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What's Rocking in Bognelv? A Case Study in Hydromorphological Conditions Before, During and After Restoration of a Channelized River by Studying Tracer Rocks and Aerial Photos

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Environment and Natural Resources

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Acknowledgments

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Abstract

From 1930-1990 the river Bognelv in Troms-Finnmark County was strongly affected by technical intervention related to flood security which led to interruption of bed material transfer, and dramatical declination of salmonid densities. The first restoration measurements were conducted in 2006 and are still ongoing. This thesis is the fifth study or river restoration in Bognelv and highlights the importance of having knowledge of hydromorphological constraints on bedload transport, such as channelization, since it controls and defines both channel morphology and habitats.

The meandering but still channelized river Bognelv was studied in order to analyse whether the conducted measurements up to date have had a positive effect on bedload transport and the hydromorphological environment in the way that the river system is more dynamic and capable of changing its own hydromorphology with natural processes.

This has been analyzed by means of tracking transportation of rocks, taking hydromorphological cross sections, and analyzing changes of hydromorphological features from aerial photographs. Data from bedload tracer experiments were compiled between May 2019 and November 2019. Sediment tracking was done by using Passive Integrated Transponders (PIT) tags inserted into 111 gravel rocks which were registered in the river after one transport episode. Conditions in field during late fall 2019 highlights the limitation of data and recovery rate.

Analysis from the data compiled showed that magnitude of peak discharge could not be set to be the major transport control, but tracer travel distances showed some scale dependence in the morphological configuration of the channel. Transport distances were different in restored versus unrestored river sections. Rocks seemed to travel longer in the channelized river sections, as pools seems to be a more efficient trap for travelling gravels. It is expected that in the future with more data and transport episodes, the weak tendency with effect of pools slowing down travel distance will be enhanced and much clearer. These results from tracer travel distance and comparison of aerial photographs highlights that river restoration is heading in the right direction, and has a positive effect on the river hydromorphology in the way that the river has achieved more structural variation. Bognelv has changed its pattern from fully channelized to some meandering with riffle-pool sequences. Both river width and length has increased, and more morphological features such as meanders, pools, riffles, and island are formed in the river.

As some of the data in this study shows weak predictions, they are assumed to be insufficient to draw decisive conclusions about the rivers capability of changing its own morphology. With more measurements and transport episodes predictions can be improved. Bognelv is a river with many different interests that limits the river to only be partial restored. It is recommended that restoration measures should still be conducted as the hydromorphology only can become better with improved strategies and knowledge from past projects through monitoring. A favourable situation for the river to become more natural again with free lateral movement would be if they removed all erosion security and replaced them with vegetation zone where it is necessary for flooding.

Sammendrag

«Hva ruller I Bognelv?» En case studie om hydromorfologiske forhold før, under og etter restaurering av en kanalisert elv basert på sporing av stein og flyfoto.

Fra 1930-1990 ble Bognelv i Troms-Finnmark fylke sterkt påvirket av tekniske inngrep relatert til flomsikring. Dette relaterte i avbrudd av transport av bunnmateriale, og dramatisk tilgang i fisketetthet. De første restaureringsmålingene ble utført i 2006 og pågår fortsatt. Denne studien er den femte masteroppgaven som er relatert til elverestaurering i Bognelv, og understreker viktigheten av å ha kunnskap om de hydromorfologiske begrensningene, slik som kanalisering, som påvirker bunntransport siden de både kontrollerer og definerer elvemorfologien samt habitater.

Den svingete, men fremdeles kanaliserte elva har i denne studien blitt studert med ønske om å undersøke om de utførte restaurerings tiltakene hittil har hatt en positiv effekt på bunntransport og det hydromorfologiske miljøet, i den grad at elva er mer dynamisk og er i stand til å endre sin egen morfologi med naturlige prosesser. Undersøkelsen har blitt analysert ved å spore transport av steiner, ta hydromorfologiske tverrsnitt og analysere hydromorfologiske endringer fra flyfoto. Data fra bunntransport ble innsamlet mellom mai 2019 og november 2019. Steinsporing ble gjort ved å bruke passive integrerte radiosendere (PITs) som ble drillet inn i 111 steiner som senere ble registrert i elva etter én transport episode. Forhold i felt høsten 2019 og vinter 2020 fremhever begrensningene av data og gjenfinningsraten av steinene.

Analyser fra de dataene som ble samlet viste at styrken på vannføringen kunne ikke bli satt til være den viktigste transport kontrollen, men transport avstandene viste en tendens til morfologisk avhengighet der distansen var forskjellig i fra tiltak og ikke tiltaks områder. Det så ut til at steinene reiste lengre i de kanaliserte delene av elva, da kulpene bremset opp distansen. Det forventes i framtiden at den svake tendensen med effekten av kulper vil med mer data og transport episoder kunne forbedres og vises mye tydeligere. Disse resultatene sammenlignet med flyfoto fremhever at eleverestaureringa beveger seg i riktig retning med en positiv effekt på hydromorfologiske kvaliteter i den grad at elven har oppnådd en mer strukturell variasjon. Bognelv har forandret sin fysiske form fra sterkt kanalisert til noe meandrerende med sekvenser av kulper og terskler. Både elvebredden og lengden har økt, og flere morfologiske enheter som svinger, kulper, tersker og øyer har blitt formet i elva, der noen er tilrettelagt.

Ettersom noe av dataene i denne studien viser svake forutsigelser, antas de å være utilstrekkelige til å trekke avgjørende konklusjoner om elvens evne til å endre sin egen morfologi. Med flere målinger og transportepisoder kan mange av prediksjonene forbedres. Bognelv er en elv med mange ulike interesser noe som begrenser elven til å bare bli delvis restaurert. Det anbefales at restaureringstiltakene bør fortsette slik de startet da hydromorfologien bare kan bli bedre med forbedrende strategier og kunnskap fra tidligere prosjekter. For elva å bli enda mer naturlig igjen med fri horistonal bevegelse hadde en ønsket situasjon vært å fjerne alle eleveforebygningene og erstattet dem med kantsoner der det er fare for flom.

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1. INTRODUCTION

Rivers have always been of great importance to humans. They provide benefits to society with freshwater supply, agriculture, sustenance and recreation. However, these benefits get compromised when rivers are modified with technical interventions (Hohensinner et al., 2018b). As a reaction to technical intervention, running water ecosystems experience not only changes in river dynamics and water flow, but also a significant loss of habitat and biodiversity. Such consequences of technical intervention have in recent years led to a growing consensus about the importance of river restoration (Schmutz et al., 2014). River restoration is an important field that addresses physically altered rivers by restarting their naturally processes in an effort to return the river back towards their natural, undamaged state. By reintroducing the natural river processes, the river can be able to constantly change its physical structure by eroding and moving sediments from one place to another.

European Water Framework Directive (WFD) includes river restoration a fundamental part of river management, and requires countries to improve the ecological status of their rivers by improving the hydromorphological quality (Schmutz et al., 2016). Hydromorphological factors such as channel geometry (flow velocity, quantity and dynamics of flow), riverbed (water depth, bed stabilisation, substrate), and water and transition zone (river width variation, stabilization, bedload accumulation) can affect ecological processes (Newson and Large, 2006, Halleraker, 2020). It is therefore critical to understand and manage hydromorphological pressures, such as channelization, alteration, etc. However, there presently exists no required register for hydromorphological measurements in Norwegian rivers (Harby et al., 2018).

Channelization as defined by the Water and Commision (2001) is as a shortening of the natural length of the river conducted by straightening the channel and removing the natural turns by replacing them with an erosion-preventing wall of rock filling. Typically consequences related to channelization is the disruption of river continuity, riverbed incision, flow alteration, and degradation in both reduction of instream original habitat complexity and habitat availability. Such changes over time determine the competitive interactions that can occur among species such as fish and benthic invertebrates that are preferring moderate or lower flow velocities (Lau et al., 2006, Hohensinner et al., 2018a).

An example of this situation is the ongoing restoration of Bognelv, in Troms-Finnmark County. In favour of agricultural land use and flood control, the river was channelized by NVE (The Norwegian Water Resources and Energy Directorate), and experienced the consequences related to it (Josefsen and Hoseth, 2005). The technical intervention with erosion control resulted not only in a decrease of salmonid abundance, but also in an interruption of bed material transfer and change in river morphology. As a reaction to this, NVE began restoration measures in 2005 with the aim to restore the ecological processes (Hoseth, 2008a, Hoseth, 2008b, Hoseth, 2010b, Hoseth, 2013b, Josefsen and Hoseth, 2005, Bjordal, 2019b).

My study is the fifth study examining the restoration process in Bognelv. Previous master studies from Bognelv have used salmonids and macroinvertebrates as the main biological indicator of success (Schedel, 2010, Austvik, 2012, Sødal, 2014, Nordhov and Paulsen, 2016). I will use hydromorphology for the first time as an empirical tool, to test the theory of whether the restoration measurements have had a positive effect on bedload transport in the way that the river is constantly capable of changing its physical morphology. This will be tested by studying tracer rocks and aerial photos.

1.1 BEDLOAD TRANSPORT

An evaluation of sediment with measurement of bedload transport is necessary to determine potential or existing channel responses to channelization. (Fraley, 2004). It provides a major process linkage between river channel form- and hydraulic conditions (Hohensinner et al., 2018a). Estimations of bedload transport can be helpful in quantifying changes in water flow and morphology due to channelization and river restoration. Tracer data can yield information about the fluvial transport rates of sediments, transport distances and pathways, sediment sorting by particle size or shape, and deposition areas (Habersack, 2003, Lamarre et al., 2005).

Bedload transport material is defined as material larger than 0.2 mm, from fine sand and coarser. Finer material is often in suspension in the river, but such dissolved load has little impact on channel form compared to bedload material, and is therefore not focused on in this thesis (Gomez, 1991, Fergus and Bogen, 1998). In a watercourse, bedload transport is defined as the part of material transport that moves in contact with the river bottom (Gomez, 1991, Bogen, 1999, Hicks and Gomez, 2003).

Transport in gravel rivers such as Bognelv is known for having bedload particles that move discontinuous in water streams, compared to bedload transport in a sandy river, where there is ongoing transport in every water flow. In general, the most important factors influencing bedload transport is transport capacity (function of slope, discharge and channel form), transport competence (maximum size it can transport) and availability of sediments (Hicks and Gomez, 2003, Wainwright et al., 2015).

There are many methods that can be used to measure bedload transport (Fergus and Bogen, 1998, Gomez, 1991). One of the first bedload equations were introduced by Du Boys in 1873, and many more probabilistic views have been created, such as Einsteins equation from 1937 and more (Habersack, 2003, Bagnold, 1966). The most traditional method to measure bedload transport is to use visual tracers where painted particles are placed in the river, and then picked up after a given time period to measure length of transport. A newer method is the mark-recapture method with the use of passive integrated transponders (PIT). Sediment tagging has become a common technique in geomorphological studies, and several studies have used tracer data with the aim to investigate relationships between tracer travel distances and flow magnitude (Vázquez-Tarrío et al., 2019, Lamarre et al., 2005, Lamarre and Roy, 2008, Liébault et al., 2012, Schneider et al., 2010). Both these methods will be presented in more detail in method chapter.

Researchers are familiar with the difficulties in making exact, and reliable measurements of bedload transport due to extreme temporal variations in transport rate and river morphology (gradient, substrate distribution etc) (Habersack, 2003, Fergus and Bogen, 1998, Froehlich, 2003, Knighton, 1999, Hicks and Gomez, 2003, Schneider et al., 2014). Due to this diversity in hydraulic and channel conditions, different bedload-transport equations are not applicable to all gravel bed rivers (Wainwright et al., 2015). For additional details, several reports have been published regarding different bedload transport methods: (Fergus and Bogen, 1998, Ferguson and Wathen, 1998, Engvik, 2011, Knighton, 1999, Froehlich, 2003, Habersack, 2003, Hicks and Gomez, 2003, Lamarre et al., 2005, Fraley, 2004, Ford, 2014, Schneider et al., 2014, Vázquez-Tarrío et al., 2019)

1.2 STUDY AIM AND HYPOTHESIS

Previous tracer analysis of bedload transport has observed that smaller particles show larger displacements than larger particles. (Ferguson and Wathen, 1998, Schneider et al., 2014, Hassan et al., 1992). Where the bed-surface is coarsened, rocks will be prevented from entrainment and therefore indicate a greater transport capacity (Montgomery and Buffington, 1997, Vázquez-Tarrío and Batalla, 2019). Due to these observations it is hypothesised that the smaller tracer rocks in Bognelv will travel the longest, especially in the unrestored river sections where channelization often result in higher velocity which again results in coarser grain size of the substrate (Hohensinner et al., 2018a). Several tracer studies that have studies the relationships between tracer travel distance and flow magnitude claim that hydraulics is the major force on fluvial gravel transport (Lamarre et al., 2005, Lamarre and Roy, 2008, Schneider et al., 2010, Liébault et al., 2012, Vázquez-Tarrío et al., 2019, Vázquez-Tarrío and Batalla, 2019). Some of these studies also claimed that there could also be strong influence of controls other than flow magnitude on tracer displacement, such as cannel morphology (Lamarre and Roy, 2008, Hassan and Bradley, 2017, Vázquez-Tarrío et al., 2019, Vázquez-Tarrío and Batalla, 2019). Both of these claims will be tested in Bognelv.

As literature from Hoensinner et al (2018b) highlights, channelization modifies physical configuration of the river with the aim to increase flow velocity and sediment transport capacity. It is expected that after channelization there will be a decrease not only in river width and length but also in hydromorphological features. But as Haase et al. (2013) assumed in their restoration study, will a decrease like this change after river restoration.

Hypothesis:

- **H1)** Sediment travel distance is assumed to be longer in the channelized part of the river
- **H2)** Travel distance and travel competence (maximum size it can transport) will increase with a higher flow magnitude
- **H3)** Bedload transport in Bognelv is likely to be controlled by factors other than flow regime, such as restoration type and channel morphology
- **H4)** After a channelization, cross sections of the river width and river length are shortened

H5) Channelization creates one steady flow that makes it difficult for the river to build riffles, point bars, islands and pools

H6) After conducted restoration measures, more structural variation in environmental variables and morphological features will develop

The aim of this master thesis was to investigate whether restoration measures conducted up to the date of my fieldwork have had a positive impact on the hydromorphological environment of the river, in a way that the river system is more dynamic and capable of changing its own morphology than 15 years ago when it was a “locked system” because of channelization.

I test my hypotheses by linking bedload transport data, environmental variables, aerial photos and previous biological results. I present ideas for future measurements in order to increase hydromorphological variation and ecological qualities.

At first, I introduce the methods and materials used to yield my presiding results. Lastly, I will justify the findings in relation to existing knowledge and draw some conclusions along with suggestions for further research.

2. MATERIAL AND METHODS

2.1 STUDY AREA AND CHANNELIZATION HISTORY

This study was conducted in Bognelv river in Langfjordbotn (Bávnnajajohka). The river runs along Bognelvdalen valley from south to north in Alta municipality, Troms-Finnmark county (Figure 1). The valley river originates by the county border between Finnmark and Troms County (Colman, 2011) with an outlet that tempties into Langfjorden (UTM 33 7785049 N, 7776120 Ø) (norgeskart.no).

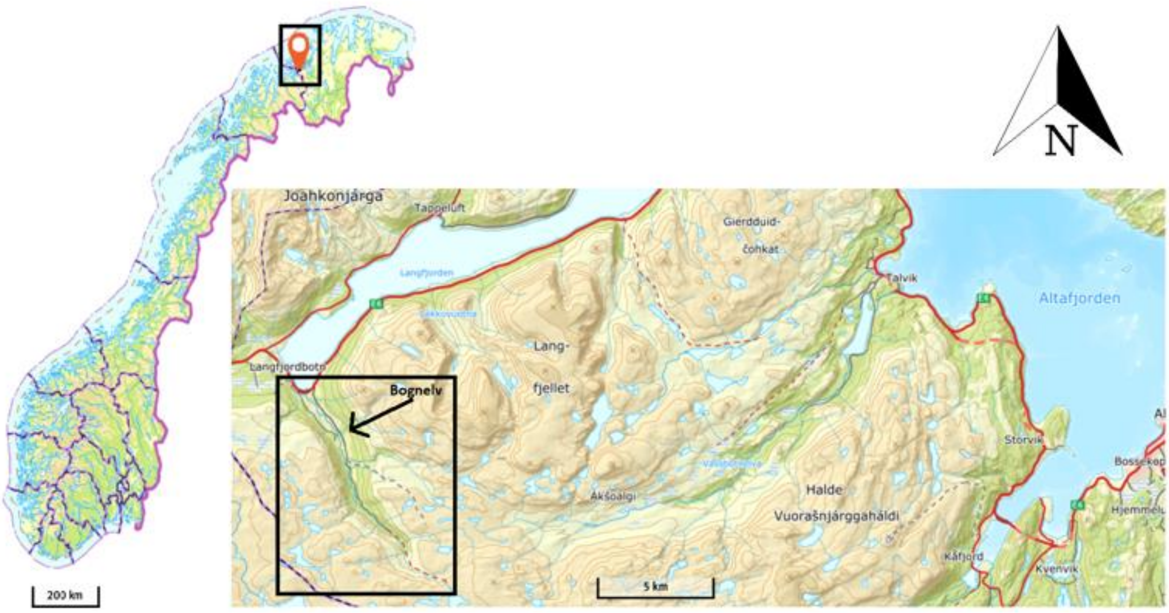

Figure 1. Location of the study area (black square) in Bognelvdalen, Troms-Finnmark County, Northern Norway. (www.norgeskart.no). The valley and river are located west of Alta city. This thesis focus on the lower restored 3.5 km of the river.

Information for the study area is based on a previous background report from Josefsen and Hoseth (2005) containing a general environmental restoration plan for Bognelv.

The river (watercourse number 211.8A0) has a catchment area of 89 km^2 (a flood calculation by NVE in 1997), where the largest areas are situated above the tree line with stable winter conditions. This makes the spring flood more significant, with a higher discharge rate than late summer and fall (Josefsen and Hoseth, 2005). The area has a yearly precipitation of around 781.49 mm and a runoff around 1021.03 mm/yr (NVE) (Appendix 8)

The landscape of Bognelvdalen has a U-valley form with steep hillsides and a flat alluvial valley bottom formed by glaciers, marine deposits and flooding (Mæhlum, 2015, Bryhni, 2020). The geology is dominated by calcareous rocks, which make it more nutrient-rich (NGU, 2020). Further up the hillsides, the bedrock is predominantly granitic gneis. The river course is generally narrow and shallow, with a river gradient at 34.59 m/km (NVE). The substrate of Bognelv is characterized by relatively coarse bottom material (coarse gravel, rock). According to Fergus and Bogen (1998), the bed material in the majority of Norwegian rivers is generally within in a gravel-to-cobble size range with small fractions of sand, often due to increased water velocity. More field qualities can be read in Appendix 8.

Before the 1930's, Bognelv existed in a state of a natural river, undamaged river (Figure 17). Newson and Large (2006) have defined a natural river as an intact channel that has shape, and features that fully interplay with uncontrolled water. Natural rivers are therefore free to adjust their movement and flow velocity, either by erosion or sedimentation of material, but also free to move laterally and interact with the surrounding floodplain. A lateral displacement of the river course over time is a result of a natural rivers tendency to have stronger current velocity in outer turns with greater erosion effect, and sedimentation in inner curves (Newson and Large, 2006).

From the 1930's to the early 1990's, improvements for agricultural conditions in Bognelv were conducted. Due to a flood in 1978, the river was even more channelized (Josefsen and Hoseth, 2005). The lowest 3.5 km of the river was channelized with the intentions to improve flood control by preventing lateral erosion and increasing the water velocity (Hohensinner et al., 2018b). With these technical interventions, Bognelv became a more homogenic, fast-flowing river that lost its natural state. The meandering river with oxbow lakes, pools and floodplain areas was straightened out into one strait channel (Appendix 6). Higher flow velocity and sterile bottom material led to a lack of suitable heterogenic habitats for flora and fauna, resulting in a decline in salmonid abundance (Josefsen and Hoseth, 2005). As a reaction to the loss of fish, The Norwegian Water Resources and Energy Directive (NVE) started together with locals and Langfjorden Hunting and Fishing Association (LJFF), a pioneer project of river restoration for Norway. Restoration measures started in 2006 and are ongoing. The aim of the restoration measures planed in Bogenelva were to enhance the unsuitable habitats that were negatively affected by channelization. This can be done by making the river more natural again and increasing the diversity in water flow, where lower discharge can create more active erosion and sedimentation processes, that again, can form pools and riffles (Josefsen and Hoseth, 2005, Bjordal, 2009, Bjordal, 2019b). Bognelv today (2020) still remains channelized in the lower parts of the river, and erosion preventing rock walls still occur in parts of the river in favour of protecting agricultural land. Old water ways have been re-opened as side channels and pools with constructed weirs have been created. Additionally information on river morphology and aerial photographs will be presented in the results, along with details and information for restoration measures. Complete information for restoration measures can be read in the reports published by NVE and others, and in Appendix 1 and 2 (Josefsen and Hoseth, 2005, Hoseth, 2008a, Hoseth, 2008b, Hoseth, 2010b, Bråthen Schedel, 2011, Austvik, 2012, Hoseth, 2013b, Sødal, 2014, Nordhov and Paulsen, 2016)

2.2 STUDY SITES

2.2.1 Station selection

Fieldwork was undertaken in three separate rounds in 2019. The first round occurred between May 30th to June 1st, the second between October 15-18th, and the last round between November 6-7 th.

