DOWNSTREAM MIGRATION SOLUTIONS FOR ATLANTIC SALMON (*Salmo salar*) IN REGULATED RIVERS

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Downstream migration solutions for Atlantic salmon (*Salmo salar*) in regulated rivers

A collection of case studies from Europe for the implementation of future projects

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Disclaimer

Abstract

The ecological connectivity of rivers around the world is under threat due to several anthropogenic influences. Dams and weirs for hydropower production are being constructed at unprecedented rates mainly to satisfy the increasing energy demands and the shift towards renewables. Many migratory species of fish like Atlantic salmon (*Salmo salar*) are threatened by these barriers.

Since fishways and other techniques to facilitate upstream migration have been largely studied in the past, the aim of this thesis is to identify which measures could improve at best the downstream migration of Atlantic salmon in regulated rivers and to provide guidelines for the implementation of future projects in Europe.

The most important requirements for salmons during their downstream migration have been identified through literature research and summarized in order to reduce duplication effects. Eight case studies have been carefully selected and the techniques proposed have been analysed and compared. Eight are also the measures presented by the present report. The selected measures have been evaluated according to the three most important parameters (fish mortality, migration delay and hydraulic conditions) that have been identified after the literature review and an advantage/disadvantage analysis.

Most of the cases investigated by this thesis are small and medium hydroelectric plant (HEP) that are responsible for massive ecological impacts when compared with the energetic output produced. There is no general optimal solution for every site. Local conditions have to be assessed at each HEP facility and the river needs to be examined as a whole system, taking in consideration the cumulative effect on fish of other barriers along its course.

However, physical solutions such as inclined (α-racks) and angled (ß-racks) screens coupled with a bypass have been identified as most efficient and suggested for small and medium size HEP respectively. Other measures such as floating structures and river engineering need to be investigated. They could be used in combination with the suggested measures to increase the level of guidance and improve the overall efficiency. A computer-based simulation program called CFD (Computational fluid dynamics) has been identified as viable solution to analyse the impacts of the selected measures on the hydraulic conditions before the implementation.

In addition to the scientific recommendations, common standards and stricter guidelines are needed at national and international level to regulate and improve the downstream migration of fish in regulated rivers.

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Preface

This thesis has been officially written for the exam committee of Aeres UAS and the topic has been chosen from the professional sector. The aim is for a wide target group that includes water authorities, the hydropower sector, fish biologist and environmental engineers. I hereby confirm that I have written the thesis by myself, without contributions from any sources other than those cited in the bibliography. Some of the figures used in this report are taken from other publications and therefore cited accordingly.

I would like to thank my university supervisor and coach Annet Pouw and the senior researcher Teppo Vehanen from LUKE who has assisted me in the elaboration of this research.
A special word also for Jari Ilmonen and Viliina Evokari for their guidance and suggestions during the first stages of this thesis.
Last but not least I would like to thank my family for the support given continuously during the whole course.

1. Introduction

Hydropower experienced an extremely rapid growth that started in North America and continued all over the globe during the 20th century. From the first turbines operating in small plants at the beginning of the 1900 today the world has a cumulative capacity of more than 1250 gigawatts (GW) converting in electricity the hydraulic power of water (figure 1). Considered the best way to meet the growing energy demand and seen as an infinite renewable energy source, hydropower dams continued to be built on the rivers across the world. However, towards the end of the 20th century, the environmental and social impacts became clear and as a consequence the industry tried to dedicate an increasing number of resources on sustainability issues (International hydropower association, 2019).

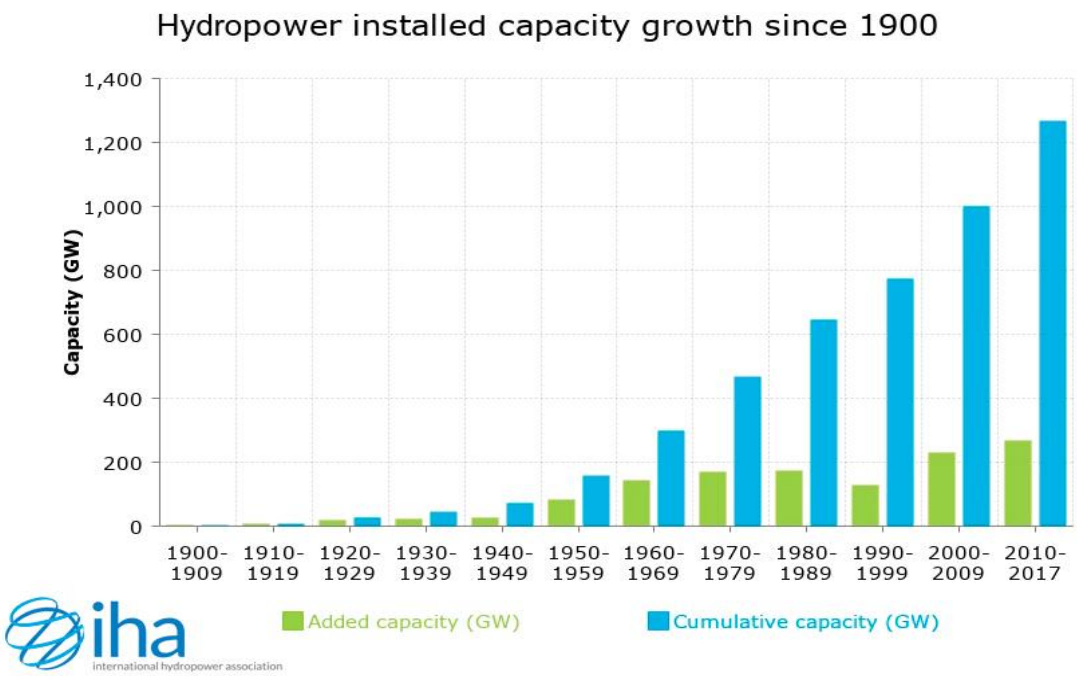

Figure 1. Hydropower installed capacity growth since 1900 (International hydropower association, 2019)

These impacts include drastic changes in the natural flow regimes, disruption of fish migration, sediments' entrapment and landscape degradation among others. Hydropower production infrastructures range from small run-of-the-river to massive hydroelectric dams and their negative impacts are different in type and size. The facilities are categorized based on their installed capacity: large (>10MW), small (<10MW), mini (<1MW) and micro (<0.1MW) (Hoes, Meijer, van der Ent, & van de Giesen , 2017). Hydropower is marketed as green energy and as a major component in achieving the Sustainable Development Goals by 2030 which is why it is supported and funded by most of the national and international investment banks (sustainabledevelopment.un.org, s.d.). In Europe 90% of the installed capacity is covered by large hydropower plants and the rest by the 21800 small hydropower plants which are going to rise to 24000 by 2020. The EU, in fact, still supports the economic feasibility of small-scale hydropower plants with projects like SMART (Strategies to promote small scale hydropower electricity production in Europe) which is part of the so-called "Intelligent Energy – Europe" program (European Commission). Renewable energy sources supply 22.3% of the world electric generation and hydropower is already the leading source among them, accounting to almost three quarters of the share (73,2% in 2014) which can be translated to over a sixth of the total electricity production (16,4% in 2014) (figure 2) (International Energy Agency, 2016).

Artificial barriers built for hydropower such as dams and weirs are the biggest threat to the ecological connectivity of rivers in all four dimensions (longitudinal, vertical, lateral and temporal) (Calles & Greenberg, 2009). The longitudinal alterations are the most relevant structural and functional disruptions to stream connectivity and they represent a physical barrier for a high number of species, not to mention the impact on sediment transport and water quality. Fish migrate up or downstream for different purposes, from feeding to reproduction, and in order to complete their life cycle certain fish species need diverse habitats and the continuity between them (Nyqvist, et al., 2017). Habitat fragmentation is one of the most relevant threats of human pressure in riverine ecosystems mostly due to physical barriers built for different purposes such as electricity production, agriculture, flood control and drinking water supply. In Europe only 28% of large rivers is still considered to be free flowing (Seliger & Zeiringer, 2018).

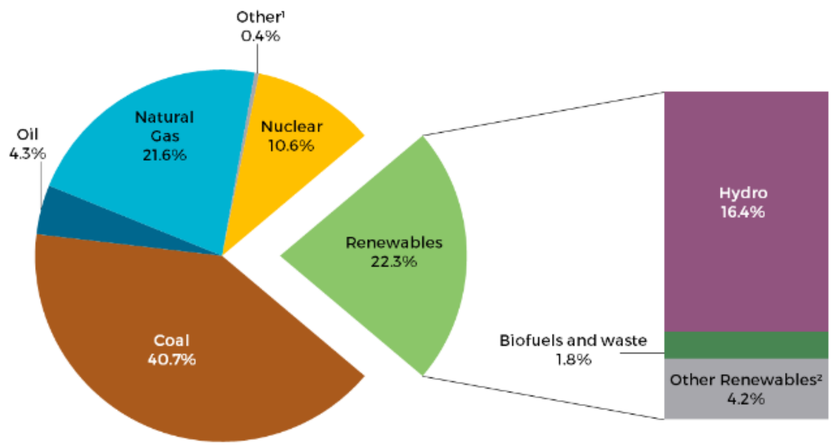

Figure 2. Fuel shares in world electricity production in 2014 (International Energy Agency, 2016)

It is estimated that there are between 600.000 and 1.8 million dams and weirs in Europe even if the precise number of barriers is unclear and there is no complete inventory (Gough, Fernández Garrido, & van Herk, 2018). Due to this reason one of the goals of the AMBER project (Adaptive Management of Barriers in European Rivers) is to create the first complete assessment of stream fragmentation across Europe, locating all the barriers in order to pivot the river restoration measures where needed. So far 450 000 have been mapped, also through citizen science program, and in some part of the continent the data are still under process (Adaptive Management of Barriers in European Rivers, 2018).

1.1 Aims of the thesis

In order to understand what can be done in the future to reduce to the minimum the negative impacts of hydropower it is important to start by explaining the reasons behind the current expansion of the industry which is driven by increasing energy demand (Hoes, Meijer, van der Ent, & van de Giesen , 2017). A lot can be done for old infrastructures built without taking in consideration fish migration and a lot more to make sure that the same mistakes are not repeated in the future when new powerplants are planned.

Besides damming rivers, humans' activities influenced fish migration degrading the water quality and overfishing the stocks resulting in a drastic decline of migratory fish. Some salmonids species such as Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*) have great ecological, social and economic importance (Jordan, O'Higgins, & Dittmar, 2012). Therefore they have been studied with great effort to find solutions to allow these species to reach their spawning grounds located upstream, or through the release of hatchery-reared smolts to compensate losses to the wild population (Huusko, 2018). When migration routes are opened by building efficient fishways for upstream connectivity often the planning lacks attention to the downstream migration, omitting a crucial part of the life cycle. In the recent years more studies have been carried out with scientific approaches to monitor the downstream migration, there is still deficit in knowledge when compared to the knowledge and functionality of upstream migration solutions (Nyqvist, 2016; Heiß, 2015). Due to the lack of comprehensive information about downstream passage methods and fish guidance, the aim of this thesis is to collect experiences from different countries in Europe to share expertise and knowledge necessary to improve the migration patterns of Atlantic salmon (*Salmo salar*) and in particular the technics adopted to facilitate the natural downstream migration of smolts (stage of a salmon life cycle that is getting ready to go out to sea for growth).

This work aims at facilitating the choice for the most applicable solution to improve downstream migration patterns. The final output aspires to be a useful toolkit that can be used when restoring, adapting or planning a hydropower infrastructure.

1.2 Atlantic Salmon (*Salmo salar*) life cycle

Each salmon begins its life inside an egg the size of a pea (figure 3) that along with other thousands is well hidden in a redd, a depression dug by the female with her tail into the gravel in a suitable spot surrounded by highly oxygenated waters. Once the eggs are fertilized by the male, the female completes the redd that will provide protection from predators and debris until spring when the first *alevins* will start to hatch. Alevin is the stage when juvenile salmon are still attached to their yolk sac which will eventually be fully absorbed, a process during which they do not leave the gravel and they stay in the proximity of the redd. In the next stage they are called *fry*, a critical moment of the life cycle as they start to swim up to the surface in order to fill their swim bladder with air. They are about 2 cm in length when, with the appearance and first development of the eight fins, they start to swim freely withstanding the current of the river. They are called *parr* when autumn approaches and vertical markings used for camouflage start to appear on their skin. They become territorial and can maintain this stage between one to three years, depending on the fertility of the waters, before starting the sea-bound migration.

Figure 3. Salmon life cycle (Miramichi salmon association, s.d.)

