The effects of stream channelization on salmonid habitats in western Norway

Thesis submitted in partial fulfilment of the requirements for the degree of: Master of Science in Biodiversity, Evolution & Ecology

by

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Preface

This study was done as part of the research project Mer laks og sjøørret på Sunnmøre (More salmon and sea trout in Sunnmøre) project, led by Marius Kambestad at the Laboratory for Freshwater Ecology and Inland Fisheries (LFI) at NORCE. All field work was conducted by Rowan Hamper, Marius Kambestad and Lisa Hansen Simonsen. Aerial drone photos were taken by Marius Kambestad, while differential GPS data and RTK drone footage was compiled in Agisoft Professional and QGIS by Erlend Mjelde Hanssen. This thesis is presented in the format of a scientific paper.

Acknowledgements

I would like to express my gratitude to multiple people for their support in the completion of this thesis. Firstly, to my three supervisors, Gaute Velle, Knut Wiik Vollset and Marius Kambestad. Even during your busiest times, you always found time to read my texts and give feedback, even if it was close to midnight and you had been doing field work all day. For that I am extremely grateful. Thank you for your excellent guidance and expertise. I must also extend an extra special thank you to Marius. Nobody else has dedicated as much time and energy into helping me with this project. You have been deeply involved every step of the way – whether valiantly trying to teach me proper usage of the Oxford comma, instructing me in electrofishing techniques, or ensuring I took breaks so you could beat me in table tennis. This paper would look very different without your influence, and for that I express my very deepest gratitude.

I would also like to thank the entire staff and my fellow students at LFI for making me feel welcome from day one and making the process so enjoyable. Working alongside such passionate and knowledgeable people is a huge source of inspiration. I thank every one of you, with special mentions to Ulrich Pulg for assisting with my project and allowing me to assist you with yours, and Nadja Meister for always being generous with your advice on writing and statistics. Also a big thanks to Lisa Hansen Simonsen for assisting with field work and making maps, and Erlend Mjelde Hanssen for helping me out with QGIS.

I could not talk about the most important people in this process without mentioning some of those closest to me. My parents Chris and Hilary. You are both a constant source of inspiration and support. To mum, thank you for always being there with wise and comforting words. To dad, thank you for kick-starting my interests in salmon and trout. Even while writing now, I look back fondly on memories of us fly fishing and watching *Salmo the leaper* on VHS. To my girlfriend, Marlen: thank you for always being there, for helping me relax during my more stressed moments, and being willing to listen to me drone on about rivers and fish for hours. Finally, a big thanks to my sister Josie for proofreading my text, and my four year old nephew Hugo for always keeping me on my toes with the most profound questions about fish biology, like: *"Do fish have to go to the toilet?"*

Abstract

Amidst the Anthropocene era's heightened human influence on the environment and escalating habitat degradation, this study investigates the impacts of channelization on salmon and sea trout habitats in small streams in western Norway. Through hydraulic measurements, habitat mapping, and juvenile fish surveys, the research aimed to assess channelization effects on spawning gravel proportion, shelter availability, and juvenile fish density. Surprisingly, while shelter availability was lower in channelized sites, no significant effects of channelization were observed on spawning gravel proportion or juvenile fish density, challenging initial hypotheses. These findings underscore the complexity of relationships between channelization, habitat, and fish population dynamics in these ecosystems. In conclusion, the study highlights the necessity for comprehensive pre-intervention assessments and consideration of diverse approaches to preserve habitat integrity while considering channelization in these environments, while also highlighting the limitations of standardized habitat mapping methods.

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1 – Introduction

In the Anthropocene era, characterized by increased human influence and rising temperatures on the planet, habitat degradation due to human intervention has emerged as a prominent ecological challenge (Dudgeon, 2019; Steffen et al., 2011). Freshwater ecosystems have been particularly impacted, as the hydrological cycle is undergoing transformation due to climate change both directly and through physical interventions, with the result that habitats are threatened in 65% of rivers (Bridgewater et al., 2017; Dudgeon, 2019; Vörösmarty et al., 2010; Woodward et al., 2010). In recent decades populations of Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*), hereafter referred to as salmon and sea trout, have experienced dramatic declines, leading to their endangerment or extinction in numerous North American and European rivers (Chaput, 2012; Finstad et al., 2011; Jonsson, 1999; Parrish et al., 1998; Vollset et al., 2022; WWF, 2001). In Norway, the total number of salmon returning to their natal rivers from the sea has been reduced by more than half since the 1980s, with the steepest decline seen along the west coast, while threat assessments for sea trout have consistently shown that they are under threat (Thorstad & Forseth, 2022; Thorstad & Forseth, 2023; Vollset et al., 2022). Many populations are below critical conservation thresholds, despite extensive efforts to mitigate the declines (Lennox et al., 2021; Thorstad & Forseth, 2022; Thorstad & Forseth, 2023). Hydropower, genetic introgression from escaped farmed salmon, salmon lice (*Lepeophtheirus salmonis*), overfishing, acid rain and morphological interventions have all been named as leading causes (Forseth et al., 2017; Hohensinner et al., 2018).

As anadromous fish, salmon and sea trout spend part of their life cycle at sea and part in freshwaters, and thus require access to healthy riverine habitats (Klemetsen et al., 200; Lennox et al., 2021). Along with the density of benthic invertebrates, two of the most important limiting factors for salmonid production in rivers are access to spawning areas and sufficient shelter for juveniles (Aas et al., 2011; Forseth & Harby, 2014; Jowett, 1992; Pulg et al., 2013). Salmon and sea trout eggs are deposited in spawning nests (redds) in the gravel and subsequently fertilized and buried (Aas et al., 2011; Kondolf, 2000; Pulg et al., 2017; Sear & DeVries, 2008). As excessively large sediment grains prevent redd building, and small grains, such as sand and silt, have to low water permeability for the eggs and alevins to survive in the substrate, salmonids prefer sediments with diameters ranging from approximately 1 cm to 10 cm (Kondolf, 2000; Hauer et al., 2018; Sear & DeVries, 2008). In addition to spawning areas, areas in which fish can find shelter from fast-flowing water and predation play a pivotal role in decreasing density dependent mortality among juveniles (Finstad et al., 2007; Forseth & Harby, 2014; Pulg et al., 2017). Juvenile salmon and sea trout use cavities between or underneath rocks and boulders, overhanging banks, riparian vegetation, macrophytes, and moss as shelter, and shelter availability is positively correlated with juvenile density (Aas et al., 2011; Finstad et al., 2007; Finstad et al., 2009; Forseth & Harby, 2014; Velle et al., 2022).

Morphological alterations in rivers, such as channelization, embankments and floodplain disconnection represent some of the most widespread interventions in Norwegian and European rivers and streams (Aas et al., 2011; Belletti et al., 2020; Hauer et al., 2018; Pulg et al., 2017). Channelization, a common engineering practice used to control flooding, prevent river bank erosion and manage river channels, significantly impacts riverine ecosystems (Brooker, 1985; Brookes, 1983; Hohensinner et al., 2018). Channelization typically leads to an increase in river gradient, leading to an increase in shear stress, which is directly correlated to a river's capacity to transport sediments (Emerson, 1971; Fergus et al., 2010). This can over time highly impact the composition of the substrate in a river (Fergus et al., 2010), and along with the direct removal and replacements of sediments by humans, often associated with channelization, could impact the habitat for a wide variety of organisms, including salmon and sea trout. Changes in substrate composition and stability affects the amount of spawning gravel, shelter, and fish density in rivers (Duvel et al., 1976; Hauer et al., 2018; Hohensinner et al., 2018; Whitney & Bailey, 1959). As Norway experiences a rising frequency of floods due to increased precipitation resulting from climate change, the need for protection against floods and erosion from streams increases (Vormoor et al., 2016). Additional research on the ecological effects of these interventions is therefore of great importance, and the need for nature-based solutions increases (Pulg et al., 2023).