Stations were scouted and defined with help from Anders Bjordal from (NVE) based on the interest of studying the difference of bedload transport in areas with and without conducted restoration measures. Table 11 below shows an overview of the restoration measures conducted at the six different stations, and why exactly these measures were conducted at the different river zones. A station is defined as a cross section of the river. It has no certain length, only width. Six stations were selected for this thesis. Four stations represent river sections with restoration measures (station 1,2,3,4), and two stations (station 5 and 6) represented river sections related to stretches without restoration measures, called “reference conditions”. In this case, reference conditions are the stretches in the river that still have disturbed conditions with structural modification, such as the channelized parts in lower agricultural land (Figure 2).

Table 1: Overview of restoration measures that have been done at the six different stations, and why exactly these measurements were conducted at the different river zones.

Station	**River zone**	**Restoration measure**	**What was done at this station?**	**Why was it done?**
1	8	7	Upgrade and removal of erosion control systems, placement of rocks in river and building thresholds	Create more variation in water flow, avoid bottom erosion, and create/enhance existing pools.
2	6	5	Removed flood embankment left side downstream towards cultivated land. Opened a side channel.	Create a more varied and natural river course by increasing the diversity in water flow and create a wider river width where natural water course processes can occur. Will in the future be deposition of sand and gravel in the new river turn, and thereby a more varied bottom substrate.
3	6	5	Placed rocks downstream the inflow and by the outflow of side channel	Increase the water levels. Alter currents and create more variation in water flow,
4	4	2014	Constructing an island by taking rocks from right side of the river downstream. Creation of “bunes” (rows of rocks that leads the water flow) up and downstream the new island.	Create more variation in water flow. Water moves free on both sides of the island. “Bunes” gather water flow for creation of pools.
5	5/5	-	No conducted measurements, reference area. Still channelized.	
6	5/6	-	No conducted measurements, reference area. Still channelized.	

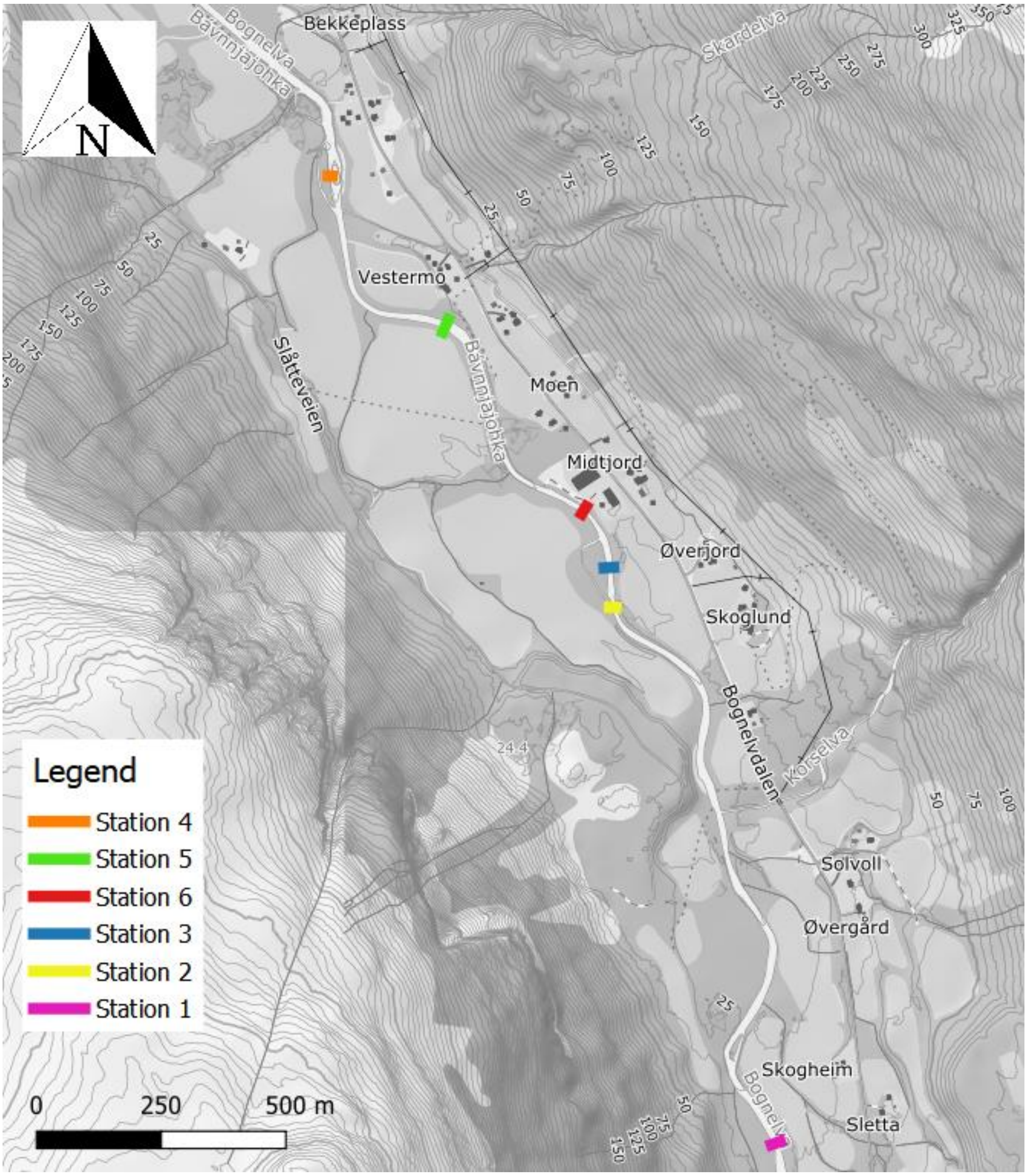

Figure 2. Overview map over the six selected and sampled stations in Bognelv.

2.2.2 PIT Telemetry

The method for the fieldwork is based on methodology used in former tracer studies, especially in biology with wild animals and juvenile fish (Gibbons and Andrews, 2004, Hewitt et al., 2010, Beeman et al., 2012). PIT telemetry is based on inserting passive integrated transponders (PIT tags) into clasts, placing them in the river channel and later tracking them with a radio antenna (Nichols, 2004, Lamarre et al., 2005, Allan et al., 2006, Lamarre and Roy, 2008, Schneider et al., 2010, Smyth and Nebel, 2013, Phillips et al., 2013). PIT tags are small (in my case 23 mm long and 2 mm wide) glass-encapsulated transponders with an electronic microchip that activates when sufficiently close (i.e., within detection range) to an antenna near them. Each tag is characterized by its own unique identification number, and has a typical detection of 0.5-2 m when mounted perpendicularly to the riverbed (Allan et al., 2006).

Detection range depends on methodological, environmental factors and, technique (Zydlewski et al., 2006), ambient electromagnetic disturbance (Beeman et al., 2012), tag size, tag orientation (Burnett et al., 2013), transmission type, presence of more than one tag in the antenna field at a time, , etc. Additional factors such as stream velocity, stream width, and water temperature (Connolly, 2010) also influence the range. Since the PIT-tags do not need any battery, but rather access power from the antenna, they in principal las forever (Allan et al., 2006, Smyth and Nebel, 2013). Antennas for detection can be of different types; short-ranged handheld scanners or long-range, stationary copper antennas placed in the river. These types of PIT antennas are located at strategic sites where tagged rocks are likely to pass. A combination of portable-and fixed antennas were used to maximise PIT tag detections for the study area (Banish et al., 2016)

In this study, a stationary antenna (Oregon Single Antenna Reaser, ORSR- https://www.oregonrfid.com/products/hdx-long-range-readers/next-generation-single-antenna-reader/) was mounted above the old E6 in August 2019, by the river outlet. Unfortunately, this stationary antenna did not function correctly, and was most of the time not activated for detecting rocks that could have been transported out of the river system. During the last sampling round, a circular mobile handheld pole antenna with GPS tracking (Oregon RFID Mobile Reader kit, https://www.oregonrfid.com/products/hdx-long-range-readers/mobile-reader-kit/) was used for scanning the main river channel, side tributary and side channels. The portable antenna gives an exact definition of the deposition point (Habersack, 2003). Such antennas have become a useful technique for tracking fish sampled with PIT tags (Banish et al., 2016, Nese, 2019, Johnsen, 2013). In cases when the RFID system had trouble with locating positions, a handheld GPS (GARMIN etrex 10) was used.

An individual tagging study like this, marking individual rocks with PIT-tags, is relevant for process studies where knowledge of transport pattern in streambeds is desired. With such a study, it is possible to analyse details such as where and when the sediments move regarding to rock shape and weight, etc (Fergus and Bogen, 1998, Froehlich, 2003, Vázquez-Tarrío et al., 2019). Sediment tagging has become a common technique in geomorphological studies with different intentions. Some studies have used traced rocks in order to investigate relationships between tracer travel distance and flow magnitude (Schneider et al., 2014), while others have researched the control of macroforms and channel morphology on tracer dispersion in bar-pool channels (Liébault et al., 2012). One of the latest PIT studies on sediments was done by Vázques-Tarrió et al. (2019). They analysed a large set of tracer data from 33 scientific papers with a wide diversity of mountain rivers in order to explore the role of geomorphological, hydromorphological and sedimentological constraints on fluvial gravel transport in gravel-bed rivers.

2.2.3 Marking painted rocks with PIT tags

The first round of field work was conducted from May 30th to June 1st. A total of 111 well consolidated, sub-rounded, rocks from an older gravel pit in Bognelvdalen were collected (i.e. the geology of all rocks was similar). A 23mm PIT tag was inserted into each rock by drilling a hole and filling it with white Tec7 glue. All rocks were then painted white so they would be easier to visually identify and trace as coarse particles when registering in later rounds of fieldwork (Figure 3). A white colour would not pollute the river with unnatural colour, while still providing relatively easy recognition. Marking sediments with painting is an old visual method, and is known for being the first tracer grain techniques used in gravel-bed rivers to classify morphological properties (Chase, 1994, Lamarre et al., 2005). All rocks were individually weighted, but diameter not measured. Therefore, the intermediate length (B-axis) of each rock was calculated from a curve from Leopold (1970) showing the empirical relationship of metamorphic sub-rounded gravel size in millimetres to average weight in grams :$ln(D) = 0.34 * ln(W) + 1.923,$ where D is the diameter of the rock and W is the weight. Rocks were divided into three size groups: class 1 (0.2-0.7 kg), class 2 (0.7-1.8 kg), and class 3 (1.8-2.5 kg) and then placed in six buckets. Each bucket contained all three rock sizes with random amounts of each size (Table 2).

The rocks were then "released" at the six stations. Due to high discharge during the time of field work, 17.31 m^3/s (Figure 7), the well consolidated rocks were placed across the river by a way of randomly lobbing them out (Figure 3). Since the conditions were unconstrained and rocks were not arranged and pressed into the bed by hand (constrained conditions), the tracer stones were free. Displacement was therefore assumed only depending on absolute size effect and not on the flow to break up bed texture and particle arrangements. According to Fraley (2004), rocks settle into a more stable configuration after they have been moved by the flow.

Figure 3. Left: Photograph of painted white rocks that have an inserted pit-tag, and divided into rows of each of three weight classes. Right: Releasing of rocks in field. Picture is taken at station 5.

Table 2: Information about released rocks in Bognelv, 31.05.2019.

	Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
Coordinates	550743 E 7766214 N	550401 E 7767286 N	550390 E 7767365 N	549837 E 7768151 N	550077 E 7767864 N	550354 E 7767488 N
Average length in B-axis (mm)	77.94	72.88	76.98	66.29	73.31	74.42
Amount of small rocks, Class 1 (0.2-0.7 Kg)	5	6	8	6	5	7
Amount of medium rocks, Class 2 (0.7-1.8 Kg)	9	10	9	13	14	11
Amount of large rocks, Class 3 (1.8-2.5 Kg)	3	2	2	0	0	1
Total amount of rocks placed out	17	18	19	19	19	19

2.2.4 Tracking in field

Registration, and relocation of the tagged rocks took place after 6 months (6-7th November). Relocating the marked tracer particles after their transport is technically simple, but time consuming, and depends on weather conditions. Detection is easier to complete at lower amounts of water; therefore I waited until early November (7-8th of Nov). However, winter came early to Bognelv in 2019. During fieldwork, temperatures dropped to -20 °C with combined snowfall. Parts of the river bottom froze, making it slippery to walk the entire width of the river and register. Side channels were partly frozen making it easier for registrations through the ice (Figure 5). At the three lowest stations -3, 5 and 6- the river was partly ice-covered, but the ice was not thick enough to walk on, and the pressure from floating ice made the pools even deeper. Due to these conditions, the entire river was not sampled during this round (Figure 4).

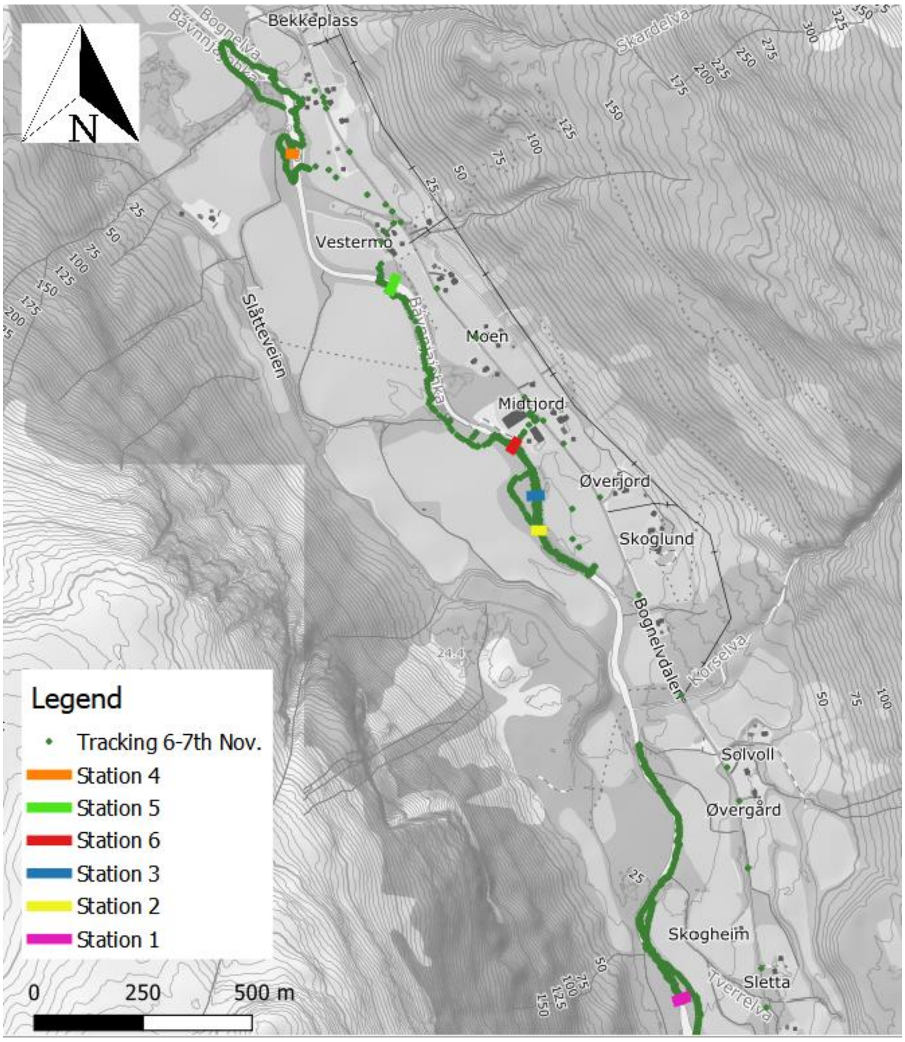

Figure 4. Tracking data from the handheld GPS from registration in November, when the portable PIT antenna was used.

Figure 5. Left: Station 5. With this onset of freezing water and uncertain ice conditions, it was impossible to register traced rocks at this station. Right: Station 2. Solid ice made it possible to scan the side channel (notice the portable antenna).

In hope of a solid ice-covered river, a new registration round began in February. PIT-tags can also be registered through ice and snow cover, as long as it is not thicker than the detection range of the antenna (Linnansaari et al., 2007). In December 2019 and February 2020, the closest weather station, Sopnesbukt, measured around 192 cm of snow (yr.no). Due to snow amount and wind drift, parts of the river had snowdrift higher than 1-2 meters, while parts of station 6 were open (Figure 6). The antenna was tested and capable of registering visual rocks seen at station 6, but was not able to register through the high snow cover at station 5.

Figure 6. Left: A picture of the snow cover at station 6 in February. Snow depth measured over 1 meter, so no rocks could be registered through the snow. Right: Picture from station 5 shows how difficult conditions were in February for another possible round with registration.

2.2.5 Hydromorphological cross sections of the riverbed

October 18th, sampling of cross sections was conducted at each station, at the same position as the marked rocks were released. This was conducted in order to get a better picture of the geomorphology of each site, and to investigate variations within the stations related to restoration measures. Environmental variables such as width (bankfull and wetted width), depths, bedload size, bedload roundness, and river discharge were measured. Also, the division of substrate were estimated visually. An estimation of division of substrate was estimated at each station with the same methodology as Sødal (2014) and explained in more details in Appendix 4. The categories were based on a percentage score. Substrate composition was classified in five percentage grain-size groups.

Information on bed particle size and shape is needed for a variety of purposes. Among them is an understanding of stream processes, bed stability, and flow hydraulics. Gravel and cobble-bed streams have a large range of grain size (from fine sand of 0.06mm to boulders of 4000 mm) (Bunte and Abt, 2001), and therefore might involve more complicated sampling processes than homogenous beds. According to the report from Bunte (2001) related to sampling in wadable streams, few papers provide specific information on bed-material sampling in small mountain streams with coarse beds, due to a wide range of bed material particles sizes. Methods for sampling bed-material in gravel-and cobble-bed streams will therefore depend on study objectives and stream conditions. Sampling may need to cover areas of the streambed about 5-7 channels in width, and can be done with different techniques, such as surface sampling, subsurface sediment sampling or a combination of both (Ramos, 1996, Bunte and Abt, 2001). Surface sampling collects bed-surface particles that are exposed on top of streambeds; the bed is either dry or submerged, and can be sampled in different ways depending on spacing distance, size of sampling area, field time vs lab time etc (Wolman, 1954, Bunte, 2001b, Fraley, 2004). Surface sampling is affected by the character of the fluid flow. It is therefore the primary interest in studies of hydraulic characteristics, such as size distribution of surface sediments, flow resistance, stability and surface coarsening (Hohensinner et al., 2018a). For sampling particles there are two commonly used techniques for pebble count (Wolman, 1954, Bunte, 2001b).

During fieldwork in Bognelv pebble count was sampled at even-spaced marks along a measuring tape. A measuring tape was stretched across the river's bankfull width at the six stations, exactly where the rocks were released. Particle selection was done under-water where a pin was used for identification of particles to select. Spacing between particles depends on bed-material particle size and is set to a value larger than the b-axis of the largest particle of concern. This is done in order to prevent double counting of large particles. In this case the top width of all river stations varied between 10-18 m, and the particles were selected at intersection with nine even spaced marks along the edge of the tape, due to a majority of boulders with a b-axis larger than 50 cm (Wohl et al., 1996) (Appendix 5). Size of the bedload sample was measured in cm as the length of the intermediate B-axis (Fraley, 2004, Bunte and Abt, 2001). Bedload roundness was defined after Power's index of roundness at a class from 1 to 6, where class 1 is very angular, and class 6 is well rounded.

2.3 Data processing and other statistical analysis

Raw data was prepared in Microsoft Excel 2018 (Microsoft Office 365 ProPlus) before being exported into a statistical computing software program, R (Team, 2019) and geospatial software program QGIS 3.2.3 for processing, analyses and visual representation. A level of significance of 0.05 was used in statistical tests.

2.3.1 Tracer data and aerial photograph analysis

To analyse the spatial movement of the rocks, and for comparison of aerial photos I used QGIS. The recaptured GPS positions from the mobile antenna were uploaded to QGIS with an orthophoto from Bognelv in 2015 as a base map. Travel length was determined with the measurement tools, and travel path was assumed to be perpendicular from the starting line.