The parr undertake a series of changes including smelting (the vertical stripes turn into a silvery shine) and the beginning of the osmoregulation mechanism, preparing them for the life in salt water. When in spring they migrate downstream in schools they get to be called *smolts*. The environmental condition, pheromones and a series of other factors are imprinted on the smolts who will be able to return after the life in the ocean to the spawning grounds where they were born with extreme accuracy. After completing the necessary adaptation to the life at sea in the brackish waters of estuaries they are ready for the adult stage. After a long journey they reach their feeding grounds in the Arctic ocean, from western Greenland to the Norwegian Sea depending on the population. Here they grow fast for a period between one to four years (in some exceptional cases more) and they are ready to return to the river where they were born based on hormonal responses. The fish that are mature after one winter are called *grilse* and they weight between 0.8 and 4 kg while those that reach the maturity after few years, keep feeding on the abundant smaller fish and crustaceans and possibly reaching 15kg in weight. The journey to complete the reproduction cycle is full of dangers and obstacles. Natural predators, illegal coastal fishing, pollution and ultimately the man-made barriers drastically reduce the number of salmons that make the journey back. They start the so called "salmon run" to their original spawning grounds between February and November during which they stop feeding, surviving only with the fat reserves accumulated during the life in the ocean. After spawning they are referred to as *kelts*, they are very weak and even more exposed to diseases and predation but unlike pacific salmon species, Atlantic salmon might survive and start the journey again (Marine Institute, 2019).

1.3 Research question and sub-questions

What is the most appropriate measure to improve the downstream migration of Atlantic salmon (*Salmo salar*) in regulated rivers?

1) What is already known about downstream migration?
2) How did previous studies assess the major fish requirements during the planning and monitoring phase of a measure?
3) How can the measures be compared?

2. Material and methods

The method adopted for gathering the material necessary for writing of this thesis has been mainly literature research and literature review.
The search engine and database used to gather literature about the subject are ScienceDirect Springer, Wiley and sporadically Google Scholar. The list of keywords used for the research are presented in table 1. In the third column of the table is also specified to which sub-question the keywords research aims to respond.

Table 1. Keywords strategy

KEYWORDS	DATABASE	SUB-QUESTION
Hydropower, river connectivity, habitat fragmentation	ScienceDirect / Springer / Wiley / Google scholar	introduction
Downstream migration, salmon	Web of Science	1
Downstream migration, Atlantic salmon, smolts	ScienceDirect / Springer / Wiley	1,2
Fish guidance solutions, downstream migration, Atlantic salmon, telemetry	ScienceDirect / Springer / Wiley	2
Behavioural systems, physical screens, trash-rack, downstream migration	ScienceDirect / Springer / Wiley	2,3
downstream migration measures analysis	ScienceDirect / Springer / Wiley	3

In order to provide an answer to the first sub-question, the description of the importance of downstream migration and what is known in the scientific community about the subject is given with the support of four graphs. These graphs are presented in chapter number 3.1 called “Downstream migration” and they have been created with excel using data from the website Web of Science (Web of Science, s.d.).The keywords used for the research in the database have been "salmon" and "downstream migration". The graphs and charts have been exported as a picture and added to the results. The raw data can be found in the Appendix 1.

The second sub-question was approached with an extensive literature research aimed at collecting and selecting the most meaningful papers about downstream migration measures. The final choice has been made balancing year of publication (as update as possible), country and type of technique assessed. Only European studies have been selected from four countries (Germany, France, Sweden and Norway). Table 2 in chapter 3.2 collects the eight case studies giving an overview about the main author, the year, the country, the measures assessed, the number of sites and the species studied for each paper. In addition to this a code has been given to each case study to improve the identification. The answer to the sub-question number 2 lead to the selection of the parameters used to reply to sub-question number 3.

The third sub-question has been answered creating two tables that help to visualize the findings and they have been added to the result in chapter 3.3 (table 3 and table 4). Both are based solely on the selected eight case studies that are the only source for the evaluation. Additional studies have been used in the following discussion to try to validate the evaluation. Eight measures (also called techniques and solutions) have been deduced from the eight case studies. Table 3 lists and organizes the major advantages and disadvantages of the eight measures. The codes next to each measure refer to the case studies where the above-mentioned measure has been presented and assessed.

Table 4 provides an evaluation of the effects of the eight selected measures. The evaluation rate has been given on a scale from -3 to 3 where 0 indicates neutral impact, 3 maximum positive effect and -3 maximum negative effect. This table has been created with the aim of quantifying the findings about each measure based on the results and conclusions of the 8 case studies. The three parameters evaluated are relevant indicators for fish during the migration: fish mortality, migration delay and hydraulic conditions (Szabo-Meszaros, et al., 2019; Fjeldstad, Pulg, & Forseth, 2018).

3. Results

3.1 Downstream migration

The construction of passages to facilitate fish migration at barriers such as windmills dates back several centuries but only during the 1800s the recent technical development started to become widely available. During the last 50 years the rate of fishways construction peaked up even though the technology and the performance of these structures is not the same in all the regions of the planet (Silva, et al., 2018). Research and technology development are in general much more advanced for upstream migration compared to its downstream counterpart (Larinier & Travade, 2002). The latter was almost an irrelevant subject until the beginning of the 90s when the first articles and papers started to discuss the importance of a successful two-ways migration. The study

and installation of downstream migration facilities is necessary to allow migratory fish species to complete the full life cycle also in regulated rivers (Fjeldstad, Pulg, & Forseth, 2018).
The challenge of creating a summary of available knowledge that could serve as a “road map” for future downstream migration solutions was first investigated by a proposed project in 2014 by the EIFAAC (European Inland Fisheries and Aquaculture Advisory Commission). The project did not take off, but the issue is still under exploration five years later.

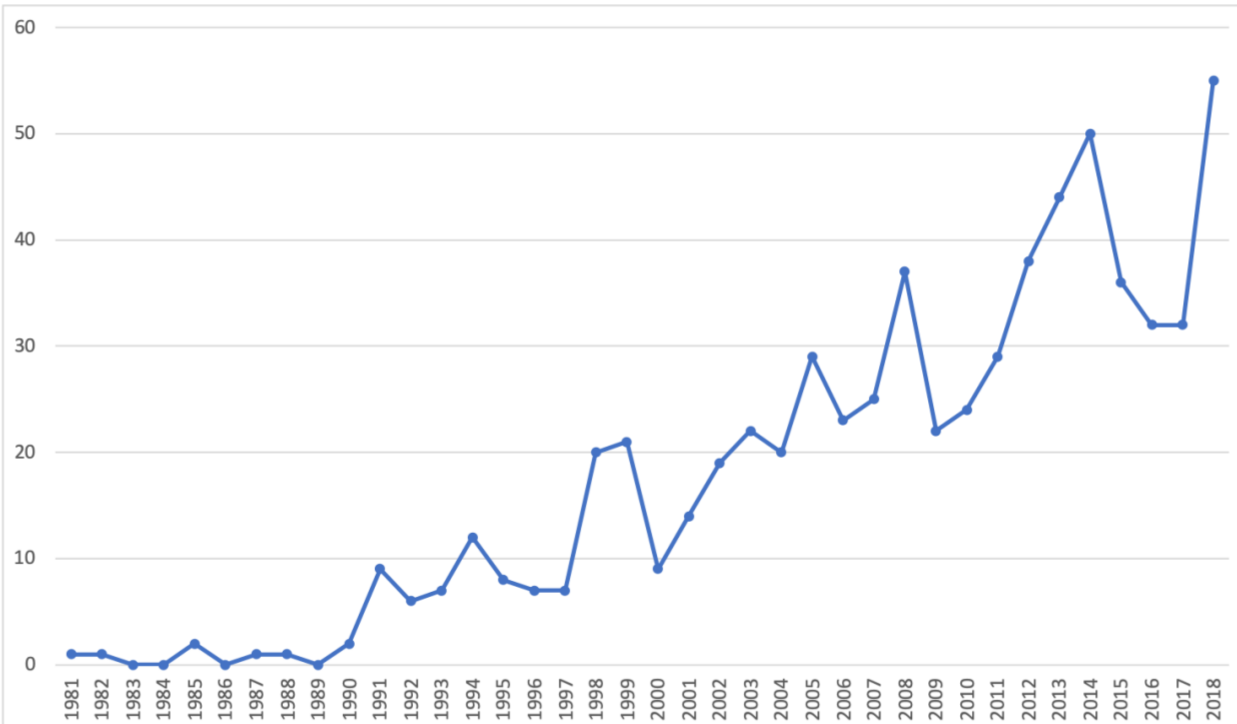

Figure 4. Number of published peer-reviewed papers and articles about downstream migration of salmon per year (1981-2018)

Even where upstream migration fishways have been built it is not always possible for downstream migrators to pass the obstruction and the problem of the findability of the bypass is of high concern (Nyqvist, 2016; Larinier & Travade, 2002). The main issues faced by fish migrating downstream in regulated rivers are mortality and migration delay. Mortality is divided in direct and indirect. Direct mortality is higher where there are no facilitation measures and migratory fish species are obliged to pass through the intakes that lead to the turbines in order to pass the obstacle created by the dam or weir. The causes of direct mortality include blade-strike with the turbines, grinding, barotrauma caused by sudden increase or decrease of pressure (cavitation) and shear stress (Vikström, 2016; Deng, 2014). Among the indirect causes of mortality there are increased predation, susceptibility to diseases, sport fishery, exhaustion, loss of migratory urge, and injuries after the passage (Nyqvist, 2016; Travade & Larinier, 2006). Upstream of the hydropower plant, in the impoundment created by the dam, piscivorous birds and fish predators have more chance to feed on the migrating smolts. After the passage through the turbines, or via alternative ways, injuries and altered fish behaviour can significantly increase predation and consequently post-passage mortality (Nyqvist, 2016). Mortality can also be caused by a change in water quality which

specifically refers to oxygen depletion in reservoirs created by a dam or supersaturation of gases in the tailrace due to spillway (Larinier & Travade, 2002). Eventually the migration delay is accentuated by a cumulative effect due to multiple consecutive hydroelectric plants (Nyqvist, et al., 2017). Mitigation measures need to be studied, tested and evaluated in order to facilitate the passage of fish at hydroelectric power stations (Nyqvist, 2016). Figure 4 displays the increasing number of publications during the recent years (a third of the total since 1981 has been published during the last 5 years) on the possibility to reduce the knowledge gap between upstream and downstream migration facilities with a benefit on the overall fish life cycle.
Figure 5 shows how the publications are divided by category of interest. As the same paper or article can be classified in multiple categories the total number of the records is higher. The real total of 665 publications between 1981 and 2018 becomes 1150 in this graph if all the records are summed up. The meaning is that almost every paper or article has been placed under 2 categories (1,7 on average).

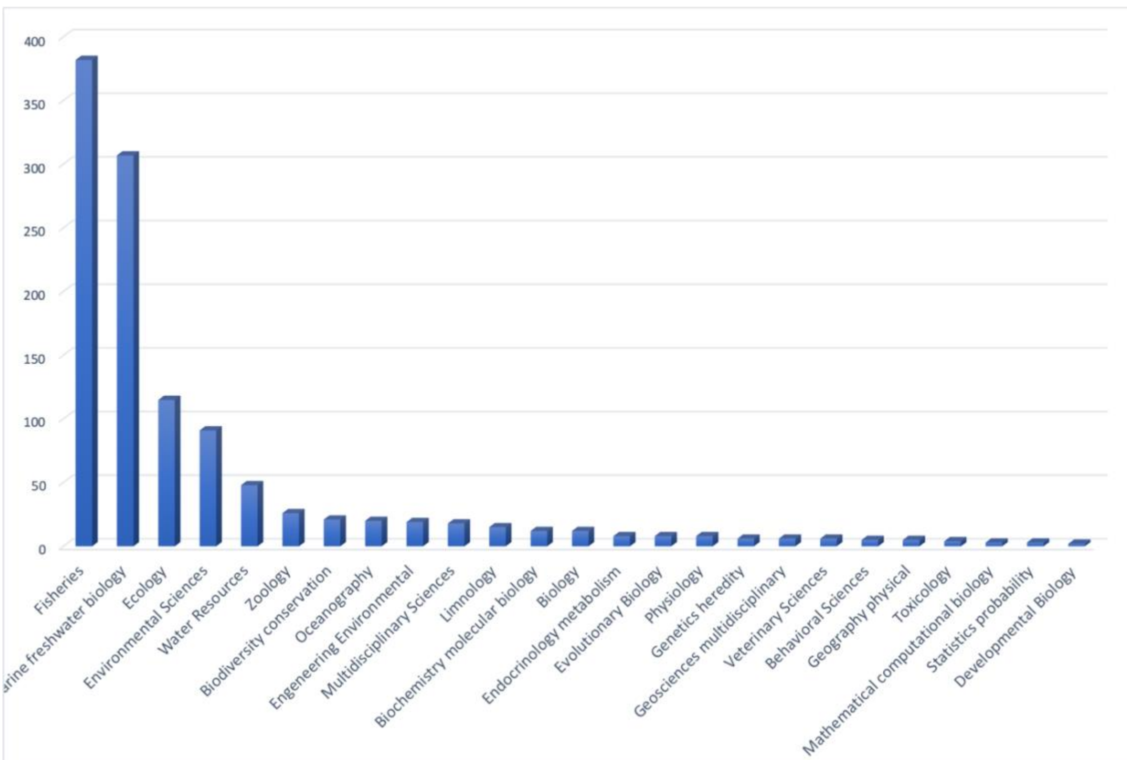

Figure 5. Number of articles and papers published by category (1981-2018)

The institutes mainly interested in downstream migration research are those related to Fisheries. This underlines the economic value and market relevance of the Atlantic salmon (*Salmo salar*) which is among the most studied fish species in the world (Nyqvist, 2016). Fish and Fisheries, Fisheries and Aquaculture journal and Fishery Bulletin are just some of the scientific journals where articles about downstream migration of salmon have been published and then grouped under this category. Marine and freshwater biology follows in terms of number of publications and along with the field of Ecology and Environmental Sciences represent almost 80% of the total.

