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Sea Trout Habitat Restoration in Unnebergsbekken: A Strategic Adaptive Management Approach

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This thesis is worth 60 study points

Abstract

This thesis evaluates in-stream habitat conditions and production potential as the basis for habitat restoration in Unnebergsbekken, a small anadromous stream in southeastern Norway, to enhance spawning and rearing habitats for sea trout (Salmo trutta). The study combines habitat mapping with the calculation of production potential, followed by implementing restoration measures in selected areas, including gravel placement and habitat structure installation, within a Strategic Adaptive Management (SAM) framework.

A Before-After-Control-Impact (BACI) design was used to establish baseline data and monitor long-term changes. Physical mapping and biological surveys revealed significant spatial variability in habitat conditions, identifying key bottlenecks in substrate composition, shelter availability, and riparian condition, particularly in downstream reaches. Electrofishing surveys indicated varied juvenile densities across stations, though no significant correlation to habitat type was found.

The study highlights the importance of spatial habitat assessment in identifying potential habitat bottlenecks when prioritizing restoration efforts. A comprehensive monitoring plan was developed to evaluate future biological responses and guide ongoing restoration measures. The findings highlight the need for a holistic approach to habitat restoration, combining physical improvements with long-term ecological monitoring to enhance sea trout populations and the broader ecological function of Unnebergsbekken and similar streams in Norway.

Foreword

This thesis was written as part of the master’s program in Ecology and Environmental Management at the University of South-Eastern Norway and focuses on stream restoration for sea trout in Unnebergsbekken. The work was conducted in collaboration with Levende Bekker and Sandefjord Municipality and builds on previous action planning and field assessments.

This thesis assumes a basic understanding of sea trout ecology, physical habitat characteristics, and ecological restoration principles.

I would like to thank my supervisor, Morten Stickler, for his dedicated guidance and support throughout this project. I also want to thank the Sandefjord Municipality for its compliance. Special thanks to Rike Varelman, Line Resvold, Håkon Larsen, and Petter Andersen for their assistance during fieldwork and data collection. Most importantly, I would like to thank the landowners who allowed us access to the stream. Without their cooperation, this thesis would not have been possible.

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1 Introduction

1.1 Background

Freshwater ecosystems are among the most biodiverse systems on Earth. However, they are also among the most threatened (Gutiérrez-Rial et al., 2023). Rivers and streams are degraded by land use changes, hydromorphological alterations, pollution, and climate change (Birk et al., 2020). Land-use changes, including agriculture, urbanization, hydromorphological alterations (e.g., channelization, dredging), and forestry, are the primary causes of biodiversity loss (Gutiérrez-Rial et al., 2023). This degradation is significant because freshwater ecosystems support nearly 10% of all known species while covering less than 1% of the Earth's surface (Acero et al., 2021), making them irreplaceable for global biodiversity. These ecosystems also provide various irreplaceable human services, such as water purification, flood control, and tourism (Covich et al., 2004). In response to global biodiversity loss and ecosystem degradation, the UN has declared 2021–2030 as the "Decade on Ecosystem Restoration" and has called for large-scale efforts to restore degraded ecosystems, including freshwater environments.

Given their ecological and societal importance, maintaining freshwater ecosystems in good ecological status is vital for the sustainability of aquatic and human life. This goal is included in the European Water Framework Directive (2000/60/EC) (WFD), which provides a legislative framework for protecting and restoring inland surface waters, coastal waters, and groundwater across EU member states. One of the core components of the WFD is the requirement for regular ecological monitoring, which enables members to assess water conditions, track the progress of environmental targets, and adjust management and monitoring based on outcomes. The WFD also encourages the use of adaptive management strategies, where restoration efforts are revised in response to monitoring results, and supports an ecosystem-based approach to restoration planning and implementation.

Small streams are vital for sustaining ecological health throughout various landscapes. Although their small size and accessibility can complicate monitoring and restoration, these streams can support a high level of biodiversity and play a crucial role in essential ecological processes (Lowe & Likens, 2005). Headwater and low-order streams comprise the majority of the total stream length in most catchments, and their health directly influences downstream water quality and biodiversity (Freeman et al., 2007). When small streams are damaged by pollution, hydrological alteration, or changes in land use, it can affect the health of entire river systems. Understanding the ecological significance of these systems is necessary for an effective water management strategy. Small streams account for 70% to 80% of total river length (Wohl, 2017). However, they are often underrepresented in monitoring programs, which may lack the spatial resolution to capture their ecological conditions (Konrad & Anderson, 2023). As a result, many small streams remain degraded due to agricultural practices, urban runoff, or channelization, resulting in adverse effects throughout entire catchments. Practical restoration efforts must be supported by detailed, site-specific monitoring, ensuring that interventions are responsive to local conditions (National Academies of Sciences, Engineering, and Medicine, 2017).

Although not a member of the EU, Norway has integrated the WFD into national legislation since 2008, emphasizing the protection and restoration of water bodies. This aligns with broader environmental initiatives, including its National Strategy for the Restoration of Rivers and Streams (2021–2030) and the Naturavtalen, which aims to halt biodiversity loss by 2030 (Regjeringen.no, 2022). Norway's restoration efforts focus on improving water quality, restoring natural hydromorphology, and enhancing fish passage, with a particular focus on small streams facing ecological pressures like agricultural runoff, sedimentation, and hydrological changes (Wenng, 2020). These efforts are directly aligned with the goals of the WFD, which emphasize improving ecological status through habitat restoration, water quality improvements, and enhancing biodiversity.

In the context of these national and global efforts, the restoration of Unnebergsbekken, a small anadromous stream in southeastern Norway, is essential for achieving both WFD targets and national restoration goals. Unnebergsbekken is impacted by habitat degradation, substrate composition, shelter availability, and riparian condition. Restoration efforts, such as gravel placement and the enhancement of structural habitat features such as boulders and woody debris, align with WFD objectives by improving spawning and rearing habitats for sea trout (Salmo trutta). These measures not only address key habitat bottlenecks but also support WFD goals of enhancing biodiversity, improving water quality, and promoting ecosystem resilience in small streams.

1.2 Objectives

The main objective of this thesis is to map spawning and rearing habitat quality and evaluate potential bottlenecks as a baseline for potential restoration measures in a small anadromous Norwegian stream, Unnebergsbekken. A holistic approach was applied in combination with a strategic adaptive management approach to implement physical habitat improvements for enhancing spawning and rearing for native sea trout. Restoration measures included the addition of gravel and improvement of stream complexity. These actions followed the principles of Strategic Adaptive Management (SAM), which emphasize constant decision-making and monitoring in response to outcomes. A Before-After-Control-Impact (BACI) framework will assess the ecological response to restoration, with an emphasis on sea trout rearing habitat, spawning activity, and substrate conditions.

To support the restoration of Unnebergsbekken and its recovery of sea trout populations, this study will focus on the following sub objectives:

1. Map physical habitat conditions, conduct biological surveys, and estimate production potential to establish a baseline for sea trout spawning and rearing habitat, identifying key bottlenecks for future restoration measures.

   Hypothesis**:** It is expected that areas with greater habitat complexity will support higher juvenile densities, helping to identify habitat bottlenecks and inform restoration measures.

2. Plan, coordinate, and implement targeted stream restoration measures to enhance sea trout spawning and rearing habitats in selected reaches, with the target of increasing habitat quality and production potential based on sub objective 1.

   Hypothesis**:** Restoration measures will increase the area of potential spawning habitat and sea trout production in restored areas compared to baseline conditions.

3. Develop a monitoring and evaluation plan based on strategic adaptive management principles for the implemented stream restoration that focuses on pre- and post-restoration changes in habitat quality and juvenile sea trout densities to serve as a foundation for future learning and results-oriented analysis.

   Hypothesis**:** A monitoring plan based on BACI principles will effectively assess restoration outcomes and guide future restoration plans.

1.3 Limitations

This thesis builds on an action plan for Unnebergsbekken developed in 2023 (Lund & Wulff Tollefsen, 2023), which identified bottlenecks, and guided 2024 restoration efforts and locations. Building on the action plan, this thesis includes physical mapping and analysis, electrofishing surveys, and site-specific restoration measures. While the research focuses on sea trout habitat restoration, it is important to acknowledge several limitations that may influence results.

The spatial scale of this study is relatively limited. The research is focused on one small stream (Unnebergsbekken) and includes only three small, restored areas. As a result, the spatial scale and broader application of the findings may be limited. The study emphasizes habitat conditions relevant to sea trout, such as substrate and mesohabitat, but it does not address other ecological factors, such as macroinvertebrate populations or water chemistry. These factors also play a role in stream health and fish productivity, and their absence from the study may affect the overall ecological context of the restoration.

Additionally, the monitoring period for this study was relatively short. Although before and after comparisons are made, the lack of extensive pre-restoration data may limit drawing stronger conclusions about the long-term success of the restoration measures. The short duration of monitoring means that the complete ecological impacts of the restoration have not yet been determined, thus emphasizing the importance of developing a monitoring plan.

This study was conducted in conjunction with another master's student, whose focus was on improving fish passage at an upstream migration barrier. While collaborating provided valuable insight, it may potentially complicate the restoration results. The removal of the upstream barrier now allows fish that were blocked from accessing upstream habitats. Although this does not directly affect the restoration sites, it could alter fish distribution within the stream. Fish that were once confined to the downstream areas may move upstream into the newly accessible habitats, which could complicate the interpretation of future population changes in the restored areas. While removing the migration barrier may not reduce fish density downstream, it could affect fish distribution across the stream. This potential short-term effect emphasizes the need for longer-term monitoring to see how fish populations settle and to better understand the actual impact of habitat restoration once the initial effects of barrier removal subside.

Spawner and redd survey data used in this thesis were collected by the project supervisor, whose expertise allowed for more efficient and accurate identification under field conditions. Although the author participated in and performed the methods independently during the project, the supervisor’s data was used due to their higher reliability. This represents a minor limitation regarding direct authorship of all data but strengthens the overall quality and consistency of the dataset.

Generative AI tools were used in a limited manner throughout the development of this thesis. ChatGPT assisted with coding support for figure creation (e.g., R and Python code for data visualization), troubleshooting QGIS, refining data presentation, and receiving structured feedback on text clarity, structure, and consistency with scientific tone. Grammarly was used to support grammar and style corrections during the editing process. AI-generated suggestions were reviewed and used when appropriate. The use of AI was supplemental and did not replace authorship.

This study offers insight into site-specific restoration outcomes and helps to improve the understanding of sea trout habitat restoration in smaller streams. However, when interpreting the results, it is important to consider these limitations.

1.4 Structure of Thesis

This thesis is organized into six chapters. After this introduction, Chapter 2 presents the theoretical background by discussing ecological concepts that guide stream restoration. These concepts include sea trout's habitat requirements, substrate and mesohabitat theory, riparian zone function, interstitial shelter, and adaptive management and monitoring principles. This chapter provides the scientific framework for the restoration and monitoring efforts, which are detailed in the subsequent chapters.

Chapter 3 describes the methods used to evaluate habitat conditions and monitor the impact of the restoration conducted at each site. It provides a detailed overview of the study sites, the field methods used, and the analysis used to interpret the results, incorporating BACI and SAM principles.

Chapter 4 provides the results of habitat mapping, electrofishing, restoration actions, and initial monitoring efforts, focusing on elements relevant to sea trout spawning and habitat quality. This chapter includes the proposed monitoring plan.

Chapter 5 analyzes the results and considers the broader effects of the restoration efforts.

Chapter 6 summarizes and discusses the thesis's main findings and considers its significance for stream restoration, monitoring design, and sea trout conservation in small streams. It also provides recommendations for future restoration work in Unnebergsbekken.

2 Theory

Effective freshwater restoration is based on theoretical foundations that guide choices and measure success over time. This chapter outlines the theoretical framework that supports this thesis, focusing on ecological restoration, strategic adaptive management, and monitoring design in small stream systems. It begins by defining key concepts such as ecological status, production area, and stream health. The SAM framework focuses on constant learning and flexible planning in restoration efforts. Additionally, the chapter discusses the use of BACI design in ecological monitoring, which provides a basis for evaluations of restoration outcomes. These frameworks are designed to improve spawning and rearing habitats for sea trout in degraded stream areas, and they inform monitoring strategies for specific site conditions. Overall, this chapter establishes a foundation for understanding the rationale behind the chosen restoration methods and highlights the importance of adaptive monitoring.

2.1 Stream Habitat and Salmonid Ecology

Sea trout (Salmo trutta) are part of the salmonid family and display considerable life history variation. They can occur as resident brown trout that spend their entire lifecycle in freshwater, or as anadromous sea trout that migrate to the marine environment and return to spawn in freshwater. Both forms depend on structurally complex stream habitats to support essential life functions such as spawning, feeding, shelter, growth, and migration. Habitat complexity, characterized by variability in substrate types, flow regimes, pool and riffle sequences, in-stream cover, and longitudinal and lateral connectivity, is crucial for maintaining diverse and resilient salmonid populations (Jonsson & Jonsson, 2011).

Spawning typically occurs in the autumn in well-oxygenated, shallow riffle areas with coarse gravel substrates. Females excavate redds to deposit their eggs, and embryo survival depends on sufficient flow through the gravel and low levels of fine sediment (Kemp et al., 2011). After hatching, juveniles (alevins and fry) initially remain in the gravel before emerging to occupy shallow margins and low-velocity habitats. As they grow, habitat use shifts. Parr (life stage after fry) seek deeper pools with cover such as boulders, woody debris, or undercut banks. These features provide shelter from predators and high flow events while also enhancing hydraulic variability and food availability, which are necessary for optimal growth and survival (Jonsson & Jonsson, 2011).

Smoltification typically occurs between two and seven years of age, followed by seaward migration in spring or early summer. After a marine feeding phase, adult sea trout return to their natal streams to spawn in autumn. Many complete this cycle multiple times. Throughout this lifecycle, habitat needs vary seasonally. In winter, trout seek shelter in deep pools, root wads, or interstitial spaces to reduce energy consumption and avoid displacement. In contrast, summer habitat use is shaped by feeding opportunities, social interactions, and competition. Year-round availability of both shelters and foraging areas is critical for maintaining stable populations. An overview of the brown trout life cycle and associated seasonal movement patterns is shown in Figure 1.

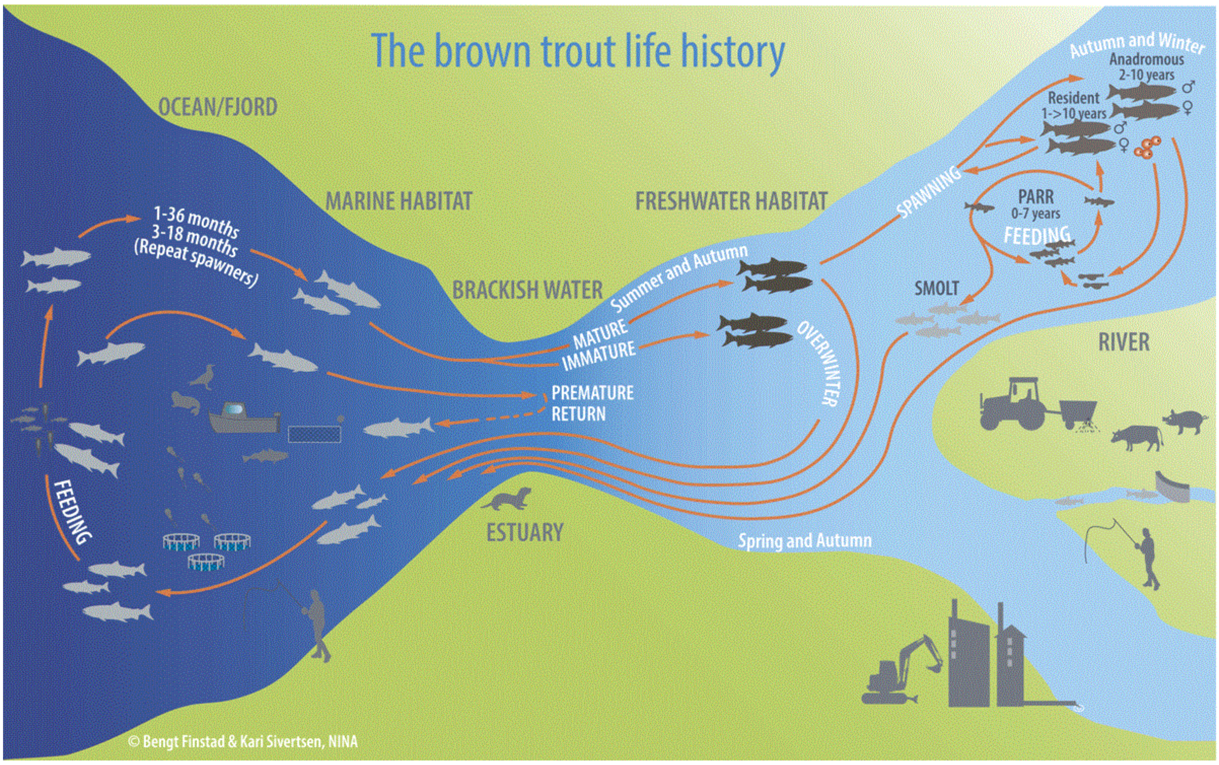

Figure 1. *The brown trout life history, showing the seasonal habitat use of both anadromous and resident forms. Source: Bengt Finstad & Kari Sivertsen, NINA.*

Stream habitat degradation caused by channel modification, riparian deforestation, sedimentation, and altered flow regimes reduces physical complexity and habitat connectivity. These pressures can remove or fragment key habitats for different life stages, reduce the stream’s carrying capacity, and increase the vulnerability of salmonid populations to disturbance (Lake, 2000). Because of their ecological importance and sensitivity to environmental change, salmonids are widely used as indicator species in freshwater monitoring and restoration programs. Their presence and abundance are often used to assess habitat quality and overall ecosystem health (Hering et al., 2006).

2.2 Habitat Structure

2.2.1 Substrate and Embeddedness

Substrate composition is a defining feature of stream habitat and is critical throughout the life cycle of sea trout. Coarse, well-oxygenated substrate is essential for spawning, as it allows females to excavate redds where eggs can properly develop. Clean gravel promotes higher survival rates of embryos and newly hatched fish by maintaining interstitial flow and reducing the risk of hypoxic conditions (Kemp et al., 2011; Pulg et al., 2019). Substrate heterogeneity enhances shelter and foraging opportunities for juveniles. Medium and large substrate particles create microhabitats and trap organic matter, supporting benthic invertebrate communities as a primary food source for growing fish (Pulg et al., 2019).

Embeddedness refers to the degree to which fine sediments, such as sand and silt, fill spaces between larger substrate particles. High embeddedness reduces substrate permeability and eliminates critical interstitial space. For salmonids, this can lead to decreased oxygen delivery to redds, reduced egg survival, and limited shelter availability for early life stages. Studies have shown that high embeddedness can negatively affect the growth rates of first-year sea trout by limiting access to prey and refuge (Bolliet & Bardonnet, 2017).

Excessive sedimentation is particularly problematic in small streams, where erosion, agriculture, or forestry inputs can degrade spawning habitats. Fine sediments clog gravel beds, slow water exchange, and smother developing eggs, making it more difficult for alevins to emerge. The accumulation of fine material reduces the availability of suitable spawning sites, increases competition among spawners, and forces reproduction into lower-quality areas (Dubuis & De Cesare, 2023; Soulsby et al., 2001).

