Modeling the trade-off between production of Atlantic Salmon (Salmo salar) and power at Laudal Hydropower plant.

Ana Adeva Bustos

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Abstract

As part of the CEDREN EcoManage project, a modelling study on the trade-offs between the production of Atlantic salmon (Salmo salar) and the production of power at Laudal hydropower plant was conducted. The study examined the use of physical mitigation measures versus - and in addition to - changes in release of water. The study objective is an optimization of the environmental design through and downstream of the Laudal Hydropower plant in the Mandalselva River in Southern Norway, through demonstration and evaluation of a proposed methodology, to be used in other projects/rivers. The methodology is a tool for a) prediction of the potential trade-offs between smolt production and power generation b) evaluation of cost-effectiveness in smolt production and loss in power production (spill of water), and c) evaluation of principles of off-setting versus mitigation measures. Examining smolt production under different flow regimes using the proposed by the government as a baseline. The power producers and the scientist results show that the government proposed release of water past the hydropower plant could be adjusted with lower environmental flows while still having the same smolt production. Introducing habitat restoration measures further reduced the need for release of water. The study concludes with setting the proposed environmental flows (with or without habitat restoration) in an economic framework in regards to loss of power production and loss of income in relation to cost of habitat rehabilitation/improvement.

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Glossary

CEDREN Centre for the Design of Renewable Energy in Norway

Gauge. A particular site on a stream, canal, lake, or reservoir where systematic observations of gauge height or discharge are obtained.

Hec-RAS Hec-River Analysis System

nMag Hydropower operations simulation program

NTNU Norwegian University pf Science and Technology

NVE Norwegian Water Resources and Energy Directorate

Smolt Fully silvered juvenile salmon migrating or about to migrate to sea

Smolt migration period A four-week period in spring during which the vast majority of smolt migrate from the river. The start of this period may vary from year to year

Intake Structure where the water comes inside to feed the intake tunnel

Intake tunnel Diversion tunnel or pipe that is feeding with water from the intake with the purpose to pass through a turbine

Outlet Place where the water is returned to the river after being turbine

Trade off a situation that involves losing one quality or aspect of something in return or gaining another quality or aspect

Bypass section A river reach where flow is reduced or withdrawn, but where a flow release is required.

WFD Water Framework Directive

1. Introduction

1.1 Scientific Background

Effects in freshwater ecosystem produced by hydropower

It is worldwide known that hydropower development has negative effects in the freshwater aquatic ecosystems. Some of the most relevant are described below.

Flow regime can be consider as the primary driving force of riverine communities and processes (Zolezzi et al. 2009). The importance of the river flow regime for sustaining biodiversity and maintain the ecological integrity is well established (Poff et al. 2010) with the five key components of variability, magnitude, frequency, duration, timing and rate of change. A vast number of scientific research support that the natural flow content these five components (Tharme 2003, Acreman & Ferguson, 2010). All of these components are affected by the hydropower development. As it is mentioned before the flow regime is the driver of process, therefore, the alteration of the flow and the construction of the different hydropower structures (as dams) will produce major effects in the landscape process.

A common effect from hydropower regulations is the reduction of large flood events in rivers, and increased discharge fluctuations (hydro-peaking). Due to reservoir operation, streamflow alteration and change over the time in relation to the energy market, will lead changes in the discharge and temperature regimes (Zolezzi et al. 2009). Changes in discharge affect water velocity, sediments, water quality and temperature. Temperature effects are especially noted in the high head system in Norway due to deep water intakes.

Among the several effects produced by the construction of structures like dams, the loss of longitudinal, lateral and vertical connectivity added to the loss of the temporal component is a vital issue affecting freshwater ecosystems. This alteration and fragmentation of the longitudinal connectivity can result in effects on downstream/upstream migration of diadromous species. Disconnecting the floodplains and riparian ecosystems with the water, as well as the ground water with the surface water is another example of loss of connectivity. Changes in water velocities will change the river structure converting flowing in standing water habitats, reducing the heterogeneity and dynamism (Renöfält et al. 2010, Gopal and Vass, 2013).

Among the several potential biological effects, macrophytes are changed in species composition and density related to the different habitats (Gopal and Vass, 2013).The composition and quantity of the invertebrates benthos and the drift in running water is also affected. (Johnsen et al. 2011). Changes in riparian vegetation can be produced since the richness of species is highly dependent on the hydrological regime. Fragmented rivers have fewer species and lower population densities than comparable free-flowing rivers (Lejon, 2012). A critical issue is that macroinvertebrates are substantially affected[24] and they are responsible for several relations in the food web as well as being the main food organism for salmonids.

Effects produce by hydropower in Atlantic salmon

Due to the importance of the hydropower sector in Norway as well as the preservation of the Atlantic salmon population, some effects produce in Atlantic salmon by hydropower are described. The hydropower development affect different life stage of Atlantic salmon (survival, growth, migration and production). The effects in the Atlantic salmon population from hydropower are common reported as negative. However, the hydropower has lead positive effects in some cases.

Changes in survival are relate to the destruction and degradation of spawning and rearing habitat, with dramatic effects in the population, increasing in sediments after the spawning will lead a reduction in the eggs survivals, and a reduction in fry survival due to the obstruction of gravel pores. The mortality of eggs could be also related to changes in discharge during season, as stranding redds in winter due to low discharge.

The growth of the Atlantic salmon is affected by the hydropower regulation. There are many examples and evidences about the relation between growth, discharge and spring temperature. In Surna River (Norway) was documented a reduced growth downstream the power station of both Atlantic salmon and brown trout compare with the upstream part relate with this changes in discharge and temperatures (Saltveit, 1990). In contrast, in the River Stjørdalselva an increase in the growth was detected after the regulation, mainly relate with a favorable change in water temperature (Arnekleiv et al. 2006).

Downstream/upstream migration and the effects from hydropower development has been widely studied. Showing how increased smolt mortality can be caused by direct turbine blade strikes and other sub-lethal impacts on the sensory system and successful downstream passage rely on a synchronized and unrestricted migration. Increases in the water releases can reduce turbine migration and thereby fish mortality. The presence of dams and weirs may delay or even block the migration (Mills, 1989). The discharge size and the proportion of the river discharge through turbines can determine the speed and direction that the salmon choose for migration. A too low bypass discharge may generate an attraction for the power plant outlet rather than an attraction for the bypass section.

As was mentioned before some positive examples has been reported between hydropower development and Atlantic salmon production. The case of Alta, Norway, where after the construction of the dam the salmon production and parr densities were in decline. After the implementation of mitigation measures as diversion valve and improvement of operative routines the sudden drops in water discharge was minimize. The overall production of Atlantic salmon after 20 years of regulations is as good as was before regulation (Ugedal et al.2008, Brodtkorb 2002, Næsje et al.2005). In Orkla River, Norway, a higher minimum discharge in winter after regulation has led both improve parr survival rates and smolt production (Hvidsten et al. 2004).

Mitigation measures

The several effects described above has led the needed of study and implement mitigation measures in Norwegian Rivers.

The stocking of fish has a long tradition in Europe. In Norway the most common stocking techniques are fry and fingerlings, but it is becoming more common to plant eyed eggs in large-scale restoration projects (Fjellheim & Johnsen 2001, Moen et al. 2007). In the late 1970s, the construction of weirs in Norway became very popular as an aesthetic mitigation measure (Fjeldstad, 2011). Weirs can help to maintain a certain water level in regulated rivers with reduced minimum discharge, and help create suitable habitat for fish. Nowadays, there are more than 1000 weirs in Norway. However, not all the effects produce by weirs as a mitigation measure are positive. The construction of dams and weirs is particularly harmful in rivers with

diadromous fishes (Scruton et al. 2008). Many studies have demonstrated the positive effect in upstream migration by the removal of weirs (American River, 2002). In Nidelva River, Norway, after the removal of two weirs, was observed that salmon spawning sites were recreated in the old bed substratum immediately in the first season after removal (Fjeldstad. 2011). Furthermore, in Norway, fish ladders have opened around 3700 km of new river to anadromous fish (DN 2002 in Johnsen et al. 2011). Adding gravel can help to rehabilitate spawning areas. A study shows how in five Norwegian rivers salmon spawned in all the gravel added at spawning sites (Barlaup et al. 2008). Another mitigation measure is habitat enhancement, like the construction of pools, riffles, deflectors and changes in the river bed material with the introduction of stones and cobbles.

Many organisms have biological characteristic that are relate to the flow regime of unregulated rivers, as the Atlantic salmon who has different environmental-flow requirements during his life cycle (**Annex 1**). Therefore, regulated flow regime will affect their behavior. According to this, mitigation measures as artificial freshets, altered flow regime and artificial floods and minimum flow are implemented. It has been demonstrated that release artificial fleshets will not help the Atlantic salmon to pass the power station outlets, weirs or find the fish way (Thorstad et al. 2008). In the case of longer fleshets these could stimulated the upstream migration of salmon.

The minimum water flow is one of the oldest mitigation measure used in regulated Rivers. Several studies have documented a positive correlation between winter discharge and the winter survival of juvenile salmon (Næsje et al. 2005). In regulated rivers with higher winter discharge have in some case demonstrated a higher smolt production (Hvidsten et al. 2004). It is important to highlight that this minimum water flow as mitigation measure was applied as voluntarily act for many hydropower licenses in Norway.

However, it is the special interest make notice the difference between minimum flow and ecological flow. Minimum flow is a term that is common used in legal requirements for hydropower licenses. As was mentioned above, is one of the oldest mitigation measures applied in Norwegian regulated rivers. However, this minimum flow often lacks an ecological base. The ecological flow defined in the Brisbane Declarations (2007) "describes the quantity, quality

and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems".

1.2 Norway and Hydropower

The use of water can varied greatly between countries, while a country can obtain greater benefits from fisheries, other can obtained from agriculture or energy. The energy produced by hydropower is 16% of the world's power (Johnsen et al 2011). In 1882, Norway was the first country in Europe hosting a hydroelectric. During years, the hydropower development have been increasing until become the largest hydropower producer in Europe. It is covering the 97% of the electricity production (NVE, 2013). With around 70% of the freshwater aquatic ecosystem regulated by the hydropower production, many of them are designated as Heavily Modified Water Bodies (HMWB), and more than 2500 water bodies considered as negative affected by hydropower production (Bakken et al. 2012). In addition, there are 452 Norwegian rivers, which have or have had self-reproductive Atlantic salmon populations. According to Hansen et al. 2008, 84 (19%) of these rivers are influencing by the hydropower development and among the 45 Norwegian salmon population that have been lost the 19% is due to hydropower development. Under this situation, Norway has an important challenge in order to harmonize the hydropower generation while preserving and improving Atlantic salmon populations.

Old hydropower licenses and their relation to Water Framework Directive

Hydropower development in Norway started more than 100 years ago. Many licenses are old and approaching the time for re-licensing. License conditions are supposed to protect against environmental harm or mitigate the negative effects, and the revision of these older hydropower licenses has been actualized as a result of the implementation of the Water Framework Directive (WFD, 2000) in the EEA-agreement (2007).

From 1970 when the minimum flow started to be required in Norway until today, the methodology to assess the minimum flow have been improved. From 1970 until 1980, the requirement were a low and constant minimum flow different between summer and winter. From 1980 onwards, the minimum flow requirement is established with an individual

assessment in each case, due to the lack of a standardized method. Due to the magnitude of Norwegian hydropower development, changes are needed in many licenses in order to reach a Good Ecological Status or Good Potential Status as the main requirement of the WFD. According to a recent study carried out by the Norwegian Water and Energy Directorate and the Environmental Agency (NVE, 2013), around 50 watercourses have a high priority and 53 lower priority for include mitigation measures as environmental flows. Other source stated that nearly 400 hydropower licenses are eligible for revisions before 2022 (Rønningern et al. 2011).

1.3 The Mandalselva case

The case of the present project is a more special situation. Laudal the lowermost power plant in the Mandalselva power system is located in the anadromous part of the Mandalselva River (Southern Norway). It was constructed in a period with no Atlantic salmon production in the river due to the acidification of the water produced by acid rain. However, in the license was specified that if one day the Atlantic salmon will be productive in the river the license should be change according to gain a good status of the Atlantic salmon population.

In 1997 after twenty years of extinct salmon stock, a liming program was started and the progressive reduction of the acidity added to a re-stocking strategy has resulted in a rapid increase of salmon population. In 2001 was catched 11 tons of salmon. Therefore, in 2002, the procedure for revise the license was started by the NVE. Nowadays, Laudal hydropower is running the second of the five years trial period used to test the minimum flow specified by the NVE.

From 1995 until 2012, Laudal Hydropower was releasing a voluntarily minimum discharge in the bypass section of 1.5 m^3 s^{-1} in winter and 3 m^3 s^{-1} in summer. The NVE minimum discharge suggested a doubling of the voluntary release of water: 6.0 m^3 s^{-1} in winter and 8-25 m^3 s^{-1} dependent on inflows in summer. The new NVE discharge has the main purpose of improve the up- and downstream migration between Laudal and Mannflåvann. Furthermore, it is assumed to improve the production of smolts and conditions for recreational fishing.

However, this discharge is not really based on scientific advises or studies carried out in the Mandalselva River. The minimum flows proposed lack a foundation in what was the natural

(pre-regulation) status in Mandalselva. Better knowledge of the pre-regulation period and how restoration work in the weir areas could influence the performance of the proposed regime. It is known that the use of the suggested rules will generate a loss of energy produced in the Laudal Hydropower plant. Conversely, the effects on fish migration, production and fishing needs to be investigated and monitored. The present project will be focus on the study and evaluation of the smolt production.

1.4 Objectives

The main objective proposed is:

The optimization of the minimum flow regime proposed by NVE using environmental design methods through and downstream of the Laudal Hydropower plant in the Mandal River in Southern Norway.

This aim will be meet through the follow specific objectives:

- ➢ To establish the natural flow regime (pre-regulation) for Mandalselva from model and data analysis of the area.
- ➢ To evaluate the regulated flow regime against the natural (pre-regulation) regime for the key flow parameters.
- ➢ To understand the effects of the weirs and how changes in weir configuration could influence flow in the bypass reach.
- ➢ To evaluate the effect of the proposed regime on Atlantic salmon using the IB-salmon model for the Laudal bypass reach trough the generation of different scenarios.
- ➢ To simulate the energy production in Laudal power plant under the regime proposed and the scenarios generated.
- ➢ To compare the cost-effectiveness of habitat adjustment versus minimum flow regime past the Laudal Hydropower plant in different scenarios.
- ➢ To compare the smolt and energy production under the different scenarios at Laudal reach with the results at the upstream bypass section (Bjelland) in Mandalselva.

As it is stated in the objectives this project will investigate the effects of the removal of weirs in flow and wetted area in the bypass section, but it is important to highlight that the environmental impact of the removal of weirs will not be take in consideration. Further, a

study Fjeldstad et al. 2012 with the removal of two small weirs in Nidelva (south-east Norway) shows how after the removal immediately the next season positive effects were founded relate to spawning redds.

2. Materials and methods

2.1 Study area

The focus area of the project is located in Mandalselva River basin, more in concrete, in a 6 km bypass river reach in Laudal (Norway). Mandalselva River is located southern Norway (58º N, 7º E, **Figure 1**). The catchment covers 1800 km^2 and is classified as one of the largest in southern Norway. The river has a length of 115 km and a mean annual discharge of 88 m^3 s^{-1}. Mandalselva River is regulated by 6 hydropower plants, the first one was constructed in 1930 and the last one in 1985. The system has 9 natural and artificial lakes used as reservoir by the power plants. Nearly the 90% of the storage capacity is founded in Navann and Juvatnet mountainous lakes.

The two lowest power plants Bjelland and Laudal are located in the anadromous part of the river where salmonids migrate 47 km from the sea until a final migration barrier called Kavfossen waterfall.

The bypass sections is a 6 km reach length starting at Manflå Dam, which is located on the natural outlet of the Manflavann Lake (Error! Reference source not found.) The Manflå Dam has a sluice gate that release the minimum residual discharge into the bypass section. The intake that supplies Laudal power plant is inside Manflavann Lake. The water taken from the intake is running through a rock tunnel and the outlet is located 6 km downstream determining the end of the bypass section. The power plant has a maximum capacity of 110 m^3/s, which is equivalent to fill 11 buckets of ten liter of water, every hundredth of a second. This water is passing through 2 Francis turbines before be released at the outlet.
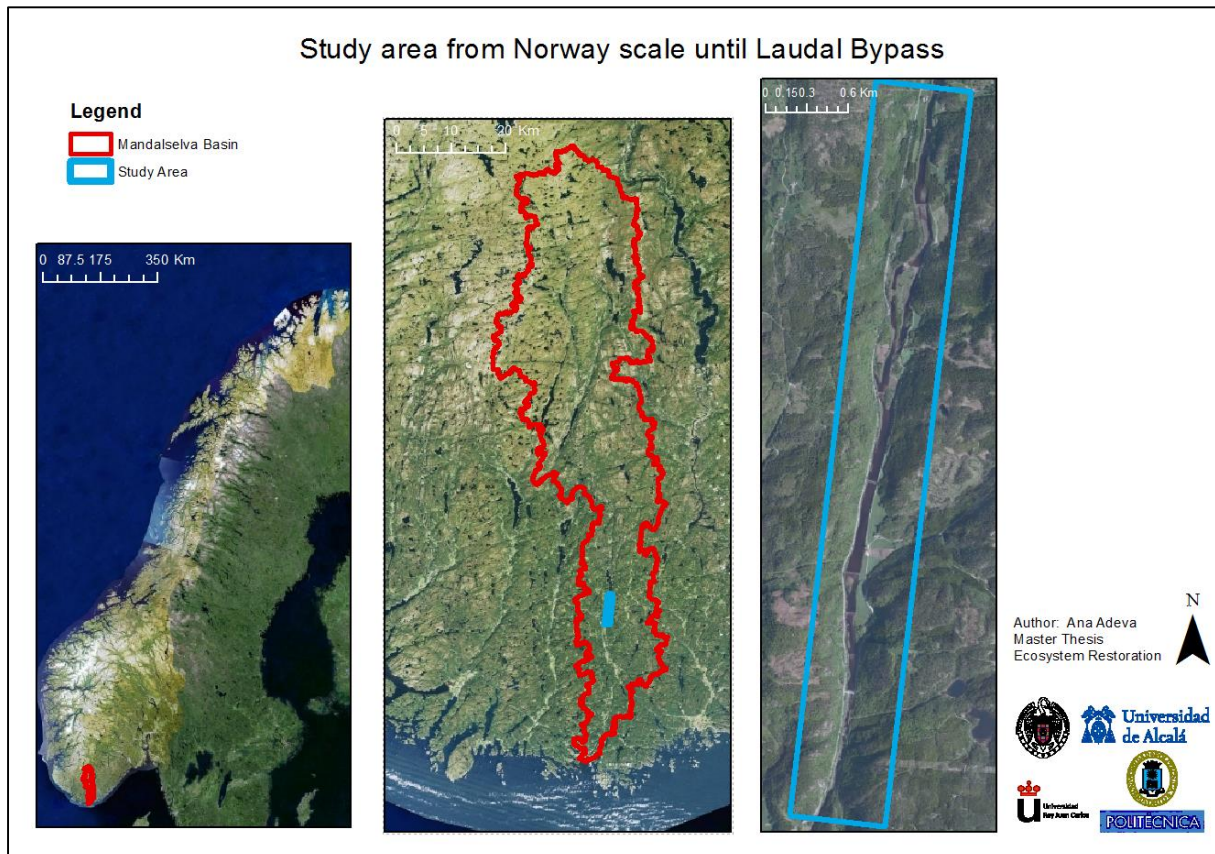
Figure 1. Representation in different scales the study area. From Norway (left) where Mandalselva Basin is represented in red, inside Mandalselva Basin the study reach is delimitated by a blue rectangle (middle) and a zoom in the study area Laudal Bypass section (right).

When Laudal power plant was designed as was mentioned before there were no salmon production, therefore physical aesthetics measures were designed in order to mitigate the effects of the low minimum flow that will be released. The result was the construction of 11 small weirs in the bypass section (see **Annex 2**).