The goal with aerial photos from Bognelv was to use airplane-based digital imagery and GIS to classify and map changes in hydromorphic stream units before and after river restoration. For comparison, aerial photos from 1946, 1972 and 2005 (Appendix 6) have been georeferenced and orthorectified in QGIS so that the photos follow the same map projection, as the newest orthophoto from Bognelv was taken in 2015.

Aerial photographs are widely used to obtain geologic information and map the characteristics of stream channels. Such characteristics put into a reach scale map are critical for both monitoring and understanding changes in floodplains, channel morphology and habitats (Casado et al., 2015). Interpretation of photographs was based on recognition of features based on photographic tone, colour, texture, shadow pattern, shape and size (Ray, 1960). In order to permit the identification of a feature it is important to relate it to its surroundings, such as riffles and pools. Riffles, pools and runs are commonly applied for predicting changes in river channel. According to Wright et.al (2000), there are several studies that have used remote sensing to map components of channel morphology in larger rivers, but few have attempted to map morphologic stream units such as riffles and pools on third and fourth-order streams like Bognelv. More information on previous studies that have used aerial photography on documenting changes in fluvial morphology can be read from: Perschbacher (2011), Wright et al., (2002), Lyons and Beschta (1983), and Syrian and Rinaldi (2003).

In Bognelv, the comparison focused on the lowest part of the river section, where most changes in river morphology have occurred. The aerial photos taken from Bognelv are not of high resolution; therefore the largest hydrogeomorphic units were most accurately classified, such as the channel outline, riffles (displays significant white water and typically have slopes), pools (displays little surface disturbance) (Montgomery and Buffington, 1997), point bars (deposition of sediments in inner turn) (Jackson, 1976, Hohensinner et al., 2018b) and islands (Osterkamp, 1998).

The results will show an overview over all features mentioned above and their location in the river channel from 1946-2015. Colour of the features are related to each year, where black colour is linked to 1946, orange to 1972, red to 2005 and blue to 2015. Further, the overview map will be simplified and analysed year by year. The numeric result of the aerial photo analysis is synthesised in a general scheme in the end of the result chapter, and summarizes the main styles of morphologically adjustments observed in Bognelv before channelization, after channelization and after river restoration.

2.3.2 Model selection

In order to investigate whether the bedload travel distance in Bognalva was affected by different hydromorphological factors, several generalized linear models were made in R (Team, 2019). One seeks to find the most supported model for these variables given the data, that explains the greatest amount of variation using fewest possible parameters.

In program R, the function "AICcmodavg" was used to aid in the model selection. This package includes functions that can create model selection Tables based on Akaike's Information Criterion (AIC). Akaike information criterion is a method for comparing the accuracy of multiple candidate moels (Bozdogan, 1987, Wagenmakers and Farrell, 2004, Burnham and Anderson, 2004, Anderson, 2007). The model with lowest AIC value will be listed first in the model selection table. By comparing each candidate model with the most supported model the metric ΔAIC, which is the difference in AIC score between the most supported model and the model being compared, a ranked list of the candidate models can be made. As a rule of thumb, models within 2 AIC units (ΔAIC< 2) can be considered substantially evident, whereas values between 3 and 7 suggest that the model has considerably less support and ΔAIC > 10 demonstrates that the model is very unlikely (Burnham & Anderson 2004). Because the sample size of recaptured rocks is small (n= 67), Akaike's second order confirmation criterion (AICc) and the Akaike Weights (Wi) were used for model selection (Grueber et al., 2011).

The "akaike-weights" (w_i) can be interpreted as probabilities for each model being the most supported model with a range from 0-1 (Bozdogan, 1987, Burnham and Anderson, 2002). More details on model selection can be found in Wagenmakers and Farrell (2004) and Anderson (2007). In order to estimate the effect of factors of interest on rock displacement, I fitted candidate linear models with distance as response and factors of interest as predictors (Searle, 1971). Each generalized linear model in this thesis contains a different combination of the variables measured in field. The aim is to know which of the independent variables measured in field can explain most of the variation in bedload travel distance. The effect model with lowest AIC values in the model selection table is the one that best describes the probability for bedload transport from the data that is available. In total, 29 different candidate models were fitted.

$\omega *$ is a variable called “Dimensionless stream power”, and has been used in previous tracer studies (Eaton and Church, 2011, Vázquez-Tarrío et al., 2019). Stream power determines the capacity of a given flow to transport sediment (Wainwright et al., 2015). Dimensionless version of unit stream power is used to obtain a strong scaling relationship between bedload and flow magnitude without using any criterion for incipient motion since the rocks were not arranged on the riverbed when they were released (unconstrained). The formula for this variable is:

$\omega * = \frac{\omega}{p*(g*R*D)^{3/2}}$, where ω* is the dimensionless stream power.

ω is peak unit stream power (Bagnold, 1966), defined as stream power per unit channel width given by the equation $\omega = \frac{p*g*Q*S}{W}$, where *p* is the fluid density (kg/m^3), *g* is the acceleration due to gravity (m/s^2), *S* is the channel slope (m/m), and *w* is the top width (m). R is the submerged specific weight of sediment and D is the calibre of sediment in transport (Eaton and Church, 2011). ω*Q50 is the dimensionless stream power for the median discharge during the transport episode, while ω*Qmax is the peak discharge during the transport episode. Velocity (m/s) is a variable measured in field in October 18th 2019. To account for a dependence of tracer transport on channel morphology and effect of river restoration, midriver measure is one of the variables in the models that gives information of what type of measure has been conducted at the stations (Table 3). Since measures conducted along the river edge overlap with measures in the channel, only mid-river measure was taken into account. For the different stations the mid-river measures were: Station 1, 2, and 4 related to riparian modification with an aim to increase the diversity in water flow and create pools. Station 5 and 6 have no conducted restoration measures and are so-called reference stations. Station 3 relates to a river section with restoration measures, but the restoration measures conducted at this station are related to increasing water levels and not related to formation of pools; and thus the river section still looks channelized. Subsequently, station 3 is also interpreted to have the same transportation effect as a reference area.

Table 3. Simplifying what restoration measures relate to each station and how they affect the river morphology by creating pools or not. Stream type is classified after Montgomery and Buffington (1997)

Station	Mid River Measure	Stream Type
1	Pools	Pool-riffle
2	Pools	Pool-riffle
3	Reference	Plane-bed
4	Pools	Pool-riffle
5	Reference	Plane-bed
6	Reference	Plane-bed

2.3.3 Hydrological data

Bognelv has no mounted flow index station. I therefore used data from nearby station fields with similar properties and scales. An optimal station for correlation might not exist (veiledning NVE), and it was therefore important to study field properties for watercourses with similar catchment areas nearby Bognelv. According to Stenius et al., (2005) the most important field properties to study include field area, height above sea, median runoff, etc (Appendix 8). In this thesis, data from the nearby station Halsnes (212.49) has been used to scale the daily water flow for Bognelv in the wanted period. Figure 5 shows a hydrological graph of the daily average water flow (m^3/s) for the period May- November based on the scaled numbers.

Halnsnes river station belongs to Vassbotnelva (Dálbmávžžejohka). Both Bognelv (watercourse number 211.8A0) and Vassbotnelva (watercourse number 212.2Z) run out from the mountains on the border between Troms and Finnmark, west of Alta. Vassbotnelva flows out south of Talvik by Altafjorden, located east of Bognelv but in the same municipality (Appendix 7). In a protection plan for watercourse in 1979-80, both Bognelv, and Vassbotnelva were assessed as fully protected against power plant development (energiderpartementet, 1979-80). Several lakes are situated on top of both watercourses, that together forms the water source towards Troms. Compared with Bognelv, which is partly channelized the last 3.5 km, the lowest parts of Vassbotnelva down to Storvannet are intact. (NVE, 2017). The last 1.8 km of Vassbotnelva is called Halselva (Dálbmejohka) and runs from Storvannet and terminates in Altafjorden. In Halselva, we find the river station Halsnes (212.49). Data parameters from Vassbotnelva/Halsnes and Bognelv can be read from the table in Appendix 8. With help from NVE (Wæringstad, 2020), a scaling factor of 0.69 was calculated as a sum of the relation between area times the relation between median runoff from both rivers. The scaling factor formula given from Wæringstad, 2020 was used for estimation of daily waterflow m^3/s in Bognelv.

$$; \frac{89\ km^2}{145\ km^2} * \frac{32.5\frac{\frac{l}{s}}{km^2}}{29.01\frac{\frac{l}{s}}{km^2}} = \ 0.69$$

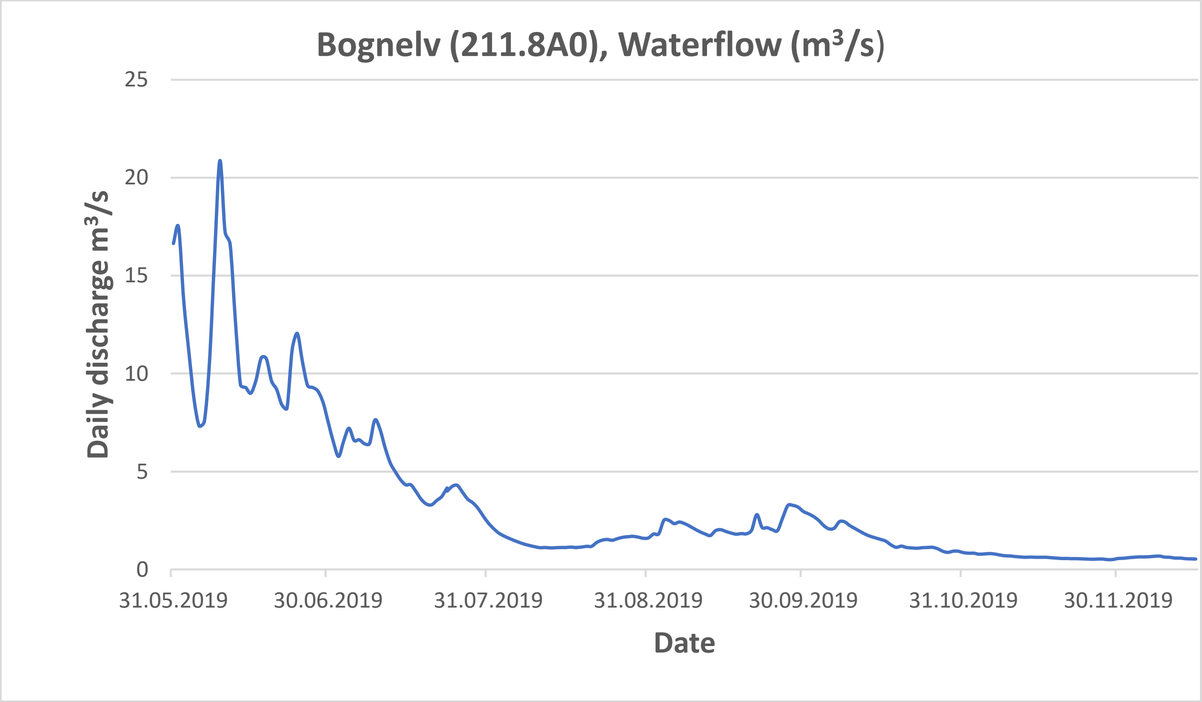

Figure 7. Hydrological graph showing the daily average water flow (m^3/s) in Bognelv in the period from May-November. Highest peak June 13, 11.00 am (32.42 m^3/s), and average flow (3.44 m^3/s). Numbers are correlated from the nearest station, Halsnes (212.49). Note that the rocks were released on May 31, almost two weeks before the highest water flow episode in June 13

3. RESULTS

3.1 ANALYSIS OF THE RECAPTURE DATA

3.1.1 Location of recaptures

Station 5, a reference station with no conducted restoration measures, has no recaptured data. The gradient at the six stations varied between 0.054 - 0.057 m/m. Be aware of the fact that the start position of each individual rock is unknown, since all rocks were chosen to be lobbed out from one position at the river edge. This decision will also affect the measured travel distance of tracer rocks.

Station 1, Restored section

Station 1 was the uppermost station in the river, zone 8 (Figure 2), related to restoration measure 7, located below Øverplasselva (Tabel 1) (Appendix 1). A total of 17 rocks were released in the river (Table 2), and 17 rocks were recaptured, a recovery rate of 100%. One rock was by mistake released above the starting line and has no registered travel distance. Figure 8 shows the travel path for each rock from where it was released (pink line) and until it was recaptured. Weight class 2 (0.7-1.8 kg) had the longest average transport length in the months from May- November with a movement of 11.6 m (Table 4).

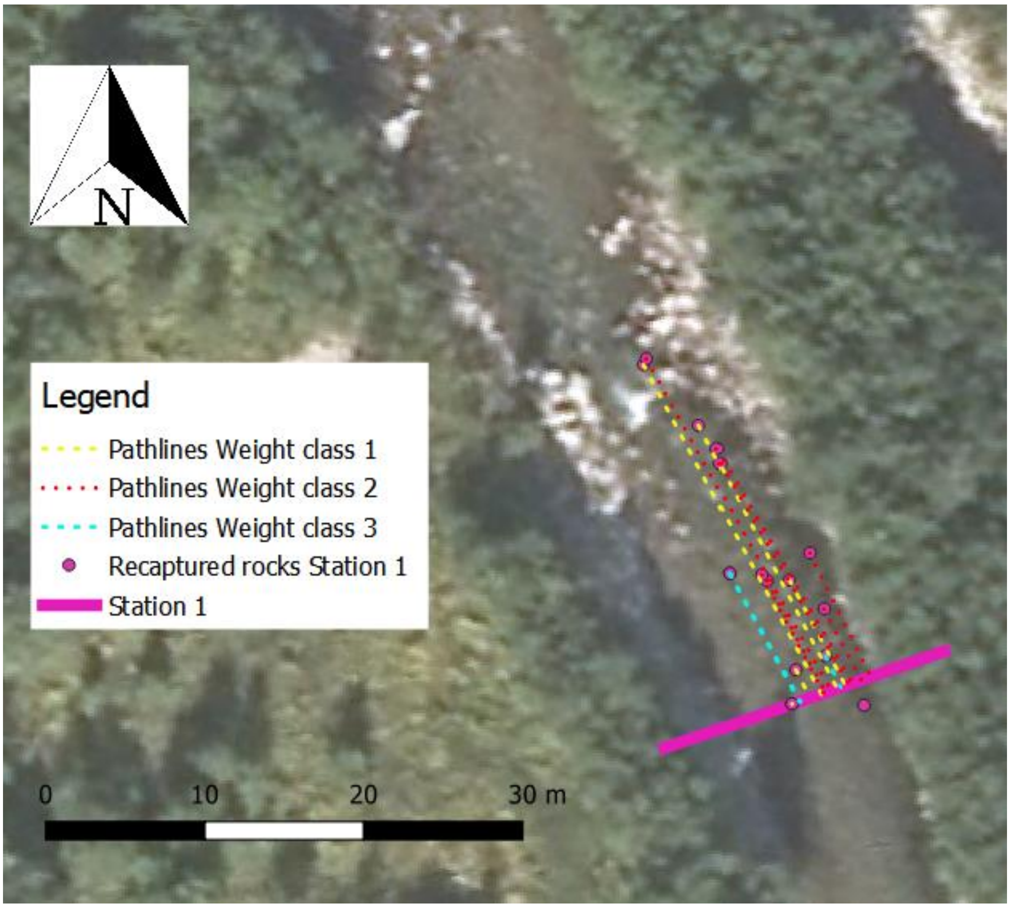

Figure 4. Overview map showing travel path for traced rocks at station 1. The pink starting line is where rocks were released, and pink dots are where they were recaptured. The colour of the path lines indicates what weight class each recaptured rock belongs to.

Table 4. Amount of rock recaptured for each weight class, and average transport length in metre for each weight class and their average median sediment size. D_{50}: median size of recaptured rock

Station 1	**Weight class 1**	**Weight Class 2**	**Weight Class 3**	**All classes**
Amount recaptured	5/5	8/9	3/3	17/17
Average transport length (m)	10.38	11.06	6.86	10.06
Average D_{50} (mm)	59.24	73.18	94.44	72.81

Station 2, Restored section

Station 2 (Figure 2) was related to restoration measure 5 (Table 1) (Appendix 1). 18 rocks where released and 16 rocks were recaptured, a recovery rate of 88%. Figure 9 shows the travel path to each rock from when it was released, and util it was recaptured. Weight class 1 (0.7-1.8) kg had the longest average transport length in the months from May- November with a movement of 13.2 m (Table 5), a longer travel distance compared with station 1.

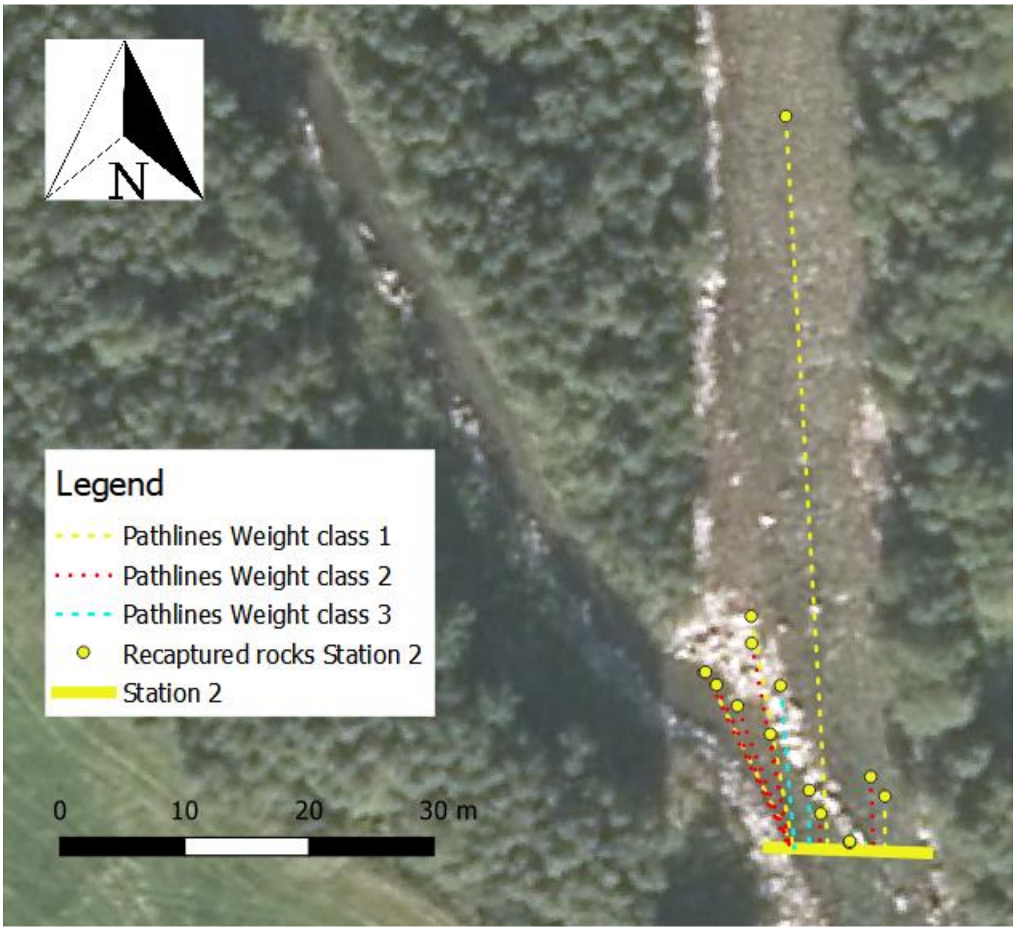

Figure 9. Overview map showing travel path to traced rocks at station 2. The yellow starting line is where rocks were released, and yellow dots are where they were recaptured. The colour of the path lines indicates what weight class each recaptured rock belongs to.

Table 5. Amount of rock recaptured of each weight class, and average transport length in metre for each weight class and their average median sediment size. D_{50}: median size of recaptured sediment rock

Station 2	**Weight class 1**	**Weight Class 2**	**Weight Class 3**	**All classes**
Amount recaptured	5/6	9/10	2/2	16/18
Average transport length (m)	10.38	12.28	8.9	10.52
Average D_{50} (mm)	56.98	73.7	90.52	70.58

Station 3, Restored section

Station 3 represents the same restoration number as station 2 (Table 1, Appendix 1), and is located below the re-opened side-channel (Figure 2). A total of 19 rocks were released and 16 rocks were recaptured, a recovery rate of 84%. As seen on Figure 10 below, two of the rocks were mistakenly thrown above the starting line and have no registered travel distance. Figure 10 shows the travel path for each rock from when it was released, till it was recaptured. In contrast to station 1 and 2, weight class 3 (1.8-2.5 kg) had the longest average transport distance in the months from May- November with an average movement of 24.7 m (Table 6).

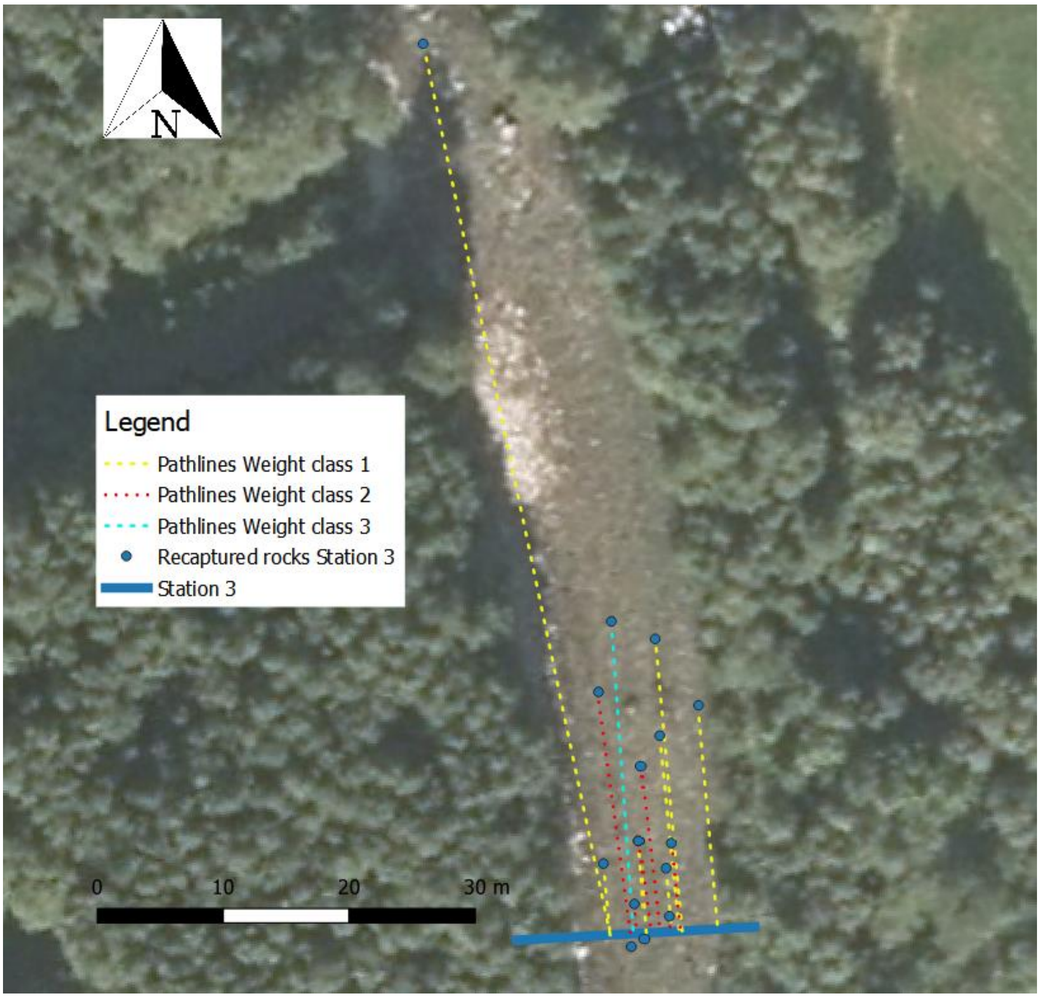

Figure 9. Overview map showing travel path for traced rocks at station 3. The blue starting line is where rocks were released, and blue dots are where they were recaptured. The colour of the path lines indicates what weight class each recaptured rock belongs to.

Table 6. Amount of rock recaptured of each weight class, and average transport length in metre for each weight class and their average median sediment size. D_{50}: median size of recaptured rock

Station 3	**Weight class 1**	**Weight Class 2**	**Weight Class 3**	**All classes**
Amount recaptured	7/8	6/9	1/2	16/19
Average transport length (m)	21.02	8.45	24.7	15.9
Average D_{50} (mm)	50.28	77.09	98.09	68.78

Station 4, Restored section

Station 4, was the furthest station downstream, and was related to measures conducted in 2014, where an island was constructed (Figure 2) (Table 1). A total of 14 out of 19 rocks were recaptured, a recovery rate of 73.6%, lower than station 1-3. Figure 11 shows the travel path for each rock from when it was released, and until it was recaptured. Weight class 2 (0.7-1.8 kg) had the longest average transport length in the months from May- November, with 8.06 m, but shorter travel distance than the other stations (Table 7).

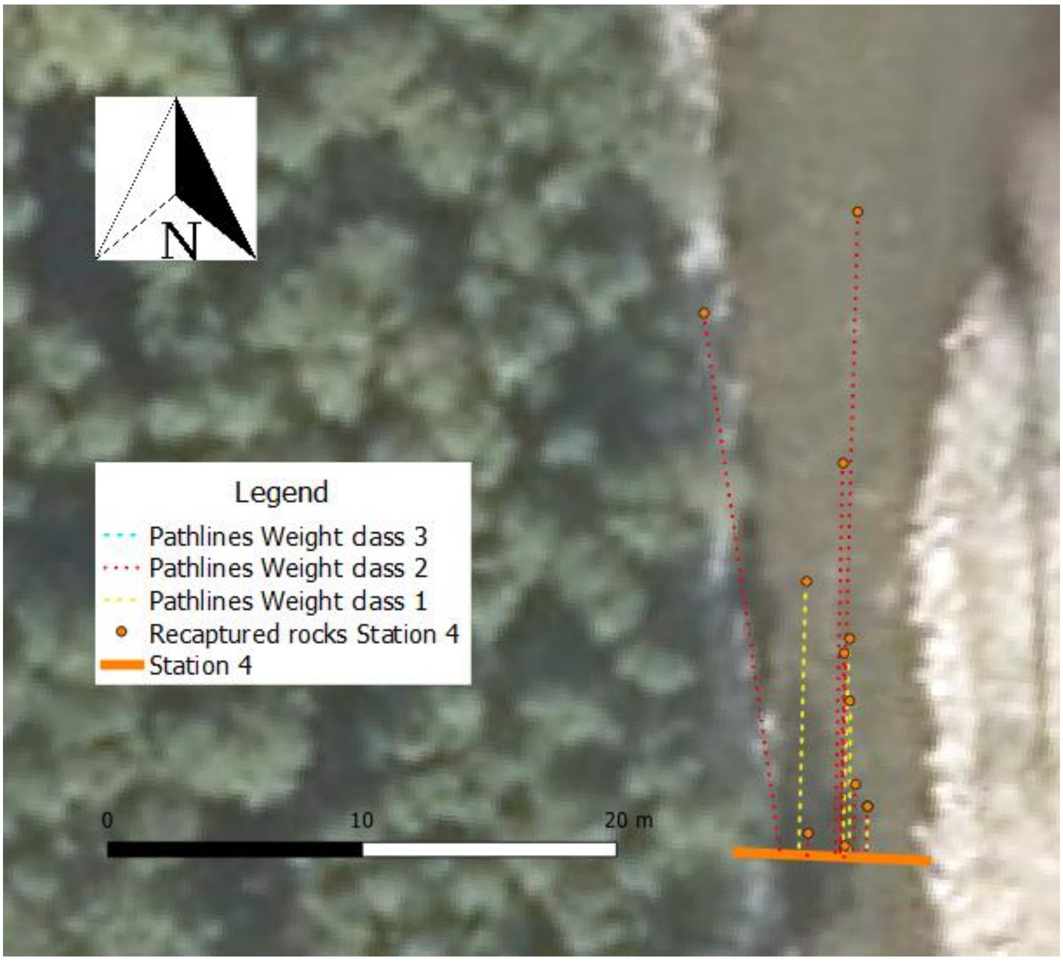

Figure 11. Overview map showing travel path for traced rocks at station 4. The orange starting line is where rocks were released, and orange dots are where they were recaptured. The colour of the path lines indicates what weight class each recapture rock belongs to.

Table 7. Amount of rock recaptured of each weight class, and average transport length in metre for each weight class and their average median sediment size. D_{50}: median size of recaptured rock

Station 4	**Weight class 1**	**Weight Class 2**	**Weight Class 3**	**All classes**
Amount recaptured	4/6	10/13	0	14/19
Average transport length (m)	6.95	8.06	0	7.74
Average D_{50} (mm)	54.13	76.73	0	70.28

Station 6, Reference station, non-restored section

Station 6 is one of two reference stations sampled where the river was still channelized, and where no restoration measures have been conducted (Figure 2). A total of 7 out of 19 rocks were recaptured 6th November, a low recovery rate of 36.8 %, lower than the other stations with recaptured data. Figure 12 below shows the travel path for each rock at station 6 from when it was released, and until it was recaptured. Weight class 1 (0.7-0.7 kg) had the longest average transport length in the months from May- November with 24.1 m.

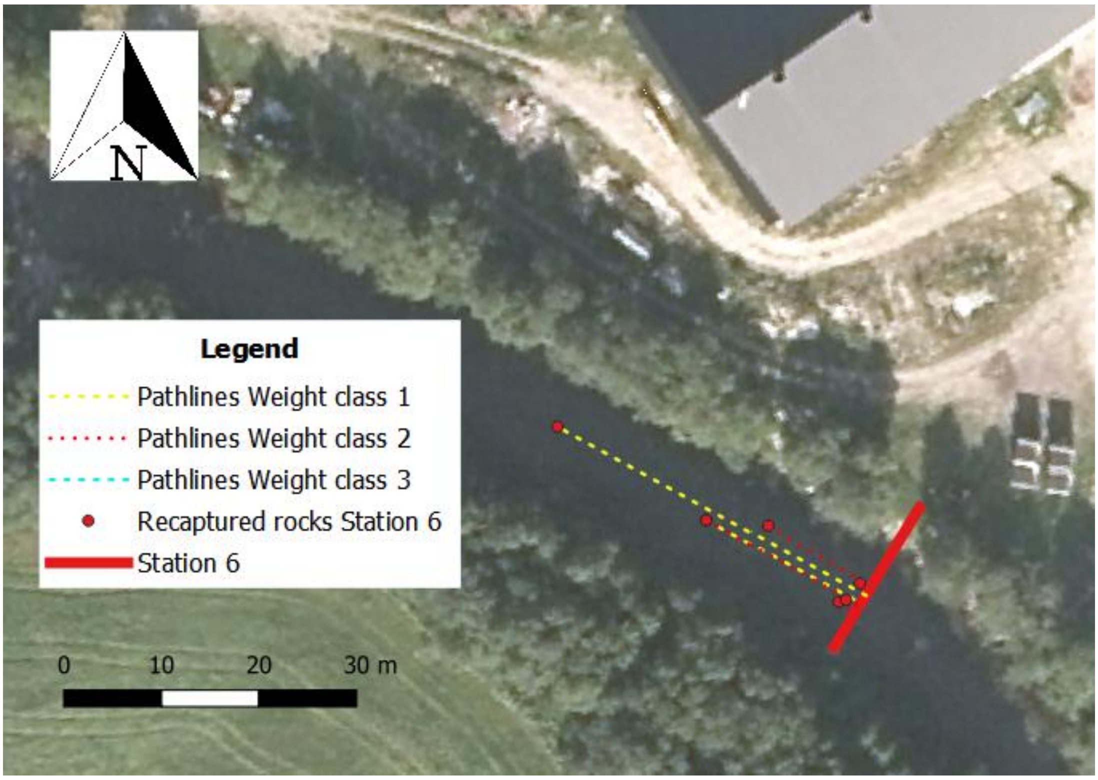

Figure 12. Overview map showing travel path for traced rocks at station 6. The red starting line is where rocks were released, and red dots are where they were recaptured. The colour of the path lines indicates what weight class each recapture rock belongs to.

Table 8. Amount of rock recaptured of each weight class, and average transport length in metre for each weight class and their average median sediment size. D_{50}: median size of recaptured rock

Station 6	**Weight class 1**	**Weight Class 2**	**Weight Class 3**	**All classes**
Amount recaptured	2/7	5/11	0/1	7/19
Average transport length (m)	24.1	8.12	0	12.68
Average D_{50} (mm)	57.36	72.01	0	67.98

3.2 FACTORS CORRELATED WITH TRANSPORT DISTANCE

3.2.1 Most supported model

From the model selection table below (Table 9) one can observe that the model with highest correlation with sediment transport distance is dimensionless stream power (ω*Q50), and the median size of the bed surface sediment (D50surf) (Model 15). It is the most supported model fitted to estimate effects on transport distance, attaining 16% of the support. The summary of the most supported model can be read from Table 11. The second most supported model had almost as high support as the most supported model (13 %) with just ω*Q50 as the only predictor (i.e., linear regression model).

Table 9: Ranged linear model selection table for prediction of bedload travel distance. Model 15, 1, 8, 11, and 9 have values within ΔAIC < 2, and are therefore the most supported models. K=number of estimated parameters, Cum.Weight = Cumulated weight, LL= Log likelihood, D50surf= median size of the bed surface sediment, ω: Dimensionless stream power at Q50 (median flow), Qmax (maximum flow).*

Results of AIC Analysis for Fifteen Competing Models (Hypothetical Data)

Model ID	**Model description**	**K**	**AICc**	**ΔAIC**	**Akaike Weight (w_i)**	**Cum.Weight**	**LL**
15	() * D50surf	5	196.56	0.00	0.16	0.16	-92.79
1	ω*Q50	3	196.92	0.36	0.13	0.29	-95.27
8	ω*Qmax	3	197.31	0.75	0.11	0.40	-95.47
11	Weight	3	197.52	0.96	0.10	0.50	-95.57
9	Velocity + Mid river measure	4	198.23	1.67	0.07	0.57	-94.79
4	(ω*Q50) + Mid river measure)	4	198.80	2.24	0.05	0.62	-95.08
16	(ω*Q50) * D50 Surf + Mid river measure	6	198.89	2.32	0.05	0.67	-92.74
14	(ω*Q50) +D50surf	4	198.99	2.42	0.05	0.72	-95.17
10	Velocity * Mid river measure	5	199.12	2.55	0.04	0.76	-94.07
12	Weight + Mid river measure	4	199.25	2.68	0.04	0.81	-95.30

Table 10. Parameter estimates for the linear model with most support for predicting bedload transport distance (Model 15). D50surf= median size of the bed surface sediment, ω: Dimensionless stream power at Q50 (median flow)*

Coefficients:	**Estimate**	**SE (standard error)**	**T value**	**Pr(>|t|)**
Intercept	67.274	33.285	2.021	0.047
ω*Q50	3.828	1.964	1.194	0.055
D50surf	-0.773	0.357	-2.162	0.034
ω*Q50: D50surf	-0.045	0.021	-2.154	0.035

Table 10 above is plotted as a contour plot (three-dimensional model) in Figure 13 where the contour lines represents the predicted travel distance based on dimensionless stream power and median size of the bed surface sediment. The selected model estimated travel distance for a small value of dimensionless stream power to increase with coarser surface substrate. And when dimensionless stream power increases, the transport decreases with coarser surface substrate (Figure 13). For instance, for a surface substrate size of 100 mm, and increasing dimensionless stream power, travel distance will gradually decrease. However, with a finer substrate size than 100 mm the opposite will occur. At substrate size of about 85 mm and dimensionless stream power of $4.5e^{-8}$ there is a so-called "saddle- point", a local maximum and minimum where the slopes of the two predictors are zero (equilibrium), at minimum of 9 meters. These prediction lines and values demonstrates how the effect of dimensionless stream power is dependent of the median size of the bed surface sediment and vice versa, as confirmed by the statistically significant interaction coefficient (Table 10).

Even though model predictors were statistically significant, the selected model had a low prediction precision of R^2=0.086.

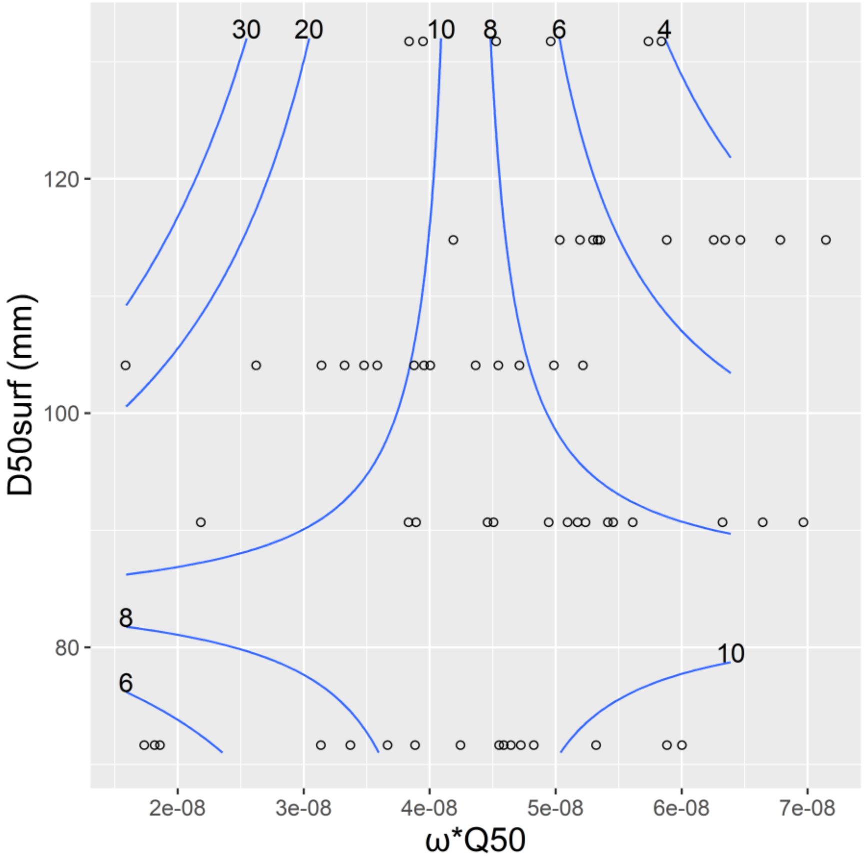

*Figure 13: Contour plot of estimated values of transport distance. The contour lines represent estimated travel distance values for different dimensionless stream power (ω*Q50) and different median size of the bed surface sediment (D50surf, mm). All the dots represent the data values, while the lines represent the model. Values in the plot are based on values from Table 9 and 10. Note that ω*Q50 values are in small numbers due to millimetre size of rocks and substrate.*

3.2.2 Most supported model including measure as effect

From the model selection (Table 9) one can observe that the most supported model including measure as effect had predictors such as velocity (m^3/s) and conducted restoration measure (Table 3). It is the most supported model with measures fitted to estimate effects on transport distance, attaining 7 % of the support. The summary of this model can be read from Table 11.

Table 11. Parameter estimates of model 9 that contains highest effect of river restoration measure.

Coefficients:	**Estimate**	**SE (standard error)**	**T value**	**Pr(>|t|)**
Intercept	2.633	0.460	5.722	3.01e-07
Velocity	-0.225	0.217	-1.171	0.246
Mid river Measurement	0.222	0.268	0.829	0.410

The summary table of the model is plotted as a prediction plot in Figure 14 where the lines represents the predicted travel distance based on flow velocity and measures on tracer travel distance. The selected model estimated travel distance to decrease with higher flow velocity (negative t-value). For instance, at a flow velocity of 1.5 m/s a rock will travel ~ 12 meters in pools and ~ 14 meter in a reference area, while at 2.5 m/s a rock will travel ~ 10 meters in pools and ~ 12.5 meter in a reference area.

Even though the model predictors were not statistically significant, with a low prediction precision of R^2=0.03, the model shows a tendency where the rocks have longer travel distance in reference areas than pools.

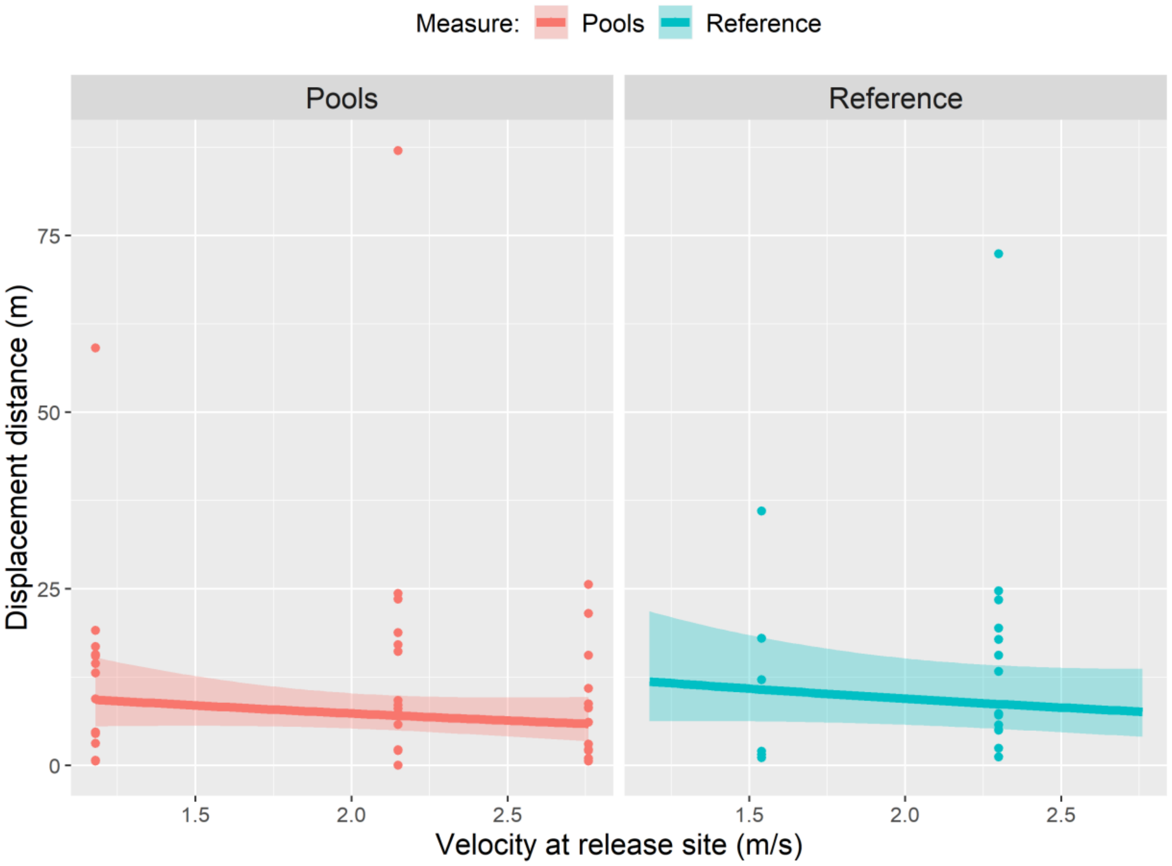

Figure 14. Prediction plot of model 9 that contains highest effect of river restoration measure (with 95% confidence interval). A predicted probability for rock distance at different velocities within pools and reference areas. The dots represent the recaptured rocks. Velocity at release site (m/s) was measured once in October 18th, 2019.

3.3 AERIAL PHOTOGRAPH ANALYSIS

Figure 15 shows an overview over all observed features and their location in the river channel from 1946-2015. Colour of the features are related to each year, where black colour is linked to 1946, orange to 1972, red to 2005 and blue to 2015. The overview map was simplified and analysed year by year. The result of the aerial photographs analysis was synthesised in a general scheme (Table 12) in the end of this chapter that summarizes the main styles of morphological adjustments observed in Bognelva before channelization, after channelization and after river restoration. The scheme represents initial intermediate and final stages of channel adjustment and relating morphologies. All four original orthophotos can be seen in Appendix 6.

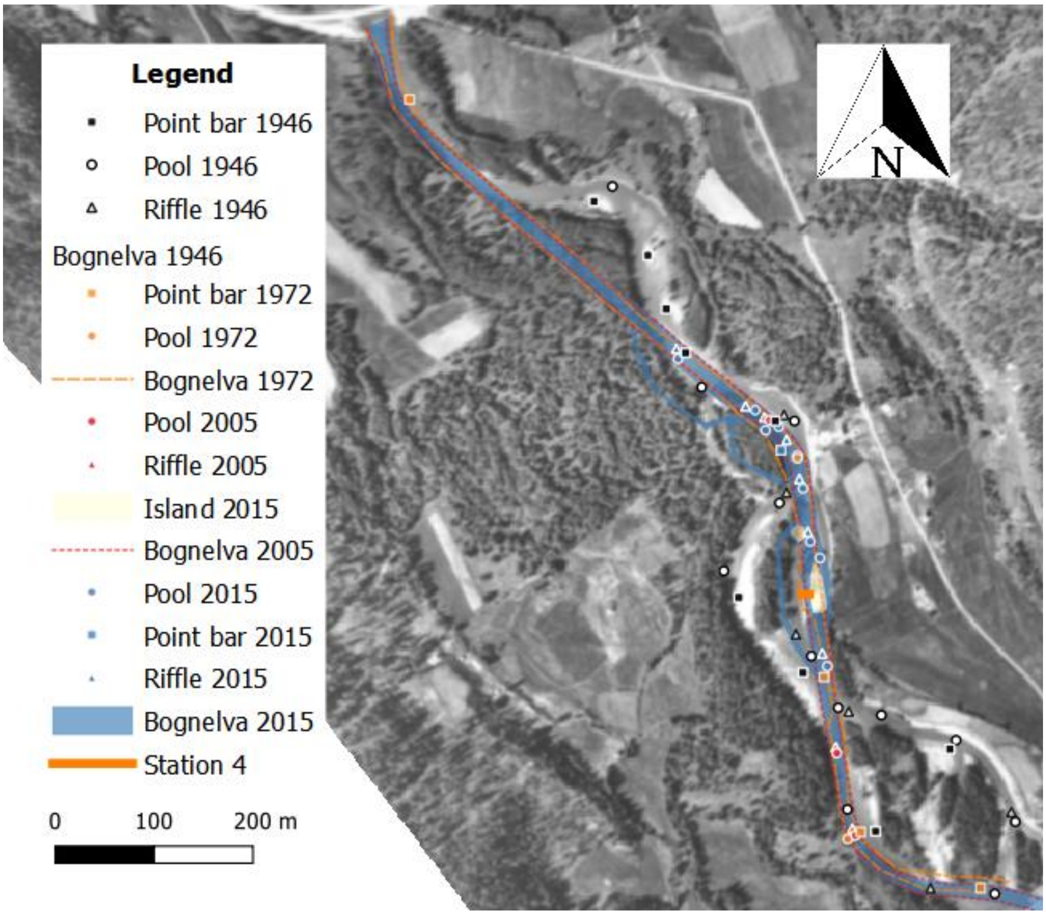

Figure 15. Observed morphological features such as channel outline, point bars, pools, riffles and islands from 1946-2015. Background photo is from 1946, while orange, red and blue outlines are from1972, 2005 and 2015, respectively. Station 4 was the lowest furthest station down the river where traced rocks were released in May 2019.

3.3.1 Changes in channel outline from 1946 - 2015

The aerial photo from 1946 showed Bognelv to have a natural river state with a dynamic river course, meandering turns, islands, and several side channels (Figure 16) (Appendix 6). Orange and red channel outlines from 1972 and 2005 illustrate how the river channel was channelized, and how meandering turns and side channels were cut off. After 2005, river restoration was conducted and the blue channel outline shows how restoration measurements re-opened some side channels.

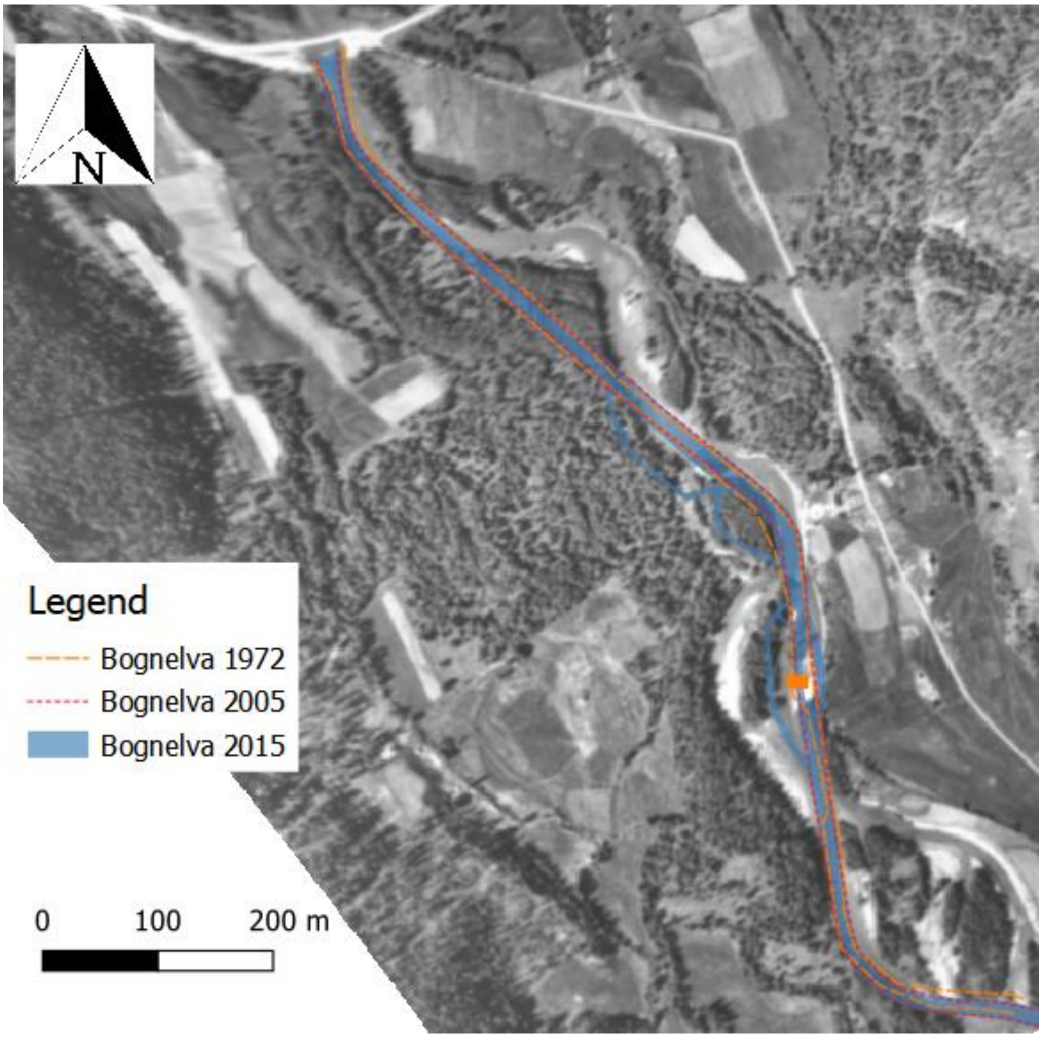

Figure 16. Changes in channel outlines from 1946-2015. Background photo is from lower Bognelv in 1946. Orange dotted line shows where the channel outline was located in 1972, red dotted line from 2005, and blue river polygon shows the channel outline from 2015.

3.3.2 Changes in river morphology year by year

River Morphology in 1946

Figure 17 below shows a dynamic meandering river with nine assumed point bars. The erosion in the outer turn creates pools, and the stream type will be classified as pool-riffle sequence (Montgomery and Buffington, 1997). It can also be observed side channels, islands, and the river is in general wider and longer than in the later years (Table 12). There was approximately similar amount of pools (n=11), point bars (sediment bars, n=4), and islands (n=9-10). Number of riffles were not as high as the other features. This can be due to a more stable water flow, where water level was probably higher.

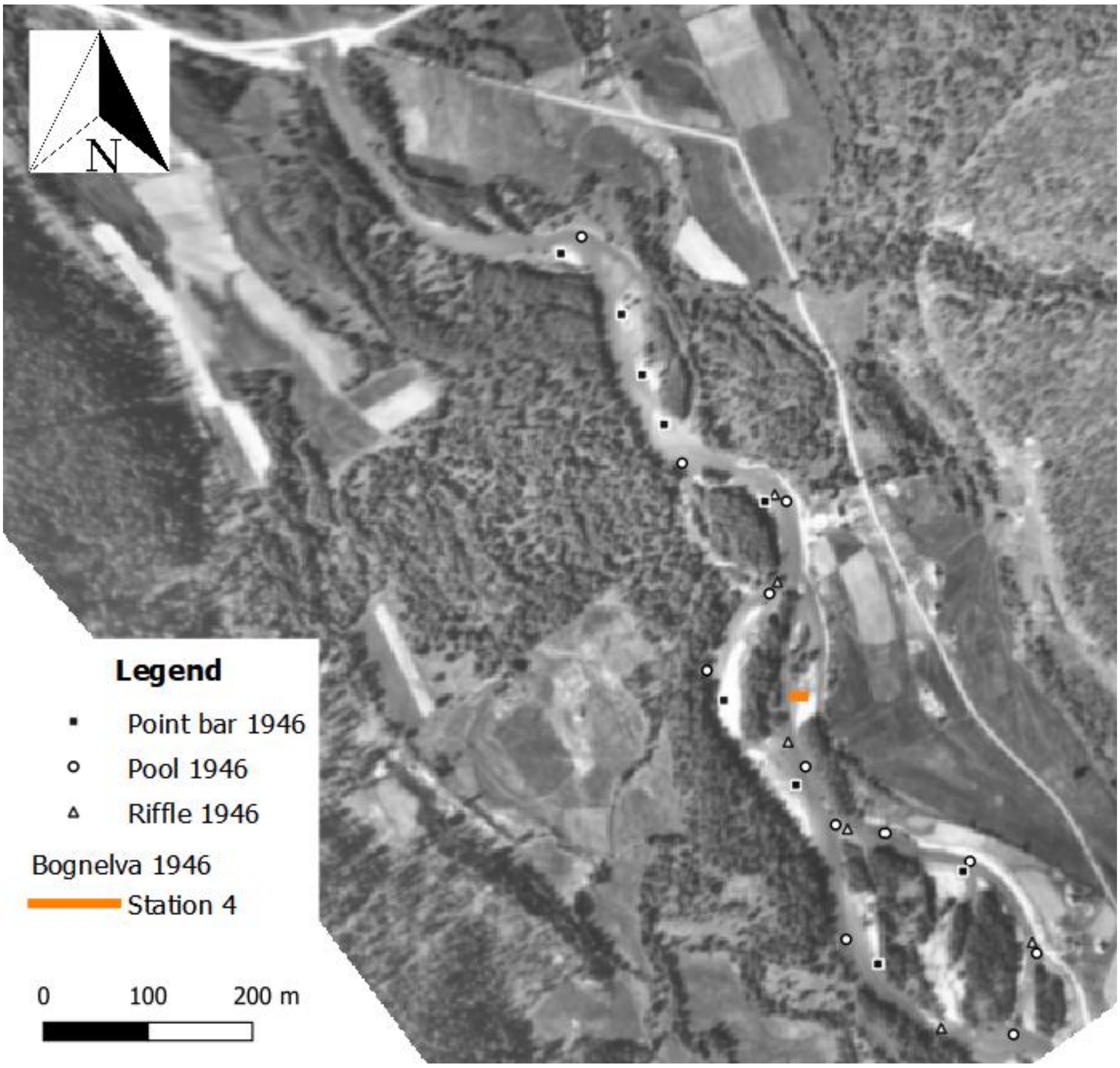

Figure 17. Aerial photo of Bognelv in 1946. Observed morphological features have been marked, such as point bars, pools and riffles. Station 4, shown as a reference point to where rocks were released in May 2019, at the station located furthest down and in a restored section of the river.

River Morphology in 1972

Between 1946 and 1972, the length of the river and river width was shortened (Table 12). With the river straightening the hydromorphological numbers of features has also decreased. Pools decreased from 11 to 2, and point bars from 9-2 (Table 12). Those remaining were in similar location as in 1946. Note that no riffles, islands, or side channels can be observed in the 1972 photograph. Figure 18 shows how the river was located a good distance away from the original river channel. The dramatic change in morphology makes the river stream change classification from a riffle-pool sequence to a plane-bed sequence (Montgomery and Buffington, 1997).

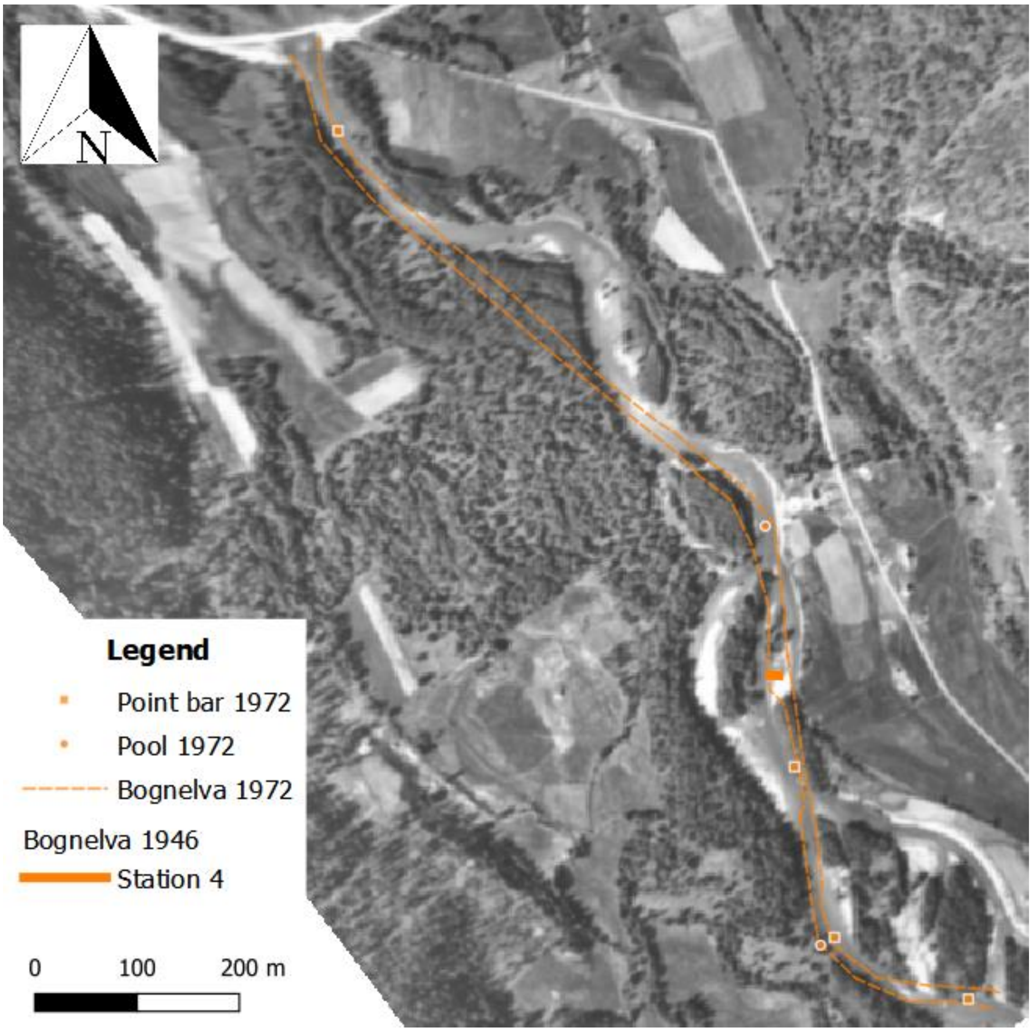

Figure 18. Aerial photo of the channel outline of Bognelv in 1972. Background map shows the channel outline in 1946. Observed morphological features have been marked, such as point bars and pools. Station 4 is shown as a reference point to where rocks were thrown out in May 2019, at the lowest restored river station

River Morphology in 2005

From 1972-2005 Bognelv was still under technical intervention. With the flood in 1978, the river was even more channelized. The average river width is getting smaller from 1972 and also the river length in this section. More riffles and pools are formed (Figure 19) (Table 12).

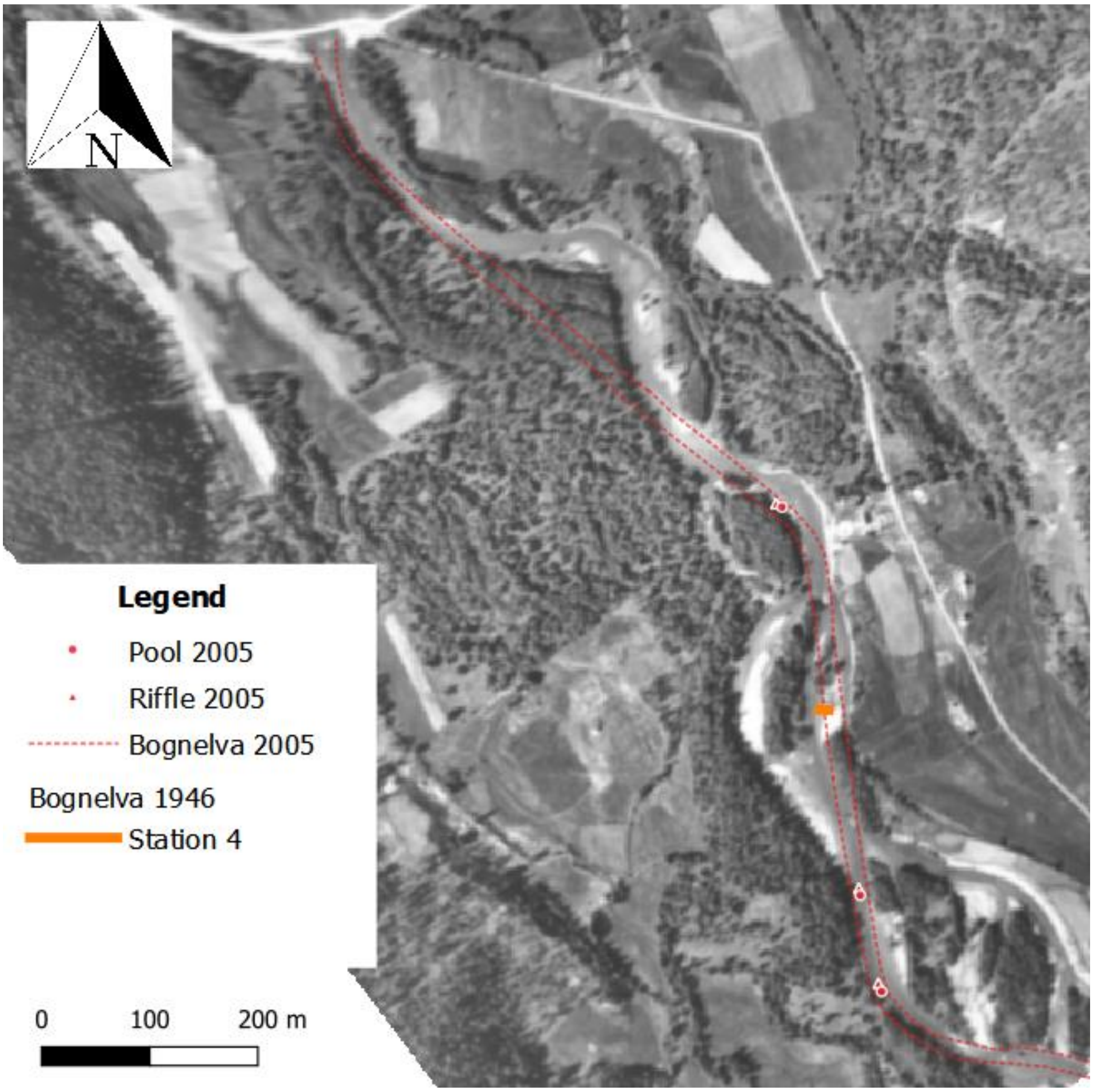

Figure 19. Aerial photo of the channel outline of Bognelv in 2005. Background map shows the channel outline in 1946. Observed morphological features have been marked, such as pools and riffles. Station 4 is shown as a reference point to where rocks were released in May 2019.

River Morphology in 2015

After 10 years with ongoing, various restoration measures, the aerial photo from Bognelv 2015 (Figure 20) revealed re-opening of side channels, constructed islands and formation of point bars, riffles and pools. The construction of the island and re-opening of side channels allowed the river to become more braided and meandering. River width and length has increased, in contrast from the years between 1972-2005 (Table 12).

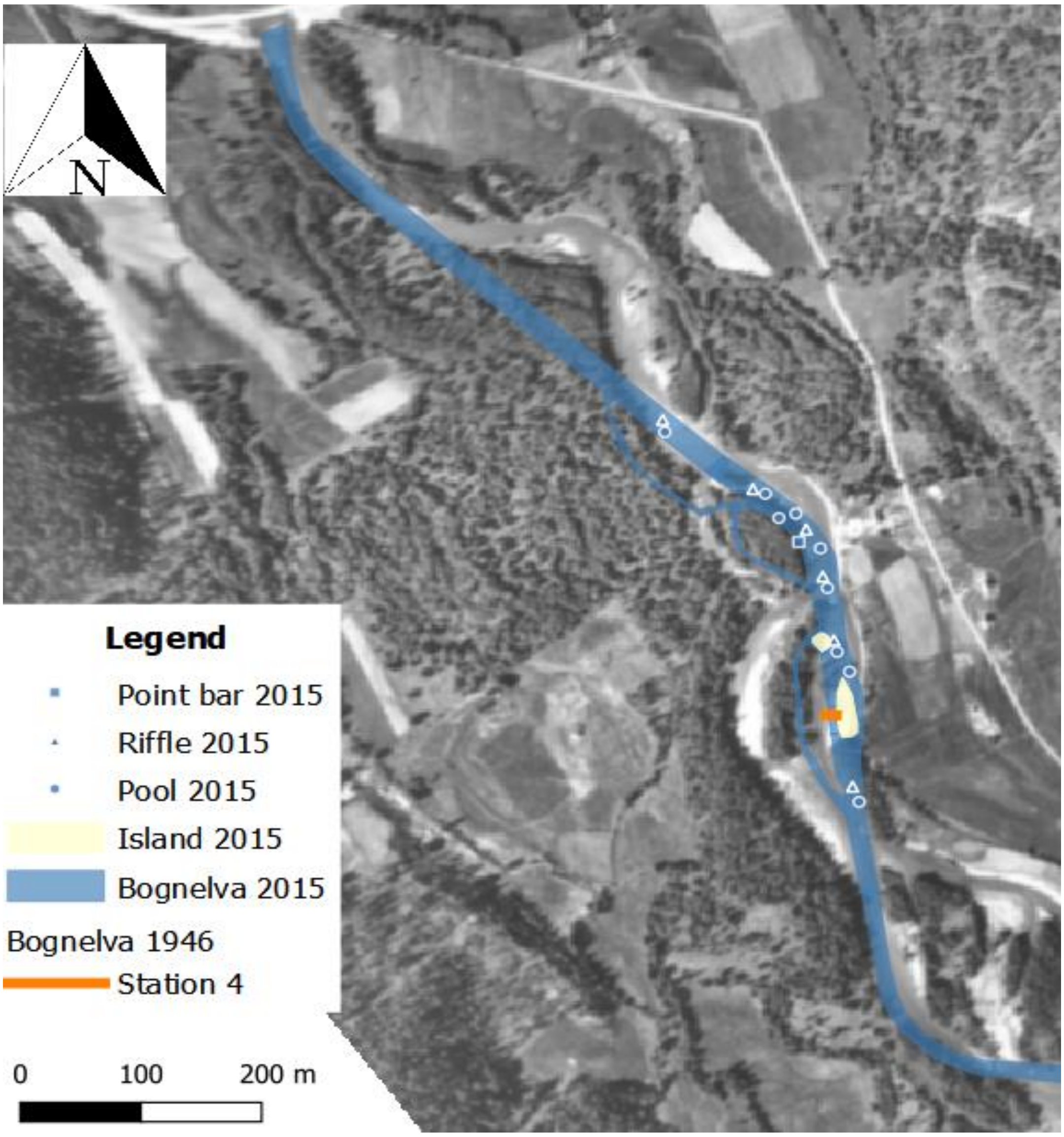

Figure 20. Aerial photograph of the channel outline of Bognelv in 2015. Background map shows the channel outline in 1946. Observed morphological features have been marked, such as point bars and pools. Station 4 is shown as a reference point to where rocks were released May 2019.

Table 12. Overview over numerical changes in hydromorphological features in Bognelv from 1946-2015. The scheme represents initial intermediate and final stages of channel adjustment and its relating morphologies

	1946	**1972**	**2005**	**2015**
Pools	11	2	3	9
Riffles	6	0	3	8
Point bar	9	4	0	1
Side channels	5-6	0	0	3
Islands	9-10	0	0	2
Stream types	Mostly pool-riffle	Mostly plane-bed	Mostly plane-bed	Combination of pool-riffle (restored sections) and plane-bed (channelized sections)
Channel pattern/sinuosity	Meandering	Channelized	Channelized	Combination of meandering and channelized
Width (m)	12.8 - 40.0	5.8 - 25	8.6 - 16.9	11.7 - 20.9
Length (m)	1285	1151	1125	1145

4. DISCUSSION

4.1 DISCUSSING THE FINDINGS AND HYPOTHESIS

4.1.1 Tracer data and transport lengths

The tracer data show that station 3 and 6, both related to channelized morphology, has the longest average transport length among all weight classes. Note that at station 3, weight class 1 had twice as long travel distance as weight class 2, but was similar to class 1. The restored stations 1, 2, and 4 had a shorter average travel distance (9.5 m), where larger particles showed shorter displacement than the combined tracers in the channelized areas. It has been observed in previous tracer studies that smaller particles show larger displacements than larger particles. (Ferguson and Wathen, 1998, Schneider et al., 2014, Hassan et al., 1992). In Appendix 5, field measures show that the channelized river sections have in general a coarser and more homogenous surface substrate with the least proportion of finer sediments, compared to the restored stations with riffles and pools. A coarsened bed-surface prevents entrainment from occurring, and therefore supports a greater transport capacity (Montgomery and Buffington, 1997, Vázquez-Tarrío and Batalla, 2019). Overall, the average bedload transport length was higher in channelized reference sections without restoration measures (14 m). River embankments shorten and limit the river width, leading to a steady and high water flow in channelized areas of Bognelv (Josefsen and Hoseth, 2005). These findings fit the theory that smaller particles experience larger displacement. The results support my first hypothesis of transport length being longer in the channelized part of the river related to areas with no restoration measurements.

4.1.2 Influence of flow magnitude; potential sources of scatter in the data

My results on influence of magnitude on tracer data unfortunately contradict the claims of Lamarre et al., (2005), Lamarre and Roy, (2008), Schneider et al., (2010), Liébault et al., (2012), Vázquez-Tarrío et al., (2019), Vásques-Tarrío and Batella, (2019). These studies claim that a high flow regime increases travel distance and transport competence (maximum size it can transport). In the results, it was expected that models that represented dimensionless stream power, and models with sediment weight, would have the highest explanatory support for bedload distance, but they did not. The model with dimensionless stream power along with weight, had a negative effect on transport distance, and were therefore not taken into consideration. Instead, the results show a different model than assumed with the highest explanatory power. It represents dimensionless stream power and median surface sediment. The scatter plot suggests for a small value of dimensionless stream power, the travel distance increase with coarser surface substrate. And when dimensionless stream power increases, the transport decreases with coarser surface substrate. This does not support existing evidence or confirm my second hypothesis, where transport should increase with coarser substrate for an increasing value of dimensionless stream power. Since size of the tracer rocks are similar to or smaller than the median surface sediment, one would assume the rocks to be more mobile and distance to increase with coarser surface sediment (Hassan et al., 1992). Even though the correlation between dimensionless stream power, median surface sediment and tracer transport were statistically significant, and the parameters depended on each other, there is a large scatter. A low $R^2=0.086$ confirms that the model has a low prediction precision, and that the relationship between bedload transport distance and the model explains less than 9% of the variation in distance. Something else must explain the remaining 91% of the variation and these unexpected results;

Firstly, it could be that the model is “spurious correlated”, meaning that that the effect of the two variables dimensionless stream power and median surface sediment have on travel distance, appear to be related but are not, and therefore might show some nonsense correlations of random artefacts. For instance, the reason why velocity has negative effect on travel distance might be due to spurious correlation. Such an appearance of relation is often due to similar movement on the graph which turns out to be coincidental caused by either a third factor, small sample sizes or arbitrary endpoints (Prairie and Bird, 1989, Ward, 2013, Kenton, 2019). It might therefore seem like the model was chosen to be good model, or at least that the correlation direction and magnitude (i.e., the slope estimates) were incorrect by coincidence.

Secondly, there are methodological uncertainties with both sampling and measurement, where the lack of enough observations could have resulted in “incorrect” values of dimensionless stream power. By looking at the formula for dimensionless stream power in the method chapter, the effect of changes in slope (S) is greater than the effect of proportionally similar changes in size of the channel width (W) and sediment in transport (D) (Eaton and Church, 2011). This might be the reason why the contour plot indicates that rocks travel further with lower values of dimensionless stream power, because of the high changes in D compared to S and W. Looking at the data for Bognelv, the changes in S and W are very small compared to D, mostly due to the low amount of measurements taken in the field, but also since the channel width does no differ in different river sections. Low amount of measures and therefore large numerical differences among the different types of measurements taken seem to collapse the compiled data. This provides a new insight into the importance of taking enough data measurements, including a wide range of data information. Note that, information for slope, width, and surface sediment size was only taken where the rocks were released, and not where the rocks were registered at the end point, which should have been done in order to collect additional data on the environment around every rock. Unfortunately, this was not possible in the field due to difficult weather conditions. Another important factor to note is that since there was only one transport episode, there is only one period of discharge. And the period of the transport episode could have been too short, and therefore, involved lower tracer transport than long, sustained floods (Hassan and Bradley, 2017). Philips and Jerolmack (2014) observed that cumulative travel distances showed a stronger inverse relation to grain size when measures over many transport events..

Even though my hypothesis and expectation were not confirmed from my results, I find it difficult to reject or accept my hypothesis. My tracer hypothesis was similar to the one found in the tracer experiment from Vászques-Tarrío et al., (2019). Tracer data from Vászques-Tarrío et al., (2019) had large data sets compiled from several transport episodes from different rivers with more measurements in a larger scale than Bognelv, and with a general high recovery ratio. It could confirm the hypothesis of magnitude of peak discharge being a major control on gravel transport and mean travel distance (m). The tracer experiment could also show a positive dependence on flow duration. Note that from my assumed spurious correlated dataset, model selection supported stream power with average discharge more than the model with peak discharge. Stronger correlations may have also occurred in my data by using stream power or discharge integrated over time instead (Haschenburger, 2013, Phillips et al., 2013, Schneider et al., 2014). The significant differences and lack in my data set compared to the ones from Schneider et al., 2014, Vászques-Tarrío et al., (2019), Vásques-Tarrío and Batella, (2019), made it difficult for a reasonable comparison.

4.1.3 Influence of channel morphology on gravel transport

In addition to Vászques-Tarrío et al., (2019) and Vásques-Tarrío and Batella, (2019) it was also expected that bedload transport in Bognelv was controlled by other factors than flow regime, such as restoration type and channel morphology. It has long been recognized that channel morphology influences particle displacement in gravel-bed rivers (Lamarre and Roy, 2008, Hassan and Bradley, 2017). Pyrce and Ashmore (2003) have shown that in riffle-pool channels, pools and bars have a major control on gravel transport distance, where riffle-pool systems require larger energy expenditure to move tracers (Vázquez-Tarrío and Batalla, 2019). My result lead in the same direction, where the selected model including measure effect showed a tendency where the rocks have longer travel distance in reference areas (plane-bed channel) than in pools. Since all predictors in the model were statistically non-significant and the model only explained 3 % of the variation in distance, the model has low relevance as a predictive tool. Doubt remain when the model predicts that velocity does not affect travel distance (in fact lending towards having a negative effect). These contra-intuitive results and uncertainties of flow not affecting transport distance could have the same explanations like dimensionless stream power, where the model parameter estimates may have resulted from “spurious correlation” imposed by low number of observations and possibly biased sampling (e.g., not all stations were accessible for recaptures). Velocity and measurements appear to be related as they have similar movement of the graph but are not, and therefore might show some nonsense correlations. The spurious correlation is most likely related to the small amount of velocity samples. There are several theoretical explanations for the assumed spurious correlation, and this unexpected result where velocity has a negative effect on bedload travel distance.

First, the result can be a result of unfortunate circumstances. The velocity measures were not from a station in the river but measured by hand in the field. This could have given uncertain numbers. It was also measured only six times, one at each station, which is very little sampling data. Secondly there were no velocity measurements taken where the rocks were registered, due to icy conditions (arbitrary endpoints). Lastly, and most importantly, transportation distance of rocks in pools and reference areas were only measured in one transport episode. Thus, there might be too few measurements of both flow velocity and transport distances to give a better explanation of variation in distance. Few measurements and small difference in velocity measure values can result in obvious effects not showing up as positive on tracer distance. This hypothesis does not need to be neglected, but it needs further assessment from the field with more data measurements.

All in all, as Hassan and Bradley (2017) discussed in their study from gravel beds, that it is difficult to quantify the function played by sediment texture and channel morphology on bed sediment transport by only using results from one single tracer experiment. The interactions between bed morphology, surface sediment, and flow are so complex that it needs several results from several tracer experiments and context to quantify a more reliable function between the different affecting factors. This suggestion fits why my results were difficult to compare with other tracer studies.

4.1.4 Changes in channel outline; river width and length

Resulting maps and aerial photos show that the most remarkable morphological change of Bognelv during the years before channelization, after channelization, and after river restoration is the change of the channel outline itself. In1946, Bognelv had various width size that expanded between 13 - 40 meters. After channelization work ended sometime shortly after the 1970, the width decreased with almost 50%. The length was shortened with 160 metres. Even though these numbers are measured approximately from aerial photos, the high variation among these numbers is enough to confirm my first expectation in my hypothesis that after heavy channelization, cross sections width and river length have decreased.

4.1.5 Changes in environmental variables and morphological features before and during channelization.

Before channelization Bognelv, was dominated by pool-riffle streams and included a diversity in morphological units due to active erosion and sedimentation processes in outer and inner turns that formed variation in water flow and formation of features.

The aerial photographs show how the straightening of river embankments from 1950-2005 cuts the meandering turns that contain important morphological features, closed side channels, increased flow speed, created a very homogenous morphology, and changed the stream types from riffle-pool to mostly plane-bed (defined by Montgomery and Buffington (1997). Plane-bed morphology is known for having long river stretches where hydraulics are not complicated by a heterogenous cross-sectional morphology such as in riffle-pool sequences

(Montgomery and Buffington, 1997, Pyrce and Ashmore, 2003, Pyrce and Ashmore, 2005). The numeric results from 1946-2005 support my fifth hypothesis of a decrease in amount of morphological and environmental features after river channelization. Even though the difference in numbers of morphological features in 1972 and 2005 can be difficult to interpret, they do not differ a lot, and they both indicate a decrease of morphological features. In the beginning of channelization in 1975 as the river was transforming from a riffle-pool channel to plane-bed channel, the variation of river width was larger than in the end of channelization, and therefore point bars might still have occurred. At the overview map over all the observed hydromorphological features from all the four years, it could look like the point bars from 1972 are the same point bars from 1964, only in a smaller scale. As the river became more channelized towards 2005, the river width decreased and became more homogenous. No point bars can be observed, a condition that is associated with low width to depth ratios and a tumbling flow that creates a more rough and homogenous river bottom (Montgomery and Buffington, 1997). Surprisingly, is the number of pools and riffles increases in the end of channelization. Montgomery and Buffington (1997) reported that even though plane-bed channels lack a sufficient lateral flow to develop pool-riffle morphology due to lower width to depth rations and one steady flow. Introduction of flow obstructions or change in bed slope may form isolated local bedforms such as pools and riffles.

4.1.6 Changes in environmental variables and morphological features after river restoration

River restoration has the intention to reinstate rivers back to their physical nature by reintroducing the natural river processes. It was therefore expected in the last hypothesis that Bognelv should now have a reduced water flow with more structural variation in environmental variables and morphological features. After 15 years with conducted restoration measures, results show positive observations of more morphological features and changes in environmental variables, compared to when the river was channelized. The number of features such as pools, riffles, point bars and islands have increased and can indicate a lower water flow. Channel pattern went from all channelized into a combination of a meandering channel with pools and riffles, where some sections still remain channelized. This combination of pattern and stream types has assumingly increased the travel length and cross section width since the end of channelization. Compared to 1946 and 1972, the width is still 50% narrower. Only one point bar feature was observed that is situated in the same area as in 1946, and could thereby be a part of the older one. Point bars are formed on the inside bend (meanders) of rivers and often exposed at seasonal low flow (Jackson, 1976, Hohensinner et al., 2018b). In order to form more point bars, the river needs to form more meanders. As mentioned in the method chapter, meanders form when the river is free to move laterally and interact with surrounding floodplains. Lateral displacement of the river course over time is a result of a natural rivers tendency to have stronger current velocity in outer turns with greater erosion effect, and lower velocity with sedimentation in inner curves that forms point bars (Newson and Large, 2006). Thus, in order to form more point bars and meanders in Bognelv, more free lateral displacement over time is needed. With more free lateral shifts in channel position during normal discharges, the river course is free to change into branches and could also create more natural formed islands (Osterkamp, 1998).

4.2 SUCCESS OR FAILURE OF RIVER RESTORATION SEEN FROM A HYDRMORPHOLOGIC VIEW

During the last 15 years, restoration measures have had one main goal of restoring the ecological processes in Bognelv. With field data and aerial photos, six different hypotheses have been discussed in order to reflect if the restoration measures conducted so far have had a positive impact and success on the hydromorphological environment in the way that the river system is today more capable of changing its own morphology.

It is important to note that in river restoration projects, full recovery of rivers may take centuries as restoration itself is a disturbance (Pedroli et al. 2002). Defining river restoration success in aquatic and riparian ecosystems can be an issue, as there is rarely fully defined and informative goals at the onset of restoration. Without clear goals and monitoring from pre-impact conditions, it is difficult to develop criteria from which the degree of success or failure a restoration project has achieved (Palmer et al., 2005, Bernhardt et al., 2005, Belletti et al., 2015). Palmer et al (2005) suggests that “an ideally ecologically successful restoration creates hydrological, geomorphological, and ecological conditions that allow the targeted-river to be self-sustainable in its new context”. There are unfortunately no data series from pre-impact conditions in Bognelv except for aerial photos.

The main goal was, as mentioned earlier to restore the ecological processes (Hoseth, 2008a, Hoseth, 2008b, Hoseth, 2010b, Hoseth, 2013b, Bjordal, 2019b, Josefsen and Hoseth, 2005) by recreating “natural” river processes and morphological features such as flow amount and velocity, stream depth and width, meanders, and riffles. But also, by removing barriers and re-opening side channels to improve continuity and connectivity between different habitats along Bognelv. I found support for the recreation of more features like diversity in waterflow (by looking at the results from tracer data in pools versus reference areas), width, pools and riffles compared to when the river was channelized and “locked”. Also, more meanders seem to have been recreated by the formation of islands and re-opening of side-channels.

Due to lack of pre-impact data series it is difficult to say something about changes in depth, but since river width has increased along with diversity in waterflow, one can assume that there also has been an increase in the variation of depth. Another indicator of changes in depth, width and flow, is that more features are visible in the river. By these findings, one could confirm that NVE has reached their goal for restoration by recreating morphological features, but it is more difficult from the results of this study to confirm if they have managed to restore the natural river processes. There are several theoretically explanations about this. First, by looking at the features it is difficult to see if all of them have been created during construction or if the river processes itself has formed them. Second, the methods used and low amount of observations in the tracer data of the rocks makes it difficult to assume processes. There could have been more information of processes if tracer data were arranged on the bed under constrained conditions with known GPS position of each rock. Environmental data should have been taken around each rock (velocity, surface, and subsurface sediment size) both at the start and ending point. With information like this one could have assumed the travel path and movement of each rock such as where in the river section they were in transport (eroded) and where they settled (sedimented).

Moreover, to better diagnose the status of rivers and give guidance for improvement it is important to compare the hydromorphological results with the other biological assessments from Bognelv related to river restoration (Austvik, 2012, Schedel, 2010, Sødal, 2014, Nordhov and Paulsen, 2016, Bjørngaard, 2020, Strand, 2020). They have all highlighted the importance of habitat heterogeneity both for density of salmonids and macroinvertebrates. Both Austvik (2012), Shedel (2010), and Strand (2020) concluded the that opening of side channels and tributaries are the most positive restoration measures conducted, as dispersal of low densities occurred in the main channel.

By relating these biological assessments to hydromorphological data, it seems like the restoration goal of ensuring sustainable populations of salmonids is partly reached, but that it still needs more time and measurements for density and diversities of macroinvertebrates to increase (Nordhov and Paulsen, 2016, Bjørngaard, 2020).

At this point, Bognelv has had very little time to settle since there is an ongoing measures and maintenance of the restored sites. Therefore, in order to improve suitable habitats with more heterogenity, it is difficult to conclude how much restoration improvement might be needed in the main channel, or if the river just needs time without human interruptions in order to settle with its own processes. With these results, it can also be discussed if the river will ever be "good enough", as a natural river system, since heavily modified streams might need a full restoration (Bernhardt and Palmer, 2011).

It is easy to come up with possible ideas for further restoration and say that the whole river should be fully restored and all erosion controls should be removed, but it is important to know the limitations. Restoration and nature management is a combination of politics and science, which involves the opinion of stakeholders, managements, politicians, and scientists that affects how restoration defines its goals (Wohl et al., 2005). Bognelv is a river with many interests such as flood control, agricultural land use, and recreation values (Josefsen and Hoseth, 2005, Hoseth, 2010a, Hoseth, 2013a, Bjordal, 2019a). The management with so many different interests limits the river to only be partial restored as it is today, and thus a full restoration is unlikely to take place. Despite this limit, it does not mean that the river cannot improve and try to reach its goals. Therefore NVE should be recommended to keep on with restoration measures as they started.

One possible measurement that is definitely worth conducting and does not need to be in conflict with other interests, is to remove more of the erosion control and make the river wider in general. The river is still 50% narrower than it was before channelization. Much of the erosion control can be replaced by vegetation that binds the soil and prevents erosion (Josefsen and Hoseth, 2005). Since the salmonides prefers the nursing habitats in side channels it means that the main channel with restoration measures need to focus on recreating the same qualities as side channels. Qualities such as lower flow rate, more meandering processes with erosion and sedimentation, and more vegetation and dead wood for shelter. These slow and varied processes make bottom substrate more varied with sand and gravel, compared to today where the main channel is mostly dominated by gravel and cobble. These qualities can be achieved by constructing a wider river so the river can move laterally again. Restoration measures up to date contsist mostly of riperian modification where parts of the erosion control have been removed or adjusted in order to care for interests of flood control and agricultural land. Results show that the restoration has enhanced and created pools, therefore the focus should now be on making the river in general wider as it was before channelization and maybe re-open more side-channels since they are good habitats, as well as keep creating, continuing, and enhancing existing pools.

By the successful restoration suggestion from Palmer et al (2005), this thesis does not have enough accurate data to conclude if restoration in Bogenelva has achieved success, neither does previous master thesis` that reports that goals have been partially achieved. But it might show the minimal set of processes that is needed to be incorporated

4.3 SOURCES OF ERROR

As mentioned before, it is difficult to strive for a natural condition as there is no accurate hydromorphological data before channelization (pre-impact data) which makes it impossible to know what the normalities are in Bognelv. Aerial photo from 1946 is the only analysis that can give some physical information. As this thesis is the first in Bognelv to measure bedload transport (mark-recapture) and study hydromorphological changes, the data from this thesis has no previous numbers to compare with. After field work, data processing, and finishing this thesis, some error sources and weaknesses show up. Many of them have been mentioned in the discussion in order to understand why some results did not fit to the hypothesis.

1. The first error in this thesis occurred in the planning period before field work. More scientific papers should have been read in order to find similar research and spatial sampling strategy that matches study objective and stream conditions. In this thesis methodologies for investigating bedload transport has been chosen based on economy, equipment, time, manpower.

2. While collecting the rocks in field more measures such as different axis sizes, roundness, density, etc. should have been taken. The amount of rocks in each weight class should also have been equally collected and placed out it the river. In the study there were not equivalent amount among the classes, where weight class 3 was under-represented and weight class 2 was overrepresented.

3. Placement of the rocks in the end of May were placed too late as they had to be lobbed out randomly due to high water discharge. Three rocks were unfortunately thrown up the river and had to be neglected in transport measurements but were regarded in recovery rate. In general, rock placement should have been done before flooding at a low water discharge. As mentioned earlier in the discussion more environmental measures such as GPS position, velocity, and substrate measures (surface and subsurface sediment size, both 50th and 85th percentile of the grain-size distribution) should have been taken for each rock at displacement site and registration site(Vázquez-Tarrío and Batalla, 2019). More measurements and data like these could have explained more of the transportation pattern in the river stream and possibly explained some of the variation/scatter in the results.

4. Bunte and Abt, (2001) confirms that a large sample size is necessary, several hundred particles may have to be collected for one pebble count, and as Belletti et al (2015) highlights, physical habitat assessment method requires very detailed site-specific data collection. My geomorphological data from the cross sections were either in large sample size or very detailed and specific. Physical conditions of collecting representative samples were challenging not only due to cold water temperatures. Fine clasts were located between large clasts on the bed, or cobbles too heavy or too wedged in the bed surface to be lifted up. Pebble counts are often subject to operator error and statistical error where operator favouring mid-sized handy particles, and avoiding too large or too small particles. To halvf sampling error hundreds of samples are required. An increasing difference in particle sizes makes the touch method more prone to error. Therefore visual estimates overemphasize the frequency of coarse particles in deposits that consist mainly of coarse gravel, such as in Bognelv.

   Bulk samples could have been preferable with surface sampling, but was seen unpractical to obtain due to rock size and lack of close by laboratory. The counting method done in Bognelv doesn't give results that are comparable with the usual sieved analysis as counting method only give a distribution of numbers and not their weights. Direct classical methods for investigating bedload transport are often expensive to apply in terms of both equipment, but also in manpower (Froehlich, 2003). As a result of this, most studies apply methods with limited objectives for short term measurements. On the other hand, it is difficult to use short term measurements for interpretation of longer term sediment transport. According to Bogen, 1999 most reliable measurements of bedload transport is indirect measurements of superimposed bedload volume in dams and pools. Such a method is expensive, and hard to measure over longer periods of time. Both direct measurements, and bedload transport samplers in dams and deltas accomplished by NVE (Norwegian Water Resources and Energy Directorate) show that bedload transport can vary over short time, and it is therefore recommended to combine direct measurements with sensors and antennas.

5. More and longer transport episodes and monitoring (Kristensen et al., 2014) could also have given more measurements and data with possibly more floods. Due to difficult weather conditions in Bognelv this fall and winter, only one transport episode was registered. Registration of this episode was not fully accomplished as icy conditions lowered the recovery rate of rocks. 90% of the recaptured rocks were recaptured at stations with restoration measures, while only 10% of traced rocks were recaptured at stations with no restoration measures. It is not only icy conditions that can explain the 62% recovery ratio. Smaller rocks could have been trapped among larger rocks. Errors in detection can also occur when particles are too close to each other, and therefore in the same detection range leading to mixed signals. This could be corrected by reducing the sample size with the reach size or reduce detection range of the antenna. Detection range of the antenna and a blind test in order to test the efficiency and accuracy should have been tested in field but were not.

6. The accuracy from recognizing morphological features from aerial photographs does also have limitations. The uncertainties of numbers of recognized features are not accurate numbers. There were difficulties both interpreting features due to low quality of the photographs, but also since the river was so straightened and the incised channel width so small compared to the height the photo was taken from. Other major factors were vegetation that obscures the river, and sun glare (or sun glint) that returns high spectral reflectance that can be confused with stream surface disturbances found in riffles. These errors could be reduced with the simultaneous collection of thermal infrared imagery or developing flight plans that consider weather conditions, flight paths, and solar angle that reduce glare and shading effects.

4.4 SUGGESTIONS FOR FURTHER RESEARCH

Several restoration measures have been conducted in Bognelv over the last decade. The river appears more nature-like today than before channelization with help from facilitated restoration constructions. But the river is still partly channelized, and as mentioned before more of the erosion control should be exchanged with riparian vegetation (Josefsen and Hoseth, 2005). Previous master thesis from Austvik (2012) and Sødal (2014) also suggested that planting of riparian vegetation could be beneficial not only for river erosion but also for the biological recovery of the system. The scheme over numerical changes in hydromorphological features in Bognelv shown in the results, summarizes the main styles of morphological adjustments since 1946. Schemes like this should be tested on the basis of more detailed data to have a wider application to fluvial systems elsewhere affected by similar types of human disturbance.

Furthermore, as PIT-tagging have been introduced with rocks in Bognelv, this project should carry on and monitor the changes in bedload transport over time and continue quantifying if there occurs differences in bedload transport between restored and non-restored river sections as this thesis partly has. As fully evaluation of sediment in the fluvial environment include not only measurement of bedload transport, but also development of particle size distribution, suspended sediment sampling, and determination of changes in sediment storage (Fraley, 2004), this Is also something that should be evaluated in the future.

As mentioned previously, Bognelv might sincerely never be fully restored. But in order to secure an improvement in river dynamics and hydromorphology, this project should keep on investigating the status of the river processes and keep on tuning the status with assessment from biological data. As recovery of rivers may take centuries as restoration itself is a disturbance, it is important to keep on with registrations.

For possible future bedload investigation in Bognelv, I highly recommend to read the tracer studies of rocks that I have referred to, and read my sources of error in this thesis in order to go further into tracer data analysis and improving the prediction of particle transport in gravel-bed rivers. An example of this is the further tracer data analysis of the data from Vásques-Tarrío et al (2019) that was accomplished by Vásques-Tarrío and Batalla (2019).

Also, for further studies in Bognelv there should be mounted more registration antennas for both fish and rocks, but also antennas for flow velocity and water depth.

In this thesis it was intended to fly with a drone in order to get new aerial photographs and study if there were any morphological changes since 2015. Another intention with the drone was to possibly get some high-resolution photos of the substrate and vegetation zone. Flying with a drone should be done in late fall when as much of the leaves from trees have fallen off and the water discharge is low. Due to high snow amounts that fell down the day we were intending to fly, this project was not accomplished and should therefore be taken into consideration and be tested again as it can give useful information and a great overview.

A suggestion that costs more but is time efficient, is the potential of using high resolution remote sensing with multiple image types to map in-stream physical habitats in Bognelv. High resolution imagery (Wright et al., 2000) in addition to Lidar and thermal imagery can be used to complement each other (Perschbacher, 2011). With these it should be possible to create accurate maps of in-stream habitats, stream power, depths, gradients, algae, wood, vegetation, and other features at sub-meter resolutions across the entire water shed. This method is based on locally intensive mapping, or on spatially extensive but low density data among cross sections. (Marcus and Fonstad, 2008). Such maps would not only transform river science and management, but it will meet the need for enhancing the science and use of restoration monitoring both before and after restoration.

5. CONCLUSION

The aim of the study was to analyse if restoration measures conducted up to date seem to have had a positive impact on the hydromorphological environment in the way that the river system is more dynamic and capable of changing its own morphology. Results confirmed the hypothesis that bedload transport distance is different in restored versus unrestored river sections. Travel distance of rocks seemed to travel longer in the channelized river sections, as pools show a tendency of sediment “trapping” and thereby slowing down transport distance. It is expected that in the future with more data and transport episodes, the weak tendency with effect of pools slowing down travel distance will be shown much clearer. Even though results show a tendency of bedload transport in Bognelv being controlled by factors such as restoration type and channel morphology, it could not find any significant correlation between flow magnitude (quantified using the stream power concept), travel competence (maximum size it can transport) and tracer travel distance. Tracer travel distance and aerial photographs highlight that river restoration is heading in the right direction and has a positive effect on the river hydromorphology in the way that the river has achieved more structural variation. Bognelv used to be fully channelized but has now a combination of meandering and channelized patterns. Both river width and length has increased, and more morphological features such as meanders, pools, riffles, and island are formed in the river, some facilitated. As some of the data in this study show weak prediction, they are assumed to be insufficient to draw decisive conclusions about the rivers capability of changing its own morphology. With more measurements and transport episodes the prediction can be improved. It is suggesting that restoration measures should still be conducted as the hydromorphology can only become better. Bognelv is a river with many different interests that limits the river to only be partially restored. A favourable situation for the river to become more natural again in the way that it can move laterally and not be locked between erosion control systems, would be if they removed all erosion security and exchanged it with vegetation zone where it is necessary for flooding.

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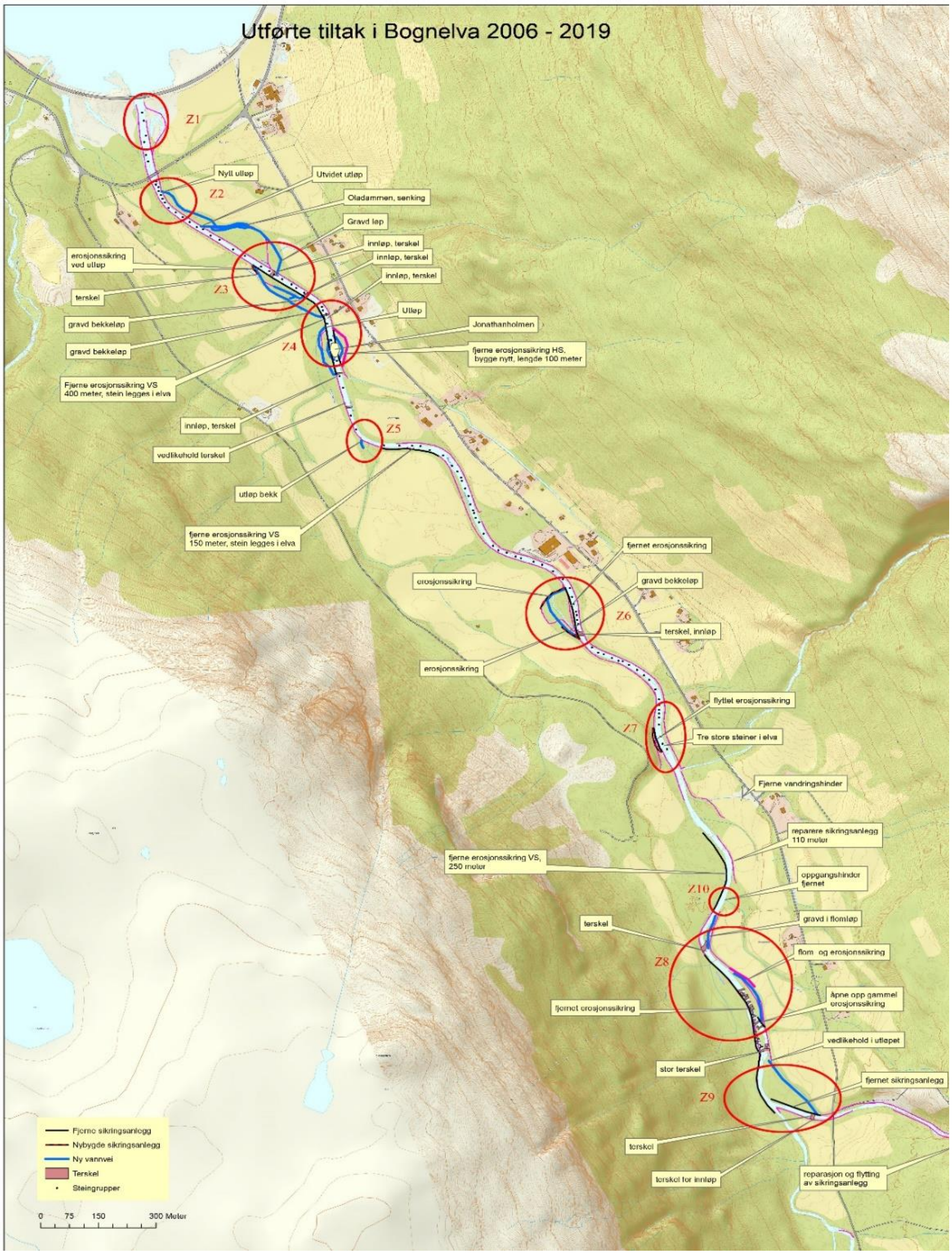
7.0 APPENDICES

Appendix 1

Aerial photo illustration of all restoration measures conducted in Bognelv between 2006 and 2019 from Zone 1-10.

Background maps from Bjordal and Hoseth (2012) and from NVE (2019)



Appendix 2

Summary of all restoration measures conducted in Bognelv in the period 2006 to 2019.

Information gathered from: (Hoseth, 2008a, Hoseth, 2008b, Hoseth, 2010b, Hoseth, 2013b, Josefsen and Hoseth, 2005, Bjordal, 2019b).

Zone	**2006** Measure 3&5	**2007** Measure 4 & 6	**2009** Measure 7	**2012** Measure 3, 4 & 7	**2014** Improvement, and adjustment of earlier conducted measures.
1					
2					
3	-Opening of side channel, two inflows and one outflow. - Placement of rock clusters downstream the inflows to increase the water levels. - Placement of weir in outflow of side channel to increase the water level.	- Supplementary work to improve the water flow	- Reinforce and increase weirs by the inflows of the side channel.	- Removal of erosion control systems in the main river - Placement of rock clusters in the main river	- Re-opening of in- and outflow to Oladammen. - Establish weir by the inflow and rocket clusters to increase the water level. -Dig deeper inflow ditch to ensure constant water flow. -Placement of rocks in the river to vary the water flow.
4	- Opening of side channel. - Placement of rock clusters downstream the inflow to increase the water level. - Placement of weir in outflow of side channel to	- Supplementary work to improve the water flow	- Reinforce and increase weir by the inflow of the side channel.	- Removal of erosion control systems in the main river - Placement of rock clusters in the main river - New erosion control system to protect farmed area	-Removal of some rocks to increase water velocity in pool upstream Oladammen -Building of an island. -Bune up-and downstream new island.

	increase the water level.				
5		-Opening of the tributary Mikkeltveita -Two weirs were removed and repaired			-Upstream zone 5, placement of rocks in the river to vary the water flow.
6	- Upgrade and removal of flood protection, and establishment of new flood protection. - Opening of side channel. - Placement of rock clusters downstream the inflow and by the outflows of side channel to increase the water levels.				-Removal of deposited sand from inlet to tributary.
7		- Relocation and improvement of flood protection - Split a large rock into several pieces.	- Relocation of flood protection systems.		-Removal of deposits to reopen pools. -Bunes from both sides to concentrate water flow.
8			- Four new weirs were made. - Opening of an old river course. - Removal of erosion control systems. - New erosion control systems to protect		-Placement of rocks in the river to better water flow into tributary.

			farmed area.		
9			- Maintenance of a weir. - Removal of erosion control systems. - Opening of the original river course for Ørplasselva. - Construction of a weir to get water into the original river course.	- Repairing of a weir in Ørplasselva - Removal of gravel	
10			- Removal of a migration barrier		
Rock clusters	- Zone 6. Rock clusters to increase diversity in water flow.	- Zone 1 – 7, from the new E6 up to Korselva. 2-3 rocks are added to each of the 78 originally single rocks, to create rock clusters. In addition 60 new rock clusters were made.	- Zone 8 and 9. Rock clusters to increase diversity in water flow.	- Zone 3 and 4. Placement of larger rock clusters in the main river.	

Zone	**2016**	**2018** Improvement and adjustment of earlier conducted measures.	**2019** Improvement and adjustment of Oladammen
1			
2			
3		-Adjusted weirs right below the inlet to Oladammen -Extended inlet to Oladammen 1 meter wider.	- Extended the two outlet of Oldammen was extended, and the stone masses from this was

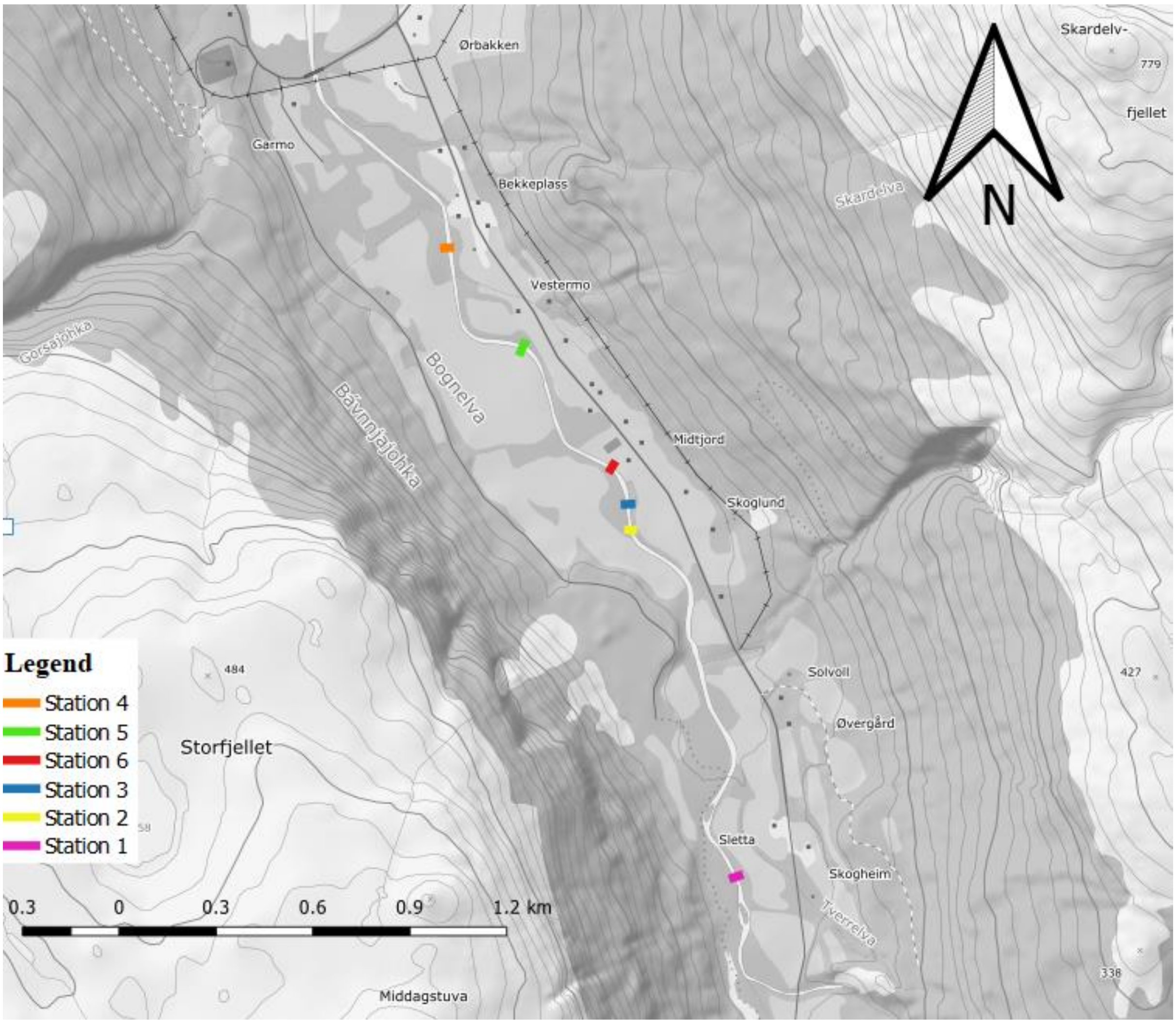
		-Lowered Oladammen with 1 metre depth to maintain an open water surface throughout the summer season.	placed out in the main channel. -Oladammen was dug deeper to maintain an open water surface throughout the summer season.
4		-Adjustment of a side channel had to be done due to sedimentation clogging.	
5			
6		Opening of side stream 50 meters above Korselva outlet.	
7			
8			
9			
10			
Rock clusters			

Appendix 3

Overview map and aerial photos of each station

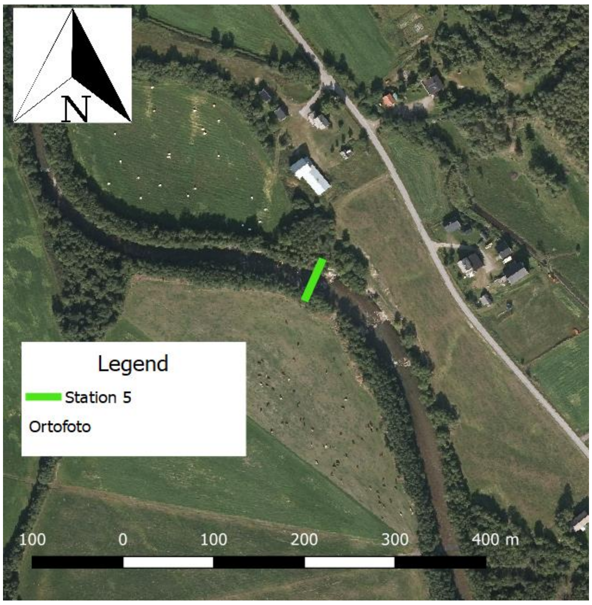
Coordinates for each station is given in a separate Table 5.

All aerial photographs are taken in 2015 and downloaded from www.norgeibilder.no as orthophotos.

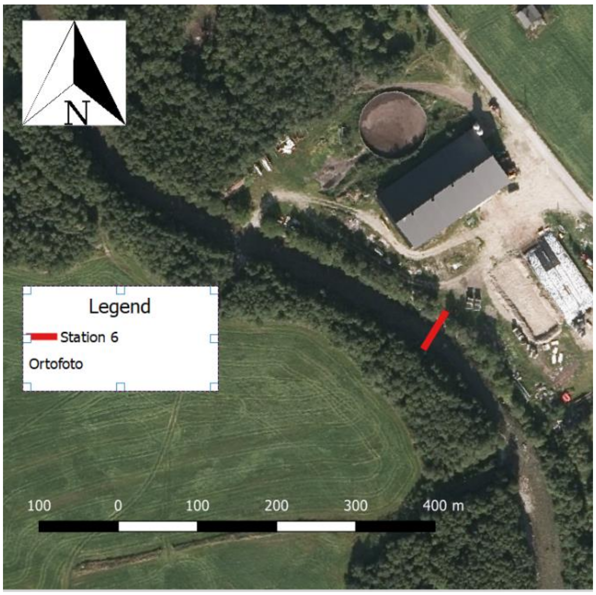


Station 4. Zone 4

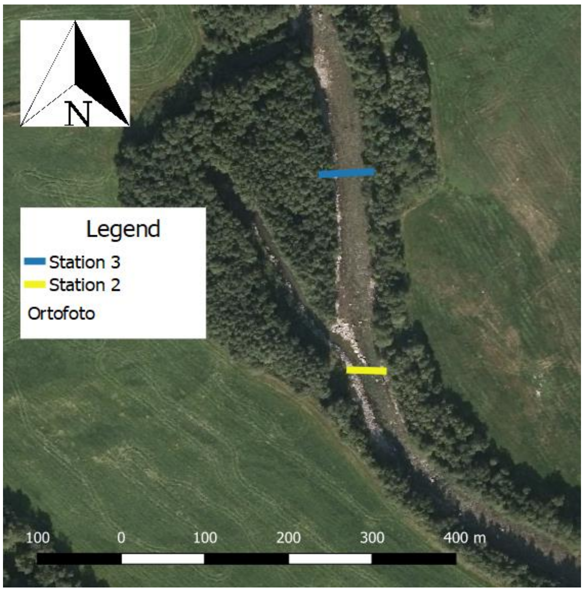
Station 5. Between zone 5 and 6.



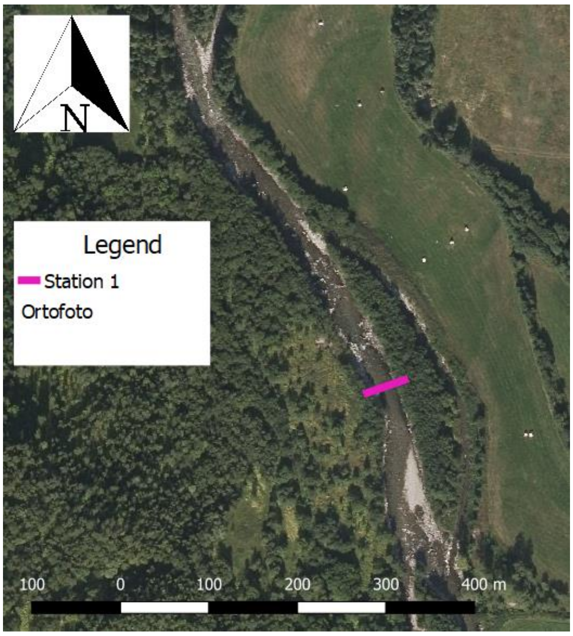
Station 6. Between zone 5 and 6



Station 3 and 2. Zone 6



Station 1. Zone 8.



Appendix 4

Data sampling.

Following habitat features were measured at each of the six station transects:

Substrate composition, percentage of surface area covered by particles of various classes

Rocks in the riverbed were classified into five categories given after dominating substrate size and expressed as percentages of the stream width.

Category 1: 0-2 mm, category 2: 2-20 mm, category 3: 20-100mm, category 4: 100-250mm, category 5: >250 mm.

Width

- Wetted width of the stream was measured at each of the six transects
- Bankfull width was measured at each transect

Water velocity

Water velocity was obstained by counting how many seconds a leaf used on 1 meter. Water velocity: Measure the time it takes an object (e.g., a leaf) to float mid-stream a specified distance

Appendix 5

Geomorphological cross sections of riverbed

Description sample size from (Bunte, 2001a)

Station 1

Station location	Top Width (m)	Width (m)	Flow rate (m/s)	Substrate %
UTM zone 34, 550743E 7766214N	14	9	2.15	5, 10, 30, 50, 5

Depth, and bedload samples taken at nine equally spaced point, at about every 1.5 meter.

Point	Distance (m)	Depths (cm)	Bedload size, b-axis (mm)	Description of particle size	Bedload roundness (Power's index)
1	1.5	0	170	Boulder	2 Angular
2	3.0	0	50	Gravel	5 Rounded
3	4.5	15	50	Gravel	5 Rounded
4	6.0	40	10	Gravel	3 Sub-angular
5	7.5	75	170	Cobble	3 Sub-angular
6	9.0	50	70	Cobble	1 Very angular
7	10.5	45	120	Cobble	5 Rounded
8	12.0	37	200	Cobble	1 Very angular
9	13.5	0	170	Cobble	4 Sub-rounded

Station 2

Station location	Top Width (m)	Width (m)	Flow rate (m/s)	Substrate %
UTM zone 34, 550401E 7767286N	13	10	01.88 s/m	0,10,10,60,20

Depth and bedload samples taken at nine equally spaced point, at every 1.44 meter.

Point	Depths (cm)	Bedload size, b-axis (mm)	Description of particle size	Bedload roundness (Power's index)
1	0	250	Cobble	3 Sub-angular
2	50	200	Cobble	5 Rounded
3	35	170	Cobble	2 Angular
4	60	120	Cobble	3 Sub-angular
5	50	150	Cobble	5 Rounded
6	80	150	Cobble	5 Rounded
7	85	250	Cobble	2 Angular
8	15	650	Boulder	2 Angular
9	0	420	Boulder	2 Angular

Station 3

Station location	Top Width (m)	With (m)	Flow rate (m/s)	Substrate %
UTM zone 34, 550390E 7767365N	15.3	12.2	2.30	5, 10, 20, 40, 25

Depth and bedload samples taken at nine equally spaced point, at every 1.7 meter.

Point	Depths (cm)	Bedload size b-axis (mm)	Description of particle size	Bedload roundness (Power's index)
1	10	20	Gravel	3 Sub-angular
2	20	20	Gravel	5 Rounded
3	35	120	Cobble	4 Sub-rounded
4	40	90	Cobble	5 Rounded
5	40	750	Boulder	3 Sub-angular
6	28	70	Cobble	4 Sub-rounded
7	23	70	Cobble	5 Rounded
8	8	70	Cobble	3 Sub-angular
9	0	150	Cobble	2 Angular

Station 4

Station location	Top Width (m)	Width (m)	Flow rate (m/s)	Substrate %
UTM zone 34, 549837E 7768151N	11.1	9	2.76	0, 0, 30, 50, 20

Depth, and bedload samples taken at nine equally spaced point, at every 1.23 meter.

Point	Depths (cm)	Bedload size b-axis (mm)	Description of particle size	Bedload roundness (Power's index)
1	0	150	Cobble	3 Sub-angular
2	0	40	Gravel	6 Well rounded
3	12	5	Gravel	3 Sub-angular
4	27	40	Gravel	3 Sub-angular
5	40	25	Gravel	3 Sub-angular
6	40	20	Gravel	4 Sub-rounded
7	16	350	Boulder	5 Rounded
8	0	230	Cobble	2 Angular
9	0	400	Boulder	2 Angular

Station 5

Station location	Top Width (m)	Width (m)	Flow rate (m/s)	Substrate %
UTM zone 34, 550077E 7767864N	18	9	1.9	0, 0, 10, 70, 20

Depth, and bedload samples taken at nine equally spaced point, at every 2.0 meter.

Point	Depths (cm)	Bedload size b-axis (mm)	Description of particle size	Bedload roundness (Power's index)
1	0	120	Cobble	3 Sub-angular
2	10	120	Cobble	2 Angular
3	20	150	Cobble	6 Well rounded
4	25	300	Boulder	2 Angular
5	30	100	Cobble	3 Sub-angular
6	40	100	Cobble	5 Rounded
7	40	500	Boulder	2 Angular
8	40	550	Boulder	3 Sub-angular
9	0	1500	Boulder	1 Very angular

Station 6

Station location	Top Width (m)	Width (m)	Flow rate (m/s)	Substrate %
UTM Zone 34, 550354E 7767488N	14	12	1,53	0, 0, 10, 40, 50

Depth and bedload samples taken at nine equally spaced point, at every 1.55 meter.

Point	Depths (cm)	Bedload size b-axis (mm)	Description of particle size	Bedload roundness (Power's index)
1	0	70	Cobble	5 Rounded
2	20	120	Cobble	4 Sub-rounded
3	14	50	Cobble	3 Sub-angular
4	20	120	Cobble	3 Sub-angular
5	19	170	Cobble	3 Sub-angular
6	14	120	Cobble	5 Rounded
7	38	120	Cobble	5 Rounded
8	46	180	Cobble	5 Rounded
9	0	250	Cobble	2 Angular

Appendix 6

Aerial photos from 1964-2015

Aerial orthophotos have been received from Roar Økseter at my university department.

Bognelv 1946

Bognelv 1972

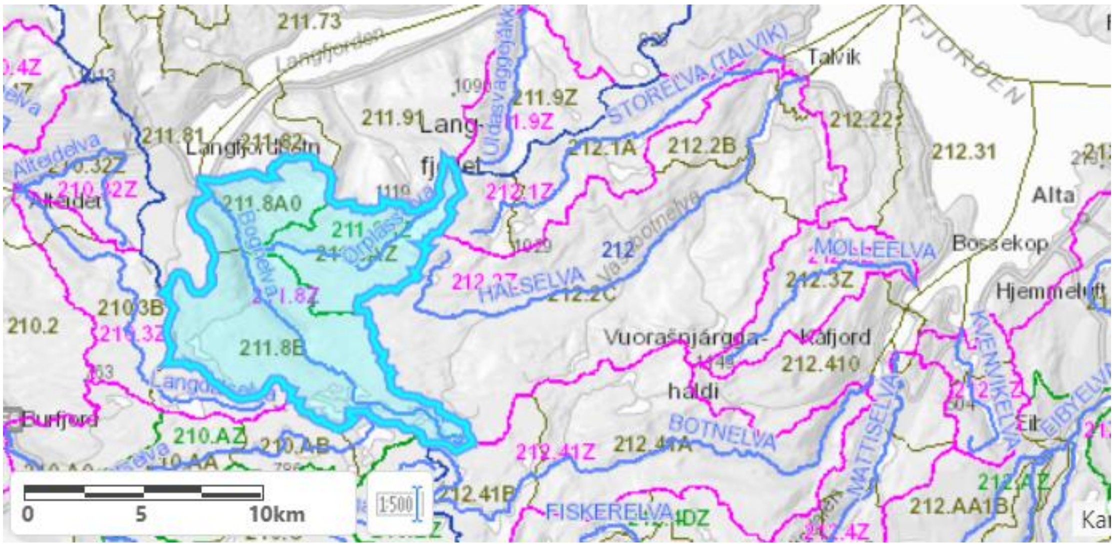
Bognelv 2005

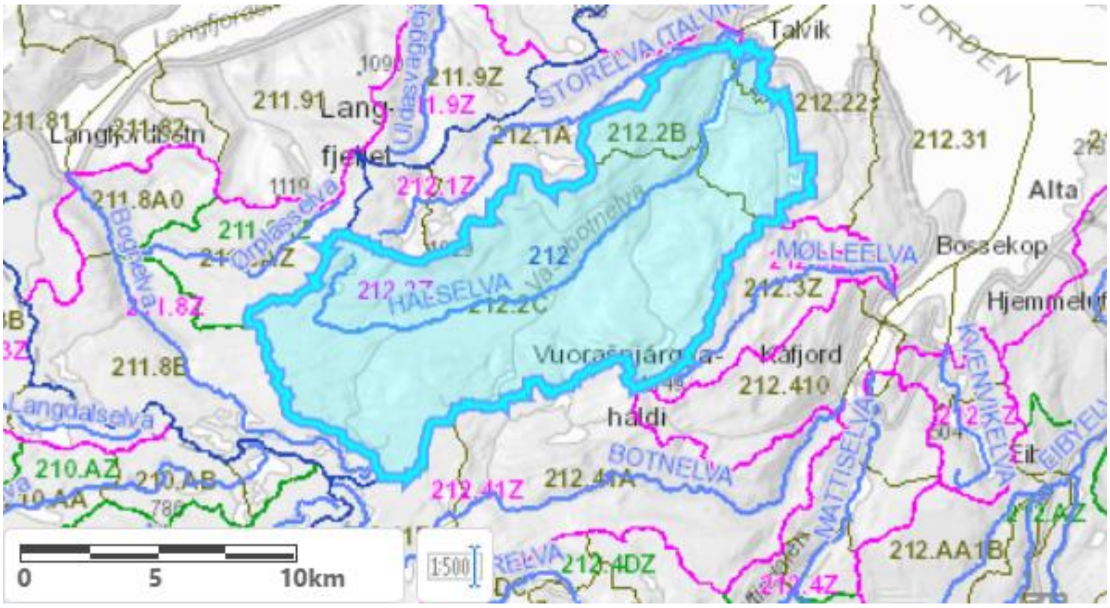
Bognelv 2015

Appendix 7

Hydrological data

Hydrological maps of the precipitation area of Bognelv and adjacent Halselva. Maps are taken from atlas.nve.no





Appendix 8

Data from Nevina.no with parameters from Halsnes and Bognelv

	Bognelv	**Vassbotnelva/Halsnes**
Watercourse number	211.8A0	212.2Z
Watercourse area	211	212
Areal	89 km^2	145.67 km^2
Median runoff (1961-1990)	32.5 l/s/km^2	29.0 l/s/km^2
Sea %	5.52 %	3.46 %
Annual precipitation	781.49 mm	735.6 mm
River gradient	34.59 m/km	31.65 m/km
Height level	1119 - 0 moh	1029 - 0 moh

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