Substrate quality and embeddedness are also important indicators in stream health assessments. These parameters are directly linked to ecological status under the WFD and are often used to evaluate restoration projects' habitat conditions. Improving substrate conditions through sediment reduction and structural enhancement can increase spawning success and support higher biodiversity in freshwater systems.

2.2.2 Mesohabitat

Mesohabitats refer to distinct hydraulic units within a stream, including riffles, pools, and glides, each supporting different ecological functions. These features are essential for sustaining the life cycle of sea trout and other salmonids. A diverse mesohabitat composition provides a range of physical conditions that meet the habitat requirements for spawning, feeding, and shelter across different life stages (Forseth et al., 2014). Sea trout typically spawn in shallow, oxygen-rich riffle habitats where coarse gravel and quick currents help maintain favorable conditions for egg development. Upon hatching, juveniles use pools and glides for calmer conditions, protection from predators, and access to invertebrate food sources. Pools offer deeper water and thermal stability, which is important during high-flow events and winter. Glides serve as transitional areas where flow and depth allow juveniles to move between habitats and continue foraging while remaining protected (Heggenes & Wollebæk, 2013; Jonsson & Jonsson, 2011).

The presence, diversity, and spatial arrangement of mesohabitats influence the productivity and stability of fish populations. Streams with a balanced composition of riffles, pools, and glides support higher juvenile survival, greater spawning success, and more resilient populations. In contrast, streams dominated by a single mesohabitat type, such as uniform channels with few riffles, often exhibit poor habitat quality, reduced oxygenation, and limited ecological function (Calderon & An, 2016). The absence of riffles can indicate problems such as sediment accumulation, low hydraulic energy, or anthropogenic alteration. These conditions reduce reproductive success and restrict juvenile development. For these reasons, mesohabitat composition is often used to indicate overall stream health.

The degradation of hydraulic diversity through channelization, sedimentation, or altered flow regimes leads to a loss of critical habitat for juveniles and adults. This can result in declines in fish populations (Lake, 2000). Assessing and maintaining mesohabitat heterogeneity is essential in planning effective restoration and monitoring strategies for sea trout streams.

2.2.3 Interstitial Habitat and Shelter

Interstitial spaces refer to the small gaps between substrate particles and are vital to healthy stream ecosystems. The pockets between gravel and rocks create shelter for juvenile sea trout (Figure 2). These spaces protect from predators and strong currents, forming microhabitats where fish can feed and conserve energy during high flow or environmental stress (Finstad et al., 2007). Substrate composition and arrangement influence the quality and availability of these habitats. Clean, loose gravel with minimal fine sediment supports greater porosity and oxygenation, which are key conditions for egg incubation and fry survival. In contrast, compacted or embedded substrate reduces interstitial space. Fine sediments clog the gaps, leading to hypoxic conditions, increased egg mortality, and reduced shelter for fry and parr (Greig et al., 2005)

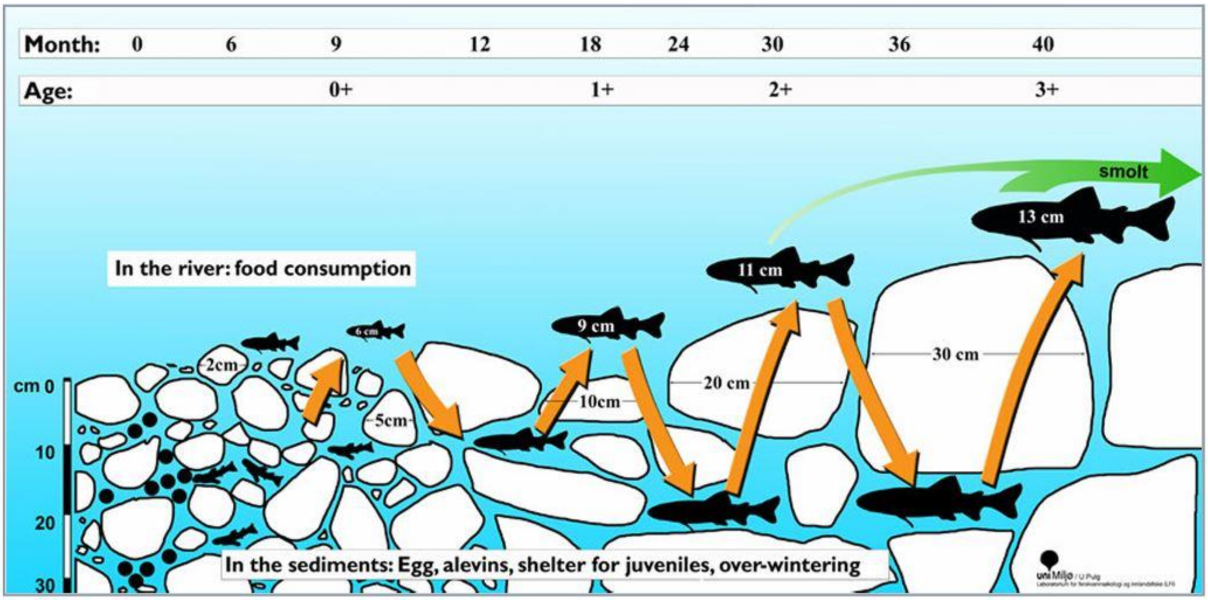

Figure 2. *Juvenile salmon exploit the entire upper layer of riverbed sediments (approx. 0-30 cm). Holes and crevices in the sediments are important for avoiding predation, resting, and refuge during floods (Forseth et al. 2014).*

Research in Norway has shown the importance of interstitial space for juvenile salmonid survival and recruitment. Hindar et al. (2019) found that juvenile salmonid densities were positively associated with the availability of interstitial shelter within suitable spawning substrates. Their findings suggest that microhabitats with sufficient interstitial space support early life stages and influence long-term population dynamics. Pulg et al. (2019) also showed that the quantity and quality of spawning gravel and shelter structures affect juvenile salmonid abundance in small streams, where competition among juveniles is high. Streams with more suitable spawning gravel supported significantly higher densities of fry and parr.

Mapping and measuring interstitial habitat is helpful in identifying suitable rearing areas and prioritizing locations for restoration. Because interstitial shelter affects the behavior and growth of juvenile salmonids, its availability can indicate habitat quality and population resilience. Reduced shelter increases predation risk and limits growth rates (Finstad et al., 2007). As stream ecosystems face pressure from sedimentation, hydrological changes, and land use, protecting and enhancing interstitial habitats remains important for supporting sea trout populations (Emanuelsson, 2023).

2.2.4 Riparian Zones and Stream Health

Riparian zones are vegetated areas adjacent to streams that are vital for maintaining freshwater ecosystems' ecological functions and physical stability. These zones act as buffers between aquatic and terrestrial environments and are essential for the health of streams. A functional riparian zone supports several key ecosystem services, including temperature regulation, nutrient filtration, bank stability, and the input of organic material (Lind et al., 2019). Shading from riparian vegetation helps regulate water temperature, which is critical in cold-water streams inhabited by salmonids. Stable water temperatures support egg development, juvenile growth, and general activity. Vegetation also acts as a filter, reducing runoff from surrounding land. This is especially relevant in agricultural and urban areas, where nutrient runoff can lead to eutrophication and habitat degradation (Gregory et al., 1991). The roots of riparian plants help anchor soil and prevent bank erosion, while fallen leaves and branches contribute to in-stream habitat by providing food, shelter, and cover.

There is a strong link between riparian zone conditions and stream habitat quality. Streams bordered by degraded or narrow riparian zones often have more unstable banks, higher water temperatures, increased sediment loads, and reduced biodiversity (Lind et al., 2019). The width of the riparian buffer is a key factor in how well it performs these ecological functions. Narrow zones less than 10 meters wide may trap sediments but are often inadequate in supporting broader ecosystem processes. Expanding the buffer to 11-15 meters significantly improves nitrogen and phosphorus retention, enhances wood recruitment, and increases bank stability. Forested zones between 21 and 30 meters are typically required to regulate temperature effectively, stabilize streambanks, and contribute larger woody debris. A 25-meter zone can support mature trees and increase habitat complexity, while a 30-meter buffer is generally required to achieve what is considered a fully ecologically functional riparian zone with stable temperatures, high floral diversity, continuous organic input, and long-term bank integrity (Lind et al., 2019).

Restoring or enhancing riparian zones is an important part of improving stream health. Healthy buffers support fish populations by regulating stream conditions, improving water quality, and increasing habitat complexity. In turn, this supports biodiversity and strengthens the resilience of the surrounding catchment. Riparian zones are significant for sea trout, which rely on shaded, cool-water habitats and benefit from stable banks, clean substrate, and organic matter input across life stages.

2.3 Seat Trout Spawning and Habitat Use

Spawning is a critical phase in the sea trout life cycle, and the availability and quality of spawning habitat directly influence reproductive success. Sea trout are selective in their choice of spawning sites, typically favoring clean, well-oxygenated gravel in areas with moderate current velocity and appropriate depth, usually between 10 and 30 cm. Ideal spawning gravel ranges from 10 to 64 mm in diameter and must be free of fine sediment to maintain interstitial flow, which is necessary for egg survival and oxygen exchange (Hindar et al., 2019; Nika et al., 2011). Water flow and depth also matter. Shallow glides and upstream ends of riffles are commonly used for spawning because they offer moderate velocities that provide sufficient oxygen without scouring the eggs. Although not a primary factor, cover from instream wood or overhanging vegetation may influence site selection by providing holding areas for adult fish before spawning (Nika et al., 2011).

Redd success depends on the presence, quality, and spatial distribution of spawning habitat. Embedded or poorly oxygenated gravel reduces the likelihood of successful egg development. Studies have shown that patchy or degraded gravel beds can lead to lower survival and weaker year-class strength (Hindar et al., 2019). The spatial distribution of spawning beds also influences population dynamics. When suitable gravel is limited, density-dependent effects can increase spawner competition, reduce fertilization success, and lower egg survival rates. Conversely, well-distributed gravel allows fish to spread out, reducing stress and enhancing recruitment (Finstad et al., 2009; Nika et al., 2011).

The proportion of high-quality gravel in a stream has been shown to correlate with the number of successful spawners and overall juvenile production. Even small changes in gravel quantity and distribution in streams, whether from sedimentation, channel alteration, or restoration, can significantly affect fish populations (Hindar et al., 2019). A lack of suitable spawning substrate is a common limiting factor in post-disturbance recovery. Gravel augmentation at strategic locations can increase the number of usable spawning sites, reduce crowding, and improve egg survival. By spreading out spawning activity, these interventions help stabilize year-class recruitment and contribute to long-term population resilience. Because sea trout are responsive to changes in substrate and flow conditions, the quality and distribution of gravel are key considerations in habitat restoration planning.

2.4 Stream Restoration Principles

Stream restoration is based on the ecological understanding that rivers are dynamic systems shaped by interacting physical and biological processes. In recent decades, restoration efforts have moved away from static, engineered designs and toward more process-based approaches to restore stream ecosystems' natural function and resilience (Finstad & Hesthagen, 2020). In Norway, this shift is reflected in national strategies that emphasize improving hydromorphological function, enhancing water quality, and supporting native biodiversity.

Process-based restoration focuses on re-establishing the physical and ecological processes that sustain stream habitat complexity. Rather than replicating habitat structures, it seeks to recover sediment transport, natural flow regimes, and channel dynamics that allow the system to maintain itself over time (Foldvik et al., 2010). Natural channel design is closely related, using geomorphological reference conditions and templates from undisturbed streams to guide restoration planning. These templates include natural meander patterns, substrate distribution, and riparian vegetation structure (Rosgen, 2006).

Restoration goals typically include enhancing habitats for target species like sea trout, reconnecting floodplains, reducing sediment loads, and improving thermal and chemical conditions. In addition to supporting biodiversity, these efforts aim to increase ecosystem resilience by restoring the stream’s capacity to absorb and adapt to disturbance from floods, drought, or changing land use (Finstad & Hesthagen, 2020).

Scale is an important factor in stream restoration. While large-scale interventions often receive more attention, small-scale projects can also generate significant ecological benefits, especially in fragmented systems. For example, moderate gravel additions or wood placements in headwater streams have increased juvenile trout densities (Foldvik et al., 2010; Bergan, 2024). In Norway, such localized measures are frequently part of catchment-based strategies that integrate actions across tributaries to support broader ecological outcomes.

These efforts contribute to the broader goal of achieving “good ecological status” under the WFD. While complete stream restoration aims to recover natural processes and self-sustaining function, many actions in small streams, including those in this project, are more accurately described as habitat improvements or enhancement measures. These interventions target specific ecological functions, such as spawning or shelter, but do not fully re-establish geomorphic or hydrological processes. Process-based and ecologically grounded approaches provide the theoretical basis for both types of interventions and support long-term ecosystem resilience and biodiversity (Beechie et al., 2010).

2.5 Strategic Adaptive Management

Monitoring and evaluation are essential for determining whether stream restoration efforts are achieving their ecological goals. Without structured follow-up, it is difficult to assess the effectiveness of interventions or detect unintended outcomes. Strategic Adaptive Management (SAM) and the Before-After-Control-Impact (BACI) design are complementary frameworks supporting robust, evidence-based evaluation of restoration outcomes.

Uncertainty is an inherent part of ecological restoration due to the complexity and variability of freshwater systems and the environmental conditions. SAM provides a structured and participatory framework for managing ecosystems under uncertainty by using monitoring results to guide iterative decision-making. As outlined in Figure 3, SAM follows four key steps:

1. Setting the desired future condition.
2. Identifying management options.
3. Operationalizing and implementing actions.
4. Evaluating and learning from outcomes.

These steps are supported by broader contextual elements such as stakeholder engagement and the social, ecological, and political landscape (Kingsford & Biggs, 2012). SAM integrates scientific knowledge, management objectives, and stakeholder input into a learning-based cycle. It benefits small stream projects, where limited data and site-specific variation require flexible strategies and ongoing adaptation. Originally developed for freshwater ecosystems in South Africa, SAM has since been applied globally in river and wetland management. In the context of stream restoration, it promotes long-term thinking where short-term results are used to improve future actions.It also promotes collaboration among scientists, managers, and local stakeholders to ensure that interventions are aligned with ecological realities.

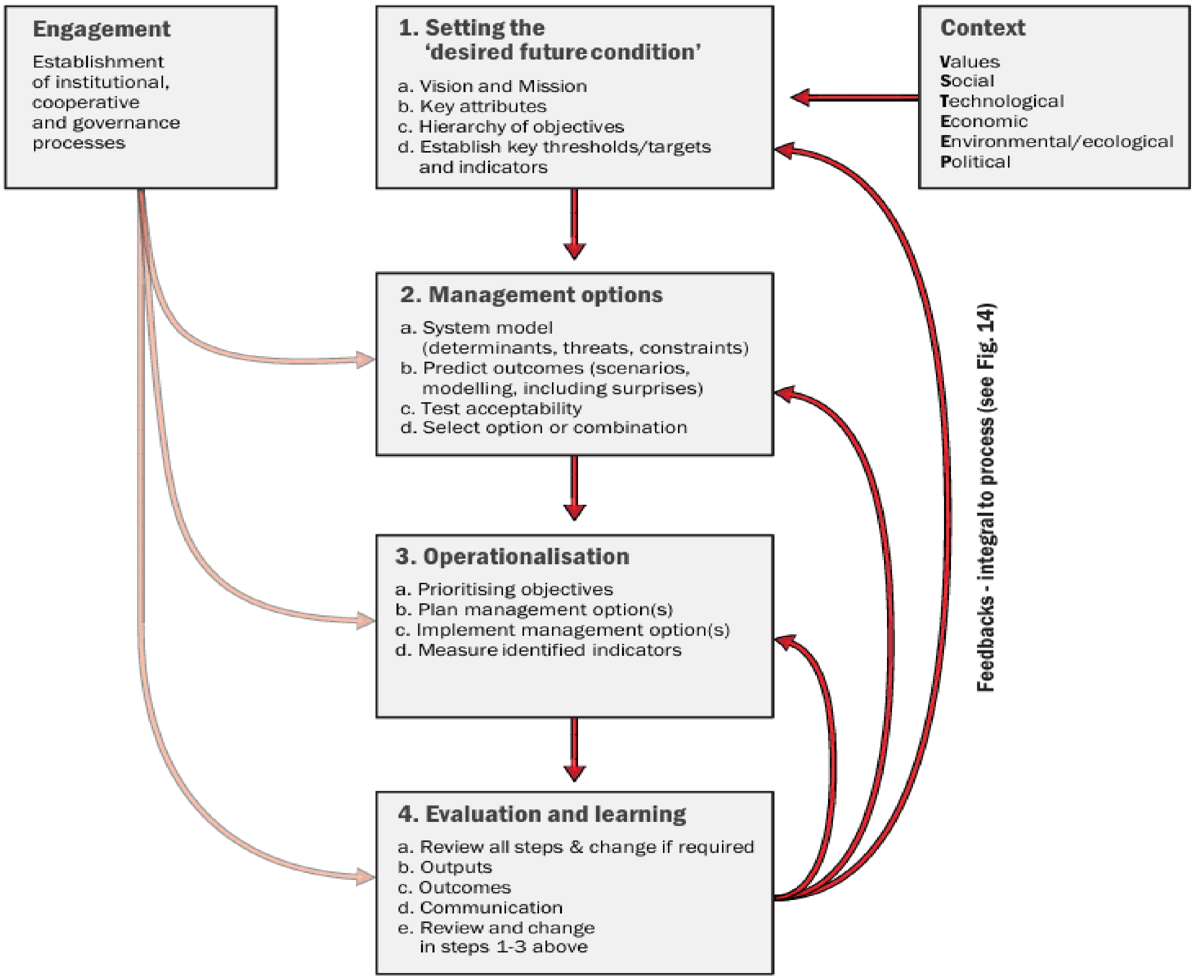

Figure 3. *Strategic Adaptive Management (SAM) framework for freshwater ecosystems. The model illustrates four iterative steps (Kingsford & Biggs, 2012)*

BACI offers a scientifically rigorous structure for evaluating change. It compares conditions before and after an intervention at both impact (restored) and control (non-restored) sites, helping to isolate ecological responses attributable to the intervention rather than background variability (Smith, 2002). This makes it especially valuable in complex ecosystems where multiple factors influence change. BACI is most effective when combined with long-term monitoring and used across various sites. It can assess a wide range of ecological responses, including changes in substrate composition, fish density, redd distribution, and broader ecosystem processes. SAM and BACI support a restoration approach that is both adaptive and evidence based. SAM facilitates goal setting, learning, and participatory management, while BACI enables clear attribution of outcomes. In this project, the SAM framework structures ongoing monitoring and evaluation, and the BACI design establishes assessments of physical and biological changes resulting from habitat enhancement. This integrated approach strengthens findings and supports long-term restoration success.