The construction of Bjelland and Laudal the two hydropower inside the anadromous part has led a reduction in the smolt production of around 20- 40 % (Ugedal et al.2006) compared with the period before the acidification of the water. The river reach upstream Laudal power plant is important for Atlantic salmon population due to the 35% (around 30.000 smolts) of the potential smolt production in Mandalselva takes place upstream Laudal intake (Fjeldstad et al. 2013). Therefore, in our reach, the upstream migration of adults that will result in smolt production upstream and the downstream migration of the smolts are vital factors to take in account.
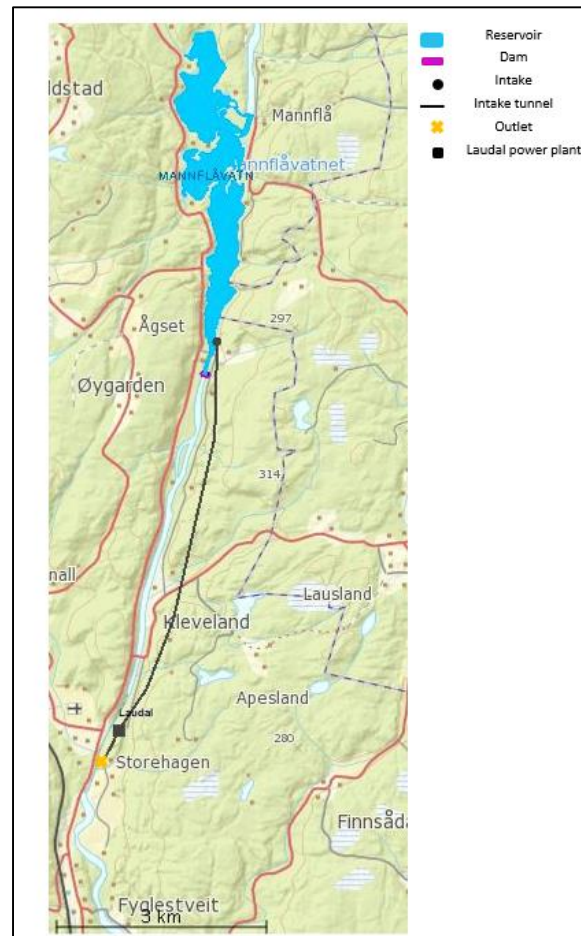
Figure 2. Laudal power plant system.

In Mandalselva River the smolt migration periods takes places during May, a period characteristic by increasing spring floods and water temperature. In this period under the past license requirement Laudal were running the production with the normal flow plant capacity except for the diversion to the bypass. Due to snow melt in this period is common flood spill to the bypass section. According to Fjeldstad et al. 2013, in years with unfavorable discharge conditions, the 90% of all smolts enter in the intake, thus they pass through the turbines. In the NVE flow regime this period is called "smolt migration period" (Starting as last day on 20 of May and finishing 14 days after) where the water released should be approximately 50% of the inflow to Mannflåvann.

After a general description of the study area, the next section describes how the data have been obtained and analysed in order to fulfil the objectives. As a general overview of the methodology used in this project the follow diagram (**Figure 3**) illustrated the process. The main objective is find an optimal discharge that will generate more production of Atlantic

salmon than was produce by the voluntarily release in the hydropower but with less energy loss than the NVE regime will produce. Therefore, a number of scenarios will be generated. For generate this scenarios the first step is compile hydrological data, then implement intermediate rules for the hydropower between the voluntarily release and the NVE rules. After generate the scenarios habitat adjustment will be included in order to see if it is possible combine less release of water with habitat modification and increase significantly the smolt production. To study the effects on smolt production under each scenario IB-salmon and Individual Based Model for the Atlantic salmon will be used. At the end, a calculation of the energy loss and the cost of the habitat modification will be estimated to evaluate the most cos-effective alternative.
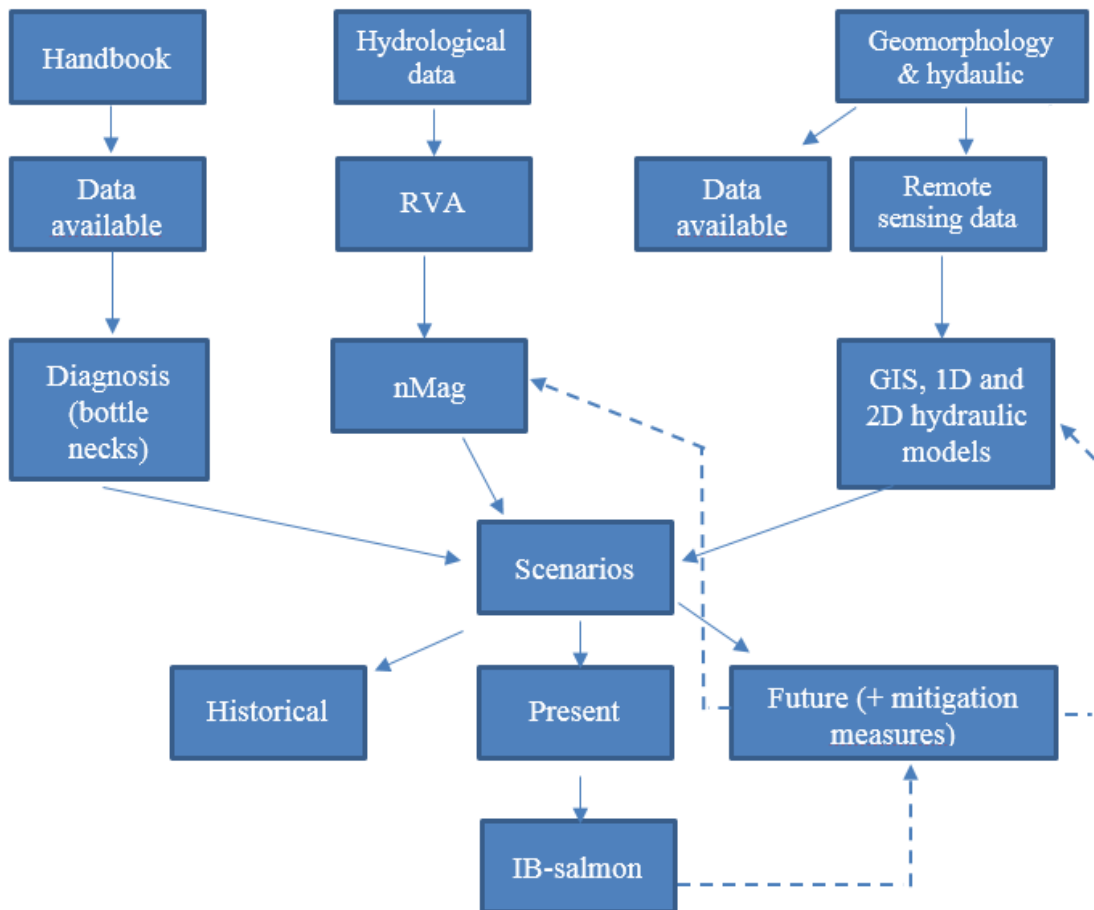
Figure 3. Methodology diagram.

2.2 Data analysis

2.2.1 Hydrological data analysis

In order to establish the natural flow regime (pre-regulation) for Mandalselva from model and data analysis of the area historical data have been analysed. Due to the lack of gauge data measured in our study area, data from Kjølemo a gauge located 18 Km downstream (see **Annex 2**) have been used. The method for apply discharge data from a downstream gauge to our study area will be called as "scaled method". The follow formula was used to carry out the scaled:

$$Q_{Laudal} = \frac{F_L * A_L}{F_K * A_K} * Q_{Kjølemo}$$

Where Q_{Laudal} is the discharge desired to obtain, which will be the discharge downstream Laudal outlet. F_L is the flow in Laudal, A_L the area of Laudal sub-basin, F_K is the flow in Kjølemo and A_K the area of Kjølemo sub-basin.

A linear regression was carried out to test the quality of the data calculated versus data measured for the period when the hydropower started to work. The result from the regression is an R^2 of 0.96. According to Chaddock (Maniak, 1997), equations with $R^2 > 0.8$ are assumed as tightly correlating, and according to Appollov (Maniak, 1997), its hydrological prediction is qualified as sufficient. Using the scaled methodology a series of discharge data from 1897 until 1981 has been obtained for our study area. From 1982 onwards discharge data are available in the NVE database from the gauge situated in the outlet of Laudal power plant. After the collection of these hydrological data from the outlet of Laudal power plant it is needed process the data according to know how much water is running in the bypass section.

2.2.2 Hydropower operation modeling

The hydrological data from the gauge downstream Laudal outlet power plant has been implemented in nMag (Killingtveit & Sælum 1995) a software for hydropower simulations. Fjeldstad et al. 2013 generated a model with nMag for the Mandalselva Hydropower system (**Figure 4**). The use of this model allows know how the discharge is distribute between the power plant systems when no measured data are available.

This model was calibrated with the assistance of the Hydropower Company Agder Energi using runoff data and old production data.
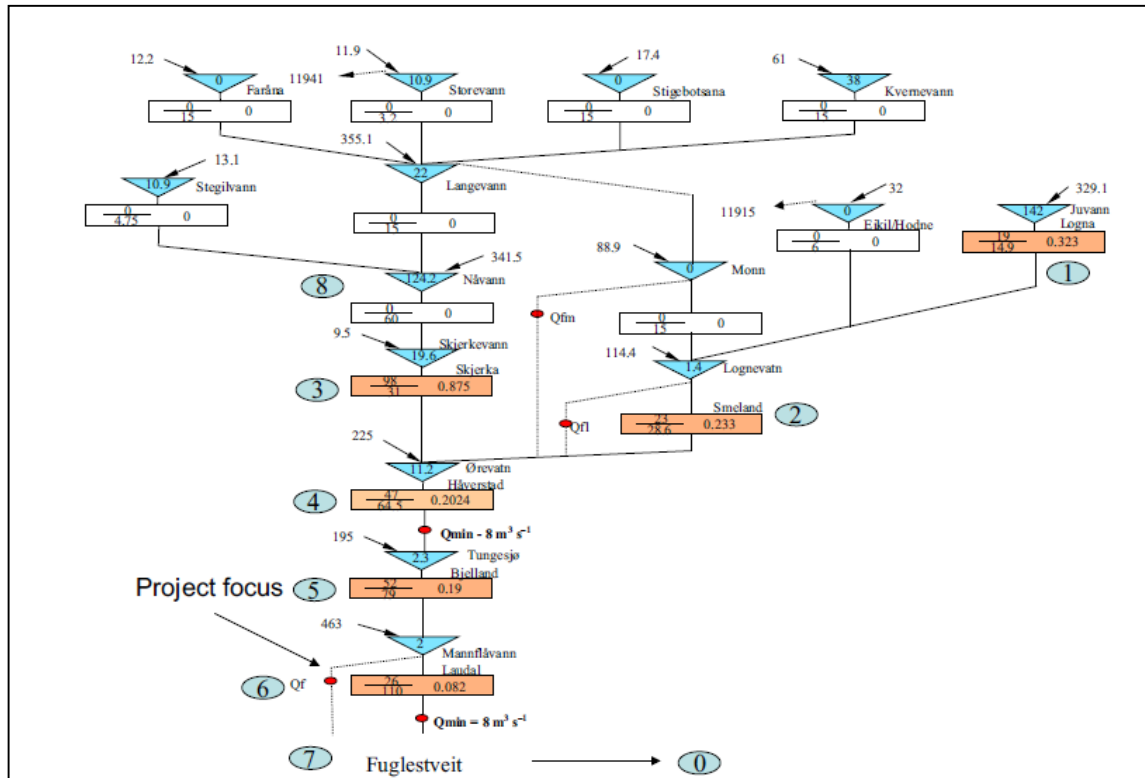
Figure 4 Representation of the river Mandalselva power system in nMag model. Triangles represent subcatchments, white rectangles represent lakes and orange rectangles represent the power plants. Inside the shapes, the number represent yearly runoff, reservoir volume, production capacity and discharge capacity, respectively. The dotted lines indicates minimum flow restriction and Project focus indicate the discharge in bypass section.

As a result, from nMag a discharge series of 20 years (1988-2007) in the bypass section has been obtained. This data series obtained from nMag correspond with the period when Laudal was releasing the voluntarily discharge in the bypass section. Therefore, an excel spreadsheet hydropower model has been generating in order to contemplate different bypass discharge and different power plant rules for generate the different scenarios.

2.2.3 Scenarios modelling

The **Table 1** summarizes all the scenarios that have been generated. These will be explained in detail in the next section.

A total of 19 scenarios have been generated, 12 of them are hydrological scenarios (**Figure 5**) and 7 have the same hydrological characteristics than the hydrological scenarios but adding

habitat adjustment (**Table 1**). Both hydrological and hydrological with habitat modification will be used in smolt model and just hydrological scenarios will be used to energy model.

Table 1. Scenarios generated.

Scenario	Winter discharge (m³/s)	Spring release	Summer discharge (m³/s)	Additional Habitat modification (H+)
A	1.5	-	3.0	x
B1	4.0	-	6.0-14.0	x
B2	4.0	25% of inflow	6.0-14.0	-
B3	4.0	50% of inflow	6.0-14.0	x
C1	6.0	-	8.0-14.0	x
C2	6.0	25% of inflow	8.0-14.0	-
C3	6.0	50% of inflow	8.0-14.0	x
D1	6.0	-	8.0-25.0	x
D2	6.0	25% of inflow	8.0-25.0	-
D3	6.0	50% of inflow	8.0-25.0	x
H1	-	-	-	-
H2	-	-		-

2.2.1.1 Hydrological scenarios

The scenarios A and D3 were already specified (**Table 1**, **Figure 5**), A was the hydrological situation with the voluntarily release and D3 the new hydrological situation suggested by NVE. H1 and H2 are discharge data that has been analysed previously and no further action are needed to generate them. In order to see if is there any possibility to find a discharge between the previous rules and the suggested rules which will facilitate a similar effect in salmon population but with lower loss of energy, two intermediate scenarios have been generated (B,C) just implementing less strict discharge rules.

In all the scenarios except in A, H1 and H2, the summer and spring migration period will depend on the inflow coming from Manflavann (Error! Reference source not found.). However, winter is specified as a minimum that does not depend on inflow.
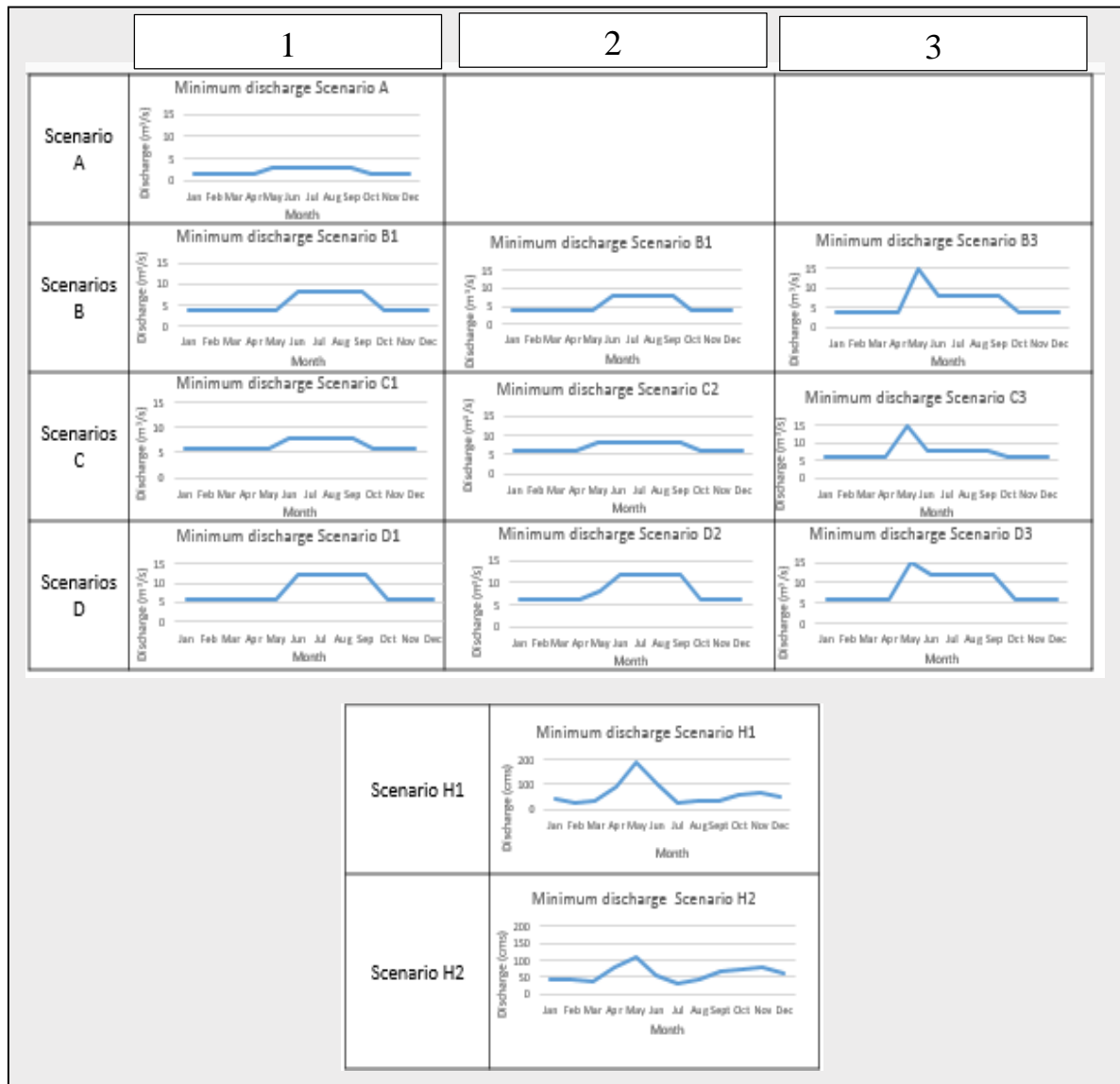
Figure 5 Hydrographs per hydrological scenario representing the minimum discharge release by the hydropower in the bypass section.

The NVEs discharge regime also suggested a period of water release called "smolt migration period" (Starting as last day on 20 of May and finishing 14 days after) where the water released should be approximately 50% of the inflow to Mannflåvann. It is important to note that this smolt migration period has been simulated with 3 different variables numbered as 1,2 and 3 (**Table 1**, **Figure 5**):

- (1) No extra water released in the smolt migration period.
- (2) 25 % of inflow bypassing hydropower plant in the smolt migration period to facilitate smolt migration past the turbines.

- (3) 50 % of inflow bypassing hydropower plant in the smolt migration period to facilitate smolt migration past the turbines.

In order to compare hydrologically the discharge release in each scenario in the smolt migration period, the 20 years data series was analysed to obtain a median minimum discharge release in bypass section rather than a percent. Due to the inflow coming to Mandalselva will be the same for each scenario the results are summarize in **Table 2:**

Table 2 Smolt migration discharge under the variables generated.

Variables	25 % of inflow bypassing hydropower plant	50 % of inflow bypassing hydropower plant
Scenarios	B2, C2, D2	B3,C3, D3
Minimum of minimum	6 m^3/s	6 m^3/s
Median of minimum	8 m^3/s	15 m^3/s
Maximum of minimum	22 m^3/s	45 m^3/s

As the scenarios will works by seasons, it is important to specify the range of these seasons. When there is no smolt migration period in spring, the scenario will be divided in winter: October to April and summer: May to September. When the scenario include spring migration period then the year is divided in winter: October to 19 May, spring period: 20 of May and finishing 14 days after (5 - 6 of June) and summer (m^3/s): 5 - 6 June to September.

It is important to highlight that in all the following scenarios when minimum, median and maximum is mentioned it referred to the minimum of minimum discharge in the bypass reach, the median of the minimum discharge in the bypass reach and the maximum of the minimum discharge in the bypass reach. This is because some water can be added to this minimum as spills in some periods. However, the minimum always has to be respected.

Scenario A

The scenario A was already specify due to is the rules and the discharge that Laudal hydropower was applying voluntarily. With a winter discharge of 1.5 m^3/s, no extra water release in spring migration period and 3 m^3/s in summer (**Table 1**, **Figure 5**).

Scenarios B

The first scenario generate as an intermediate between A and D, with a reduction in the minimum discharge in both summer and winter compare with D, and the difference between

B1, B2 and B3 is the spill release during the migration period (see **Table 2**). Summer depends on Manflavann inflow. Therefore, the relation applied in scenarios B is:

- **6**-12 m³/s as inflow from Manflavann, all water past to bypass section.
- 12-30 m³/s **8** m³/s past
- 30-50 m³/s **10** m³/s past
- 50-80 m³/s **12** m³/s past
- >80 m³/s **14** m³/s past

Where, the minimum of the minimum discharge in the bypass during the 20 years series is 6 m³/s, the median of the minimum is 8 m³/s and the median of the maximum discharge is 14 m³/s see **Figure 6.**

Scenarios C

Is the second scenario generate in order to find an intermediate between A and D. In this case, the winter discharge is the same that the specified by D but the relation applied in summer is less strict. The differences between C1, C2, and C3 are the spill in spring (see **Table 2**).The summer relation depending on the inflow for scenarios C is the follow:

- **8**-12 m³/s as inflow from Manflavann, all water past to bypass section
- 12-30 m³/s **8** m³/s past
- 30-50 m³/s **10** m³/s past
- 50-80 m³/s **12** m³/s past
- 80 m³/s **14** m³/s past

Following this relation the minimum of the minimum discharge in the bypass during the 20 years series is 8 m³/s, the median of the minimum is 8 m³/s and the median of the maximum discharge is 14 m³/s see **Figure 6**.