Although salmon and sea trout are often associated with large rivers, small streams also provide vital spawning and nurturing areas, particularly for trout (Whelan, 2014). Although channelization has been shown to have a negative effect on habitat quality in rivers and may alter the substrate composition and reduce the shelter availability for salmon and sea trout (Hahn, 1982; Hauer et al., 2018), these effects are not widely documented in small streams, which often mainly hold sea trout (Whelan, 2014). In 2011, the Atlantic Salmon Trust identified the need for research on the ecology of such small streams and asserted the need for a greater focus on their significance for sea trout production (Whelan, 2014). Small streams may be particularly vulnerable to physical alterations through climate change and human interventions, and the effects of these alterations have been identified as an important gap in knowledge (Whelan, 2014).

The aim of this project was to investigate effects caused by channelization and associated changes in shear stress on habitat quality and density of salmon and sea trout in small streams. To assess these effects, the following hypotheses were tested:

H1a. The proportion of spawning gravel will be lower where a stream has been channelized.

H1b. The proportion of spawning gravel depends on shear stress.

H2a. Shelter availability for juvenile salmonids will be lower where a stream has been channelized.

H2b. Shelter availability for juvenile salmonids depends on shear stress.

H3a. The density of juvenile salmonids will be lower where a stream has been channelized.

H3b. The density of juvenile salmonids depends on the proportion of spawning gravel.

H3c. The density of juvenile salmonids depends on shelter availability.

These hypotheses were tested by mapping twelve streams in Sunnmøre, Western Norway by taking hydraulic measurements, mapping spawning gravel and shelter, and conducting juvenile fish density surveys.

2 – Materials and methods

The hydraulic measurements and habitat mapping was performed in May 2013, whereas fish density data was collected in August and September 2023.

2.1 - Study area

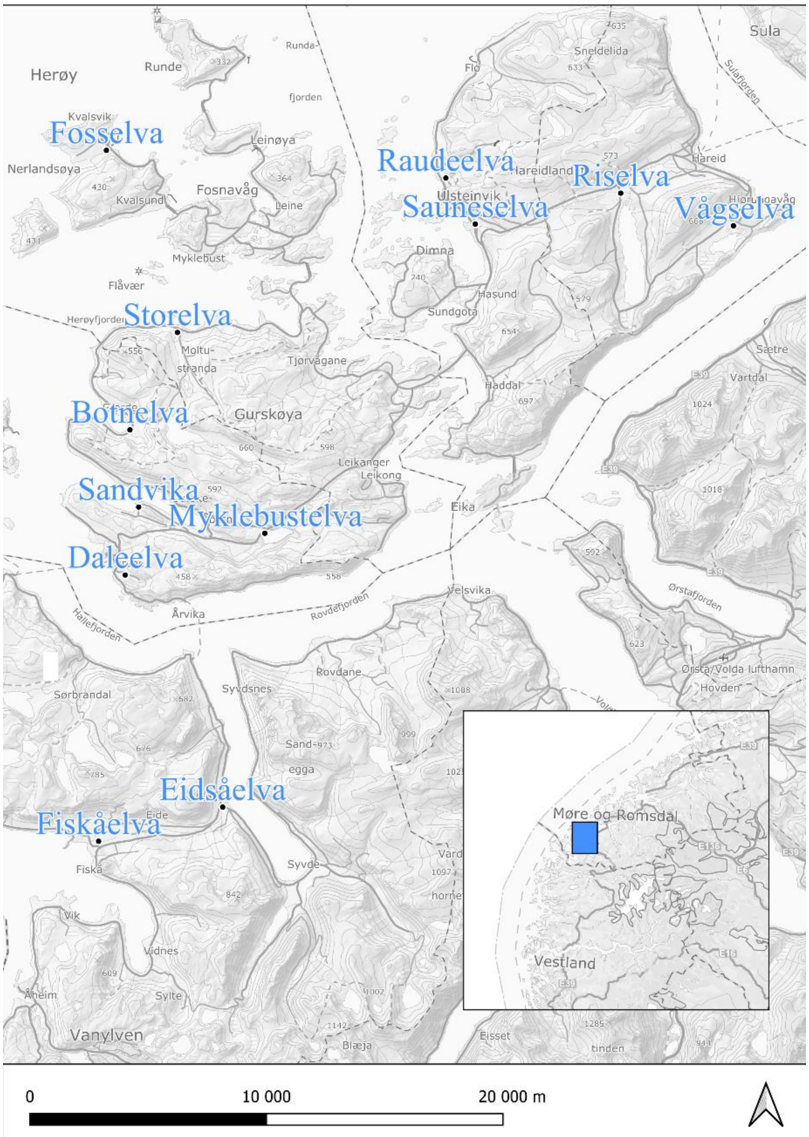

Figure 1. Map of the study area, created in QGIS by Lisa Hansen Simonsen

Twelve streams were selected in Sunnmøre in the southwest of Møre og Romsdal, Norway (Figure 1). Two study sites were selected within each stream, one natural control site and one channelized site. Both sites were selected within the anadromous length of the stream, and as close to each other as possible. Each channelized site had similar channelization structures, consisting mainly of large rocks stacked vertically, avoiding sites consisting of smooth stone plastering and cement structures. Examples of structures typical for the studied sites can be viewed in Appendix I. The NEVINA mapping software (Norwegian Water Resources and Energy Directorate [NVE], 2022) was used to estimate the catchment area and mean discharge for each stream (Table 1). The software generated the catchment areas automatically.

Table 1. Catchment area parameters for the twelve studied streams

Stream	Location	Catchment area (km^2)	Mean discharge (l/s)
Botnelva	62.2556, 5.5804	2.3	98.4
Daleelva	62.2030, 5.5760	3.4	125.1
Eidsåelva	62.1162, 5.6771	5.3	195.0
Fiskåelva	62.0973, 5.5676	15.5	891.3
Fosselva	62.3614, 5.5547	1.7	55.6
Myklebustelva	62.2215, 5.6494	5.5	234.3
Raudeelva	62.3569, 5.8219	0.8	31.8
Riselva	62.3530, 5.9803	11.7	524.2
Sandvika	62.2244, 5.5892	1.0	32.1
Sauneselva	62.3404, 5.8485	5.5	234.3
Storelva	62.2957, 5.6166	8.6	370.7
Vågselva	62.3457, 6.0671	8.6	347.4

The mean catchment area of the streams was 5.8 km^2 (range 0.8 to 15.5 km^2) and the mean discharge was 291.7 l/s (range 31.1 to 891.3 l/s). The mean width of the sites was 3.2 m (range 0.8 to 7.6 m), and the mean length was 27.1 m (range 18.4 to 43.2 m). Orthomosaic aerial photos of each site, taken with a DJI Phantom 4 RTK drone, can be viewed in Appendix II.

