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Reconstruction of a pool-and-weir fishway to a vertical slot hybrid fishway in the inland river Glomma – effects on upstream migration of European grayling *(Thymallus thymallus)* and brown trout *(Salmo trutta).*

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Preface

This master thesis is written at the Faculty of Environmental Sciences and Natural Resource Management (MINA) at the Norwegian University of Life Sciences (NMBU) during 2017. The thesis weighs 60 ECTS and is a part of my master's degree in Natural Resource Management. This thesis is a part of the SAFEPASS-project, a four year research project led by Norwegian Institute for Nature Research (NINA). The aim of the project is to find the best solutions for fish migration in regulated rivers.

I would like to thank Thrond Haugen, my main supervisor, for careful and good guidance. He has helped me with the statistical work and to structure and keep the direction of the paper through draft readings. I would also like to thank my co-supervisor, Jon Museth, for suggestions, input through draft reading and help with the design of the thesis. He also helped me gain knowledge about the conditions in the study area. I thank Trond Taugbøl (Eidsiva Vannkraft) for providing the data on fish migration from the VAKI fish counter, and water discharge and spillway operation at the Høyegga dam. He has also answered many questions about the operation of the fishway. Finally, I would like to thank everyone who works at NINA Lillehammer. You have been including and provided me with a good working environment during the last months.

The thesis is written as a report because it contains many aspects that make an overview and clear structure appropriate. Some of the data needs further explanation, and it is important that it is clear on what basis the conclusions are drawn.

By examining the effects of reconstruction of a specific fishway, I hope my thesis, can contribute to find better solutions for future fishway projects.

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NMBU Norges miljø- og biovitenskapelige universitet

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Sammendrag

Det er godt dokumentert at installasjoner i vassdrag kan ha store negative konsekvenser på ulike fiskearter og deres habitater. Demninger kan blokkere og forsinke migrasjon, samt endre den romlige fordeling av individer. Fisketrapper blir ofte implementert for å opprettholde biologisk kontinuitet og forhindre fragmentering av habitater, men problemet er at mange fisketrapper ikke fungerer tilfredsstillende. Dette kan føre til reduserte bestander og lokal utryddelse av enkeltarter. Målet med denne studien var å undersøke hvilke effekter ombyggingen av fisketrappen ved Høyeggadammen i Glomma hadde for oppvandrende harr (*Thymallus thymallus*) og ørret (*Salmo trutta*). Fisketrappen ble ombygget i 2016, fra en kulpetrapp til en hybrid spaltetrapp med naturlig substrat i hvert kammer. Spaltetrapper har ofte lavere vannhastighet og turbulens, samt kan takle større vannstandsendringer bedre enn kulpetrapp-utformingen. Spalten går helt ned til bunnen av hvert kammer og gir fisken mulighet til å svømme opp eller ned uten å hoppe mellom kammerene. Viktigheten av disse faktorene har blitt belyst i tidligere studier på lokaliteter med høy diversitet i artssammensetning.

Datasettet som ble brukt i denne studien er basert på registreringer av oppvandrende fisk i fisketrappen. En VAKI fisketeller har registrert fisk i trappen, og inneholder registreringer to år før (2014 & 2015) og to år etter (2016 & 2017) ombyggingen. Antall registrerte oppvandrende fisk økte med totalt 76.5% etter ombyggingen. Det var også signifikant endring i artssammensetning blant de registrerte individene. En zero-inflated Poisson modell ble tilpasset vandringsdataene og brukt for å kvantifisere hvilke effekter miljøfaktorer og ombyggingen hadde på oppvandrende harr og ørret. Estimatene fra modellen predikterte at oppvandring hos harr var favorisert av lavere vannføringer sammenlignet med ørret. Ørretens oppvandring viste seg å være mer avhengig av temperatur. Det er imidlertid for tidlig å konkludere med at ombyggingen av fisketrappen ved Høyeggadammen er grunnen til økt antall oppvandrende fisk. Modellene peker allikevel på en klart økende tendens for oppvandring hos harr for en gitt temperatur og vannføring etter ombygging. Økningen i antall registrerte arter indikerer også at ombyggingen har ført til positive endringer. Denne studien illustrerer at ombygging kan være et mulig tiltak for å forbedre mange av dagens eksisterende fisketrapper. Lignende ombygginger burde bli gjennomført og overvåket andre steder for å øke kunnskapsgrunnlaget. Et slikt tiltak vil sannsynligvis også øke funksjonaliteten og være en kostnadseffektiv endring sammenlignet med konstruering og installasjon av en helt ny fisketrapp.

Summary

It is well documented that man-made barriers in rivers can have severe negative effects on numerous fish species and their ecology. Obstructions can block and delay fish migrations, which may be critical for the life cycle and spatial distribution of many fish species. Fishways are one of the most used measures to maintain biological connectivity at artificial barriers in rivers. However, fishways often show poor functionality, which can result in fragmented and declining populations or even local extinctions. The aim of this study was to investigate the effects of a reconstruction of the fishway at the Høyegga dam in the inland river Glomma, Norway, on upstream migration of grayling (*Thymallus thymallus*) and brown trout (*Salmo trutta*). The fishway was reconstructed in 2016 from a pool-and-weir type to a vertical slot hybrid design. The vertical slot design often has lower velocity and turbulence levels, and are generally more suited to handle a broader range of discharges, compared to the pool-and-weir fishway design. The vertical slot type also allows the fish to pass the fishway by swimming close to the bottom to ascend the fishway. Previous studies have shown that these factors can be of great importance at locations with complex species composition.

The dataset in this study is based on automatically registrations of upstream migratory fish individuals collected by a VAKI Riverwatcher fish counter placed in the fishway. The two years prior to reconstruction (2014 & 2015) and the two years after reconstruction (2016 & 2017) are included in the data analysis. After the reconstruction, the number of upstream migratory individuals increased with 76.5% in total. It was also found a significant change in the species composition among registered individuals. To predict impact of external factors and the fishway reconstruction on upstream migration of grayling and brown trout, a zero-inflated Poisson model was used. Grayling and brown trout migration intensity were predicted to increase with higher temperature, and grayling was more dependent on low river discharges compared to brown trout. It is too early to state that the reconstruction of the fishway at Høyegga led to increased numbers of upstream migration of grayling and brown trout. It was, however, a clear tendency that larger numbers of grayling ascended the fishway after reconstruction for any given temperature and water discharge. The increased number of species registered, also indicates that the reconstruction led to some positive changes. This study illustrates that redesigns can have great potential for improving many of today's pool-and-weir fishways. Similar measures should be undertaken elsewhere to increase the knowledge about this method, as this is a cost-efficient measure compared to construction of a brand new fishway.

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1. Introduction

There are more than 37.000 dams higher than 15 meters in the world. Over 8000 of them are designed specifically for hydropower, which is the renewable energy source that has the greatest growth in the world (Hirsch et al. 2017; Zarfl et al. 2015). It is well documented that man-made barriers such as dams, culverts and weirs may have negative impacts on numerous fish species and their ecology (Castro-Santos & Haro 2010; Clay 1995; Dadswell 1996; Fjeldstad et al. 2012; Katopodis & Williams 2012; Linløkken 1993; Nilsson et al. 2005; Rodríguez et al. 2006; Schilt 2007; Ward 1989). Artificial obstructions can change and in worst case block for the fish's ability to migrate[1] past barriers, which can lead to declining populations or local extinction (Clay 1995). Fish migrate for several reasons, e.g. spawning, feeding, seeking refuge from predators or environmental conditions (Linløkken 1993; Northcote 1984; Tack 1980), and is of great importance regarding spatial distribution of fish populations (Zitek et al. 2004). This emphasizes the importance for well-functioning fishways that maintain connectivity between habitats for migratory fish species (Clay 1995; Katopodis 1992). Fishway, fish ladder, fish stairs, fish passage and fish bypass are all common terms for the same concept. Katopodis (1992) defines it as; "A fishway is a waterway designed to allow the passage of a species or a number of different species of fish past a particular obstruction". Hereafter, "fishway" will be used to describe this type of construction.

Fishways have been widely used as a measure to mitigate and prevent negative impacts of man-made obstacles in rivers, including hydro-power constructions. Multiple different fishway designs have been developed, but today the vertical slot, pool-and-weir and denil designs are the most common (Figure 1) (Katopodis 1992).

[1] Migration can be defined as individual alternations between habitats, often by annual events, or at least through the species life cycle. It should also involve a large fraction of the population (Northcote 1984).

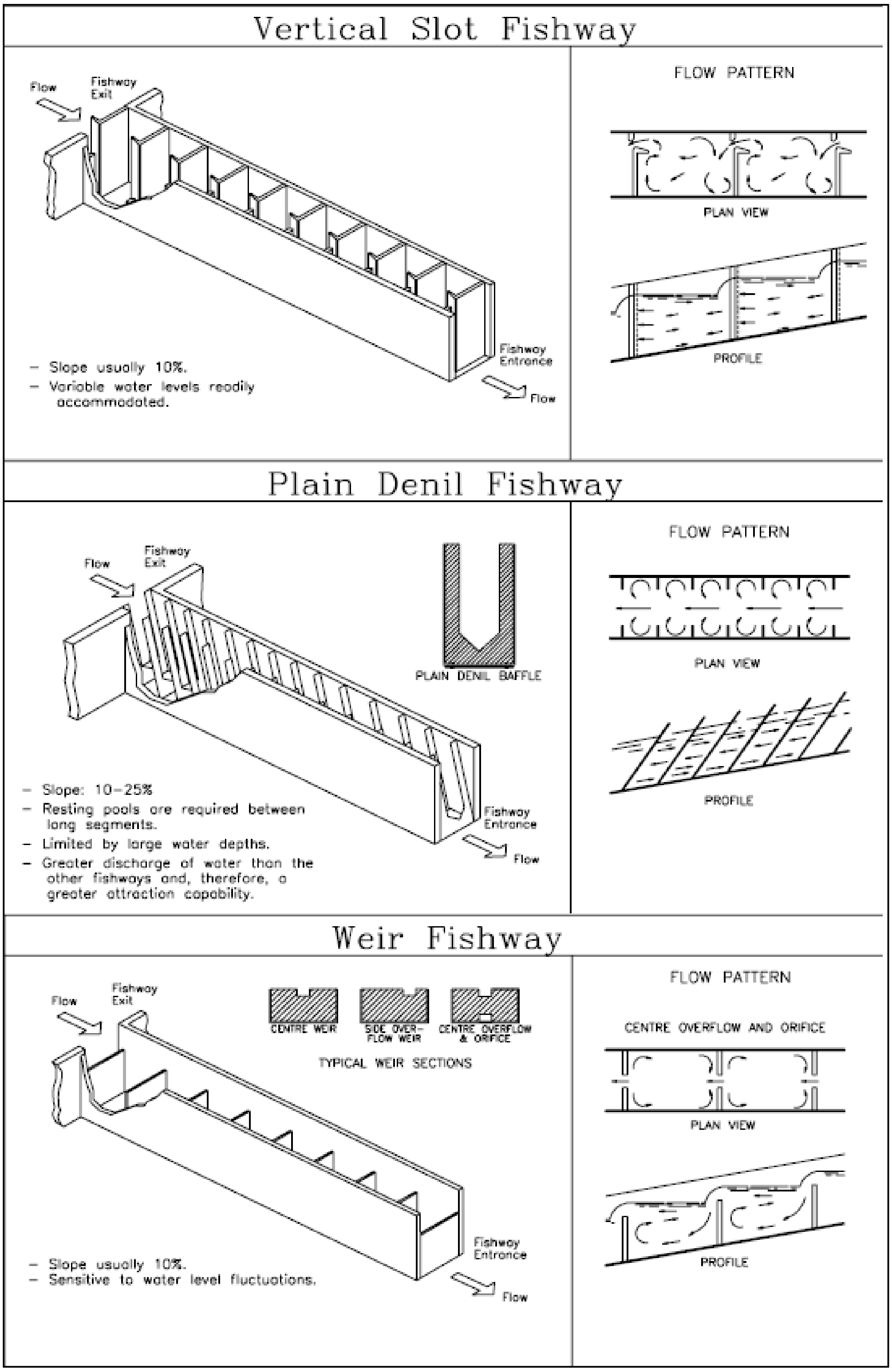

Figure 1 - *Todays most common fishway designs (Katopodis 1992). Real construction may differ from the figure, but the main characteristics of each design are general.*

Long-term studies and monitoring of fishways around the world have improved baseline knowledge about fishway use (Mallen-Cooper & Brand 2007; Qvenild 2001; Rivinoja et al. 2001; Roscoe & Hinch 2010; Silva et al. 2017). Together with an increased focus on river connectivity and restoration of natural habitats (Katopodis 2005), this has provided valuable and important knowledge for future constructions and redesign projects. However, more than 300 years of research and experience leaves no guarantee for constructing efficient fishways today. The fishways constructed in Galway, Ireland in 1853, and the one in Ballisodare, Ireland in 1856, were both designed for Atlantic salmon (*Salmo salar*), and are good examples of early constructed fishways that functioned in a satisfactory way (Lindberg 2011). However, Rivinoja et al. (2001) found that one of the fishways in the Swedish river Umeälven did not function satisfactory, even though it was constructed approximately 100 years later and targeting the same species. Aarestrup et al. (2003) and Caudill et al. (2007) are examples of other studies that demonstrate poor fishway functionality in recent time. Even if the passage facilities seem to work at many locations, several studies show fishways imposing migration delays (Gowans et al. 2003; Thorstad et al. 2003).

Earlier the focus on designing fishways in Norway was largely on economical valued species such as different salmonid species. North America and Europe where both early in the implementations of fishways in rivers were salmon were present (Clay 1995; Katopodis & Williams 2012). Many anadromous salmonid species have high swimming capacity and have evolved to handle tough flow conditions and natural barriers like waterfalls and strong riffles (Bjornn & Reiser 1991; Lindberg 2011). The capacity of other fish species to cope with fishways is less studied, and several species have through time suffered at many locations because of unsuitable fishway design (Katopodis & Williams 2012; Stuart & Mallen-Cooper 1999; Stuart et al. 2008). Main design, flow velocities, entrance location, resting pools, length and gradients are all important variables to consider when planning and constructing a fishway (Katopodis 1992; Stuart & Berghuis 2002; Stuart et al. 2008). Complex and species-rich fish communities require a broader understanding when it comes to fishway function and design, if the goal is to make a passable structure for all species present (Bunt 2001; Clay 1995; Mallen-Cooper & Brand 2007).

Previous findings emphasize that even with many years of development, research and deployment of fishways all over the world, there is still need for a better understanding of the effects of these structures. Because of great variation among locations, both in terms of different landscape characters and fish species composition, total generalisations of fishway designs are impossible (Katopodis 1992). Each construction should be designed for the particular location in order to secure desired results (Roscoe & Hinch 2010).

In Norway, Atlantic salmon has attained the largest focus when it comes to construction of fishways (Grande 2010). More recently, the focus has shifted towards preserving populations and strengthening them as their habitats have been fragmented due to human activity, in particular, hydropower constructions (Clay 1995; Direktoratet for Naturforvaltning 2002; Fjeldstad et al. 2013; Fjeldstad et al. 2012). To mitigate the negative impacts from hydropower dams, fishways have been constructed simultaneously or after the dams are built. However, many of them are old constructions and do not work satisfactory, largely due to design using Atlantic salmon as target species (Direktoratet for Naturforvaltning 1990; Fjeldstad et al. 2013; Grande 2010). Inland fishway constructions are largely based on knowledge concerning Atlantic salmon's ability to use fishways, also in fish communities with other fish species. As a result the most common fishway design in Norway comprise the pool-and-weir type (Direktoratet for Naturforvaltning 2002; Fjeldstad et al. 2013; Grande 2010). This design has often been shown to be well-functioning for Atlantic salmon (Fjeldstad et al. 2013), however, other species with other characteristics may face passage problems due to unsuited hydrological properties (Kraabøl & Nashoug 2010; Mallen-Cooper & Brand 2007; Petts 1984).

