manuscript.

II Tammela S, Jormola J, Järvenpää L & Kløve B (2008) 2D Water flow and habitat modeling of a nature-like bypass at Montta water power plant in River Oulujoki. Proceedings of the Fourth ECRR Conference on River Restoration.

III Tammela S, Palosaari O, Kamula R & Kløve B (2012) Optimisation dilemma: Combining well-functioning entrance, varying flows, habitat and landscaping in the Montta fishway at the River Oulujoki, Finland. Published in the 9th International Symposium on Ecohydraulics 2012 Proceedings. Edited by Helmut Mader & Julia Kraml.

IV Tammela S, Marttila H, Dey S & Kløve B (2010) Effect and design of an underminer structure. Journal of Hydraulic Research 48(29): 188–196.

V Marttila H, Tammela S & Kløve B (2012) Hydraulic geometry, hydraulics and sediment properties of forest brooks after extensive erosion from upland peatland drainage. Open Journal of Modern Hydrology 2: 59–69.

The author's contribution to publications:

I: Designed the study, performed flume tests and modelling and wrote the article. Bjørn Kløve critically commented on the manuscript.

II: Planned and modelled the bypass and wrote the article with co-authors, who critically commented on the manuscript.

III: Participated in the planning process for fishways in the river Oulujoki and wrote the article together with co-authors. Bjørn Kløve critically commented on the manuscript.

IV: Designed the study with co-authors, organised, conducted the laboratory work and data analysis and wrote the article with Hannu Marttila. Bjørn Kløve and Subhasish Dey critically commented on the manuscript.

V: Designed the study with co-authors, organised, conducted the field measurements and data analysis and wrote the article with Hannu Marttila. Bjørn Kløve critically commented on the article.

Contents

1 Introduction

People have been interested in the life cycle and migration of Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*) since they first began to be used for food. Differing outlines of their life cycle were presented during the 16th Century, but general agreement was reached during the 1860s (Mills 1989). In 2011, Aas *et al.* published a literature review "Atlantic salmon ecology" with over 50 contributors and reviewers. The following three paragraphs provide a short summary of that review.

The life cycle of Atlantic salmon and brown trout begins in a gravel pack in a riffle of a river. Buried eggs need a steady flow of water through the gravel to deliver oxygen. The oxygen demand grows with increasing water temperature and size of eggs. Deposited sediment decreases the oxygen concentration, causing poor survival of eggs (Louhi *et al.* 2008). Fertilised eggs remain in the gravel nest until spring, when *alevins* hatch from the eggs. The alevins remain in the gravel for 3–8 weeks before emerging and starting feeding as *fry*. Juveniles spend at least one year in fresh water close to the area where they were born. This *parr* phase is typically from 1 to 2 years, but can last up to 8 years, depending on the latitude, environmental conditions and genetics, before the parr *smoltify*. Smolts migrate to feeding areas in the sea, driven by water temperature and partly by spring floods. Salmon migrate far away from the home river, while trout feed closer to the shoreline. Trout often have freshwater populations feeding in lakes and some local populations can be found in rivers (Jonsson & Jonsson 2011). Salmon also have freshwater population in large lakes.

Feeding migration of salmon lasts from 1 to 4 years, whereas trout migration is from a few months to 5 years. Salmon and trout start their first spawning migration on reaching maturity. Migration timing varies according to latitude of the home river and distance to be travelled. Migration often stops at the river mouth while the fish wait for suitable migration conditions, for example discharge and water temperature. Salmon can also stop in river pools or lakes for varying periods. The salmon migration distance is often several hundred kilometres to over one thousand kilometres.

The spawning grounds of salmon are often in the main river channel or large side channels. The salmon enter the river well before spawning time, but the final approach to the spawning grounds happens just before actual spawning. Migration distances of trout are shorter and more continuous, without long stops in pools. Trout spawn in smaller reaches of rivers up to very small forest brooks with discharge of only few hundred litres per second. Local populations can migrate a few kilometres between spawning grounds and feeding areas. The Atlantic populations of salmon and trout spawn several times during their life. Post-spawning individuals, *kelts*, often return to feeding areas soon after spawning, but they can also stay in the river until the next spring. Both Atlantic salmon and brown trout survive reproduction and can spawn again (Jonsson & Jonsson 2011).

In the 19th Century, hydropower was used to run sawmills and grain mills. The first hydropower dam in Finland was built in Tammerkoski, Tampere, in 1891. Until the mid-20th Century, it was forbidden to block whole rivers in Finland, but because of the great energy need after World War II and war reparation to the Soviet Union, the laws were changed to allow full blockage of rivers in the Bothnian Bay area (Erkinaro *et al*. 2011). Hydropower development disregarded environmental and social impacts and dam building broke the life cycle of Atlantic salmon and brown trout (Erkinaro *et al*. 2011). Upstream migration is impossible without fishways. Downstream migration is possible, but turbines and pressure changes through turbines cause high mortality (Calles & Greenberg 2005, Rivinoja 2005). In addition, hydropower dams cause delay and increased predation (Koed *et al.* 2002, Aas *et al.* 2011). Hydropower usage has changed the characteristics of rivers. Hydropower dams are often built at the downstream end of riffle sections and riffles are replaced by pools. This changes the hydraulic conditions to make them unsuitable for spawning and affects salmon spawning in particular. In 1987, a new law to protect free rivers and riffles was passed in Finland and new permits to build hydropower dams have not been granted since then.

Drainage of forest and peatland in Finland has caused massive erosion in the drained areas and sedimentation into headwater brooks. This has resulted in a permanent thick sediment cover on top of the gravel beds used by trout, preventing spawning. In the smallest rivers, where both salmon and trout have spawned in the past, dredging to allow log floating has destroyed rivers with natural gravel suitable for spawning. The largest rivers have also been dredged for log floating and to reduce losses for hydropower production (Erkinaro *et al*. 2011). Rivers in northern Sweden have suffered from similar dredging, removal of large woody debris and stones and bank armouring. Large woody debris and boulders are important factors in natural bar-pool formation and greatly affect the sediment-carrying capacity of rivers. Restoration activities to date in Northern Fennoscandia have focused on channel widening and removal of bank armouring, while in coastal British Columbia restoration work has concentrated on reducing sediment supply and restoring wood input (Rosenfeld *et al.* 2011). The majority of dredged log floating rivers have been restored to enhance spawning, but poor planning and lack of monitoring and research have led to erosion of spawning gravel (Erkinaro *et al.* 2011). In addition, erosion from upper reaches and drained areas has led to sedimentation in these smaller rivers, affecting egg survival in spawning areas (Laine *et al.* 2001).

The recreational value of many rivers has diminished because of loss of natural salmon and trout populations. Public pressure for fishway building and river restoration to recreate naturally breeding salmon and trout populations has grown and several projects have been launched. Naturally born salmon are a much more valuable sports fishing catch than hatchery fish. In Sweden, hatchery fish have their adipose fin cut off to distinguish them from wild fish. At Norrfors Dam in Umeälven, only wild fish are allowed to continue their migration upstream (Rivinoja *et al.* 2001). The European Water Framework Directive also aims for good ecological potential in heavily modified watercourses (Kamula *et al.* 2010, Erkinaro *et al.* 2011). The Directive does not require building of fishways, but fishways can raise the ecological state of heavily modified rivers from good to best ecological potential. The national fishway strategy was initiated in 2009 to create guidelines for strengthening the endangered fish populations. The main principle in the fishway strategy is to move the effort from fish stocking into fishway building. It also encourages stream restoration and water quality improvement actions.

Fishways can also be built to compensate for lost spawning grounds. Water flow and habitat modelling can be used as a tool in planning optimal spawning habitats in the natural-like bypass sections of fishways. Technical sections, vertical slot fishways for example, are often needed to control the discharge into the fishway and reduce the effects of water surface elevation fluctuations in the forebay and tailrace. The actual entrance is the most important part of the fishway. To improve the attractivity of the entrance to fish, higher discharge is often recommended. The direction of the jet from the entrance is also important.

Modelling can also be used in restoration planning in other river sections, including hydropower affected areas. In my Master’s thesis (Tammela 2006), I modelled restoration options for a section of the river Oulujoki to introduce spawning areas and create some possibilities for recreational fishing. The model output was then used to estimate the water surface elevation rise caused by restoration.

This thesis presents methods and technical solutions for use in hydropower-dominated rivers, where discharge is typically large and the variation in water surface elevation and discharge in the tailrace is rapid. This must be taken into account in fishway design (Papers I-III). The lack of spawning and rearing areas in the main channel can be compensated for by designing natural-like bypass channels instead of purely technical solutions such as vertical slot fishways. The current state of boreal forest brooks in the North Ostrobothnia and Kainuu areas is described in Paper V. To restore spawning and rearing areas in small forest brooks used by trout, these brooks can be restored and maintained by passive restoration methods. These simple and cost-effective wooden structures are presented in Paper IV.

1.1 Objectives

The main objective of the thesis was to examine the usability of 2D numerical water flow and habitat modelling in planning different types of fishways. With habitat modelling, new nature-like fishways can be designed to offer optimal spawning and rearing habitats for desired species in changing discharge scenarios. Secondary objectives were to calibrate flow models for single and twin-slot vertical slot fishways; identify characteristics of flow pattern formation in twin-slot vertical slot fishways; and develop restoration methods for sedimented forest brooks. The relationship between brook width or depth and geometry or hydraulic geometry was also studied to classify the state of northern forest brooks affected by peatland drainage.

Specific research questions were:

- Is it possible to simulate vertical slot fishways with a 2D hydrodynamic model?
- Is a twin-slot vertical slot fishway hydraulically similar to a single slot vertical slot fishway?
- Is habitat modelling useful in designing nature-like bypasses?
- Is it possible to restore the natural brook bottom profile and hydraulic characteristics by using simple wooden structures?
- Is it possible to build nature-like bypasses to offer the proper spawning and rearing habitat for Atlantic salmon and brown trout?