2.2 – Hydraulic measurements

Shear stress (τ_0) was found for each site using formula (1).

$$\tau_0 = \gamma \cdot R \cdot \sin \alpha \qquad (1)$$

where γ is the specific weight of water (9810 N/m^3), R is the hydraulic radius of the stream and α is the stream's gradient (Fergus et al., 2010).

To find R and α, points were taken along three cross sectional transects as well as the entire length of each site, using a Trimble TSC5 differential GPS along with aerial photos taken with a DJI Phantom 4 RTK drone. The wetted periphery and cross-sectional area were used to calculate R for each site (Wei, 2023) using the HEC-RAS software. The aerial photos were compiled in Agisoft Metashape Professional, using the structure from motion function. The RTK photos and GPS points were then compiled in QGIS 3.28.5 to measure the distances and difference in elevation between each point. The upper limit of each transect was found by visually identifying the top of the river channel. The aerial photos were also used to determine each site's total area in QGIS. Vågselva was an exception, as dense vegetation impeded the drone. Here, the area was found by measuring the length and width of the stream, using a laser measurer to measure the length and four measurements of the width, used to calculate the mean width.

2.3 – Shelter and spawning gravel measurements

The two habitat requirements measured were the availability of shelter and the percentage of spawning gravel in the substrate. Shelter in the substrate was measured using a 50 x 50 cm grid at a minimum of 15 locations within each site (Forseth & Harby, 2014). Placement of the grid was determined moving upstream, from left bank to middle to right bank, taking one step forward between each location and dropping the grid after each step. In addition, the percentage of the bank providing overhanging shelter, defined as any shelter within the vertical bank, was visually estimated for each site. Shelter provided by vegetation was not measured. However, in stream vegetation was scarce in all sites and would not have provided a large amount of shelter.

Substrate samples were gathered following a modified Wolman pebble count (Bevenger, 1995, Wolman, 1954). Each sample was measured using a gravelometer or calliper and sorted into standard Wentworth size classes (Table 2) (Bevenger 1995; Bunte, 2001; Wentworth, 1922). A minimum of 100 samples were taken from each site, by moving in a zig-zag pattern upstream along the entire site, taking small steps and selecting stones randomly while averting one's eyes.

Table 2. Modified Wentworth grain size classes and descriptions (Bevenger, 1995).

Size class	Size (mm)	Description
1	< 2	Sand
2	2 – 4	Very fine gravel
3	4 – 8	Fine gravel
4	8 – 16	Medium gravel
5	16 – 32	Coarse gravel
6	32 - 64	Very coarse gravel
7	64 – 128	Small cobble
8	128 – 180	Large cobble
9	180 – 256	Very large cobble
10	256 – 512	Small boulder
11	512 – 1024	Medium boulder
12	1024 – 2048	Large boulder
13	2048 – 4096	Very large boulder

2.4 - Fish densities

Fish density was found through backpack electrofishing, following the methods detailed by Bohlin et al. (1989). Prior to fishing, each site was closed off using nets across the upper and lower limits of the site to avoid immigration and emigration of fish, and the temperature and conductivity was measured (Table 3). Each site was fished from three to six times, with a minimum of 15 minutes between the start of each pass. The fish were counted, their natural length measured to the nearest millimeter, and their species determined between each pass. Salmon and sea trout were pooled, due to salmon catches being zero in most streams, the exceptions being Fiskåelva, Riselva and Storelva. The fish were then roughly divided into age groups, the young of the year (0+) and older parr. The precision threshold denoted as $CI/\hat{N}$ (where $\hat{N}$ is the estimated abundance and CI is the one-sided 95% confidence interval of $\hat{N}$) was determined by estimating the abundance for each age group after each pass (Carle & Strub, 1978). This was done in the field using the Elfish app (Kambestad et al., 2017). It was determined that a precision threshold of 0.2 or less had to be reached for both 0+ and older parr before fishing was stopped, to ensure accurate estimates. It was also decided that fishing could be stopped if the catch was zero in the previous pass and a minimum of three passes had been completed. After the final pass was completed, all fish were released back into the stream. Fish abundance and the total area of each site was used to calculate fish density. As most fish caught were trout, they were pooled with salmon to be analysed together as juvenile salmonids.

Table 3. Electrofishing parameters for each site.

Stream	Site	Date	Area (m^2)	Water temperature (℃)	Conductivity ($\frac{\mu S}{cm}$)	Passes
Botnelva	Natural	Aug 31st	72.5	12.5	41.2	5
Botnelva	Channelized	Aug 31st	82.8	12.7	42.5	3
Daleelva	Natural	Sep 2nd	93.7	13.5	57.0	4
Daleelva	Channelized	Sep 2nd	48.0	13.2	58.6	3
Eidsåelva	Natural	Sep 2nd	101.9	12.1	46.9	3
Eidsåelva	Channelized	Sep 2nd	93.7	11.7	47.5	3
Fiskåelva	Natural	Sep 3rd	111.6	11.6	47.2	3
Fiskåelva	Channelized	Sep 3rd	82.9	11.3	40.2	3
Fosselva	Natural	Sep 1st	62.0	14.3	84.9	3
Fosselva	Channelized	Sep 1st	35.6	14.1	81.0	3
Myklebustelva	Natural	Sep 1st	127.2	12.4	48.3	5
Myklebustelva	Channelized	Sep 1st	76.6	12.0	48.6	3
Raudeelva	Natural	Aug 27th	66.1	10.3	65.3	3
Raudeelva	Channelized	Aug 27th	34.4	12.2	56.4	3
Riselva	Natural	Aug 27th	101.3	10.4	89.0	3
Riselva	Channelized	Aug 27th	118.6	10.3	84.2	6
Sandvika	Natural	Aug 31st	38.9	13.1	70.2	4
Sandvika	Channelized	Aug 31st	27.3	13.1	68.8	3
Sauneselva	Natural	Sep 2nd	57.6	10.5	43.4	3
Sauneselva	Channelized	Sep 2nd	43.7	9.8	41.1	3
Storelva	Natural	Aug 31st	165.1	12.4	52.5	3
Storelva	Channelized	Aug 31st	215.6	12.2	52.0	4
Vågselva	Natural	Aug 27th	86.4	11.9	115.6	3

Vågselva	Channelized	Aug 27th	54.0	11.0	102.4	3

2.5 - Statistical analyses

All data sorting, modelling and analyses were conducted using Microsoft Excel from Office 365 and R Studio version 2023.06.2. To set up the experimental design, a causal diagram was made (Figure 2), showing the hypothesized relationship between site type (where site type is either the natural or channelized site), shear stress, habitat, and salmonid density. Where the data was normally distributed, the 'lmer' linear mixed effects models were used. Otherwise generalized linear mixed models were used, using the 'glmmTMB' function in the glmmTMB package. Q-Q plots were made to test for normality using the 'qqnorm' and 'qqline' functions, as well as running Shapiro-Wilk tests using the 'shapiro.test' function. All models are numbered in correspondence with the hypothesis being tested. For all models, backward model selection was conducting using Akaike's information criterion (Akaike, 1998) to determine which predictors to retain, opting for the model with the lowest AIC. More complex models were retained only if the difference in AIC exceeded 2 ($\Delta AIC > 2$). All models include stream as a random effect.