Scenarios D

The scenarios D are the scenarios suggested by the NVE, with the variability applied in the spring migration period that make differences between D1, D2, and D3 (see **Table 2**). The real suggested flow regime from NVE correspond to scenario D3, with a 50 % of the inflow coming from Manflavann released in the bypass section. The relation applied in summer is:

- **8**-12 m³/s as inflow from Manflavann, all water past to bypass section
- 12-30 m³/s **12** m³/s past

- 30-50 m^3/s **15** m^3/s past
- 50-80 m^3/s **20** m^3/s past

Under this relation the minimum of the minimum discharge in the bypass during the 20 years series is 8 m^3/s, the median of the minimum is 12 m^3/s and the median of the maximum discharge is 25 m^3/s see **Figure 6.**

Scenario H1 and H2

After the scaled of the historical data, the historical discharge seriess in the study area was divided into two scenarios H1, H2 (**Table 1** and **Figure 5**). Where H1 correspond to the period in which all Mandalselva River was unregulated, from 1897 to 1930. Meanwhile, H2 correspond to the period where the upper part of Mandalselva catchment was starting to be regulated but not yet the anadromous part, from 1931 to 1971.
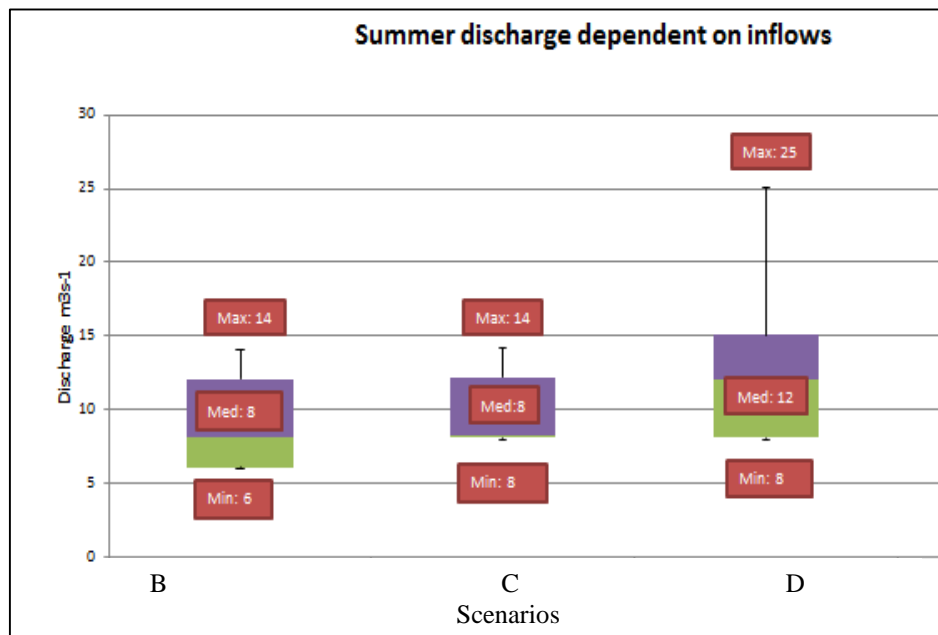
Figure 6 Minimum, median and maximum of minimum discharge for the different scenarios in summer.

2.2.1.2 Habitat adjustment scenarios

Seven of these hydrological scenarios had been repeated but in this case applying additional habitat adjustment such as removal of dams or increase of spawning habitat areas. The follow hydrological scenarios will be used: A1, B1, B3, C1, C3, D1, D3 (**Table 1**), which with habitat adjustment will be named as before but including "+H" (e.g. A1+H). These habitat adjustments are estimated as the maximum habitat improvement likely on the reach. With the objective to investigate if the maximum improvement of habitat and less strict discharge regime as B or C

(compare with D: NVEs regulation) will give approximately the same amount of smolt production as NVEs suggested rules, where no habitat modification is implemented. It is assumed that the removal of the weirs and the increase in the discharge will led all the spawning areas in use.

Removal of weirs

As has been mentioned in study area, Laudal bypass section has 11 weirs. Manflå Dam, which is a 1.5 meters height concrete weir, 9 weirs form by cobbles and 1 small concrete weir in Kleveland Bru with 1.3-1.5 meters height. The habitat adjustment simulated the removal of 10 of the weirs and a reduction of 0.5 meters in Manflå Dam (**Figure 7**).

Figure 7. Weirs in Laudal bypass section (Mandalselva River). On the upper left corner Manflå Dam, upper right corner Kleveland concrete weir, both on the bottom are one of the 9 cobbles weirs view from two sides. Photos: Berit Köhler and Ana Adeva.

In the scenarios that include removal of weirs, it is assumed the removal of 11 of them (9 cobbles weirs and Kleveland Bru weir), and a reduction of 0.5 meters in the east side of Manflå Dam. The data of river bed topography are available just for some parts of the river reach. However, a previous study carried out in Mandalselva River was defining the relation between wetted area and discharge (Sauterleute. 2011). The bypass section was defined following the same relation for the rate of change. It made possible simulate the removal of weirs with the data available and assume the same rate of change in the parts were no data is available.

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Using a 1D hydraulic model, HEC-RAS (2008) and the topography available, the removals of dams have been simulated obtaining the follow relation (**Figure 8**) based on the methodology of Sauterleute, 2011.
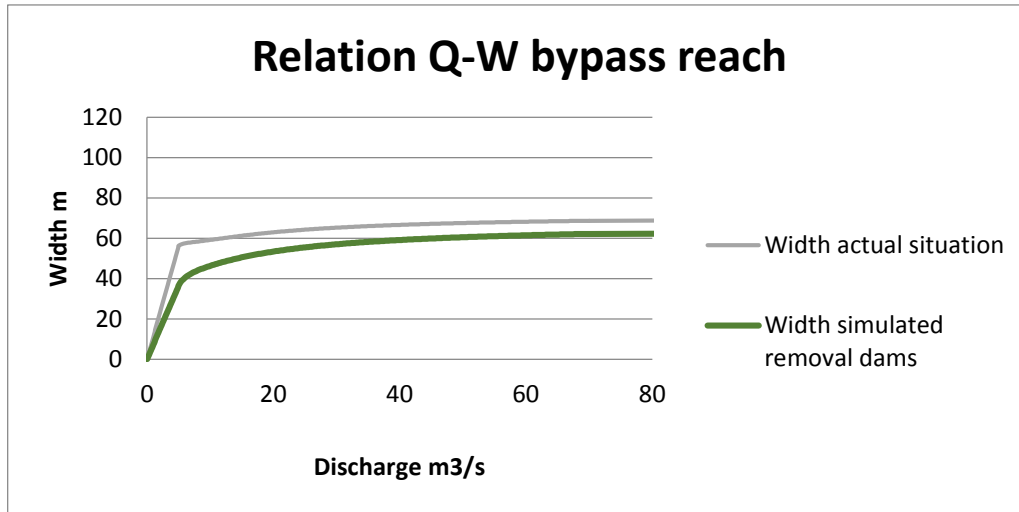
Figure 8. Relation discharge-width in the bypass reach before and after the removal of weirs.

Addition of spawning habitat

During a previous project carried out in Mandalselva (Forseth, 2012) the spawning habitat in used was studied but also potential spawning habitat that today are not used due to the low velocities or the excess of water (higher depth). The **Figure 9** shows the bypass reach between Manflå Dam and Kleveland weir, where the orange dots are the present spawning areas, the green dots potential spawning area if water velocities are increased, and the yellow dots represent extra spawning habitat if spawning gravel is added. The areas selected to add the gravel were closed to the actual and potential due to is recommend add the gravel with the adequate size in areas where this size distribution of gravel is already in use (Forseth & Hardy, 2013). A total of 2000 m^2 of spawning area will be created. Potential spawning and fish production has been estimated with all spawning sites in use. In Barlaup et al. 2008, argued that after the addition of artificial spawning ground in five regulated Norwegian rivers was found that fish spawned at all sites where gravel has been added.
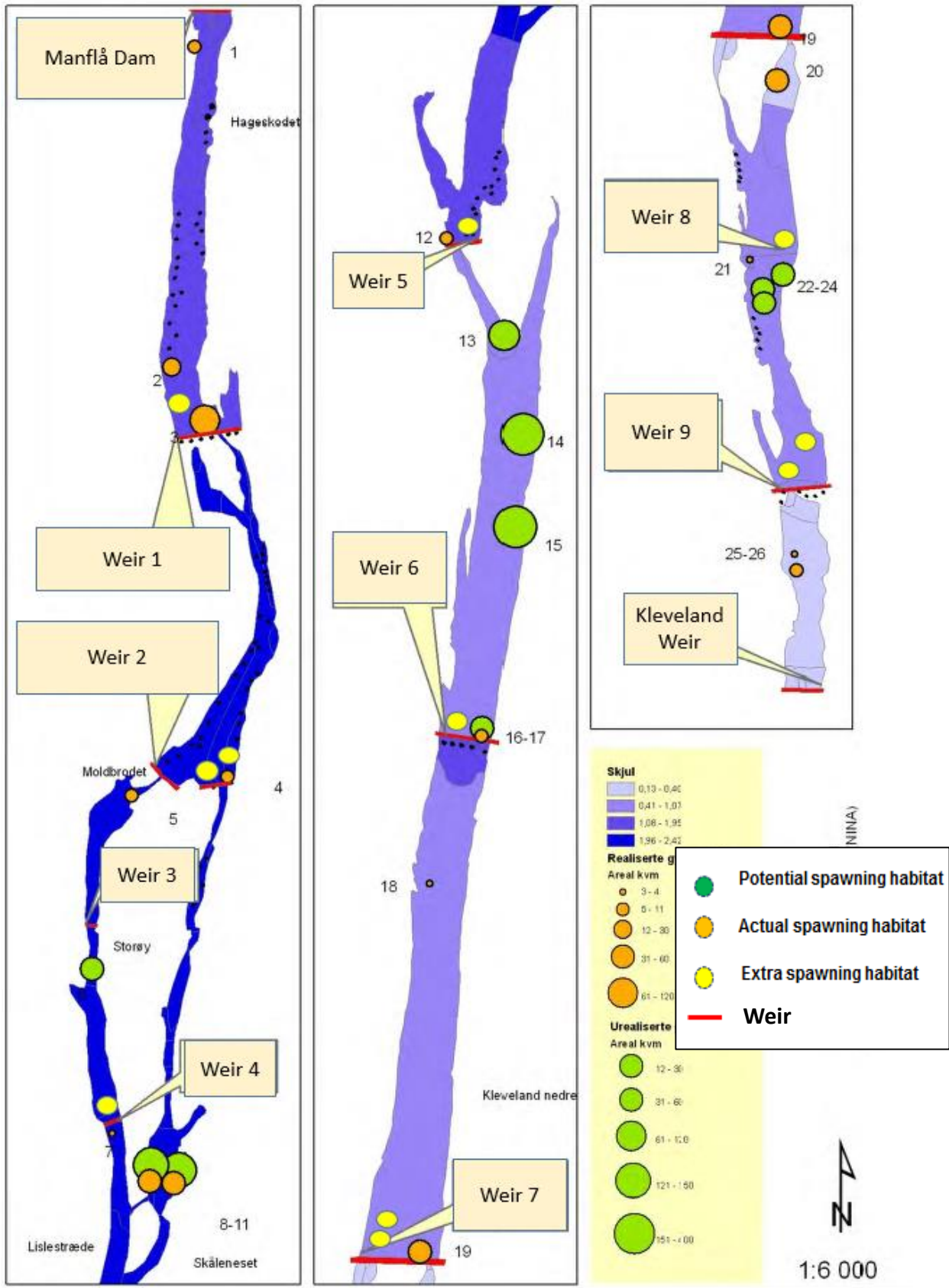
Figure 9. Present, potential and added spawning habitat in Mandalselva between Mannflå Dam and Kleveland.

2.1 Comparison between unregulated and regulated flow regime

In order to evaluate the regulated flow regime against the natural (pre-regulation) regime for the key flow parameters the hydrological scenarios A, H1 and H2 have been compared (**Table 1**). As has been defined in the introduction, the flow regime is formed by five key components (Poff et al. 1997):

- Magnitude, is the amount of water moving past a fixed location per unit of time
- Timing, regularity within flows of defined magnitude occur
- Frequency, how often a flow above a given magnitude recurs over some specific interval of time
- Duration, is the period of time associated with a specific flow condition
- Rate of change, is how quickly flow changes from one magnitude to another.

The methodology used by Richter et al. 1996 known as Indicator of Hydrologic Alteration (IHA) defined these 5 key components as statistics groups. However, Norwegian rivers follow a special pattern of distribution in flow regimes: low flows in winter due to snow accumulation, high flow in spring due to snowmelt, summer and autumn season depends on changes in precipitation. Therefore, the method used to evaluate these scenarios is the used by Dangelmaier (Master thesis 2004) where some other parameters are added to a first modification done by Hohl in 2003 (see **Annex 4**). This will help to analysed and relate the changes in the five key components in a Norwegian river with the life cycle of the Atlantic salmon based on the relation establish in Dangelmaier, 2004.

Table 3. Ecological impacts on salmon of the hydrological parameter analysed.

Key component (Richter et al. 1996)	Hydrological Parameter ((Richter et al. 1996, Dangelmaier, 2004)	Relevance for Atlantic salmon (Dangelmaier, 2004)
Magnitude and timing	Mean discharge value per season of the year	Key life stages relate to the periods of the year (see Annex 1).
Magnitude and duration	Annual minima and maxima 7 days means	Temporally bottlenecks in availability of suitable habitat for your fish. Decreased flow may endanger survival of juvenile in winter and spring during the period of fry emergence.

Frequency, magnitude and timing	Number of high and low pulses per year and duration of those	Limitation on availability of suitable habitat, changes in water temperature and oxygen in water.
Rate of change	Means of all positive and negative differences between consecutive daily means.	Stranding, increasing energy consumption relate to higher velocities.

According with the

Annex 4, a select number of representative hydrological parameters (**Table 3**) has been analysed. This can be categorized as follow:

a) Parameters of seasonal and monthly values: mean discharge value per season of the year
b) Parameters of annual high and low flow situations: annual minima and maxima 7 days means
c) Parameters of annual extremely high and extremely low flow situations: number of high and low pulses per year and duration of those
d) Parameters of rapid flow increase and decrease: means of all positive and negative differences between consecutive daily means.

2.2 IB-salmon modeling

The use of an Individual Based Model IB-salmon (Hedger, 2013) gave us the possibility of evaluate the effect of different mitigation measures on salmon populations in Mandalselva River. IB salmon is able to simulate the production of Atlantic salmon in a river under different boundary conditions, allowing the prediction of the effect of real implementation measures. The advantage of this ecological modelling approach is that it enables modelling long-term effects (over several decades) of mitigation measures, which may not be apparent in physical habitat models.

As it is showed in the **Figure 10**, IB-salmon is working with abiotic factors as wetted area and river temperature, and biotic as egg deposition, or spawning abundance among others. The temperature has a constant variation in the simulation model for this project, as the main

purpose is see the effects of different discharges and wetted areas rather than effects from temperature changes.
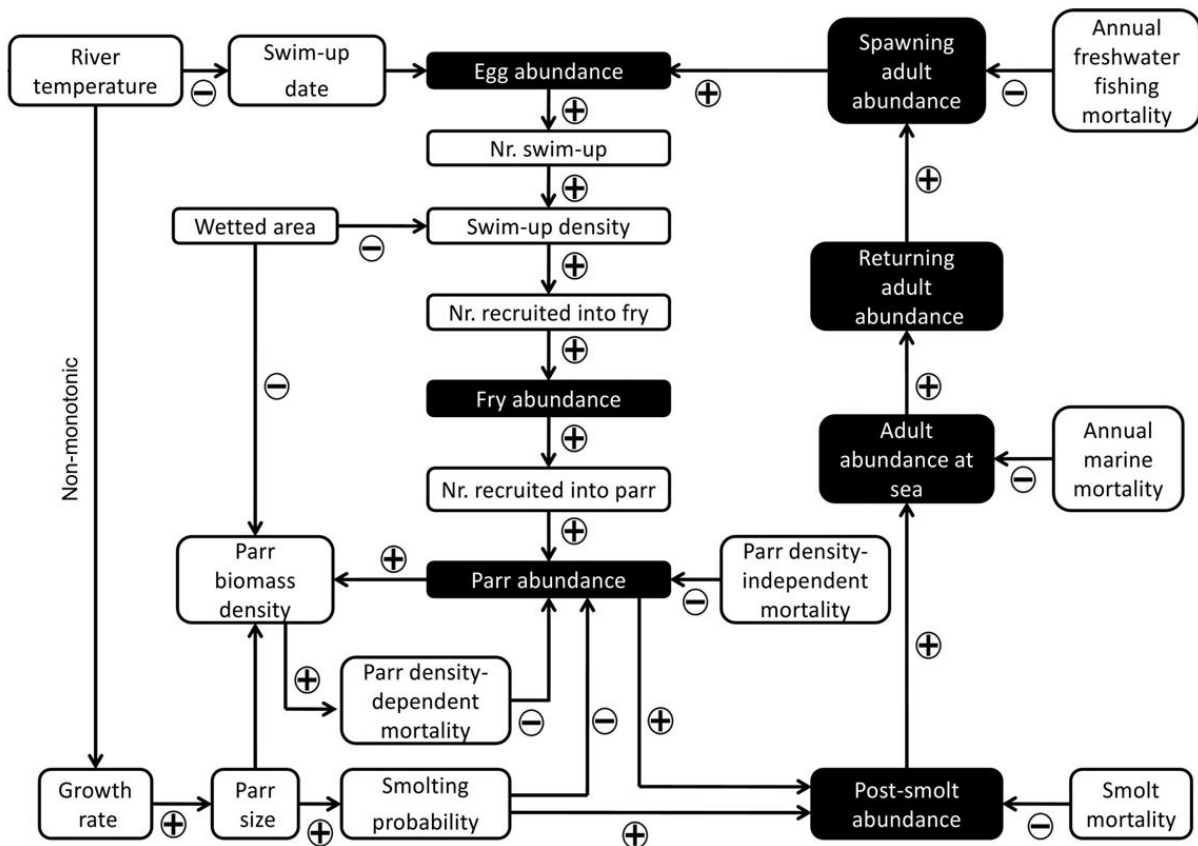
Figure 10. Structure of the model showing mechanistic relationships. Negative signs and positive signs by the flow arrows indicate negative and positive relationships respectively (Hedger, 2013).

All the scenarios generated (**Table 1)** are running in IB-salmon. For run the model, the inputs that have been used are Discharge, wetted area and deposition of eggs.

Discharge
All the hydrological scenarios are used as input data (**Figure 5**).

Wetted area
The wetted area is directly proportional to changes in discharge and habitat modifications. For all the scenarios, the wetted width-discharge methodology mentioned before has been applied. In the scenarios without habitat modification (**Table 1**) the relation was already established by Sauterleute. 2011, for the scenarios with habitat modification has been calculated using hydraulic modelling (HEC-RAS, 2008) and the relation Q-W. For the historical scenarios (H1,

H2) the analysis of historical picture using remote sensing (ESRI, 2011) have been applying obtaining the relations in **Figure 11**
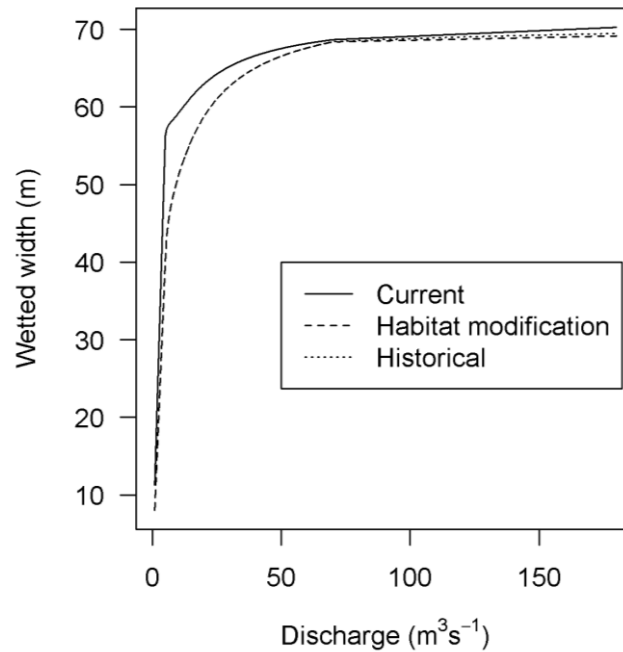
Figure 11. Discharge – wetted width relationships for Laudal bypass under current, projected habitat modification and historical situation.

Egg deposition

Based on field data the egg deposition has been estimated as 1.45 eggs per gram of female biomass. Therefore, relations have been applied in order to calculate egg deposition assuming the spawned of a female per spawning ground.

In order to run IB-salmon simulations, the combination of discharge with 20 years data series, wetted area and egg deposition, will results in a combine input of 20 years data series for each scenario. Where the 10 first years will be used as Burn-in series to generate a good age-distribution of spawning adults, this will allow for egg deposition in year 11, and the analysis of smolt results will be done from year 12 until 20.

2.3 Energy modelling

In order to compare the results obtained from run IB-salmon with the energy produce under each scenario, all the hydrological scenarios except H1 and H2 (**Table 1**) have been used to generate the energy production as a first order estimate, not taking into account system

optimization conditions. Laudal power plant has two Francis turbines, a vertical height of 36 meters and an installed capacity of 26 MW with an average annual production of 146 GWh. Using the follow formula it is possible to reproduce the potential power production under each scenario.

$$P = \frac{Q.H.\eta.g}{1000}$$

Where:

P = potential power output in (kW)

Q = water flow through the turbine (Discharge) in (m³/sec)

H = net head of water (m) (the difference in water level between upstream and downstream of the turbine)

η = efficiency of the turbines (it has been assumed an efficiency of 0.9)

g = acceleration due to gravity of 9.8 m/s²

To calculate the available energy that can be generated within 24 hours in (GWh), the following equation has been applied:

$$E = P_m.d_m.h_d.10^6$$

Where:

E = energy (GW)

P_m = monthly potential power output in (kW)

d_m = days per month (number of days)

h_d = hours per day (number of hours per day, 24 h)

10^6 = conversion factor from kW to GW

2.4 Cost of mitigation measures

For the energy cost, we assume that the price is approximately 0.04 € per kWh for May 2012 to May 2013 according to the estimation of the energy Norwegian Market (Fjeldstad et al. 2013).

For the habitat adjustment a very roughly estimation has been done because the price can vary between companies, location, river, etc. As it has been mentioned there are 9 low weirs formed by cobbles and two small concretes, one of these last two will be lowered the head and the other removed. It has been assumed that the removal of weirs and the addition of the spawning

grounds is planned and constructed in the same operation. Where 100 m^2 of spawning gravel is approximately 20-30 m^3 of gravel and its cost approximately 35-40 € per m^3 of spawning gravel, adding the machinery and transport. In our case, we assumed that the removal of weirs and deposition of the cobbles in the river are included in this price. It is planned to add 600 m^3 of gravel.

2.5 Comparison of smolts production and energy production.

In order to evaluate the cost-effectiveness of physical measures versus spill of water past the Laudal Hydropower plant a comparison between the smolt production and energy in Laudal power plant under each scenario has been conducted.

First smolt production has been compare between scenarios (**Table 1**), having as a baseline the NVE (Scenario D3) and as a reference the historical (H1, H2). From IB-salmon modeling the smolt production output has been analysed for each scenario, comparing the median of smolt produced each 50 m of the bypass section and the total number of smolt in the bypass during the last 10 years of the 20 years series. Since was mentioned before, the first 10 years are used as Burn-in series. This has been representing using graphs and maps that will be presented in the result section.

Second, the energy produced under each scenario has been also compare between each scenario having again as a Baseline the NVE (Scenario D3) and the reference in this case is the scenario A (**Table 1**), because correspond with the higher energy production that Laudal power plant would like to maintain. The results will be represented in graphs in the results section.

Third, a comparison between smolt production under each scenario versus the energy produce by these scenarios will be used to evaluate the optimal minimum flow in terms of salmon production and energy production.

Fourth, as the last point of this thesis a comparison between the results obtained at Laudal bypass with the results obtained in Bjelland bypass as the upstream section in Mandalselva has been carried out.

Bjelland study area

Bjelland Hydropower is located upstream Laudal hydropower and both are located in the anadromous part of Mandalselva River. The stretch has a length of 12 km at it is divided in two sections (**Annex 5**) Bypass section (4km) from Kavfossen (a natural waterfall and the end of the anadromous part) until the outlet of Bjelland, known as Monan. The second section is downstream the outlet, from Monan until Mannflåvann (8km). The flow in the bypass stretch has been greatly reduced after the development of Bjelland power plant in 1974, with exceptions periods of overflow over the dam at Tungesjø. Two weirs are located at the bypass, weir 1 known as Fossekilen and weir 2, Sunde, (**Annex 5**). After the regulation the flow in this reach is mainly determined by the discharge in Kosåna. It is an unregulated river with the inlet located some meters after Kavfossen. From 1997 it was decided that the minimum discharge on the bypass should be 2 m^3/s in the summer and 1 m^3/s in winter. This means that it is just released water over the dam at Tungesjø when the discharge from Kosåna is lower than the minimum requirements.

According to Ugedal et al 2006, the average discharge in Kosåna for the period 1980 to 2005 was 8.2 m^3/s. As yearly average, in winter (December to April) Kosåna has an average of 21 days (range 0-78 days) with less than 1 m^3/s. In summer (June-September) it has 56 days (range 12-106 days) with less than 2 m^3/s. The intake of Bjelland power plant in Tungesjø has a yearly average inflow of 58.6 m^3/s, while the intake capacity of the plant is about 78 m^3/s. It will be therefore not unusual that the discharge on the stretch from Kavfossen to Bjelland will be equal to the minimum flow both winter and summer.

Once the main characteristics of Bjelland study area has been described, it is possible to think that the consequences of implement a new rule as it has been proposed to Laudal will bring great losses of energy. In order to see what are the differences, between implement mitigation measures in Laudal, rather than in Bjelland, or in both stretches, the same methodology that has been developed for Laudal has been implemented in Bjelland stretch. In order to simplify the procedure, the methodology will not be explained or develop and just the main results will be shown in summarize graphs at the end of the results section.

3   Results

In the results section the main results obtaining from this project will be shown.

3.1   Comparison of natural (pre-regulated) flow regime with regulated flow regime.

The parameters choose to analyse the hydrological alteration between scenarios is explained in **Table 3**. The follow legend (**Figure 12**) will be applied for all of the graphs. Where dark blue represent scenario H1, light blue H2 and red A (**Table 1**)
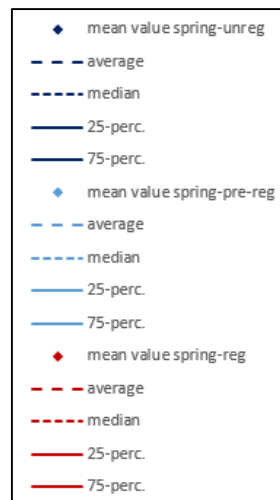
Figure 12. Legend

   a) Parameters of seasonal and monthly values

The annual winter mean discharge value in the bypass section is a slightly higher for H2 than for H1. However, for A the values are greatly reduced. The median winter mean discharge for H1 is 56 m^3/s, for H2 is 60.4 m^3/s and for A 7.8 m^3/s (

Figure 13) The annual spring mean discharge for H1 is higher than for H2 and A, where this last is extremely low. The median spring discharge for the scenario H1 is 111 m^3/s, for H2 is 85 m^3/s and for A is 7 m^3/s (

Figure 13). In May where the smolt migration occurs, the median discharge for the scenarios are: H1 has a median of 180 m^3/s; H2 has 127 m^3/s and A 5 m^3/s. This graph and the monthly median discharge is represented in **Annex 6.** In summer (

Figure 13) there is a slight difference in annually discharge between H1 and H2 meanwhile in A the discharge are extremely low. The mean discharge for the H1 is 72 m^3/s, for H2 57 m^3/s and for A is 3 m^3/s. In autumn (

Figure 13) as the same than in winter H2 shows slightly higher values than H1, and A has reduce values but higher than any other season. The median discharge for H1 is 84.9 m^3/s for H2 is 93 m^3/s and for A is 12.6 m^3/s.
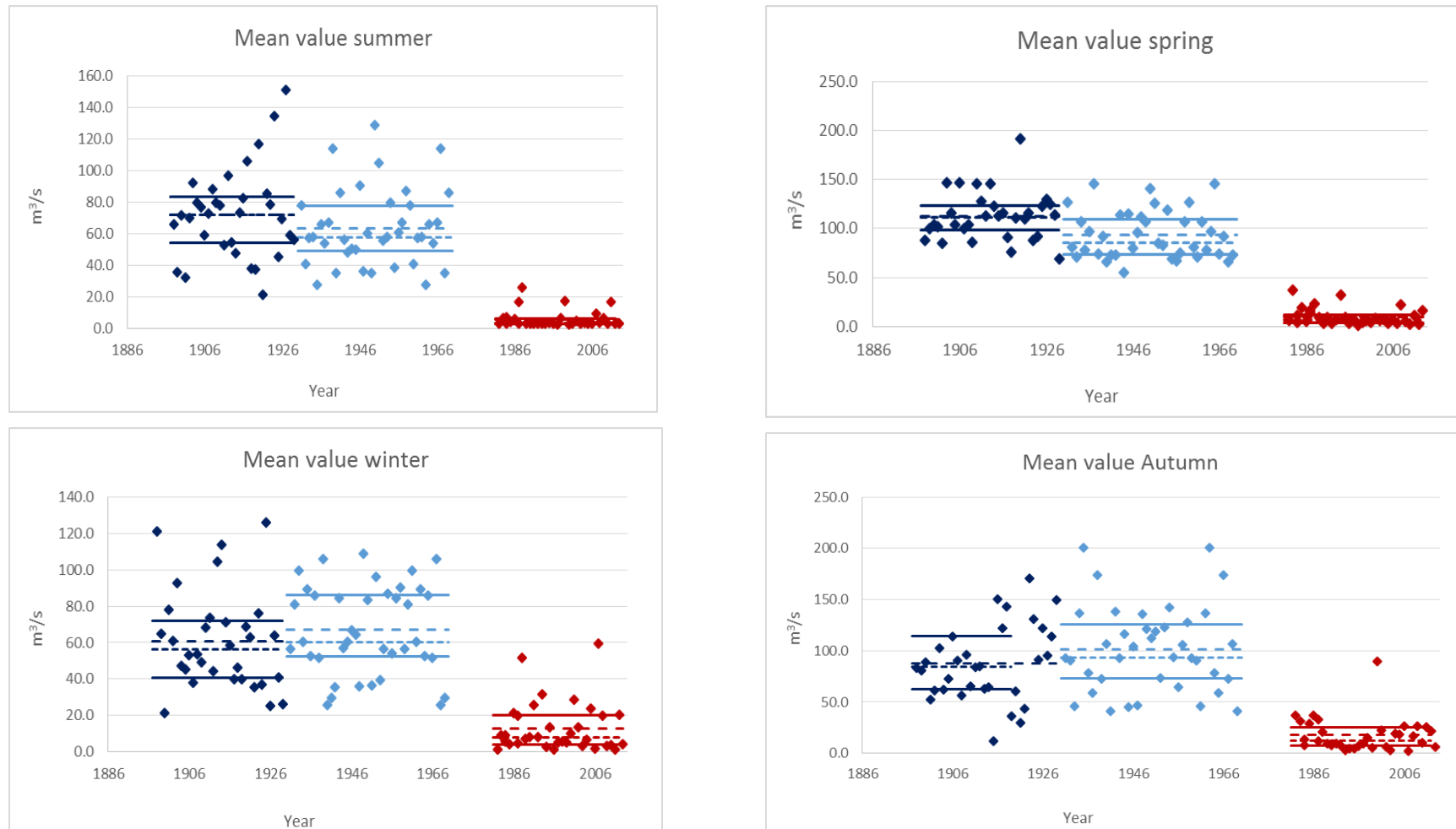
Figure 13. Annual mean discharge value (m³/s) for seasons: winter, spring, summer and autumn for scenarios H1, H2 and A.

b) Parameters of annual high and low flow situations

The annual maximum discharge during 7 days according to the **Figure 14** are quite similar between H1 and H2. Scenario A shows lower values than H1 and H2. However, the annual minimum discharge for 7 days are higher in H2 than H1 and scenario A shows extremely low values.
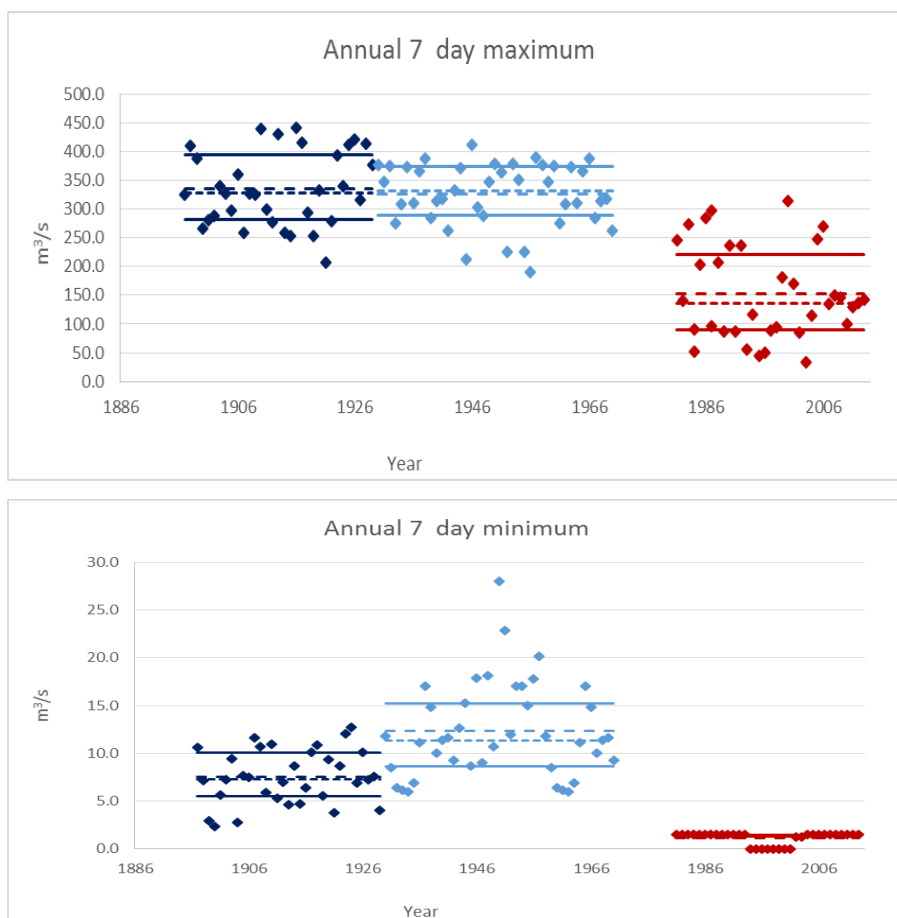
Figure 14. Annual 7 days maximum and minimum discharge (m^3/s) for scenarios H1, H2 and A.

c) Parameters of annual extremely high and extremely low flow situations

The number of both high and low pulses are quite similar, but higher in H2 than in H1 however, the duration of those pulses are higher for H1 than H2 in both cases. For the scenario A, there are higher number of high pulses but with a lower duration than the few number of low pulses, that shows higher duration (**Figure 15**).

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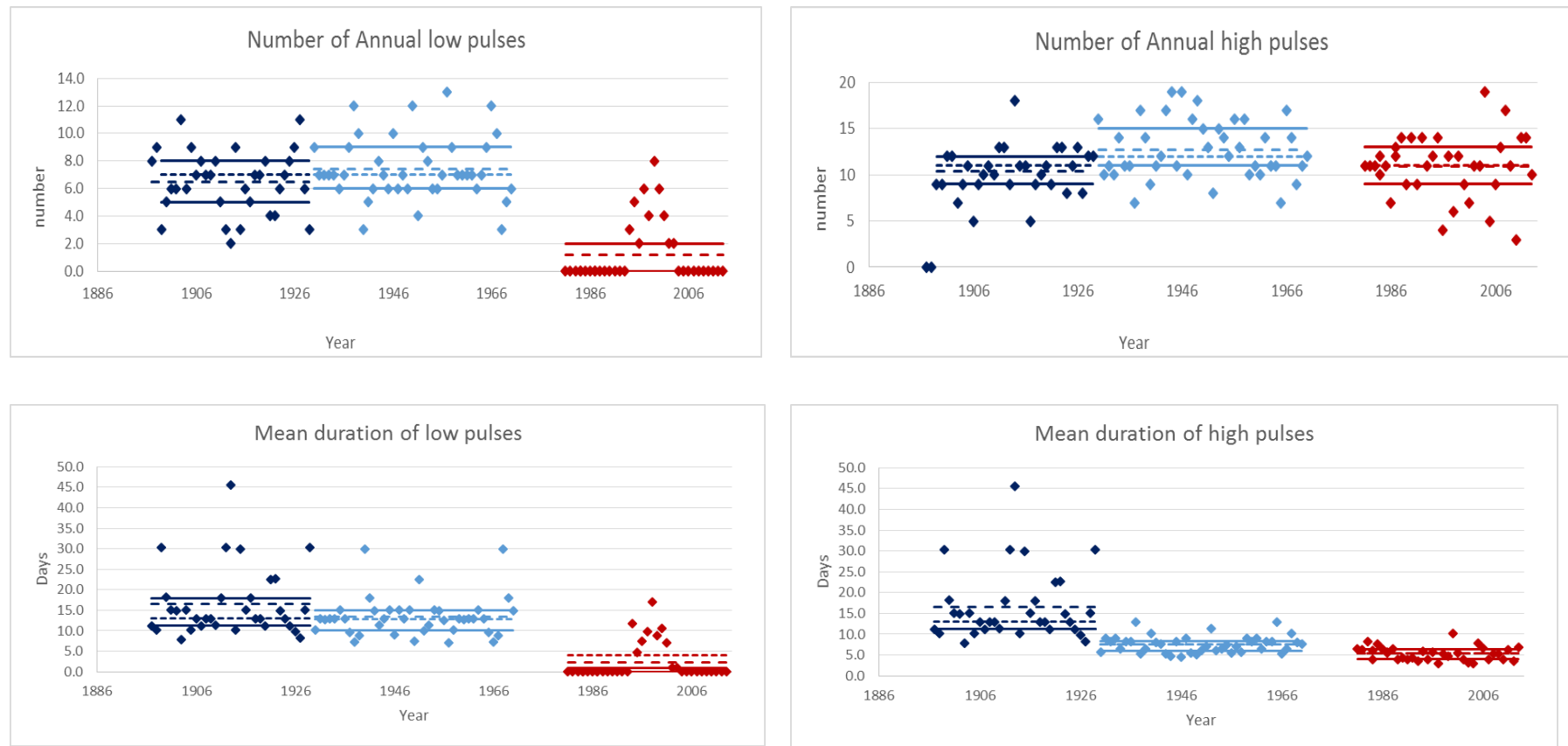
Figure 15. Number of annual low and high pulses in the upper part, and mean annual duration of low and high pulses on the bottom for scenarios H1, H2 and A..

   d) Parameters of rapid flow increase and decrease

For both positive and negative the differences between daily mean discharge per year are higher in scenario A, follow by scenario H2 and the lower H1 (**Figure 16**).
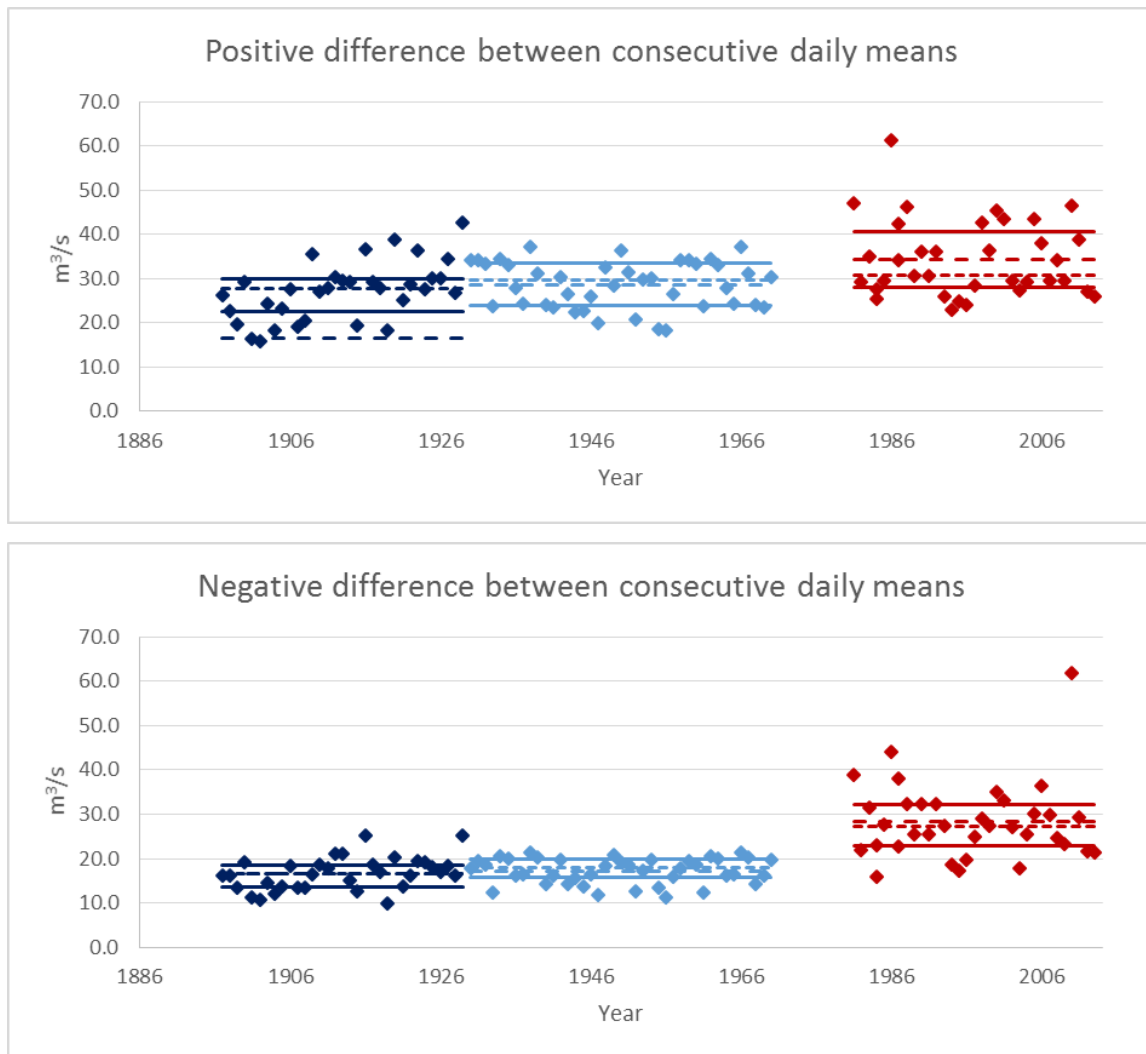
Figure 16. Positive and negative difference between consecutive daily discharge means for scenarios H1, H2 and A..

3.2 Effects of weirs and changes in wetted area

Wetted area is one of the most important factor affecting our results, it is important understand and analyse changes in wetted area with the implementation of the new scenarios and scenarios with habitat adjustment which include removal of weirs. The follow results are funding as relevant:

a) Changes in wetted area derived from the implementation of hydrological scenarios and hydrological with habitat adjustment scenarios.

The relation used as Q-W and the removal of the weir with 1D model HEC-RAS results has been tested according to a previous study Fjeldstad et al, 2004 (**Figure 17**) where some weirs in the bypass sections were removed. As general results, if the weirs are removed but the low minimum discharge as Scenario A is maintained, the wetted area will be reduced dramatically, however the removal of weirs combined with higher discharged will led the amount of wetted area as was before of the removal or even higher.

Figure 17. Changes in wetted area after the removal of two weirs in Kleveland stretch. Left picture is actual situation and right represent the changes in wetted area after the removal of weirs at different discharges, red line: 3 m³/s and blue line: 15 m³/s.

b) Changes in wetted area for the historical situation H1, H2.
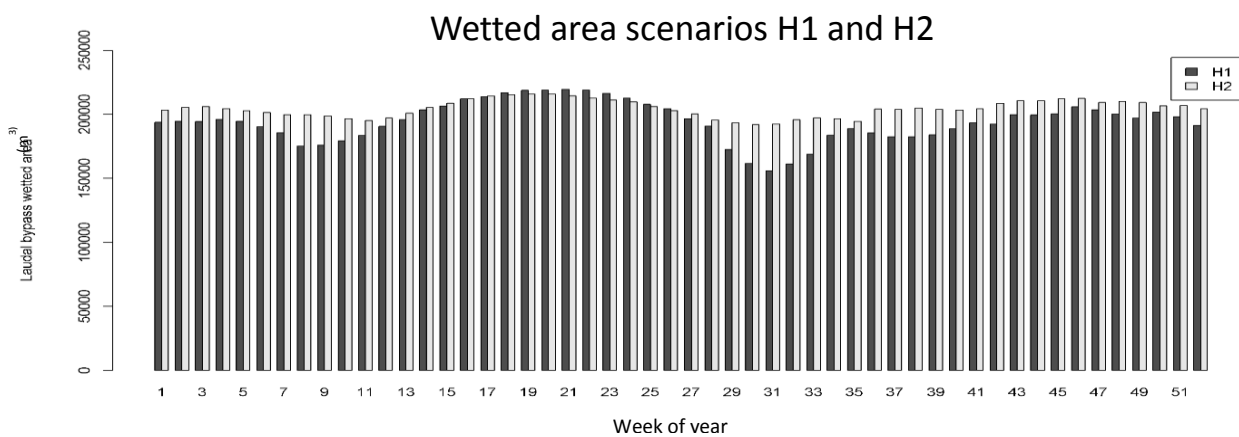
Figure 18. Difference between scenario H1 (dark bars) and H2 (grey bars) for the mean wetted area per week of the year.

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This change has been simulated analysing orthopothos, maps and historical sources. Generating and implementing the results in new Q-W relations. The mean wetted area of the 20 years series per week of year in the total bypass section is represented in **Figure 18.** The total wetted area for H2 is higher than the wetted area in H1 during all the year except from week 19 to 26 where H2 is slightly higher. It is also possible to observe that the variation per week for H1 is higher than the variation of wetted area in H2.

3.3 Effects of the proposed NVE regime in Atlantic salmon production compare with other scenarios

The follow section will show the results obtained from IB-salmon modeling where it is possible to see the effect produce by the implementation of the different discharges by hydrological scenarios and hydrological scenarios with habitat modification (**Table 1**). To make it easy the results will be shown in a graph summarizing all the results and the most representative results have been implemented in maps.

3.3.1 Graph

The follow graph (**Figure 19**) represents the density of smolt production in the study area under each scenario. It will be explained from left (scenario A) to right (scenario H2). Scenario A shows the low density among all the scenarios, highlighting the difference between A and H2. A+H shows higher values than A, but still smaller than the rest. Scenarios B, where the different between them is the spill during the smolt migration **(Table 1)** show the same density, higher density appear when habitat modification is implemented in scenarios B+H. For the scenarios C at the same than in B, there is no different between 1, 2 or 3. Scenarios C without habitat adjustment show smaller densities than B with habitat adjustment. When habitat adjustment is applied, scenarios C+H show the higher densities than any of the previous one. Scenarios D and D+H show the same densities than scenarios C and C+H. Highlighting than D3 correspond to the NVE regime. For scenarios H1 and H2 the higher densities are show, but with higher density in H2 than in H1.
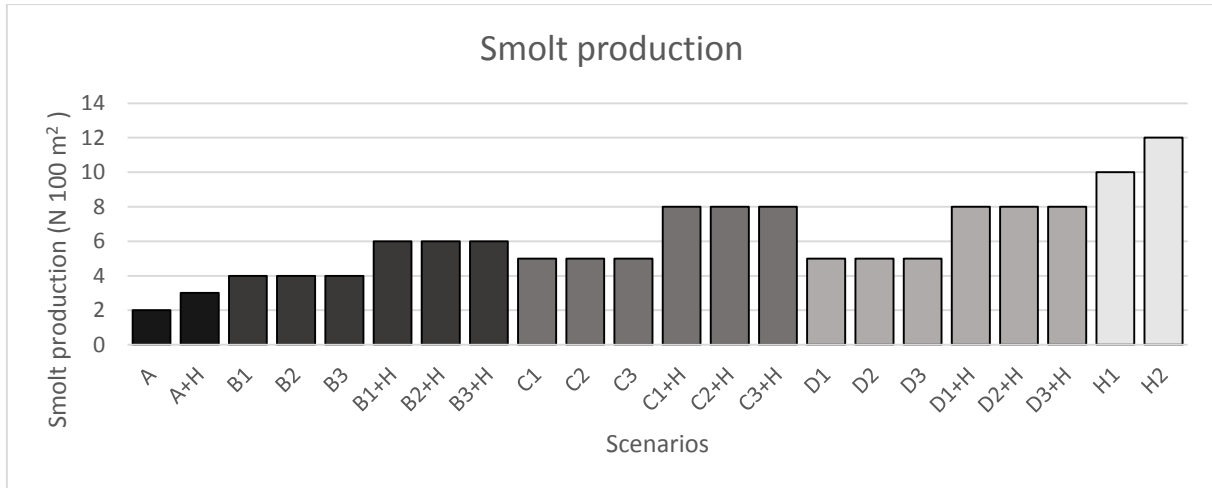
Figure 19. Number of smolts produce per 100 m² in Laudal bypass section under all the scenarios.

3.3.2 Maps

The follow section will illustrate the results obtained from IB salmon as smolt production spots in maps. A representative sample for the results obtained will be illustrated with:

A, A+H, B, B+H, C, C+H and H1, H2. In the maps in not taking in account the scenarios divided by 1, 2, 3 due to as it has been shown before there is no different densities between them. Therefore the results have been simplifies. From **Figure 20** to **Figure 24** maps for the study area are show with the smolt production represented by graduated circles an divided by 5 groups. The results are represented in a coordinate longitudinal line draw in the middle of the river width. IB-salmon works with the wetted width of a unique channel, therefore in cases that there is a division in the channel in two brands, the line is still represented in the middle of the channel. Laudal bypass has been divided in 3 sections in the maps, starting on the left rectangle with Manflå Dam and finishing on the right with Kleveland Bru. All the figures include a table per scenario with the number of smolt per stretch. The study area have been divided in 8 stretches that are specifically marked in the figures, starting in Manflå Dam the stretch 1 and finishing in Kleveland Bru with the stretch 8.

As general results for all the scenarios, the scenarios that include habitat adjustment show higher number of smolt production than the scenarios without, as was also show in **Figure 19**. The total number of smolts produce under each scenario is show in Table 4. This is the sum of the smolts produce in each stretch.

Table 4. Total number of smolts produce in Laudal bypass section under each scenario.

Scenario	Smolt*1000
A	4237
A+H	7400
B	11061
B+H	19198
C	13801
C+H	24132
D	13762
D+H	24052
H1	26304
H2	29891

In the scenario A (**Figure 20**) the only stretch that shows higher number of smolts is the stretch number 1, with around 1000 smolts, after the addition of habitat adjustment the scenario A+H (**Figure 20)** the production is higher in all the stretches even where before there were no production.

Scenario B **(Figure 21)** shows also the highest number of smolts in the stretch 1, but higher number in all the stretches compare with A and A+H. Scenario B+H **(Figure 21)** shows higher number of smolts in all the stretches compare with B and with scenarios A.

The scenarios C **(Figure 22)** and D **(Figure 23)** shows higher reproductive stretches compare with A and B, however there are still some stretches like the stretch 4 with almost no production. This situation changes significantly once the habitat adjustment is include in both C+H (**Figure 22**) and D+H **(Figure 23)**.

For scenarios H1 and H2 **(Figure 24)** is possible to observe the highest number of production in all the stretches compare with the rest of scenarios. Showing higher production the stretches in H2 than H1.

These results can be also reflected in **Table 4** where the smallest number of smolts is produce in the scenario A, the highest in the H2, and no significant difference between scenarios D and C. Scenario B shows intermediate values between A, C and D.

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Figure 20. Total smolt production each 50 meters in Laudal bypass section for scenarios A (left) and A+H (right).
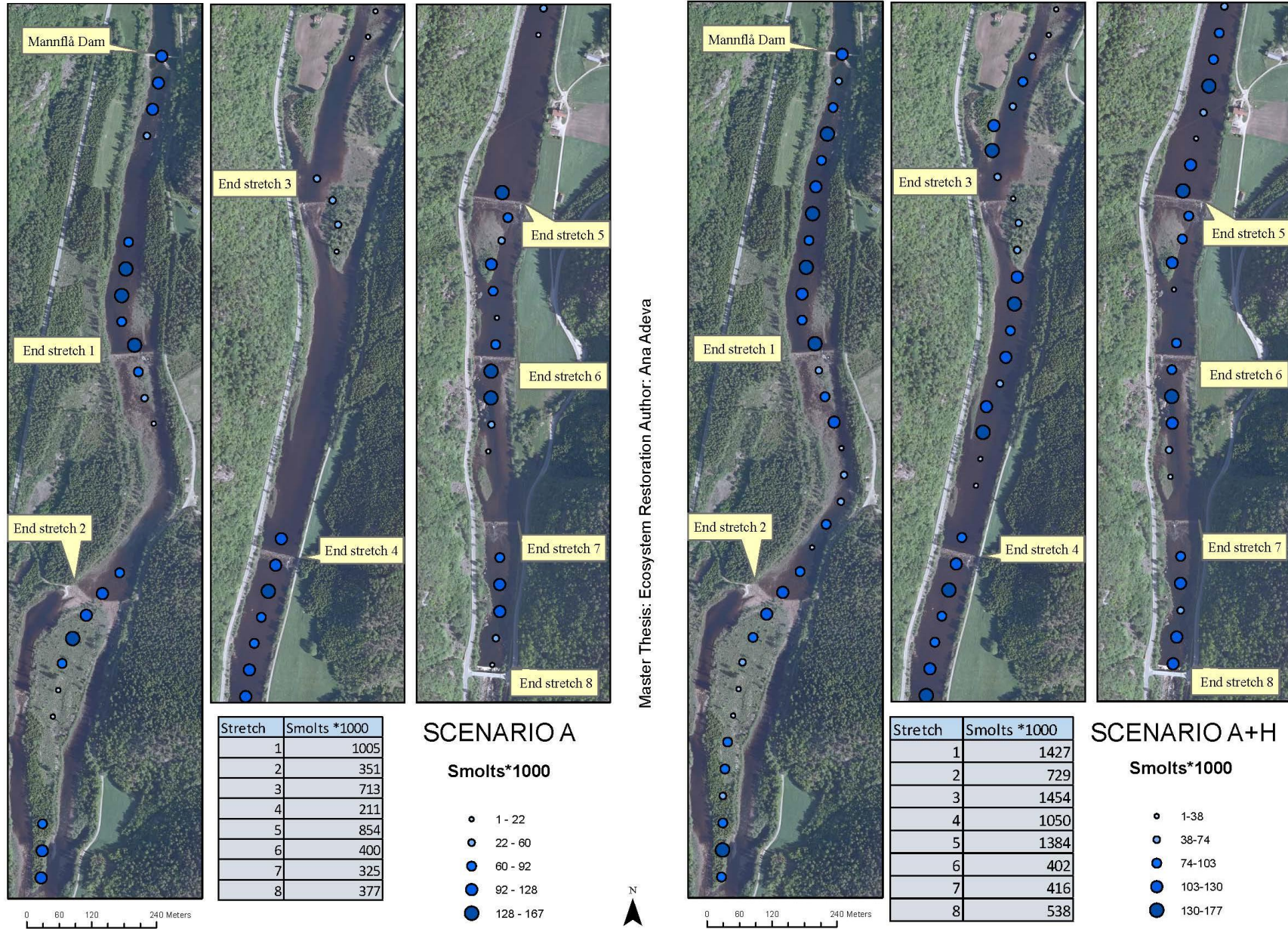
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SCENARIO A

Stretch	Smolts *1000
1	1005
2	351
3	713
4	211
5	854
6	400
7	325
8	377

Smolts*1000

- 1 - 22
- 22 - 60
- 60 - 92
- 92 - 128
- 128 - 167

SCENARIO A+H

Stretch	Smolts *1000
1	1427
2	729
3	1454
4	1050
5	1384
6	402
7	416
8	538

Smolts*1000

- 1-38
- 38-74
- 74-103
- 103-130
- 130-177

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Figure 21. Total smolt production each 50 meters in Laudal bypass section for scenarios B (left) and B+H (right).

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Stretch	Smolts *1000
1	2777
2	855
3	1894
4	596
5	2112
6	1003
7	846
8	973