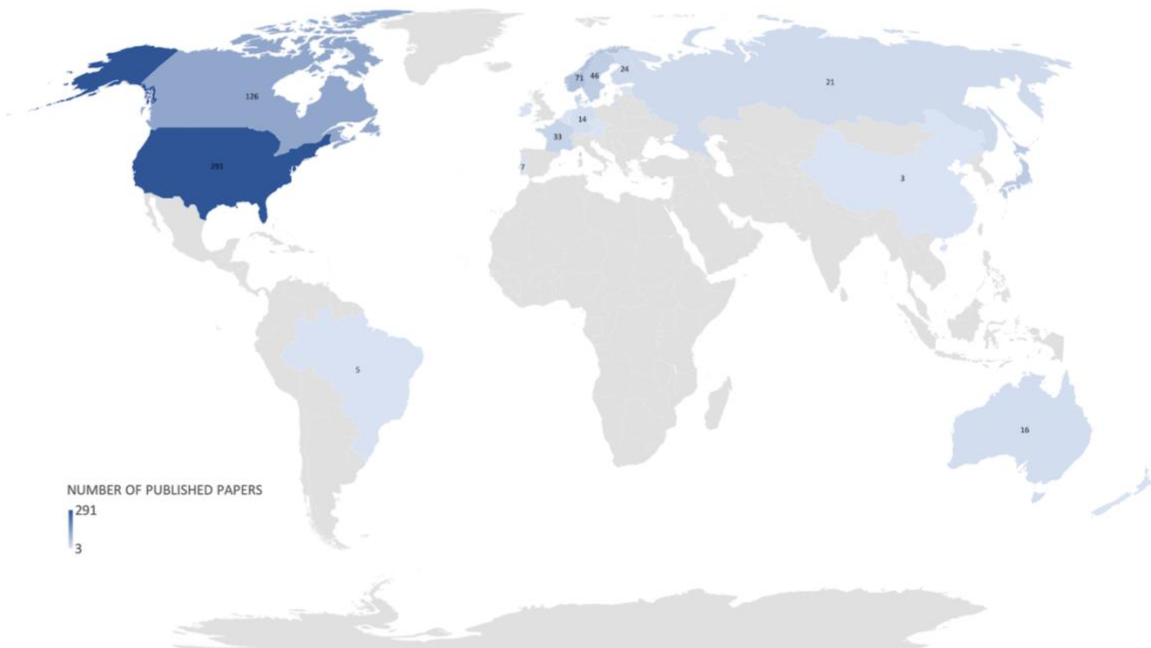

Figure 6. World distribution of published articles and papers on the subject of salmon downstream migration (1981-2018)

Looking at the two following figures (6 and 7) is possible to assess which region of the world has developed more interest in salmon and into research methods to improve its downstream migration. Again, the total number is higher than 665 because it is based on the nationality of the authors of the publications (Web of Science, s.d.). Often the authors from a specific country research this topic in his/her country but it is not always the case. Therefore, the following result gives just a rough idea about the geographic areas where the issue of downstream migration of salmon have had relevance in the period between 1981 and 2018.

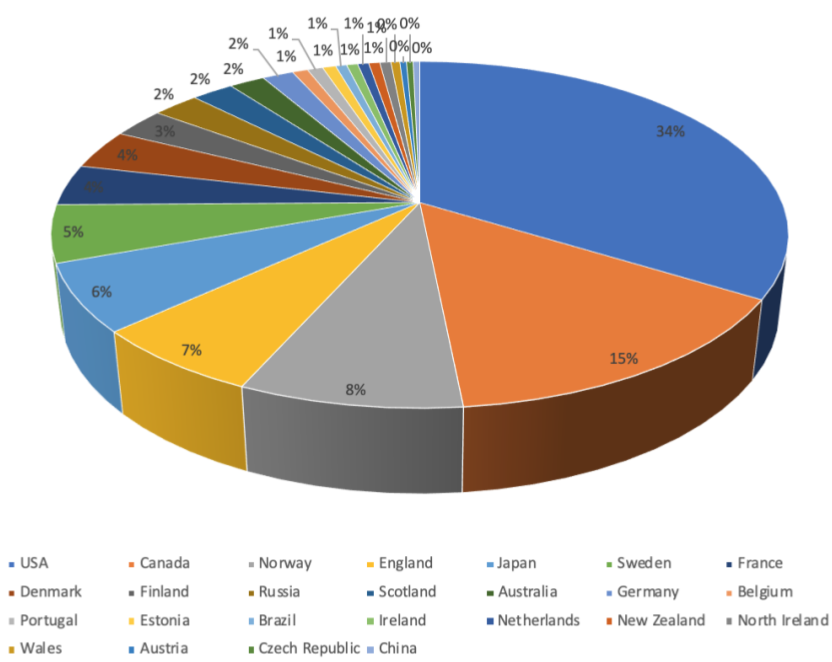

Figure 7. Percentage of published articles and papers by authors' nationality (1981-2018)

The attention of researchers and decision makers on the need for downstream migration solutions started from the western United States and during the past two decades has extended also elsewhere (Nyqvist, 2016). Combining the publications made by authors from the Unites States and Canada the result shows that almost 50% have been produced in North America since 1981 (Web of Science, s.d.).

The number of papers published by Norwegians, Swedish and Finnish authors combined represent 16% of the total worldwide. Another area where the interest for this species is notable is the UK which is divided by countries in this statistic. Altogether the publications in England, Scotland, North Ireland and Wales make up 13.5% of the total.

Other relevant areas in Europe where research about Atlantic salmon and downstream migration is noteworthy are France, Denmark and Germany respectively with 33,32 and 14 papers and articles published.

3.2 The case studies

Table 2 lists the case studies analysed in this thesis. They have been chosen because they are recent researches studying the latest techniques to improve the downstream migration of fish in regulated rivers. They also represent a balanced set in terms of countries and type of measures evaluated. A short description of each study is given presenting the measures studied, the location of the sites and the most relevant conclusions. In the following chapter the techniques analysed by these eight studies are going to be compared and evaluated.

Table 2. The case studies

TITLE	MAIN AUTHOR (YEAR)	COUNTRY (CODE)	MEASURES STUDIED	STUDY SITES	SPECIES
Fish behaviour and fish guidance at hydropower intake screens for fish downstream passage	Geiger (2018)	Germany (G1)	Inclined racks / Horizontal screens / bypass	lab	Multispecies
Downstream migration of Atlantic salmon smolt at three German hydropower station	Økland (2016)	Germany (G2)	Inclined screen / Fish-friendly turbines	3	Atlantic salmon smolts
Protecting efficiently sea-migrating salmon smolts from entering hydropower plant turbines with inclined or oriented low bar spacing racks	Tomanova (2018)	France (F1)	Inclined racks / angled-oriented rack	4	Atlantic salmon smolts
Downstream migration: problems and facilities	Larinier (2002)	France (F2)	All	multiple	Multispecies
Upstream and downstream passage of migrating adult Atlantic salmon: Remedial measures improve passage performance at a hydropower dam	Nyqvist (2017)	Sweden (S1)	Angled rack / bypass	1	Atlantic salmon kelts
Effectiveness of a fish-guiding device for downstream migrating smolts of Atlantic salmon (Salmo salar L.) in the River Piteälven, northern Sweden	Vikström (2016)	Sweden (S2)	Floating structure	1	Atlantic salmon smolts
Experimental hydraulics on fish-friendly trash-racks: an ecological approach	Szabo-Meszaros (2018)	Norway (N1)	Angled racks / behavioural techniques	lab	Atlantic salmon & European eel
Modelling mitigation measures for smolt migration at dammed river sections	Szabo-Meszaros (2019)	Norway (N2)	Flow deflectors / river bank modification / floating structures	1	Atlantic salmon smolts

3.2.1. G1

Geiger, Cuchet, & Rutschmann (2018) investigated under laboratory conditions the efficiency of inclined and horizontal screens with different bar clearance (17.5, 20, 30 and 50 mm). The research starts from the assumption that the biggest challenge for the fish is to locate the entrance of a bypass (when present) and therefore the main question is how to guide them there.

Different inclinations of the screen have been tested together with different bar clearance and bypass depth (figure 8). An alternative is provided by a submerged horizontal screen (90°) that feeds water into the turbines (three side-lines) while the fourth side-line provides the necessary water through a gate used as bypass (figure 9).

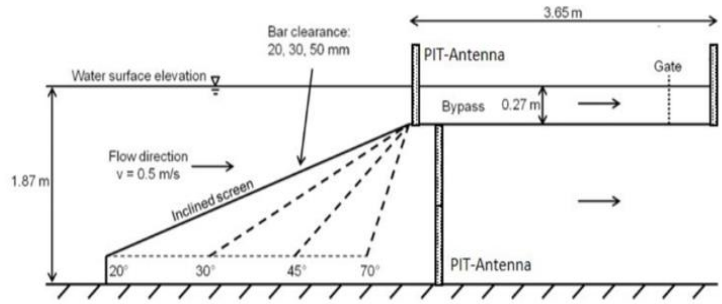

Figure 8. Scheme of different inclinations tested by the study (Geiger, Cuchet, & Rutschmann, 2018)

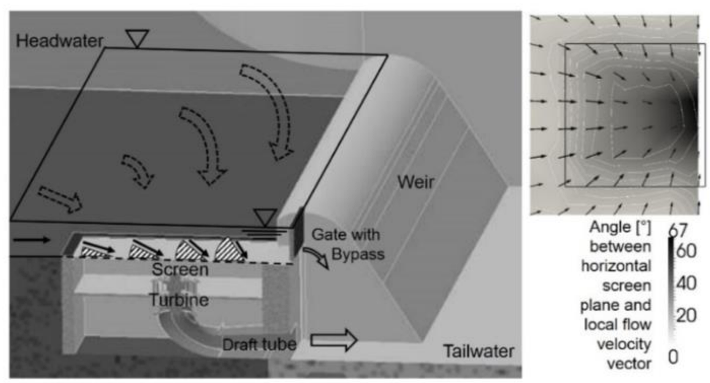

Figure 9. Visualization of flow velocity components. The four side-lines are represented by the arrows (Geiger, Cuchet, & Rutschmann, 2018)

This study looked at many fish species of different sizes (including salmonids like *Salmo trutta* and *Thymallus thymallus*) comparing the behaviour when inclination, bar clearance and approaching flow velocity changes. Abiotic parameters and hydraulic condition were controlled, modified and recorded to be analysed in relation to different fish behaviour.

The authors report no impingement in the racks in any of the configurations nor serious injury. The more inclined the axis of the screen the less interference with swimming capabilities. Moreover, in the experiments with large bar clearance (up to 50 mm) some species tried to swim across suggesting the benefit from small bar clearance that intensifies behavioural repulsion. The horizontal screen associated with a near-bottom bypass showed a safe passage for most of the species. The general conclusion is that the efficiency increases lowering the inclination of the screen (<45%) and diminishing the gap between the bars (20mm) (Geiger, Cuchet, & Rutschmann, 2018)

3.2.1. G2

The second study is a product of the collaboration between the University of Cologne and NINA (Norwegian Institute for Nature Research) (Økland, et al., 2016). Three hydropower station on three different rivers in Germany are the study areas. In Unkelmühle power station (Sieg river) fish is prevented to enter the turbines by a narrowly spaced rack positioned at the intake. In Gengenbach station (Kinzig river) the turbine is a movable Kaplan (one of the three main types of turbines reviewed in detail in the discussion of this report, chapter 4) protected by a rack (bar clearance: 15 mm). In Kuhlemühle power station (Diemel river) is equipped with two Francis turbine and a 4-bladed Archimede screw turbine (so called fish-friendly turbine). The aim of the research is to compare the mortality of tagged smolts in free-flowing stretches of the same river where the power stations are located. It also aims at mapping the preferable routes during the migration at the three power stations as it is shown in figure 10.