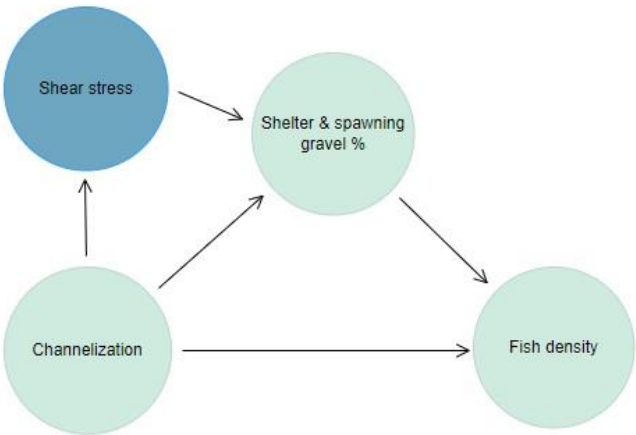

Figure 2. Causal diagram showing the hypothesized relationship between channelization, shear stress, habitat, and salmonid density.

The substrate samples gathered by the Wolman pebble count were sorted using Wentworth size classes (Table 2). The sediment substrate sizes were plotted into cumulative distribution graphs, used to determine median size class for each site, and percentage of gravel suitable for spawning. As salmon and trout prefer gravel between 1 and 10 cm for spawning, suitable spawning gravel was determined to be all sediments within size classes 4 to 7, or medium gravel to small cobble (Table 2). To test hypotheses H1a and H1b, the effect of channelization on proportion of spawning gravel was tested as well as the effect of shear stress and the interaction between channelization and shear stress, using a generalized linear mixed-effects model (M1, Table 4).

To examine the effects of channelization on shelter, the mean shelter index (SI) was calculated for each site (Forseth & Harby, 2014). To test hypotheses H2a and H2b, the effect of channelization on shelter index was tested, as well as the effect of shear stress and the interaction between channelization and shear stress, using a linear mixed-effects model (M2, Table 4).

Salmonid abundance was estimated following the methods detailed by Carle & Strub (1978), using the FSA package (Ogle et al., 2023). Abundance was estimated for both age groups (0+ and older) as well as three separate size groups. The age groups were determined by using length frequency diagrams and analyzing size gaps for each stream. Size groups were determined following average sizes for streams within the given stream's discharge range, found by Jonsson & Jonsson (2001). The size groups were divided as group 1: 0 – 70 mm, group 2: 71 – 130 mm, group 3: > 130 mm, corresponding to fish of age 0+, older parr and fish of smolt size respectively. Salmonid abundance along with the site's area was used to determine salmonid density (number of fish per 100 m^2). In the channelized sites, the area of the site was adjusted what was assumed to be closer to its pre-disturbed area, by using the width from the natural site. To test hypotheses H3a and H3b, the effects of channelization on salmonid density were tested, as well as the effects of the proportion of spawning gravel and the interaction between spawning gravel proportion and channelization, using a generalized linear mixed model (M3, Table 4). To test hypothesis H3c, the effect of channelization on salmonid density were tested, as well as the effects of SI and the interaction between channelization and SI (M4, Table 4).

Table 4. Statistical models used to test each hypothesis.

Hypotheses tested	Model
H1a, H2b	M1: glmmTMB(gravel proportion ~ site type + shear stress + (site type: shear stress) + (1|stream))
H2a, H2b	M2: lmer(shelter index ~ channelization + shear stress + (site type: shear stress) + (1|stream)
H3a, H3b	M3: glmmTMB(salmonid density ~ site type + gravel percentage + (site type: gravel proportion) + (1|stream)
H3c	M4: glmmTMB(salmonid density ~ site type + shelter index + (site type: shelter index) + (1|stream)

3 – Results

3.1 – Hydraulic measurements

The shear stress for natural sites ranged from 213 Nm^2 in Fiskåelva to 3336 Nm^2 in Daleelva (Figure 3), with a mean value of 1331 Nm^2. For channelized sites the shear stress ranged from 610 Nm^2 in Fiskåelva to 3700 Nm^2 in Sauneselva, with a mean value of 1579 Nm^2.

3.2 – The effects of channelization and shear stress on spawning gravel proportion

The Wolman pebble count found that 68% of the substrate samples in natural sites and 65% in channelized sites were suitable for spawning (Figure 4).

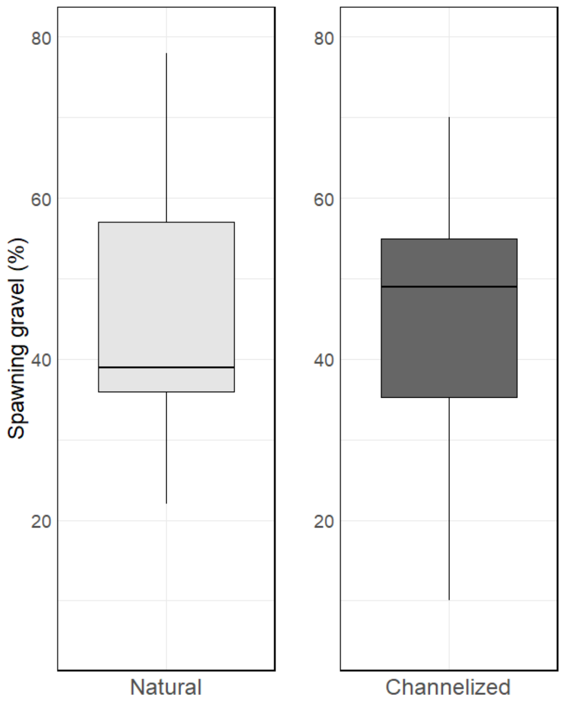

Figure 4. Proportion of spawning gravel for natural and channelized sites. Each box plot displays the median and interquartile range from the 25^{th} to 75^{th} percentile, as well as minimum and maximum (bars) and outliers (black dots).

Model M1 was used to determine the effects of channelization on the proportion of spawning gravel, as well as the effects of shear stress and the interaction between channelization and shear stress. Using backward model selection through an AIC analysis on M1, it was shown that none of the predictors were suitable to explain changes in the proportion of spawning gravel between natural and channelized sites. Hypotheses H1a and H1b were thus rejected.

Cumulative distribution curves were made for the size class (Table 2) of all sediment samples found in each site (Figure 5). These show the difference in dominating size class found in each site, with the red line representing natural sites and the blue representing channelized sites.