The river Glomma is the most fish species rich river system in Norway, with 29 different species present in the lower parts and seven species present in the upper reaches (Huitfeldt-Kaas 1918; Qvenild 2008). It is also Norway's longest river with its approximately 610 km length, running through four counties from lake Aursunden to the river mouth in Fredrikstad (Qvenild 2001; Qvenild 2008). Today, Glomma is heavily regulated and fragmented with multiple dams, mostly designed for hydropower. Prior to dam constructions, migrating fish species had the opportunity to migrate up and down most of the river (Kraabøl & Museth 2007). The first man-made barrier in Glomma north of the river Vorma confluence, was the dam at Skjefstadfossen (60.83281º N, 11.61476º Ø). This dam was finished in 1910, but had no fishway, and was a complete barrier for 41 years before a fishway was installed (Kraabøl & Museth 2007). Today, Norwegian laws and regulations require the power industry to maintain biological functionality when installing a hydropower plant. This framework helps to prevent new episodes like the one in Skjefstadfossen. Fishways are one of the main measures to be implemented when building hydropower constructions (Direktoratet for Naturforvaltning 2011).

Multiple dams mean multiple barriers, which can be unfortunate for brown trout (*Salmo trutta*) and European grayling (*Thymallus thymallus;* hereafter grayling) because of their long-distance migration (Linløkken 1993). As a part of the Glomma project[2], traps were installed in several fishways in 1985, including the fishway in Høyegga. The aim was to monitor the annual migration and the trends over time. All upstream migratory individuals were captured and tagged with Floy anchor tags. During the 22 years between 1985 and year 2006, 1526 brown trout and 9497 grayling individuals were registered in Høyegga (Qvenild 2001; Qvenild 2007; Taugbøl 2012). A few whitefish (*Coregonus lavaretus*) were also registered. Both the grayling and brown trout population showed an increase in use of the fishway over time in the period between 1985 – 2006 (Qvenild 2001; Qvenild 2007). Fish registrations continued in the manually operated trap after the Glomma project was finished in 2006. The mean number of registered grayling and brown trout in the period 2007-2012 were 384 and 105 individuals, respectively (Taugbøl 2012).

As mentioned, most of today's fishways are of the pool-and-weir type, which is a suboptimal design in many cases, especially at locations with a complex fish community. A possible measure

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[2] The Glomma project (1985-2007) was established by "Glommens and Laagens Brukseierforening" and K/L Opplandskraft with the aim to improve the recreational fishing value in Glomma. The project has led to knowledge about specific fishways, mortality, harvesting rates and migration patterns for grayling and brown trout in the Glomma river (Qvenild 2008).

to mitigate these challenges is to tear down the existing fishways and construct new ones. Rebuilding or modifying existing fishways, and thereby make them more suitable for a wider range of species, is another option. As a part of the ongoing SAFEPASS project, the fishway in Høyegga was reconstructed during the first half of 2016 with the aim to make it more suitable for the particular location and the species present. The fishway was reconstructed from a pool-and-weir type to a vertical slot hybrid with added substrate *(see chapter 2: Material & Methods for details)*. Vertical slot design has its origin from Fraser River in Canada, where great variations in discharges occurred (Katopodis & Williams 2012; Rodríguez et al. 2006). One of the advantages found in vertical slot design, is that it is able to handle a broader span of discharges and still be functional compared to the pool-and-weir and denil designs (Katopodis & Williams 2012).

Studies on the effects of rebuilding a fishway from pool-and-weir to vertical slot is limited. However, Stuart and Mallen-Cooper (1999) studied a reconstructed fishway in Fitzroy river, Queensland, Australia. The original fishway was a pool-and-weir type, but due to unsatisfactory function it was reconstructed two times. The new vertical slot design improved fish passage success, and numbers of species passing the fishway increased from 15 to 24 (Stuart & Mallen-Cooper 1999). Stuart and Berghuis (2002) also discovered enormous effects after rebuilding a fishway in Burnett River, Queensland Australia. They reduced the gradient from 10% to 6.3% by making the fishway longer and implemented vertical slots instead of the old weirs. Less turbulence, lower water velocities and the fish's opportunity to swim along the bottom were shown to be of importance. The numbers of fish ascending the fishway increased, smaller fish were able to pass as well as a broader number of species started to use the fishway after the reconstruction (Stuart & Berghuis 2002). Both studies were carried out in tropical/subtropical environments, but they show that adjustments can make fishways more effective and more suitable for a wider range of species in complex environments. There is a wide range of studies of fishways effectiveness in northern Europe, but the effects of modifications have attained little focus.

The aim of this study was to investigate the effects of reconstruction of the fishway at the Høyegga dam from a pool-and-weir type to a vertical slot hybrid design on the upstream migration of grayling and brown trout. More exactly, the main objective and research questions of this study are:

Main objective: Can a redesign from pool-and-weir to a vertical slot hybrid fishway increase the upstream migration of grayling and brown trout?

Research questions:

- Does the reconstruction change grayling and brown trout migration patterns in terms of "time of year" and "time of day"?
- How does discharge and temperature influence grayling and brown trout migration and has it been altered after reconstruction?
- Has the reconstruction of the fishway led to changes regarding fish size among registered individuals of grayling and brown trout?
- Does the reconstruction change the fishway use in other species than grayling and brown trout?
- Was the reconstruction successful in relation to general use of the fishway?

2. Material & Methods

2.1 Study site

Since 1910 there have been constructed several dams in the Glomma river system, one of them is Høyegga dam. The Høyegga dam (62.02043º N, 10.82188º Ø, Figure 2 and Figure 3) is located in the upper reaches of Glomma, approximately 14 km downstream of the community Alvdal, and has been in operation since 1971. The dam construction at Høyegga is made of concrete and measures 175 meters in length, 10 meters in height (Qvenild 2002) and has four different spillways where water can be released.

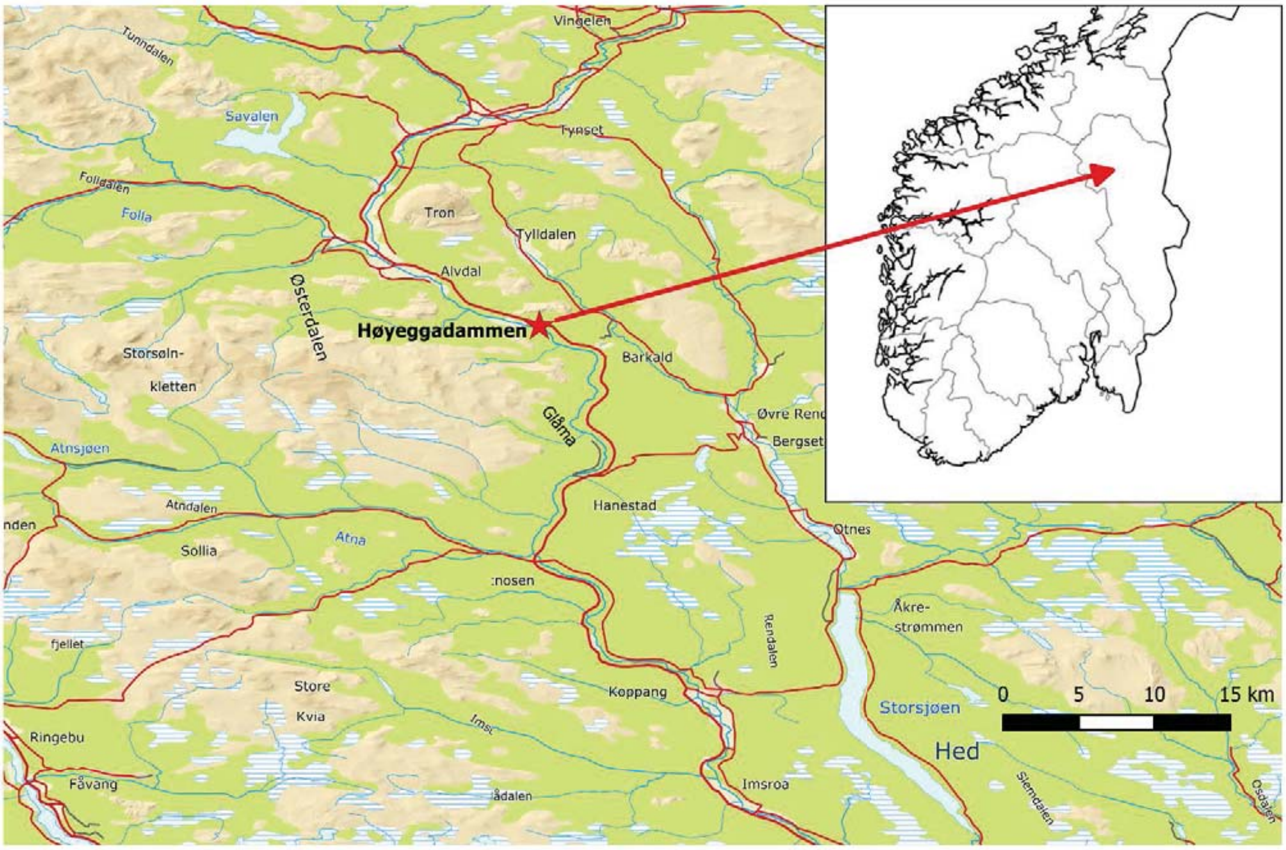


Figure 2 – *The Høyegga dam and fishway location relative to the southern part of Norway.*

Figure 3 – *Aerial photos of dam Høyegga with the fishway located on the east side of the river. The red dot shows the fishway entrance. The two pictures give an impression of how it looks like during low and high flow.* ***Upper:*** *The observed mean observed discharge this day was 33 m^3/s divided on to spillways. 15 m^3/s in the tap-spillway and 18 m^3/s in "flood-spillway 2". The picture was taken 29.09.2015 (Norgeibilder.no 2015).* ***Lower:*** *The observed mean discharge this day was 325 m^3/s divided on three spillways. 10m^3/s in the tap-spillway, 141 m^3/s in the "flood-spillway 1" and 175 m^3/s in "flood-spillway 2". The picture was taken 23.07.2013 (Norgeibilder.no 2013).*

Høyegga is not a hydropower plant, but a dam with the function of collection and transportation of water through a 28 km long tunnel to the neighbouring waterway, Rena river and Rendalen power station. The tunnel has a maximum capacity of 60 m^3/s and the water enters Glomma again at the Rena and Glomma confluence (63.03498º N, 10.30058º Ø). This means that the river section between Høyegga and Rena (approximately 120 km) is a minimum water flow section with a minimum flow of 10 m^3/s. At the time of dam- and tunnel construction, a pool-and-weir fishway was constructed on the east side of the river. This fishway was later reconstructed during the first half of 2016. When the river runs low, the minimum flow of 10 m^3/s is usually only released through the spillway closest to the fishway entrance (Figure 4)(hereafter referred to as the "tap-spillway"). In periods with high discharges the other spillways are in use and the amount of water that went through each of them during the monitoring period varied from 0-230 m^3/s. The river character upstream the dam is slow flowing with lake characteristics the first two kilometres, while downstream reaches are characterized by pools and riffles (Qvenild 2008).

Figure 4 - *These two pictures illustrates how it looks around the fishway entrance when 15 m^3/s of water is led through the tap-spillway. The tap spillway opening is seen in the left picture, while the fishway entrance is seen in the right picture. The water velocity in the lower sections of the fishway is low compared to the flow released from the tap spillway. Picture taken April 10, 2017.*

2.2 The fishway

Before reconstruction in 2016, the fishway at Høyegga was a pool-and-weir type without substrate. During the ongoing SAFEPASS-project it has been desirable to look at the opportunities for reconstruction of pool-and-weir fishways, in search for improved and cost-effective solutions for improving fishways in regulated rivers. Norwegian Institute for Nature Research (NINA), Eidsiva and UNI Research have been central in the planning and practical implementation of the redesign at Høyegga. The fishway was reconstructed during the spring and early summer of 2016 to a vertical slot hybrid. This was done by cutting 30 cm wide slots in each chamber all the way down to the bottom of the fishway (Figure 5). The exit opening at the top of the fishway, which is located below the surface, has also been changed after reconstruction by increasing the opening from 20 cm to 50 cm. Substrate consisting of rocks and gravel was distributed in each chamber to simulate as natural habitat as possible (Figure 6). A total of 36 m^3 (12 m^3 in the size range 200-300 mm, and 24 m^3 in the size range 64-128 mm) was spread between the chambers by an excavator. The new design allows fish to swim along the bottom all the way through the 64 meters long fishway. There is a total of 22 chambers, whereas the last six are located inside/under the dam. The light level in these six chambers is lower compared to the chambers located outside the dam.

The fishway has been open continuously since the reconstruction was finished 16th of June 2016. Prior to this it was closed throughout the winter months (November – April/May). During the monitoring period (2014-2017) the discharge through the fishway has been stable, and the only way to increase or decrease the flow is to manually adjust the opening. Continuous data of the discharge in the fishway itself does not exist. One excursion to the study site was carried out April 10, 2017, with the intentions of getting a better picture of the dam installation with its fishway (Figure 6). During this excursion we closed the fishway intake and walked from chamber to chamber. No fish were observed and the fishway was closed for approximately one hour.

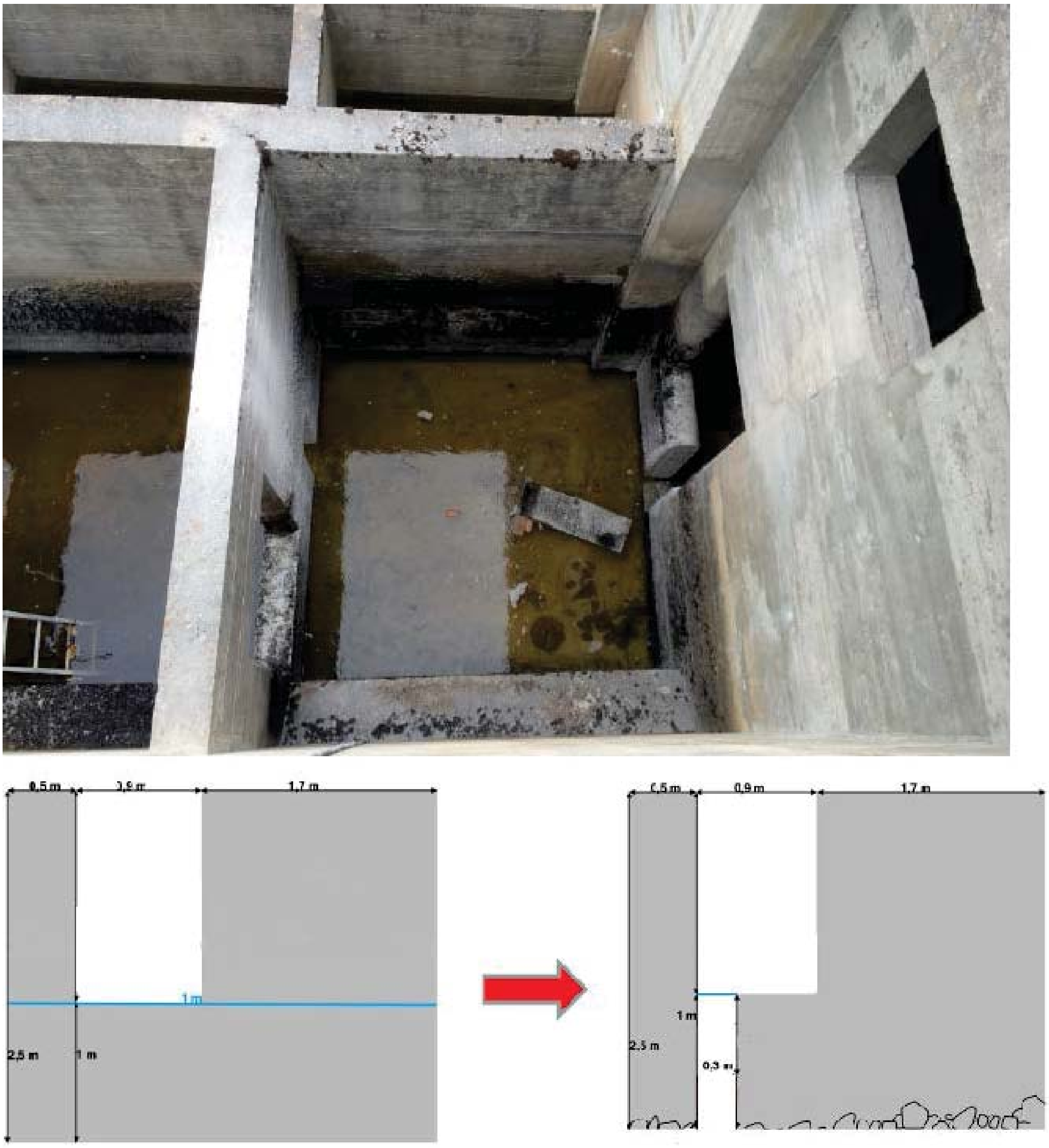


Figure 5 - ***Upper:*** *The last chamber outside the dam has just been modified to a vertical slot hybrid. The picture was taken before substrate was added.* ***Lower****: Drawing that shows the specific measurements before and after reconstruction of a chamber (Pulg 2016; Taugbøl 2016).*

Figure 6 - **Left:** *The new design with 30 cm wide slots and added substrate allow fish to swim along the bottom to ascend the fishway.* ***Right:*** *The picture is showing how it looks in two chambers when the fishway is in operation. Both pictures was taken during the excursion April 10th, 2017.*

2.3 Discharge data

Water discharge data is logged continuously for every spillway, as well as total observed and total calculated river discharge. Data is presented as mean values pr. day. I have only included discharge data for the period when the VAKI Riverwatcher has been in operation. I merged the fish count data and discharge data to get a better view of the discharge for each individual fish passage, before analyses in R were undertaken.

2.4 VAKI Riverwatcher

The VAKI Riverwatcher is designed to count fish as they pass a certain point in the machines chamber. This monitoring instrument was installed for the first time in 2013, and has been used since then. The VAKI Riverwatcher is placed into the fishway each spring and taken up late autumn by Jan Kristian Hagen on behalf of Eidsiva *(see monitoring periods in* Table 1*)*. The instrument also logs water temperatures every third hour. Before 2013, it was a trap mounted in the fishway, which had the same purpose as the VAKI Riverwatcher, but it was manually operated while the VAKI Riverwatcher counts automatically. The VAKI counter was in 2013 placed in the same chamber as the trap had been placed in previous years, chamber number 15 of 22 (Figure 7 & Figure 8). Chamber 15 has been used every year since then.

All upstream migration goes through the fishway and therefore all individuals need to swim through the VAKI Riverwatcher to pass the dam. When it comes to downstream migration the fish have other alternative routes (different spillways) in addition to the fishway. Each registration contains date and time, direction (up/down), calculated length, scanned picture of the passing fish and a video clip of the passing fish (Figure 9). In Høyegga, video has been taken of upstream migrators only. The fish species have been determined manually each year by Trond Taugbøl (Eidsiva) by looking at the recorded video and scanned photo (Figure 9). Fishes that are difficult to determine to species are indexed “fish”. Difficulties with species determination can occur due to different reasons, high turbidity, fast swimming individuals, turbulence or poor light conditions being some of them. Many registrations have been given the name “not fish”. This can happen if something else has drifted through the VAKI Riverwatcher and trigged the sensors, or if the fish is missing on the videoclip and the scanned photo is impossible to interpret. The “not fish” category has not been included in the analysed data. If an individual migrates up- and downstream within the same minute, it gets the index name “repeat”. These are also not included in the analysed data. During a fish passage the VAKI Riverwatcher turns on a light to get the best pictures possible.

Figure 7 - *The VAKI Riverwatcher gets lowered into chamber nr.15 of the fishway on the 16th of June, 2016 (Taugbøl 2016).*

Figure 8 - *Both pictures are taken after the reconstruction on the 10th of April 2017, before deployment of the VAKI Riverwatcher. The red arrow illustrates where the right picture is taken relative to the left picture.* ***Left****: Chamber number 15, seen from above.* ***Right****: The exit of the same chamber. It is almost no added substrate in the bottom of this chamber because the VAKI Riverwatcher needs to be mounted in a stable position.*

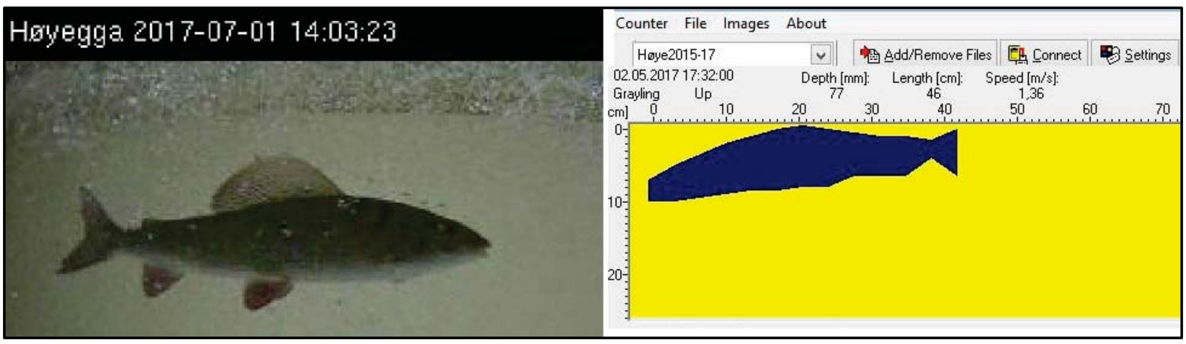


Figure 9 - ***Left****: Snapshot from the recorded video when a grayling was passing the VAKI Riverwatcher on the 1st of July 2017. The water temperature at this point was 12.5 °C and the discharge was 71 m^3/s.* ***Right****: Scanned picture of another grayling swimming upstream the fishway on May 2, 2017. This individual had a calculated length of 46 cm and a speed of 1.36 m/s, while the daily mean water temperature was 5°C and the mean river discharge was 10.2 m^3/s.*

2.5 Monitoring periods

The VAKI Riverwatcher has collected data in the fishway since June 2013, but because it needs to be removed manually before winter, it has not been installed and started at the same time each spring. However, the ending date is the same for 2014 and 2015 (10th of November), while it was removed on the 1st of November in 2016. In 2017 it was removed 7th of November, but to get enough time to finalize my results, I had to base my analyses on data from May 2nd to 17th of October for 2017. Between the 17th of October and 7th of November, when the VAKI Riverwatcher was removed, only one brown trout passed the fishway. See Table 1 for start, stop and interruption periods for each year.

Table 1 - *The table shows when the VAKI Riverwatcher was in operation and its interruptions for each year. The periods shown in the table below are included in the data analyses. The VAKI stop time for 2017 does not represent dismantling of the VAKI Riverwatcher, but the day I had to set as a final day to get time to analyse these data. The VAKI Riverwatcher was dismantled 7th of November 2017. Only one brown trout ascended the fishway between the 17th of October and the 7th of November in 2017. The interruption periods can vary with up to 3 hours less than registered in each end, because of the logger interval. Date and time indicate the last log before interruption and the first log after interruption.*

Year	**VAKI start date**		**VAKI stop time**		**Interruptions**	
	Date	**Time**	**Date**	**Time**	**Date**	**Time**
2014	06.06	15:00	10.11	09:00	11.06-12.06 13.06-16.06	09:00-18:00 12:00-06:00
2015	29.04	21:00	10.11	06:00	05.05-06.05	15:00-12:00
2016	16.06	23:30	01.11	09:00	18.10	09:00-15:00
2017	02.05	15:00	17.10	20:00	28.05-29.05	21:00-12:00

2.6 Data analysis

The data has been organized in Microsoft Excel and later imported to R version 3.2.5 (R Development Core Team 2017). In order to quantify the combined influences external factors and dam water management had on upstream migration of grayling and brown trout, a zero-inflated Poisson (hereafter ZIP) modelling method was used to fit the data (Lambert 1992; Zuur et al. 2009). The idea behind using a ZIP modelling approach, rather than ordinary Poisson regressions (McCullagh 1984), was the excess of zero-observations and over-dispersion pertinent to the data (Figure 10). Another potential modelling approach was also undertaken to determine what model that suited the data best. A Voung test between comparable, highly parameterized ZIP and generalized linear models (GLM), gave further support to the superiority of the ZIP model approach (Vuong 1989).

ZIP models comprise of two sub models, where one models the probability of zero-observations (Pr y=0, y=number of individuals) and the other models number of individuals migrating given more than zero individuals migrate (y | Pr y>0). The first, so-called zero model is fitted using logit link to linearize and normalize the response distribution, whereas the second, so-called count model, is linearized and normalized using a log link. Both sub-models can be constrained by additive and multiplicative combinations of environmental variables and factors of interest resulting in a number of candidate models, largely fitted to address the key objectives of my thesis. In order to assess which of the candidate models that attained most support in my data, I undertook model selection using a corrected version of Akaike's Information Criterion (Akaike 1974; Anderson 2007). The ZIP models were fitted using the "zeroinfl" function available from the pscl-library in R. Backward selection was then undertaken to refine the model structure. The "calclength" variable, which represents each registered individual calculated length in centimetres, was used to count individuals of fish.

The external factors implemented in the candidate ZIP-models were chosen based on published studies demonstrating their impact on fish migration (Clay 1995; Gilligan et al. 2003; Katopodis 1992; Mallen-Cooper & Brand 2007; Stuart & Mallen-Cooper 1999). These variables (e.g., water temperature and discharge) are also relatively easy to measure and have been collected continuously at the site. In all models, the daily operation time of the VAKI Riverwatcher was used as an offset variable to account for variation in observation time. Migration numbers of grayling and brown trout were sorted by migrants/hour/day. Apart from the migration peak periods, migrants per hour are low and contain excessive hours with a count of zero migrants (Figure 10). The external variables used were *water temperature, discharge, day of year, year and fraction of water led through the tap-spillway.* At low discharges all the water was led through the tap-spillway and high fraction of water in the tap-spillway generally resulted in low mean discharge. Fraction of 1 (100%) in the tap-spillway happened usually only when the river discharge was at the minimum flow of 10 m^3/s. Because the discharge through this slot during the monitoring time always were between 3 and 22 m^3/s, higher discharges will decrease the fraction of water running in the tap-spillway.

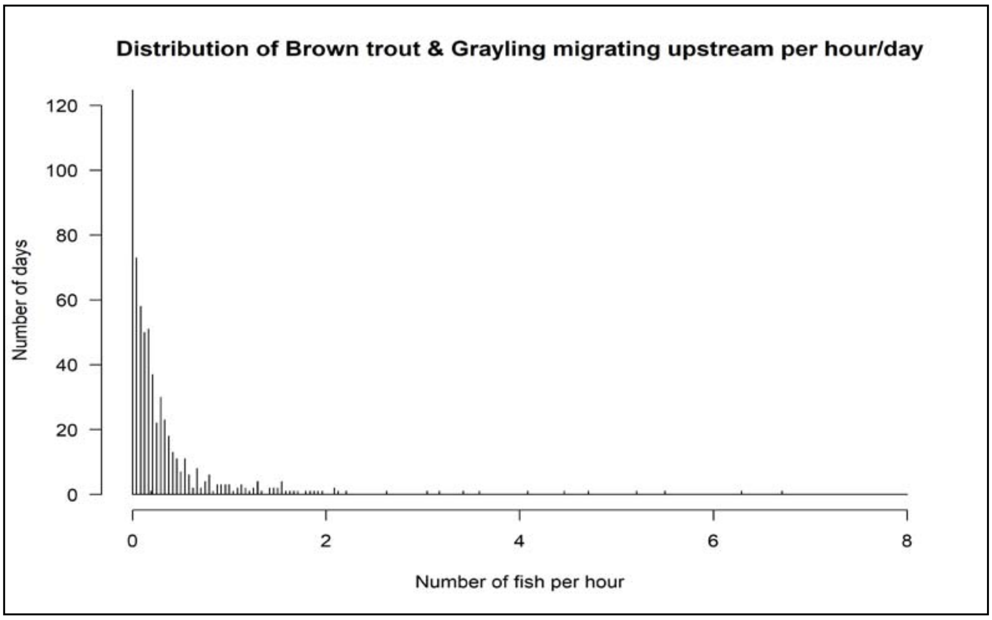


Figure 10 -*Distribution of brown trout and grayling upstream migration per hour/day through 2014-2017. This figure is included to underline the need of a zero-Inflated model (ZIP) approach.*

To test if individual size distribution changed across years and months, ordinary linear models with the associated analysis of variance were fitted the data. This was done by starting with fully factorial design (i.e., year*month) and undertaking backwards selection if the interaction effect was non-significant (Sokal & Rohlf 1981). A similar approach was undertaken when testing change in monthly and annual counts of individuals. However, these models were fitted using generalized linear models with log link and the associated likelihood ratio tests (chi-square statistics)(McCullagh 1984). Changes in number of individuals before and after reconstruction were testes by using ordinary contingency-table-based chi-square tests (Sokal & Rohlf 1981).

Data analysis predictions have been conducted for grayling and brown trout, because they are the most frequent species registered in the fishway at Høyegga during 2014-2017. This amount of registrations provides sample numbers with higher statistical power than the other registered species. However, other species will also be mentioned in order to highlight and describe the changed use of the fishway.

3. Results

3.1 Grayling & brown trout use of the fishway

3.1.1 Variation and patterns in migration metrics

Grayling used the fishway throughout the monitoring period, but the density of registered individuals varied between and within years. Figure 11 shows that low numbers of grayling used the fishway in 2014, compared to the other three years. For 2015-2017 there are two peak periods with considerable higher migration intensity of grayling. The first peak occurs from the middle of May to early June and the second peak occurs around the beginning of July, depending on year. The highest number of grayling individuals, registered per hour during the monitoring time, was on the 2nd of July 2017, with a mean of 6.08 grayling per hour and a total of 146 individuals during the entire day. The total number of upstream migratory grayling increased after reconstruction (2016 & 2017). The total number of upstream migratory grayling increased from 1404 individuals before reconstruction (2014 & 2015) to 2436 registered individuals after reconstruction (2016 & 2017).

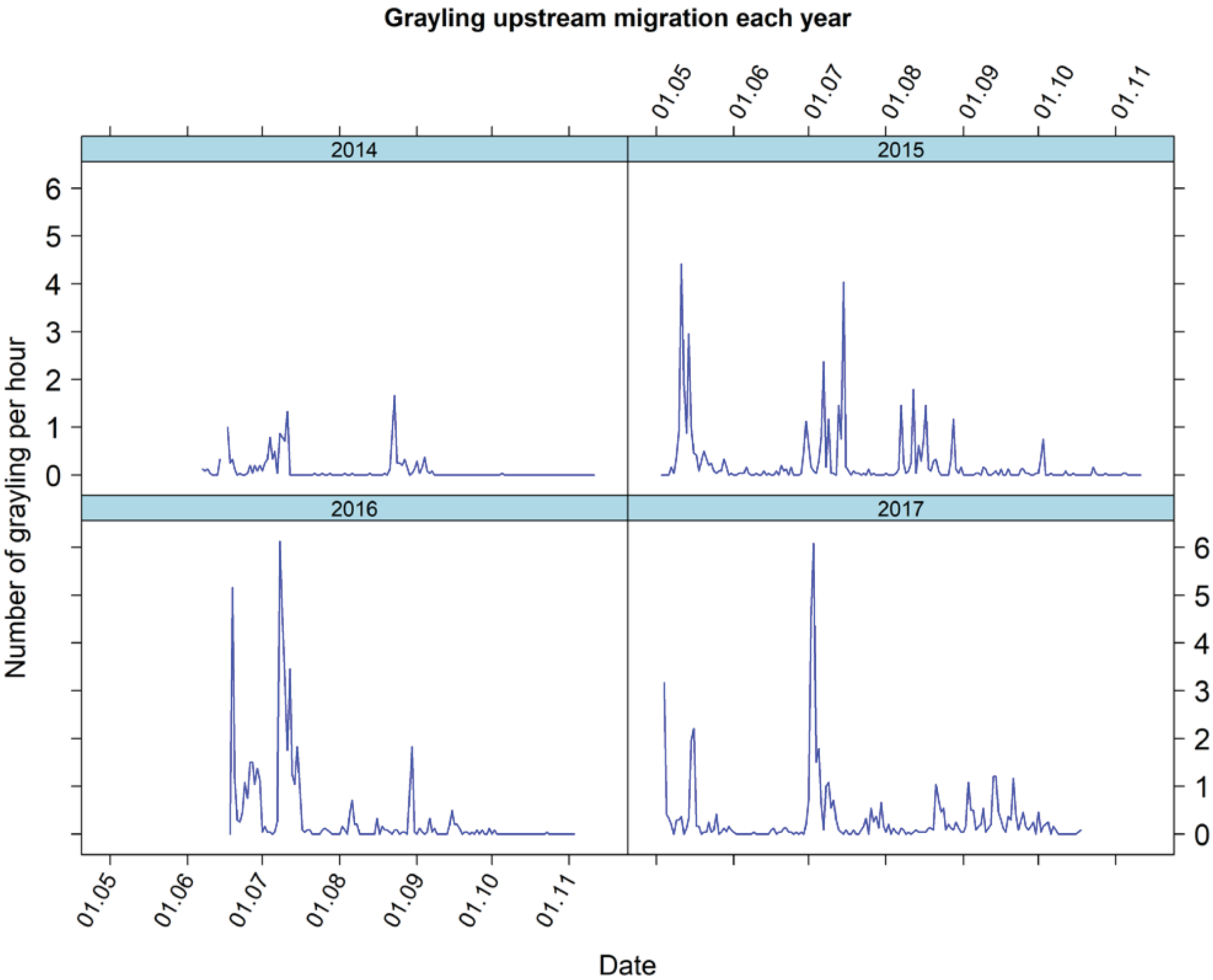


Figure 11 - *Number of upstream migrating grayling per hour for each monitoring year in Høyegga fishway. 2014 showed relatively low numbers compared to the other years. 2015-2017 have two peak periods, respectively in the beginning of each monitoring period and one in the beginning of July. The highest peak was on the 2nd of July 2017 with a mean of 6.08 grayling per hour and a total of 146 individuals during the day.*

The numbers of upstream migratory brown trout each year were lower compared to grayling (Figure 11 & Figure 12). The migrating brown trout individuals were more evenly distributed throughout the year compared to grayling. However, most of the registered individuals migrated after 1st of August (Figure 12). The highest intensity of upstream migratory brown trout was on 19th of September 2017, with 0.79 brown trout per hour and 19 individuals in total during the entire day. The total number of upstream migratory brown trout increased from 676 individuals before reconstruction (2014 & 2015) to 810 registered individuals after reconstruction (2016 & 2017).

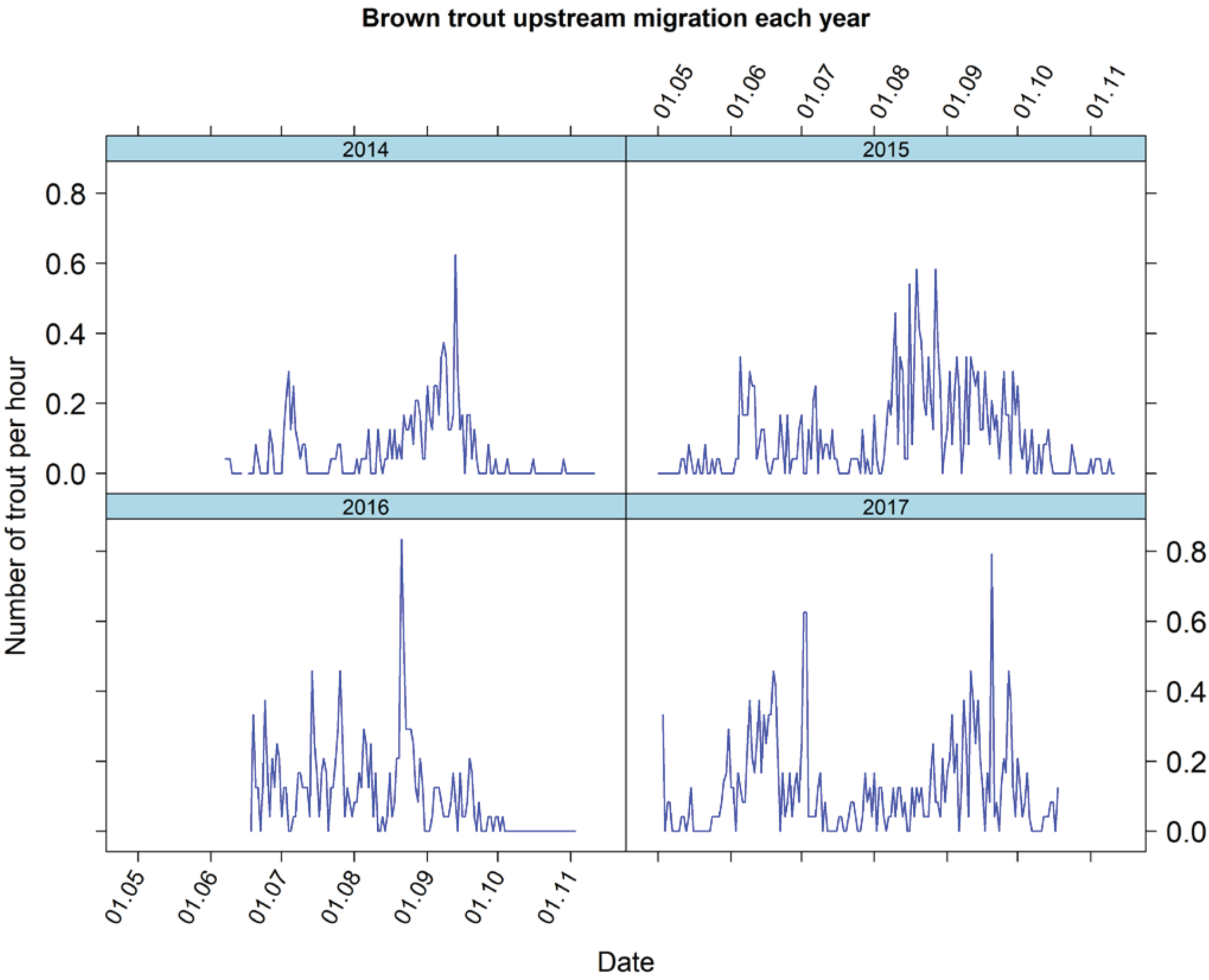


Figure 12 – *Number of upstream migratory brown trout individuals per hour per day. Brown trout individuals was registered almost every month during the monitoring period. However, the majority migrated from August to October. The highest registered density per hour was on 19th of September 2017 with 0.79 brown trout per hour and a total of 19 individuals during the day.*

The mean calculated length differed between months and years during the monitoring period (Figure 13). Grayling shows larger variation compared to brown trout, both within and across years and months. A significant among-month difference in grayling total length distribution was discovered using one-way ANOVA ($p_{month}<0.0001$; Figure 13). Registered grayling also increased in mean length over the four monitored years, with a mean (±sd) of 34.5 cm in 2014(±4.5), 37.9 cm in 2015 (±4.6), 37.9 cm in 2016 (±5.5) and 41.1 cm in 2017 (±5.8). Across all monitored years, the mean length was highest in May with 40.73cm (±5.6) and lowest in August with a mean length of 36.7cm (±5.4). It was no significant interaction effect between year and month on length variation in brown trout (anova: $p_{month*year}$=0.39). However, the ANOVA test showed significant differences in mean length among years after correction of the additive monthly effects (p_{year} <0.0001). This means that if the mean length was high in May one year, the mean length was also high in the coming months within the same year. The highest mean (±sd) calculated length for brown trout was 39.6 cm (±7.0), and this was found in 2016.

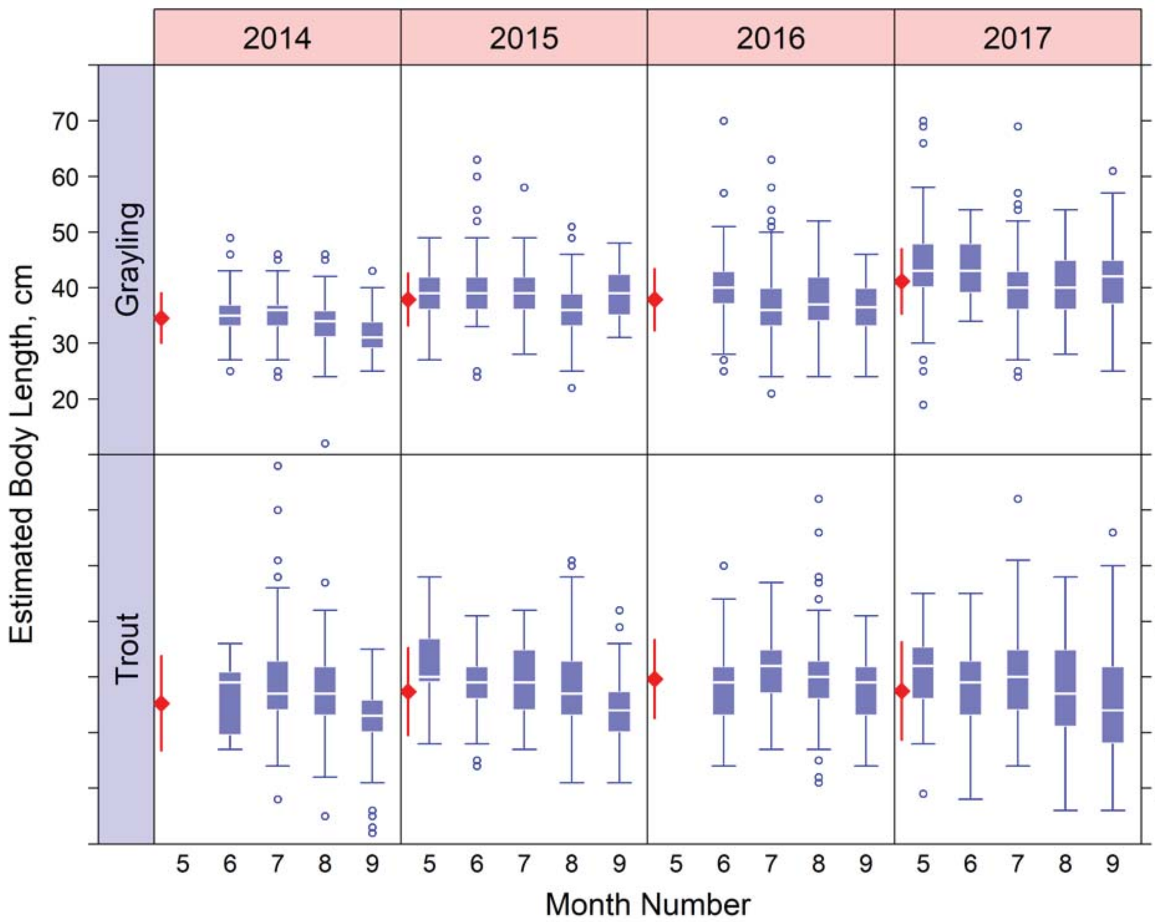


Figure 13 - *Estimated mean length of the registered grayling and brown trout individuals in Høyegga fishway each monitoring month over the four monitoring years (2014-2017). The mean length is showed with box plot from May to September in 2015 and 2017 and from June to September in 2014 and 2016. The red dots show the yearly mean with red lines showing the standard deviation.*

The majority of grayling migrated around mid-day (Figure 14). However, early in the season and especially close to the opening day after reconstruction in 2016, grayling individuals migrated throughout the whole day to a greater extent. Brown trout migrants were more evenly distributed throughout day (Figure 15) compared to individuals of grayling. One similarity is that the majority of the migrating individuals among both species migrated during daylight. There were not found big differences in changed migration patterns regarding time of day, before and after reconstruction.

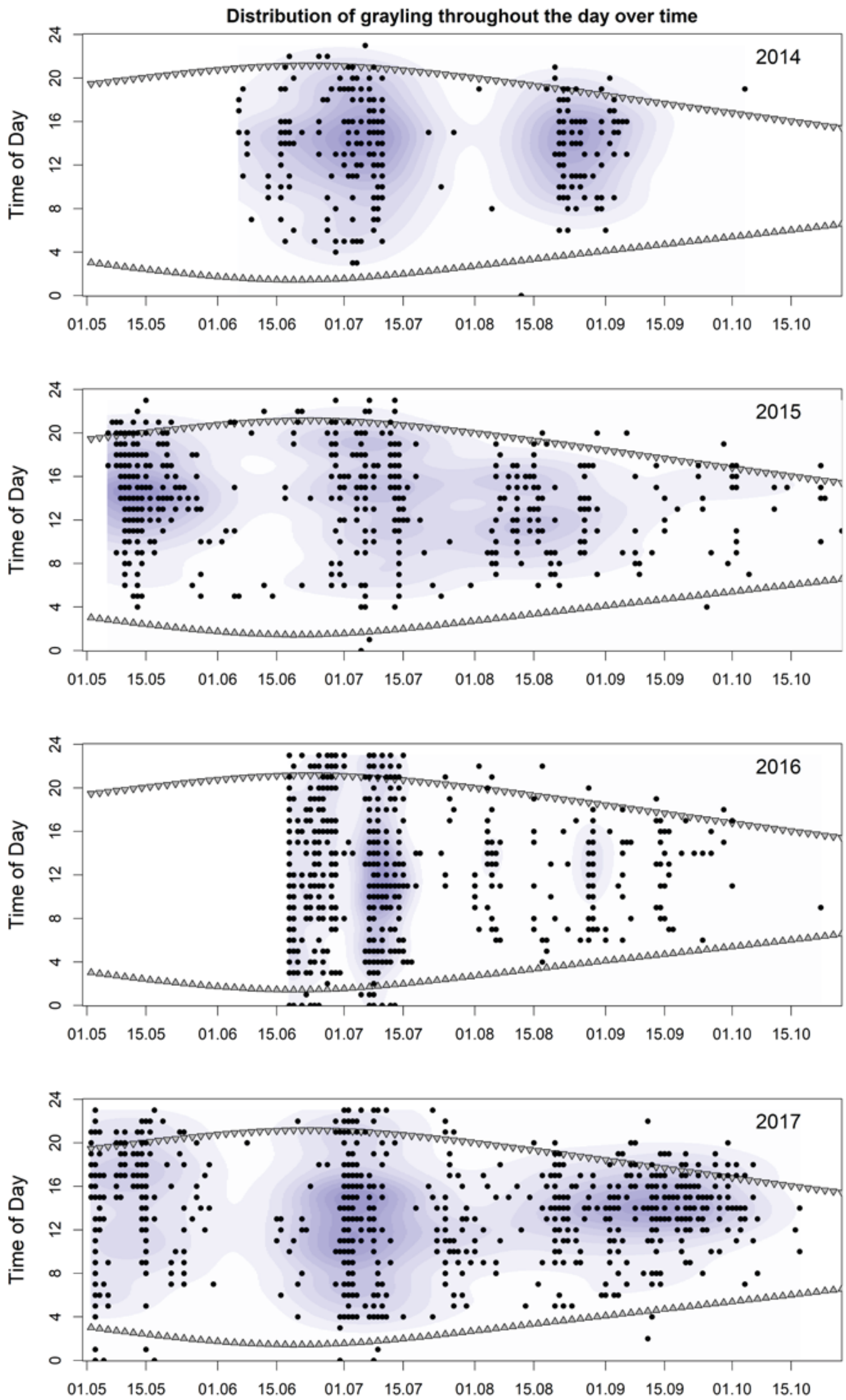


Figure 14 – *Registered grayling migration in Høyegga fishway through the day over time divided in each year in the monitoring period, 2014-2017. Each black dot represents one or more registered grayling individuals. The purple kernel density colour is graded, and the darkest areas contain a higher number of migrants in a shorter period of time, which gives a picture of when the intensity is at its highest. Each year is shown from 1st of May to the 1st of November. The triangles represent sunrise and sunset, and the data behind these triangles are based on the location coordinates for the fishway at Høyegga. The time of sunrise and sunset are the same each year.*

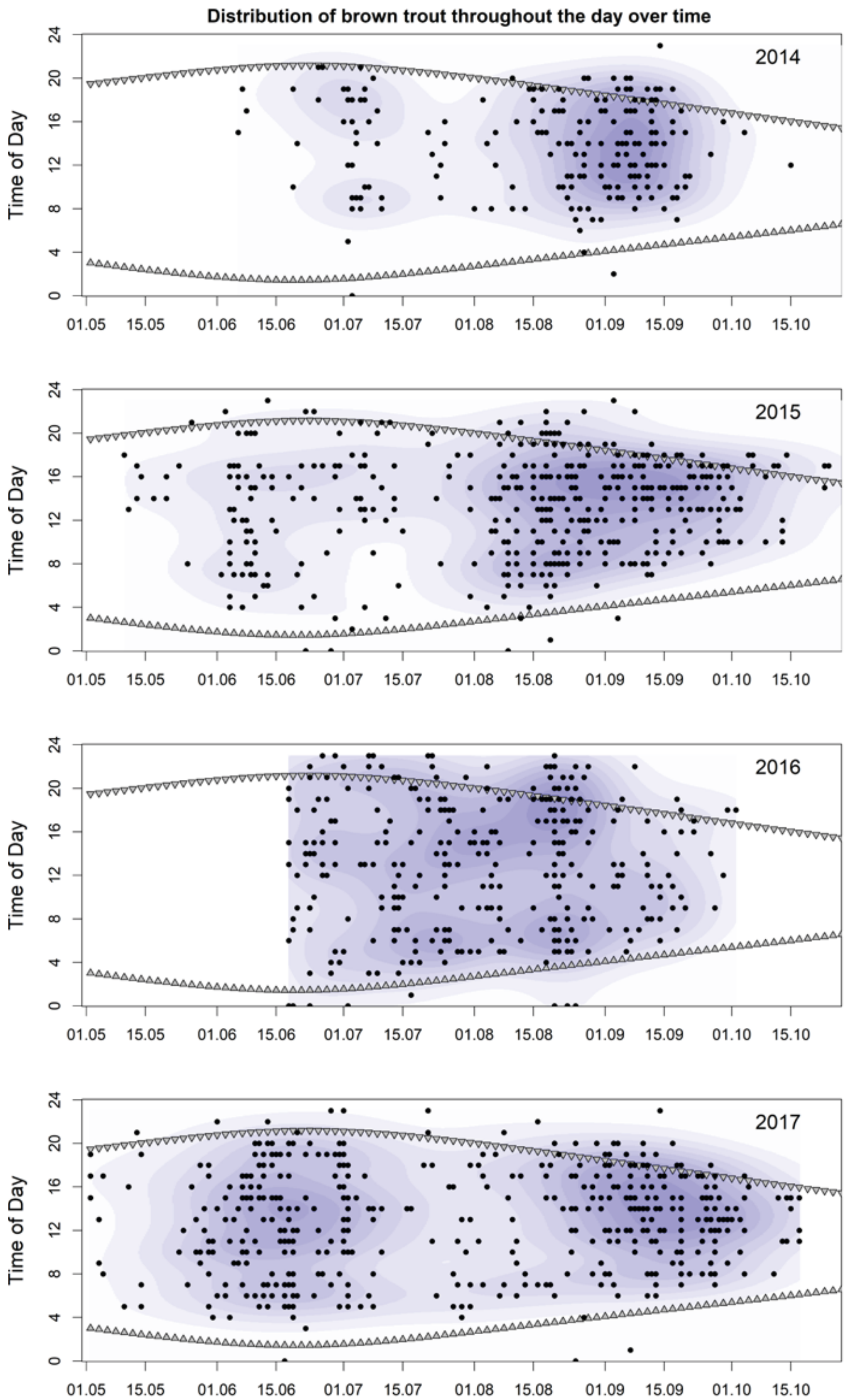


Figure 15 - *Distribution of brown trout migrants in Høyegga fishway throughout the day over time divided in each year in the monitoring period, 2014-2017. Each black dot represents one or more registered brown trout. The purple kernel density colour is graded, and the darkest areas contain a higher number of migrants in a shorter period of time, which gives a picture of when the intensity is at its highest. Each year is shown from 1st of May to the 1st of November. The triangles represent sunrise and sunset, and the data behind these triangles are based on the location coordinates for the fishway at Høyegga. The time of sunrise and sunset are the same each year.*

The mean discharge past Høyegga dam during the monitoring period varied over the four years, with the lowest mean in 2016 and the highest in 2017 (Table 2). The lowest discharge registered each year is 10m^3/s, which is the minimum discharge.

Table 2 – *Mean (±sd) discharge (m^3/s) past the dam during the monitoring period each year.*

Year	2014	2015	2016	2017
m^3/s	48.9 (±44)	78.4 (±65)	32.7 (±20)	113.7 (±112)

Water temperatures varied between 0.2 and 19.0 °C throughout the monitoring period, peaking during July every year (Figure 16 & Figure 17). Water discharge throughout the monitoring years varied from 10 m^3/s to almost 600 m^3/s. In 2017, a period of high discharges early in the season was followed by low to moderate discharges from the beginning of July. The peak of 576 m^3/s contributed to a high mean in 2017. The annual temperature curve shows similarities between the monitored years. Because of large annual variations in environmental factors it was not possible to discover if discharge or temperature effected migration differently after reconstruction of the fishway.

The grayling migration was characterized by long periods of low migration intensity and short time periods with high migration numbers. The brown trout migration differed from the grayling migration by being more evenly distributed throughout the season. However, very few individuals migrated before 1st of June and after 15th of September. In May 2017, 113 grayling and brown trout individuals (mostly grayling) ascended the fishway between the 13th and 15th. During these two days the grayling and brown trout migration numbers increased each day along with increasing water discharge. However, on the 16th of May 2017, when the water discharge exceeded 200 m^3/s, the migration started to decrease. Only eight individuals ascended the fishway between the 16th and 18th of May. These two days the mean daily water temperature also dropped from 5.5°C to 3.5°C. Grayling continued to migrate during the high flow regime, but in lower numbers for the rest of May in 2017. On the 27th of May the observed water discharge was 357 m^3/s, but with increasing water temperature. Brown trout ascended the fishway in higher numbers than grayling for the rest of the month. From the 25th to the 31st of May in 2017 the daily mean temperature was between 4.6°C and 7.8 °C.

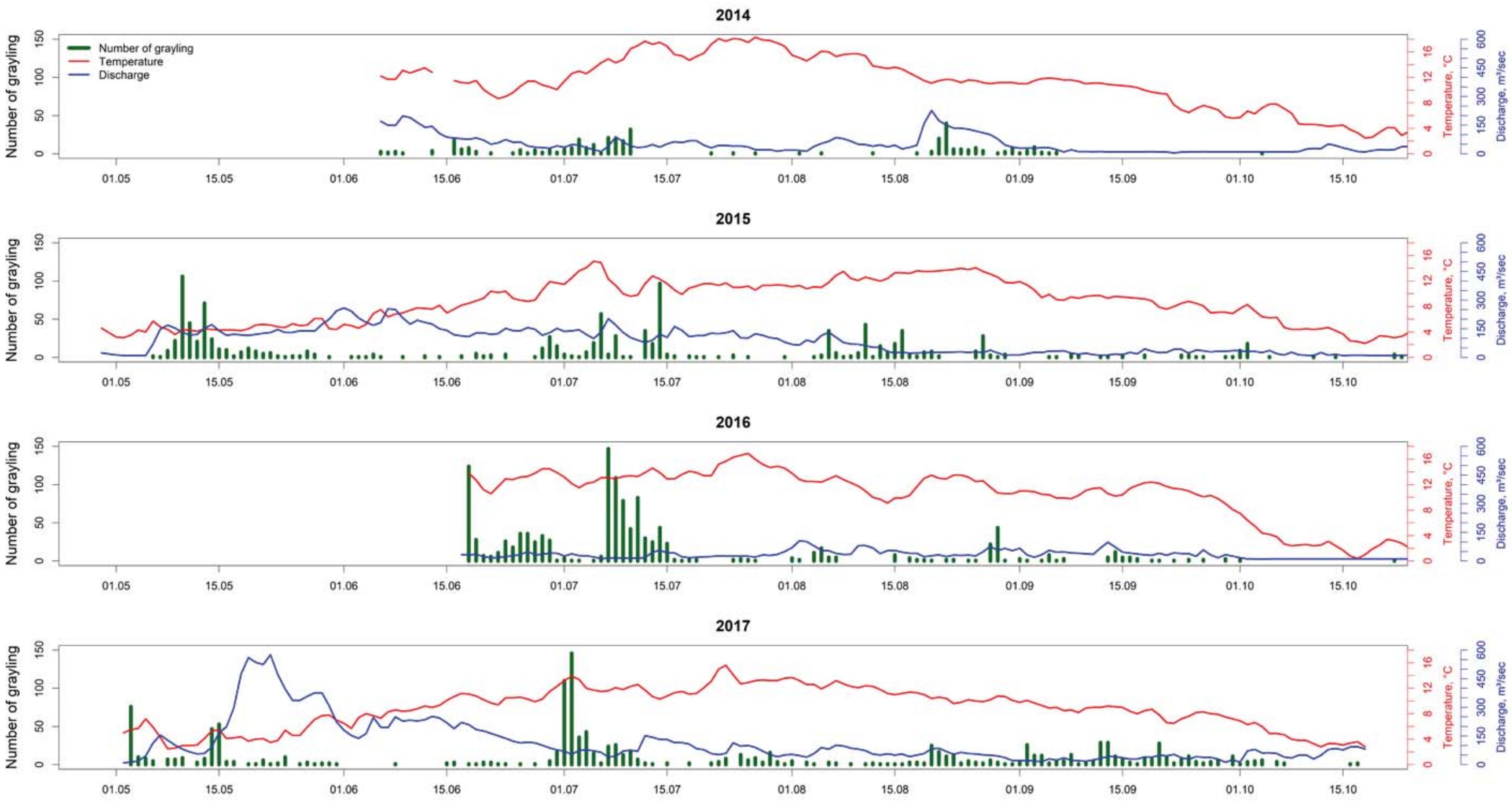


Figure 16 - *Overview of upstream grayling migration intensity between each monitored year with discharge and water temperature showed as lines. The y-axis on the left side represents number of fish, which is set to an interval between 0 and 150. The x-axis represent date, which has been set to the same for each year to easier compare across years. The VAKI Riverwatcher was not in operation until the early or mid-June in 2014 and 2016.*

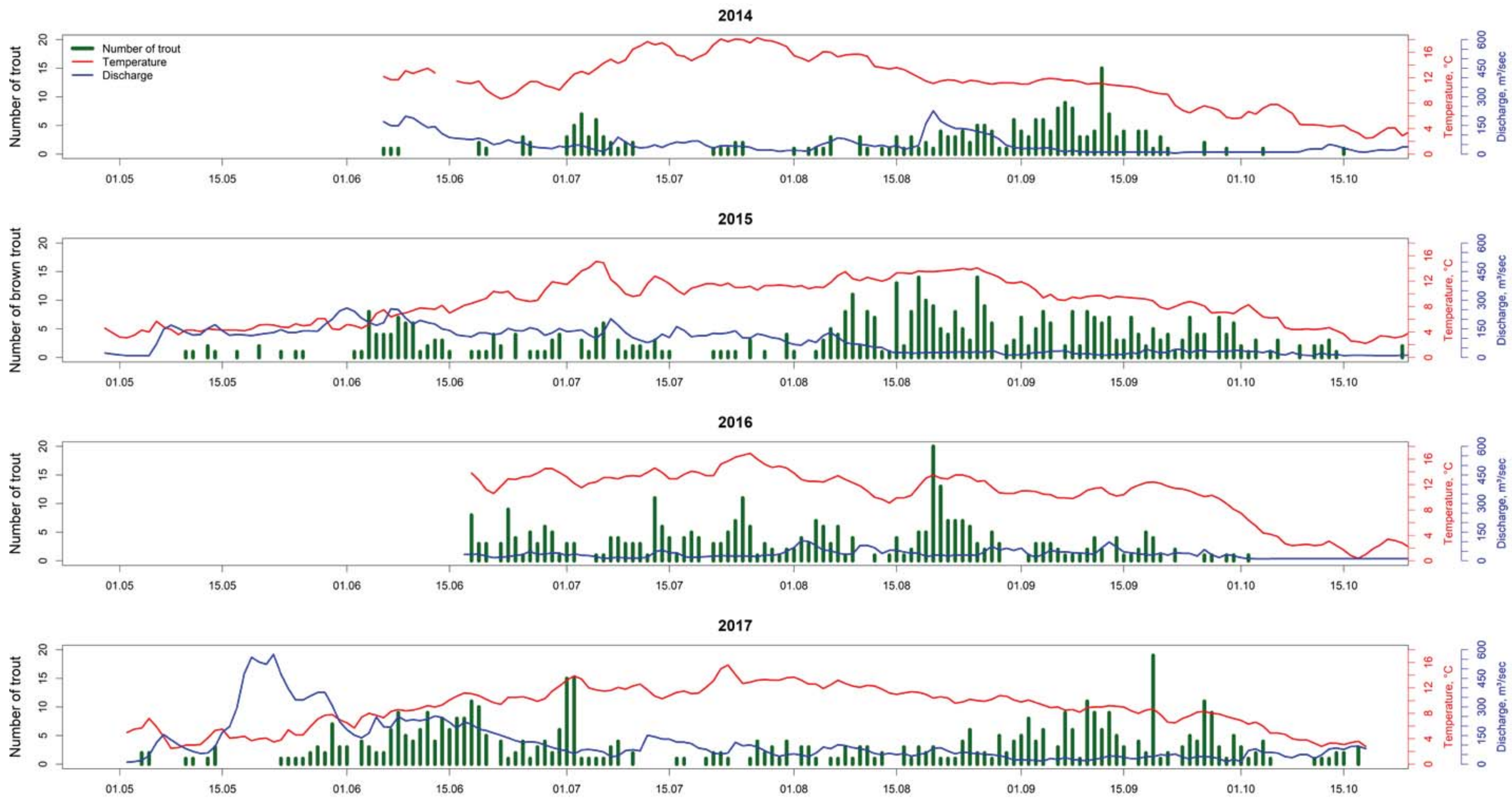


Figure 17 – *Overview of brown trout upstream migration intensity between each monitoring year with daily mean discharge and water temperature showed as lines. The y-axis on the left side represents number of fish, which is set to an interval between 0 and 20. The x-axis represent date, which has been set to the same for each year to easier compare the figure across years. The highest intensity of migratory brown trout was seen from August to October. There was also an increase in registered upstream migration early in the season of 2017, between 1st of June and 1st of July. The highest number of migratory brown trout was registered on the 19th of September 2017 with 19 individuals.*

3.1.2 Quantitative analyses of fishway use

The ten ZIP models achieving the highest AICc support for grayling and brown trout upstream migration at Høyegga fishway during the monitoring period from 2014-2017 are listed in Table 3 & Table 4. The same model structure attained the lowest AICc value in both grayling and brown trout, and is referred to as the most supported model. This model (number 27) includes *year, day of year, water temperature and fraction of discharge* led through the tap-spillway. This model does not include the *before and after* effect for the count part of the model, but is included in the zero-part of the model.

Table 3 - *AIC table showing the ten most supported ZIP models of grayling upstream migration at Høyegga between 2014-2017. To fit the table in one page, abbreviations of the variables have been undertaken: K: number of model parameters; ΔAIC: difference in AIC between the most supported model; LL: log likelihood; Yr: year; DoYc: day of year/100; WT: water temperature; fVF: fraction of water discharge flowing through the tap-spillway; BA: before and after reconstruction of fishway; VF: observed mean water discharge; BS: backward selection.*

ID	Count model	Zero-model	K	AIC	ΔAIC	LL
27	Yr*$DoYc^4$+WT*fVF	$DoYc^2$*VF*BA(BS)	33	7062.84	0.00	-3496.62
25	Yr*$DoYc^4$+WT*fVF	$DoYc^2$*VF*BA	35	7084.23	21.38	-3505.09
26	Yr*$DoYc^3$+WT^2*fVF	$DoYc^2$*VF*BA	33	7109.96	47.12	-3520.18
33	BA*$DoYc^4$+WT*fVF*BA	$DoYc^2$*VF*BA(BS)	26	7131.26	68.42	-3538.52
31	BA*$DoYc^4$+WT*fVF*BA	$DoYc^2$*VF*BA	28	7131.80	68.96	-3536.61
32	BA*$DoYc^4$+WT*fVF*BA	$DoYc^2$*VF*BA(BS)	27	7133.39	70.54	-3538.49
24	Yr*$DoYc^3$+WT*fVF	$DoYc^2$*VF*BA	31	7299.55	236.70	-3617.19
22	Yr*$DoYc^2$+WT*fVF	$DoYc^2$*VF+BA*VF	23	7413.25	350.40	-3682.75
21	$DoYc^2$+WT*fVF	$DoYc^2$*VF+BA*VF	23	7413.25	350.40	-3682.75
20	Yr*$DoYc^2$+WT*fVF	$DoYc^2$*VF*BA	27	7415.07	352.23	-3679.33

Table 4 - *AIC table showing the ten most supported ZIP models of brown trout upstream migration at Høyegga between 2014-2017. To fit the table in one page, abbreviations of the variables has been undertaken: K: number of model parameters; ΔAIC: difference in AIC between the most supported model; LL: log likelihood; Yr: year; DoYc: day of year/100; WT: water temperature; fVF: fraction of water discharge flowing through the tap-spillway; BA: before and after reconstruction of fishway; VF: observed mean water discharge; DsSo: days since snow melt; BS: backward selection.*

ID	Count model	Zero-model	K	AIC	ΔAIC	LL
27	Yr*DoYc^4+WT*fVF	DoYc^2*VF*BA(BS)	33	2382.49	0.00	-1156.5
25	Yr*DoYc^4+WT*fVF	DoYc^2*VF*BA	35	2382.87	0.38	-1154.4
26	Yr*DoYc^3+WT^2*fVF	DoYc^2*VF*BA	33	2438.42	55.93	-1184.4
24	Yr*DoYc^3+WT*fVF	DoYc^2*VF*BA(BS)	31	2553.38	170.89	-1244.1
31	BA*DoYc^4+WT*fVF*BA	DoYc^2*VF*BA	28	2594.92	212.44	-1268.2
32	BA*DoYc^4+WT*fVF*BA	DoYc^2*VF*BA(BS)	27	2598.33	215.85	-1270.9
33	BA*DoYc^4+WT*fVF*BA	DoYc^2*VF*BA	26	2602.67	220.18	-1274.2
28	BA*DoYc^4+WT*fVF	DoYc^2*VF*BA	25	2619.42	236.93	-1283.7
20	Yr*DoYc^2+WT*fVF	DoYc^2*VF+BA*VF	27	2640.06	257.57	-1291.8
29	BA*DsSo^4+WT*fVF	DsSo^2*VF*BA	25	2645.13	262.65	-1296.5

The effect of *year, day of year, water temperature, fraction of water discharge* in the tap-spillway are all parameters with significant values in both the count- and zero-model regarding the explanation of upstream migration of grayling (Table 5). However, the interaction effects (i.e YR[2015]*DoYc) will override the underlying additive effects. The effect of *before and after* reconstruction alone, and in interaction with *day of year*, do not show significance in the zero-model. *Water temperature* together with *fraction of water discharge* do not show to be of significance in the count-model.

Table 5 - *Parameter estimates for the most supported grayling ZIP model (number 27). YR: year; DoYc: day of year/100; WT: water temp; FVF: fraction of water discharge; VF: mean water discharge; BA: before and after reconstruction of fishway. Levels of the various factor predictors are provided in square brackets.*

COUNT-MODEL				ZERO-MODEL			
TERM	**Est**	**SE**	**p**	**Term**	**Est**	**SE**	**p**
INTERCEPT	-4264.00	383.3	***	Intercept	8.98	4.76	.
YR[2015]	4390.00	383.1	***	DoYc	-11.56	4.69	*
YR[2016]	3272.00	401.0	***	$DoYc^2$	3.04	1.12	**
YR[2017]	4159.00	382.1	***	VF	-0.17	0.04	***
DOYC	8498.00	762.0	***	BA[Before]	-5.04	5.05	0.32
$DOYC^2$	-6335.00	564.1	***	DoYc*VF	0.19	0.04	***
$DOYC^3$	2080.00	184.3	***	$DoYc^2$*VF	-0.05	0.01	***
$DOYC^4$	-250.00	22.43	***	DoYc*BA[Before]	6.85	4.79	0.15
WT	0.35	0.016	***	$DoYc^2$*BA[Before]	-1.75	1.13	0.12
FVF	1.90	0.33	***	VF*BA[Before]	-0.01	0.00	**
YR[2015]*DOYC	-8785.00	761.4	***				
YR[2016]*DOYC	-6657.00	792.2	***				
YR[2017]*DOYC	-8318.00	759.2	***				
YR[2015]*$DOYC^2$	6537.00	563.6	***				
YR[2016]*$DOYC^2$	5035.00	583.3	***				
YR[2017]*$DOYC^2$	6193.00	561.8	***				
YR[2015]*$DOYC^3$	-2143.00	184.2	***				
YR[2016]*$DOYC^3$	-1678.00	189.6	***				
YR[2017]*$DOYC^3$	-2034.00	183.5	***				
YR[2015]*$DOYC^4$	261.30	22.41	***				
YR[2016]*$DOYC^4$	207.70	22.97	***				
YR[2017]*$DOYC^4$	248.60	22.33	***				
WT*FVF	-0.52	0.28	0.067				

The same parameter estimates patterns were seen for brown trout as for grayling. The parameter *before and after* alone, and together with *day of year* do not contribute to explain the upstream migration of brown trout in the fishway at Høyegga. *Year*, *day of year*, *water temperature* and *fraction of water discharge* as well as the combinations of them are important parameters regarding explanation of brown trout upstream migration in the fishway.

Table 6 - *Parameter estimates for the most supported brown trout ZIP model (number 27). YR: year; DoYc: day of year/100; WT: water temp; FVF: fraction of water discharge; VF: mean water discharge; BA: before and after reconstruction of fishway*

COUNT-MODEL				**ZERO-MODEL**			
TERM	Est	SE	p	Term	Est	SE	p
INTERCEPT	-793.60	184.70	***	Intercept	32.103	16.987	0.059
YR[2015]	684.90	185.80	***	DoYc	-36.082	17.338	*
YR[2016]	781.10	327.40	*	$DoYc^2$	8.771	4.181	*
YR[2017]	462.30	187.60	*	VF	-0.818	0.179	***
DOYC	1509.00	350.40	***	BA[Before]	2.964	15.625	0.850
$DOYC^2$	-1099.00	246.70	***	DoYc*VF	0.816	0.173	***
$DOYC^3$	351.00	76.43	***	$DoYc^2$*VF	-0.193	0.040	***
$DOYC^4$	-41.43	8.79	***	DoYc*BA[Before]	5.730	15.533	0.712
WT	0.27	0.03	***	$DoYc^2$*BA[Before]	-2.532	3.766	0.501
FVF	1.34	0.58	*	VF*BA[Before]	-0.039	0.016	*
YR[2015]*DOYC	-1330.00	352.20	***				
YR[2016]*DOYC	-1465.00	614.40	*				
YR[2017]*DOYC	-874.80	356.60	*				
YR[2015]*$DOYC^2$	959.90	247.80	***				
YR[2016]*$DOYC^2$	1018.00	428.90	*				
YR[2017]*$DOYC^2$	620.50	251.50	*				
YR[2015]*$DOYC^3$	-304.40	76.70	***				
YR[2016]*$DOYC^3$	-309.80	132.00	*				
YR[2017]*$DOYC^3$	-194.90	78.02	*				
YR[2015]*$DOYC^4$	35.78	8.81	***				
YR[2016]*$DOYC^4$	34.84	15.12	*				
YR[2017]*$DOYC^4$	22.86	8.99	*				
WT*FVF	-0.09	0.05	0.078				

To investigate the effects of temperature and the fraction of water led through the tap-spillway on grayling and brown trout migration, prediction plots based on the most supported ZIP-models were made. The predictions are conditional on fishway use (i.e., the associated zero-model must predict probability of zero migration to be less than 1) from either grayling (Figure 18) or brown trout (Figure 19). The plots predict number of upstream migratory grayling or brown trout per day for a given temperature and fraction of water led through the tap-spillway. This model sums up the combined effects of all variables. The mean discharge (Q_R) for each month each year is also included in the prediction plots to increase the understanding of the actual conditions. However, this makes it difficult to compare each month and year.

Grayling migration is predicted to increase with increased temperature and fraction of water led through the tap-spillway (Figure 18). Higher fraction of water discharge (x-axis) result in lower mean discharge, because a higher fraction of the water is led through the tap-spillway. The discharge in the tap-spillway was usually between 5-15m^3/s. The higher fraction of water going through the tap-spillway the higher number of grayling are predicted to use the fishway. The model also predicts higher numbers of migrating grayling with increased temperature. Despite the model's predictions of grayling fishway usage being favoured by high temperatures, relatively high numbers of grayling migrate early in the seasons at temperatures below 5°C. The model predicts the highest grayling numbers to be in May, June and July.

Brown trout does not seem to be as affected by the fraction of water going through the tap-spillway compared to grayling, but rather more dependent on water temperature (Figure 19). However, early and late in the season the fraction of water discharge led through the tap-spillway is of some importance. Brown trout is also predicted to migrate in higher numbers with increased temperature. It seems like it is little change in fishway use after reconstruction regarding migration intensity for grayling and brown trout during low temperature conditions (<5°C), but this is difficult to determine due to the lack of data in May 2014 and May 2016.

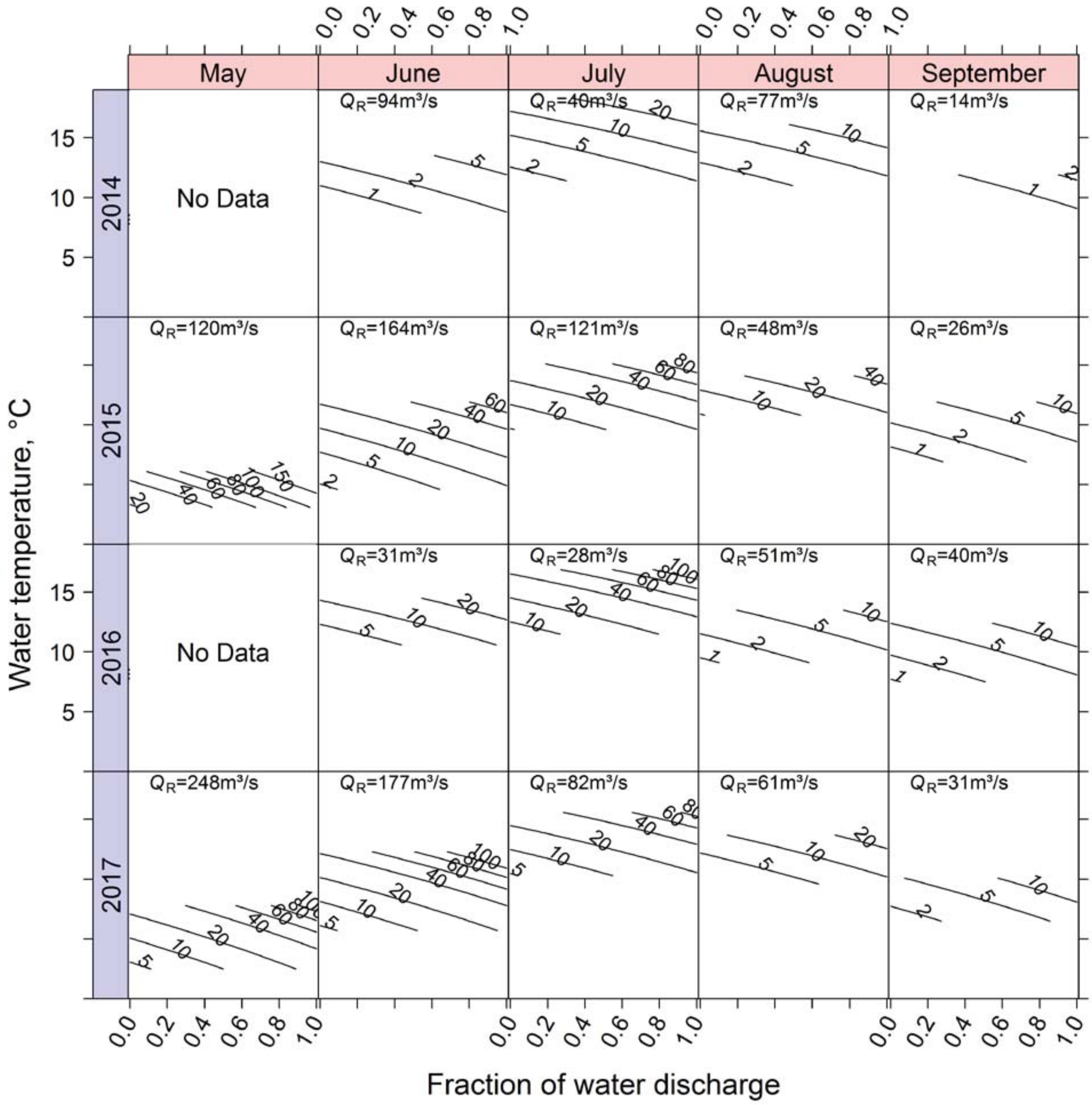


Figure 18 – *Predicted numbers of upstream migrating grayling per day at a given water temperature and fraction of water discharge going through the tap-spillway. The predictions are plotted within the temperature span registered each month, and are based on the most supported ZIP model (number 27) and requires that grayling migrates at that time. Higher fraction number equals lower mean discharge. In order to increase the understanding of the actual conditions, the average discharge for each month is included (Q_R). The model predicts the highest grayling numbers to be in May, June and July. The higher fraction of water going through the tap-spillway the higher number of grayling are predicted. The model also predicts higher number of grayling with an increased temperature.*

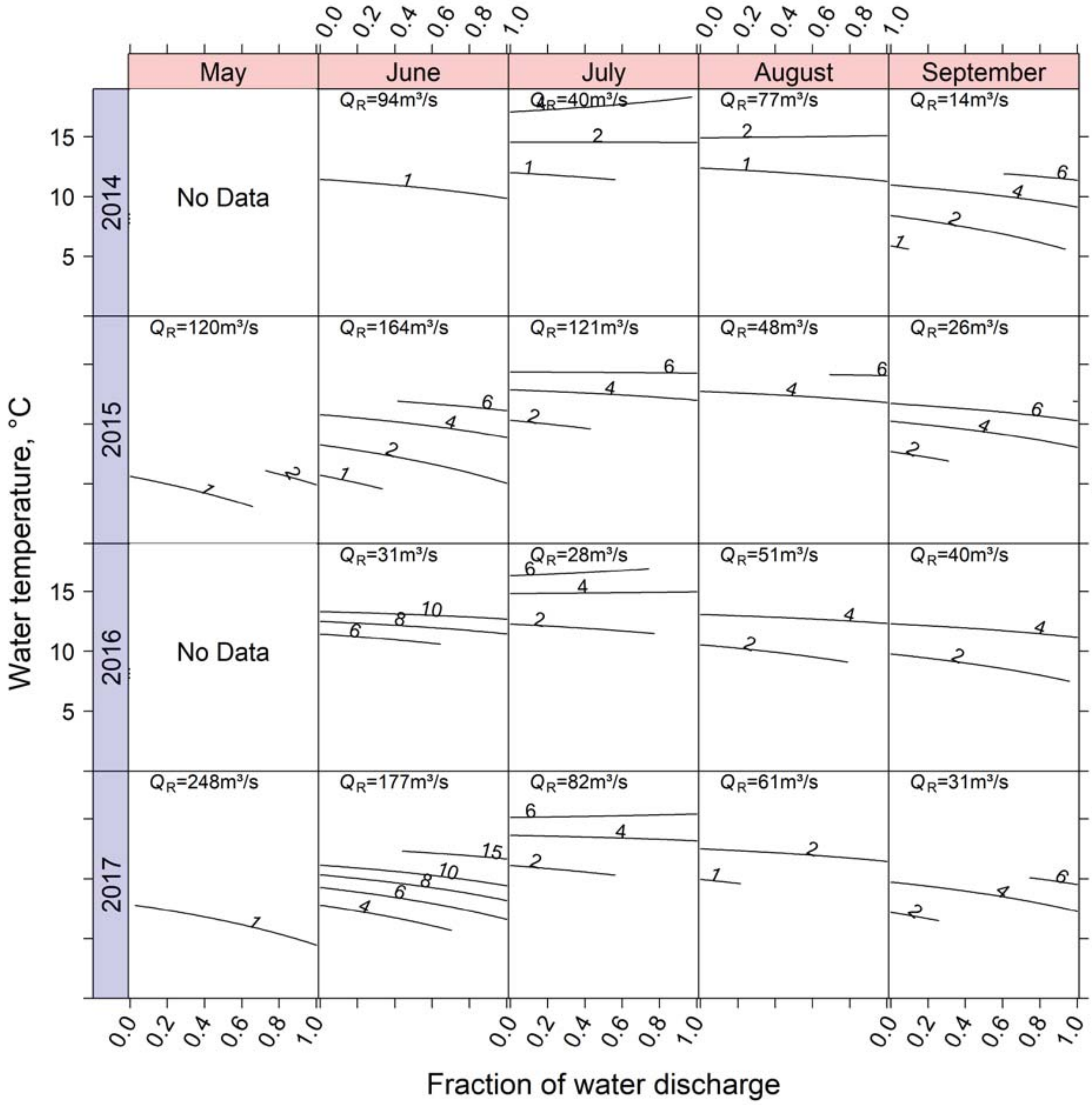
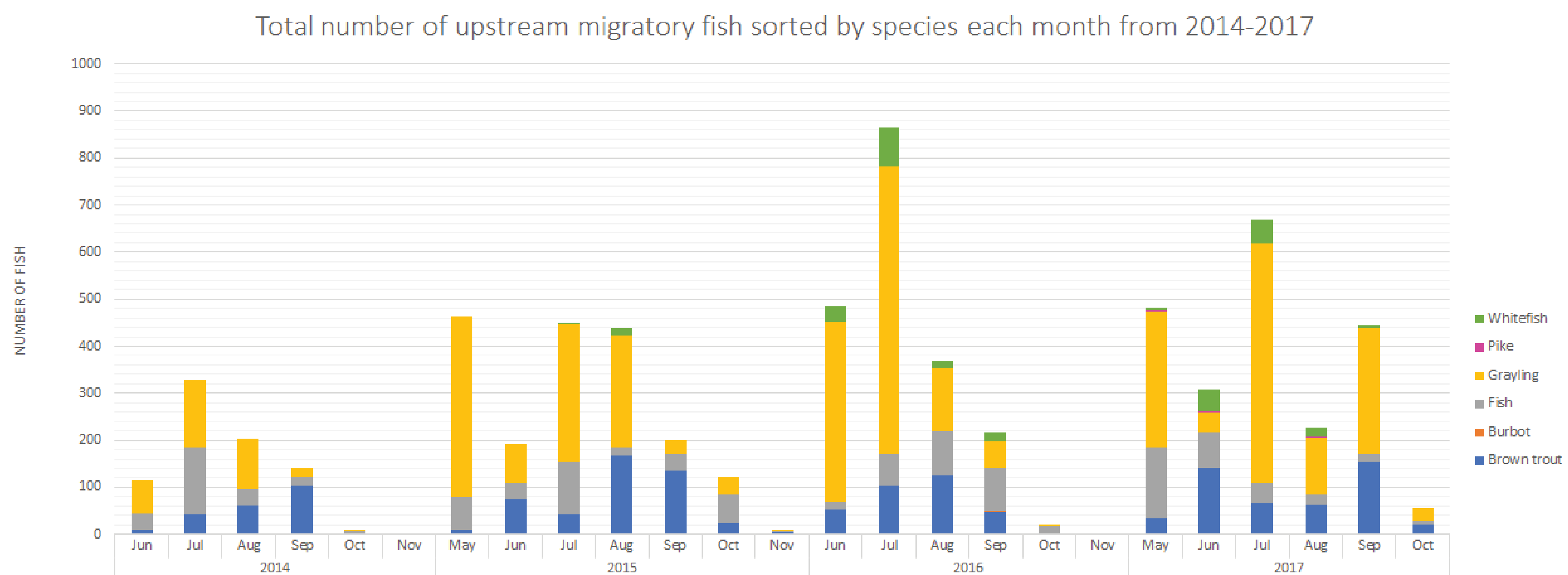


Figure 19 - *Predicted numbers of upstream migrating brown trout per day at a given water temperature and at a given fraction of water discharge going through the tap-spillway based on the most supported ZIP model (number 27), and requires that brown trout migrates at that time. The predictions are plotted within the temperature span registered each month. High fraction number equals lower mean discharge. In order to increase the understanding of the actual conditions, the average discharge for each month is included(Q_R). From this model brown trout are more dependent on the temperature rather than the discharge to ascend the fishway. Higher temperatures predict a higher number of migrating individuals. The lines have a slightly tendency to tilt down towards the right corner, especially in May/June and September, which means that higher discharge in the tap-spillway is favoured.*

3.2 Seasonal species composition development

Individuals of grayling and brown trout were present every month during the four monitoring years except in November 2014, 2016 and 2017 (VAKI Riverwatcher was dismantled 10th of November 2014, 1st of November 2016 and 7th of November 2017, Figure 20). In addition to significantly increased numbers of grayling and brown trout using the fishway after reconstruction (Grayling: $\chi^2 = 277.35$, df = 1, $p < 0.0001$; Brown trout: $\chi^2 = 12.083$, df = 1, $p < 0.001$), the numbers of whitefish also increased (Whitefish: $X^2 = 228.38$, df = 1, $p < 0.0001$), from 18 registered individuals before reconstruction to 278 individuals after reconstruction (Table 7). Pike *(Esox lucius)* and burbot (*Lota lota)* have also been registered in low numbers in the VAKI Riverwatcher after reconstruction of the fishway, but not before (Table 7). Chi-square test revealed significant differences in species composition before and after reconstruction of the fishway (Species composition: $X^2 = 216.33$, df = 3, $p < 0.0001$). Figure 20 shows the distribution of fish, presented by species each month during the monitoring period from 2014-2017. After reconstruction, the majority of upstream migratory individuals have been registered during July. Grayling dominated the numbers, but also a large fraction of the whitefish migrants ascended the fishway this month. The numbers of ascendants decreased rapidly after the end of September.



	Jun	Jul	Aug	Sep	Oct	Nov	May	Jun	Jul	Aug	Sep	Oct	Nov	Jun	Jul	Aug	Sep	Oct	Nov	May	Jun	Jul	Aug	Sep	Oct
	2014						2015							2016						2017					
Whitefish									3	15				33	83	17	20			5	46	50	20	4	
Pike																				3	2	1	3		
Grayling	70	146	107	19	1		382	83	290	239	28	37	2	382	611	132	56	1		290	43	509	119	268	25
Fish	34	142	34	19	4		70	35	115	17	37	62	4	16	68	94	92	17		148	76	44	23	17	9
Burbot																	2								
Brown trout	11	41	62	103	3		11	74	41	167	135	24	4	54	104	126	47	1		35	140	65	63	154	21

Figure 20 – *Overview of the amount of fish registered in the VAKI Riverwatcher in Høyegga fishway each month during the monitoring period sorted by species. The "Fish" category is individuals that is not specie determined due to difficulties or missing video of the upstream migrating individual. However, the scanned picture has been good enough to determine that it is a fish. After reconstruction (2016 &2017), July has been the month with the highest migration intensity, mostly grayling but also the majority of the migrating whitefish migrated this month.*

In total, 6810 individuals of fish ascended the fishway throughout the monitoring period from 2014 to 2017. The total amount of upstream migratory individuals, as well as the number of species, increased after reconstruction (Table 7). When correcting the number of migrants according to fishway operation hours both before and after reconstruction, there was a clear increase in fishway use after reconstruction (Table 7). Brown trout had an increase in use of 37.5%, grayling had an increase in use of 97.5% and whitefish increased with 1659%. Total registrations of upstream migratory fish increased with 76.5% after reconstruction. The numbers in the category *fish* increased less, with 20% more registered individuals in the VAKI Riverwatcher after reconstruction. Burbot and pike were also registered in the VAKI Riverwatcher after reconstruction, however, in low numbers.

Table 7 - *Total number of each specie registered in the VAKI Riverwatcher and grand total of fish individuals before and after reconstruction. The use of the fishway across all species increased with 76.5% after reconstruction. The total hours of monitoring before and after reconstruction differed with 1020 hours (42.5 days). This is mainly due to the reconstruction period which led to a late opening in 2016. In the calculation of percentage of change in use, "open hours" was included.*

	Brown trout	*Grayling*	*Whitefish*	*Burbot*	*Pike*	*Fish*	*Hours open*	*Grand Total*
Before	676	1404	18	0	0	573	8376	2671
After	810	2436	278	2	9	604	7356	4139
Change (%)	37.5%	97.5%	1 659%			20.0%	-12.2%	76.5%

4.Discussion

This study has investigated upstream migration of fish before and after the redesign of Høyegga fishway from a pool-and-weir to a vertical slot hybrid design, in the river Glomma, Norway. The results indicate that the reconstruction of the fishway led to increased numbers of ascending grayling and brown trout. Numbers of registered whitefish also increased after reconstruction of the fishway. The two species pike and burbot, which prior to reconstruction never had been registered during any monitoring periods in Høyegga, started to use the fishway after reconstruction. During this monitoring period (2014-2017), 6810 individuals ascended the fishway, 2671 individuals before and 4139 individuals after reconstruction. After taking "hours open" into the calculation of change in use, the increase of total registered fish was 76.5% after reconstruction.

Grayling is known for its spring spawning migrations (Northcote 1995; Nykänen et al. 2001) and previous research in the Glomma waterway has shown that grayling is most likely to spawn in the period between 10th of May – 5th of June (Museth et al. 2012). Therefore, it was expected that the largest fraction of the migratory grayling would ascend the fishway before and within this time span. However, in this study, the largest fraction of migratory grayling was registered in the fishway during July. Fish can migrate for other reasons than spawning, for example feeding, seeking refuge from predators or environmental conditions (Linløkken 1993; Northcote 1984; Tack 1980). Prior to the reconstruction of the fishway, Linløkken (1993) also found migration peaks in June-July for grayling in the fishways at Høyegga dam and Løpet dam in the Glomma river. Linløkken (1993) stated that the June-July peaks constituted feeding migrations. However, the new fishway design seems to lead to even higher numbers of migrating grayling in July. The reasons for this increase advocates for further investigation, but a possible explanation can be that fish find it difficult to ascend the fishway during low temperatures (<5°C) early in the season. Especially in combination with high discharge (<200m^3/s), as temperature can have an impact on swimming capacity (Katopodis 1992; Lucas & Baras 2001; Taugbøl et al. 2017; Wardle

1980). The most supported AIC models for predicting brown trout and grayling migration in the fishway also indicate that temperature have great effect on upstream migration.

The increase of registered brown trout after reconstruction of the fishway in Høyegga was relatively small compared to the other species. This can indicate that the fishway functioned better for brown trout before reconstruction compared to the other species. It is still more registered brown trout in the fishway after reconstruction, indicating that the vertical slot hybrid design seemed to work as good as the old fishway in Høyegga. The registrations of brown trout throughout the seasons were more evenly distributed compared to grayling, with the majority ascending the fishway in August and September. This is probably, for the most, spawning migration as previous research indicate that the spawning period for brown trout in Glomma river is between 15th of September and 15th of October (Museth et al. 2012). June 2017 observations differs from the other years with higher numbers of migrating brown trout (140 individuals). These migrations can be feeding migrations, but this study is not designed to answer this question. If this pattern continues in the coming years, more extensive research should be undertaken as this potentially can be an effect of the fishway redesign. There were relatively low numbers of migrating brown trout in June 2016 (54 individuals), but this may be due to late opening of the fishway this year (16th of June).

With four comparable years only, this study indicates that the redesign of the fishway has been successful in relation to significant increased species diversity and migration numbers ascending the new fishway design. In a review study, Noonan et al. (2012) evaluated fishway efficiency based on 65 papers and concluded that salmonid species had higher passage success compared to other sympatric fish taxa regardless of design. Previous research has also shown that pool-and-weir fishways can be unfortunate by being selective on certain species (Gilligan et al. 2003; Museth & Qvenild 2003; Stuart & Mallen-Cooper 1999). Pool-and-weir fishways in Australian rivers have had challenges with low numbers of migrating fish. Prior to 1985, 44 fishways were constructed in New South Wales, Australia, none of them designed specifically for Australian native fish species (Gilligan et al. 2003). As a result, most if not all of these fishways, were found to be ineffective at providing fish passage (Gilligan et al. 2003). Native fish had ascending success less than 1% of the population. This resulted in fifty years of declining populations of native fish species and motivated reconstruction of fishways in Australia (Mallen-Cooper & Brand 2007). Stuart and Mallen-Cooper (1999) examined the effects of a reconstruction of a fishway in the subtropical Fitzroy River in Australia. The original pool-and-weir fishway did not function satisfactory for the native species present, but after modification of the fishway into a vertical slot, the numbers of ascending fish increased (Stuart & Mallen-Cooper 1999). This was especially the case for bottom dwelling fish species, as the new design allowed fish to swim along the bottom to ascend the fishway.

Studies show that species with lower swimming capacity and species with strong connection to the bottom, such as burbot (McPhail & Paragamian 2000), can have difficulties with pool-and-weir design and the fishway itself can become an obstacle (Noonan et al. 2012). This can prevent fish from reaching their spawning grounds in time, which may be crucial for the population (Fleming & Reynolds 1991; Gowans et al. 2003). The non-salmonid species pike and burbot were, after reconstruction, registered in the Høyegga fishway for the first time. This can indicate that the fishway has become easier to ascend for species with lower swimming capacity and for species without leaping behaviour in relation to obstruction passage (Clay 1995; Gardunio 2014). Particularly the bottom dwelling fish species, burbot, have probably benefited from the redesign to vertical slot which made it possible to swim along the bottom to ascend the fishway. When the fishway was reconstructed, substrate was also placed in all chambers. The added substrate provides more natural conditions in the fishway by increasing the roughness and decreased velocity near the bottom (Heimerl et al. 2006). Adding substrate is normally done in all fishways found in German-speaking countries to better facilitate for bottom dwelling fish species to ascend the fishways (Heimerl et al. 2006; Heimerl et al. 2008). Burbot jumping abilities has also shown to be poor by Gardunio (2014) witch strengthen the positive outcome of reconstruction from pool-and-weir to a vertical slot hybrid design with added substrate.

This study indicates that the reconstruction has been successful in terms of increased use, but what is considered as desired results depends on what the basis for the decision is. It is important to not forget that barriers can be natural and prevent upstream migration for all or a variety of the present fish species and length groups. If a man-made installation gets constructed at a natural barrier, is it then correct to implement fishways? This can cause unnatural spread of species and introduction of species to new areas in the same waterway. Discussing this was not the mandate for this study, but it highlights the importance of having knowledge about species compositions, their life stages, abilities and migration patterns before a dam instillation. Prior to construction of dam Høyegga, the fish most likely had the opportunity to migrate up- and downstream the river section (Kraabøl & Museth 2007). This imply that the fishway at Høyegga shall function in a way that allows all motivated fish individuals to ascend without difficulties, and not only economical valuable species such as brown trout and grayling.

Based on this study, the results indicate that the vertical slot hybrid is a better design for a more complex fish species composition compared to the previous pool-and-weir design. Previous research supports this assumption (Gilligan et al. 2003; Mallen-Cooper & Brand 2007; Stuart & Mallen-Cooper 1999). However, this improvement is no guarantee for being the best solution possible. Olstad and Museth (2016) discovered higher concentrations of alpine bullhead (*Cottus poecilopus*) compared to brown trout and grayling during electrofishing downstream Høyegga in the autumn of 2016. The alpine bullhead is a bottom dwelling species with limited dispersal ability compared to migratory species (Paśko & Maślak 2003), but their motivation and capability to ascend the fishway in Høyegga is not studied. Alpine bullhead has never been registered by the VAKI Riverwatcher in the fishway at Høyegga. The alpine bullheads size can be the reason for zero registrations, as the VAKI Riverwatcher do not register individuals under 2 cm in height. The alpine bullhead is small bodied, and it may be able to pass the VAKI Riverwatcher without being registered. The Alpine bullhead may also be able to swim between the sprinkles in the entrance of the VAKI Riverwatcher. Another possible explanation is that the alpine bullhead, because of its small size, has too low swimming capacity to successfully pass the fishway.

With the data present, it is impossible to determine the reason for zero alpine bullhead registrations at the Høyegga fishway. However, other studies, show that several vertical slot fishways have been suitable for small individuals and bottom dwelling fish species (Stuart & Mallen-Cooper 1999; Stuart et al. 2008). Therefore, it was unexpected to find that the calculated mean length among the registered grayling and brown trout individuals increased significantly after the reconstruction of the fishway at Høyegga. Strong annual cohorts and increased numbers of mature individuals can be a possible explanation for this result. However, this is impossible to determine from the data used in this study. A significant decrease in mean body length would have been an indication of better functionality. Small individuals are often found to have lower swimming capacity compared to larger individuals within the same species, and can therefore struggle in pool-and-weir fishways if the hydrological properties exceeds the fishes swimming abilities (Farlinger & Beamish 1977; Lupandin 2005; Sambilay Jr 1990; Webb et al. 1984). Stuart and Mallen-Cooper (1999) discovered an increase among small individuals for several species after reconstruction from a pool-and-weir to a vertical slot fishway in Fitzroy river, Australia. This effect is however, not seen in the fishway at Høyegga for either grayling or brown trout, rather the opposite effect was observed. If the increase in mean length after reconstruction of the fishway at Høyegga is due to changes in the fish population structure or an effect of the redesign, is not investigated and needs further research. Variations in mean length within each year, as well as variations between years for grayling and brown trout in this study, also makes it difficult to conclude if the redesign has resulted in favourable conditions for longer fish. But, as mentioned, earlier research indicate that this effect should be the opposite (Stuart & Mallen-Cooper 1999; Stuart & Berghuis 2002; Stuart et al. 2008).

The redesign from pool-and-weir to vertical slot hybrid has probably changed the hydraulic conditions in the fishway. Velocity and turbulence are known to effect swimming capacity and the vertical slot design, compared to the pool-and-weir design, generally reduces both factors in a fishway. Earlier studies have experienced that a vertical slot with reduced turbulence and lower water velocity lead to greater diversity of fish species ascending the fishway (Stuart & Mallen-Cooper 1999; Stuart & Berghuis 2002). Linløkken (1993) found that low river flows were of importance regarding the use of the Høyegga fishway, as high discharges reduced grayling numbers in the fishway. Grayling entered the fishway in large numbers when the discharge was 20 m^3/s. Similar observations, but less clear, were also made in other fishways in the Glomma river (Linløkken 1993). The most supported AIC model for predicting migration of grayling in the Høyegga fishway indicates the same. Low discharge when ascending the fishway were favoured by grayling at any given temperature throughout the season. In this study the effect of discharge on upstream migratory brown trout is less clear. Linløkken (1993) highlighted that fishways in Glomma river should be constructed to cope with considerably higher discharges. The redesign at Høyegga has hopefully lead to the fishway being more functional also at higher discharges, since vertical slot designs are known to handle high flows in a better way than pool-and-weir fishways (Katopodis & Williams 2012). To determine if this also is the case for Høyegga fishway needs to be investigated further.

To what degree the motivation behind fishway designs are influenced by human's preferences also determine whether fishways are considered successful. Fishways have largely been installed for economical valued species such as different salmonid species (Direktoratet for Naturforvaltning 2002; Grande 2010). The Glomma project (1985-2007) was also established to improve the recreational fishing value in river Glomma (Qvenild 2008)*(for description of the Glomma project see footnote on page 5)*. Lately, it has been a greater focus on more versatile fishway constructions to maintain biological functionality for all fish species present when installing hydropower plants (Fjeldstad et al. 2013; Fjeldstad et al. 2012). In that respect, the reconstruction of the fishway at Høyegga has been successful by increasing the species diversity using the fishway.

As mentioned, it is not certain that this reconstruction is the best change possible, but the results indicate a step in the right direction. Todays most used fishway designs are structures made of concrete that are distinctively different from the river character. Both the pool-and-weir and the vertical slot are such designs. An alternative to these structures could be natural-like side channels. These fishways are usually longer and have a lower gradient compared to the most common designs. This can give a greater potential for a broader range of species to successfully pass the barrier (Roscoe & Hinch 2010). A meta-analysis undertaken by Bunt et al. (2012) discovered that nature-like fishways gave better results regarding passage efficiency, than the most common designs did. However, the attraction efficiency for natural-like fishways were low compared to other designs. On the other hand, Aarestrup et al. (2003) studied sea trout in a Danish natural-like fishway, and found great attraction efficiency, but low passage efficiency. These inconsistent findings underline the importance of site-specific evaluations (Calles & Greenberg 2007; Roscoe & Hinch 2010). A fully vertical slot design may be more efficient regarding fish migration than the hybrid version at Høyegga. However, as most fishways in Norway are of the pool-and-weir type, redesign projects to vertical slot hybrid fishways with added substrate are more cost efficient, compared to construction and deployment of completely new fishways. The great variety within and between fish species highlights the need of versatile constructions. This must be emphasised to preserve river connectivity to different length groups and a bigger span of species (Roscoe & Hinch 2010).

4.1 Limitations and sources of error

The change in use after the fishway reconstruction can be a result of changed population structure or environmental factors, and not a result of a more effective fishway. The data on migrating individuals in this study-period does not illustrate the population size or explain how large fraction of the motivated individuals in the population that successfully ascend the fishway. During the monitoring at Høyegga fishway from 1985 to 2012, all fish were caught in a trap and registered. Annual numbers of registered fish differed a lot in Høyegga fishway during these 22 years (Qvenild 2007; Taugbøl 2012) and compared to other monitored fishways in the Glomma river system, the yearly registrations varied most in Høyegga (Linløkken 1993). In 2003, it was a peak of fish in the fishway, with 1575 grayling and 169 brown trout individuals registered. In 1994 only 46 grayling individuals were registered, while 1989 was the year with lowest numbers of brown trout, with only four registered individuals. The amount of grayling in 2003 exceeded all other years, even the years after reconstruction (2016 and 2017). The mean number of annually registered individuals generally increased after the manually operated trap was removed in 2012 and replaced with the automatically operated VAKI Riverwatcher in 2013. This indicates that the registrations became more accurate from 2013, and the data before and after the new method was implemented, cannot be directly compared. Data from 2013 is excluded because the fishway opening was manually adjusted. This resulted in much higher water discharge in the fishway that led to totally different hydrological conditions compared to the other years. The reconstruction of the fishway only took place two years ago and therefor the data analysed in this study is only from the last four years (2014-2017). As data from very few years are used in this study and large annually variations in registered fish are observed in the Høyegga fishway, the higher numbers of registered fish may be due to other factors than the reconstruction. This can also be the reason for that this study did not find big changes in migration after the reconstruction regarding discharge and temperature. It was expected to observe migration under more extreme conditions after reconstruction as the vertical slot fishway is known to reduce water velocity and handle a broader range of discharges.

Late opening of the fishway in 2016, because of the reconstruction, and earlier collection of the data in 2017, because of the time limit, contributed to a shorter analysed opening period after reconstruction. In 2017, registrations after 17th of October are not included in the analysis. Between this date and 7th of November only one brown trout ascended the fishway, so this is not considered as a source of error. It is not known if the delayed opening in 2016 affected the amount of migrating fish. However, migration numbers in May 2015 and 2017 were both close to 500 individuals, which indicates that May is an important month regarding migration. The late opening in 2016 may have resulted in migration delays. This could especially be unfortunate for the individuals that spawn during late spring, which is the case for grayling, as they may not arrive to the spawning grounds in time (Caudill et al. 2007; Jungwirth et al. 1998; Larinier 2001). The fishway itself has been open all year around since the reconstruction in 2016, and it is planned to continue with this procedure in the future. Because of this, it will be important to deploy the VAKI Riverwatcher in time to capture all migrating individuals in the coming years. According to results from this study, the 10th of November seems like a reasonable date to stop the counter. However, the migration data should be investigated each year before dismantling the VAKI Riverwatcher, to ensure that the migration intensity for a period has been low or near zero fish per day.

Individuals with index name “repeat” have not been included in the data analyses. These individuals have potentially chosen to turn around within the first minute after passing the VAKI Riverwatcher. If individuals have chosen to stay for a longer time-period in any chamber upstream the VAKI Riverwatcher before turning around, these individuals are counted twice, both upstream and downstream. To handle this issue, the VAKI Riverwatcher should be moved from chamber number 15 to the top exit of the fishway. This change is planned to be completed in 2018. By doing this, all registered upstream migratory fish will be a result of successful passage.

Results in this study are compared to other studies on vertical slot fishways, but the Høyegga fishway is not a fully vertical slot, but a hybrid version. However, the vertical slot design is nevertheless the closest type regarding design and thereby natural to compare with. To strengthen the results from this study, measures of physical properties should be undertaken in order to determine the hydrological similarities between these two designs.

Data errors may have occurred during the monitoring periods and in relation to species determination. Some registrations may have been fish, but due to uncertainties, they have not been counted. Error regarding species determination may also have occurred during the monitoring period. Turbulence, coloured water and fast swimming individuals can make it difficult to separate the different species. The data set was checked, review and cleaned for detected errors using various tools in Excel, so that the final dataset contained the least possible errors and misleading values. All the punching of the data was done by the same person which potentially reduced the errors in the dataset or the errors were more consistent. However, error in relation to punching and processing of the data may have occurred and cannot be excluded as a source of error.

To quantify the combined influences from external factors and dam water management on upstream migration, ZIP model selection was undertaken. A set of variables that have been measured and are known to affect fish migration was used in this selection. There could, and most probably are, other factors that also determines the migration of grayling and brown trout in Høyegga fishway (e.g. hydrological properties of the fishway). This is emphasized because the "day of year"-variable remained a highly influential predictor variable even after including discharge and temperature. It seems likely that some important variables may be missing in order to determine what controls migration the most. However, most of the variables used had a significant impact on the migration in the most supported model. It is important to emphasize that this is a model prediction and that the natural conditions on the site will influence migration and also can override factors used in this model. Different models can yield different results with very different interpretations. The selected zero-inflated Poisson model is designed to deal with data that has extensive numbers with the count zero. However, the model approach has some limitations and adds some assumptions, as all models do. This model approach assumes that the zero observations have two different origins; sampling and structural. Some sampling zeros are assumed to happen by chance, because of the Poisson distribution, and some zeros are registered because no variation in the prediction variables could change the count. These "structural zeros" can for instance be individuals that are not sexual mature and therefore do not migrate to spawn. The zero-inflated modelling approach is much used in research and is shown to be easy to interpret and lead to more refined data analysis (Lambert 1992; Zuur et al. 2009). Generalized linear model (GLM) approach and negative binomial GLMs were tested against the ZIP model approach to investigate if alternative model approaches would be more suitable. However, the ZIP model came out as superior against both. It is still important to point out that other models could be more appropriate to predict what factors contribute the most to grayling and brown trout migration. However, a model that can contribute to increased knowledge regarding factors that influences use of the Høyegga fishway, and potentially lead to a more successful migration, is still preferable.

4.2 Further research

To gain more knowledge about the fishway effectiveness and functionality, investigation of the proportion of successfully migrants in Høyegga fishway should be undertaken. If just a small proportion of the motivated individuals are able to ascend the fishway further measures should be considered implemented. However, the appearance of other species with assumed lower swimming capacity (burbot, pike, higher numbers of whitefish) after reconstruction indicates that the fishway is easier to ascend for a broader range of species.

Analysis of the water velocity and energy density in each chamber at different discharges through the fishway should be undertaken and compared to the measurements taken before reconstruction. These data will give a better picture and understanding of the hydrological changes in the fishway. It is known that vertical slot fishways are able to handle big changes in discharge better than the pool-and-weir type (Katopodis & Williams 2012). However, the fishway at Høyegga is not a fully vertical slot design, but a hybrid type. Analysis of the hydrological properties is needed and measures of the water velocity around the fishway entrance is also suggested to be undertaken. It is important to investigate if the water velocity from the tap-spillway is too high during periods with low temperatures (<5°C) and therefore lead to less migration.

In addition to the measures mentioned, it is also important to keep monitoring the fishway at Høyegga in the coming years. This will increase the dataset and its reliability, and hopefully lead to more knowledge about the effects on migratory fish after fishway reconstruction from pool-and-weir to a vertical slot hybrid. There is little research that examines changes in fish migration when a fishway is reconstructed from pool-and-weir design to a vertical slot. Similar studies in other fishways should also be undertaken to determine if the effects of a redesign are seen under other environmental conditions and fish communities. If the redesign to a vertical slot hybrid is good enough to ensure satisfactory migration past a barrier among all motivated species, this will be a cost-efficient solution which is applicable to many locations in the world.

4.3 Management implications

From this study it is clearly two important migration periods for grayling in Høyegga, one during May and one around the beginning of July, respectively. From 2016 the fishway has been open all year around, but in order to get the best picture of migration patterns it is important to deploy the VAKI Riverwatcher before these peaks each year. This is valuable data which will be important in the future in order to follow up the effectiveness and use of the fishway. Evaluation and monitoring of changes is important to ensure that the fishway is functioning as purposed (Clay 1995; Roscoe & Hinch 2010). Results from this study indicates that grayling favour low water discharges at any given temperature. Managers should have this in mind during the most important migration periods for grayling. High discharges combined with low water temperatures seemed to decrease grayling and brown trout migration during mid-May 2017. High discharges can possibly make it difficult for fish to locate the entrance of the fishway or make fish struggle with ascending the fishway. Experimenting with different spillway settings is suggested during periods with low temperatures (<5°C). In order to enter the fishway all individuals must pass the current created by the water led through the tap spillway. The minimum flow of 10 m^3/s is usually led through the tap spillway, which may be too much for grayling and brown trout when the mean temperature is low. This can potentially be the reason for low registered numbers during low temperature regimes. The downside with reduced discharge in the tap-spillway is reduced attraction water, which is known to be of importance for migratory fish species in order to locate the fishway entrance (Katopodis 1992).

The majority of the migratory fish mainly ascend the fishway during daytime at Høyegga. Jonsson (1991) review of studies regarding migration in relation to water flow, temperature and light, stated that most salmonids and fish in general migrates upstream during dark hours. Daytime migrations generally occur under special conditions according to Jonsson (1991). However, results from this study indicates that upstream migratory individuals, especially grayling, migrate mainly during daytime. The light conditions are poor in the last six chambers at the Høyegga fishway because they are located under the dam. This can potentially be a barrier if the fish is dependent on good light conditions to ascend the fishway. Therefore, it is suggested to increase the brightness in the last six chambers during daytime and evaluate if this has a positive effect on the passage success. The VAKI Riverwatcher can potentially be a migration barrier for certain species and small individuals because of high velocity and lack of substrate. To decrease the velocity and increase the roughness it is suggested to install a plate with stones attached to the floor of the VAKI Riverwatcher chamber. A measure like this can potentially lead to increased fishway use by bottom dwelling species with low swimming capacity, such as burbot and alpine bullhead.

The findings at Høyegga is especially valuable for the rest of the Glomma river, as most of the fishways in this system still are of the pool-and-weir type. Other locations, both in Norway and in the rest of the world, can also take advantages of these findings. As the reconstruction to a vertical slot hybrid seems to be a better design regarding numbers of fish and species ascending it, compared to the pool-and-weir design. This reconstruction is also a cost-effective change compared to construction and implementation of brand new fishways. Even though other rivers have other hydrological properties, fishway characteristics and fish species compositions, the change from pool-and-weir design to vertical slot, has shown to be successful in very different environments, both in temperate, subtropical and tropical climate zones (Gilligan et al. 2003; Stuart & Mallen-Cooper 1999).

Conclusion

It is too early to say if the reconstruction of the fishway at Høyegga in Norway, led to increased numbers of upstream registered individuals. The two years studied before and after reconstruction are very different, both in treatment groups and environmental factors. These annual effects can influence and override the variables used in the ZIP model and the other results from this study, and are especially critical because of the few sampling years. It is however a clear tendency that higher numbers of grayling ascended the fishway after reconstruction for a given temperature and water discharge.

Both grayling and brown trout migrated primarily during daylight and approximately within the same time periods each year. However, from mid-May to mid-June 2017, higher numbers of brown trout ascended the fishway compared to previous years. The prediction plots showed that the migration patterns were the same before and after reconstruction. Both species favoured higher temperatures compared to low. Grayling showed to favour low discharges, while brown trout upstream migration depended more on temperature. Both species showed increased mean size over the four monitored years. If this is a result of the reconstruction or a result of changed population structure is not known. An increase in registered numbers of species were also observed.

The Høyegga fishway needs to be studied further to increase the knowledge about the effects on migratory fish after fishway reconstruction from pool-and-weir to a vertical slot hybrid. A large number of fishways show poor functionality, and many more have an unknown status. Most fishways in Norway are of the pool-and-weir type, which can be an unsuited design at locations with a complex fish-species composition. If the redesign to vertical slot hybrid is good enough to ensure satisfactory migration past a barrier among all motivated species, this will be a cost-efficient solution, which is applicable to many locations in the world.

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