On the Sieg river the loss in the free-flowing stretch was 1.6% per km (2015) and 9.6% per km after passing through the reservoir created by the dam. At the Unkelmühle power station another 12.8% of the tagged fish was lost.

On the Kinzig river the results were 0.7% (free-flowing stretch), 1.9% (reservoir) and between 3.1 and 6.3% (Gengenbach power station).

On the Diemel the results were 2.5% (free-flowing stretch), 1.5% (reservoir) and 8% (Kuhlemühle power station).

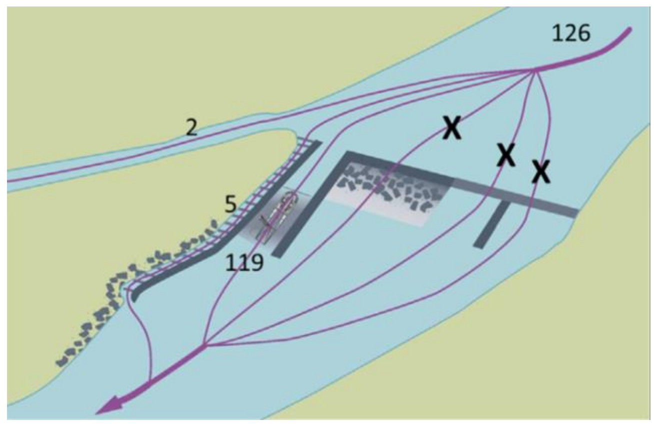

Figure 11. Example of mapped routes used by smolts at Gengenbach dam (Økland, et al., 2016)

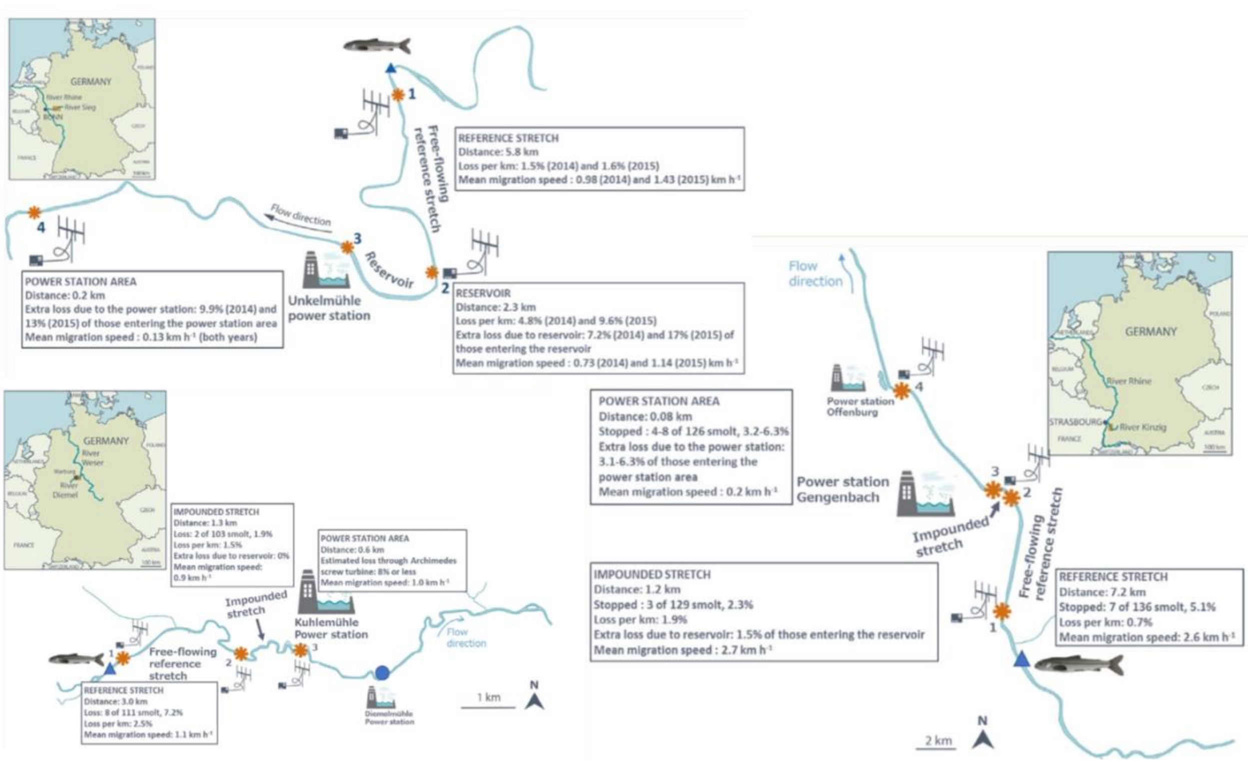

Figure 10. Results of radio-tagged smolts in the 3 studied rivers (modified) (Økland, et al., 2016)

The results show a clear increase of predation in the impounded waters near the reservoirs (in Kuhlemühle water flow is only slightly slowed down and the dam does not create an impoundment). Moreover, the results presented for the mortality after the stations have to be defined as minimum estimates since delayed mortality was not taken into account. No significant difference was observed in regards of migration speed between the reference stretches of the three rivers (mean 1.07, 0.93 and 1.03 km/h) (figure 11).

3.2.1. F1

Tomanova et al. (2018) assess the bypass efficiency at four hydroelectric plants (HEP) in France. They all have protection systems composed by 20mm spaced bar racks. Three of them are horizontally inclined at 26° and one is 64° inclined with bars oriented 15° to flow. The results of this research are among the highest rates of fish passage through non-turbine routes (88%) and fish survival (98%) ever recorded. Average guidance towards the bypass was really high (between 80.9% and 87.5% depending on the site) and also other routes were used by fish (fish pass and evacuation canal) increasing the survival and leaving only a limited number of fish passing through the turbines (0.4-11.8%) (figure 12).

Site	Bypass passage minimum efficiency (%)					
	all individuals		ind. ≤ 200 mm		ind. ≤ 190 mm	
	mean	min–max	mean	min–max	mean	min–max
Auterrive	80.9	75.5–89.2	78.9	74.4–85.3	78.5	71.4–86.4
Trois-Villes	87.5	78.8–97.1	87.2	78.6–96.9	87.7	79.2–96.4
Gotein	80.9	71.2–100.0	78.8	68.9–100.0	76.9	65.7–100.0
Halsou	87.0	78.8–94.4	86.9	78.3–94.0	85.7	75.0–95.5

Figure 12. Bypass passage minimum efficiency of the 4 study sites (Tomanova, et al., 2018)

Migration timing shows variability based on the individuals (75% during the first few hours) but in general it can be regarded as low. It is remarkable the difference between day and night migration. The groups released in the evening crossed the barriers much faster than those released during the day.

The last conclusion of the authors is that even if these results of this study might look encouraging, the cumulative effects of a cascade of power plants is much greater and before implementing any measure the entire catchment should be assessed as a whole and not every single HEP separately.

3.2.1. F2

The report published by French professors M. Larinier and F. Travade (2002) is a comprehensive study that starts from the analysis of the species involved (even if most of the discussion is based on salmonids species) and the possible available routes for downstream migration in harnessed rivers.

The authors divide the downstream migration solutions in physical barriers and behavioural barriers. The location studied are several and they are mostly from France, but some examples are from the US and UK.

Four different types of screens are discussed among the physical barriers:

- Temporary (migration period only) fine-mesh screens placed in front of the intakes
- Vertical angled screens (angle 15° to 45°) with associated surface bypass. Lateral or V configuration depending on the width of the channel.
- Rotating drum screens. Widely spread in US irrigation channels due to their easy automatic cleaning procedure.
- Submerged travelling screens (normally installed only at large scale HEP).
- Eicher screens. Wedge-wire bars very narrowly spaced (2mm). Withstands high flow velocities and it is practical being self-cleaning. System used in combination with trash-racks upstream to stop large debris (figure 13).
- MIS (modular inclined screen)

The behavioural barriers examined by the authors are:

- Light
- Electricity
- Sound
- Louvers

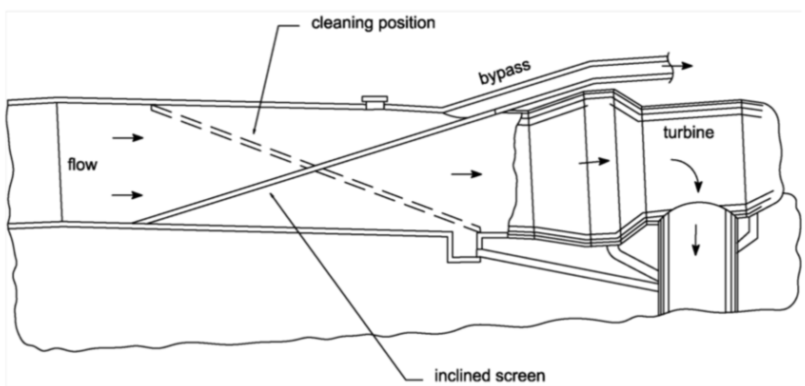

Figure 13.Eicher screen example (axle-mounted MIS screens are very similar to Eicher) (Larinier & Travade, 2002)

In the test with behavioural solutions the fish were either attracted or repelled by stimuli created by those facilities where these types of barriers have been tested. Results from these techniques are classified as very unreliable and most of them with very low levels of efficiency (electricity for example has been tested in the site of Nine river in France and it is around 15%). Some other tests in the UK gave variable results and were strongly dependant on river conditions. Shallow rivers with large bypass and proportional high discharge found sounds screens to be efficient during the day (70%) but poor during the night. Other tests of the same technique in France showed overall very low efficiency (close to nil). Louvers (or hydrodynamic screens) have been tested in the US in rivers with constant discharges and velocities

throughout the migration period with promising results. At Holyoke HEP on Connecticut river efficiency for Salmon smolts resulted to be 97%.
Lastly, the paper analyses the combination of the suggested measure (trash-racks) with bypasses or fish transport. The two factors that influence the efficiency are the effect of trash-racks on fish behaviour (repulsion) and the velocity in front of the trash-rack at the intake. Efficiency increases by just improving the flow conditions at the entrance of the bypass as studies performed at Soeix and Camon (France) demonstrate (from 15-35% to 60-75%) (Croze, Chanseau, & Larinier, 1999). The main outcome of the publication is that in France (and elsewhere) more research is needed since the fish's reactions to hydrodynamic conditions are far from being understood. Physical barriers are suggested as the best solutions at the moment of the research (2002) and in particular MIS screens showed to combine the ability of withstanding high approaching velocities (0.6-3.0 m/s) and, in scale-model tests, very high survival rates (99%) (Larinier & Travade, 2002; Taft, Winchell, Cook, & Sullivan, 1992).

3.2.1. S1

Nyqvist, et al. (2017) studied the fish passage conditions before and after the improvement of upstream and downstream migration facilities. Figure 14 shows the study area which is on the Ätran river in Sweden and Herting hydroelectric plant (HEP) is the first obstacle from the sea (23 km from river mouth). Mean annual discharge of the river is 57 m^3/s and during the last 10 years between 2000-4000 Atlantic salmons came back to spawn.

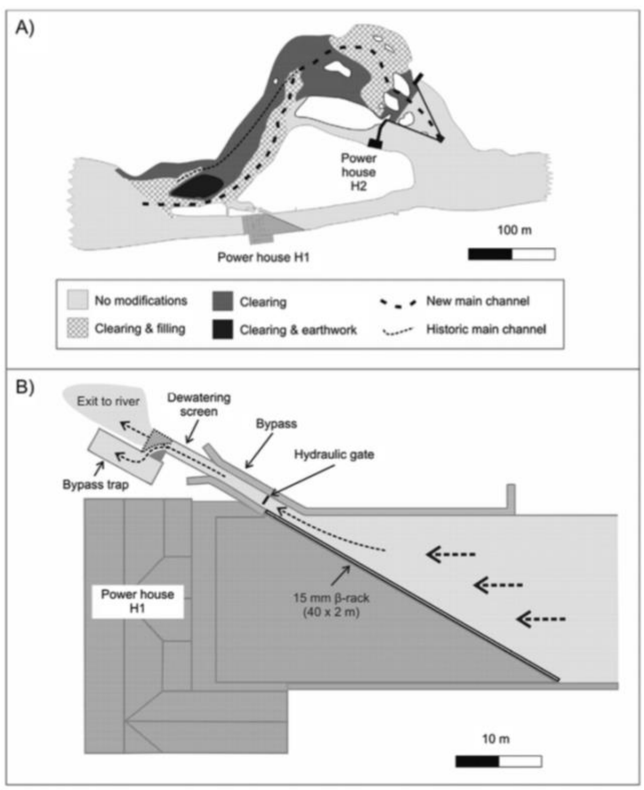

Figure 14. Combination of measures at Herting dam: natural-like fishway and low-sloping rack (Nyqvist, et al., 2017)

At Herting dam there are two HEP (H1, intake capacity=40m^3/s and H2, intake capacity=25m^3/s) before the completions of the works there was a technical fishway for upstream migration and a simple bypass/trash gate for downstream migrators. The upstream migration technique has been replaced with a natural-like fishway and a low-sloping rack has been installed to guide fish towards the already existent bypass. In 2013 when the works have been completed, the old racks covering the intake of H1 have been replaced by an angled rack (30°) with horizontally orientated bars (gap 15 mm). In this way the approaching flow velocity has been adjusted at 0.5m/s. The bypass is also equipped with a fish

collection trap which is not used in normal operations when flow is discharged through a close-to-bottom and surface gate as shown in figure 14.
Before the modifications fish migrating downstream could pass through the bypass or the spillway. After the works fish could be guided by the angled rack passing through the bypass or being spilled in the natural-like fishway.
After the implementation of the measures a telemetry study has been performed and 29 out of 30 salmons kelts passed the barrier (97% efficiency) with a significant reduction in migration delay. In this case the combination with the natural-like fishway improved the overall downstream migration because of a continuous surface spill that ensured an additional route to the fish. The variation of discharge of the river has no influence on the performance which indicates a good result. Passage performance has also been analysed in relations with abiotic parameters and has been discovered to be higher in higher temperatures and during the day compared with night time.

3.2.1. S2

Vikström (2016) evaluates the potential of an innovative fish guidance structure assessing the effectiveness of a floating structure installed upstream of Sikfors, the only hydroelectric plant (HEP) on Piteälven river in Northern Sweden. The total capacity of the plant is 260m^3/s equipped with two Kaplan turbines producing 25MW each. Since the importance of the spawning grounds for salmons and trout located upstream has been acknowledged, a fish ladder for upstream migration was built in the 90s. At the dam there are three spill gates: two discharge from the bottom and one from the surface. The latter can provide a passage for downstream migrators. Recently a guiding structure composed by 26 floating booms tied together (figure 15) has been installed in order to improve the findability of the spill gate.

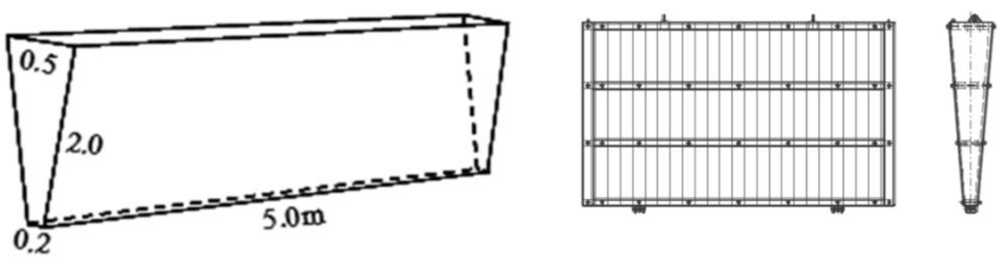

Figure 15. Model of the floating boom (Vikström, 2016)

The structure has been orientated in a way that the main current could guide the smolts away from the turbine intakes. Water flow and temperature was recorder during the study (25th May-15th June). Flow dropped from 600m^3/s to 280m^3/s and temperature rose from 7.9°C to 16.2°C. Adjustments to the water released by the spill gates were made to test the passage in different discharges and averages were different for each spill gate.
117 Atlantic salmon smolts were tagged and released in different batches during the study period from a location 2.6 km upstream of the obstruction. An additional release of 58 smolts (29 alive

and 29 dead) tested the migration route of living and dead individuals at different flow rates (25, 50 and 100m^3/s).
Faster migration was observed when temperature increased. 74% successfully migrated from the release location to the power station and out of these 87 individuals 85% passed through the spill gate. The remaining 15% through the turbines. Mortality was higher for the smolts that passed through the turbines (30,8%) compared to those that died passing through the spill gate (18,9%). When compared with the flow, mortality was higher with higher flow (100 m^3/s) showing higher survival when the regime was in the range between 25 and 50 m^3/s.

3.2.1. N1

Szabo-Meszaros, et al. (2018) studied only angled trash-racks, maintaining a steady flow in laboratory conditions. Six types of trash-racks have been investigated: they were all 30° angled to the flow (ß racks) with different bar configurations (vertical-streamwise, vertical-angled and horizontal bars). Each configuration was tested with two bar profiles (rectangular and drop shape). Bar spacing was constant (15mm). Velocity measures were taken at the centre of the racks and calculated using a system called V3V (figure 16) (Szabo-Meszaros, et al., 2018).

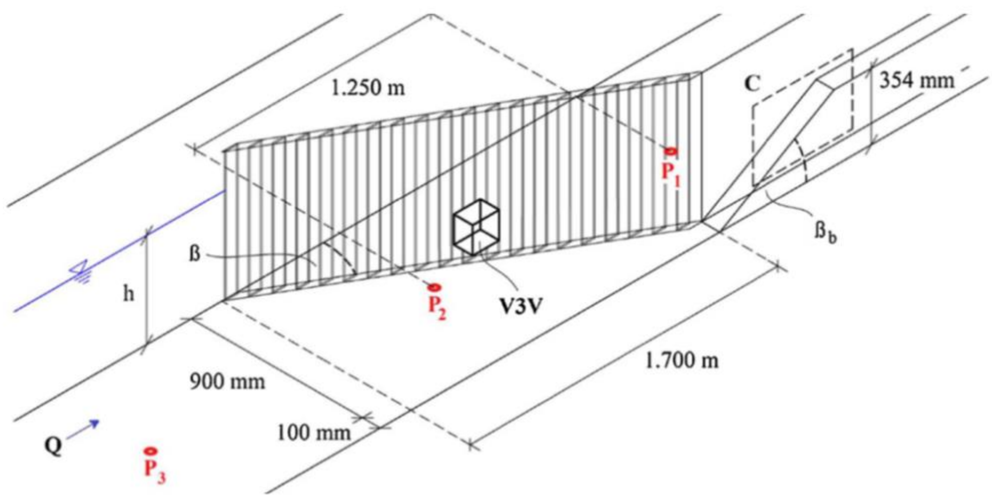

Figure 16. Set-up of the experiment: ß rack with bypass and the locations where measurements were taken (Szabo-Meszaros, et al., 2018)

Vertical-angled configurations (60° angled to the flow) gave the worst ecological results and they were not the best in terms of head loss. This type of bar orientation produces high turbulent flows in the vicinity of the rack and at the bypass entrance creating problems with fish behaviour and swimming capabilities. Only if discharge is diminished this configuration can be competitive with the others but this would imply losses for the hydropower plant. Vertical-streamwise were found to be advantageous for hydropower production compared to the other configurations because of the lowest values of head loss (12%) but not as good as horizontal bar orientation from an ecological point of view. Figure 17 represents with a + or - the advantages and disadvantages of the 3 types of rack tested in the study.

Subjects		Vertical-streamwise trash-racks (Rack I–II)	Vertical-angled trash-racks (Rack III–IV)	Horizontal trash-racks (Rack V–VI)
Operational questions	Required material	+		−
	Maintenance complexity	−	+	−
	Retrofitted built in	+	+	−
	Head-losses	+	−	+
	Diverted discharge	+ (o)/−(e)	−(o)/+ (e)	+ (o)/− (e)
Bypass section[a]	Velocities	+	+	+
	Accelerations	+	+/−	+
	Turbulence	+	−	+
Upstream of the racks[a]	Velocities	+	−	+
	Accelerations	+	−	+
	Turbulence + Curl		−	+

[a] Based on the literature existent for salmon and eel//+ recommended/advantageous − not recommended/disadvantageous +/− under certain conditions.

Figure 17. Advantages and disadvantages of the three configurations (Szabo-Meszaros, et al., 2018)

3.2.1. N2

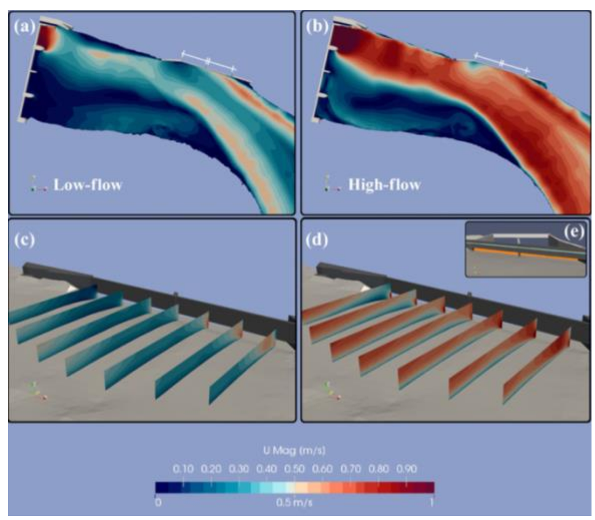

Figure 18. Simulated hydraulic conditions at Bjørset dam and at the entrance of the intakes of Svorkmo power station (Szabo-Meszaros, et al., 2019)

The last case study presented by this thesis has been carried out and published in Norway (Szabo-Meszaros, et al., 2019). The river where the experiment took place is the Orkla and the hydropower plant is called Svorkmo, located hundred meters upstream of Bjørset dam. The plant is equipped with Francis turbine and it has high-head. At the dam site there are 4 spillway gates. Only one (Gate 1) discharges water during the migration period. Majority of the flow is directed towards the intake entrance and the study focus on which measure could potentially divert the flow and consequently the migratory smolts towards the opened gate. Computational fluid dynamic (CFD) is a modelling computer-based method adopted to avoid the classical "trial and error" approach normally used in most of the facilities. It has been used in this study to assess the mitigation measures proposed. The model was initially calibrated and validated, then the first step has been the calculation of hydraulics conditions under Low (LQ) and High Flow (HQ) (figure 18). The same figure shows the velocities simulated at the near-bottom openings of the intake entrance (c and d).

The mitigation measures proposed and evaluated are illustrated in figure 19 and are the following:

- Spillway gate change (from number 1 to number 4)
- Flow deflectors (also called spurs): one structure on each bank (30 and 40 meters long) that rises between 0 to 0.5 meters above water level depending on the conditions and divert the water flow
- Increase the width of the river by 20-25% modifying the bend located upstream
- 1-meter deep floating guidance structure positioned upstream of the intake entrance. 2 types: permeable (solid material) and impermeable (trash-rack type equipped with horizontal bars)

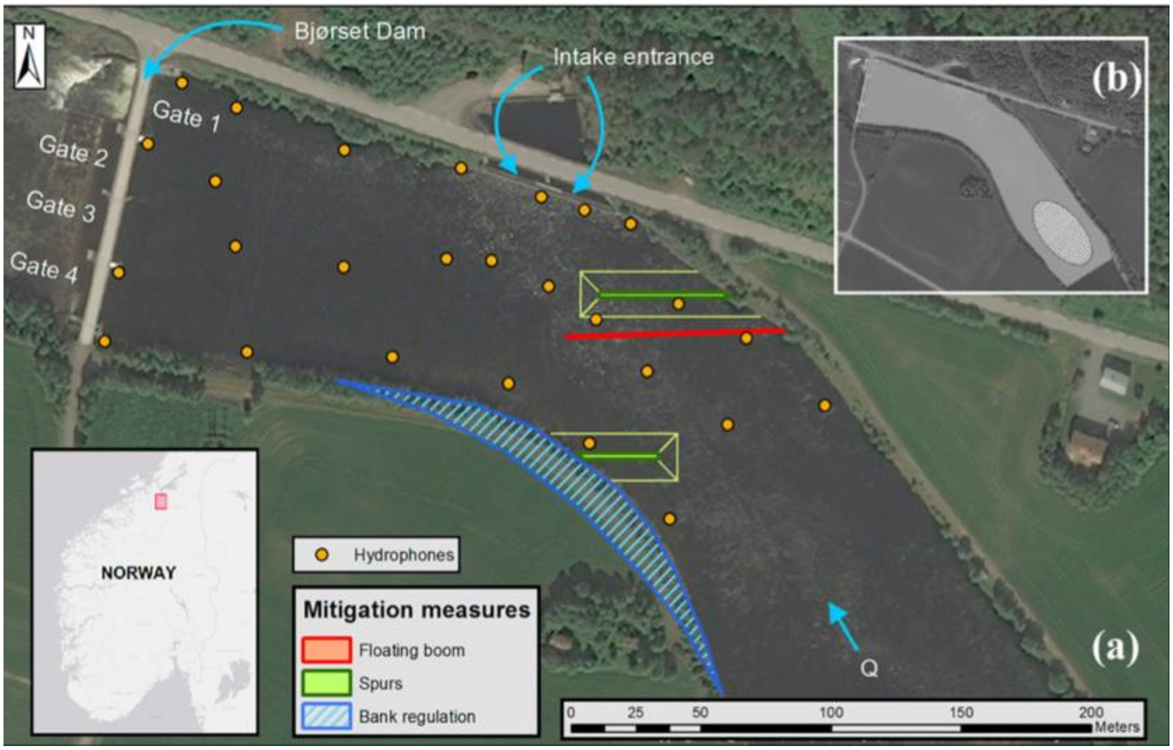

Figure 19. The four mitigation measures at Bjørset dam (Szabo-Meszaros, et al., 2019)

The outputs of the CFD models are illustrated in figure 20. The first measure (1.1 and 1.2) had only minor effects on the flow in the proximity of the intake entrance and therefore it is not likely that just changing the gate will turn in favour of smolts during their downstream migration.

In the second measure the flow deflectors twist the flow directing it towards the intake entrance (velocity increased above 1m/s). With this configuration even the smolts that follow the southernmost part of the current are most likely dragged in the intake. This measure clearly shows negative impacts on the migration.

Enlarging the river width with the purpose of creating an even flow, the third measure, shows a reduction of the overall values of velocity but maintaining the pattern with higher velocities leading towards the intakes (3.1 and 3.2). For this measure there is a high level of uncertainty about the impacts on migrating smolts.

Both floating booms, permeable and solid, provided the most satisfactory results. Simulations 4.1 (solid) and 4.3 (permeable) show only a uniformization of the flow during LQ but do not show significant difference compared to the initial situation.

The solid structure (4.4), at HQ and in combination with a different gate opened, showed a consistent continuous flow towards the desired outflow. However, it also caused an increase of velocities under the boom deflecting the flow in the proximity of the intake. Similar velocities might pose a threat to the fish. Confused by which is the primary flow they might follow the current that leads under the structure and ultimately end up in front of the intake. The situation was different for the trash-rack type solution that, being permeable, did not create high variations in flow velocities under the boom. The floating booms in general and the permeable structure in the specific are suggested to be the measures that would increase the probabilities of successful guidance of smolts towards the gate outflow (Szabo-Meszaros, et al., 2019).

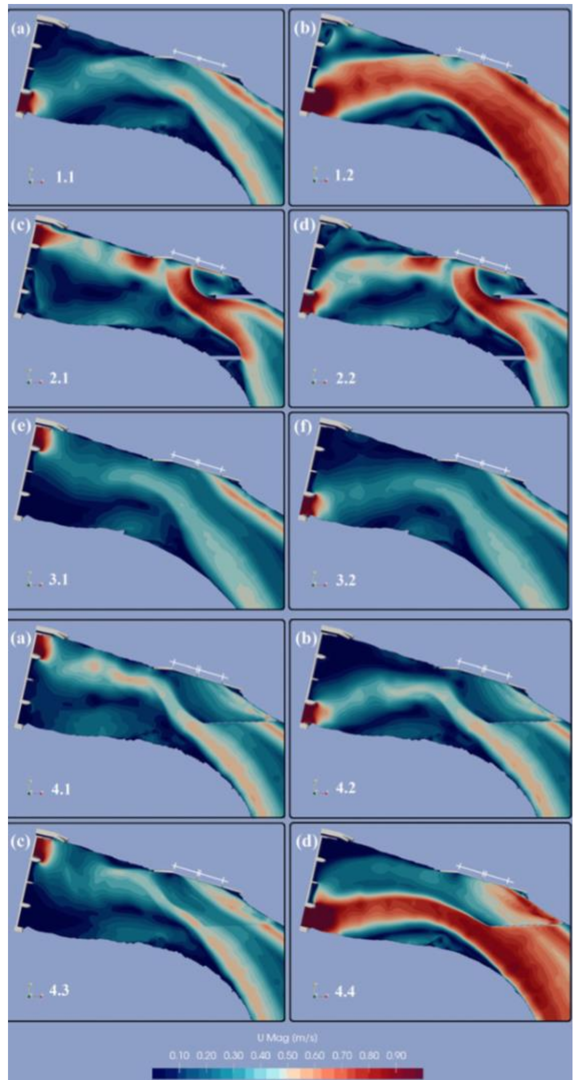

Figure 20. Simulated effects of the mitigation measures (adapted from Szabo-Meszaros, et al., 2019)

3.3 Measures evaluation

Table 3. Measures: advantages and disadvantages

MEASURES	ADVANTAGES	DISADVANTAGES	REMARKS
Fish-friendly turbines (G2)	• economically valuable (minimal loss in power production)	• Fish size: high mortality of kelts	• Suggested minimal gap between the runners
	• No fine screens needed (Archimede screw turbines)	• Low head application only	• Suggested reduction of operating velocities
Simple Bypass entrance (G1)	• Costs	• Findability of the entrance	• Advised minimum 2-10% of the total discharge
	-	• Hydraulic turbulences	• Surface bypass most suitable for salmonids
Electric, acoustic and light devices (F2)	• Minimal cleaning	• Low efficiency (case dependent)	• Recommended only in combination with other measures
	• No clogging problems	• field application less reliable than controlled conditions	-
Flow deflectors (N2)		• Possible increase in migration delay	-
River engineering (N2)	• No structures in the river	• Marginal effects (case dependent)	-
	-	• Highly uncertain fish response	-
Floating structure (S2) (N2)	• Possible large sites applications	• Restricted ability to withstand flooding conditions	• excellent rate of guidance towards desired flow
	• Low turbulence (if permeable)	• Strong vertical flow under the boom (if solid and not permeable)	-
Inclined screen/ α-racks (G1) (G2) (F1)	• Behavioural repellent effect (fine-mesh)	• Head pressure loss (especially when retrofitted)	• Bar clearance less than 20mm
	-	• Dependent on shallow water depth	• Inclination must be less than 45° (26° recommended)
Angled screen/ ß-racks (F1) (S1) (N1)	• Minimal head loss	• Maintenance complexity (for streamwise configurations)	• Bar clearance less than 20mm
	• Cleaning (only for vertical-angled configurations)	• Risk of impingement (depending on the angle to the flow)	• Streamwise bar configuration recommended

The findings from the review of the case studies has been summarized in table 3 and they will consistently help to steer the discussion of the thesis. All the techniques studied, and their configurations, have been named and organized in eight categories:

- Fish-friendly turbines
- Simple bypass entrance
- Electric, acoustic and light devices
- Flow deflectors
- River engineering
- Floating structure
- Inclined screen/ α-racks
- Angled screes/ ß-racks

The advantages or disadvantages are considered for the single measure and not in combination with each other. Moreover, table 3 helped with the evaluation presented by table 4.

Table 4. Evaluation of measures' most relevant parameters for downstream migration

MEASURES	Fish mortality	Hydraulic conditions	Migration delay
Fish-friendly turbines (G2)	0.5	0	-2
Simple bypass entrance (G1) (S1) (F2)	0.5	-1	0
Electric, acoustic and light devices (F2)	1	0	1
Flow deflectors (N2)	-0.5	-2	-3
River engineering (N2)	1	1.5	-1
Floating structure (S2) (N2)	2	3	2
Inclined screen/ α-rack (G1) (G2) (F1)	2	2	2
Angled screen/ ß-rack (G1) (G2) (F1)	2	2.5	2

As already described in chapter 2, the present evaluation has been given solely on the basis of the case studies. The three parameters assessed are fish mortality, hydraulic conditions and migration delay. The scale ranges from -3 (maximum negative impact) to 3 (maximum positive impact) with 0 that refers to unaltered situations after the implementation of the measure.

Fish-friendly turbines have been rated with a 0.5 in regards of fish mortality and they have no impacts at all on the hydraulic conditions (0). The migration is delayed by the dam or weir, but it is also worsened by the absence of alternative routes. Mortality is still present when fish pass via the turbine route and it is not proven to be improved by this measure alone (Økland, et al., 2016).

The creation of bypass, without any guidance system or modification of the flow, has very minor impact on fish mortality (0.5), it worsens hydraulic conditions (-1) while it has no effects on the timing of the migration (0). If the flow remains unaltered salmon smolts will follow the main flow which leads to the turbines and only randomly can identify the entrance of the bypass (Larinier & Travade, 2002). For the same reason it is difficult that this measure can improve the migration delay since the findability of the passage is very low. The hydraulic conditions inside the bypass, without any measure to regulate them, would be ineffective and potentially dangerous (Geiger, Cuchet, & Rutschmann, 2018).

Behavioural techniques have little influence on the fish mortality (1) and the delay (1) while none on the hydraulic conditions.

Flow deflectors showed negative impacts for all the characteristics. The significant negative impact (-2) on the flow guiding the fish in the vicinity of the intakes' entrance resulted in high potential delay (-3) and possible effects on mortality (-0.5) (Szabo-Meszaros, et al., 2019).

The bank modifications and enlargement of the river width can alter the hydraulic conditions (1.5) in order to guide the flow where needed. The migrating fish have potential benefit following the main current in this scenario. The result is an improvement in mortality (1) even if the delay increases due to the normalization of the flow without the presence of a major current to be followed (-1) (Szabo-Meszaros, et al., 2019).

The floating structure showed optimal results decreasing the mortality (2) normally associated with turbines passage guiding the salmons towards a bypass or spillway gate. This measure reduces the delay efficiently guiding the smolts (2) (Vikström, 2016). Permeable structures also have very positive impacts on the flow (3) (Szabo-Meszaros, et al., 2019).

Inclined racks (α-racks) has been rated with a 2 for all parameters. Covering completely the intakes this measure provided excellent results depending on inclination and the distance between the bars (Geiger, Cuchet, & Rutschmann, 2018; Tomanova, et al., 2018).

The same applies to angled racks (ß-racks) depending on the angle to the flow and the bar clearance. Under certain arrangements (streamwise bars for example) this measure showed numerous benefits in regards of hydraulic conditions (2.5) (Szabo-Meszaros, et al., 2018).

4. Discussion of results

This thesis is methodologically a desk qualitative research, and, in this chapter, the results will be discussed and also compared with other studies that might support or contradict the findings. The discussion will follow the structure of chapter 3. In order to investigate the most appropriate measure to improve the downstream migration of Atlantic salmon (*Salmo salar*) in regulated rivers a set of sub-question have been formulated at the beginning of this work and they will be used as a guideline.

In the first section of the results (3.1) the number, location and category of each publication about downstream migration of salmons during the past 38 years has been mapped using data from the database of the platform "Web of Science". The high number of publications from US and Canada (50% combined) can be explained by the presence of numerous important salmon rivers, the more dynamic availability of budget for research and by the diversity of the species. In fact, in North

America research has not been performed only on Atlantic salmon (*Salmo salar*) but on other species of the genus Oncorhynchus (commonly called Pacific salmon) such as Chinook salmon (*Oncorhynchus tshawytscha*), Coho salmon (*Oncorhynchus kisutch*), Chum salmon (*Oncorhynchus keta*), Sockeye salmon (*Oncorhynchus nerka*) and Pink salmon (*Oncorhynchus gorbuscha*) (Weitkamp, Goulette, Hawkes, O'Malley, & Lipsky, 2014). In this part of the world these fish species have been historically very important for their cultural, economic and ecosystem values (Jordan, O'Higgins, & Dittmar, 2012).

In Scandinavia, where the social and economic value of Atlantic salmon is also very high, the interest for improving the downstream migration and allowing restoration of ancient salmon populations is growing also at governmental level as demonstrated by the implementation of laws such as the National Fish Passage Strategy in Finland (Ministry of Agriculture and Forestry of Finland, s.d.).

One of the encouraging findings is that the large gap between upstream and downstream migration facilities seems to get smaller in the recent years considered the increase in publication and interest paid by researchers (Web of Science, s.d.). The objective of this thesis seems to be in line with the direction where the scientific community and governmental policy makers are going

The second part of the results (3.2) aims at finding out what are the migratory needs of Atlantic salmon and how they are influenced by the barriers that support hydropower production. The collection of numerous publications that have tested several measures to improve these fish requirements in their downstream migration have been analysed and compared.