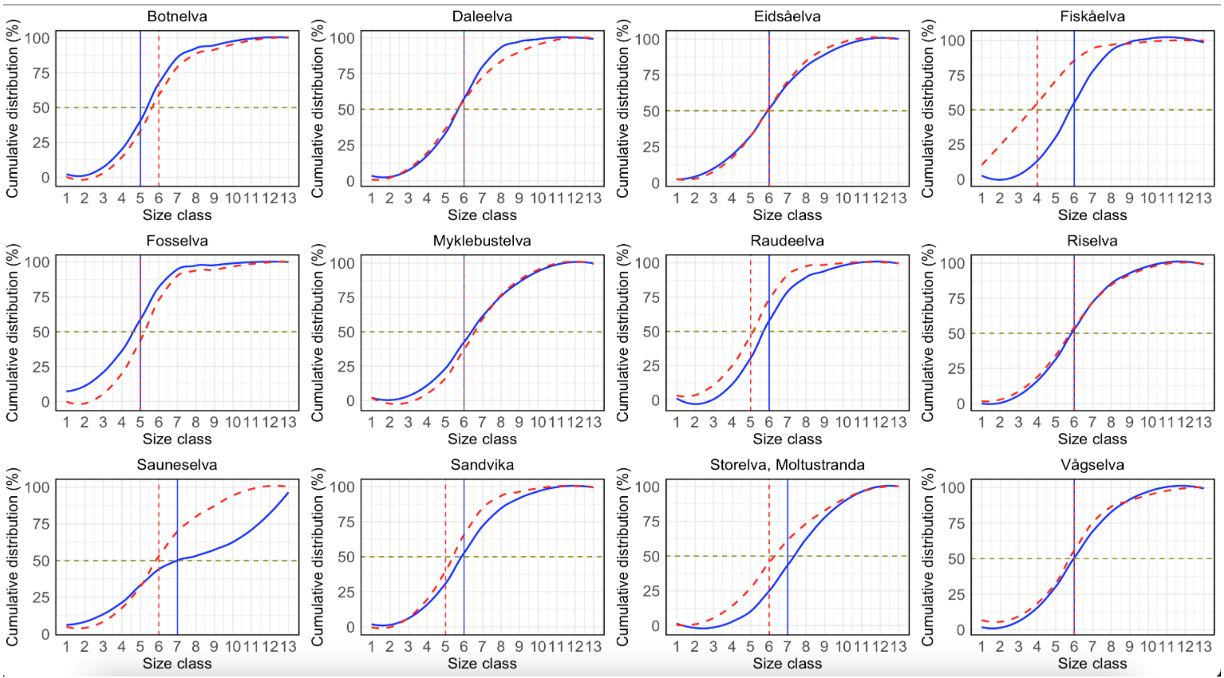

Figure 5. Cumulative distribution curves for the sediment samples in all streams. The curved lines represent the size distributions for natural (red) and channelized (blue) sites. The vertical lines show where the curve reaches 50% along the y-axis, and the correlating size class along the x-axis.

The natural sites had an average median grain size class of 5.6, falling between coarse gravel and very coarse gravel (Table 2). Channelized streams had an average median size class of 6.0, equating to very coarse gravel (Table 2).

3.3 – The effects of channelization and shear stress on shelter

The mean SI was 5.7 in natural sites, and 3.8 in channelized sites (Figure 6), indicating moderate shelter in natural sites and poor shelter in channelized sites (Forseth & Harby, 2014).

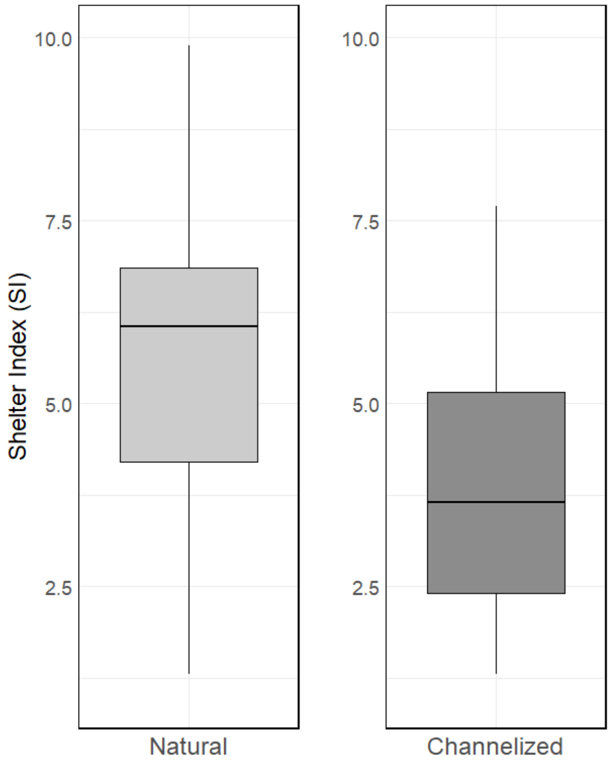

Figure 6. Mean SI natural and channelized sites. Each box plot displays the median and interquartile range from the 25th to 75th percentile, as well as minimum and maximum (bars) and outliers (black dots).

Model M2 was used to determine the effect of channelization on SI, as well as the effects of shears stress and the interaction between channelization and shear stress. Using backwards model selection through an AIC analysis of M2, it was shown that the model containing channelization as the only predictor was most suitable. Shear stress and the interaction between channelization and shear stress were therefore removed from the model. There was a significant effect of site type on SI (Model M2, $p = 0.005$). Thus, hypothesis H2a was confirmed, while H2b was rejected.

The proportion of banks that were suitable as shelter for salmonids (Figure 7) had a mean value of 29% for natural sites and 30% for channelized sites.

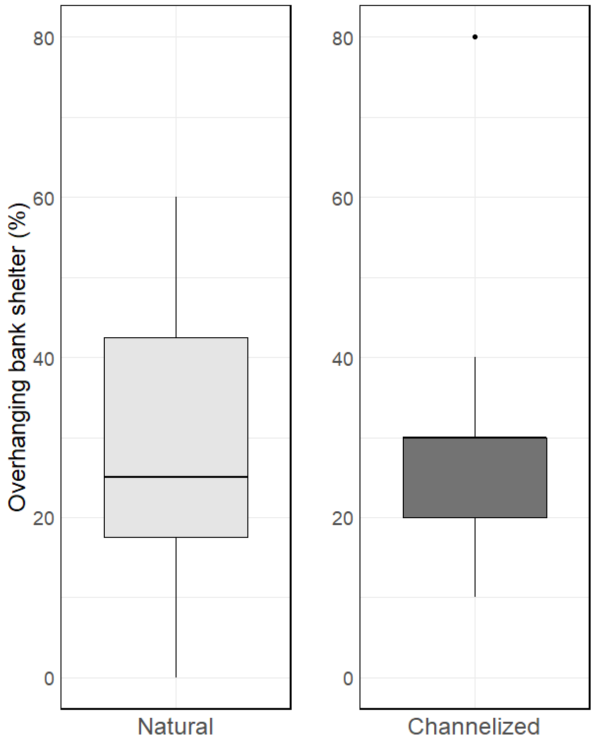

Figure 7. Overhanging bank percentage for natural and channelized sites. Each box plot displays the median and interquartile range from the 25th to 75th percentile, as well as minimum and maximum (bars) and outliers (black dots).

3.4 – The effects of channelization, spawning gravel and shelter index on salmonid density

The mean density for 0+ was 31 fish per m^2 for natural sites and 38 fish per 100 m^2 for channelized sites (Figure 8). Older salmonids had a mean density of 30 fish per m^2 for natural sites and 32 fish per m^2 for channelized sites. Size class one had a mean density of 34 fish per 100 m^2 for natural sites and 38 fish per 100 m^2 for channelized sites (Figure 9). Size class two had a mean density of 29 fish per 100 m^2 for natural sites and 28 for channelized sites. Size class 3 had had a mean density of 4 fish per 100 m^2 for natural sites and for channelized sites.