2 Previous studies

The first known actions in aiding migrating fish past barriers by building fishways were in the 17th Century in Europe (Clay 1995). In 1909, Denil developed a new type of fishway which was still used and studied in Finland and Canada in the 1980s (Clay 1995, Laine *et al.* 1998, Kamula 2001). Since then, a wide range of different technical solutions for solving the fish migration problem have been studied and built around the world (Clay 1995). Fishways are traditionally divided into three types, denil, pool-weir (Fig. 1) and vertical slot fishways. The vertical slot fishway is similar to the pool-weir fishway, but each weir has a vertical slot reaching from near the top of the wall to near the bottom of the fishway. During the past few decades natural–like small brooks have also been built. For example, the Merikoski fishway in the city centre of Oulu is a combination of vertical slot and natural-like fishways, while the Isohaara fishway in Kemijoki is a combination of vertical slot and Denil fishways. Hydraulically, vertical slot fishway performance is independent of water depth changes, while denil and weir fishways function only with a pre-set water surface elevation (Clay 1995). Another great advantage of vertical slots over weirs and orifices is that fish are able to swim through the slot at any desired depth (Clay 1995, Guiny *et al.* 2005). Fish lifts can also be considered a type of fishway. The main focus in this thesis was on studying vertical slot fishways with one or two slots and modelling natural-like fishways.

In the past, fishways were typically designed for migration of one or two species, but recently multi-purpose fishways for migration of all species present and also natural channels for reproduction purposes have been designed and built (Katopodis 1981, Laine *et al.* 1998, Jormola 2012). Many types of fishways are functional, but the most critical feature is the attractivity of the fishway entrance (Rivinoja *et al.* 2001, Laine *et al.* 2002, Karppinen *et al.* 2002, Lundqvist *et al.* 2008). Discharge through the fishway is typically only a fraction of the river discharge and the fishway discharge should stand out from the river flow. The efficiency of fishways has been studied mainly with radio telemetry (Webb 1990, Gowans *et al.* 1999, Rivinoja *et al.* 2001, Karppinen *et al.* 2002, Aarestrup *et. al.* 2003, Rivinoja 2005, Isomaa & Laine 2008, Lundqvist *et al.* 2008), fish counters (Isomaa & Laine 2008), visual observation (Webb 1990, Laine *et al.* 1998, Laine *et al.* 2002, Mader *et al.* 2012), tag return methods (Karppinen *et al.* 2002, Lundqvist *et al.* 2008), echo sounding (Lundqvist *et al.* 2008) and traps (Laine *et* *al.* 1998, Rivinoja *et al.* 2001, Mader *et al.* 2012). These studies have shown that fish entering the fishway very often also migrate through the fishway.

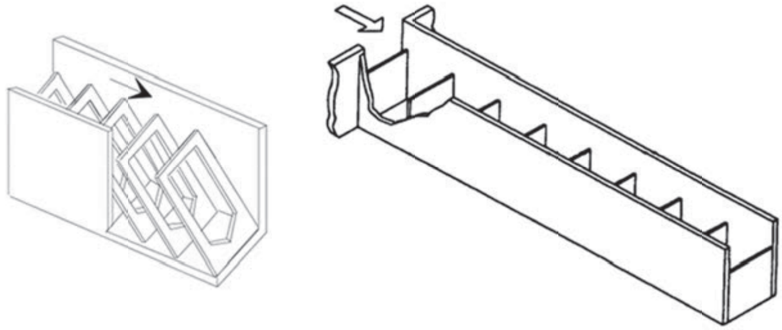

Fig. 1. Schematic picture of (left) a Denil fishway (modified after Kamula 1999) and (right) a pool-weir fishway (modified after Clay 1995).

2.1 Vertical slot fishways

Most vertical slot fishway studies reported during the past 30 years mention Hell’s Gate in the Frasier River in British Columbia, Canada, as the first vertical slot fishway built. According to Clay (1995), thorough physical model testing was done for Hell’s Gate planning, but these studies remain unreported. The first hydraulic studies on vertical slot fishways were reported by Rajaratnam *et al.* (1986) and Rajaratnam *et al.* (1992). They conducted model studies with 18 different vertical slot fishway designs with three slopes (5%, 10% and 15%) and wide range of discharges. They defined the relationship between discharge Q and dimensionless discharge Q_* and rating curves between Q_* and relative depth of the flow, y_0/b_0, where y_0 is average depth in the centre of the pool and b_0 is the characteristic slot width. Rajaratnam *et al.* (1992) recommended three designs for practical use because of their hydraulic performance. These structures are referred as designs #6, #16 and #18 (Fig. 2). Design #6 has a small deflector (0.5 b_0) at b_0 distance downstream from the slot. In designs #16 and #18, the opening between long baffle and side wall is 2.5 b_0 and short baffle length is 1.79 b_0. The distance between long and short baffles is b_0 and 0.7 b_0, respectively. Both these designs have an additional deflector upstream from the long baffle. In design #16, deflector length is 2 b_0 and it is located 0.71 b_0 away from the slot. In design #18 the additional deflector is a quarter circle with radius 1.5 b_0 and the perimeter of the deflector meets the edge of the long baffle. Rajaratnam *et al.* (1992) also recommended that pool dimensions length 10 b_0 and width 8 b_0 be used. These dimensions and designs, together with design #1, have been used in published studies by many other researchers. Wu *et al.* (1999) continued this research by measuring the flow velocities in the slots and pools of design #18. They also observed flow patterns and defined two flow patterns, 1 and 2. The difference between these patterns is the direction of the jet from the slot. In pattern 1, the jet is directed through the centre of the pool to the next slot, while in pattern 2 the jet is directed to the opposite corner of the pool. According to measurements by Wu *et al.* (1999), the flow is mainly two-dimensional (2D) with 5% slope and mainly three-dimensional (3D) with 10% and 20% slope. Kamula (2001) refined the scaling factor presented by Rajaratnam *et al.* (1986) by suggesting scaling factor and dimensionless discharge equations:

$$Q_* = \frac{Q}{\sqrt{gS_0 b_0^2 L^3}} \tag{1}$$

$$Q_* = 0.85\left(\frac{y_0}{L}\right)^{\frac{9}{10}} \tag{2}$$

where y_0 is mean depth in the pool, L is length of the pool, Q is discharge, g is gravitational acceleration, S_0 is slope, and b_0 is the width of the slot.

Liu *et al.* (2006) continued research on design #18 by measuring mean flow and turbulence structure. They noticed that flow velocity and mean flow kinematic energy dissipated faster in flow pattern 2. The flow from the slot could be treated as a planar jet, although there are number of differences from the planar jet. The mean velocity distribution is well described by the planar jet, but the growth rate varies at different horizontal planes. For example, the turbulence is different between the left and right halves of the water jet or with different slopes. A numerical free surface model was built by Barton *et al.* (2008) to predict flow velocity and turbulence in design #18. The model was verified by Barton *et al.* (2009) using datasets from White (2003) and Wu *et al.* (1999).

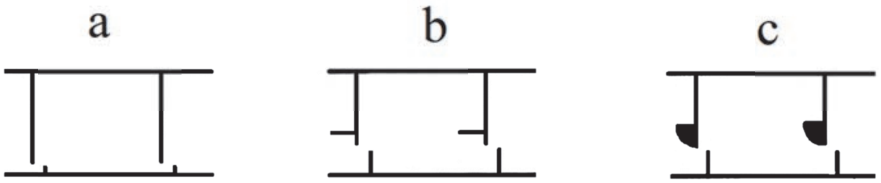

Fig. 2. Vertical slot fishway designs (a) #6, (b) #16 and (c) #18 (modified after Rajaratnam *et al.* 1992). Schematic view of designs with flow direction from left to right.

A research group in Spain has performed a series of studies on vertical slot fishways. Their main focus has been on designs #6 and #16. Puertas *et al.* (2004) measured 3D flow velocities and water depths in the slots and pools in the cases of two slopes and a wide range of discharges. They calculated dimensionless relationships between dimensionless discharge (Q_*) and Y_0/b, where Y_0 is mean depth at the middle traverse section and b is real slot width. Rodríguez *et al.* (2006) evaluated the same designs of vertical slot fishway in terms of fish swimming capabilities. They defined minimum discharges for salmon and trout with different slot widths assuming minimum depth to be 0.5 m for salmon and 0.4 m for trout. Maximum swimming distances were estimated by maximum swimming speed and endurance time as a function of fish length, considering also different water temperatures. The energy dissipation depended only on fishway slope and baffle geometry and was independent of discharge when discharge and depth were linearly related. The energy dissipation was very similar in both designs and, with the most commonly used slot widths (less than 40 cm), the acceptable values for salmon and trout were not exceeded (Rodríguez *et al.* 2006). Cea *et al.* (2007) used hydraulic data from Puertas *et al.* (2004) to test three different turbulence models with depth-averaged shallow water flow equations. Their results showed that 2D flow models can be used in modelling vertical slot fishways with gentle slopes, despite the fact that some modelling assumptions are broken, especially around the slot region. The most important of these assumptions is uniform flow profile in the vertical direction. With slopes higher than 10%, the flow field in the pools has more 3D characteristics and a 2D model is incapable of modelling these. Cea *et al.* (2007) also performed a sensitivity analysis on bed roughness and found no effect on flow velocities and patterns. Bermúdez *et al.* (2010) studied pool dimension effects on the biological efficiency of vertical slot fishways using design #6 with several different variations of pool length and width. They observed two different flow patterns, similar to Wu *et al.* (1999), and the 16 models they studied fell into four rating curves depending only on pool length/slot width ratio. Increasing pool length increased flow velocities in the slot and in the pools because of the higher drop between the pools. Bermúdez *et al.* (2010) also used a numerical model for each physical model and verified that the 2D depth-averaged shallow water equation with ƙ-Ɛ turbulence model is able to calculate water flow velocities and flow patterns accurately. Puertas *et al.* (2012) developed a computer application to quickly calculate important hydraulic parameters for vertical slot fishway designs #1, #6, #16 and #18. The application requires as input fish species, fishway type, total height of the obstacle, slope and maximum water depth to calculate pool and slot dimensions, pool number, length of the fish swimming route and minimum and maximum discharges.

Tarrade *et al.* (2008) measured changes in flow velocities and turbulences with a vertical cylindrical pole installed in the path of the jet from the slot. The pole diameter was equal to the slot width. Test runs were conducted with three slopes, three discharges and four pool widths. The aim of the study was to find solutions to ease the passage of small species, which can be trapped in large circulating areas in the pools. The cylindrical pole split the jet into two, reducing flow velocities below the slot, creating two smaller recirculation areas behind the pole and reducing the size of the large recirculation area. Tarrade *et al.* (2008) also tested half cylinders and two cylinders, but one cylinder at location X= 2.1 b_0 downstream and Y = 3.1 b_0 from the slot proved to be the best solution to prevent strong recirculation flows being formed.