The most relevant factors for the overall survival of the fish are the speed of the migration and the mortality (Huusko, 2018). Crucial for survival is also the cumulative effect of the number of obstacles to pass along the river before reaching the sea (Travade & Larinier, 2006). The speed is very important due to the increase in predation when the process is slowed down, and other fish or avian fauna can have favourable conditions to predate on the migratory smolts. Not only the presence of the obstacle but also the reduced flow velocity that drives the migration route can be lost in the impoundment upstream of a dam, which is another element that affects the delay. In addition, huge behavioural impacts have been assessed by Huusko (2018) on river Kemijoki, in Finland, where smolts were reluctant to go through the intake of the second power plant after surviving the first one. They spent more time in the forebay of the second dam compared to the first one, before taking the decision to pass again through the turbines due to the lack of alternative routes (Huusko, 2018). This is an example of how barriers create migration delay, and, in some cases, the result can be the complete loss of migration urge (Nyqvist, 2016).

The evaluation table presented by this thesis (table 4 in 3.3) provides qualitative orientation for adaptable measures but the transferability and replicability to other sites it is not always suitable. In other words, the evaluation is strongly case-specific, and it needs to be examined with respect to the local biotic and abiotic factors prior implementation. Often only a single kind of measure is assessed within a research and not many publications tried to compare all the mitigation measures available to date that could improve the downstream migration of Atlantic salmon.

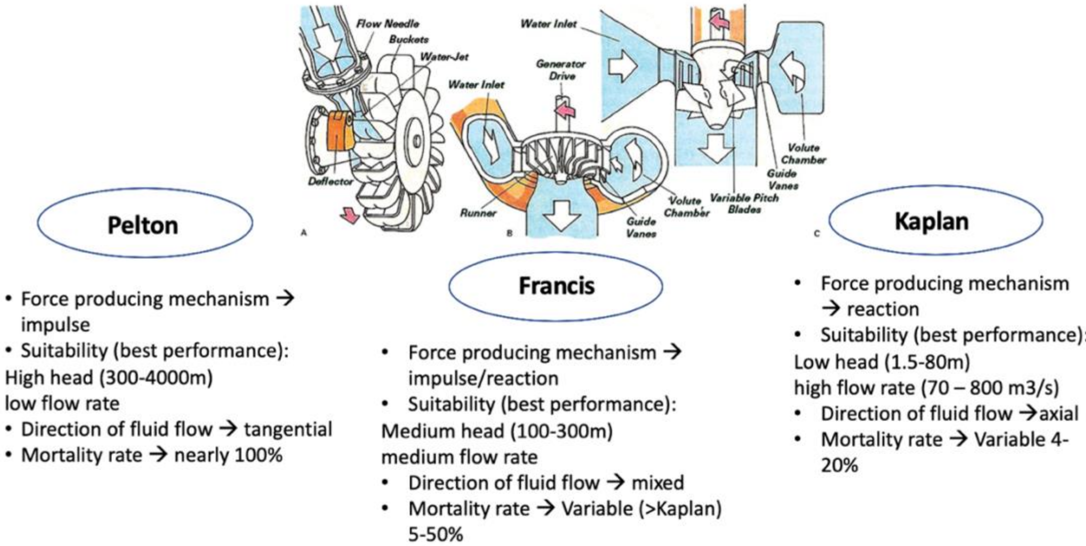

Figure 21.Characteristics of the three most common turbines used for hydropower production (adapted from Pumpsandsystems.com using data from energy.gov, s.d.)

Fish-friendly turbines and simple bypass entrance have been assessed alone while the rest of the measures are guidance techniques and therefore assessed in association with a bypass or spillway. Turbine passage presents itself a high risk of direct and indirect mortality. Mortality depends on variables such as the turbine type, the speed at which they are operated, the head and the size of the fish (Larinier & Travade, 2002).

Figure 21 describes briefly the differences between the three types of turbines most commonly used for hydropower production: Pelton, Francis and Kaplan. Pelton turbines are the worst for fish to go through being lethal in most of the cases. Mortality rates are the lowest in power plants fitted with Kaplan turbines and similar values for some Francis turbines (Cada, 2001). Normally Kaplan operates with lower heads compared to Francis and this explains the reason why mortality rates are generally the lowest (especially for observation on small-sized fish). A possibility of blade strike can increase up to 100% mortality rate depending on the fish length. Moreover, the susceptibility to barotrauma depends on the species, the type of swim bladder and the different abilities to fill it, the pressure exposure and several additional factors (Hogan, Cada, & Amaral, 2014). It is really difficult to establish the cause of death of the fish and the precise stage at which it occurs because researchers cannot observe what happens inside the turbines but only the number of fish tracked with telemetry studies after the passage or predict it with the help of modelling with computational fluid dynamics (CFD) (Cada, 2001).

Archimedes screw turbines (figure 22) are considered fish-friendly turbines, or rather turbines that are thought to be more sensible to aquatic wildlife. In the case study G1 (Økland, et al., 2016) fish-friendly turbines operate with low head (3.2 m for the movable Kaplan bulb turbine and 2.6 m for the Archimedes screw turbine) and this is the major restriction for these types of turbines which represents a clear disadvantage since they can only fit a relatively small number of sites.

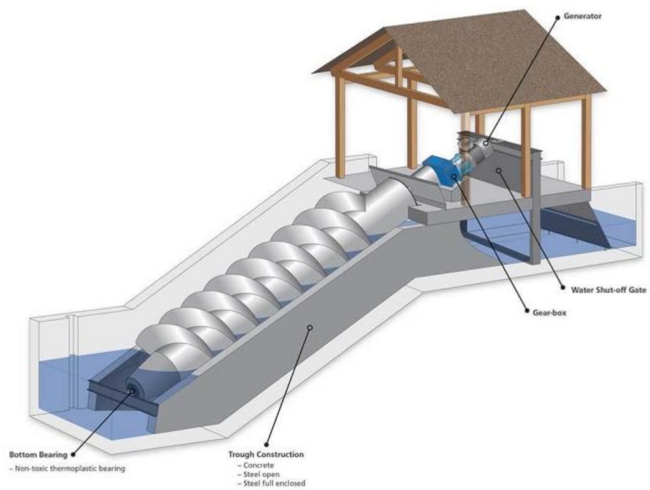

Figure 22. Archimedes screw turbine (MicroPico Systems Ltd., s.d.)

Furthermore, the results are controversial and do not show significant reduction of fish mortality and migration delay (Økland, et al., 2016) while the consulting and engineers' reviews claim 90 to 100% survival rate for all species using MGR, Alden, VLH and Archimedes turbines. Additional precautions are turbines larger in size with minimal gap between the runners that aim at a reduction of the velocities (Amaral, 2017). Retrofitting project are always very costly (Fjeldstad, Pulg, & Forseth, 2018) especially for large power plants where replace a Francis turbine with an Archimedes screw turbine would be completely unfeasible. This thesis will not dive deeper into engineering technicalities but instead conclude that this measure alone is not enough to guarantee a safe two-way migration in regulated rivers.
Salmons, like other species of fish, follow the strongest uniform current which normally leads to the turbine's intakes. Where the turbine routes can be avoided, fish should be given the possibility to have a safer way to continue their migration and that is why many stations have been retrofitted with bypass solutions. In some cases, bypasses are tailored for the purpose and in other facilities they work in combination with existing spill-gates or upstream migration facilities. Fundamental factors that influence the effectiveness of the measure are the findability, the position and number of the entrances (surface or bottom), the hydraulic conditions at the entrance and in the bypass itself (discharge, velocities, accelerations, depth) (Travade & Larinier, 2006; Larinier & Travade, 2002).
It is true that salmonids prefer surface bypass entrance but when compared with all the other species near bottom bypasses provide a wider range of preferences (Geiger, Cuchet, & Rutschmann, 2018). The decision where to place the entrance, as well as all the other parameters, needs to be supported with an assessment on local aquatic fauna for each site and chosen accordingly depending on the species present, flow conditions, regime of the river, size of the barrier and of the powerplant.
Some bypass design includes a fish collection trap, but fish capture and transport are classified as inefficient because of the complicate and very technical operations (Larinier & Travade, 2002).

Bypass alone are not a viable solution and they need the support of a system that guide the flow and the migrating fish towards the entrances. The following guidance measures are all evaluated in combination with a bypass of any kind. They can be divided in behavioural and physical solutions, but it can be difficult in some occasions to distinguish the characteristics of one from the other since every physical structure also have effects on fish behaviour.
Behavioural techniques include electric, acoustic, light and hydrodynamic (or louvers) screens. They can guide the fish towards the entrance of the bypass or repel it from the turbine's intakes.
Electricity screens tested in France showed 15% mean in efficiency (Larinier & Travade, 2002). Results from experiments using repellent sound barriers are very variable. Species of fish have different reception to sound frequency as some are sensitive to high-frequency (*Clupeidae* for example) while low-frequency (less than 3kHz) are effective on a wider range of species (Salmonids are sensitive until 50 Hz). An additional problem is the discrepancy between night and day results, with efficiencies of only 30% in experiments conducted in the UK (Whelton, Beaumont, Ladle, & Masters, 1997). Another system called BAFF (Bio-Acoustic Fish Fence) which combines sound and air-bubbles pulsating 3 times per second was tested in France with virtually no efficiency (< 1%) (Travade & Larinier, 2006). Strobe lights repulse fish but also for this technique result did not show very interesting outcome for salmonids fish. Variation with different species has been noted. Only tests performed on eels (*Anguilla anguilla*) seemed to respond well to continuous stimuli from stroboscopic lamps in order to divert them towards a near-bottom bypass (Larinier & Travade, 2002; Hadderingh, Van der stoep, & Hagraken, 1992). Mercury vapor lamps (50 – 80 W) are thought to attract fish and therefore they have been tested in 5 locations in France between 1991 and 2005. The first attempts were made using the light intermittently and then with constant illumination. It is found very efficient during the night in one location reaching 99% efficiency (Travade & Larinier, 2006) but during the day it arguably provided any behavioural response.
Among the advantages there is for sure the management that is reduced to the minimum since nothing needs to be cleaned from debris accumulation. Unfortunately, in field researches they have not shown the same good results demonstrated in controlled conditions in laboratory tests. Behavioural screens bring up several opportunities, but they do not seem sufficient to provide a reliable instrument for safe downstream migration of Atlantic salmon.
It is known that migrating smolts follow the main current which normally leads to the turbines. At most of the sites the main flow is directed towards the turbine's intake. Flow deflectors (spurs) and river engineering (river banks or main channel modification) are measures focused only on the alteration of the flow to guide fish.
Trapezoidal spurs placed upstream of the intake entrance on both banks aim at joining the major currents into one single major flow, but results did not produce a favourable outcome. Different combinations of conditions have been tested in the model (low and high water, discharge into different spillway gates) but the outcome was in general a negative effect on the migration. The smolts that would have been swimming in a portion of the river that previously was modelled as

safe, after the implementation of this measure they will have more chance to end up in front of the turbine intake (Szabo-Meszaros, et al., 2019).

Another solution recently investigated by Szabo-Meszaros, et al (2019) was the possibility of normalizing the velocities in the river channel through modification of the river banks and evaluate the effects using Computational Fluid Dynamics (CFD) models. The effect was the one desired in this case: more uniform velocities. Even if in this way the main flow does not lead to the intakes, the impact on migrating smolts is not fully certain since the findability of the bypass or spillway might be more difficult without a leading flow to follow. In this case there is the possibility of migration delay. This measure has restricted application since the possibility to perform extensive works on the banks or in the river channel to divert and uniformize the flow is not always possible. The modification of the curvature of the river and river engineering in general is a flow alteration measure that would need further investigation since no other example have been found in literature. Floating structures are innovative techniques that combine the effectiveness of physical barriers and a significant influence on the flow with a wide range of adaptability. These structures can be permeable (rack-type) or impermeable (solid-type) (Szabo-Meszaros, et al., 2019). Vikström (2016) demonstrated an efficiency of 85% testing a solid-type floating structure in Sikfors (Sweden) covering almost all the area of the intake. This research was performed on the field with tagged released smolts while Szabo-Meszaros et al. (2019) tested two types of floating booms using CFD simulations. Even if what could be observed with the latter study was just the changes in flow and velocities many conclusions can be inferred since it is well known the effect of flow on small juvenile fish. The guidance structure is designed to guide the salmons that normally prefer the upper portion of the water column (0.5 m from the surface). The structure studied are, in fact, 1 to 2 meters deep. Regarding the discharge conditions at which floating booms function at best the solid type of structures gave opposite results. In Sweden highest survival of smolts was observed at LQ (less than 100 m^3/s) (Vikström, 2016) while in the Norwegian study the most effective and continuous flow was generated at HQ. The simulation model showed that the flow is better directed towards the spillway when discharge is high (Szabo-Meszaros, et al., 2019) but in flooding conditions the disadvantage of this measure could be the fragility and the integrity of the booms might be prone to structural damages, becoming ineffective. In facilities where there are multiple spillway gates, CFD could be used beforehand to assess the different flow patterns. Based on the outcome the best combination could be implemented. Possible applications also on large rivers where other measures would be physically and economically unfeasible. In this case, as already discussed, validation is also needed in practice and not only with flow simulations. The rack-type permeable structure with horizontal bars was the most promising for fish guidance reducing the migration delay and for flow effects (Szabo-Meszaros, et al., 2019).