3 Methods

3.1 Study Area

Unnebergsbekken (water body #014-113-R) is a small anadromous stream in Sandefjord municipality, located in South-East Norway. It is primarily comprised of marine clay deposits resulting from the end of the last ice age, where clay from glacial erosion was deposited in the sea. This is common along Norwegian coasts (Schneider & Skarbøvik, 2022). Its current ecological status is considered "moderate," with its greatest pressure coming from runoff from plowed lands (vann-nett, n.d.). The total catchment area is 15.0 km². The total stream length within the catchment, including tributaries, is approximately 17 km. However, the main stem of Unnebergsbekken is 7.4 km. The land cover is primarily agriculture (45.9%) and forest (43.1%), with smaller contributions from urban areas (7.5%) and unclassified surfaces (3.4%). The catchment is low, ranging from 1 to 147 meters in elevation. The stream gradient averages 11.2 (1.12%) meters per km. The entire catchment area can be seen in Figure 4.

Figure 4. *Map of Unnebergsbekken and catchment area in Sandefjord, Norway (NEVINA, NVE).*

The mean annual runoff for 1991–2020 is 601.4 mm, corresponding to 19.1 l/s/km². The catchment's drainage density is 1.1 km/km². Climate data from the period 1961–1990 show a mean summer temperature (May–September) of 13.5°C and an annual precipitation of approximately 850 mm, with rainfall distributed between the summer (384.5 mm) and winter (465.1 mm) seasons. Rainfall and snowmelt events in late spring and autumn contribute to peak flow conditions, with November accounting for 110 mm of runoff from combined rain and snowmelt. According to NVE flood estimates for small, ungauged catchments, the 5-year flood (Q5) in Unnebergsbekken is estimated at 7.0 m³/s, while the 100-year flood (Q100) may reach 13.7 m³/s, with slightly lower values estimated by the RFFA-2018 model. These values indicate moderate peak flow potential and underscore the need to consider flood dynamics in restoration design and gravel stability. Field surveys and QGIS measurements revealed stream width ranging from 1.5 meters to over 7 meters in downstream pooled areas. Observed depth ranged from less than 2 cm to approximately 1 meter.

All hydrological, land cover and climate parameters were obtained from the Norwegian Water Resources and Energy Directorate's NEVINA tool (NVE, n.d.).

This thesis is structured around two spatial scales. The first is the full mapped length of Unnebergsbekken (7.6 km). Starting at roughly 500 meters upstream of the sea estuary this included 6.2 km of the main stem along with roughly 1.4 km of a tributary that forks at 2.5 km from the sea. This approach provided a holistic assessment of habitat conditions and ecological bottlenecks throughout the stream. The second is the specific restoration reach (370 m) located 2.9 km from the sea, as recommended by Lund and Wulff Tollefsen (2023), where physical interventions were implemented and mapped in detail. This section includes the three treatment sites where restoration was performed. It serves as the focus for comparing restored and unrestored conditions and will be used to establish pre-restoration benchmarks as part of the BACI framework. Spatial scales can be seen in Figure 5.

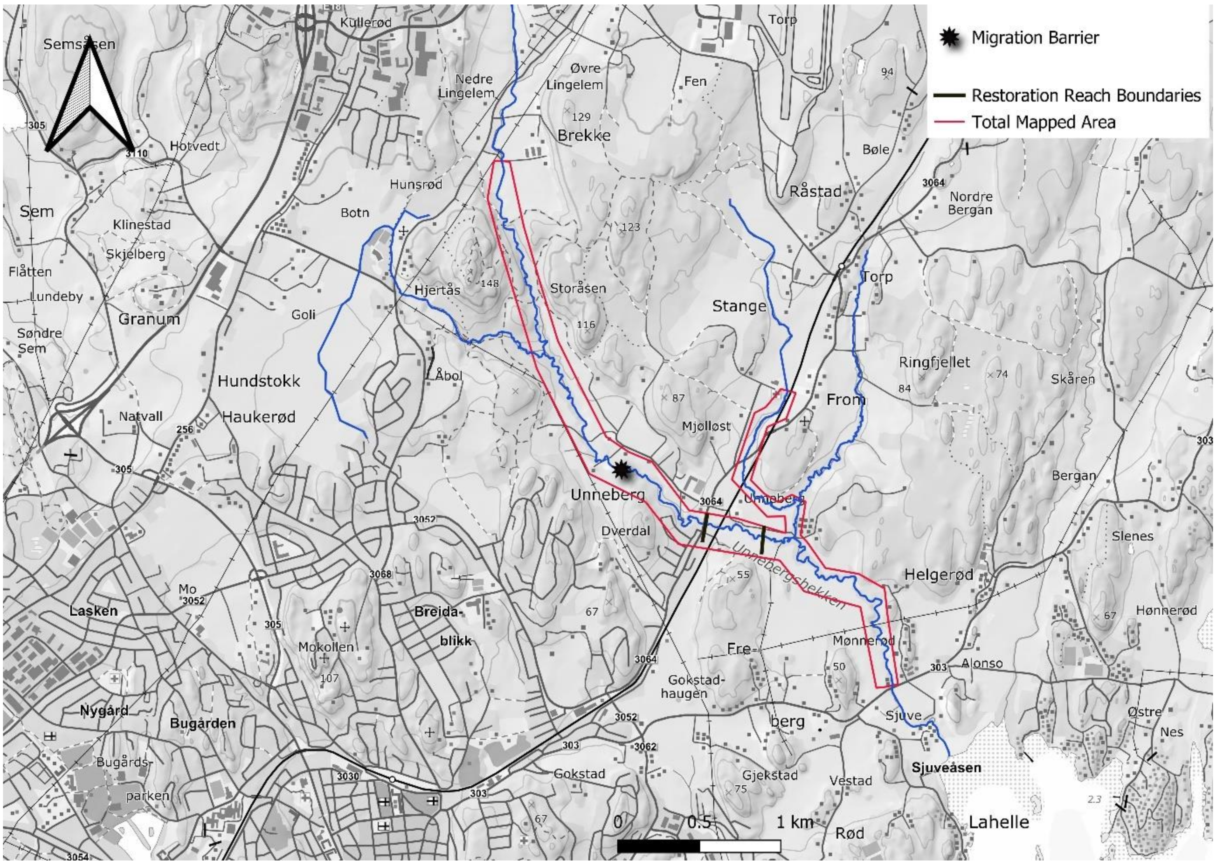

Figure 5. *Map of spatial scale used in Unnebergsbekken. Red boundaries represent entire mapped area along. Black lines represent the restoration reach, and the black point represents the natural migration barrier location*.

Additionally, it should be noted that during fieldwork, a section of the stream located between 2.6 and 2.8 km from the sea showed evidence of gravel augmentation that is not documented in any official records. The source and timing of this intervention are unknown.

3.2 Physical Habitat Mapping

To establish baseline conditions for sea trout spawning and rearing habitat, key physical parameters were mapped throughout the full 7.6 km survey reach of Unnebergsbekken. These included substrate composition, mesohabitat structure, interstitial shelter availability, and suitable spawning gravel. Mapping was conducted during late summer and autumn 2024 under low-flow conditions, when streambed features were most visible and ecologically limiting. All habitat mapping was performed during daylight hours using polarized sunglasses to improve visibility of underwater features, and surveys were conducted by walking upstream to avoid disturbing sediment and water clarity. In addition to increasing accuracy, low-flow conditions also allowed for safer and more efficient fieldwork. Physical habitat mapping parameters can be seen in Table 1.

Table 1. *Table outlining physical mapping parameters with brief description of purpose, and*

Parameter	Purpose / Objective	Reference
Suitable spawning substrate	Mapped visually during field survey and to estimate spatial distribution and area.	Forseth et al. (2014)
Substrate	Classified substrate types visually across the streambed to understand sediment distribution and suitability for spawning and shelter.	Wentworth (1922); Forseth et al. (2014)
Mesohabitat	Identified mesohabitats (pool, glide, riffle) to evaluate hydraulic diversity and habitat structure.	Gabrielsen et al. (2021)
Interstitial shelter	Measured depth of interstitial space at transects using plastic tubing to assess shelter availability	Finstad et al. (2007) Forseth et al. (2014)
Riparian zone	Mapped buffer widths using satellite; classified into size categories that represent filtration effectiveness	Lind et al. (2019)
Redds and spawners	Surveyed for redds and observed spawners during peak season to establish baseline spawning activity. Locations were marked in the field for spatial reference.	Forseth et al. (2014)

3.2.1 Substrate

Substrate composition was mapped along the entire 7.6 km survey reach to assess spatial variation in streambed conditions relevant to sea trout spawning and rearing habitat. This measure was used to identify areas with suitable sediment structure for spawning, locate potential bottlenecks caused by fine sediment accumulation, and support later interpretation of electrofishing and shelter data. Substrate also forms the baseline for evaluating physical changes at the restored sites.

Classification followed a modified version of the Wentworth scale adapted from Forseth et al. (2014). Streambed sections were categorized by dominant and subdominant substrate type, using five size classes: clay, sand/silt, gravel, rock, and large blocks. Specific parameters for classification can be seen in Table 2. These categories were chosen to reflect ecological relevance to sea trout life stages and to allow consistency in field application. Observations were made visually and recorded within each segment of dominant substrate. A new segment was recorded whenever the dominant substrate changed visibly. Observations were made while walking upstream during low-flow conditions to ensure visibility and minimize disturbance. An example of how mapping was digitized in QGIS can be seen in Figure 6.

Table 2. *Size categories for mapped substrate in Unnebergsbekken.*

Substrate Type	Size (cm)
Clay	n/a
Sand/Silt	< 2
Gravel	2 - 12
Rocks	12 - 29
Large Blocks	≥ 30

Only the dominant substrate was used in spatial calculations, while subdominant types were noted for context. Substrate classification was performed consistently across the full mapped reach, providing a continuous record of sediment structure to support later spatial analysis and comparisons within and outside the restoration reach.

Figure 6. *Example of substrate mapping in Unnebergsbekken. All physical mapping followed the same procedure.*

3.2.2 Mesohabitat

Mesohabitat was mapped throughout the 7.6 km survey reach to characterize hydraulic diversity and support the evaluation of habitat composition relevant to juvenile sea trout. This method was used to identify spatial patterns in mesohabitat distribution, which informed assessments of spawning and rearing potential, site selection for future restoration, and interpretation of biological data, including shelter and fish density. Units were classified in the field into three categories: riffles, glides, and pools (Table 3). These categories were selected based on their relevance to sea trout ecology. This system was based on methods adapted from Gabrielsen et al. (2019). Working upstream the mesohabitat was noted and a polygon was digitized in the Qfield app. When the mesohabitat transitioned to a different type, a new segment was recorded.

Table 3. *Attributes of mesohabitat types.*

Type	Velocity	Depth	Habitat Use
Pool	Slow	Deep (>50 cm)	Shelter and feeding
Riffle	Fast/Turbulent	Shallow (<30 cm)	Spawning
Glide	Moderate	Variable	Connectivity and rearing

The dominant mesohabitat type was used to delineate each section. This data was later used to calculate mesohabitat composition by area and to analyze distribution patterns along the stream gradient. This provided a baseline for evaluating physical habitat variation across the system and comparing conditions before and after restoration interventions.

3.2.3 Suitable Spawning Habitat

Potential spawning areas were mapped along the 7.6 km survey reach to quantify the distribution and availability of spawning habitat suitable for sea trout. This measure was used to identify the spatial area and spatial distribution of spawning habitat, inform future restoration site selection, and serve as a baseline for evaluating changes following restoration efforts. These areas were identified based on visual and physical assessment of gravel size, depth, water movement, and embeddedness. Patches with gravel between 10 and 120 mm in diameter were recorded as suitable if they were located in visibly flowing water and had a gravel depth of at least 5 cm. Gravel less than this depth was excluded from suitable spawning consideration. The depth of gravel was measured by inserting a stick until it reached the clay beneath the surface substrate. Gravel in slow or deep sections was aslo excluded. Embeddedness of gravel was assessed physically using a stick to disrupt the substrate, and areas with high fine sediment or compacted structure were not recorded. Suitability determinations were made at the surveyor's discretion based on these criteria. Mapped spawning areas were digitized as polygons to calculate the total area and the distance from the sea. Although this method offers comprehensive coverage of gravel suitability, it may overestimate spawning usage. This discrepancy can arise from the assessment scale and the subjective nature of field classification.

3.2.4 Interstitial Shelter Measurements

Interstitial shelter was measured at selected transects along the mapped reach of Unnebergsbekken to evaluate substrate conditions relevant to juvenile sea trout rearing. This parameter was used to assess the availability of microhabitat features that provide concealment and flow refuge for age 1+ juveniles and to identify spatial variation in shelter quality across the system. Shelter data also supports interpretation of juvenile density and substrate composition. Shelter was measured using an adapted version of the Finstad method, as described by Forseth et al. (2014). As discussed in the theory chapter, access to shelter in interstitial spaces between substrate is essential for the growth and survival of sea trout (Hindar et al., 2019). Due to time constraints and project prioritization, shelter measurements were observed at a limited number of transects.

Individual interstitial space dimensions were measured by counting how deep a 12 mm-thick plastic hose was inserted into the holes between substrate within a 50 cm x 50 cm steel frame (Figure 7). The sizes of interstitial spaces are determined by how deep the hose can reach between the rocks. Three shelter categories are recognized: **S1: 2-5 cm, S2: 5-10 cm, and S3: >10 cm**. Typically, this method utilizes three measurements: one near the bank, one as close to the middle of the stream as possible, and one in between. These three measurement sites form a transect. However, due to the stream width of Unnebergsbekken, three measurements were not practical and would have created redundancies. Therefore, for this project, only one or two measurements would form a transect. If the site was more than two meters wide, two measurement locations were chosen: one near the center and one near the eastern bank. These sites were selected randomly by tossing the steel frame into the stream. The location of each transect was marked using GPS waypoints.

Figure 7. *Method of interstitial shelter measuring. 12 mm plastic hose used for insertion.*

The average number of sheltered habitats for each of the three categories is calculated for each transect. The values are summed and weighted to provide a value for weighted shelter using the following formula;

S1 + **S2** x 2 + **S3** x 3

Based on these values of weighted shelter, each transect is assigned a class: "low shelter" (< 5 cm), "moderate shelter" (5-10 cm), or "high shelter" (> 10 cm).

In a short stream such as Unnebergsbekken, shelter measurements are ideally taken at 100-meter intervals to better understand shelter composition. However, due to time constraints, this method was not viable. Therefore, each transect location was selected by dividing the mapped area into three sections to ensure complete randomness without bias. The reach was divided into three longitudinal sections to ensure randomized but spatially representative sampling. The first section extended from the lowest portion of the mapped reach downstream up to the confluence with the mapped tributary. The second section was the area upstream of the tributary, including the 2024 restoration sites extending up to the known migration barrier. The third section covered the portion of the stream located upstream of the migration barrier. Section locations can be found in the appendix (Figure 31).

Upon sectioning the reach, each mesohabitat polygon was counted within each section. Then, using Google's random number generator, two of each category (glide, pool, riffle) were selected within the designated section, totaling 18 transects to be measured. As some of these mesohabitats covered longer distances, randomness was again applied to select where within the designated mesohabitat the transect would be placed. This was performed by measuring the distance in meters of the area covered and again using the random number generator to select the transect. Transect mesohabitat types and locations can be found in the appendix (Table 16)**.** Five measurements were taken within the steel frame at each location: four near the corners and one near the center.

3.2.5 Riparian Zone

Riparian zone width was mapped along approximately 6.2 km of the main stem of Unnebergsbekken to assess buffer conditions and identify areas where riparian vegetation may be insufficient to support stream functions such as shading, sediment retention, and organic matter input. This measure was used to classify riparian conditions spatially, inform potential future restoration measures, and support the interpretation of stream habitat structure and bottlenecks. Mapping was conducted entirely through remote sensing using aerial basemaps in QGIS and classified based on visible vegetation cover and proximity to the stream. Riparian width was measured using spatial analysis, with 30 meters set as the maximum value based on the upper threshold for ecologically functional riparian zones (Lind et al., 2019). The buffer area was visually assessed and categorized into four width classes based on observed riparian vegetation:

- **<5** meters: poor nutrient filtration
- **5 to 10** meters: adequate nutrient filtration
- **11 to 20** meters: significant nutrient filtration

- **21 to 30** meters: forested zones

The riparian zone was not mapped for the tributary, as restoration measures and biological monitoring were limited to the main stem. The mapping effort was focused on the main stem to ensure consistency between the spatial scale of riparian assessment and the areas relevant to restoration outcomes and evaluation. While other field-based parameters were collected in the main stem and tributary to provide a broader system context, the riparian zone was treated as a core variable only within the primary management reach

3.3 Sea Trout Production Potential

3.3.1 Electrofishing

Electrofishing is an efficient and non-lethal method for assessing fish populations. The method uses electric current to temporarily immobilize fish, making them easier to capture and identify. For this project, the Norwegian standard electrofishing method developed by Bohlin et al. (1989) was followed. Electrofishing was conducted to collect data on juvenile sea trout density and distribution across the stream, supporting assessments of rearing habitat conditions and establishing a biological baseline for evaluating restoration effectiveness. This contributes to the first subobjective of this thesis by quantifying production potential and identifying spatial bottlenecks in habitat occupancy and availability.

Following Norwegian standards, stations measuring approximately 100 m² were selected. Because Unnebergsbekken is a small stream with variable width, station sizes were close approximations rather than exact measurements. Electrofishing was performed in autumn during low-flow conditions, before water temperatures dropped below 5°C. Five stations were sampled in 2024: three within the 370-meter restoration reach and two upstream. One upstream station was previously established, and the other served as a control in an area with similar hydrological conditions. These stations were positioned to support a BACI evaluation of restoration effects.

Three rounds of electrofishing were conducted at each station. Working upstream, fish were captured by a two-person team, one operating the equipment and the other capturing and storing the fish. Both using polarized sunglasses to improve visibility. Captured fish were sorted into buckets labeled by round and held until all passes were complete to avoid duplicate counting. Water in the buckets was replaced regularly to ensure oxygenation and minimize stress. A 15-minute break was taken between rounds to allow fish to recover from the electrical exposure and to improve data accuracy by reducing stress-induced behavior.

At the end of the third pass, captured fish were identified and measured for length. Only fish under 200 mm were included in the juvenile density calculations. Length represents age class, allowing identification of 0+ and older juveniles (Table 4). This data provides insight into age structure, growth, and population health. Proportions of 0+ and older juveniles were calculated to allow later interpretation of population structure relative to potential recruitment or shelter limitations, following criteria outlined by Forseth et al. (2014). Low 0+ populations can be a sign of spawning habitat limitations, while lower populations of older juveniles can signify limited access to shelter. Sampling dates were 8 September, 9 September, 28 September, and 24 October. The spatial distribution of stations and juvenile length data support interpretation of whether restoration sites show evidence of recruitment or shelter bottlenecks, contributing to the evaluation of rearing capacity and restoration outcomes. The full details of the conditions of each station are in the appendix (Table 18). Locations of each station can be seen in the appendix as well (Figure 32).

Table 4. *Age of juvenile sea trout based on length. 0+ represents this year's summer old trout. 1+: survived two summers since hatching. 2+: survived more than two summers. (Heggenes, 2023)*

Age Class	Age (Summers)	Length Range (mm)
0+	1	<70
1+	2	<110
2+	>2	>110

3.3.2 Juvenile Density

Fish density was calculated to provide a measure of juvenile sea trout abundance, supporting comparisons across stations and forming a key metric for evaluating rearing habitat conditions before and after restoration. Density estimates contribute directly to assessing the stream's production potential. Calculations followed the method developed by Bohlin et al. (1989), which estimates population density based on declining catch numbers across the three rounds of electrofishing. The approach assumes fewer individuals will be captured with each pass as the population is progressively reduced. This method generated density estimates for each station and standardized them to individuals per 100 m².

$$y = \frac{T}{1 - \left(\frac{T - C_1}{T - C_3} \right)^3}$$

y = density, T = total number of fish caught, Cx = number of fish caught at round x. Density is given as number of fish per 100 m^2 and is calculated for each individual station.