Chorda *et al.* (2010) computed flow velocities, depths and patterns using the TELEMAC-2D model for a modified version of design #1 and compared the results obtained to measurements from a 1:4 scale physical model. Their conclusion was similar to that of Bermúdez *et al.* (2010), i.e. that the 2D depth-averaged flow equation with second order ƙ-Ɛ turbulence model is suitable for vertical slot fishways, but overestimates turbulence in areas of strong velocity gradient. Khan (2006) also simulated modified design #1, with the STAR-CD 3D model, and produced results that match physical model results reported by Wu *et al.* (1999) and Puertas *et al.* (2004). Khan (2006) estimated swimming distance and time on three assumed swimming paths and constant swimming speed. Boavida *et al.* (2012) studied the uncertainty in habitat modelling with the 2D model. They used River2D, which is a "2D depth-averaged finite element hydrodynamic model coupled with a habitat modelling module" (Steffler & Blackburn 2002). Boavida *et al.* (2012) compared model results with measured values and found the uncertainty in simulated depth to be smaller than that in velocity. However, the uncertainty in measured depth was also smaller than the uncertainty in measured velocity. Electrofishing was used to locate and count numbers of target species in the study area. Comparison of these count data to habitat model output revealed that 27–49% of modelled weighted usable area (WUA) was occupied by fish. A maximum of 21% of fish were found in areas with WUA = 0. Three typically used variables are depth, velocity and bottom substrate, but according to Boavida *et al.* (2012) coverance should also be considered, as in their study individuals clearly chose highly covered areas. However, evaluating the amount of cover and submerged vegetation of woody debris is difficult. The value of these variables can change quickly through floods flushing woody debris or overhanging vegetation dropping leaves in autumn. The preferences of fish also change during the year and fish do not seek specific values of depth, velocity, substrate and cover, but a suitable combination of these (Mäki-Petäys *et al.* 1997).

A research group at the University of Applied Life Sciences in Vienna, Austria, has developed a multislot fishway (Tauber & Mader 2009). This, the enature® fishpass, is protected by patent and its name is copyrighted. In the enature® fishpass design there are two consecutive vertical slots separated by a local widening between each pool. These two slots are on a slightly different alignment in a narrow channel. This divides the drop between the pools into two, which reduces water flow velocities. The slot pairs alternate from side to side and water flows through the structures by a strongly meandering route. Tauber & Mader (2010) compared the hydraulics of a standard vertical slot fishway and the enature® fishpass. The fishway slope was adjusted to 7.5% and slot width was 15.75 cm. The minimum water depth of 60 cm was achieved with 44% lower discharge in enature® than in the standard vertical slot fishway. The maximum water flow velocity was 27% lower and the mean turbulent energy 19% lower. Mader *et al.* (2012) monitored the behaviour of two weak-swimming Danube fish species, the Danube salmon (*Hucho hucho*) and the catfish (*Silurus glanis*) in the enature® fishpass. Weak swimmers can have difficulties passing through vertical slot fishways and suffer damage from rubbing on the sides and bottom of the fishway. Mader *et al.* (2012) found that both these species migrated through the enature® fishpass easily, with no visible injuries caused by rubbing.

2.2 Natural-like fishways and spawning channels

Like fishways, spawning channels are often designed for one species, but several other species use them for spawning or for other purposes, e.g. wintering or feeding (Mundie & Crabtree 1997). The first spawning channels were built in British Columbia, Canada. The Seton River, a tributary of the Fraser River, has spawning channels that were built in the 1960s (Sneep 2012, Jormola 2012). The discharge to the channels is 1.12 m^3/s, average depth 0.38 m, gradient 0.1–0.7% and total length 3.6 km (Jormola 2012). The lower channel was restored in 2003 and use of the channel was studied during 2010–11 by counting and identifying fish individuals spawning in the channel and also other aquatic species (Sneep 2012). Based on the results, future restoration possibilities and research ideas were recommended.

The Weaver Creek spawning channel has helped save the declining sockeye salmon (*Oncorhynchus nerka*) stocks and has multiplied the return of spawners, adding value to catches in the sea. The spawning channel is also a popular sightseeing place during spawning time (Jormola 2012). During the period 2004–2007 the Dunglass spawning channel was built in the river Conon, Scotland. Soon after construction, Atlantic salmon found the channel and since then the juvenile densities have been higher than in natural rivers (Jormola 2012).

Rosenfeld *et al.* (2008) studied juvenile fish densities in side channels and found that fish density and biomass were significantly higher in stream-type than in pool-type side channels, but fish size was 47% lower in stream-type side channels. Stream-type channels were defined as flowing water, either constructed, groundwater-fed or natural. Pond-type habitats have higher water depth and practically no water flow velocity. Side channels should be a combination of both these types, as juveniles need different habitats at different times of the year. If discharge into side channels is constant year round, sedimentation into gravel could create a problem for spawning and egg survival. Side channels should be able to be flushed periodically to keep up the natural scour-sedimentation processes.

Mundie & Crabtree (1997) studied the effect of cleaning the Little Qualicum spawning channel on salmon juveniles and their food organisms living in or on top of the gravel. Sediments had occupied 25% of the interstitial space, reaching through the 56 cm thick gravel pack, and the egg-to-fry survival rate had dropped from 80% to 12% in 5 years. Cleaning was done by scarifying the gravel with a bulldozer and pumping the water to dryland grass fields for filtration. Fry of Coho salmon (*Oncorhynchus kisutch*) showed no significant mortality due to the cleaning process. An almost 90% reduction in food organisms was detected, but salmon fry managed to survive with marginal food supplies until the channel was recolonised 8 weeks later (Mundie & Crabtree 1997). Jones *et al*. (2003) reported a 57% reduction in grayling (*Thymallus thymallus*) young of the year's mass in a groundwater-fed artificial side channel compared with the mass in the natural river. They attributed this to the effect of cold groundwater on the growth of juvenile graylings.

Natural-like fishways are another application of spawning channels that combine the features of spawning channels and fishways. Natural-like fishways can be built to support natural reproduction of fish (Jormola 2012). Aarestrup *et al*. (2003) studied meandering sea trout in a natural-like bypass at Tirsbæk brook, Denmark, using PIT (passive integrated transponder) tag telemetry and found that 90% of the tagged trout found the natural bypass, but only 50% of these successfully passed through it. Long distance combined with low discharge could have limited pass efficiency. Calles & Greenberg (2005) studied the efficiency of two consecutive natural-like fishways in the river Emån, Sweden, and found that 89–100% of trout that entered the lower fishway passed through successfully. The attractivity of the upper fishway was observed to be poor, as it was located by only 50% of fish. This is most likely because the fishway is located in an old river channel, away from the main river discharge at the tailrace (Calles & Greenberg 2005).

2.3 Factors affecting salmon and trout migration

Salmon and trout migrating in hydropower production rivers face multiple problems. Salmonids migrate back to the same river and to the same riffle section where they were born (Aas *et al*. 2011, Jonsson & Jonsson 2011). It is not fully known which conditions fish seek or avoid during their spawning migration, but water flow velocity, velocity gradients, discharge and temperature are reported to be important factors (Karppinen *et al*. 2002, Williams *et al*. 2012). High summer flood discharge launched salmon migration at the Merikoski fishway in the river Oulujoki in Finland in late August 2012. Around 100 salmon individuals passed through the fishway in one day, which represented almost 25% of total salmon migration in 2012 (Orell *et al*. 2013). High daily variations in the river discharge can delay migration and lead to so-called yo-yo behaviour, whereby salmonids migrate upstream while discharge is high and drift back downstream when discharge declines (Rivinoja 2005, Isomaa & Laine 2008, Karppinen *et al*. 2008, Lundqvist *et al*. 2008) This causes excessive energy consumption by fish which cannot be regained during spawning migration, since salmonids do not eat during this phase of their life (Lundquist *et al*. 2008). High turbine flow and also high spill flow have been observed to distract fish (Webb 1990, Karppinen *et al*. 2002, Rivinoja 2005, Lundqvist *et al*. 2008). Because of low discharge in fishways, addition of water by pumping or by guiding it through a small hydropower turbine close to the entrance of the fishway is often recommended (Williams *et al*. 2012). Unsuccessful passage can also be the result of the fish population having no migration instinct. Hatchery-bred fish have been observed to gather in the areas where they were stocked, such as in brackish water at river mouths and the spill pipes of hatcheries (Rivinoja *et al*. 2001, Karppinen *et al*. 2008).

Upstream migration is not the only problem affecting salmon and trout populations. Downstream migrants (smolts and kelts) mainly drift with the main water column (Rivinoja 2005, Williams *et al*. 2012). While drifting with the current, the fish have much less time to assess hydraulic conditions than in upstream migration (Williams *et al*. 2012). In studies of migration routes and survival of smolts in the rivers Emån and Piteälv in Sweden, Rivinoja (2005) reported 17% mortality through a Kaplan turbine, while Calles & Greenberg (2005) reported only 9% mortality through a Kaplan turbine and 38% mortality through a Francis turbine. This is characteristic for these turbine types, as the Kaplan has fewer blades than the Francis. However, in the study by Calles & Greenberg (2005) the Kaplan turbine was also larger in diameter (2.1 m) than the Francis turbine (0.8 m). Mortality in turbines is dependent on fish size, the diameter of the turbine and the head of the dam (Rivinoja 2005, Calles & Greenberg 2005). Calles & Greenberg also reported injuries and deaths caused by trash racks.

3 Status of northern river systems

Finnish water courses have been altered for many purposes. Forest and peatland have been drained, mainly between 1950 and 1980, to improve tree growth and to allow peat extraction and crop production. The water level of lakes has also been lowered or they have been completely dried out in order to increase the area of farmland available. Within brooks, to improve drainage some meandering parts have been straightened, increasing the mean gradient of stretches. This has changed the hydraulics of the brooks, with higher and shorter flood peaks and longer and lower minimum water levels.

Rivers of all sizes in Finland, from the largest main tributaries to small headwater brooks, have been dredged for log floating in the past. Stones and boulders were originally moved to the shore by manpower and later by bulldozers and sometimes even dynamite. Similar interventions have been made in rivers in Northern Sweden (Rosenfeld *et al*. 2011). In larger rivers the logs were tied into bundles or rafts. Log floating in Finnish rivers ended mainly in the 1980s and since then river restoration actions have been underway.