SCENARIO B

Smolts*1000

- 1-33
- 33-120
- 120-260
- 260-370
- 370-500

Stretch	Smolts *1000
1	3779
2	1860
3	3655
4	2772
5	3559
6	1034
7	1080
8	1455

SCENARIO B+H

Smolts*1000

- 1-88
- 88-200
- 200-280
- 280-350
- 350-500

6
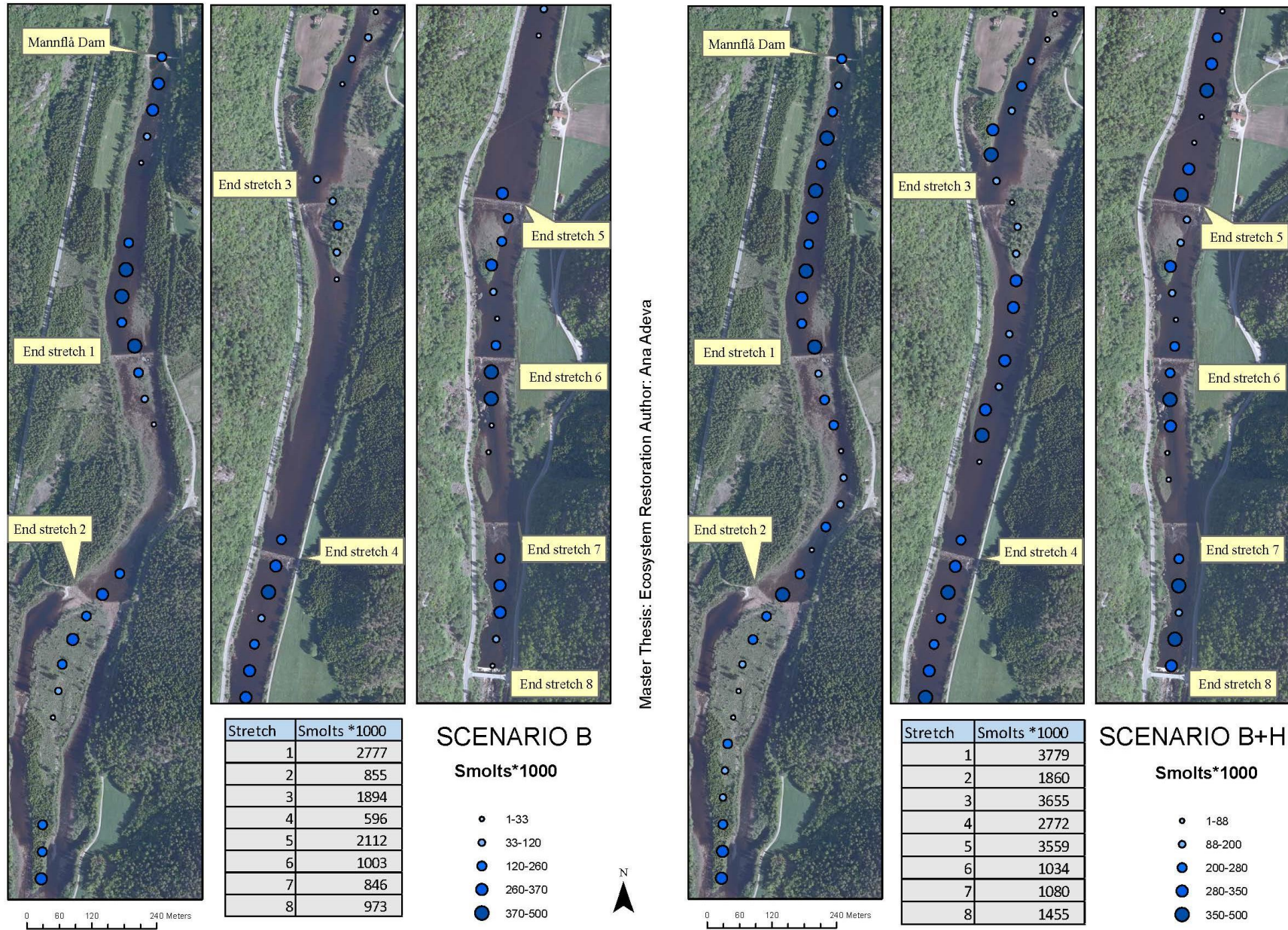
Figure 22. Total smolt production each 50 meters in Laudal bypass section for scenarios C (left) and C+H (right).
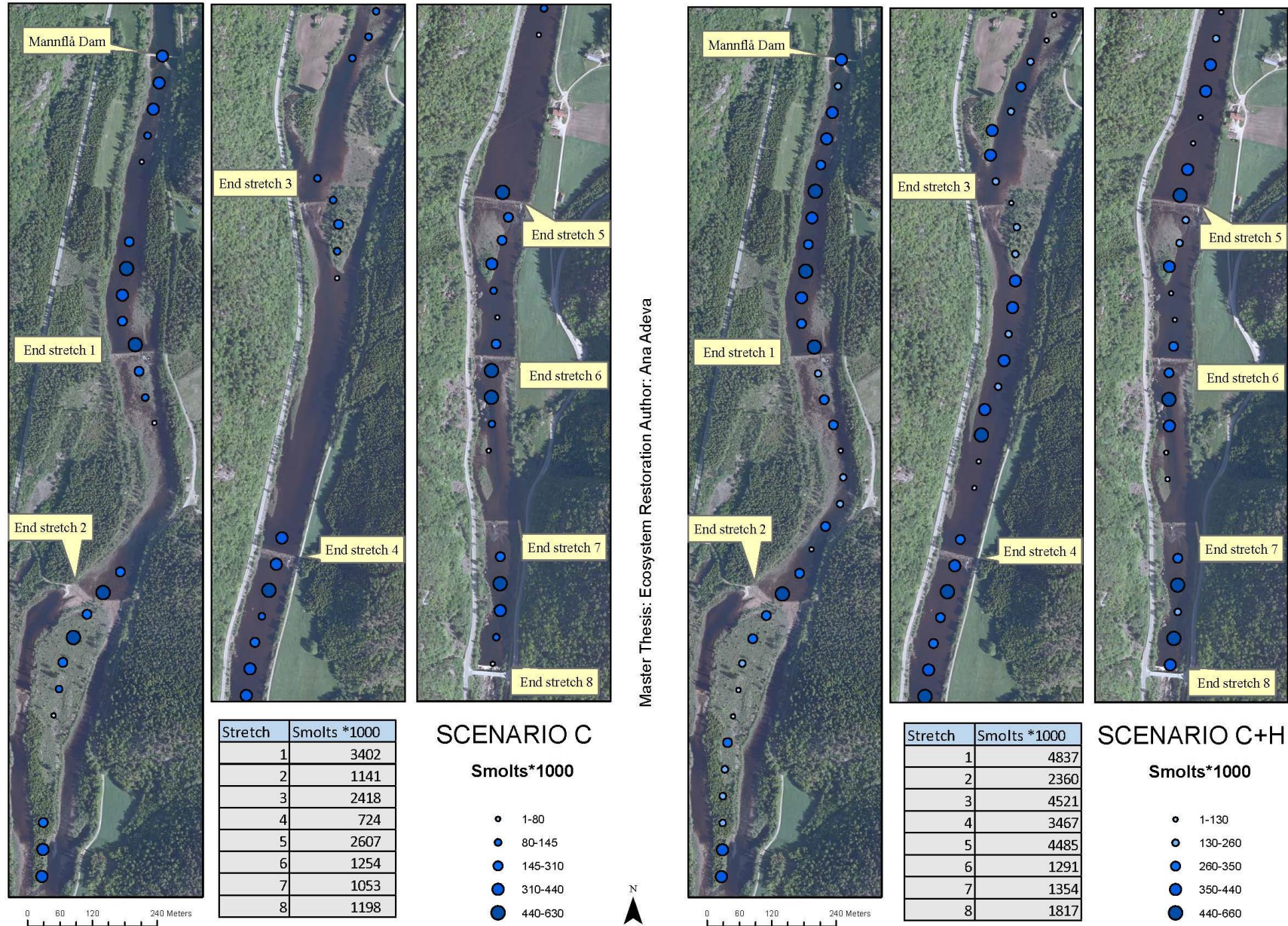
Figure 23. Total smolt production each 50 meters in Laudal bypass section for scenarios D (left) and D+H (right).
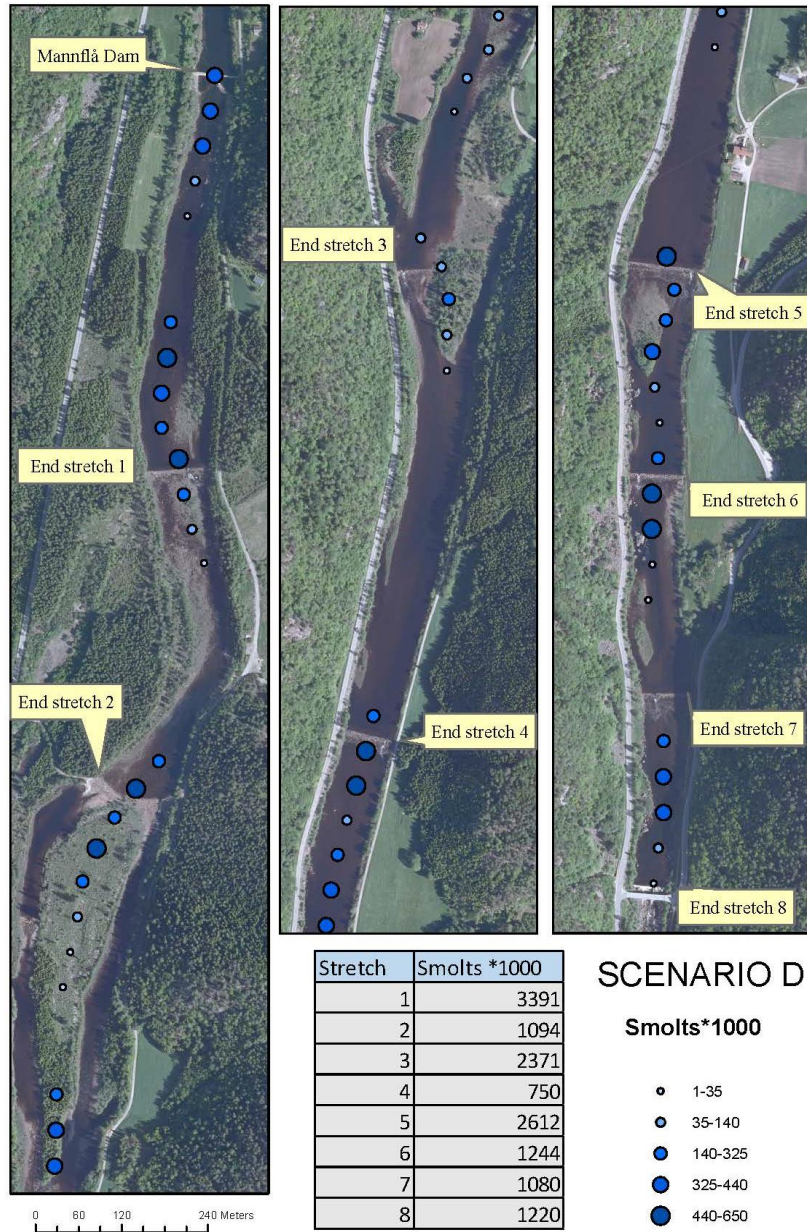
Master Thesis: Ecosystem Restoration Author: Ana Adeva

Stretch	Smolts *1000
1	3391
2	1094
3	2371
4	750
5	2612
6	1244
7	1080
8	1220

SCENARIO D

Smolts*1000

- 1-35
- 35-140
- 140-325
- 325-440
- 440-650

Master Thesis: Ecosystem Restoration Author: Ana Adeva

Stretch	Smolts *1000
1	4739
2	2407
3	4557
4	3401
5	4480
6	1283
7	1367
8	1817

SCENARIO D+H

Smolts*1000

- 1-124
- 124-250
- 250-326
- 326-411
- 411-650

8
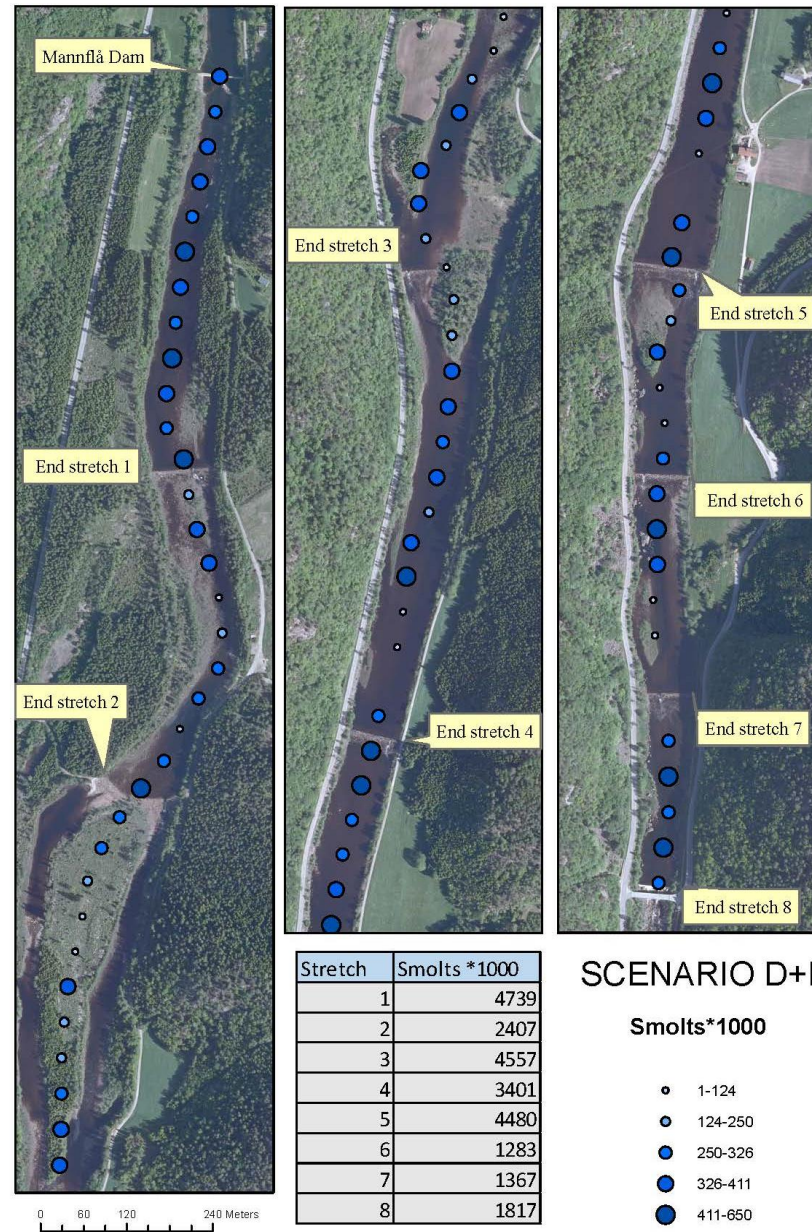
Figure 24. Total smolt production each 50 meters in Laudal bypass section for scenarios H1 (left) and H2 (right).

Masther Thesis: Ecosystem Restoration Author: Ana Adeva
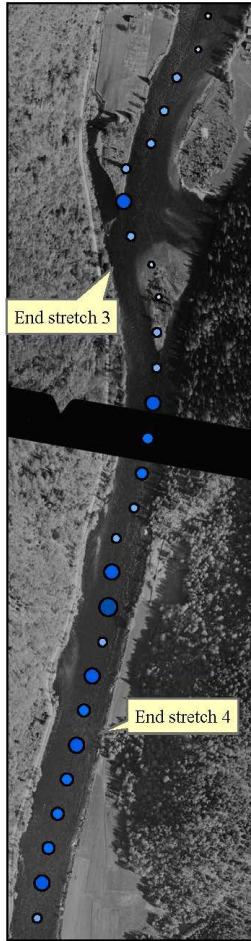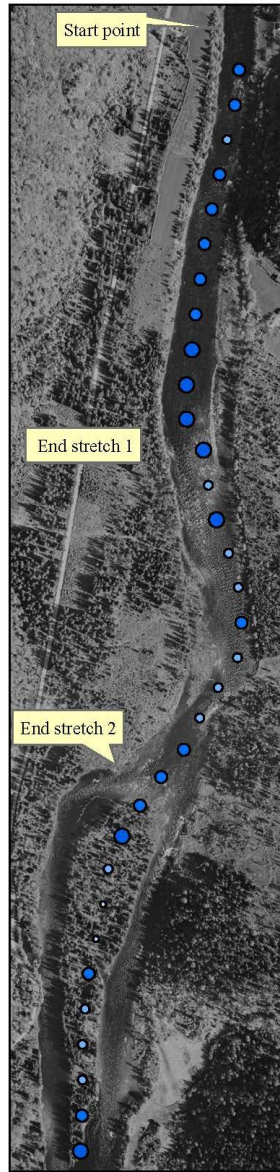
Stretch	Smolts *1000
1	4116
2	2599
3	4403
4	4153
5	4913
6	1717
7	2123
8	2281
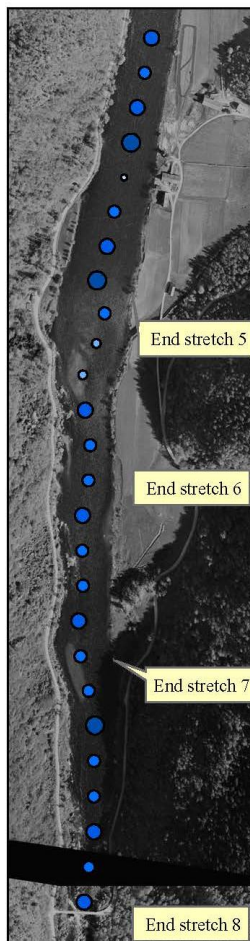
SCENARIO H1

Smolts*1000

- 50-150
- 150-300
- 300-400
- 400-520
- 520-630

Masther Thesis: Ecosystem Restoration Author: Ana Adeva
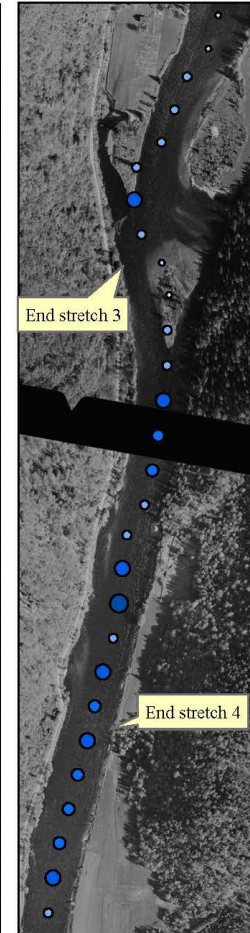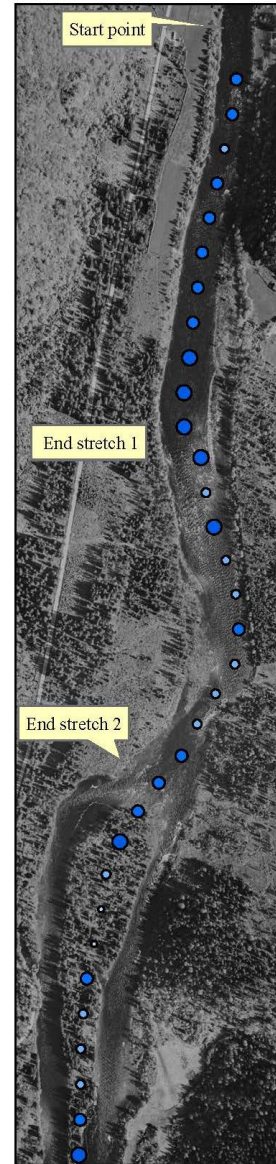
Stretch	Smolts *1000
1	4669
2	2941
3	4993
4	4745
5	5610
6	1944
7	2384
8	2605

SCENARIO H2

Smolts*1000

- 52 - 155
- 155 - 302
- 302 - 401
- 401 - 515
- 515 - 629

.9

3.4 Energy production

The energy curve production under each scenario has been plotted (**Figure 25**) in order to see how the production is distributed during the year in the different scenarios. High production during winter with a peak of production during spring and low production during summer.
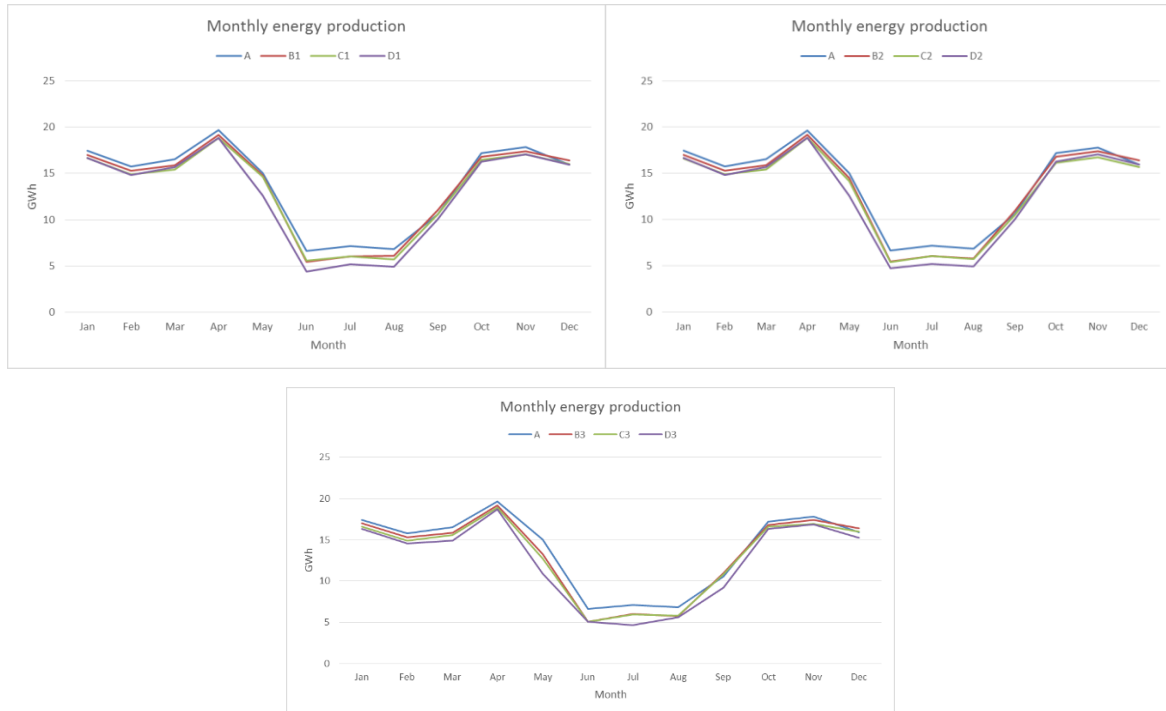
Figure 25. Annual energy production curve for hydrological scenarios except H1 and H2.

The scenario A has been plotted in all the graphs to see the different in the production, the scenario A will give the higher energy production meanwhile the D3 will give the lowest one. There is a small different between all of them that can be notice in May and summer compare with A. To appreciate better the changes in production the follow graph (**Figure 27**) shows how the different rules in discharges will affect the production in Laudal power plant. There is a loss of 12.3 GWh/year between A and D3. Further, it is possible to observe than between B1, B2, B3 there is a different in production around 1.10 GWh/year is loss for B2 compare with B1 and 1.30 GWh/year of energy loss between B3 and B1. The same relation can be applied for scenarios C and D.

3.5 Smolt production versus energy production

Both results, smolt production and energy production are plotted together in **Figure 26.** The results show how the scenarios A is producing the higher energy production but the less productive for smolts. Between smolts there are no different if water is released during the smolt migration period. However, it is possible to appreciate the differences in terms of energy production. Therefore, in general the scenarios with habitat adjustment and no release of water numbers (1) show higher number of smolts (compare with no habitat modification) and higher number of energy production. Scenarios B+H show the highest energy production after A and higher number of smolt compare with scenarios C and D without habitat adjustment. Scenarios C and D show the same number of smolt production but D has lower energy production and the same for C+H and D+H, in terms of smolts both have the same number but C+H will produce higher amount energy than D+H. For the scenarios H1 and H2 no energy was produce.
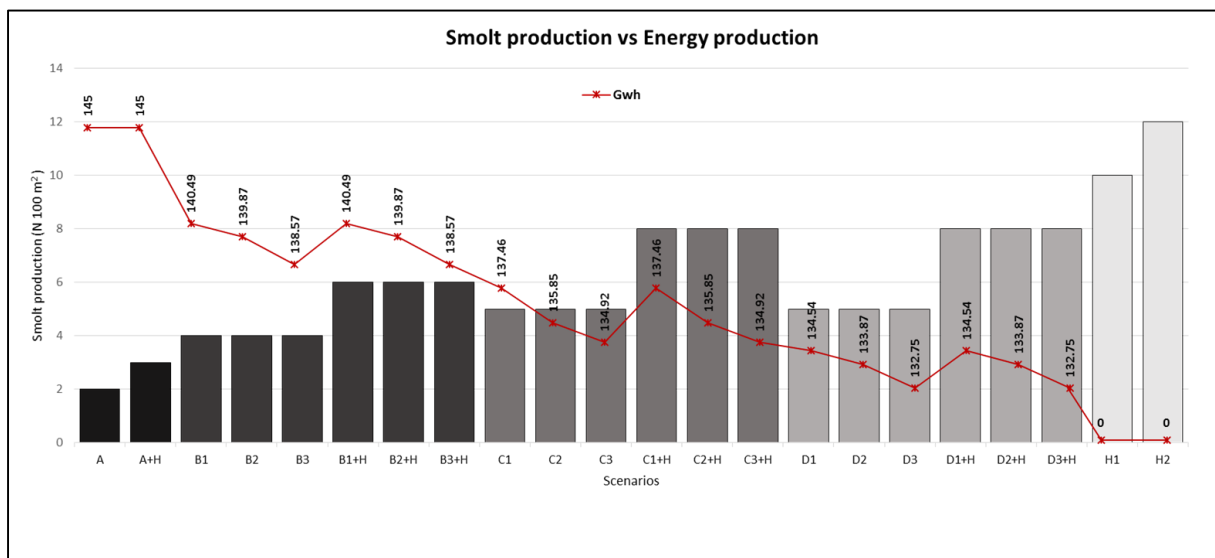
Figure 26. Smolt production and energy production under each scenario at Laudal stretch.

3.6 Cost-effectiveness of physical mitigation measures versus changes in minimum flow regulation.

The NVEs suggested regime will result in an energy production loss of approximately 12.3 GWh/year **(Figure 27)** but, as was mentioned above, this is a rough approximation (also based on historic inflow). This can be compare with data estimated by Agder Energi for 2012 with a loss between 28 and 19 Gwh/year or the calculation made by NVE with 20 GWh/year of losses. The scenario D will potentially result in a power production loss of 12.3 GWh/year relative to

the scenario A. With a cost of 0.04 € kWh, the annual loss of power of scenario D versus A is equivalent to about 440,000 €/year as a first order estimate without system optimization. Habitat modification costs (removal of weirs a one-time expense, introduction of spawning gravel potentially with a three-year cycle) is roughly estimated as 240,000 €/investment.
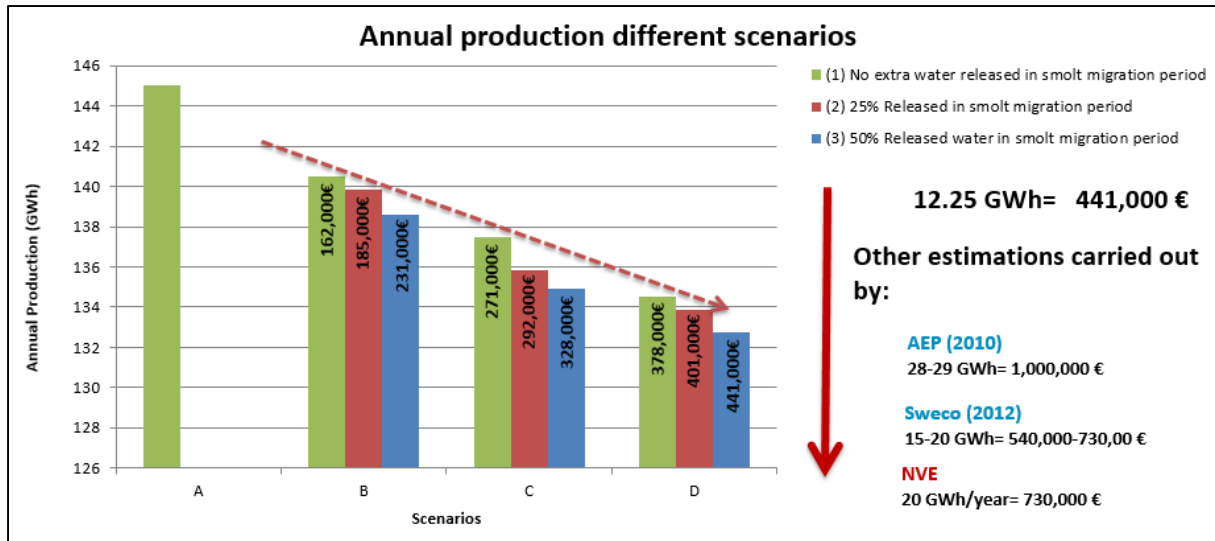
Figure 27. Total annual production for different scenarios in Laudal power plant and cost per scenario.

3.7 Comparison between Laudal and Bjelland stretches

As the **Figure 28** shows, for the scenario A is the same in Bjelland than in Laudal, scenario A is producing the higher energy production but the less productive for smolts. Between smolts there are no different also in this case if water is released during the smolt migration period (1,2 or 3) due to the implementation of turbine mortality is still in process. However, it is possible to appreciate the difference in terms of energy production as in Laudal. In general, the scenarios with habitat adjustment and no release of water numbers (1) show higher number of energy production. Scenarios B+H show the highest energy production after A and higher number of smolts compare with scenarios C and D without habitat adjustment. Scenarios C and D show the same number of smolt production but D has lower energy production and the same for C+H and D+H.

In terms of energy production and cost of each scenario, the **Figure 29** shows that in the hypothetical situation that NVE will suggest the same rules in Bjelland it will result in a loss of energy production of approximately 25.4 GWh/year, but as for Laudal it is a rough estimation. In this case, no other data are available for comparison due to it is a hypothetical case. With a

cost of 0.04 € kWh, the annual loss of power of scenario D versus A is equivalent to about 915,000 €/year as a first order estimate without system optimization. Habitat modification costs (removal of the two weirs a one-time expense, introduction of spawning gravel potentially with a three-year cycle) is roughly estimated as 200,000 €/investment. In this case, the access to the area is greatly complicated compare with Laudal. Furthermore, the two weirs are made by concrete, and weir 2 (**Annex 5**) is located in a gorge.
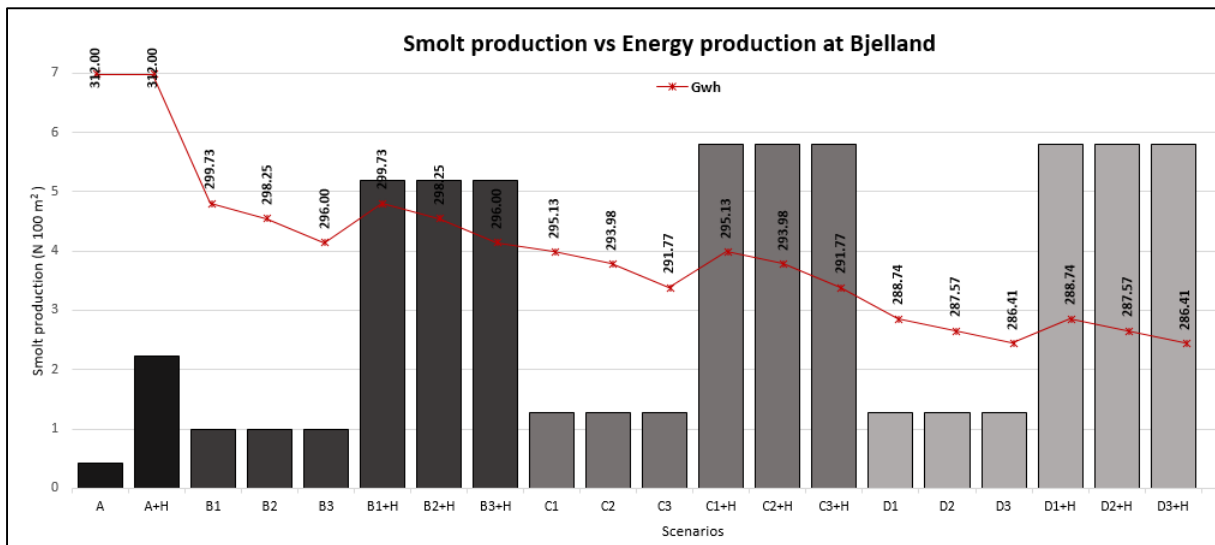
Figure 28. Smolt production and energy production under each scenario at Bjelland stretch.
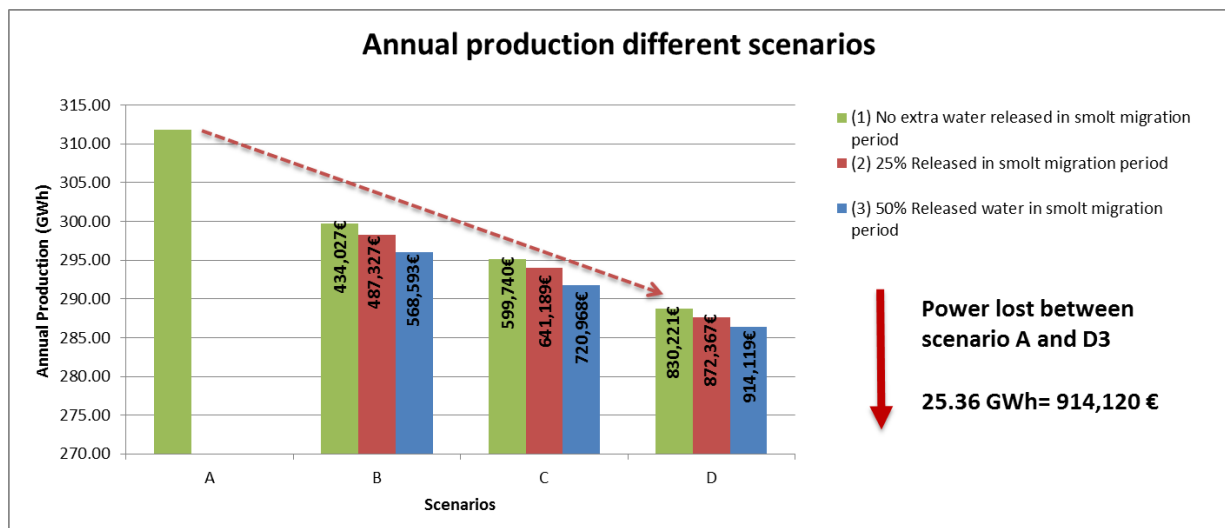
Figure 29. Total annual production for different scenarios in Bjelland power plant and cost per scenario.

4   Discussion

This project shows that using a simple methodology that combines hydrological, geomorphological and biological data with different software, it is possible to generate results that can be used in decision making with a cost much lower than running the five years of trial testing at different discharges.

The use of nMag has been demonstrated as a useful tool when data for discharge are not available in the study area, giving the possibility to test the results obtained according with the energy production data that usually is an easier data to obtain. Other authors as Fjeldstad et al 2013 have tested this; nMag was combined with smolt models for the analysis of smolt migration in order to explore the possible mitigation scenarios. Casas-Mulet et al. (under review) used nMag together with 1D hydraulic model in order to assess potential alternative hydropower operations for hydropeaking management. The use of 1D hydraulic model, HEC-RAS for estimation of water-covered area on different discharge regimes has been proved as successful for generate inputs for IB-salmon. Casas-Mulet et al. 2014 proved that the use of 1D hydraulic model is adequate to simulate both high and low flows in an accurate manner. The relation generated by Sauterleute, J. (2011) and the use of remote sensing aerial images to analyse changes in wetted areas combine with HEC-RAS has been tested as an adequate method to simulate changes in wetted area where no hydraulic model is available. The removal of weirs simulated by the section where hydraulic 1D model area is available proved as adequate method. The results has been compare with a previous 2D model study in the area where the removal of the weirs were simulated (Fjeldstad et al. 2004). The method used for habitat adjustment includes the removal of the 10 weirs and the lowered of the Manflå Dam head and the addition of the spawning grounds is assumed as the maximum habitat improvement that will be gain. This measures are based on the report presented by Forseth (2012) where was evaluated the bottlenecks in the area and were proposed mitigation and restoration measures as the removal of the weirs.

All this data has been implemented as input in IB-salmon model, which has been proved as a model that predict adequately the effects in population abundance even using some relative simplistic functions and relationships. This model has been tested and calibrated (Hedger et al. 2013a) in a Norwegian river where the model predicted similar abundances and age

composition of Atlantic salmon population to those that were observed within the river. IB-salmon has been tested also to predict climate change (Hedger et al.2013b).

The estimation for energy production is a first order estimate, not taking into account system optimization conditions. It has been assumed as correct, but should need further analysis, because the assumption of a constant efficiency for the turbines rarely happen. In the case of Laudal there are two Francis turbines with a capacity of 55 m^3/s each one. One of them started at 20 m^3/s and the other at 35 m^3/s and after that, the efficiency is lower. Therefore this should be further tested and evaluated in order to study how the different scenarios and the future implementation of a new rule will affect to the energy production.

Examining the hydrological results is important to highlight that the analysis of the historical discharge was divided in two periods and some important finding has been observed. The decision to divide the series in two period was in order to evaluate the change in discharges between total unregulated catchment, the discharge when the upper part of the catchment started to be regulated but not yet the anadromous part and the regulated discharge in the study area. For the hydrological analysis some of the IHA parameter from Richter et al. 1996 and some additional from Gundula. 2004 for Norwegian rivers were examined. Observing that the scenario H2 where the upstream of the catchment started to be regulated the discharge values for winter and autumn were higher than the discharges in H1 when the catchment was fully unregulated. This is also possible to be observed for scenario A with higher mean discharges in winter and autumn than in spring and summer. This can be explained with the hydropower management, which is characterise because generate a "smoothly" distribution of the discharges during the year rather than in H1 where the higher discharges are in summer and spring but with a rapid decrease during winter and autumn. The same pattern is reflected in the annual 7 days maximum and minimum graphs. It is also possible to observe that frequency and duration between low and high pulses has been changed from each one of the scenarios and the same for the rate and frequency of water condition changes. It is possible to assume that all of the five key components: magnitude, timing, frequency, duration and rate of change have been greatly altered after the hydropower development.

Changes in wetted area has been proved as adequate. Applying the methodology of Sauterleute, remote sense images. 1D hydraulic model and testing the results with a previous study it is

possible to conclude that after the removal of the weirs it is necessary the implementation of higher discharge scenarios to avoid a drastic reduction in wetted area. Recent studies has demonstrated the effectiveness of the removal of weirs (Fjeldstad et al, 2013) were after the removal of the weirs the salmon spawning sites were recreated in the old bed substratum and were occupied immediately after the first season after the removal, mainly due to water velocities were more suitable for spawning. Accordingly, the mortality in eggs was reduce and juvenile's densities showed a marked increase. It is important also to consider that the removal of weirs will change the actual structure of the reach (pools and rapids). Deeper water, weir-enclosed reservoirs constitute important refuges for fish prior spawning. Therefore, if after the implementation of the mitigation measures, this situation is found and could be consider as a bottleneck, could be feasible the implementation of the measure known as "River in the river". In minimum flow reaches, usually the natural course will no longer be adapted to prevailing flow conditions. The physical process are altered dramatically, designing measures could help to remediate this situation "river in the river" involve confining the stream course and introducing alternate reaches of rapids and pools (Forseth & Hardy, 2013).

In order to analyse and relate the results obtained from IB salmon it is important to mention that NVE regime proposes a period of water release called "smolt migration period" where approximately 50 % of the inflow to the upstream reservoir Manflåvann will provide the amount of release. The aim of this specific "smolt migration period" release is to facilitate the migration from the production areas upstream of Manflåvann, thus not corresponding to the river reaches modelled in our simulations in IB Salmon, which are downstream of Manflåvann. Therefore any different is founded between no releases of water in spring, release the 25% or release the 50% of the inflow. However, the release of this amount will affect in the energy production. For this, it was considered important to take it in account in order to find the optimal discharge for the production of energy and for the production of smolts.

Using discharge scenario D (as proposed by NVE) as a baseline, the results on smolt production showed no significant difference when compared to discharge scenario C. This indicates that the summer discharge does not have to exceed 14 m^3/s. Scenario A showed the lowest smolt production all over, but introducing habitat modifications doubled the smolt production. According to Forseth (2012), the extremely minimum flow in the bypass section and the habitat changes led a relatively small production compare with the historical situation. The construction

of Bjelland and Laudal has led a reduction in the smolt production of around 20- 40 % (Ugedal et al.2006) compared with the period before the acidification of the water. Discharge scenarios B with maximum habitat modifications resulted in a 25 % higher smolt production when compared to discharge scenario D or C with no habitat modification.

The results for the scenarios H1 and H2 show how it is possible that the hydropower development could led positive effects in smolt production. When the catchment was fully unregulated the winter discharge was lower than in the scenario H2 when the hydropower development started in the upper part of Mandalselva catchment. The winter discharge together with temperature are known as the most important bottlenecks in smolt production. Several studies have reported the same a positive correlation between winter discharge and the winter survival of juvenile salmon (Næsje et al. 2005). Our results can be compare with Orkla River, in Norway, where a higher minimum discharge in winter after regulation has led both improve parr survival rates and smolt production (Hvidsten et al. 2004).

Analysing the maps, the higher production is shown in the stretch 1 (the upper part of the bypass section) and is increasing in the rest of the stretches when habitat modification and different discharges are implemented. Forseth, 2012 argued that the reach is classified as a potential area for spawning but is not in use because pools and small weirs dominate the area where the water velocity is not the adequate. Therefore, the removal of the weirs, the addition of spawning grounds and the increasing in discharge will significantly increase the production.

In terms of energy production discharge scenario B with habitat modification achieves both higher energy production and higher smolt production, compared to scenario D without habitat modification, as proposed by NVE. The latter scenario will potentially result in a power production loss of 12.3 GWh/year relative to the pre-2013 regime. Given a 0.04 € per kWh income, the annual loss of power of scenario D versus A is equivalent to about 440,000 €. Habitat modification costs around 240,000 € but is a unique investment with a maintenance of 3 years. Therefore, the habitat modification is a cost-effectiveness measure to achieve higher smolt production.

The comparison of the data between implement the same mitigation measures in Laudal than in Bjelland shows that in Bjelland the implementation of different discharge regimes scenarios

gives similar smolt production, meanwhile the smolt production under scenarios with habitat modification is significantly bigger than the production from merely discharge scenarios. This difference are not that significant in Laudal. Comparing the energy loss produce by the implementation of different discharge scenarios, in the hypothetical case that NVE will propose the same rules than for Laudal, Bjelland power plant will loss approximately double of the loss in Laudal with a yearly cost of 915,000 €. The roughly estimation for the habitat modification cost is similar to the estimations in Laudal. Even if the number of weirs in Bjelland is two compare with the eleven weirs in Laudal stretch the accessibility to the area in Bjelland is more complicated for both, the removal of the concrete weirs, and for the addition of the artificial spawning grounds. Therefore, if Bjelland should face the implementation of mitigation measures there are two options that look the most feasible, first and the most cost-effective is the scenario A+H, which is the removal of the two weirs and the maintenance of the actual energy production. The second option could be the scenario B1+H whit the lowest loss of energy compare with the rest of scenarios and the removal of the weirs. The results obtained from these simulations reveal that the implementation of the same minimum discharge rules for the two hydropower in the anadromous part is not a cost-effective decision. Therefore, further and detail analyses will be needed if Bjlland hydropower will need face a license revision in the future.

5   Conclusions

This project shows how this methodology can be used in other similar or related projects/rivers as a tool to predict offsetting effects (i.e. habitat modification versus water release/power production loss).

The methodology using the IB-Salmon model in combination with 1) 1D hydraulic models for estimation of water covered area on different discharge regimes, 2) the introduction of habitat modifications and 3) the power production loss due to water release, is valuable for the study of the trade-off between salmon production and power generation.