3.3.3 Smolt Production Estimate

Estimating smolt production provides a metric for evaluating the potential output of sea trout from Unnebergsbekken. This measure supports the first subobjective by connecting juvenile density to habitat area and converting it into a population-level estimate of production capacity. Stock-recruitment models, such as Ricker (1954), are commonly used in fisheries to estimate production. However, these models require long-term datasets to be reliable and could not be applied in this study due to the lack of multi-year data.

To maintain consistency with the prior work in Unnebergsbekken, smolt production was estimated using the approach described by Lund & Wulff Tollefson (2023), which combines juvenile density data from electrofishing with GIS-based measurements of the total wetted area. This method is based on the work of Hesthagen & Hansen (1991), who reported smolt survival rates of 20-30% in several streams in western and southern Norway. These survival estimates were used in conjunction with Bohlin’s method (Bohlin, 1989) for calculating juvenile density to estimate the total number of smolts potentially produced within both the full mapped area and restoration reach of Unnebergsbekken.

Production was calculated using Bohlin’s method, which estimates population density from electrofishing data. These densities were applied to the total wetted area to estimate the number of juveniles within the stream. A 20% survival rate was then used to estimate the number of smolts produced annually.

Bohlin’s Method:

$$\text{Production} = \left(\frac{\text{Total Area} \times \sum \text{Density}}{\text{Electrofished Area}}\right)$$

Multiply this equation by 0.2, the lowest survival rate percentage, to estimate total production within an area. Densities used in this calculation were derived from the five electrofishing stations along with four stations located upstream of the migration barrier provided by Varelman (2025).

3.3.4 Spawning and Redd Surveys

Redd and spawner surveys were conducted to identify active spawners and spawning areas, contributing to the understanding of sea trout distribution during the spawning period. This measure supports the first subobjective by providing validation of gravel suitability, identifying areas of successful reproduction, and helping to detect potential errors in the initial assessment of suitable spawning habitat. Observations also provide a pre-restoration baseline that can be used to evaluate the effectiveness of habitat improvements through post-restoration comparison and to support future production estimates by contributing to long-term data on spawning activity. Surveys were conducted along the 6.2 km main stem of Unnebergsbekken.

Redds were identified visually during daylight hours under low-flow conditions, when substrate disturbance is most visible and water clarity is high. Redds appear as pale, oval-shaped areas of disturbed gravel, typically recognized by their contrast against surrounding undisturbed substrate (Forseth et al., 2014). Surveys were conducted while walking upstream using polarized sunglasses to reduce surface glare and improve visibility. Observed redds were georeferenced in the field and digitized in QGIS as point features.

Spawning sea trout (>30 cm) were observed at night using headlamps and flashlights. Surveys were conducted by slowly walking upstream and scanning the channel for large, active individuals. Nighttime observation was selected because sea trout are more active and visible during this time due to reduced predation risk. Spawner positions were also recorded as GPS points. These observations helped verify active spawning sites and supported identifying functional habitat areas.

3.4 Restoration

3.4.1 Restoration Methods

Habitat improvement was conducted at three sites within the main stem of Unnebergsbekken during the autumn and winter of 2024. This 370-meter restoration reach was predetermined based on recommendations by Lund and Wulff Tollefson (2023). Within this reach, the specific enhancement design, including gravel placement, shelter installation, and riparian planting, was developed as part of this thesis. Mapping of physical and biological parameters was not used to guide the location of interventions; instead, it serves as the before condition in a BACI framework, where the habitat measures represent the impact. Sites were selected to align with electrofishing stations to support post-restoration monitoring of biological responses. These actions follow the process-based principles described in the theory chapter. Habitat enhancement in small streams addresses specific ecological functions without fully restoring geomorphic processes (Beechie et al., 2010).

Restoration involved two primary strategies: adding spawning gravel and installing structural habitat shelter. Gravel (10–100 mm in diameter, with 50% of the weight near 50 mm) was added to create suitable spawning habitat. To stabilize the gravel and promote subsurface flow, trenches approximately 30 cm deep and 2–3 meters wide were excavated at two of the three sites (Figure 8). This technique helps anchor the gravel and encourages water to flow through the substrate, increasing oxygenation and improving egg survival conditions.

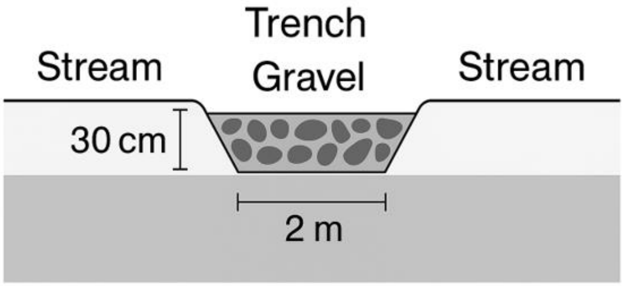

Figure 8. *Sketch outlining how gravel is placed into dug trench in the center of the stream during restoration.*

Structural shelter was introduced using boulders, rock clusters, and large woody debris such as logs (Figure 9) and root wads. Smaller organic material was buried beneath gravel across each site to increase structural stability and microhabitat development. The specific functions and installation methods for each restoration feature are summarized in Table 5. These combined elements improve flow diversity, increase interstitial cover, and provide critical refuge for juvenile sea trout. In areas where the machinery had disturbed riparian zones, native trees were also planted to support the recovery of riparian vegetation.

Figure 9. *Example of how woody debris is placed in the stream.*

Table 5. *Restoration features, functions and methods of installation.*

Restoration Feature	Primary Functions	Installation	Reference
Boulders	• Increase flow diversity • Provide cover from predators • Stabilize introduced gravel	• Sourced locally • Placed near stream edges to guide flow • Match natural stream conditions	Kjøsnes, A. J. (2018)
Rock Clusters	• Promote complex flow patterns • Increase turbulence and interstitial space • Enhance invertebrate production	• Grouped in clusters to mimic natural formations	USDA (2012)
Large Woody Debris	• Provide cover and shade • Trap organic material (leaf litter) • Form pools and undercut banks • Boost nutrient cycling	• Installed diagonally • One end anchored into bank • Angled ~15° downstream • Rootwads driven into banks	Kjøsnes, A. J. (2018)
Organic Material Burial	• Stabilize gravel beds • Enhance interstitial microhabitats • Release nutrients as wood decays	• Buried with gravel • Improves long-term structure and stream health	USDA (2012)

3.4.2 Restoration Design and Implementation

Three different restoration approaches were implemented at the selected sites within the restoration reach (Figure 10). These approaches varied regarding trenching, gravel placement, and adding structures such as boulders and logs. This variability supports subobjective three by enabling future evaluation of how restoration design influences site stability and biological response. Site One measured approximately 153 m^2 and included trenching and gravel distribution, but no structural additions. Site Two measured approximately 128 m^2 and involved surface-level gravel placement without trenching or structural elements. Site Three measured approximately 154 m² and included trenching, gravel placement, and the installation of structural habitat.

Figure 10. *Location of sites with ID's in Unnebergsbekken. Black lines represent the boundaries of the restoration reach.*

Budget limitations partially influenced the differences in treatment among sites, but the resulting variability also provides a valuable basis for comparing the effectiveness of different restoration strategies under similar environmental conditions. This includes assessing how trenching and structural additions affect gravel retention, flow dynamics, and potential fish response. Trenching is expected to improve gravel stability by anchoring the material and promoting subsurface flow, whereas gravel placed without trenching may be more prone to scouring during high-flow events. To track these outcomes, substrate and mesohabitat distribution were mapped before and after restoration, and gravel depth was measured at 30 random points within each site upon completion. These depth measurements establish a baseline for evaluating morphological change over time, particularly in response to flow stressors such as floods or high discharge.

3.5 Monitoring Plan

A monitoring plan was developed as part of this thesis to allow evaluation of habitat enhancement measures in Unnebergsbekken. The plan was designed to support a BACI framework and aligns with SAM principles by facilitating feedback-based learning and adaptive decision-making. It builds on the physical and biological parameters mapped before restoration and provides a basis for future assessment of ecological response.

The plan was developed by identifying key variables relevant to the thesis subobjectives, including spawning and rearing habitat quality, physical habitat stability, and biological indicators of stream health. Monitoring frequency and duration were determined based on the ecological sensitivity of each variable, the probability of change, and the feasibility of future data collection. Many components reflect direct continuation of baseline methods, but the plan also includes adjustments and additions based on field limitations, observed gaps, and opportunities for improved ecological insight.

The plan emphasizes spatial consistency, with repeated measurements of actions taken in this thesis. However, in accordance with SAM, several improvements were proposed. These include increased spatial resolution of shelter measurements, the addition of benthic macroinvertebrate sampling, and the inclusion of high-flow mesohabitat mapping. Such updates were identified through evaluation of initial methods and serve as adaptive corrections aimed at strengthening long-term monitoring. Methodologies aim to replicate baseline protocols wherever possible to ensure comparability. This plan serves as a foundation for continuous and adaptive evaluation of restoration outcomes and is intended to guide future efforts by stakeholders, researchers, or local managers.

3.6 QGIS

QGIS (version 3.42.2) was used throughout the project for spatial mapping, analysis, and figure production. Field data collection was supported by the QField mobile application, which enabled accurate georeferencing of substrate, mesohabitat, and potential spawning areas. Within QGIS, spatial analysis tools were used to calculate stream length, segment area, and the total and proportional coverage of mapped habitat categories across the full survey reach. Distributions were analyzed relative to distance from the sea to identify longitudinal trends. Basemaps and aerial imagery were obtained from Geonorge and were particularly important for riparian zone classification. QGIS was also used to produce all map figures and to extract coordinate data for reporting.

3.7 Statistics

This study relied on descriptive statistics to organize and interpret the ecological data collected during fieldwork. Key metrics, such as the total spawning area, and observed fish density, were used to characterize stream conditions and estimate production potential. These descriptive figures were presented by site and stream for comparisons across different locations and time periods.

Results of key parameters were visualized using histograms and evaluated for skewness. A skewness analysis (Doane & Seward, 2011) was performed to assess the spatial distribution of key habitat parameters along the stream. Skewness is a statistical measure that describes the asymmetry of a distribution relative to its mean. This study used skewness to assess whether habitat variables, such as potential spawning grounds, substrate type, mesohabitat composition, and riparian width, are more concentrated upstream or downstream.

A Kruskal-Wallis test (McKnight & Najab, 2010) was used to explore possible differences in juvenile sea trout density and length distribution between electrofishing stations. This is a non-parametric test that is suitable due to the limited sample size and the likelihood that fish density data may not be normally distributed. The test compares densities and length distribution of all five stations.

A chi-squared test (Agresti, 2018) of independence was used to evaluate changes in mesohabitat composition before and after restoration. This non-parametric test assesses the statistical significance of the association between categorical variables: mesohabitat type (riffle, glide, pool) and time period (before and after restoration). Observed values were based on the area (m^2) of each mesohabitat class recorded during mapping surveys at each restoration site. The test was performed separately for each site.

4 Results

4.1 Physical Mapping and Smolt Production Estimates

4.1.1 Mesohabitat

Mesohabitat mapping was conducted to establish a physical habitat baseline for Unnebergsbekken. This baseline supports the assessment of habitat quality and is directly linked to the project's first objective, which includes mapping production areas and evaluating stream conditions relevant to sea trout spawning and rearing.

A total of approximately 32,280 m² of stream area was surveyed under low-flow conditions, roughly 7.6 km of the 17 km (45%) total stream network within the catchment.

Within the mapped area, pools accounted for 36%, followed by glides at 34%, and riffles at 30% (Figure 11). Spatially, pools were more frequent in the downstream reaches of the surveyed section, particularly where natural logjams and channel obstructions were present. In contrast, riffles and glides were more evenly distributed across the stream length.

Spatial analysis was conducted to visualize the distribution throughout the stream. A histogram was created to display the area of each mesohabitat type in relation to the distance from the sea (Figure 12). The results indicate that pools are the most common mesohabitat and are primarily found in the downstream sections of the stream. Glides are mainly concentrated in the lower to middle sections of the stream, whereas riffles are distributed more evenly, with a slight increase observed upstream.

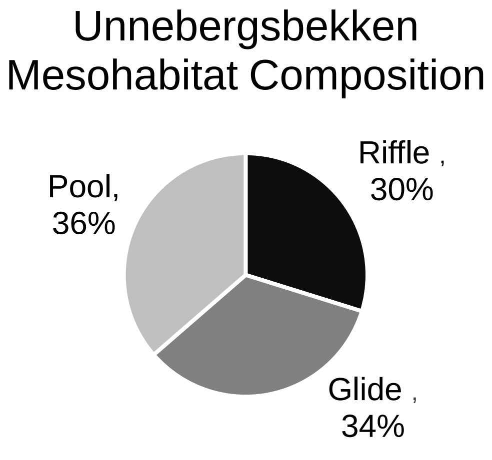

Figure 11. *Pie chart displaying composition of mesohabitat at Unnebergsbekken*

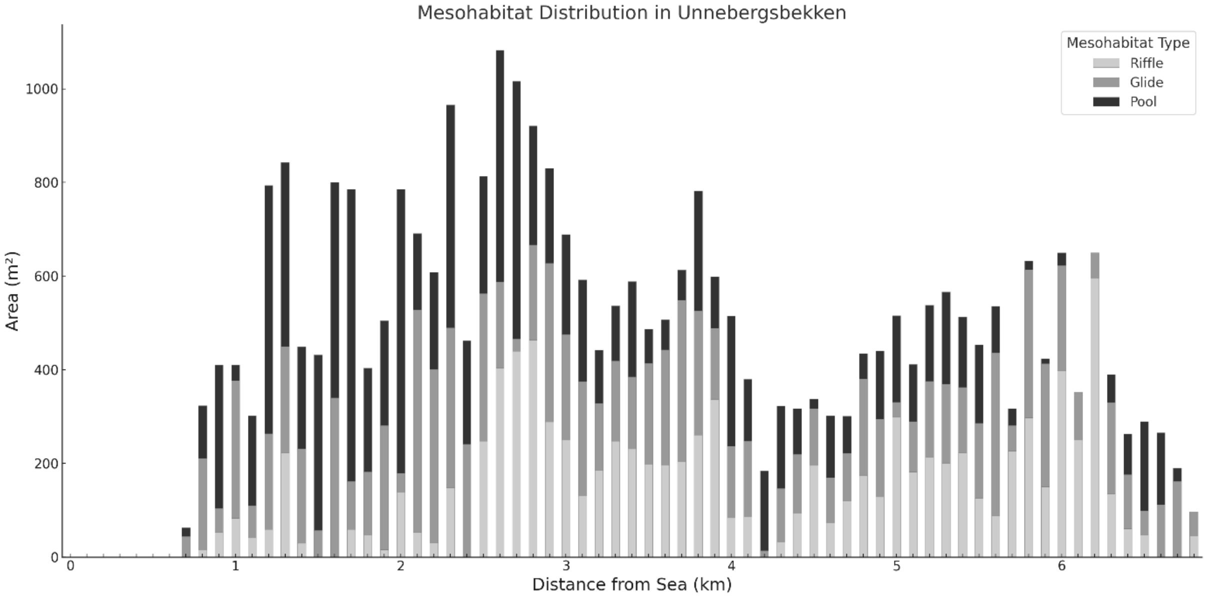

Figure 12. *Histogram showing spatial distribution of each mesohabitat class in Unnebergsbekken.*

Skewness values were calculated for each mesohabitat type using the area-weighted distribution along the stream (Table 6). A positive skewness value indicates a downstream skewed distribution, while a negative skew suggests an upstream skewed pattern.

Table 6. *Skewness results of mesohabitat distribution in Unnebergsbekken.*

Mesohabitat	Skewness	Interpretation
Pool	0.76	Downstream skewed
Glide	0.23	Moderately downstream skewed
Riffle	–0.08	Close to even distribution

4.1.2 Substrate Mapping

The substrate composition in the surveyed area of Unnebergsbekken was mapped to assess the availability of potential spawning and rearing habitat for sea trout. It revealed that sand and silt dominated the mapped area, mostly coinciding with pools and glides. They comprised approximately 52% of the total area. Rock accounted for the second most abundant substrate, at 23%. Gravel made up 16%, representing the most suitable spawning area. Large rocks and blocks were less common, comprising 7%, and clay represented the least common substrate at 2%. The composition distribution can be found in Figure 13.

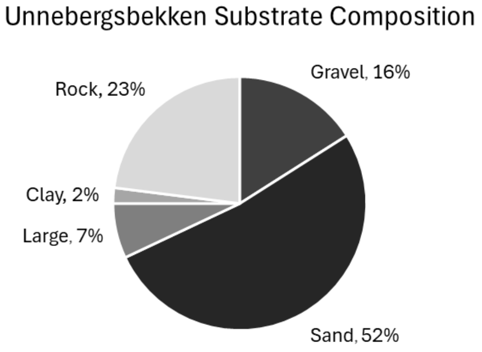

Figure 13. *Composition of substrate distribution in mapped area of Unnebergsbekken.*

To support the overall mapping of substrate types in Unnebergsbekken, a spatial analysis was also performed to better visualize how substrate classes are distributed throughout the stream. A histogram was produced showing the area of each substrate type in relation to distance from the sea (Figure 14). The histogram shows that sand/silt is the most widespread substrate and tends to dominate in the downstream reaches of the stream. Gravel appears more evenly distributed, with rises in both the middle and upper stream sections. Rock and large block substrates show higher occurrence farther upstream, while clay tends to have a more random distribution.

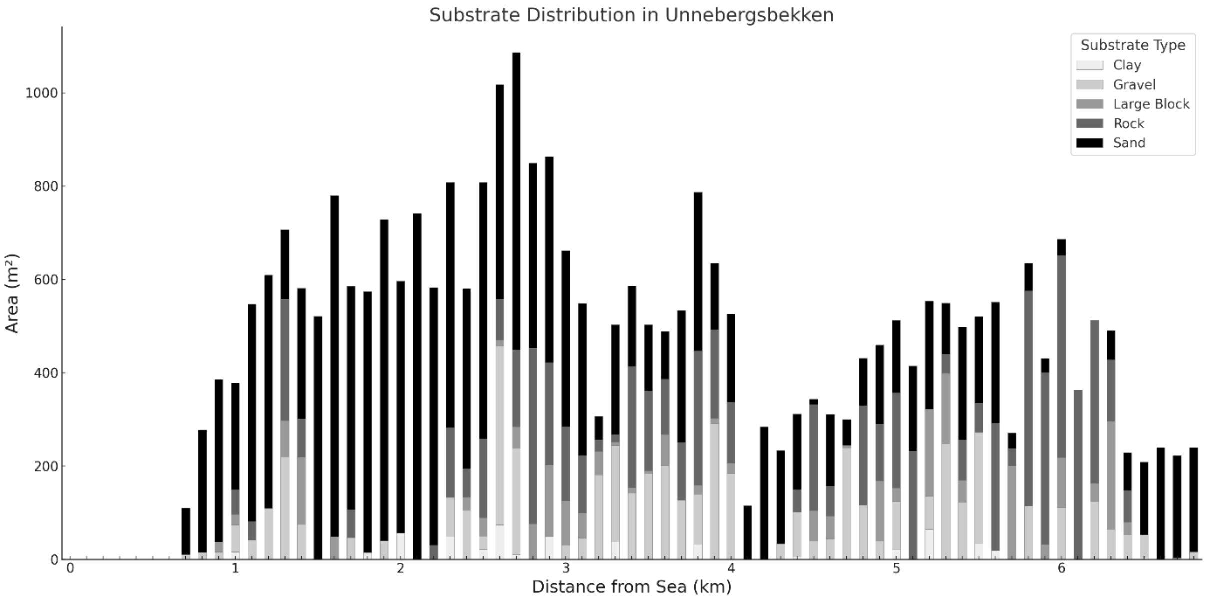

Figure 14. *Histogram showing spatial distribution of each substrate type in Unnebergsbekken.*

Skewness values were calculated for each type of substrate using the area-weighted distribution of substrate polygons along the stream to quantify these observations

(Table 7). A positive skewness value indicates a downstream-skewed distribution (greater concentration at lower distance values), while a negative skew suggests an upstream-skewed pattern.