Hydropower construction after 1940s has altered rivers physically and hydrologically. Hydropower dams and power plants are often built at the downstream end of riffles because the highest head can be achieved at this location. This has led to the disappearance of riffles and many hydropower rivers are a series of long, narrow, slow-flowing lakes. The granting of hydropower dam permits in Finland ended with the introduction of legislation to protect riffles on 23 January 1987. A few power plants have been built since then, on permits granted before the legislation came into force. The optimisation of water use in controlled water courses often reduces and postpones the spring flood, while the summer minimum flow is also often reduced and lasts longer. Daily discharge adjustment following the total usage of electricity is called hydropeaking. During hydropeaking discharge changes rapidly, in the worst case from minimum to maximum several times a day. This causes large variations in water surface elevation, especially downstream from the hydropower plant. This reduces the value of properties next to the river, can temporarily change the flow direction of small tributaries close to the power plant and forces fish to move along a changing shoreline. Similar hydropower installations and problems have been reported in Northern Sweden (Lundquist *et al*. 2008).

3.1 Silted northern forest brooks

During the period from the 1950s to the 1980s, a large proportion of Finnish forest and peatland was drained in order to improve tree growth and dry out land for farming or peat harvesting. In addition to the hydraulic changes mentioned earlier, such drainage has caused severe erosion, deposition and water quality problems. Drainage operations were concentrated in peatland areas with a thick peat layer. Fine organic sediment accompanied by some nutrients eroded from the ditch banks created, even at low flow velocities. Drainage was also carried out in areas with a thinner peat layer, where the drains reached into the underlying mineral soil. Combined with high gradient in some areas, this led to massive sand and small gravel erosion. Fine organic sediment and sand were transported to forest brooks, which filled with sand. The majority of brooks in North Ostrobothnia and Kainuu were filled with fine sand (Ahola & Havumäki 2008, Paper V). Natural changes in depth and gradient were destroyed and the constantly moving sand bed prevented growth of any vegetation. The conditions in 14 typical brooks suffering the consequences of peatland drainage are described in Paper V.

In the North Ostrobothnia region the old sea bed contains sulphuric materials. Drainage and drying of these areas has allowed oxidisation of sulphide, which dissolves into water as sulphuric acid. This has caused lethally low pH values for fish and other aquatic species in some North Ostrobothnian rivers. Restoration methods for this type of problem were studied in two projects (SaKu, HaKu) during 2008–2011 (Tertsunen *et al.* 2012). The river Sanginjoki had a naturally low pH initially, but land use changes in the 1970s decreased the pH value. It should be noted that the acidity of the river Sanginjoki does not originate from sulphate soils, but from its humic and fulvic acid load (Tolkkinen *et al.* 2013).

3.2 Regulated northern rivers

Most of the large rivers in Finland are blocked by dams for hydropower production. The river Oulujoki is a typical example, with seven dams (Fig 3). Because of its large catchment area, large discharge and large central lake, the Oulujoki is one of the most important hydropower-producing rivers in Finland. The Oulujoki is 107 km long and the level of the central lake, Oulujärvi, varies between 120.5 and 123.2 m. The power plant at Montta, Muhos, is the only one with a minimum discharge demand, 50 m^3/s (Sinisalmi *et al.* 1996). However, because the natural river has no reservoir capacity such as lakes in between dams, all power plants must follow the same discharge pattern, which is decided by the electricity demand in Finland (Sinisalmi *et al.* 1996). This causes extreme discharge and water surface elevation variations. The mean discharge at Merikoski is 250 m^3/s, the maximum turbine discharge at each power plant is 450 m^3/s and the highest flood peaks at Merikoski to date have been almost 900 m^3/s. Typically for hydropower, the water surface at the forebay is fairly constant, but the water surface elevation at the tailrace can fluctuate by several metres. This is the case in the river Oulujoki itself too. For example at the Montta power plant, the tailrace water surface elevation with 50 m^3/s discharge is 11.05 m (Laajala *et al.* 2008) and with its maximum turbine discharge 12.85 m (Sinisalmi *et al.* 1996). At the same time, the forebay elevation at Merikoski, 35 km downstream, remains fairly stable at slightly below 11.00 m. Ice conditions during winter and floods can raise the water surface elevation even further at Montta and may force the water surface elevation in the forebay of Merikoski to be lowered.

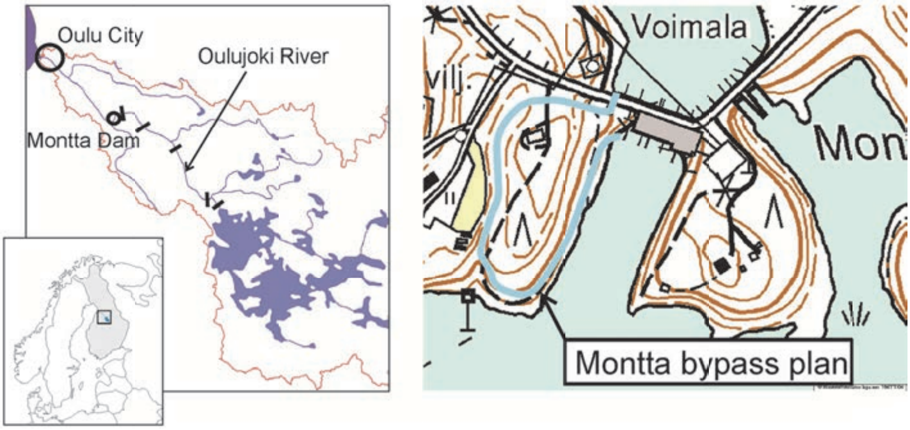

Fig. 3. Hydropower plants in the river Oulujoki. The Merikoski dam is located in Oulu city (large circle). The Montta dam is indicated by a small circle and other dams by black lines. The blue line in the diagram on the right shows the original plan for alignment of the mostly natural-like bypass at the Montta dam.

The river Oulujoki suffers most of the problems experienced in a typical hydropeaking river. The recreational value of the river and shoreline are impaired basically along the river, but water surface elevation changes are largest downstream of each dam and decline with distance from the dam. The changing water surface elevation causes the shoreline to move back and forth, which reduces the usability of the shore. The changing water depth and shoreline also force fish to move along to find suitable conditions, which causes excessive stress and energy consumption, increasing mortality and predation. Changes in water flow velocity also affect salmon and trout migration, causing the yo-yo behaviour described in section 2.3, reducing habitats suitable for spawning and increasing egg mortality when water surface elevation drops below the gravel elevation.

In 2003, the Merikoski fishway was opened. This is a combined vertical slot and natural-like fishway. The natural-like section consists of a series of pools separated by concrete vertical slots framed by large stones. During the period 2003–2012, around 150–500 salmon and 40–150 trout migrated through the fishway (Isomaa & Laine 2008, Orell *et al*. 2013). With salmon migrating into the river section between the Merikoski and Montta and some fish caught by anglers, the public pressure for fishway building has grown. In a feasibility project in 2006–2007, alignments and basic designs of fishways were determined, spawning grounds in the main river and side branches were located and some juvenile stocking was started in promising reproduction areas, even upstream of power plants (Laine *et al*. 2008). As part of this project, a natural-like fishway was designed and modelled for the Montta power plant (Paper II). It was followed by a project covering planning of fishways for the six power plants in the river Oulujoki including Montta. The project was started by the North Ostrobothnia and Kainuu Centres for Economic Development, Transport and the Environment and the Finnish Game and Fisheries Research Institute and funded by the European Regional Development Fund. In the fishway design project, the Montta fishway was moved further away from the earth dam and roads of the hydropower plant. At the same time, the whole upper part was given a much more meandering form to increase the area of the channel. A walking trail was planned close to the bypass and surrounding areas were landscaped for recreation. Vertical slot sections were added to the entrance, exit and middle section of the fishway. Water surface elevation changes at forebay and tailrace and attraction flow pumping into the entrance section forced the inclusion of vertical slot solutions in the design. In the middle section the vertical slot was the best choice because of limitations in space, steep slopes and accuracy of hydraulic design. During design work, several sections of the fishway needed special attention. Natural channel and vertical slot fishways have very different hydraulic behaviour in changing discharge. The connecting areas between each vertical slot section and natural section were designed using a 2D flow model to ensure functionality of the fishway in each discharge scenario. The design of the Montta fishway is presented in Paper III.

4 Methods to enhance salmonid life cycle: Results and discussion

During the work described in this thesis, many issues in brook restoration and fishway building were solved. Different methods were used in the work to improve the reliability of the results. Scale model tests were used in defining the hydraulic properties of different structures to be used in small forest brooks and fishways, while numerical water flow and habitat models were used in planning and evaluating a new hydropower plant bypass channel. Through modelling, flow velocities and water depths can be adjusted to match the requirements of spawning salmon and trout. In Paper I, flow patterns in a twin-slot vertical slot fishway were studied in a flume scale model and by numerical modelling. Papers II-III deal with issues arising in the planning process for the Montta hydropower bypass, including verification of the suitability of water flow and habitat modelling to provide decision support for planning and decision making. FESWMS (Finite Element Surface Water Modelling System) FST2DH (Flow and Sediment Transport) 2D water flow model (Froehlich 2003) in SMS (Surface-water Modelling System) graphical user interphase was used for water flow modelling and presenting habitat data. Habitat data were processed in Microsoft Excel.

In habitat modelling, flow and channel variables are generally given values from 0 to 1, where 0 is not suitable and 1 is a perfectly suitable habitat. Each variable is divided into classes and each class given a habitat preference value. Habitat preference values are created from extensive research on fish behaviour and separate habitat values need to be created for each age of fish and for different times of the year. The overall habitat preference values of different species and ages of fish are then obtained by multiplying selected habitat preference values. Papers IV and V of this thesis focus on habitat issues farther upstream, in heavily sedimented forest brooks.

4.1 Laboratory tests and modelling of vertical slot fishways (I)

In laboratory flume tests, the hydraulics of single and twin-slot vertical slot fishways were found to be very similar. Discharge through two slots was double the discharge through one slot (Fig. 4). A flow pattern with two large eddies combining in the middle formed with a width of 14 * b_0, but was more stable with a width of 16 * b_0. These test runs also confirmed the linear correlation between dimensionless discharge and water depth in the pool. Dimensionless discharge was calculated by equation 1.

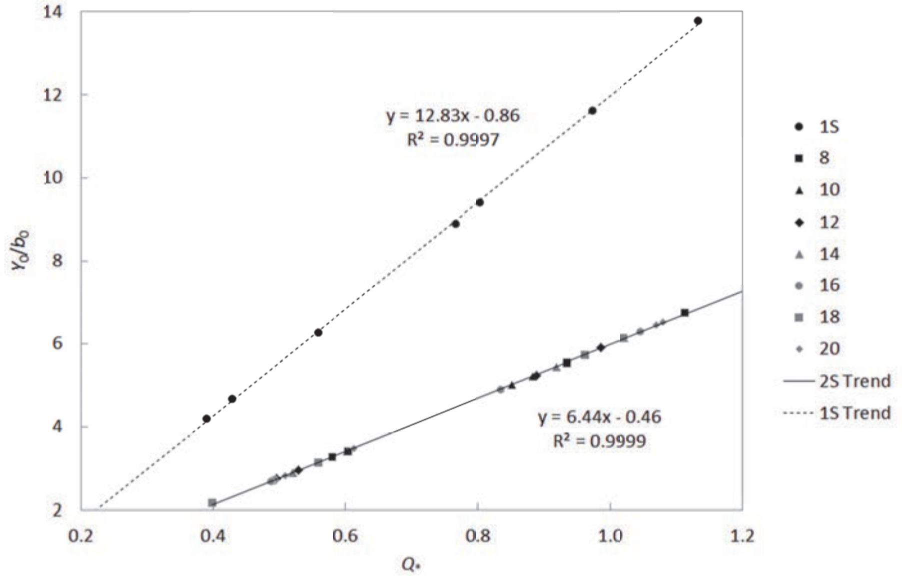

Fig. 4. Flow depth/slot width ratio as a function of dimensionless discharge in model test runs on a single slot fishway #6 (1S) and twin-slot fishway (2S) with varying flume width (numbers 8–20).

In FST2DH, kinematic eddy viscosity is calculated with three different kinematic eddy viscosity factors, base kinematic eddy viscosity ν_{t0} and dimensionless coefficients $c_{\mu 1}$ and $c_{\mu 2}$. The value of kinematic eddy viscosity strongly affects water depth and flow patterns in the pools. Water depths for calibration of kinematic eddy viscosity in Paper I were calculated using equation 2. Each factor correlated with dimensionless discharge Q*. With base kinematic eddy viscosity, flow pattern 2 resulted from most of the discharges tested. The opposite situation happened with dimensionless coefficient 1, which was unstable in some situations because of too low viscosity and very strong eddy in pools. Dimensionless coefficient 2 gave the best results in terms of flow pattern formation. The relationship between dimensionless discharge and the dimensionless coefficient 2 was roughly the same, irrespective of slot number, width or slope. However, the value of dimensionless coefficient 2 varied over a large range in the area of discharge studied. Values of base kinematic eddy viscosity and dimensionless coefficient 2 increased with increasing dimensionless discharge, while values of dimensionless coefficient 1 decreased. The flow model was unstable with dimensionless discharge below 0.4, especially with 8% slope and 0.5 m slot width. This could be caused by high flow velocities and shallow water depth and in two slow cases by the two jets combining in the middle of the pool, strengthening each other.

Combinations of these factors were studied and a test series was run in the numerical model with $\nu_{t0} = 0.01$, $c_{\mu 1} = 0.21$ and $c_{\mu 2} = 2.1$. In the range of discharges tested and with 0.3 m slot width, the model gave good results, with only 0.05 m maximum deviation from the calculated value. The range of discharges tested was wider than the discharges typically used in Finnish fishways considering also possible pumping of attraction flow. With 0.5 m slot width the deviation from the calculated water depth was larger, especially with lower discharges.

The element mesh had a small effect on the results of the flow model. Reducing the number of elements in the slot decreased the water depth in the slots and in the centre of the pool. The difference increased with increasing discharge. Increasing the number of elements also increased the water depth in the pools. Changes with lower flows were in the order of millimetres, but with larger discharges the difference was 0.04–0.06 m.

Table 1. Wetted, spawning and rearing areas for Atlantic salmon in two different modelled natural-like channels with different discharge values. Spawning and rearing areas are shown for habitat preference values greater than 0.5 and 0.75. Values from Paper III are for the upper natural-like section only.

	Discharge	Wetted area	Spawning [m^2]		Rearing <10cm [m^2]	
	[m^{3}s^{-1}]	[m^2]	> 0.50	> 0.75	> 0.50	> 0.75
Paper II	0.5	1842	1358	749	1748	895
Paper II	1.0	2265	1396	557	1874	939
Paper II	2.5	2745	824	196	1215	296
Paper III	0.8	1855	1039	390	1540	1169

4.2 Methods to improve salmon and trout reproduction possibilities (II, III)

The bypass at the Montta hydropower plant was designed and simulated in two separate projects. Paper II presents the first design for an entirely natural-like channel. In the subsequent project the alignment was changed into a more meandering and lower gradient to give more area (Paper III). Since the main channel of the river Oulujoki lacks spawning grounds and the existing areas suffer from extreme hydropeaking, stable hydraulic conditions in side channels would be a valuable starting point in restoring migrating salmon and trout populations. According to the modelling results in Paper III, most of the areas planned for spawning are suitable in terms of habitat values for salmon, with 0.5 m^3/s discharge (Fig. 5) and with 1.0 m^3/s discharge (Fig. 6), but also with the highest modelled discharge (Table 1). A large part of the bypass is also suitable for juvenile salmon (Table 1, Fig. 7) and for juvenile trout (Paper II). All the habitat areas decrease with increasing discharge and wetted area, owing to increasing water depth and flow velocity. Lack of salmon juvenile winter habitat (Fig. 8) is caused by the absence of deep sections and by providing the wrong material size in the only pool in the initial bypass design. Introducing more pools would have reduced the spawning area and in this study spawning area and habitat suitability index were optimised. The habitat preference data used in this study were taken from Mäki-Petäys *et al*. (1997), Mäki-Petäys *et al*. (2004) and Louhi *et al.* (2008). More detailed tables of habitat areas are presented in Paper II. It should also be noted that all spawning areas have to be located in sections of the bypass channel that remain under water during low discharge periods in winter if discharge changes between times of the year.

Fig. 5. Spawning habitat suitability for salmon at 0.5 m^3/s discharge in the entirely natural-like bypass at the Montta hydropower plant in the river Oulujoki.

Fig. 6. Spawning habitat suitability for salmon at 1.0 m^3/s discharge in the entirely natural-like bypass at the Montta hydropower plant in the river Oulujoki.

Fig. 7. Summer rearing habitat suitability for juvenile salmon with >10 cm body length at 1.0 m^3/s discharge in the entirely natural-like bypass at the Montta hydropower plant in the river Oulujoki.

Fig. 8. Winter habitat suitability for juvenile salmon with <11 cm body length at 0.5 m^3/s discharge in the entirely natural-like bypass at the Montta hydropower plant in the river Oulujoki.

In the second project, a new design for the Montta fishway was introduced (Fig. 9). This new design has a vertical slot section in the entrance, middle and exit and two natural-like sections in between the vertical slot sections. The upper natural-like section is designed to match salmon spawning habitat preferences as reported by Louhi *et al.* (2008), with three deeper pools for winter habitat. Mäki-Petäys *et al*. (1997) found juvenile trout using areas with deeper water, lower water flow velocities and large rocks as bottom material. While the local flow conditions caused by single large boulders cannot be modelled with 2D water flow models, they can be taken into account in habitat modelling by using the habitat preference value of a suitable bottom material. The wetted area of the natural-like sections is 2257 m^2 at 1.0 m^3/s discharge and 2060 m^2 with the summer design discharge of 0.8 m^3/s. The majority of this area (1855 m^2) is in the upper natural-like section, with design discharge (Table 1). Habitat modelling was run only for water flow velocity and water depth, because the habitat preference of the bottom material can be considered to be optimal, with a preference value of 1. The combined habitat suitability index in the upper natural-like section with design discharge is over 0.5 for salmon spawning (Fig. 10) in 56% of the wetted area and for juvenile salmon <10 cm (Fig. 11) in 83% of the wetted area. The combined habitat suitability index is >0.75 for areas of 21% and 63%, respectively. The limiting factor for spawning suitability index is mainly the high water depth. Most of the channel water depth is 0.5–0.6 m. The optimal depth for salmon spawning is 0.3–0.5 m. While the aim was to design a spawning channel for salmon, the low winter flow and demand for a wide channel resulted in slightly too great a water depth for summer flow. The most important factor is that areas where salmon and trout are spawning should not dry out or freeze. The lower natural-like section was designed as a concrete flume for reasons of structural strength, but filled with stones to give a natural appearance. This section was designed to have flow velocities and depths suitable for 1- to 2-year-old salmon and trout in summer and winter time. A flow model was also applied in this section. Without proper calibration to similar structures or measured data, the results presented are rough estimates. Habitat modelling also resulted in some suitable areas for rearing. However, because the wetted area was fairly small compared with the upper natural-like section, these areas were negligible.

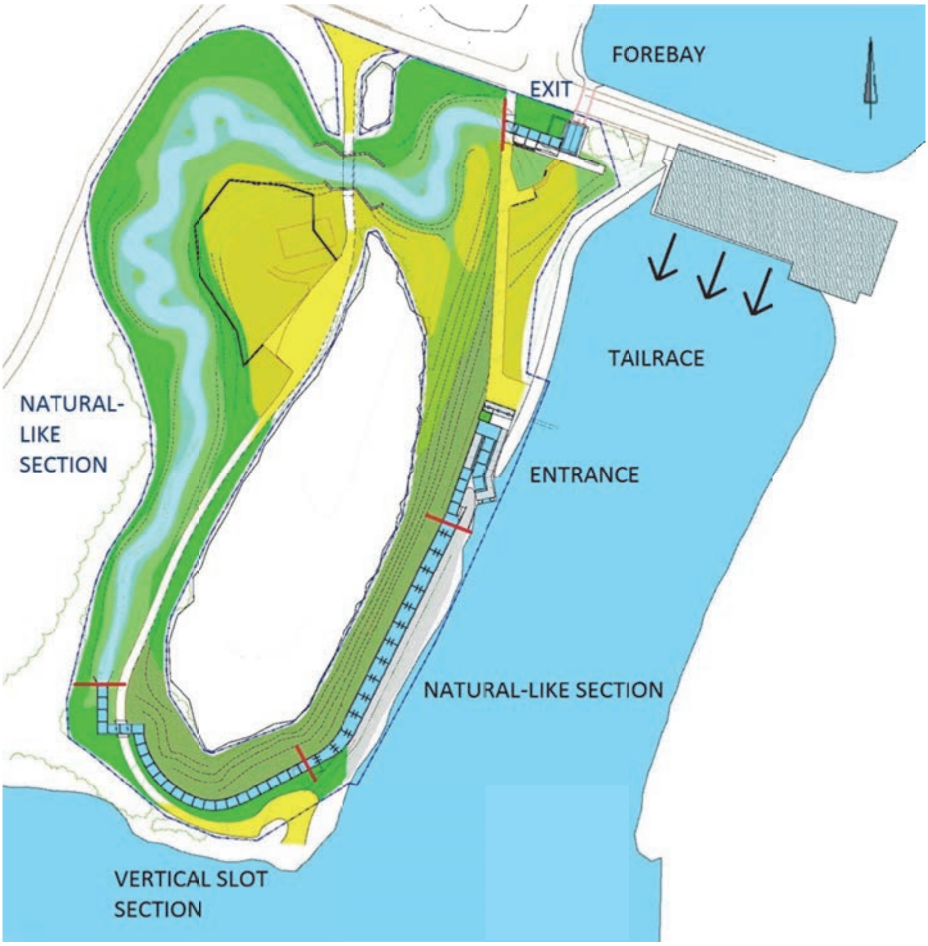

Fig. 9. The new design of the Montta bypass. The bypass consists of three vertical slot sections and two natural-like sections. Section change areas are marked in the diagram with red lines. Diagram prepared by VSU Arkkitehtuuri- ja viheraluesuunnittelu Oy.

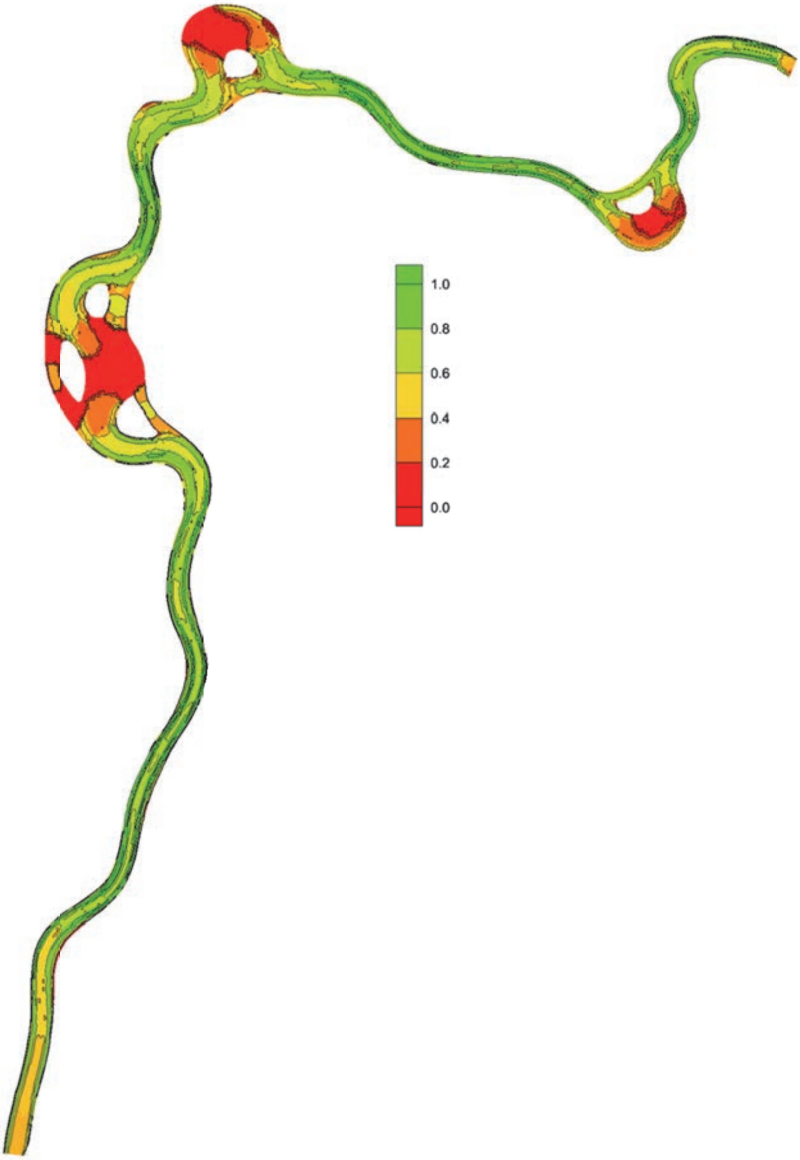

Fig. 10. Spawning habitat suitability for salmon at 0.8 m^3/s discharge in the upper natural-like section of the new design bypass at the Montta hydropower plant in the river Oulujoki. Suitability value calculated assuming bottom material habitat value to be 1.

Fig. 11. Juvenile habitat suitability for salmon at 0.8 m^3/s discharge in the upper natural-like section of the new design bypass at the Montta hydropower plant in the river Oulujoki. Suitability value calculated assuming bottom material habitat value to be 1.

4.3 Exit section of the Montta bypass (III)

The exit section (i.e. water intake) of the Montta bypass is a short section of vertical slot fishway. The dimensions of the uppermost slot are defined by the forebay water surface elevation. Water flow velocity and surface elevation were modelled to define suitable measurements for the exit section and the beginning of the natural-like section downstream. Water surface elevation is above 23.90 m for 95% of summer flow (lower contours in Fig. 12). At this water elevation, discharge into the fishway is 0.8 m^3/s. The water surface elevation in the forebay rarely drops down to 23.24 m (upper contours in Fig. 12). When the water surface elevation drops, the discharge is also reduced. The reduced discharge and lower water surface elevation cannot be allowed to lead to a situation where the water surface elevation drops below the beginning of the natural-like section bed elevation. This also defines the length and slope of the exit section. Water depth change in the following natural-like section is much smaller than in the vertical slots. Therefore the bed in the natural-like section is designed roughly 1 m higher than the bed at the end of the vertical slot fishway. Water surface elevation with winter flow of 0.3 m^3/s at the beginning of the natural-like section was matched to this minimum water surface elevation in the forebay. This prevents drying out of the fishway at low water surface elevations in the forebay. Reduced discharge with almost stable water surface elevation caused by the natural-like section causes water flow velocity to decrease drastically in the lowest slots of the exit section. This could prevent salmon and trout ascending. During migration time conditions which cause forebay water surface lowering are rare. Adjustment of slot width or height in the exit section is required between summer and winter to adjust the discharge for winter while the water surface elevation remains close to the maximum of 24.00 m.

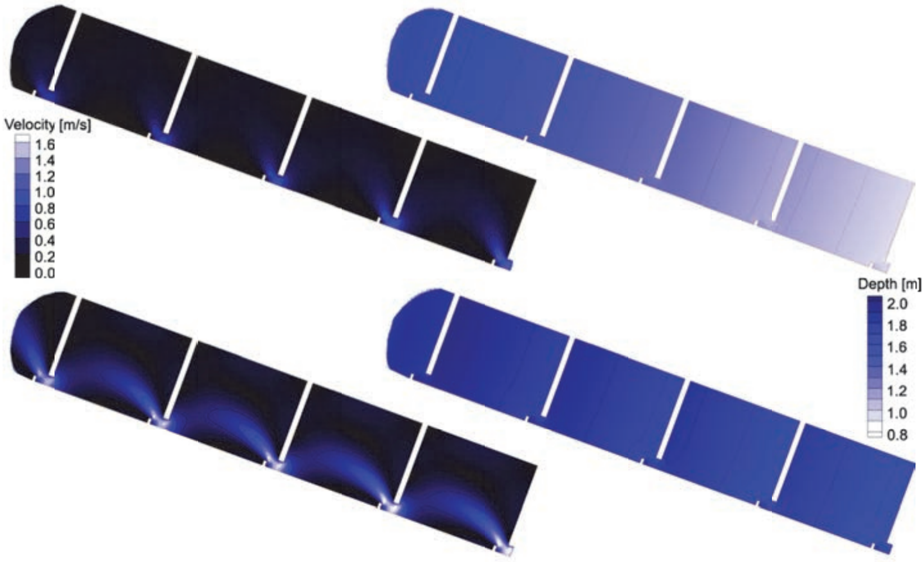

Fig. 12. Flow velocities (on left) and water depths (on right) at winter discharge of 0.3 m^3/s (upper contours) and summer discharge of 0.8 m^3/s (lower contours). Flow direction is from right to left. In the flow model the slot width is constant in both discharges to estimate the water surface elevations in the case of low forebay water surface elevations during summer. Slot width should be adjusted for winter discharge with the normal forebay water surface elevation.

4.4 Natural-like sections and the middle vertical slot section (III)

Water depth change between summer and winter flow is only 0.1–0.2 m, while the change in vertical slots is more than 1 m. This was taken into account in the connection between the upper natural-like section and middle vertical slot section. The last 50 m of the natural-like section is designed by conditions set by 0.3 m^3/s discharge and winter conditions. In summertime, with 0.8 m^3/s discharge, this leads to mild ponding in this section (Fig. 13). The spawning and rearing suitability index values are lower in this area because of deep water and slow flow velocity.

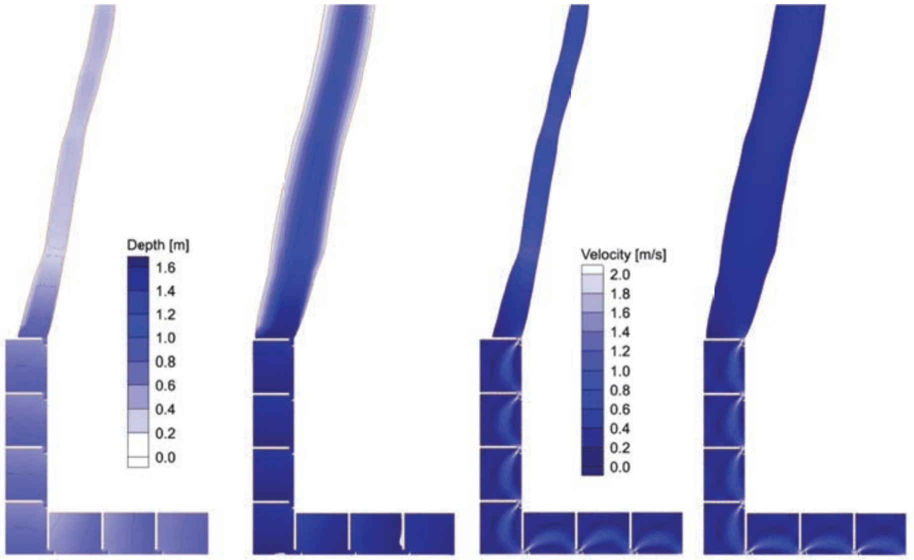

Fig. 13. Flow velocities (on right) and water depths (on left) at winter discharge of 0.3 m^3/s (first and third contours from left) and summer discharge of 0.8 m^3/s (second and fourth contours from left). Flow direction is from top to bottom in the diagram.

The middle vertical slot section was modelled in full length only because of the continuity requirement in the model. Important sections in the model were only the connecting areas between the different type of fishways. The middle vertical slot section has two 90 degree turns in alignment where a small road crosses the fishway. The location of the slots and baffles was considered carefully in terms of the direction of the jet into the pool and location of the next slot, in order to avoid jet carryout from slot to slot.

The lower natural-like section in this system is similar to the natural-like section of the Merikoski fishway at the mouth of the river Oulujoki in the centre of Oulu city. It is designed as a concrete flume for construction reasons to stabilise the steep slope next to the channel. Concrete baffles divide long pools with vertical slots in the middle that are narrower at the bottom than close to the surface (Fig. 14). This keeps water depths higher with winter flow, but reduces water depth change to summer flow. Pools and baffles are framed with gravel and stones to give a natural appearance, with some water flowing over the baffles in summer flow to give a natural riffle look. Because of the vertical slots in this section, the difference in water depth change between the vertical slot fishways below and above and the natural like-section is not as large as in the upper natural-like section. However, similar compromises with water flow velocities and depths had to be made to fit these sections together.

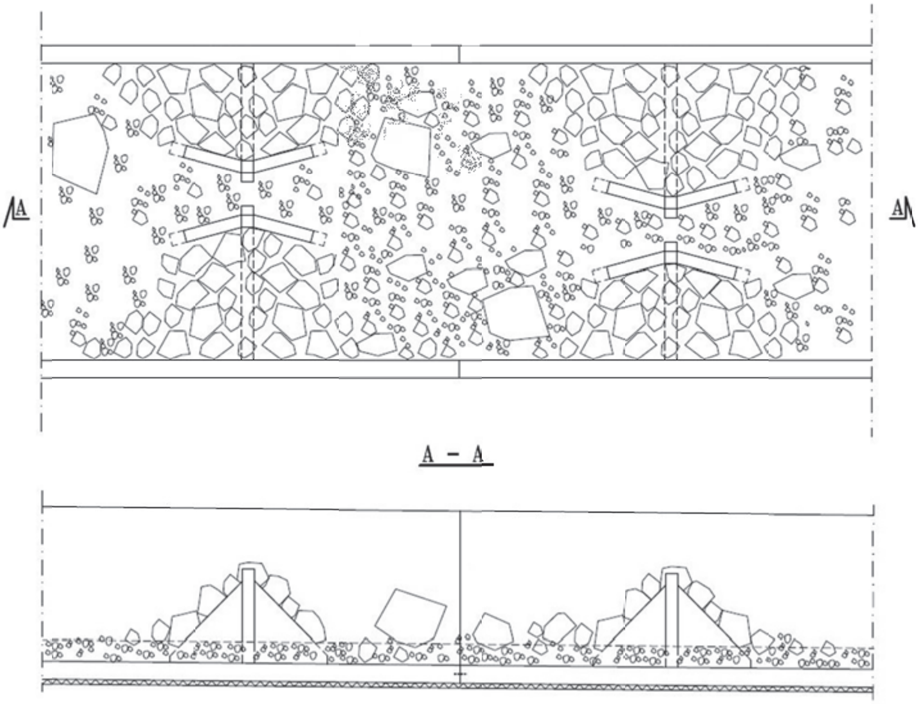

Fig. 14. The planned baffles separating pools in the lower natural-like section in the bypass at the Montta hydropower plant in the river Oulujoki. Diagram prepared by Insinööritoimisto Ponvia Oy.

4.5 Entrance and pumping station (III)

To increase the attractivity of the entrance, additional water was designed to be pumped to the entrance section. The pumping of attraction flow made it necessary to look for solutions for a vertical slot section that accepts higher discharge changes without excessive water depth fluctuations. In addition, the water surface elevation at the Montta tailrace fluctuates between 11.1–13.4 m. In planning, several different options were considered, starting from three separate entrances at different elevations to a natural-like entrance. The steering group of the project wanted the entrance to be in one location in all situations. This led the water depth in the lowest section to fluctuate between 2 and 4.5 m and discharge between 0.8 and 2.0 m^3/s in summertime. The pumping is not steered by water surface elevation in the tailrace, but by detection of fish close to the entrance and changes occurring in power plant discharge. This can lead to possible situations where tailrace water surface elevation is 11.1 m and pumping is on, or tailrace elevation is 13.4 m and pumping is off. In a natural-like section or single vertical slot section, higher water surface elevation in the tailrace would lead to low water flow velocities, which would not attract fish to enter the fishway or ascend in the fishway.

To solve this problem, a study of two-slot vertical slot fishways was launched. During the planning process, the two-slot design was changed to two parallel vertical slot sections. This design was applied to the section between the tailrace and the pumping station. However, in this solution changes in flow velocities were still too large, so an entrance with two parallel vertical slot sections was introduced (Fig. 15). The raising gate moves by pontoons along with the tailrace water surface elevation. This keeps the water surface in the first pool approximately 0.3 m higher than in the tailrace. The water surface elevation difference creates plunging flow into tailrace, which was considered to be the best solution for attracting salmon approaching the entrance. Between the first pool and pumping station are two separate vertical slot sections. The main section is functional in all flow schemes. By water flow modelling, the uppermost slot of the parallel section was designed so that water will flow into the parallel section only if pumping is on, while tailrace water level is above 12.0 m (Fig. 16). If the water level in the tailrace rises above 12.0 m, water elevation in the fishway will also rise and some water will flow into the parallel section.

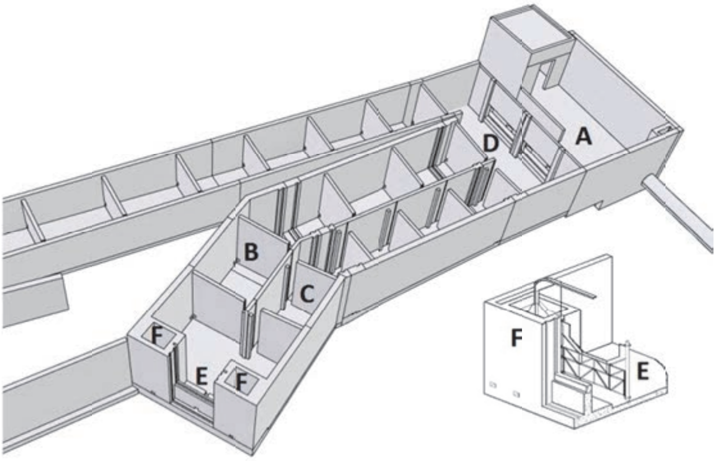

Fig. 15. Entrance of the Montta bypass. A) The pumping station, B) main vertical slot section, C) parallel vertical slot section, D) larger pool in which the attraction flow is pumped, E) raising gate and F) chambers for the pontoons. Diagram prepared by Insinööritoimisto Ponvia Oy (Paper II).

The whole entrance section was studied using the water flow model. The objective was to ensure functioning of the section in all schemes tested. Water surface elevation in the end of the section had to be stable in all schemes. Fig. 17 shows the computed water surface elevations in the entrance section along two lines, in the main section (continuous line) and in parallel vertical slot sections (dashed line). Water surface elevations in the parallel section are at the same level as in the lowest pool and some pools are dried out when pumping is not engaged with tailrace water surface elevations 11.2 m and 12.0 m. This proves that the uppermost vertical slot draining to the parallel section is planned correctly, not allowing water to flow into the parallel section without pumping. With this design, the flow velocities in the main section remain high enough to maintain the attraction for salmonids to ascend the fishway.

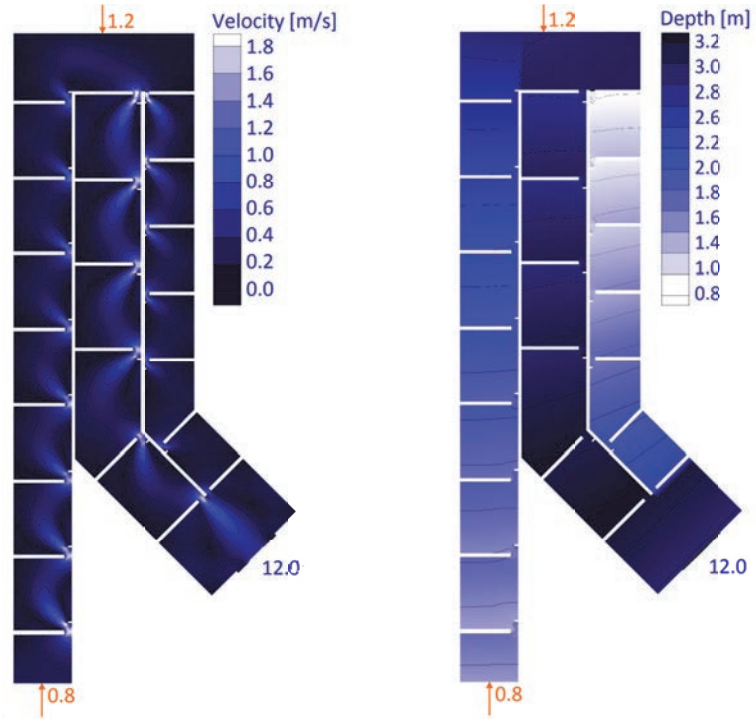

Fig. 16. Flow velocities (on left) and water depths (on right) with 0.8 m^3/s discharge from the fishway plus 1.2 m^3/s pumping. Water surface elevation in the tailrace is 12.0 m. The fishway discharge flows into the section from the lower side at arrow 0.8 and pumping discharge enters the section from the upper side at arrow 1.2. The value 12.0 in blue is the water surface elevation boundary of the model (12.0 m).

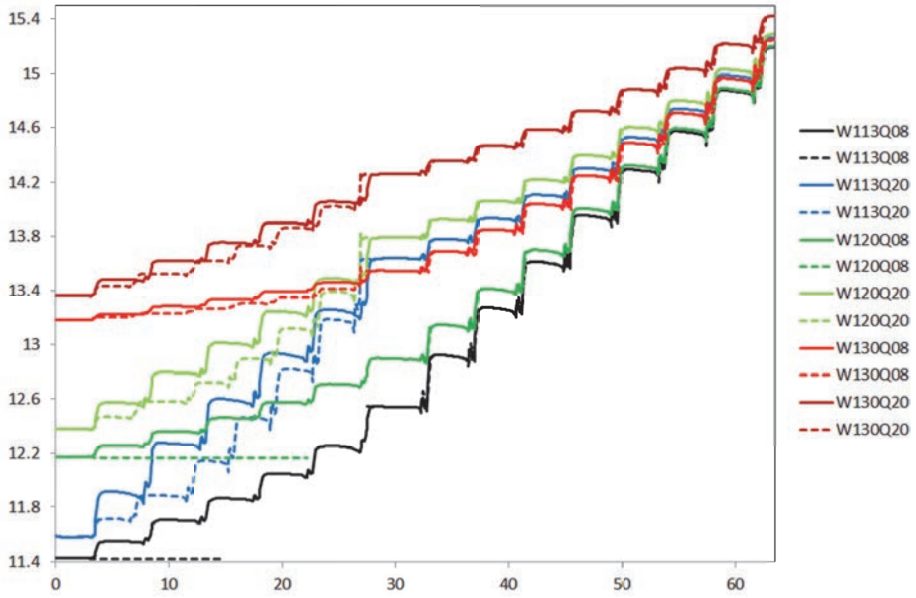

Fig. 17. Water surface elevation (Y-axis [m]) in the entrance section (X-axis distance to entrance [m]) of the Montta fishway. Water surface elevation in the tailrace 11.3 m, 12.0 m or 13.0 m and each situation computed with pumping (Q20 = 2.0 m^3/s) and without pumping (Q08 = 0.8 m^3/s). Continuous line in main vertical slot section and dashed line in parallel section.

4.6 The underminer structure (IV)

Laboratory flume experiments on underminer structures (Fig. 18) resulted in recommendations for a perpendicular structure reaching from below the existing sand surface to the bank level. In some cases higher structures can be built to divert more flood flow under the structure or to guide the flood flow to a floodplain surrounding the brook. Turning the structure creates a larger scour hole by area, but volume decreases. This also creates a more variable bottom surface (Fig. 19a) and scour under the bank. The distance between structures and the orientation of structures affect scour formation under and between the structures (Fig 19c-e). In order to increase the variability of depth changes, structures with some angle should be used. According to laboratory tests, a distance of 2–3 times brook width between structures should be used, but ultimately in nature the orientation and the distances between structures should be decided on the basis of each channel restored. Underminer structures can also be used in small natural-like bypass channels in maintaining higher flow velocity. Locating an underminer structure between pool and possible spawning place would increase flow velocity above the spawning area, preventing sedimentation and also increasing flow into the gravel pack. Underminer structures could also be used in wider and deeper sections to increase flow velocities in order to improve conditions for spawning.

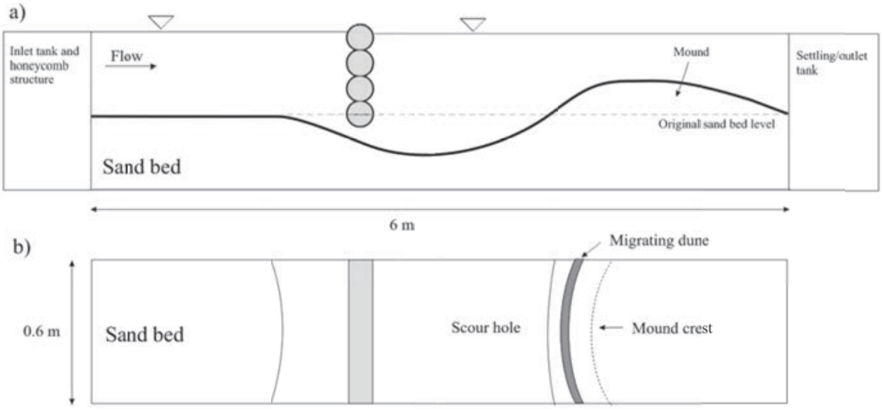

Fig. 18. Schematic view of the experimental set-up: a) elevation and (b) plan view (not to scale). Reprinted with permission from IAHR (modified).

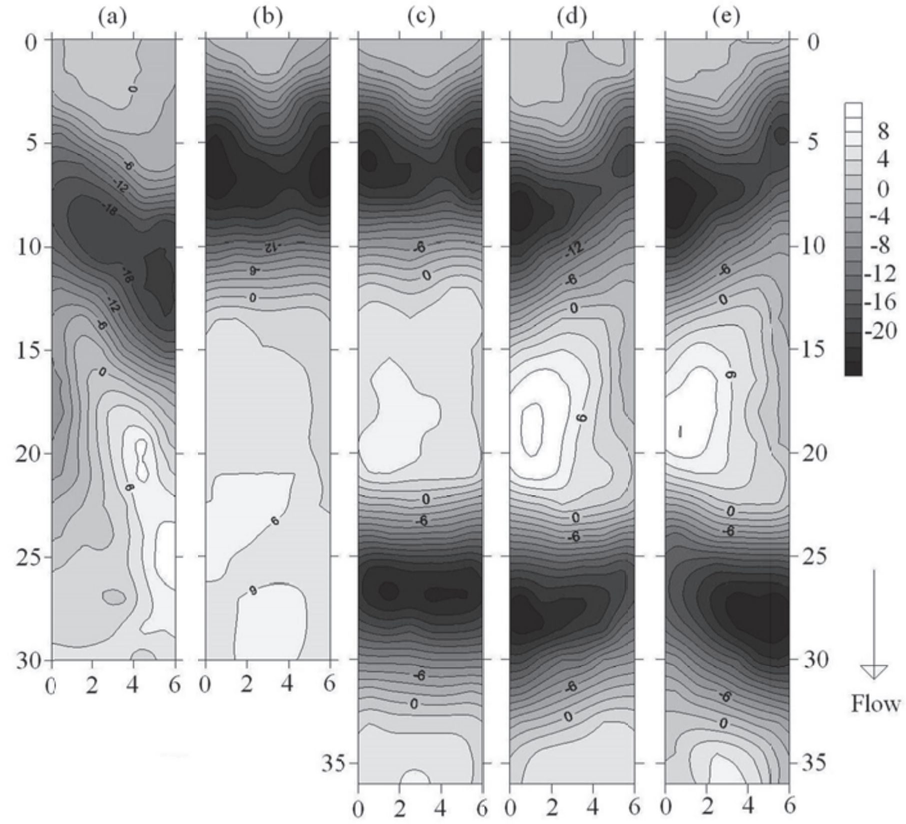

Fig. 19. Bed topography profiles after single structure (a and b) and perpendicular structure (c, d and e) test runs. A value of zero represents bed elevation in the beginning of the test run. Contour profiles in centimetres with respect to flume bottom in decimetres. Reprinted with permission from IAHR.

5 Conclusions

The life cycle of migrating salmon and trout begins in nature in a river gravel pack, but drainage, dredging and hydropower production have destroyed these sites. Restoring gravel beds and reopening migration routes to these beds are key factors in re-establishing self-sustaining migratory fish populations.

This thesis charted the state of silted-up boreal forest brooks and examined a passive method to restore natural depth and width variation. The underminer structure can be hand-built and installed at the restoration location without heavy machinery. The underminer structure does not affect water surface elevation, but increases the water volume and local depth changes in the brooks by scour holes. Spawning gravel could be placed under the structure or to the downstream side of the structure, where it would be stable and kept clean of sand by the increased flow velocity caused by the structure. By using structures with some degree of angle, meandering forms can also be created, leading to possibilities of vegetation settling on the brook bottom on the inside curve of the meanders.

Water flow and habitat modelling proved to be a good tool in fishway planning. With the information obtained from habitat modelling, the topography of natural-like sections of fishways can be optimised to salmon and trout spawning and rearing grounds. However, there are still many factors that can affect actual spawning success and use of these areas which are not included in the models used in this thesis.

The most problematic issue is the attractivity of the fishway. Fishway discharge is often a fraction of that in the whole river and the water surface elevation in the tailrace often fluctuates greatly. The two-slot vertical slot fishway may be the solution to this problem. The hydraulics of the two-slot model were found be similar to those of a single slot model with corresponding slot, deflector and pool dimensions. Water flow model parameters were calibrated for use with vertical slot structures with commonly used slot widths, slopes and discharges. The calibration altered slot width, slope and discharge. The bottom friction proved to have no effect on the flow patterns in the vertical slot fishway. In planning a fishway for the river Oulujoki, the design was refined into two parallel sections that allow pumping of additional attraction water into the lowermost section of the fishway without an additional water surface rise. Water flow modelling was an important tool in designing this kind of structure with varying water surface elevation in the downstream end and changing discharge. The connection areas between natural-like and vertical slot sections also demand careful design, because of varying water depth change between summer and winter discharges.

There is often a conflict of interest when discussing the amount of water used for fishways, as all water flowing through the fishway represents a loss of hydroelectricity to hydropower plants. Higher discharge in the entrance of fishways improves the attractivity, but increases the size of the structures and the cost of building for vertical slot fishways. In natural-like fishways the increased discharge allows the area to be increased and therefore improves the possibilities for spawning and rearing. However, the change between summer and winter discharge cannot be too large if the spawning grounds are to remain underwater even during low flow periods in winter.

There are several fishway planning projects going on in Finland, and many have been already finished. At Oulujoki, lack of funding has prohibited the building of fishways. In complying with the national fishway strategy, the hydropower companies should invest more funds in fishway building instead of fish farming and stocking. This thesis presents solutions for re-establishing the valuable spawning areas in small forest brooks and in rivers controlled by hydropower production. Structures developed for brook restoration have already been used for several years in restoration actions in the North Ostrobothnia area. Water flow modelling should be used in designing bypasses comprising different type sections. In most cases this is essential because vertical slot fishway sections are needed at the entrance and the exit to handle changing water surface elevations. By water flow and habitat modelling, the natural-like sections can be optimised for desired species reproduction. The results presented in this thesis provide a firm foundation for the fishway design process.

Once the first natural-like fishway is built, hopefully at Montta, there are several details to be studied and refined. The attractivity of the entrance is the bottleneck of the fishway. Future research should concentrate on identifying the conditions that attract fish, but also the conditions fish avoid when seeking their migratory route. At Montta, pumping the outlet water from a fish farming plant close to the power plant could increase the attractivity not only because of the increased water volume, but also because of a “scent of home”. In the fishway itself, the behaviour of fish should be monitored to verify the applicability of the habitat preference curves in small channels with discharges as low as 300 l/s. Research is also needed on whether spawning individuals are disturbed by migrating individuals or vice versa.

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