In regards to IB Salmon model simulation, further data collection is needed to reduce the uncertainty. This would include a strategy for monitoring effects during five years of the trial regime (NVE), including results related to NVE's purposes that are not possible to represent

using the IB-Salmon model and the evaluation of habitat modifications suggested by Forseth (2012). Further development of this study will include an evaluation of the habitat modifications and the mitigation effect of the environmental flow regimes against mitigation measures in other reaches upstream (spatial offsetting). This is being modelled in IB-salmon and will give the possibility to IB-salmon to generate data that can be relate with longitudinal connectivity.

Furthermore, power production calculations under each scenario could be made more accurate by considering optimization of the power system in the Mandal River.

This project emphasizes the needed of a detailed and scientific research in order to decide and manage the revision of hydropower licenses, even in the same river two different stretches can demand completely different management in order to obtain the desire results, in this case the balance between energy and smolt production.

The hydrological assessment for the historical situation compared with regulated situation evidence that each one of the five key components presents in natural flows according to a vast number of scientific are greatly altered after the regulation.

This project highlights the importance of combine physical with hydrological mitigation measures in order to control the total area available for fish population.

Examining the results, the impact on smolt production following discharge scenario D (NVE) can be achieved with lower power production loss. Introducing habitat modifications by removing weirs and adding spawning gravel would potentially achieve the same effect on smolt production as the water release through discharge scenario D.

This project can be an example of how not always the effects from hydropower has to be negative, leaving open the possibility of implement an hydropower development in the upper part of the catchment and managing the hydropower operation in the anadromous part. Releasing water according to the requirement of target species will give the possibility of compensate the loss of energy in the lower part with the increase in the production of a target species.

This methodology has been found as a potential tool to generate outcomes that will cover the need to find a methodology to support the decision making in order to apply the Water Framework Directive in regulated rivers in Norway. Finding the correct environmental flow and balancing the production of renewable energy could benefit both the environment and the production. Then it will also represent a cost effective methodology because it makes use of existing data and computer tool. Not just due to the benefits obtained from gaining a GES/GEP ecosystem, but also in terms of saving money that now is invested in mitigation measures that have not been previously tested (as is happening in this moment in Laudal). Even with vast amounts of data available, the authorities still do not compile and use it fully in decision-making due to the lack of a standard methodology.

A continuation of this project will be use in a Multi Criteria Decision Analyse (MCDA) to evaluate the equivalence of measures in terms of ecosystem services for other user interests. As has been mentioned in the introduction the hydropower in Norway is one of the most important sectors the same as the fishing and therefore there are many stakeholders involve in the management decision.

For finalise, has been demonstrated that it is possible to find a sustainable management in terms of hydropower management that can meet the social needs for water and power while will protect in a long-term the health of the river ecosystem. This can be illustrated using a simple "flower" diagram as is shown in **Figure 30** (modified from Foley et al. 2009). It represents a conceptual framework for comparing freshwater consumption and trade-off ecosystem services. Where the right diagram represent a hydropower production that is manage to maintain other environmental requirements, which will support a broader portfolio of ecosystem services.
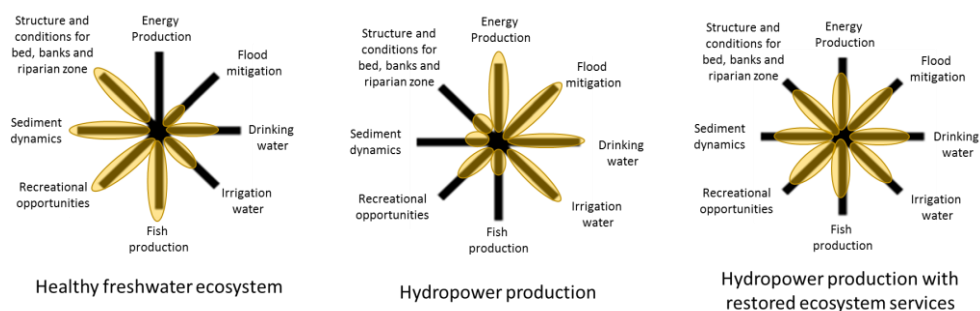

Figure 30. Conceptual framework for comparing water consumption and trade-off of ecosystem services (modified Foley et al. 2009).

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7. Annex

Annex 1. Key life stages corresponding periods of the year and rationale for assigning flow values for Atlantic salmon (Bakken et al. 2012)

Life-stage	Time of the year (week no.)	Rationale for setting flow values (key words, see details in Alfredsen et al, 2009 & Alfredsen et al, 2012)
Winter discharge	Winter	Winter discharge was set at a level which maintains a large abundance of the wetted area without unnecessarily high flows. The flow was set to be as stable as possible (constant).
Outmigration of smolts	19-22	Mid-May was assumed to be the time where the bulk of the smolt run occurs. Therefore, a block of water with a high discharge event with variations in magnitude and duration for each of the three flow situations was introduced in mid-May. The quantity of water was based on the knowledge that the water release must be large enough relative to winter flow to trigger the migration. In a normal and wet year, it was suggested that the reduction after the trigger release would follow a 'natural' recession pattern which should facilitate further migration.
Hatching	19-22	This coincides in time with outmigration of smolts. Outmigration asks for high flows while high flows during hatching increases mortality. Based on knowledge about the natural system, it was clear that the smolt migration block takes precedence over discharge controls for hatching.
Swim-up	25-26	The discharge at the time of swim-up should be kept stable (and low), as the high discharge during the first week after swim-up increase mortality, and no hydropeaking should happen during this life-stage. As for the hatching, swim-up is to a large extent determined by water temperature, but as data on water temperature is limited, this factor introduces uncertainty in the proposed time period for this life stage.
Summer discharge / Rearing of juveniles	27-37	Increased discharge in summer compared to winter flows will ensure a larger amount of wetted area available for fish production, to ensure that the competition due to space limitation for the newly hatched young-of-the-year will be minimized. The summer block is proposed dynamic in order to save water for hydropower productions in some periods and justifying some higher summer flood events for migration purposes.
Adult migration	Episodes during the summer period (27-37)	The timing of the 'migration freshets' should coincide with the natural flows, but not too early in order to avoid disturbing the swim-up phase. The magnitude of the attraction floods should be sufficiently high to overcome the effect of production releases from the hydropower plant, in the case of Daleelva asking for co-ordination of the releases of water from the plants K2 and K5.
Spawning	43-47	According to some studies referred to in Alfredsen et al. (2012) spawning is mainly controlled by water

		temperature and to a limited extent water flow. However, high flows in periods of spawning might increase the risk of spawning in areas that are later (during winter low flows) dried out. Based on this, a maximum level is set on this block, determined by analysis of the relation between flow and wetted areas. The timing of the spawning was set based on the (limited) water temperature data.
Recreational salmon fishing	Summer	Fishing opportunities and other possible recreational uses are also improved by higher flows, and a proposition of high flows for the Summer discharge / Rearing of juveniles regime (+ adult migration) will be supported by the fishing interests. The recreational catches of adult salmon are very low during June and the low flow regime proposed during swim-up period is hence considered not being in conflict with the fishing interests.
Channel maintenance		Despite the fact that the river is regulated, it regularly experience large (natural) floods with. Probably due to this the river is dominated by cobble and experience minimal degree of embeddedness, and no specific flow requirements are set for channel maintenance.

Annex 2. Laudal Bypass section in Mandalselva River under a discharge of 3 m3/s on the 30/05/2009.

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Annex 3. Runoff Basins for Laudal and Kjølemo control points

Runoff Basins for Laudal and Kjølemo control points

Control points	Basin Surface	Runoff average
Laudal	1529.91 km^2	82.58 m^3/s
Kjølemo	1757.7 km^2	81.95 m3/s

Legend

Control points
- Kjølemo
- Laudal
- Mandalselva Basin
- Rivers

Runoff Basins
- Kjølemo
- Laudal

N

Meters
0   6,500   13,000   26,000

Ana Adeva
MSc Ecosystem Restoration
NTNU Master Thesis
Data from NVE
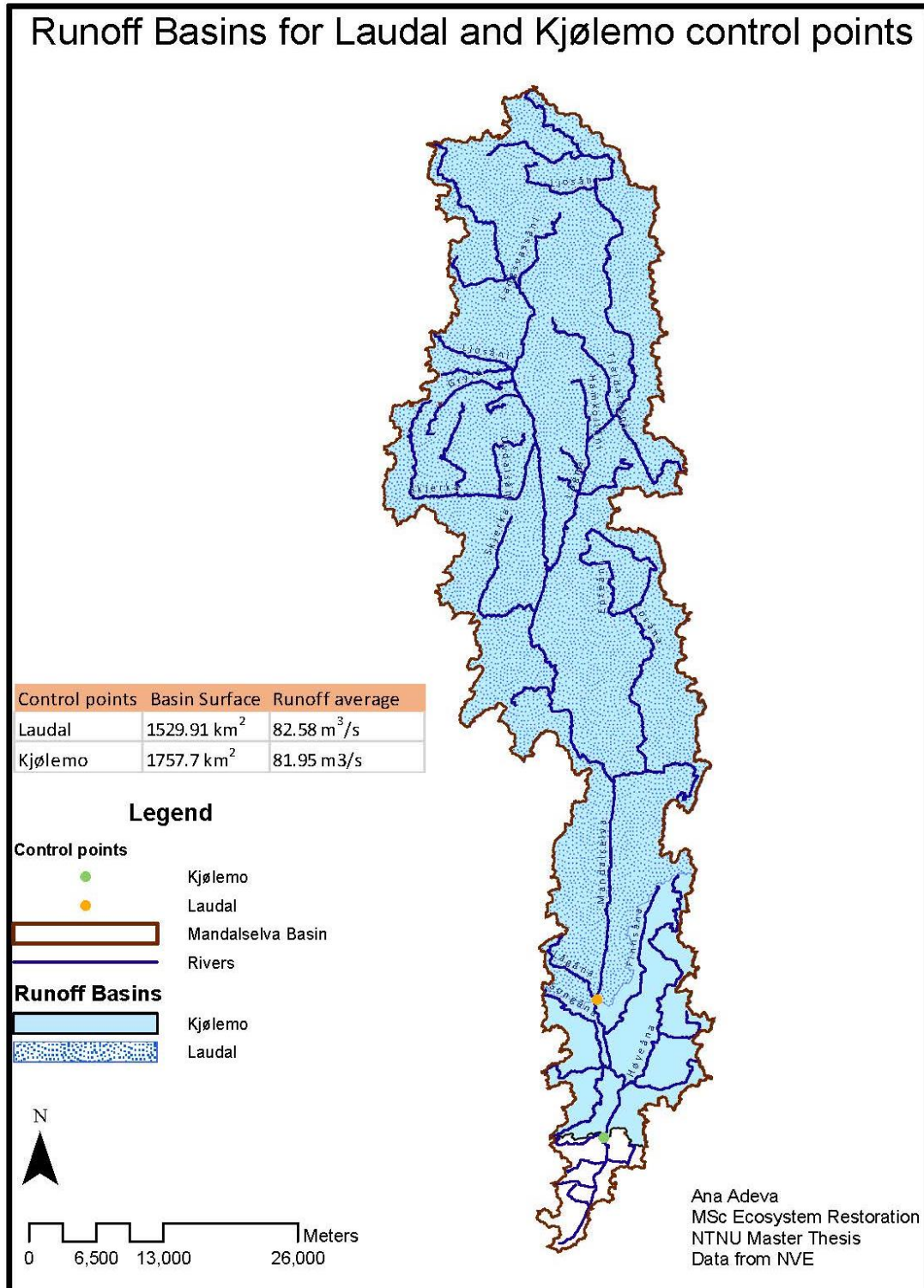
Annex 4 IHA parameter from Richter et al.1996 (a) and the additional parameters from Hohl. 2003 and Dangelmaier. 2004 for Norwegian Rivers (b).

a) *Summary of hydrologic parameters used in the Indicators of Hydrologic Alteration and their characteristics (modified after RICHTER et al., 1996)*

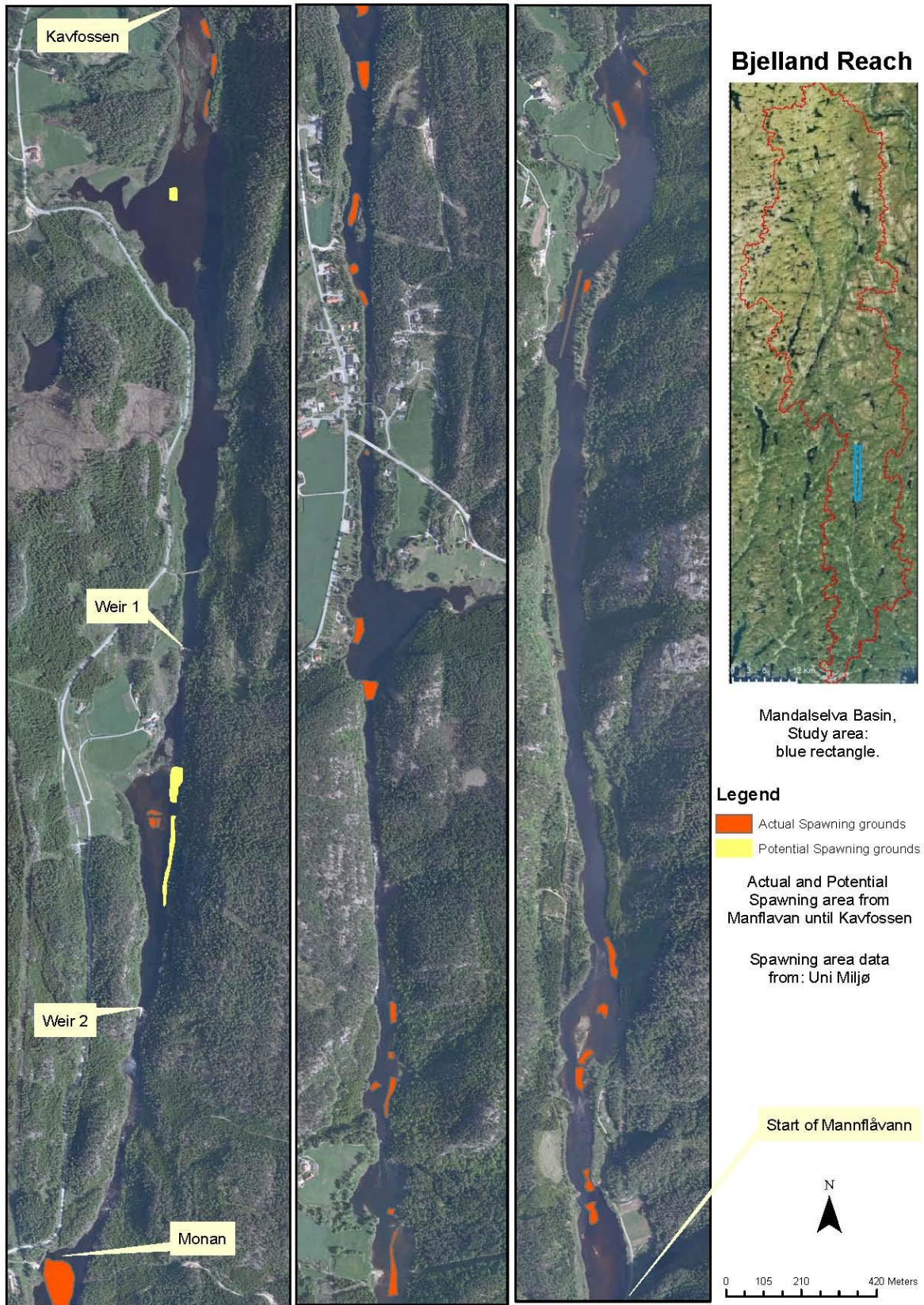| IHA statistics groups	Regime characteristics	Hydrologic parameters	Description
1. Magnitude of monthly water conditions	Magnitude Timing	Mean value for each calendar month	Describes "normal" daily water conditions and thus provides a general measure of seasonal habitat suitability or availability
2. Magnitude and duration of extreme water conditions	Magnitude Duration	Annual minima 1-day means Annual maxima 1-day means Annual minima 3-day means Annual maxima 3-day means Annual minima 7-day means Annual maxima 7-day means Annual minima 30-day means Annual maxima 30-day means Annual minima 90-day means Annual maxima 90-day means	Provides measures of environmental stress and disturbance; conversely, they might be necessary for reproduction process of certain species
3. Timing of annual extreme water conditions	Timing	Date of each annual 1-day-maximum Date of each annual 1-day-minimum	Describes seasonal nature of environmental stresses to which key life-cycle phases can be linked
4. Frequency and duration of high and low pulses	Magnitude Frequency Duration	No. of high pulses each year (discharge above 75-percentile) No. of low pulses each year (discharge below 25-percetile) Mean duration of high pulses each year Mean duration of low pulses each year	Portrays the shape of pulsing behaviour of environmental variation
5. Rate and frequency of water condition changes	Frequency Rate of change	Means of all positive differences between consecutive daily means Means of all negative differences between consecutive daily means No. of rises No. of falls	Provides a measure of the rate and frequency of intra-annual environmental change

b) Added parameters that display specific Norwegian characteristics concerning hydrology and biota (modified from Hohl, 2003 and Dangelmaier 2004).

IHA statistics groups	Additional hydrologic parameters	Definition	Description
1. Magnitude of (monthly) water conditions	Mean value winter Mean value spring Mean value summer Mean value autumn	Seasonal versus annual discharge winter: Dec., Jan., Feb. spring: Mar., Apr., May summer: June, July, Aug. autumn: Sept., Oct., Nov.	Describes seasonal variation
	Average runoff	Annual average runoff	Describes characteristic of the entire year
	Low flow (nor. def.)	Daily discharges are sorted from highest value to smallest. Discharge no. 350 is taken out and with these values from all years a new seriess is built. The average from the upper 2/3 is calculated.	Evaluates dry period with regard to biotic life-cycles
2. Magnitude and duration of extreme water conditions	Winter/spring 1-day max Winter/spring 1-day min	Max/min daily average discharge during snowmelt (01/01 – 06/30)	Measures maximum magnitude of snowmelt and seasonal extreme low flow conditions
	Winter 1-day max	Max daily average discharge (12/01 – 02/28)	Evaluates stress for certain species
	Summer/autumn 1-day max Summer/autumn 1-day min	Max/min daily average discharge caused by precipitation (07/01 – 12/31)	Measure maximum magnitude of discharge due to rain falls and seasonal extreme low conditions
3. Timing of annual extreme water conditions	Date of winter/spring 1-day max Date of winter/spring 1-day min	Date of max/min daily discharge during snowmelt (01/01 – 06/30)	Timing of maximum runoff due to snowmelt and seasonal extreme low flow conditions
	Date of summer/autumn 1-day max Date of summer/autumn 1-day min	Date of max/min discharge caused by precipitation (07/01 – 12/31)	Timing of maximum runoff due to rainfalls and seasonal extreme low conditions
	Beginning of snowmelt	Date of first day of the year with discharge over 10% of average of the whole period and when absolute discharge is >20% higher than the day before and this >20%higher than the one 2 days before	Describes timing of snowmelt which can be an important factor in the life-cycles of certain species
4. Frequency and duration of high and low pulses	No. of winter high pulses No. of winter low pulses No. of summer low pulses	Number of periods with discharge below 25-/ above 75-percentile (12/01 – 02/28 and 06/01 – 08/31)	Measures possible stress for biota
	Mean duration of winter/spring low pulses Mean duration of summer/autumn low pulses	Average duration of a period with discharge below 25-percentile (01/01 – 06/30 and 07/01 – 12/31)	Measures possible stress for biota Seasonal parameters
5. Rate and frequency of water condition changes	No. of rapid rises No. of rapid falls	Number of periods with continuous increase/decrease in discharge over defined limit for rapid rises/falls	Measures possible stress for biota
	Max 24h rise Max 24h fall	Max increase/decrease in runoff compared to the day before	Measures possible stress for biota

Annex 5. Study area at Bjelland, bypass section in Mandalselva River under a discharge of 7.2 m³/s and downstream section under a discharge of 65.7 m³/s on the 30/05/2009.

Bjelland Reach

Mandalselva Basin,
Study area:
blue rectangle.

Legend

Actual Spawning grounds

Potential Spawning grounds

Actual and Potential
Spawning area from
Manflavan until Kavfossen

Spawning area data
from: Uni Miljø

Kavfossen

Weir 1

Weir 2

Monan

Start of Mannflåvann

N

0   105   210   420 Meters

Annex 6 Annual mean values for May (a) and Mean monthly values (b) scenarios H1, H2 and A.