Table 7. *Skewness results of substrate distribution in Unnebergsbekken.*

Substrate	Skewness	Interpretation
Sand	0.88	Downstream skewed
Clay	0.48	Downstream skewed
Rock	–0.36	Upstream skewed
Large Block	–0.42	Upstream skewed
Gravel	–0.09	Close to even distribution

Sand and clay showed positive skew values, indicating a greater presence in downstream sections. Rock and large block substrates were skewed toward upstream sections. Gravel was relatively evenly distributed across the mapped stream length, with a skew value close to zero.

4.1.3 Riparian Zone

A histogram was generated to illustrate the spatial distribution of riparian zone widths along both sides of Unnebergsbekken in relation to distance from the sea (Figure 15). The west and east banks were analyzed separately, and average riparian widths were recorded in meters. In areas where the riparian zone extended beyond the 30-meter buffer used for mapping, values were set to 30 meters. This upper threshold was applied to maintain consistency with the mapping extent and to prevent extreme values from skewing the analysis.

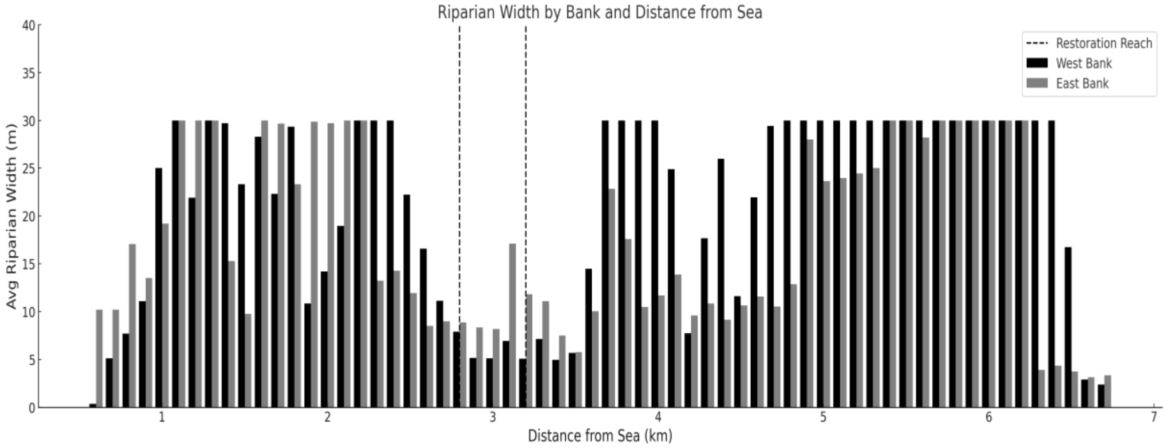

Figure 15. *Histogram showing average widths of riparian zone along each side of Unnebergsbekken relative to distance from the sea. Values of 30 represent the max value due to the 30-meter buffer used for mapping.*

The histogram shows several upstream and midstream sections, especially along the west bank, reached the 30-meter threshold, indicating extensive riparian coverage in these areas. In contrast, several narrow stretches were identified closer to the downstream end of the stream, particularly between 600 and 1500 meters from the sea, where widths were often below 10 meters or nearly absent. The final 200-meter stretch of the upstream portion shows virtually no riparian zone. Low values consistently coincide with agriculture or urban areas.

Skewness values were calculated for each bank to quantify spatial patterns. The west bank showed a skewness of -0.61, indicating an upstream-skewed distribution, with wider riparian zones more dominant in the stream's upper reaches. The east bank exhibited a skewness of 0.17, indicating a slightly downstream-skewed pattern, although the distribution was nearly symmetrical.

4.1.4 Interstitial Shelter

The majority of transects in Unnebergsbekken were classified as having moderate interstitial shelter. A limited number were categorized as low, and no transects recorded high shelter. Shelter availability was lowest in pools and glides, where sand and silt were the dominant substrate. In contrast, riffles generally supported higher shelter values, with several transects showing moderate levels of deeper interstitial space. The riffle transect located 5.7 km from the sea had the highest shelter score, showing the presence of multiple larger spaces between substrate. The lower reach (0-2 km from the sea) demonstrated a lack of shelter availability, primarily due to the dominance of sand and silt in the downstream area. In contrast, the midstream sections (2-4 km) each had an equal number of transects showing moderate shelter. All riffle transects, regardless of location, showed moderate shelter, while glides recorded the lowest weighted scores for shelter availability. A full summary of results can be found in the appendix (table 17). The Kruskal–Wallis test showed no significant difference in weighted shelter between mesohabitat types ($p = 0.279$). Figure 16 shows their spatial distribution across the stream at each transect and Figure 17 shows the distribution of shelter across the different mesohabitats.

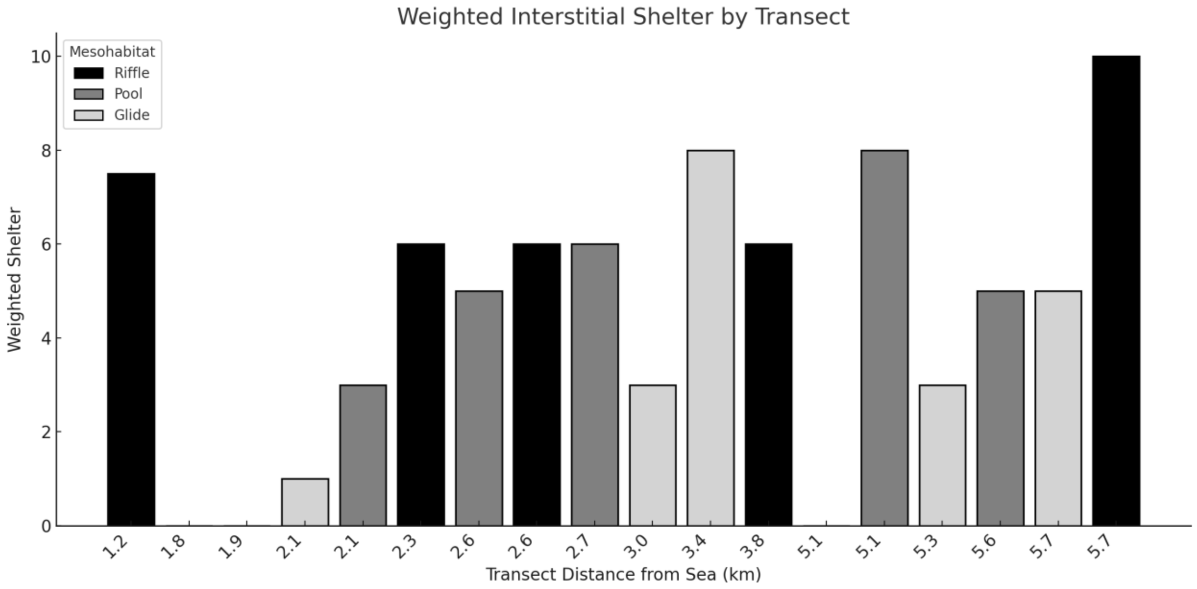

Figure 16. *Bar chart showing weighted scores for interstitial shelter at each transect and distance from the sea. Scores <5 represent a low shelter class and scores of 5-10 represent moderate class.*

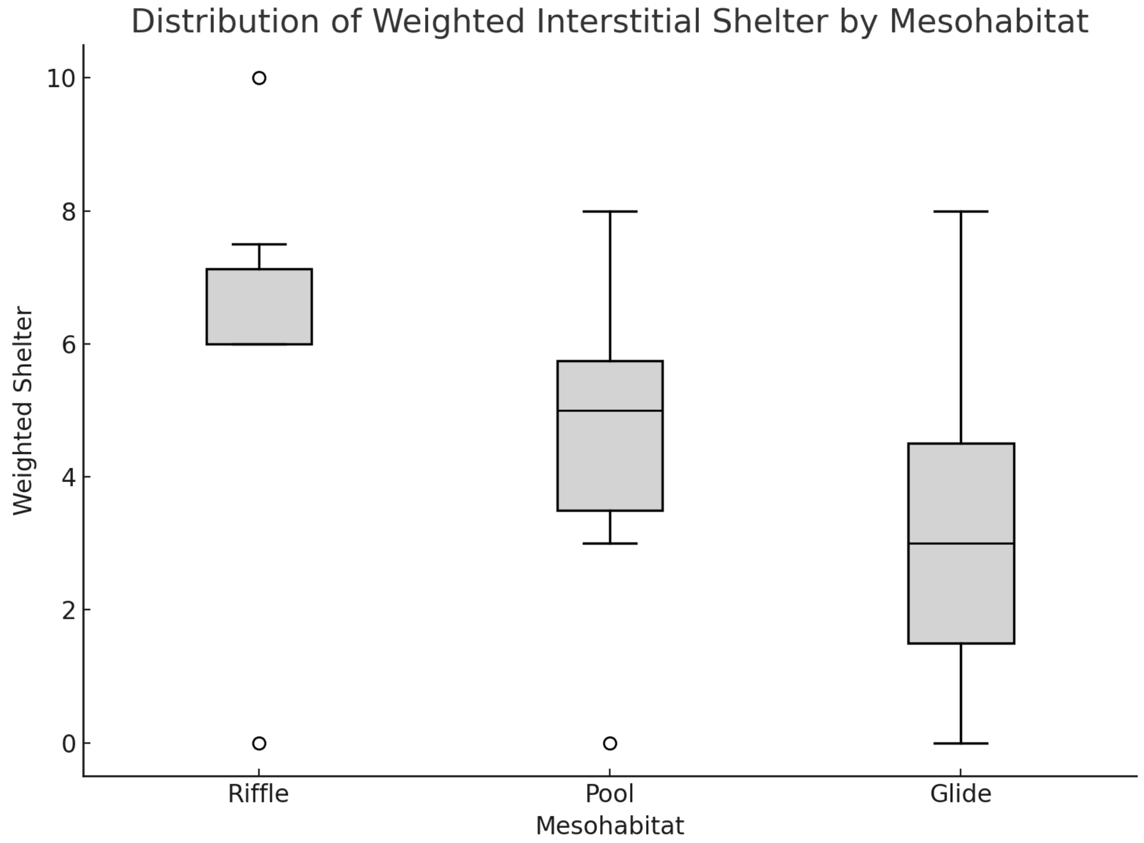

Figure 17. *Box plot of interstitial shelter at Unnebergsbekken grouped by mesohabitat class.*

4.1.5 Potential Spawning Area

Overall, 4447.8 m^2 of the 32,281 m^2 (13.78%) in the mapped area of Unnebergsbekken was evaluated as areas suitable for potential spawning grounds. Spawning potential was unevenly distributed throughout the stream. No potential spawning habitat was detected in the lower 2.5 km. From this point, there was a sharp increase, coinciding with the presumed undocumented additions of gravel. From this point, spawning potential remained relatively high but varied spatially, with several peaks between 4.5 and 6 km. There was a noticeable drop in spawning potential near the migration barrier at approximately 4.3 km. The skewness value was 1.65, indicating an upstream-skewed distribution, which confirms that suitable spawning habitat was mainly located in the upper reaches. Figure 18 shows the results of the potential spawning area found in Unnebergsbekken pre-restoration.

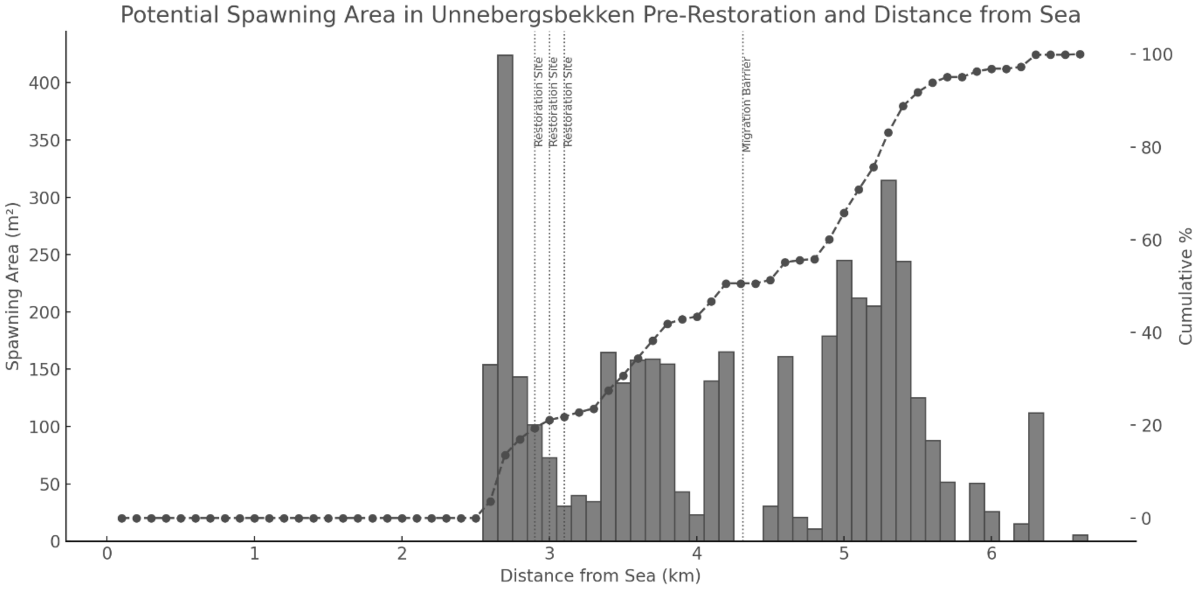

Figure 18. *Potential spawning area per 100 m in Unnebergsbekken prior to restoration, shown in relation to distance from the sea (km).*

4.2 Production Potential

4.2.1 Electrofishing

Substrate composition varied across the five electrofishing stations. Rock was the dominant substrate type at most stations, making up more than 50% at Stations 1, 2, and 4. Gravel was less common, except at Station 5, which comprised 28% of the substrate. Sand/silt was most abundant at Station 3 (48%) and Station 5 (34%), while clay was only present at Station 1 (27%). Large blocks were present at all stations except Station 5, with the highest coverage at Station 1 (21%). Complete results for substrate composition at each station can be seen in Table 8.

Table 8. *Results of substrate composition of each electrofishing station at Unnebergsbekken*.

Station	Gravel	Rock	Sand/Silt	Large Block	Clay
1	0.0%	52%	0.0%	22%	26%
2	0.0%	53%	34%	13%	0%
3	2%	35%	48%	15%	0%
4	3%	53%	26%	18%	0%
5	28%	38%	34%	0%	0%

Mesohabitat composition also showed differences between stations. Riffles were most abundant at Stations 1 and 2 (>50%), while glides were dominant at Stations 4 (80%) and 5 (62%). Station 3 had the highest proportion of pools (43%), whereas Station 4 had none. Complete results of mesohabitat composition can be seen in Table 9.

Table 9. *Results of mesohabitat composition of each electrofishing station at Unnebergsbekken.*

Station	Glide	Riffle	Pool
1	38%	50%	12%
2	10%	52%	38%
3	22%	35%	43%
4	80%	20%	0%
5	62%	12%	26%

4.2.2 Juvenile Density

Juvenile sea trout densities varied across the five electrofishing stations in Unnebergsbekken. The highest density was recorded at Station 4 (86.1 juveniles per 100 m²), while the lowest was observed at Station 5 (8.0). The median density across all stations was 24.7, with a standard deviation of 30.2. A Kruskal-Wallis test was performed to evaluate if the differences were statistically significant. The result showed no significant difference at the 0.05 level (0.081). Results of each round and densities can be found in Table 10.

Table 10. *Results of electrofishing at Unnebergsbekken including round totals with density calculations based on Bohlin's method (Bohlin et al., 1989).*

Station	Round 1	Round 2	Round 3	Total	Juvenile Density (Per 100 m²)
1	9	6	4	19	25
2	18	2	4	24	24.7
3	5	5	0	10	11.4
4	38	21	12	71	86
5	4	2	1	7	8

4.2.3 Juvenile Length Distribution

131 juvenile sea trout were measured across the five electrofishing stations (Figure 19). Of these, 74 (56.5%) were 0+, and the remaining 57 (43.5%) were classified as older juveniles The length of individuals ranged from 48 mm to 166 mm. Median lengths varied between stations (Figure 20)., with Station 5 recording the highest median length (115 mm), while Station 4 had the lowest (66 mm). A Kruskal-Wallis test was performed to determine if the differences were statistically significant. The results showed a significant difference ($p < 0.001$).

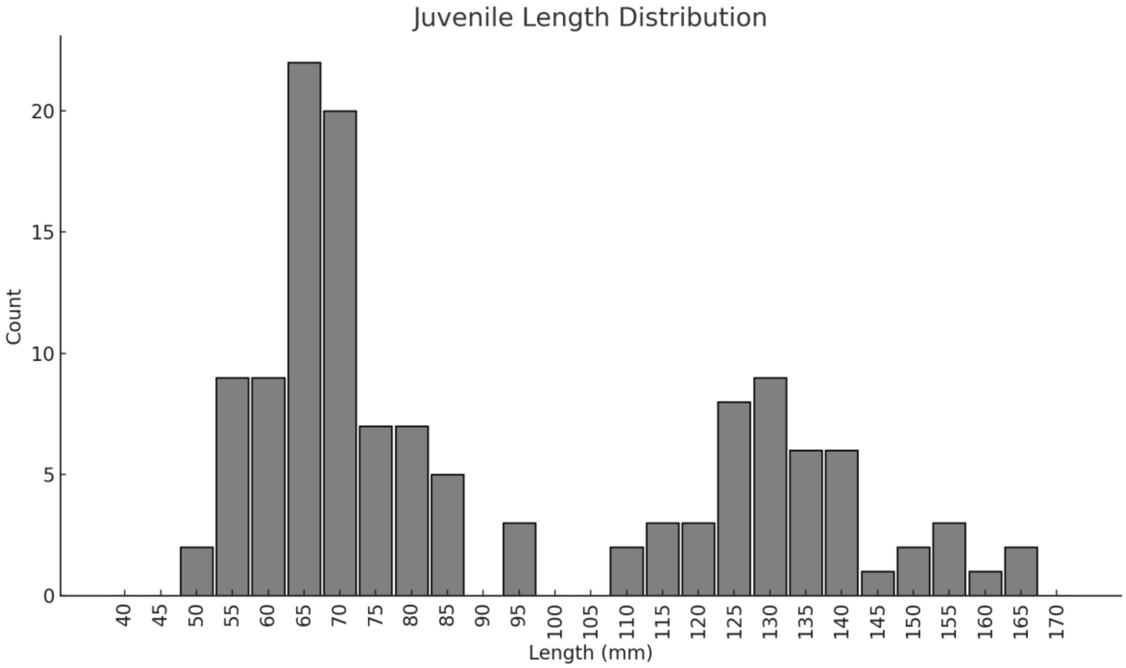

Figure 19. *Length distribution for juvenile sea trout caught at all stations at Unnebergsbekken.*

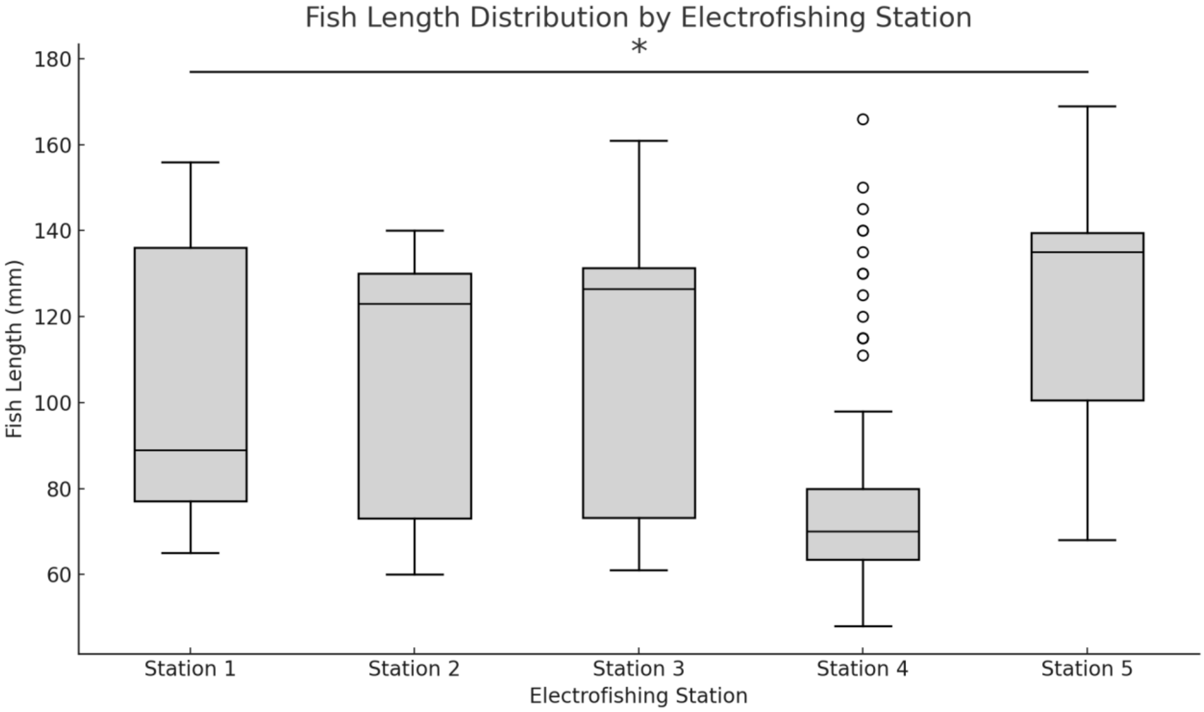

Figure 20. *Length distribution of juvenile sea trout captured at five electrofishing stations in Unnebergsbekken. Asterisk represents significant difference in distribution across stations.*

4.2.3 Production

Using the method for estimating fish production from Bohlin et al. (1989), juvenile production was calculated for both the entire mapped area, the restoration reach, upstream of the migration barrier, and from the beginning of the restoration reach up to the barrier. This calculation was based on the results from electrofishing and the size of the stream area. Table 11 displays each parameter and the corresponding estimated production for each measured area.

Table 11. *Estimated juvenile sea trout production in Unnebergsbekken, based on electrofishing results and stream area.*

Stream Area	**Total Area (m²)**	**Electrofished Area (m²)**	**Density Sum**	**Estimated Production (fish/year)**
Mapped Area	32,281	1000	379.96	2,725.66
Restoration Reach	1,857.16	300	61.1	75.65
Upstream of Barrier	10,735.6	400	224.8	1,206.68
Restoration Reach to Barrier	5,354.99	500	155.16	332.35

4.2.4 Spawners and Redds

A total of 167 redds and 40 spawners were documented during the survey period. Spawning activity was concentrated in select reaches, with some areas showing high densities of redds while others were unused. Spawners observed were all over 30 cm and were typically located near recently constructed or natural gravel beds. Figure 21 shows the spatial distribution of redds and spawner observations across the mapped stream section.

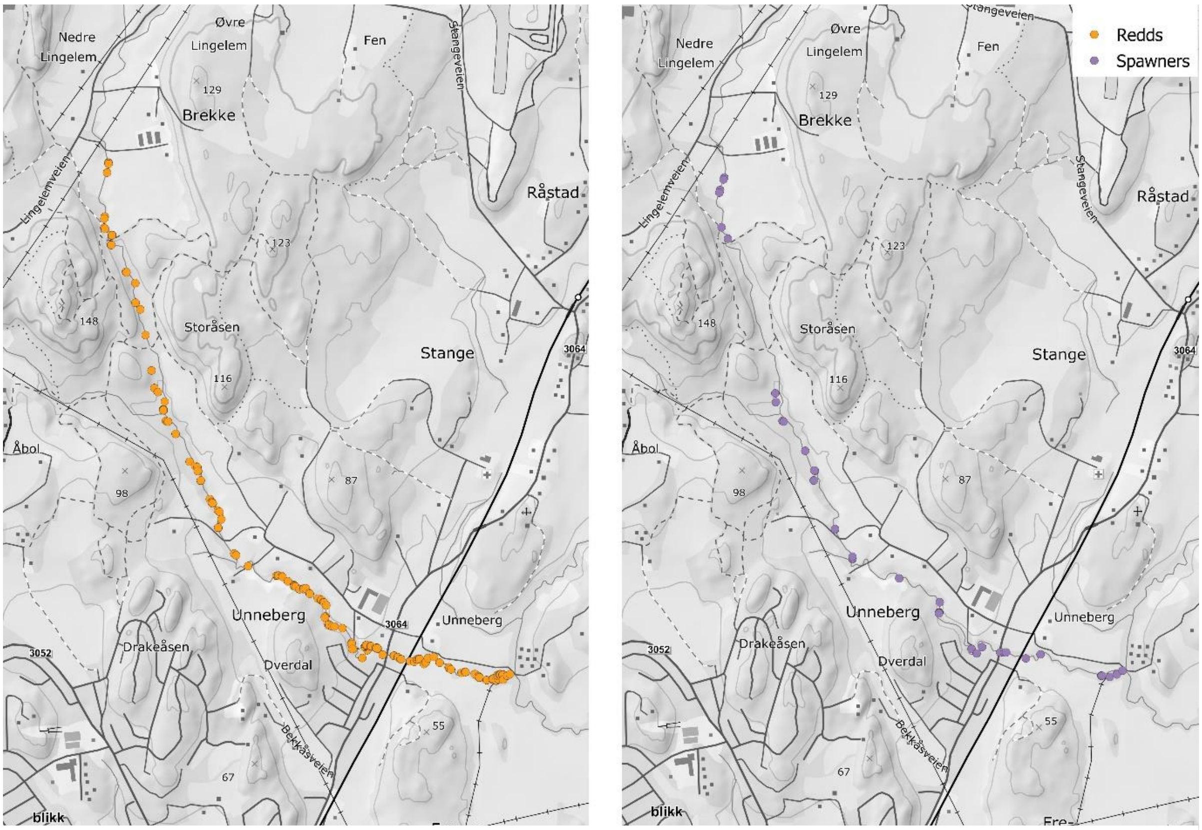

Figure 21. *Spatial distribution of redds (right) and spawners (left) in Unnebergsbekken.*

4.3 Restoration Measures

4.3.1 Physical Habitat Changes

Mesohabitat composition changed at all three restoration sites following habitat enhancement efforts.

At Site 1, riffle cover increased slightly from 48% to 52%, while glide area decreased from 42% to 28%. The proportion of pool habitat increased from 9.8% to 20.2. (Figure 22). A Chi-squared test comparing before and after restoration distributions across riffle, glide, and pool habitats yielded a p-value of 0.013.

Figure 22. *Before and after charts showing changes to mesohabitat at restoration site 1 at Unnebergsbekken.*

At Site 2, riffle area decreased slightly from 54% to 50%, while glides increased from 35% to 50%. Pool habitat was eliminated post-restoration (11% to 0%) due to substrate changes that converted slow sections into glides (Figure 23). The Chi-squared test of the second site for before and after restoration yielded a p-value of < 0.001.

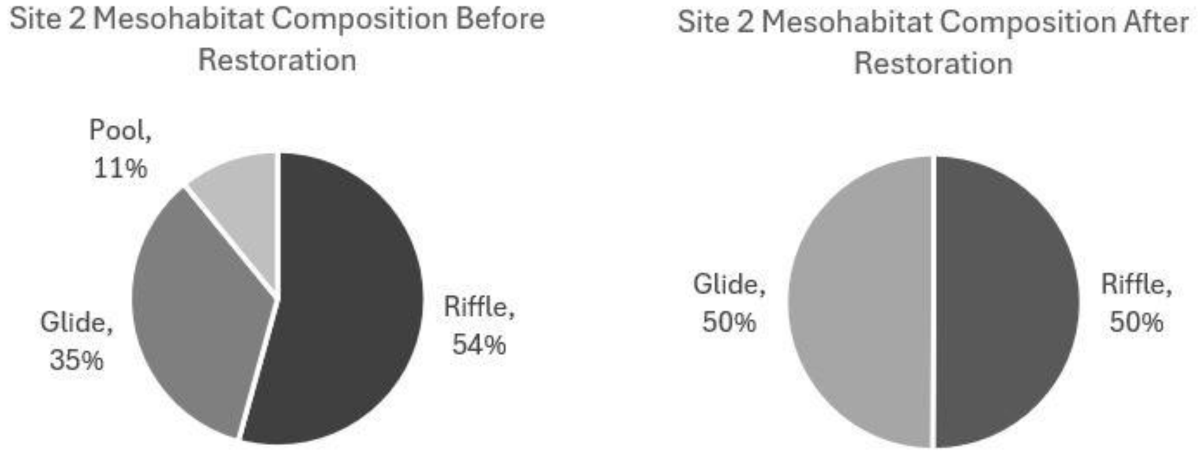

Figure 23. *Before and after charts showing changes to mesohabitat at restoration site 2 at Unnebergsbekken.*

At Site 3, riffle habitat expanded substantially, from 54% to 66%, while glides and pools declined. Glide dropped from 25% to 19%, and pool habitat decreased from 20% to 15% (Figure 24). The Chi-squared test of the third site yielded a p-value of 0.055.

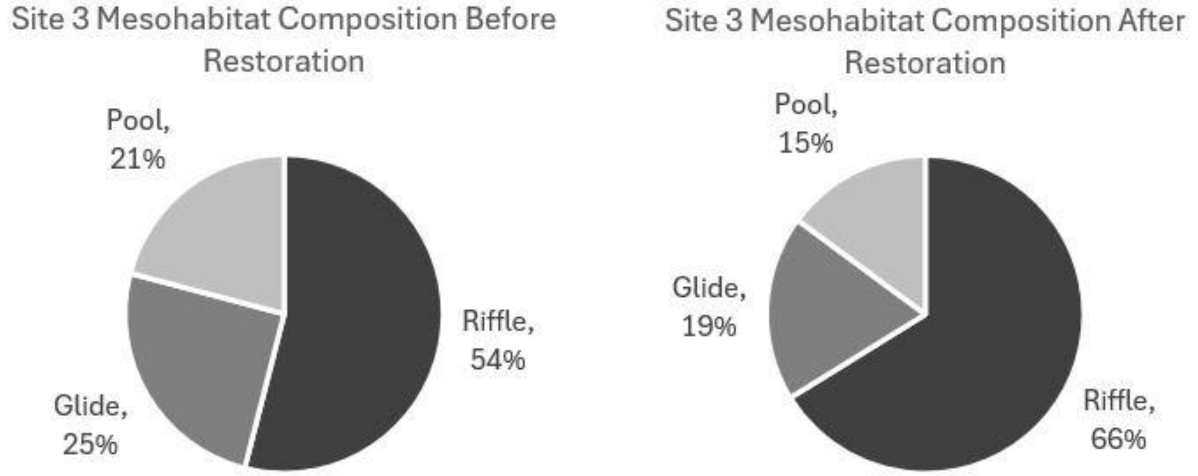

Figure 24. *Before and after charts showing changes to mesohabitat at restoration site 3 at Unnebergsbekken.*

Gravel was added at each site during restoration making it the dominant substrate throughout the entirety of each site. Figures 25 shows the substrate composition before restoration. No statistical analysis was performed.

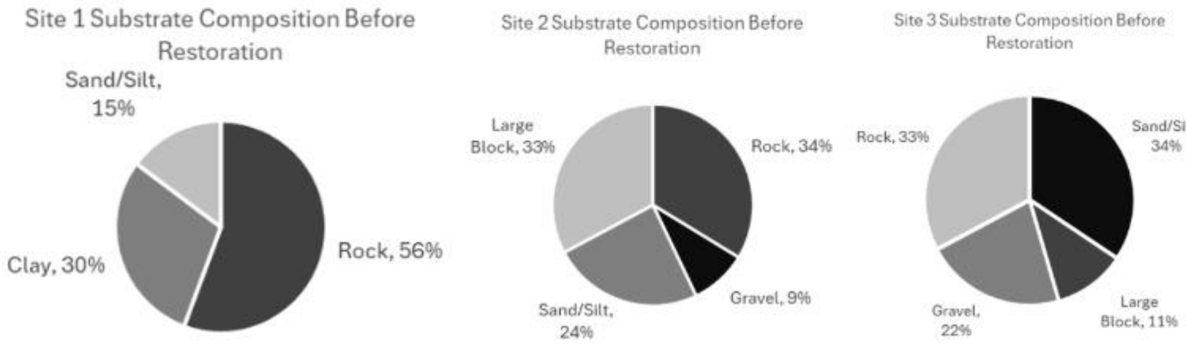

Figure 25. *Substrate composition at each restoration site before restoration was implemented*

50.06 m^3 of gravel was added to approximately 450 m^2 of Unnebergsbekken, creating a significant increase in potential spawning grounds for sea trout. Figure 26 shows the changes in spawning area compared to distance from see post-restoration. Restoration sites are marked highlighting the increase in spawning potential between 2.9 and 3.1 km. The skewness score post restoration was 1.41, still showing an upstream skew.

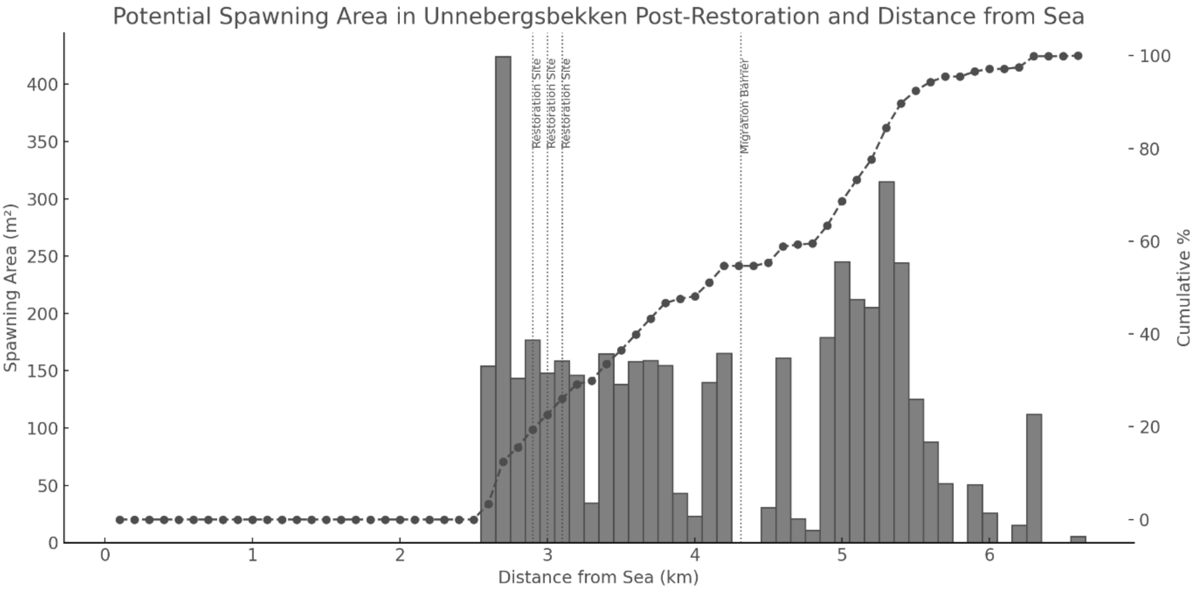

Figure 26. *Distribution of potential spawning area in Unnebergsbekken in relation to distance from the sea after restoration*.

4.3.2 Restoration Site Design and Implementation

Restoration was implemented at three sites within the main stem of Unnebergsbekken, each varying in design, treatment type, and spatial extent. Table 12 summarizes site-specific characteristics, including trenching, structural additions, and gravel metrics.

Table 12. *Details of each restoration site at Unnebergsbekken, including depth of added gravel*

Site	Distance (m)	Area (m^2)	Trench	Optimized	Avg Gravel Depth (cm)	Gravel Volume (m^3)
1	30	169	Yes	No	28.43	16.77
2	32	128	No	No	29.38	18.8
3	41	154	Yes	Yes	24.56	14.49

Sites 1 and 2 involved gravel augmentation only. While Site 1 included trench excavation to stabilize the gravel bed and promote subsurface flow, Site 2 did not. Neither site was considered optimized, as no structural elements such as boulders or woody debris were added. In contrast, Site 3 was considered to be optimized by incorporating a full range of habitat enhancement features. A trench was excavated, and the site was optimized by adding large boulders, boulder clusters, and woody debris to improve flow variability, increase shelter, and promote gravel stability.

Upon completion, gravel depth was measured at 30 points across each site. These measurements served as a baseline for future monitoring of gravel stability and habitat persistence under varying flow conditions. Gravel volume was also calculated to quantify material input per site.

A sketch of Site 3 post-restoration is shown in Figure 27, disiplaying the spatial distribution of added structural elements. The configuration at this site reflects a more complex restoration design intended to enhance spawning and rearing habitat functions. Before and after photos of Site 3 can be seen in Figure 28. Sites 2 and 3 can be found in the appendix (Figures 33 and 34).

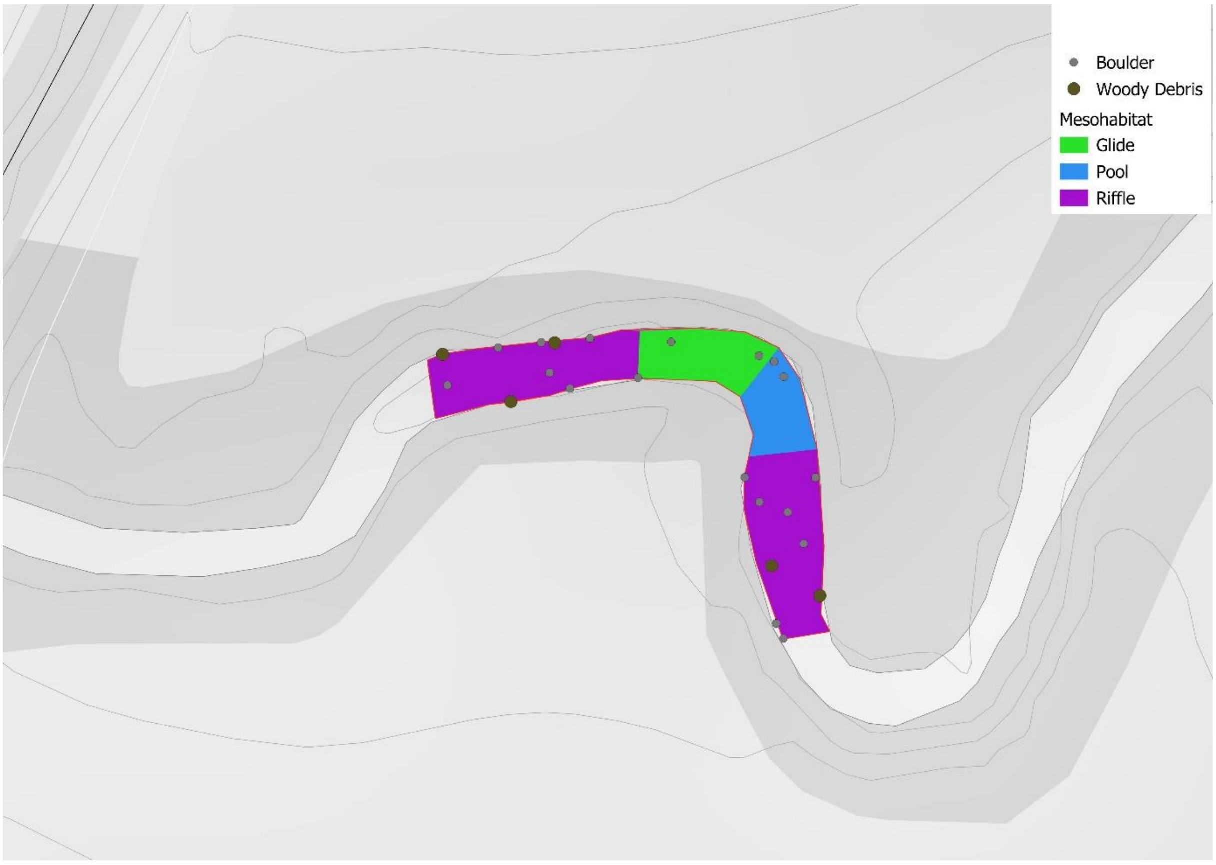

Figure 27. *Sketch of Site 3 at Unnebergsbekken post-restoration. Gray points represent large boulders and/or boulder clusters placed at the site and brown points represent large woody debris.*

Figure 28. *Before and after images of Site 3 restoration, which included full optimization measures*.

4.4 Monitoring Evaluation Plan

A monitoring and evaluation plan, including physical and biological variables, was created to guide post-restoration evaluation. Table 13 outlines key metrics, methods, frequencies, and durations for biological monitoring, and Table 14 highlights needs for physical mapping. Both plans are structured within the SAM cycle to provide feedback and adjustment (Figure 29).

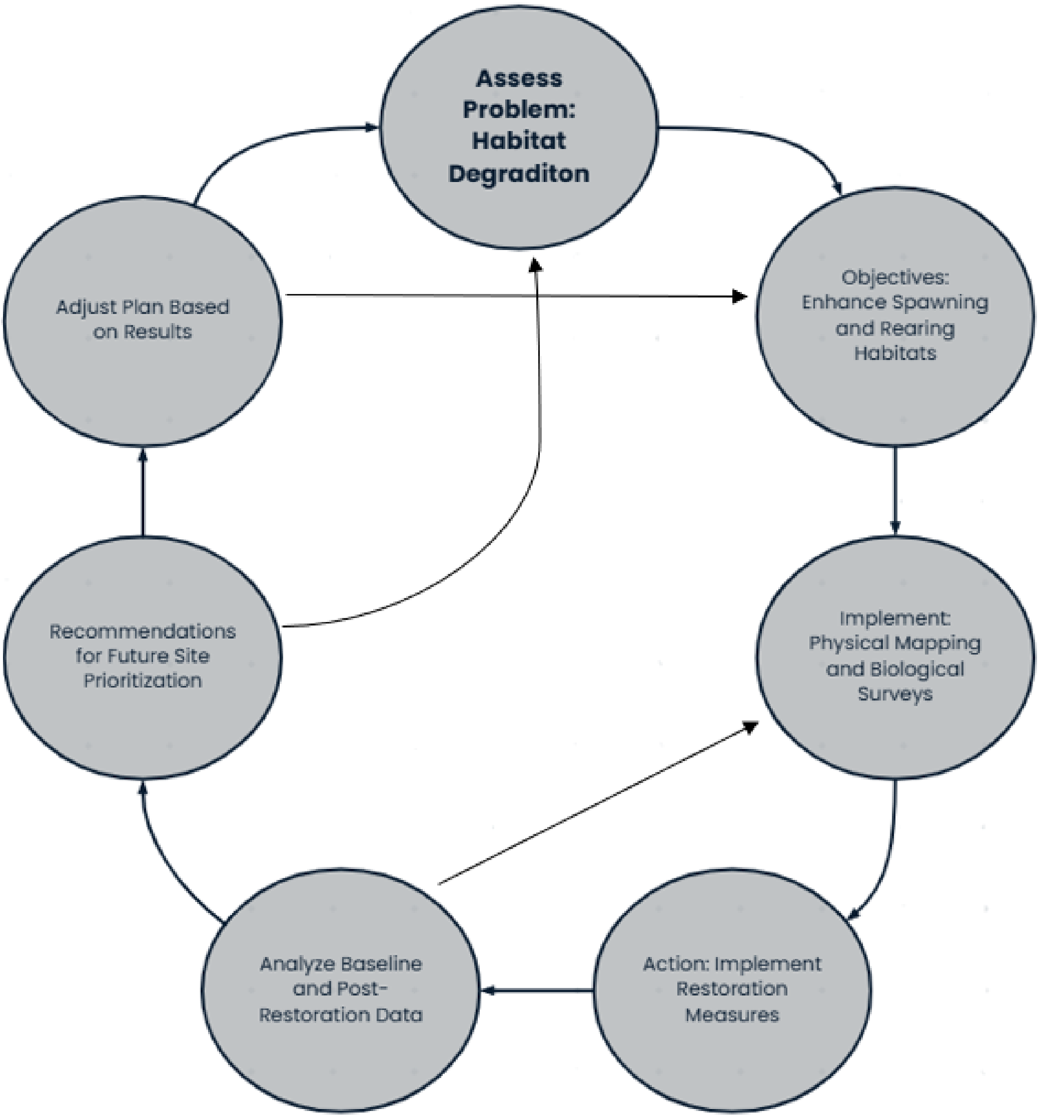

Figure 29. *Adaptive management cycle for monitoring and evaluation adapted for measures taken in Unnebergsbekken. The process shows the sequence from identifying habitat degradation through implementation, analysis, and adjustment based on results.(workcanvas.com)*

Table 13. *Monitoring and evaluation plan for biological measures in Unnebergsbekken. Including monitoring variable, methods, criteria, how often it should be performed, and objective it achieves.*

Variable	Objective	Frequency	Duration (Years)	Methods	Evaluation Criteria
Electrofishing	Rearing habitat	Annually	3–5	Norwegian Standard. Establish new stations downstream of restoration reach.	Compare with previous/trend analysis.
Redd Surveys	Production potential	Annually	3–5	Kick sampling and identification at fixed sites. To coincide with electrofishing.	Assesses biological water quality and habitat conditions; complements fish data; aligns with WFD indicators.
Spawner Surveys	Production potential	Annually	3–5	Visual surveys during peak spawning; map locations.	Tracks fish use. Provides insight into population dynamics.
Benthic macroinvertebrate sampling	Bottleneck identification	Annually	3–5	Visual surveys during peak spawning; map locations.	Tracks spawning activity in restored vs. unrestored areas.

Table 14. *Monitoring and evaluation plan for physical mapping variables in Unnebergsbekken.*

Variable	**Objective**	**Frequency**	**Duration (Years)**	**Methods**	**Evaluation Criteria**
Substrate embeddedness	Spawning habitat	Every 2 years	4	Visual assessment and classification at fixed transects.	Monitors fine sediment accumulation; supports habitat quality evaluation.
Interstitial shelter	Rearing habitat	Every 2 years	4	Finstad method using hose penetration every 100 m.	Tracks microhabitat quality; linked to juvenile refuge and survival.
Gravel stability (depth/displacement)	Spawning habitat	Annually	3-5	Measure depth and visually inspect displacement at restoration sites.	Assesses effectiveness of gravel placement and trenching.
Mesohabitat mapping (low and high flow)	Rearing/ Spawning Habitat	Every 2 years	3–5	Repeat physical mapping with QGIS/QField at low and high flows using same classification.	Tracks changes in habitat structure, floodplain connectivity, and seasonal accessibility.
Substrate mapping/Spawning Habitat	Spawning habitat	Every 2 years	4	Repeat physical mapping with QGIS/QField.	Tracks changes in spawning habitat quality; informs gravel distribution.
Riparian zone condition	Rearing Habitat	Every 3 years	5	Aerial photos and drone imagery.	Monitors vegetation recovery and buffer width over time.

5 Discussion

This study found spatial variation in physical habitat conditions and juvenile sea trout densities in Unnebergsbekken, establishing a comprehensive ecological baseline to guide restoration and monitoring. Physical habitat mapping showed that mesohabitat composition across the surveyed area comprised of 36% pools, 34% glides, and 30% riffles. This distribution appears balanced overall, but riffles were concentrated upstream, and pools dominated downstream sections, indicating reduced flow diversity in the lower reaches. Substrate mapping revealed a high proportion of fine sediment overall, with sand and silt accounting for over 50% of the streambed area. Gravel and rock were more frequent upstream. Interstitial shelter was classified as moderate at most surveyed transects, with no sites scoring in the high range. Pools and glides consistently exhibited the lowest shelter values, correlating with the dominance of sand and silt and a lack of gravel and rocks.

Riparian zones were variable in width. While some upstream reaches maintained intact riparian buffers, several downstream segments and the uppermost 200 meters of the mapped area showed minimal zones. These areas often bordered agricultural or residential areas and corresponded with greater deposits of sand and silt. Mapping of potential spawning areas showed a skew toward upstream reaches. No potential spawning gravel was identified in the lower 2.5 km of the stream. Identified spawning areas were typically small in area and located in shallow riffle sections. The upstream skew indicates a spatial bottleneck in spawning habitat availability.

Electrofishing results indicated that the population structure consists of a slightly higher proportion of 0+ juveniles at 56.5%, compared to older juveniles at 43.5%. This suggests that recruitment is not significantly limited in the system, but the relatively balanced ratio may imply moderate parr limitation, where access to suitable sheltered rearing habitats could be a limiting factor for juvenile survival beyond the fry stage. Signficant variation was recorded in juvenile sea trout densities across stations. The highest densities were observed at Station 4, a non-restored monitoring site dominated by glides (80%) and some riffle habitat (20%), with no pools. While this station showed elevated juvenile densities, no consistent differences in substrate composition were found among the stations. Other factors, such as flow conditions or microhabitats, may impact fish distribution more than substrate class alone. Overall, the results indicate that habitat conditions and juvenile sea trout densities differ significantly along the stream. Several physical limitations act as key ecological bottlenecks. These findings provide a strong reference point for assessing the effectiveness of restoration efforts and informing long-term adaptive management strategies.

5.1 Baseline Habitat Conditions and Bottlenecks

This study found significant spatial variation in habitat conditions along Unnebergsbekken, especially regarding the composition of the substrate and the availability of interstitial shelter, mesohabitat distribution, and riparian zone quality. These patterns are consistent with other Norwegian systems where sedimentation, hydromorphological simplification, and riparian degradation are known to reduce habitat quality and sea trout production (Holthe et al., 2022; Bergan & Nøst, 2022). Interstitial shelter was moderate or low in all measured transects, with no sites reaching a high classification. Pools and glides in lower sections consistently showed low shelter scores. Deeper interstitial space was more common in riffles containing coarse substrate, but these were limited spatially. Low shelter availability is a documented bottleneck for juvenile salmonids in small streams (Hindar et al., 2019; Barlaup et al., 2008), and the results from Unnebergsbekken emphasize this concern.

Potential spawning areas were insufficient. Although these areas were calculated to comprise roughly 14% of the riverbed, which is considered a moderate to high composition (Forseth et al., 2014), this value is likely overestimated due to mapping inaccuracies, and the actual proportion may be closer to half that, thus underscoring the importance of adaptive monitoring. Spawning was absent in the lower 2.5 km of the stream. The upstream skew in suitable spawning gravel suggests a spatial bottleneck that may restrict adult spawning activity, increase competition, and ultimately limit production. This is a common pattern observed in small Norwegian streams that have shown declining sea trout numbers, where the absence of spawning habitat in lower reaches is attributed to sediment buildup and limited riparian zone (Normann, 2011; Holthe et al., 2021).

Juvenile densities from electrofishing varied across stations but did not correspond clearly with substrate class or mesohabitat type. The station with the highest density was dominated by glides, which typically had low interstitial shelter and high fine sediment coverage. This suggests that other habitat factors like flow velocity, instream cover, and food availability may also influence juvenile sea trout distribution more than broader physical classifications. However, a significant limitation is the limited number of electrofishing stations, none of which were located near areas with high concentrations of suitable spawning gravel. Juvenile sea trout tend to remain close to their natal spawning sites, particularly 0+ (Jonsson & Jonsson, 2011; Forseth et al., 2014), so the absence of nearby spawning habitat likely influenced observed patterns in density. These findings do not provide strong statistical support for the first hypothesis, but they do not contradict it either. The observed variability in juvenile densities aligns with the concept that habitat complexity influences fish distribution. However, the spatial disconnect between spawning habitat and sampling locations, along with limitations in sampling, prevents a definitive conclusion. Therefore, the hypothesis remains plausible under current conditions but requires further testing through post-restoration surveys that assess fish presence in areas where spawning gravel has been increased. These results achieve the first objective of this thesis, which was to map habitat quality and identify potential bottlenecks for sea trout spawning and rearing. Field data provided a spatial overview of mesohabitat types, substrate conditions, shelter availability, and riparian cover, establishing a baseline for evaluating current limitations and informing future restoration measures. This research successfully achieves the primary objective of this thesis, which is to map habitat quality and identify potential bottlenecks for sea trout spawning and rearing.

Uncertainties in the first objective arise from methodological limitations. The mapping of spawning habitat relied on visual estimation. Although it provides accurate spatial distribution, it was not precisely mapped regarding total area, causing an overestimation. Classification of mesohabitats and shelter was also judgment-based, with the potential for inconsistency due to limited field experience. Electrofishing data were not collected in the lower 2.5 km of the stream, resulting in a data gap in the downstream reaches that may influence conclusions about production potential. Combined with the short time frame of data collection, these factors limit the accuracy of interpretations but still provide a robust baseline for adaptive management. Complete biological responses often require long-term monitoring to become detectable (Forseth et al., 2014).

Despite these uncertainties, the physical habitat assessments do provide a strong basis for identifying where future restoration efforts may be most beneficial. The evident bottlenecks in the stream are characterized by poor substrate conditions, low shelter availability, and degraded riparian zones, indicating a higher ecological constraint. Among these factors, the lack of suitable spawning gravel is the most significant ecological bottleneck impacting production potential in Unnebergsbekken. These findings are consistent with challenges documented in other Norwegian restoration projects and align with the priorities set out in national strategies. This highlights the importance of the holistic mapping approach, which provided stream-wide insight rather than limiting the analysis to the restoration reach. Identifying upstream and downstream bottlenecks is critical for informing future prioritization and ensuring that localized measures contribute to broader stream function.

5.2 Habitat Restoration Implementation

Three sites in Unnebergsbekken were restored in 2024 through gravel augmentation and structural habitat enhancement. The restoration measures targeted known bottlenecks related to spawning habitat, substrate composition, and shelter availability, which are generally recognized stream constraints (Holthe et al., 2021; Barlaup et al., 2008). Approximately 50.06 m³ of gravel was added across approximately 450 m² of streambed, with Site 3 also receiving boulders and woody debris to increase structural complexity. This represents a small-scale intervention within a limited section of the stream. Post-restoration mapping showed an increase in the extent of spawning habitat, particularly between 2.9 and 3.1 km from the sea, where the new gravel was installed. Although the upstream skewness in spawning distribution remained (post-restoration skewness = 1.41), this indicates an initial improvement in habitat availability within a reach that previously had limited spawning potential.

These outcomes support the second hypothesis that restoration can increase the area of suitable spawning substrate, at least in the short term. However, habitat additions were not evenly distributed across all sites. Site 3 was the only location with full optimized measures, such as boulders and woody debris, while Sites 1 and 2 only received gravel. This variation in design reflects site-specific planning constraints but may impact long-term outcomes. Different restoration strategies across sites were also intended to reflect realistic implementation scenarios and allow for the evaluation of how different levels of habitat complexity influence restoration effectiveness. Although no biological monitoring was conducted post-restoration within the scope of this thesis, the pre-restoration surveys and habitat improvements provide a foundation for evaluating future production potential. These results fulfill the second objective of this thesis, which was to implement targeted restoration measures to enhance sea trout habitat quality and production potential. Restoration outcomes demonstrate that immediate gains in spawning habitat were achieved.

The hypothesis of the second objective proposed that restoration would increase the area of potential spawning habitat and improve production potential in restored areas. Based on the increase in gravel area and the addition of structural habitats at Site 3, this hypothesis is supported regarding habitat gains. However, production outcomes remain uncertain due to the absence of post-restoration biological data. Future assessments using the BACI methodology will be necessary to determine if these physical improvements lead to increased juvenile densities or successful spawning activity. Previous studies have shown that spawning activity and early life-stage density are closely tied to the spatial availability of spawning substrate (Normann, 2011) and that structural additions such as wood and boulders can significantly enhance the biological use of restored areas (Barlaup et al., 2008). The results presented here reflect only short-term habitat gains. Long-term studies of gravel augmentation have shown that such improvements may have positive sustaining effects. However, they may require ongoing intervention (Pulg et al., 2021), highlighting the need for strategic adaptive management.

Uncertainties related to this objective occur from differences in site design and the inability to evaluate longer-term outcomes due to the temporal scale of this thesis. The physical changes documented only describe the initial phase of the restoration process. These uncertainties highlight the need for follow-up and emphasize the importance of establishing consistent monitoring practices to support future evaluations. While the scale of intervention was limited, the restoration actions taken align with national strategies and proposed best practices in comparable systems (Holthe et al., 2022).

5.3 Developing a Monitoring Plan

Monitoring is essential in stream restoration because it provides the only way to determine if interventions lead to ecological improvement. Without a structured follow-up, restoration becomes uncertain, lacking a basis for evaluating outcomes or adjusting future efforts. A well-structured monitoring framework enables habitat change detection, tracks biological responses, and identifies unintended effects. Monitoring is important in small, spatially variable streams like Unnebergsbekken to separate restoration effects from natural variation and support informed, site-specific management.

The proposed monitoring plan created for Unnebergsbekken aims to evaluate the ecological outcomes of the restoration measures performed in this thesis. This section addresses the third subobjective of the study, which was to develop a monitoring framework capable of assessing habitat conditions and production potential following restoration. The plan aligns with SAM principles and national restoration strategies and supports adaptive, evidence-based decision-making. Although not implemented within the temporal scope of this thesis, the plan reflects a practical framework for evaluating ecological response in small streams. The plan structure follows established BACI logic, which enables comparisons between restored and unrestored reaches to isolate the effects of restoration from other environmental variables (Kingsford & Biggs, 2012; Smith, 2002).

The combination of biological indicators (electrofishing, redd surveys, and invertebrate sampling) with physical habitat variables (substrate, mesohabitat, interstitial shelter, and riparian condition) aligns with recommended monitoring practices in Norwegian stream restoration literature (Forseth et al., 2014; Holthe et al., 2021). These variables are selected for their relevance to sea trout production and their ability to reflect direct and indirect outcomes of habitat restoration. Biological monitoring methods such as electrofishing and redd and spawner surveys are crucial for evaluating if the achieved physical changes result in fish presence or density improvements. Invertebrate sampling provides insights into water quality and overall ecological health (Barbour et al., 1999). The plan also accounts for key spatial considerations by expanding monitoring coverage beyond the restoration sites, including downstream and upstream segments, consistent with BACI practices.

Monitoring actions and evaluation metrics are summarized in tables at the end of the results chapter. Each parameter is linked to specific objectives, timeframes, and frequencies. Including mesohabitat mapping during both high and low flow provides seasonal context that was missing during baseline mapping. Interstitial shelter measurements will be expanded beyond the limited 2024 transects to improve spatial resolution and strengthen correlations with fish density. These refinements represent feedback-based learning consistent with SAM.

The hypothesis for Objective 3 stated that a monitoring plan based on BACI principles would effectively assess restoration outcomes and guide future restoration plans. Given the structure and scope of the plan, this hypothesis is supported. The monitoring design incorporates spatial and temporal replication, uses indicators appropriate to fish production and stream condition, and reflects suggested practices for restoration assessment. In addition to meeting the third objective, the proposed plan provides a framework for tracking long-term changes in the habitat and biological production potential identified in Objective 1. By maintaining consistency in survey methods and increasing spatial coverage, future monitoring will allow evaluation of whether the bottlenecks mapped in this thesis are reduced through ongoing restoration efforts.

Uncertainties associated with the monitoring framework arise from practical and methodological challenges. Several metrics, including mesohabitat classification, shelter estimation, and spawning area mapping, depend on field-based judgment and may be subject to observer variability. Biological indicators such as fish density and redd counts can change due to factors unrelated to restoration, including barrier removal, flooding, or seasonal effects. These limitations are typical of ecological monitoring in small streams and are difficult to avoid. While the monitoring design accounts for this through spatial controls and multi-year timelines, attributing observed changes to specific interventions will require long-term data collection and analysis.

These uncertainties highlight the importance of maintaining adaptive flexibility in monitoring approaches while ensuring methodological consistency over time.

6 Conclusion and Recommendations

6.1 Conclusion

This thesis investigated the spatial and ecological conditions of Unnebergsbekken, a small anadromous stream in southeastern Norway, to establish a habitat baseline, implement targeted restoration measures, and develop a framework for long-term monitoring. The project focused on improving spawning and rearing habitat for sea trout using SAM principles supported by a BACI design. Building on previous action plans and expanding spatial mapping, the project identified critical ecological bottlenecks and conducted small-scale, site-specific restoration.

Habitat mapping and biological surveys confirmed that Unnebergsbekken exhibits considerable spatial variability in physical conditions and fish distribution. Key limitations include sparse distributions of suitable spawning substrate, low interstitial shelter availability, and narrow or degraded riparian zones across multiple segments. These constraints reduce the system’s ability to support juvenile sea trout production and undermine the ecological function of the stream. Restoration measures addressed these issues by adding gravel and structural elements such as boulders and woody debris at selected sites. Although biological outcomes are not yet measurable, the restoration reach was mapped and benchmarked for future comparison. A monitoring plan was developed to track ecological response and is designed to evolve with feedback over time.

In summary, the project found that:

- Sea trout habitat in Unnebergsbekken is limited by physical and spatial constraints, particularly substrate quality due to sedimentation, shelter availability, and riparian condition.

- Field mapping and electrofishing provided sufficient resolution to identify habitat bottlenecks, enabling site-specific restoration and future evaluation.

- Site-specific restoration measures were feasible and ecologically appropriate, even in a small stream with limited treatment area

- A structured and adaptive monitoring plan was developed, linking biological and physical indicators to the project's objectives and supporting long-term learning and management.

The combined approach of holistic habitat assessment, targeted intervention, and structured monitoring provides a practical model for restoring small streams. While limited in spatial scope, efforts like this contribute meaningfully to national restoration goals under the Water Framework Directive and Naturavtalen. Small streams provide critical ecological functions and support disproportionately high biodiversity, making them a key priority for restoration planning at both regional and national scales. This thesis offers a replicable and adjustable framework for small stream restoration that balances ecological relevance with practical constraints. Although process-based restoration at this scale may not significantly affect system-wide conditions, it encourages stakeholder participation and builds trust among landowners and local partners. This early engagement is critical, as it builds trust and creates the conditions necessary for larger, more impactful restoration efforts to take place over time.

6.2 Recommendations

Based on the findings and the monitoring framework developed in this project, several recommendations can be made to guide future restoration and management measures for Unnebergsbekken and similar small anadromous streams. Table 15 summarizes these recommendations to provide a clear overview of proposed actions, their purpose, and how they should be implemented.

Table 15. *Summary of Recommendations for Future Restoration and Monitoring in Unnebergsbekken*

Recommendation	Objective	Method	Comment
Monitoring Expansion	Improve accuracy of fish production estimates and population dynamics	Establish additional electrofishing stations in the lower 2.8 km of the stream	Enhances spatial resolution of biological data, especially in previously unmonitored downstream sections
Continued habitat monitoring	Track changes in spawning habitat quality and juvenile shelter availability	Regular assessments of spawning gravel, embeddedness, and interstitial shelter	Increase evaluation frequency following significant flood events or land-use changes to detect habitat alterations

Ecological Assessment	Broaden understanding of stream health and restoration effectiveness	Incorporate macroinvertebrate sampling and riparian zone assessments into monitoring	Provides insights into water quality, pollution sensitivity, and overall ecological status, complementing fish-based assessments
Restoration Prioritization	Enhance habitat quality in degraded transitional zones	Implement restoration upstream of urban development to fish pass	Currently exhibits limited spawning habitat. Good candidate based on migration barrier reconstruction and is connectivity zone.
Stakeholder Engagement	Ensure long-term access and support for restoration and monitoring efforts	Promote ongoing collaboration with landowners	Critical for implementing physical restoration measures, preserving buffer zones, and facilitating continuous monitoring activities

The monitoring program should continue and be updated as needed. Electrofishing stations should be added in the lower 2.5 km of the stream to improve the accuracy of production estimates and provide a more complete picture of population dynamics. Spawning gravel, embeddedness, and interstitial shelter should be monitored regularly, with the option to increase evaluation frequency after major flood events or significant land-use changes. Invertebrate sampling and riparian zone assessments should also be incorporated to broaden the evaluation of stream health and evaluate long-term restoration effects.

Mapping results, biological data, and spatial analysis suggest that the next priority for restoration should be the section extending from the former migration barrier downstream to the urban area, approximately 500 meters in length (Figure 30) and approximately 3.8 km from the sea. This reach remains degraded, with fine sediment accumulation, simplified mesohabitat, and poor riparian buffers along the west bank. With longitudinal connectivity now restored due to the fish pass construction at the former barrier, this zone functions as a transitional corridor, and habitat enhancement here would support both upstream and downstream productivity. Restoration methods should include gravel augmentation, structural shelter placement, and buffer rehabilitation if possible. Another factor is that this land coincides with the fish pass location, where landowners have already granted access. This existing cooperation makes the adjacent reach a practical choice for future restoration, both logistically and ecologically.

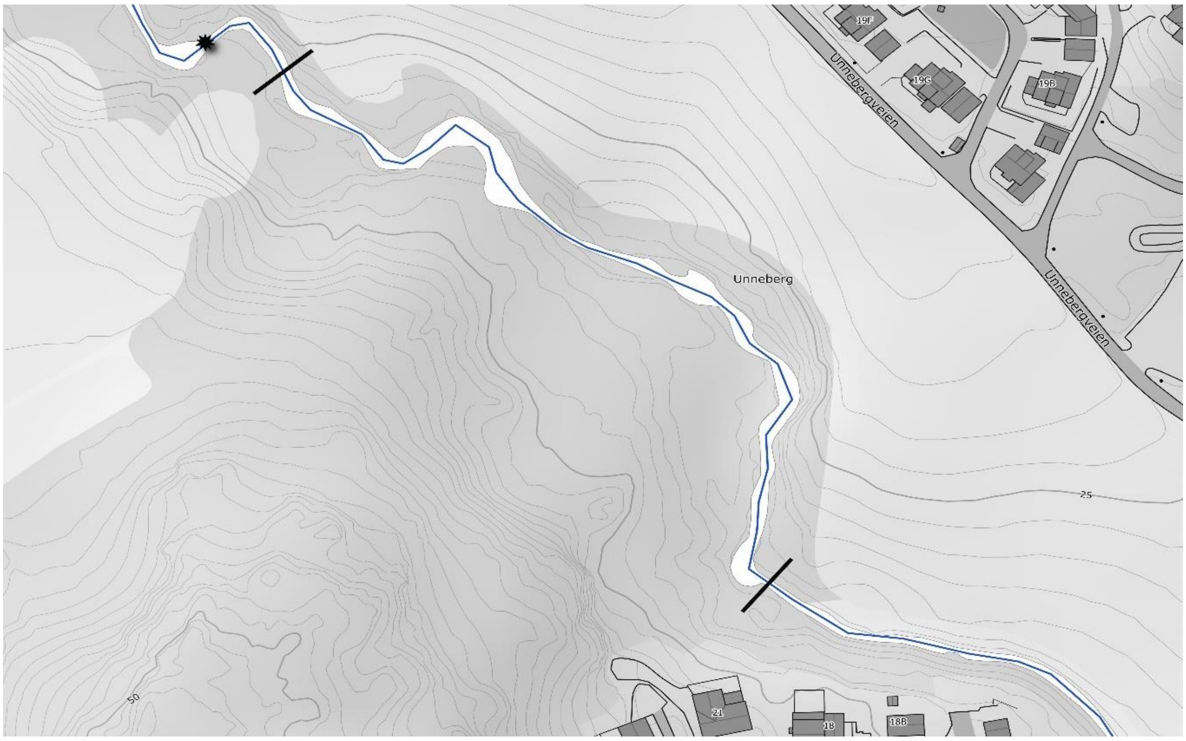

Figure 30. *Map showing boundaries of suggested future restoration reach in relation to migration barrier and urban development*.

Another candidate for future restoration is the reach located downstream of the 2024 restoration site between 2.1 and 2.5 km from the sea. This area is not currently used for spawning but appears limited primarily by poor substrate and simplified structure. However, it lies below a degraded riparian segment that contributes fine sediment. It is also directly below the tributary, likely increasing the sediment load. Restoration here should be considered only after upstream buffer zones are improved to reduce sediment input and improve habitat conditions.

The 2024 restoration reach (2.8–3.2 km) was an appropriate choice based on the conditions at the time. With the upstream migration barrier still intact at the time, this reach represented the upper limit of accessible habitat for spawning sea trout. Field data confirmed limited spawning substrate and low interstitial shelter availability, supporting the decision to prioritize this site for gravel and habitat enhancement. Given the information available then, the reach selection was justified and well-aligned with ecological and management objectives.

Long-term success depends on continued cooperation with landowners. Much of Unnebergsbekken flows through privately owned land, and access for both restoration and monitoring are only possible through sustained engagement. Future efforts must actively involve landowners in planning, buffer zone management, and habitat rehabilitation to ensure continuity and scale of intervention.

This project demonstrates the value of site-specific and adaptive stream management. The recommendations developed here can support restoration efforts under the Naturavtalen by providing a clear, data-driven framework tailored to small anadromous streams.

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Appendix

Table 16. *Locations and mesohabitat types of interstitial shelter measurements at Unnebergbsbekken. Coordinates are in WGS 84 decimal degrees.*

Section	Location ID	Mesohabitat Type	Latitude (°N)	Longitude (°E)
1	1.1	Riffle	59.146294	10.272793
	1.2	Pool	59.148404	10.268024
	1.3	Glide	59.266185	10.266185
	1.4	Glide	59.149173	10.264823
	1.5	Pool	59.149117	10.264466
	1.6	Riffle	59.149545	10.263761
2	2.1	Pool	59.150037	10.262062
	2.2	Riffle	59.150113	10.261873
	2.3	Pool	59.150169	10.260769
	2.4	Glide	59.150687	10.256428
	2.5	Glide	59.150687	10.256428
	2.6	Riffle	59.152781	10.247999
3	3.1	Riffle	59.158623	10.236519
	3.2	Pool	59.158842	10.236522
	3.3	Glide	59.159434	10. 235044
	3.4	Pool	59.161837	10.233786
	3.5	Glide	59.162053	10.233618
	3.6	Riffle	59.162337	10.233381

Table 17. *Results of interstitial habitat at each transect with weighted score representing shelter class.*

Transect	Section	Distance to Sea (m)	Mesohabitat	S1	S2	S3	Toss Count	Weighted Score	Shelter Class
1	1	1235	Riffle	6	3	1	2	7.5	Moderate
2	1	1804	Pool	0	0	0	1	0	Low
3	1	1945	Glide	0	0	0	1	0	Low
4	1	2107	Glide	2	0	0	2	1	Low
5	1	2165	Pool	4	1	0	2	3	Low
6	1	2267	Riffle	6	3	0	2	6	Moderate
7	2	2576	Pool	6	2	0	2	5	Moderate
8	2	2594	Riffle	4	1	0	1	6	Moderate
9	2	2686	Pool	4	1	0	1	6	Moderate
10	2	3009	Glide	3	0	0	1	3	Low
11	2	3388	Pool	2	3	0	1	8	Moderate
12	2	3817	Riffle	8	2	0	2	6	Moderate

13	3	5094	Riffle	5	4	1	2	8	Moderate
14	3	5122	Pool	0	0	0	0	0	Low
15	3	5292	Glide	1	1	0	1	3	Low
16	3	5611	Pool	0	5	0	2	5	Moderate
17	3	5656	Glide	3	1	0	1	5	Moderate
18	3	5702	Riffle	1	3	1	1	10	Moderate

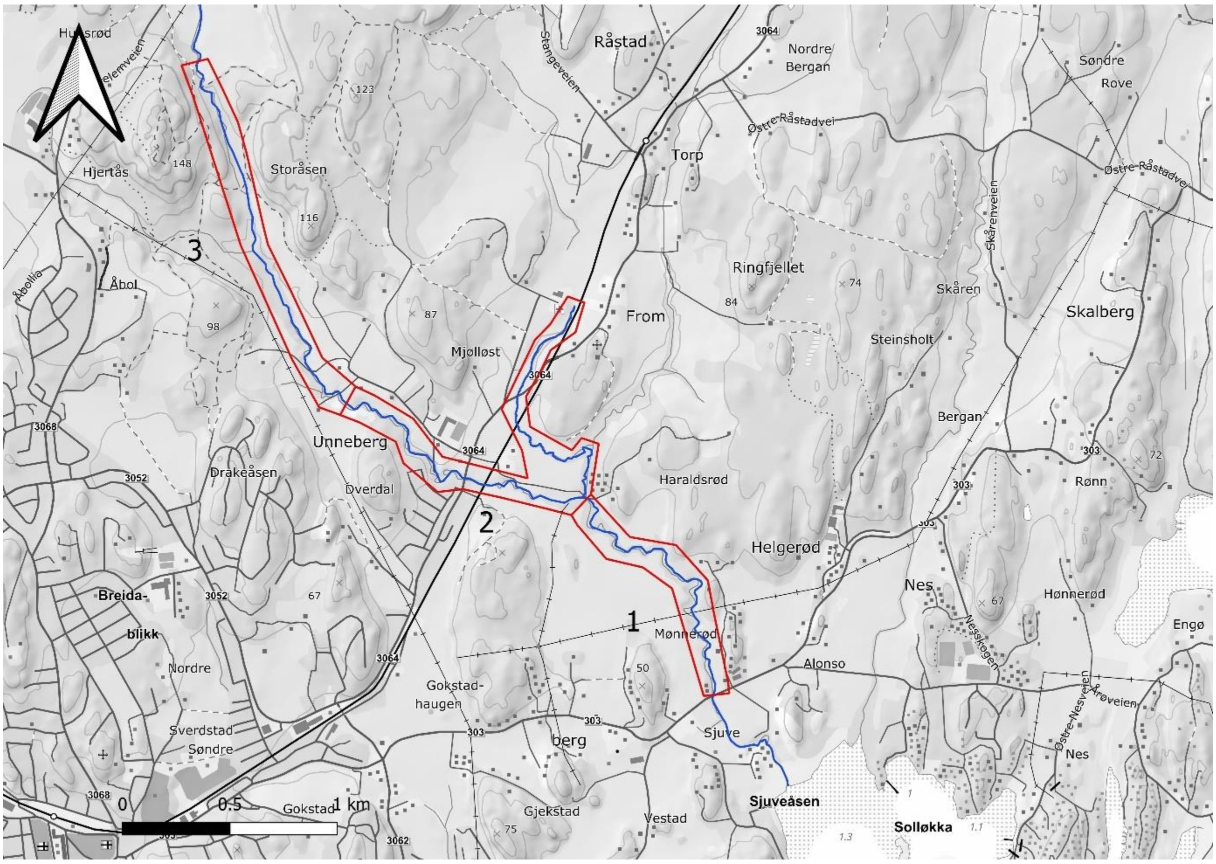

Figure 31

. Map of sections determined at Unnebergsbekken. Sections are labelled 1, 2, and 3

Figure 32. *Locations of each electrofishing station in Unnebergsbekken.Stations 1, 2, and 3 are located in the restoration reach to serve as baseline data for biological monitoring.*

Table 18. *Conditions during electrofishing in Unnebergsbekken.*

Station	Date	Water Temp	Conductivity (µS/cm)	Weather	Visibility
1	24.10.24	8.5	47.3	Overcast	Moderate
2	07.09.24	15	47	Sunny	High
3	07.09.24	15.6	47.3	Sunny	High
4	08.09.24	15.8	47.6	Overcast	High
5	28.09.24	13.2	44.7	Sunny	High

Figure 33. *Before and after photos of Site 2 restoration Gravel was only placed on top with no trenching.*

Figure 34. *Before and after photos of Site 1 restoration. Streambed was trenched for gravel placement, but site was not optimized*.