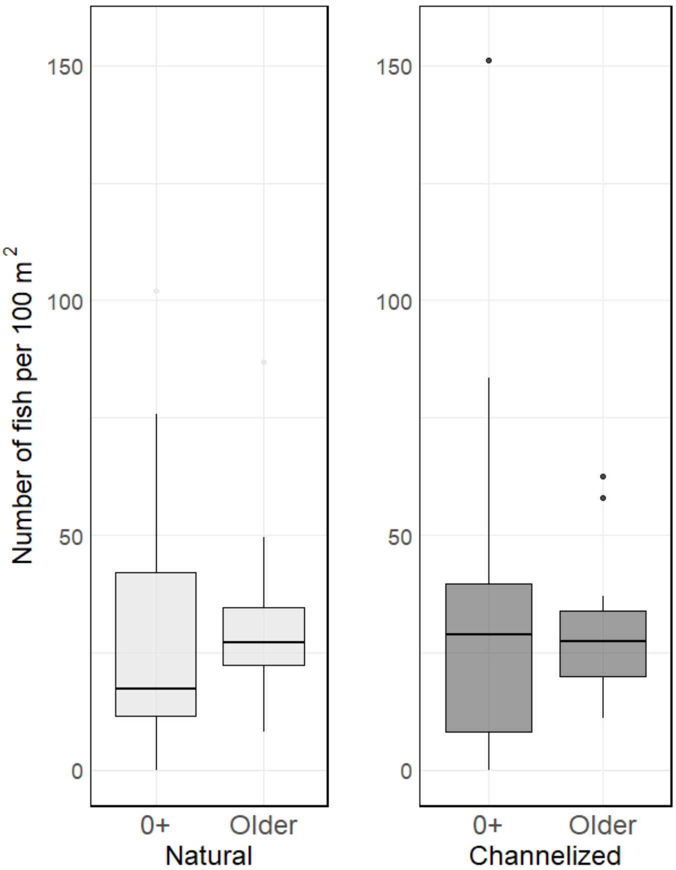

Figure 8. Estimated densities of 0+ and older salmonids in natural and channelized sites. Each box plot displays the median and interquartile range from the 25th to 75th percentile, as well as minimum and maximum (bars) and outliers (black dots).

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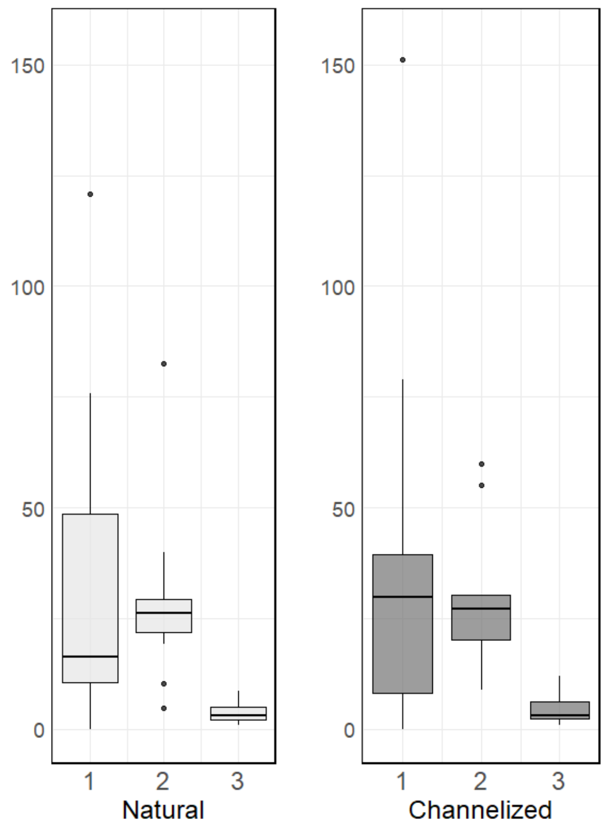

Figure 9. Estimated densities for salmonid size groups 1, 2 and 3 for natural and channelized sites. Each box plot displays the salmonid density for each size group's median and interquartile range from the 25^{th} to 75^{th} percentile, as well as calculated minimum and maximum (bars) and outliers (black dots).

Model M3 was used to determine the effects of channelization, spawning gravel and the interaction between them on salmonid density for separate age groups and size groups. The AIC analysis showed that none of the predictors in the model influenced salmonid density for any of these groups. Model M4 was used to determine the effects of channelization, shelter index, and the interaction between them on both age groups. The AIC analysis showed that none of the predictors in the model influenced salmonid density. As there was no significant effect found in any of the predictors for salmonid density in any of the age or size groups, hypotheses H3a, H3b and H3 were rejected.

4 - Discussion

The aim of this study was to investigate the impacts of channelization on both habitat quality and the production of juvenile salmonids in small streams. In addition, the effect of changes in shear stress on these impacts was examined. It was hypothesized that the proportion of spawning gravel, shelter availability and density of juvenile fish would be lower in a channelized section of a stream in comparison to a natural control site within the same stream.

There was a negative effect of channelization on shelter index, however, shear stress had no effect on shelter index. There was also no effect of channelization or shear stress on the proportion of spawning gravel, nor any effect of channelization, spawning gravel or shelter availability on juvenile fish density. Thus, only hypothesis H2a, predicting that the amount of shelter for juvenile salmonids would be lower where the stream was channelized was confirmed while the other hypotheses were rejected for the dataset researched.

4.1 - The effects of channelization and shear stress on the proportion of spawning gravel

The proportion of spawning gravel was not significantly different between natural and channelized sites in the studied streams (Figure 4), nor was there an effect of shear stress on the proportion of spawning gravel. This is surprising since it has been shown that channelization increases a stream's gradient thus increasing shear stress, and that an increase in shear stress will increase a river's capacity to transport sediments (Emerson, 1971; Fergus et al., 2010). As the shear stress was higher in channelized sites than in natural sites in ten of the twelve studied streams (Figure 3), it would be expected that the size of the substrate would also have increased as smaller particles would be flushed downstream after channelization.

The cumulative sediment distribution curves (Figure 5) show that the median substrate size class was indeed larger in the channelized site of five of the twelve streams, whereas it was lower in one and unaltered in the remaining six. The median size class had a mean of 5.6 (coarse gravel) in natural sites and 6.0 (very coarse gravel) in channelized sites (Table 2). Both coarse and very coarse gravel is suitable spawning substrate for salmon and sea trout (Barlaup et al., 2008; Kondolf, 2000; Hauer et al., 2018; Sear & DeVries, 2008). To gain a full understanding of how the substrate has been affected by changes in shear stress, we need accurate pre-disturbance data showing what the substrate composition was prior to channelization. If the substrate in the pre-disturbed channelized sites had a median grain size near the lower limit of what is suitable for spawning, then an increase in shear stress could increase the grain size substantially without the percentage of spawning gravel decreasing. However, if the available spawning gravel prior to channelization is already near the upper limit, then even a slight increase in shear stress could be enough that all spawning gravel will be washed out. In cases where the substrate in the pre-disturbed stream was lower than what is considered suitable spawning gravel, the proportion of spawning gravel may increase with an increase in shear stress.