The last two measures to be discussed are inclined (α-rack) and angled (ß-rack) racks and are clearly illustrated in figure 20. If trash racks are just placed horizontally or vertically in front of the intakes to protect the turbines from debris with no consideration of flow velocities, the risk of fish injuries is very high (impingement).

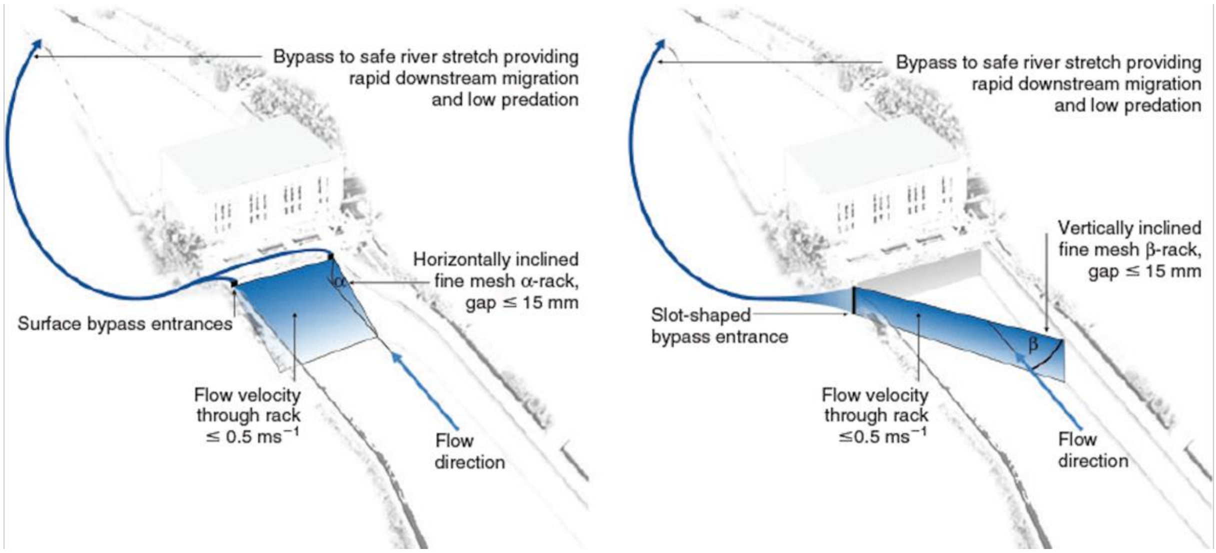

Figure 23. Inclined and angled racks with associated bypasses (Fjeldstad, Pulg, & Forseth, 2018)

The difference in bar spacing, bar shape and the angle of the racks are investigated. The bar spacing seems to be the less controversial where in most of the cases falls under the recommendation of 15-20mm gap (Geiger, Cuchet, & Rutschmann, 2018; Szabo-Meszaros, et al., 2018). Some papers suggested even shorter distance between the bars (1/10 of the fish length) (Travade & Larinier, 2006) but as it depends on the type of fish migrating in that particular river it should be decided after monitoring studies. Tangential velocities are created by the racks depending on the angle of orientation to the flow (Larinier & Travade, 2002). It is possible to adjust the bar clearance and the inclination of the rack to achieve the recommended flow velocity at the bypass entrance of 0.5 m/s (Fjeldstad, Pulg, & Forseth, 2018; Nyqvist, et al., 2017) which in return will improve the ecological potential of the system increasing significantly the passage performance (Geiger, Cuchet, & Rutschmann, 2018).

Horizontally inclined screens are efficient only below 45° of inclination. The fish guidance increases in inclined trash-racks by decreasing the angle (until the recommended 26°) and the gap between the bars (15-20mm) (Geiger, Cuchet, & Rutschmann, 2018). On the other hand, lowering the bar clearance might have negative impacts on hydro power production. Horizontally inclined racks have another limitation. The structures showed better applications in lower depth headrace (the portion of the river right before the intakes) and seems to be unfeasible at large sites.

Angled ß racks have been tested with multiple configurations. In order to avoid confusion, the “horizontal trash-racks” tested by Szabo-Meszaros, et al. (2018) refer to the bars’ set-up only and it does not need to be mistaken with the horizontally inclined racks (α-type). Multiple types of bar configurations have been studied but they all fall under three categories: vertical-angled, vertical streamwise and horizontal. The shaped of the bars can be rectangular and hydrodynamic and the latter is preferred due to its minimal effects on power production and creation of turbulence (Szabo-Meszaros, et al., 2018).

Figure 24. Inclined rack, angled rack with perpendicular bars and angled rack with streamwise bars investigated in laboratory conditions (Raynal, Chatellier, Courret, Larinier, & David, 2015)

The interference with energy production caused by the inclination or angle of the racks and the gap between the bars must be considered in detail. Raynal, Chatellier, Courret, Larinier & David (2015) compared various equation to find out how to calculate head losses in different configuration (150 different combinations). Taking in account more parameters with equations not adopted in previous studies, they found out that angled trash-racks with streamwise bars give the best results in terms of head losses. Horizontally inclined trash-racks gave similar results but angled trash-racks with perpendicular bars (not streamwise) generate five times more head loss. Another advantage for streamwise bars is that the total number of bars needed is way lower than perpendicular bars and the total bar length is estimated in less than half compared to the other 2 configurations. These findings are in line with the observations of the group of scientists (Beck, Meister, Fuchs, Albayrak, & Boes, 2019) that commented the publication of Szabo-Meszaros et al. (2018). Maintenance of the streamwise bar is not as advanced as it is for vertical-angled bars and it might be listed among the disadvantages of this measure. Eicher screens are a possible design that could solve the problem of debris accumulation. This type of screen rotates on an axle giving to this measure the advantage to be almost fully self-cleaning. They have been designed to be fitted inside intakes or penstocks (they need a protective trash-rack upstream for larger debris) and they can operate also at high approaching velocities (Larinier & Travade, 2002).

5. Conclusions and recommendations

The aim of the thesis was to evaluate the best solution for Atlantic salmon in harnessed rivers and to collect enough experiences from Europe to minimize duplication efforts in the future. The best-practice guidelines given by this report could be taken in consideration when new projects are proposed. These projects include new dams and weirs, retrofitting fish guidance devices at existing barriers or modernization of measures already present.
In North America the research about downstream migration of Atlantic salmon (*Salmo salar*) is at a more advanced stage, but in recent years the attention in Europe (especially in Scandinavia) is steadily increasing. It has been acknowledged that a two-way migration is necessary, and it cannot be supported only with the infrastructures built for upstream migration. Migratory species like the Atlantic salmon need a safe two-way migration also in regulated rivers in order to fulfil their life cycle and, therefore, it is necessary to know what requirements are needed by this species.
Literature review was performed to identify how the most important requirements of migrating salmons have been assessed by researchers and which measures have been proposed to improve the downstream migration of these species. Studying and adopting a combination of mitigation measures will partially rehabilitate the longitudinal connectivity, needed by migratory fish species, lost with the construction of barriers that is needed by migratory fish species.
The analysis of eight representative case studies from four countries in Europe found eight measures to be assessed and evaluated. The evaluation has been based on three fundamental parameters: mortality, migration delay and hydraulic conditions.
A single most appropriate solution for every facility is not realistic since the variables at each site can only be considered independently but the river must be always examined as a whole catchment taking into account the cumulative effects of multiple barriers. CFD simulations (Computational Fluid Dynamics) can be coupled with telemetry studies to produce models for a better assessment of the techniques proposed by this thesis. This method can simulate the impact of the selected measures on the flow and therefore to predict the possible routes of migratory fish. As the effects on flow dynamics influence greatly the behaviour and swimming abilities of fish (Szabo-Meszaros, et al., 2018) it is a must to study the hydraulic conditions created at the entrance of the bypass facilities. Turbulent flow characteristics can also be examined in order to create efficient bypasses for small fish such as salmon smolts. Moreover, to design the best solution at each site should be considered also economic requirements. Head-losses and maintenance are the typical issues that will be raised when downstream migration solutions are proposed (Szabo-Meszaros, et al., 2018).

Finally, as a general guideline based on the evaluation of the measure presented by this thesis, the most appropriate application to start the investigation at small hydropower plants sites are horizontally inclined racks (ß=<30°) combined with a surface bypass and vertically angled racks (α=30°) together with streamwise bars combined with multiple bypass entrances for larger HPP. Permeable floating structures and flow alteration measures such as river bank modifications need to be taken in consideration to increase the efficiency. Following CFD simulations will determine the optimal design for the investigated measures in accordance with the conditions of the selected site.

In conclusion, river management needs to be approached in a way that dams and their impoundments are considered among the major causes of the disruption of longitudinal connectivity in riverine ecosystems. Water authorities and decision makers have the responsibility to impose higher standards from the hydropower sector and the competent authority should enforce laws that are already existent. Common standards and guidelines for a two-way fish migration need to be implemented instead of continuing to subsidize the construction of new small hydropower plants in the name of a shift towards renewables.

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Appendix 1

Publications/year data

YEAR	PAPERS/YEAR
1981	1
1982	1
1983	0
1984	0
1985	2
1986	0
1987	1
1988	1
1989	0
1990	2
1991	9
1992	6
1993	7
1994	12
1995	8
1996	7
1997	7
1998	20
1999	21
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2005	29
2006	23
2007	25
2008	37
2009	22
2010	24
2011	29
2012	38
2013	44
2014	50
2015	36
2016	32
2017	32
2018	55
TOTAL	**665**

Publications/country data

COUNTRY	CODE	NUMBER OF PUBLISHED PAPERS	PERCENTAGE	
USA	US	291	42.17%	33.80%
Canada	CA	126	18.26%	14.63%
Norway	NO	71	10.29%	8.25%
England	UK (E)	56	8.12%	6.50%
Japan	JP	54	7.83%	6.27%
Sweden	SW	46	6.67%	5.34%
France	FR	33	4.78%	3.83%
Denmark	DK	32	4.64%	3.72%
Finland	FI	24	3.48%	2.79%
Russia	RU	21	3.04%	2.44%
Scotland	UK (S)	19	2.75%	2.21%
Australia	AU	16	2.32%	1.86%
Germany	DE	14	2.03%	1.63%
Belgium	BE	7	1.01%	0.81%
Portugal	PT	7	1.01%	0.81%
Estonia	EE	6	0.87%	0.70%
Brazil	BR	5	0.73%	0.58%
Ireland	IE	5	0.73%	0.58%
Netherlands	NL	5	0.73%	0.58%
New Zealand	NZ	5	0.73%	0.58%
North Ireland	UK (NI)	5	0.73%	0.58%
Wales	UK (W)	4	0.58%	0.46%
Austria	AT	3	0.44%	0.35%
Czech Republic	CZ	3	0.44%	0.35%
China	CN	3	0.44%	0.35%
TOT		**861**		

Publications/category data

CATEGORIES	RECORD COUNT	PERCENTAGE
Fisheries	382	55.36%
Marine freshwater biology	307	44.49%
Ecology	115	16.67%
Environmental Sciences	91	13.19%
Water Resources	48	6.96%
Zoology	26	3.77%
Biodiversity conservation	21	3.04%
Oceanography	20	2.90%
Engeneering Environmental	19	2.75%
Multidisciplinary Sciences	18	2.61%
Limnology	15	2.17%
Biochemistry molecular biology	12	1.74%
Biology	12	1.74%
Endocrinology metabolism	8	1.16%
Evolutionary Biology	8	1.16%
Physiology	8	1.16%
Genetics heredity	6	0.87%
Geosciences multidisciplinary	6	0.87%
Veterinary Sciences	6	0.87%
Behavioural Sciences	5	0.73%
Geography physical	5	0.73%
Toxicology	4	0.58%
Mathematical computational biology	3	0.44%
Statistics probability	3	0.44%
Developmental Biology	2	0.29%
TOT	**1150**	