There is also a wide range in time since the sites were channelized. Aerial pictures indicate that eight of the twelve streams had already been channelized by 1965, when the earliest pictures are available, whereas the most recent channelization (Sauneselva) occurred later than 2019. As the majority of bed forming material transport occurs during flooding events (Phillips, 2002), it is uncertain whether some of the more recent channelized sites will have undergone the full impact of changes in shear stress since channelization, whereas some of the older sites may even be returning to a more natural morphology due to the channelization being eroded. It is also important to consider the sediment supply and sediment transport in each stream. If the gravel is being washed out of the site, but the supply of suitable gravel is high upstream of the site, it may take a long time before the gravel is depleted, as any gravel removed from the study site may be replaced by gravel transported from upstream areas (Hauer et al., 2018). On the other hand, sediment supply may be low if the reach is situated downstream from a lake or powerplant or if the upstream portion of the stream has reduced lateral sediment supply caused by decreased stream bank erosion due to channelization (Hauer et al., 2018).

4.2 – The effects of channelization and shear stress on shelter

Shelter index was significantly lower in channelized sites than in natural sites with a mean of 5.7 and 3.8 (Figure6), equating to class “moderate” and “poor” shelter in natural and channelized sites respectively (Forseth & Harby, 2014). Overall shelter index was lower in the channelized sites in ten of the twelve studied streams. This is in line with previous studies showing that the removal of large boulders and deep pools, which often characterize natural meandering streams, causes a decrease in shelter for fish (Hahn, 1982; Hauer et al., 2018). Thus, this study confirms that channelization can reduce shelter in small streams.

In addition to shelter index in the substrate, availability of bank shelter provided both by overhanging sections and gaps in the embankment was estimated for each site (Figure 7). It was estimated that fish shelter was available in 29% of the total bank in natural sites, and 30% of the total bank in channelized sites (Figure 7). Although these were visual estimations with a higher level of uncertainty than the standardized methods used to measure shelter in the substrate, this indicates that shelter found within the banks was abundant for natural and channelized sites alike. The quality of shelter found within the banks was however not considered in the same way it was for the substrate, where each cavity is given a score of 1-3 to indicate its size. In cases where there is poor shelter in the substrate, there could still be a high amount of shelter in the banks. In some cases, where the proportion of overhanging shelter was low in the natural site, it is possible that channelizing a section could even have increased shelter in the stream, depending on the type of channelization structure implemented.

4.3 – The effects of channelization, spawning gravel and shelter index on juvenile salmonid density

Shelter index was found to be significantly lower in channelized sites compared to natural sites, however no effect was found of channelization, the proportion of spawning gravel or shelter availability on fish density. Previous studies have shown a significant negative effect of channelization on fish density, with the effect of channelization being particularly significant in brown trout (Whitney & Bailey, 1959). The changes in shelter index should also influence fish density (Duvel et al., 1976; Forseth & Harby, 2014; Hauer et al., 2018). However, there are several other factors that could affect fish density, and potentially compensate for the lack of substrate shelter in channelized sites.

Firstly, although this study focuses mainly on the shelter provided in the substrate, fish can also utilize other sources of shelter, such as overhanging banks, overhanging riparian vegetation, dead vegetation, moss, and macrophytes (Aas et al., 2011; Finstad et al., 2009; Forseth & Harby, 2014; Velle et al., 2022). Although the presence of the latter four was low in all streams and not a focus in this study, overhanging bank shelter was estimated for each site and found to be prominent. It is possible that this shelter could compensate for a lack of shelter in the substrate, offsetting any negative effect of channelization on juvenile fish density, and personal observations in the field indicate that embankment shelter is highly utilized by juvenile salmonids. This is especially likely as the streams were narrow with a mean width of 3.2 m and thus the total habitat is highly affected by the banks, as the bank to area ratio will be high.

Secondly, the sites in this study range from 18 m to 43 m in length, which is relatively short in comparison to studies that have shown reduced fish density due to channelization of reaches down to 400 m in length (Duvel et al., 1976). It is possible that the interplay between the channelized site and areas up- and downstream will be high in such short reaches, with fish migrating between them. Thirdly, it is possible that the density of juvenile fish found in many of the study sites was not high enough for shelter to be a limiting factor. The low densities found in several streams could have been caused by other factors, such as anthropogenic structures potentially limiting upstream migration of sea trout in certain streams, namely Daleelva, Fosselva, Sauneselva, and Sandvika. Removal of these potential barriers could lead to population growth, and the lack of shelter may then limit this growth. There may be other factors also affecting fish density, such as the nutritional input, which may be affected by channelization as it is often linked to agriculture (Jonsson et al., 2011).

4.4 – Implications for stream management

As channelization is listed as one of the leading causes of sea trout decline in Norway in recent years (Thorstad & Forseth, 2022; Thorstad & Forseth, 2023), understanding the specific impacts it has on key salmonid habitat features such as shelter availability and spawning gravel is critical for making informed decisions about river and stream management. The results of this study have several important implications for conservation and the practice of channelization and flood risk management. The significant negative effect of channelization on shelter index alone shows that channelization affects salmon and sea trout habitat. However, despite this reduction in shelter, no effect on fish density was found, indicating that other habitat factors may compensate for the lack of shelter in the substrate, and that the relationships between channelization, habitat, and fish density may be more complex than initially thought.

Firstly, it is important to have a full understanding of what the habitat conditions are like prior to the intervention, as bottlenecks for salmonid production will vary from stream to stream (Pulg et al., 2023). If spawning gravel supply is abundant throughout a river, and the spawning gravel present is towards the lower end of the suitable size range, it is possible that the habitat could withstand an increase in shear stress by retaining a large proportion of suitable spawning gravel (Hauer et al., 2018). It is therefore important to conduct thorough habitat mapping, and fish density surveys as well as hydraulic surveys and geomorphological mapping in the entire anadromous part of the stream to gain a full understanding of which habitat factors could be potential bottlenecks for salmon and sea trout production. This is required to be able to predict how the stream and its habitat will respond to interventions such as channelization.

It is also probable that different types of channelization will have different effects on habitat and fish density (Pulg et al., 2023). The channelization in all streams in this study was carried out using medium to large rocks, building vertical walls along the banks, in some cases overgrown with riparian vegetation, and with minimal plastering on the stream bed (Appendix I). Due to gaps between these rocks, these structures create new shelter areas, either replacing shelter previously provided by overhanging banks, or providing shelter that was not there previously. In other cases, channelization may be implemented by replacing the bank and stream bed with smooth concrete surfaces. In these cases, both shelter and spawning gravel may be removed entirely. Thus, it is important to consider what structures are used, as effective protections against floods and erosion can be implemented while retaining healthy habitats for salmon and sea trout (Pulg et al., 2023). More nature-based alternatives to channelization should also be considered, including restoration techniques such as the re-opening of flood plains or retracted erosion protection, which can also be effective in flood and erosion management while retaining a natural stream morphology (Pulg et al., 2023).

Lastly, the effect of area loss on the stream in question must be considered. Although there was no significant effect on fish density in the studied streams, despite adjusting the area of the sites to simulate the natural state, it is possible that the loss of area in the stream will have reduced the total salmonid production.

4.5 – Future research

In this study it is shown that the standardized methods used for measuring shelter for juvenile salmonids may not be sufficient for comparing the habitat in natural and channelized sites in small streams. This method places an emphasis on finding accurate shelter estimations in the substrate, while ignoring shelter within the banks. As the banks constitute a large proportion of the total habitat area in small streams, the shelter it provides may play a more important role for the fish habitat than in wider rivers and should therefore be considered. In narrow cavities in the banks may even provide more shelter for juvenile fish than in the substrate. New methods should therefore be developed, to quantify shelter provided by the banks as well as substrate shelter. By also focusing research on juvenile salmonid behavior to find out what kind of shelter they prefer, we can gain an understanding on how big a role shelter within the banks plays in comparison to shelter in the substrate.

Although this study focuses on fish and their habitat requirements, there is a wide array of organisms that will be affected by channelization. Benthic invertebrates, in-stream vegetation and riparian vegetation will all be affected. This in turn affects not only fish in the stream, but birds and mammals living along the banks. It is therefore vital to further research the effects of channelization in small streams on the entire biota and not only fish.

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Appendices

Appendix I – Examples of channelization structures

Daleelva

Fiskåelva

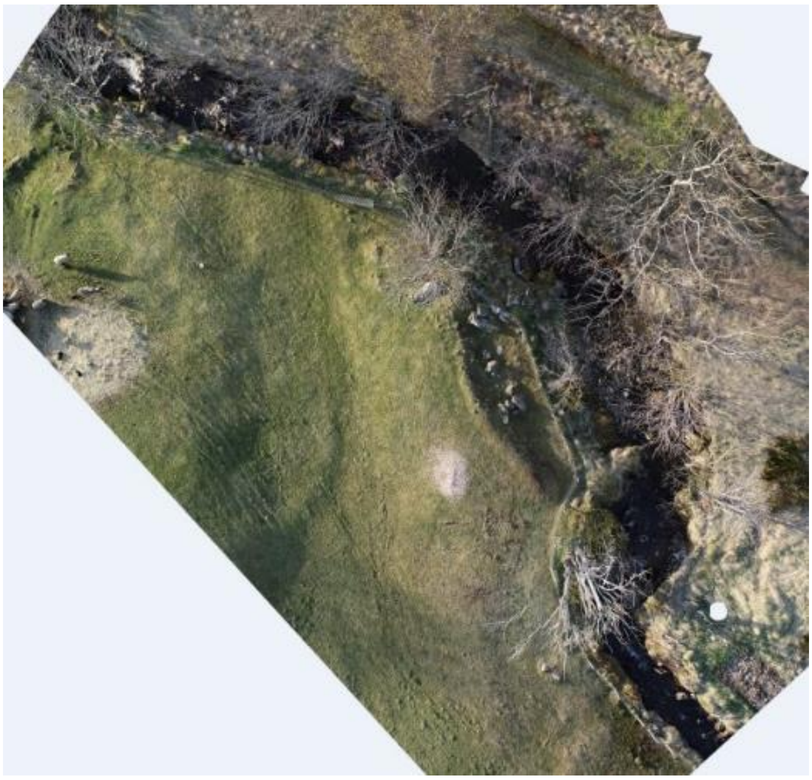
Sandvika

Sauneselva

Appendix II – Orthomosaic pictures of study sites

<u>Botnelva</u>

Natural:



Channelized:

Daleelva

Natural:

Channelized

<u>Eidsåelva</u>:

Natural

Channelized:

<u>Fiskåelva</u>:

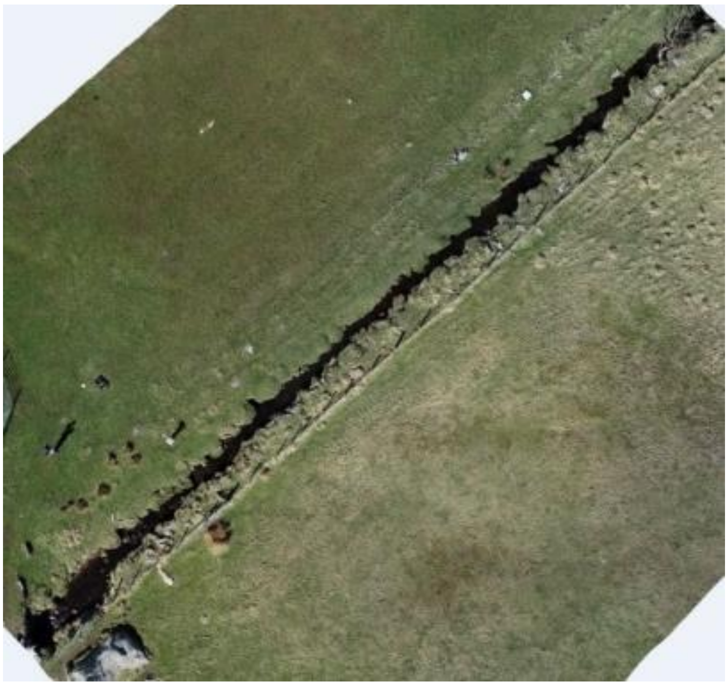
Natural:

Channelized:

Fosselva:

Natural:

Channelized:



Myklebustelva:

Natural:

Channelized:

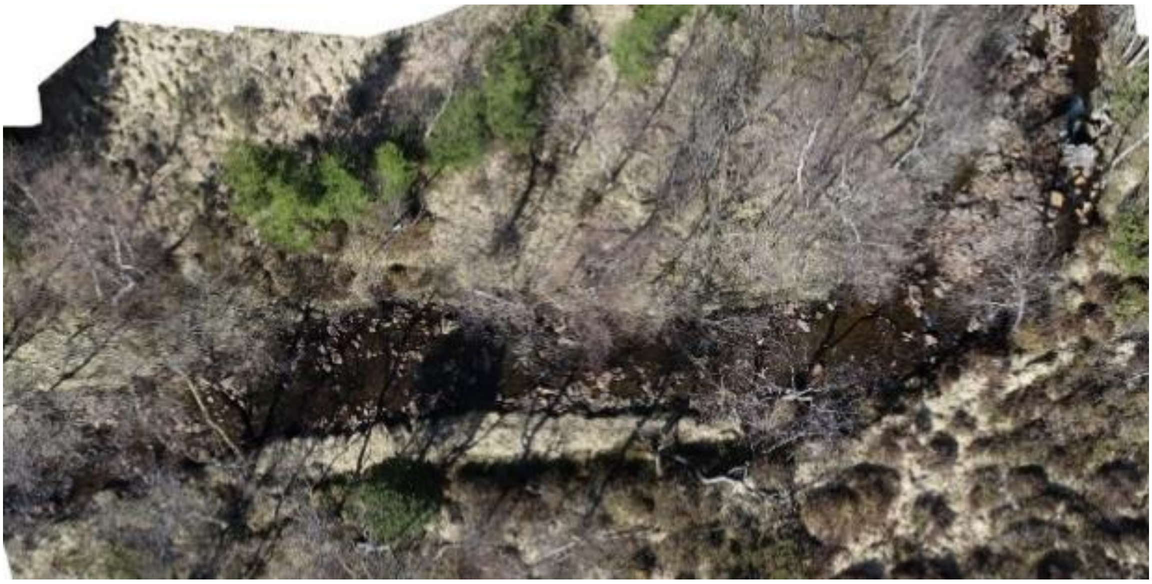
Raudeelva:

Natural:

Channelized:

Riselva:
Location:

Natural:



Channelized:

Sandvika:

Natural:

Channelized:

Storelva:
Location:

Natural:

Channelized: