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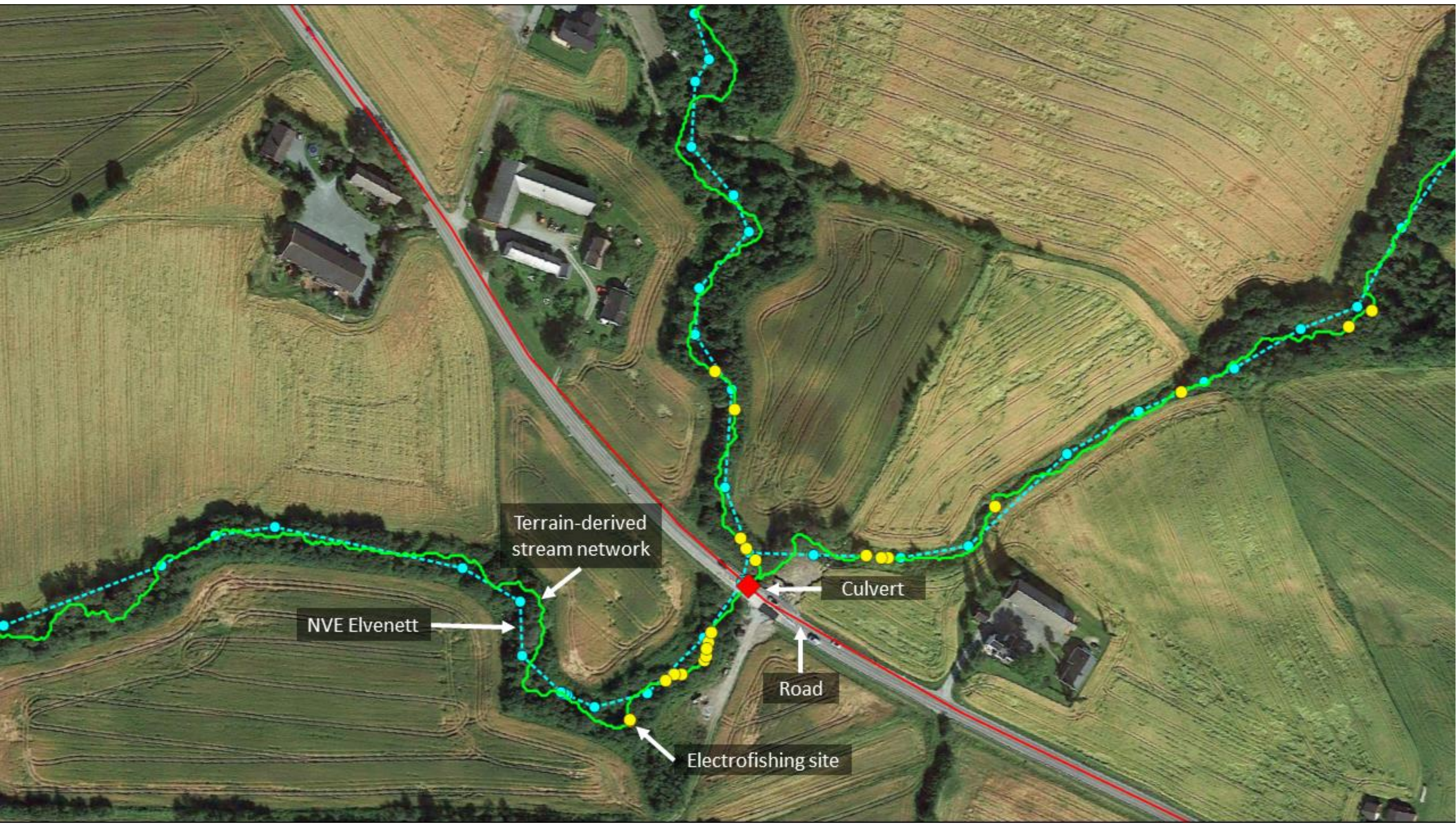
Mapping natural and artificial migration hindrances for fish using LiDAR remote sensing

Richard D. Hedger, Stefan Blumentrath, Morten A. Bergan and
Antti P. Eloranta



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Richard D. Hedger, Stefan Blumentrath, Morten A. Bergan and
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Terrain-derived network © Richard Hedger

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Abstract

Hedger, R.D., Blumentrath, S., Bergan, M.A. & Eloranta, A.P. 2020. Mapping natural and artificial migration hindrances for fish using LiDAR remote sensing. NINA Report 1833. Norwegian Institute for Nature Research.

We developed a new method to map and evaluate the impact of potential natural and artificial migration hindrances on the spatial distribution of sea trout (*Salmo trutta*) within stream networks. A stream network was derived from a 1 m^2 spatial resolution LiDAR-based Digital Terrain Model (DTM), using part of Trondheim Region as a test case. Algorithms were developed to identify potential artificial migration hindrances (stream crossings and culverts) from the DTM, and to correct the DTM to enable generation of a terrain-derived stream network that followed the topography better than manually-digitized stream networks. Stream slope was computed at multiple-spatial scales throughout the terrain-derived network because steep slopes can be a potential natural migration hindrance. Potential migration hindrances were then quantified across the network from (1) the positions of crossings and culverts (using information generated from the DTM alongside GIS databases) and (2) stream slope metrics. The impact of potential migration hindrances on the spatial distribution of sea trout was determined by analysing the relationship between these stream network properties and the prevalence of sea trout across Trondheim Region, as determined by electro-fishing surveys conducted by Trondheim Kommune, NINA and NIVA. Models showed that prevalence was negatively related to the number of crossings and culverts downstream of the electrofishing site. However, no effect of slope was identified, and the predictive power of models was low. The terrain derivation-based approach developed here offered high local accuracy, but was computationally intensive, and suffered from potential confounding effects, and investigation of the effect of stream network properties on sea trout prevalence was limited by the quantity and quality of available data. This study has shown that a GIS-based approach, reliant on semi-automated processing of high-resolution DTM data, and integrated with GIS data, can be used to construct a stream network showing potential migration hindrances for fish populations. Further, there is potential for applying this approach over a wider geographical area and in different freshwater applications.

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Vi har utviklet en ny metode for å kartlegge og evaluere effekten av potensielle naturlige og menneskeskapte vandringshindre (barrierer) for ferskvannsvandring til sjøørret (*Salmo trutta* L.). Områder av Trondheimsregionen med eksisterende kartlegging av sjøørretutbredelse ble brukt som testområde. Det har blitt utviklet algoritmer for å identifisere potensielle vandringshindre (infrastrukturkryssinger, kulverter og lignende menneskeskapte inngrep, samt generell elvetoppografi) fra digital terrengmodell (DTM). Resultatene i dette prosjektet baserer seg på digitale terrengmodeller med 1 m^2 romlig oppløsning fra LIDAR data. Det er anvendt eksisterende algoritmer for å generere og korrigere elvenett fra digitale terrengmodeller. Slike terrengavledet elvenett avspeiler topografien bedre enn eksisterende manuelt digitalisert elvenett (NVE elvenett), og er en forutsetning for å avlede elvetoppografi, og dermed vandringshindre, fra digitale terrengmodeller. Fra det terrengavledede elvenettet ble helningsgradient kartlagt for hele elevnettverket på ulike romlige skalaer. Posisjon til kulverter og lignende inngrep ble kartlagt ved å sette sammen informasjon fra terrengavledet elvenett med informasjon fra GIS databaser for infrastruktur. Potensielle vandringshindre ble deretter kvantifisert for hele elvenettet ut fra (1) posisjonene til kryssinger, kulverter og lignende inngrep og (2) ulike indekser for helningsgradient. Effekten av potensielle vandringshindre på utbredelse av sjøørret ble analysert ved statistiske modeller hvor forekomst av sjøørret fra årlige ungfisktellinger ble brukt som responsvariabel (kvantitative tetthetsberegning fra el-fiske utført av Trondheim Kommune, NINA og NIVA). Potensielle vandringshindre nedstrøms fra el-fiskestasjon ble brukt som prediksjonsvariable for forekomst. Forekomsten av sjøørret var negativt relatert til antall kryssinger og kulverter nedstrøms for stasjonsområder for elfiske. Ingen effekt av helningsgradient ble imidlertid identifisert. Modellenes prediksjonsevne var generelt lav. Studiet viser at en GIS-basert tilnærming, med støtte i semi-automatisert prosessering av høyoppløselige digitale terrengmodeller integrert med GIS-data, kan brukes til å konstruere et elvenett (vassdragsnettverk) som avdekker potensielle vandringshindre. Tilnærmingen har potensiale for anvendelse er et mer omfattende geografisk område, og som et grunnlag for prediksjonsmodellering av mulig utbredelsesområde og vandringshindre. Det er imidlertid også identifisert klare begrensninger med den nåværende metodikken. Disse er i vesentlig grad knyttet til datagrunnlag for kalibrering av modeller (bakkeverifisering). Manglende datagrunnlag for dette gir lav utsagnskraft med påfølgende store usikkerheter i prediksjoner. De viktigste her er: (1) Kartlegging av eksisterende forekomst av sjøørret er basert på eksisterende overvåkning som er målrettet mot forventet utbredelse. Dette gjør at det blir få observasjoner i områder hvor utbredelse er begrenset av vandringshindre. (2) Det mangler detaljert informasjon om i hvor stor grad identifiserte menneskeskapte vandringshindre som ikke er observerbare med fjernmålingsdata (e.g. kulverter) utgjør barrierer. Metodikken er generelt også beregningsintensiv og krever manuell korreksjon. Det vurderes at videreutvikling av metodikken vil kreve (1) bedre kunnskap på utbredelse i form av data som gjør det mulig å estimere forekomsten, (2) inventeringer og bakkeverifisering av vandringshindre. Tilnærminger beskrevet i denne rapporten utgjør imidlertid et godt grunnlag for å prioritere og målrette feltinnsats med hensyn på kartlegging av både fisk og abiotiske forhold.

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Foreword

This report presents a pilot-study for GIS-based identification of potential migration hindrances affecting the occurrence of sea trout in streams. Sea trout is particularly affected by such hindrances because it requires access to spawning grounds in small streams, and the presence of hindrances, such as culverts under road/rail crossings, may limit the required connectivity. Such loss in connectivity has contributed to the fact that many sea trout populations in Norway now have a vulnerable or endangered status. In respect to regional action plans on management of water resources and compliance with the Water Framework Directive, it is expected that local authorities will intensify work on maintaining and restoring ecological continuity within watercourses. Such work is reliant on identification of locations where migration hindrances exist. However, these are currently not well mapped, and field investigation is expensive, so there is a need to explore alternative approaches for this.

The increased availability of high resolution remotely sensed data, alongside recent advances in methodologies for processing these data, has the potential for application in this area. In particular, the 1 m^2 spatial resolution LiDAR data now available for most of Norway offers an unprecedented opportunity, both for identification of potential culvert locations and generation of a stream network that follows the topography more accurately than current manually-digitized datasets. In this study, we further develop methodologies first used in the INVAFISH project to utilize these high resolution data. We develop a method for both the identification of potential culverts and for the derivation of a terrain-based stream network. We then show how the derived information, alongside electrofishing survey data, can be used for modelling sea trout prevalence across an area of Trondheim region. We find that prevalence is negatively related to the presence of downstream crossing/culverts (although established relationships were weak, which may be due to limitations in the methods and available datasets used). The approach developed here has potential for a range of other applications including identifying features for prioritizing field surveys, finding unsurveyed ephemeral or small streams, updating existing stream networks to better follow the topography, and connecting cross-border networks.

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Trondheim, May 2020, Richard Hedger

1 Introduction

1.1 Background

Small streams play an important role in freshwater ecosystems by providing spawning and rearing habitat for juvenile resident and/or diadromous fish (Whelan 2014) and maintaining the ecological function of downstream waterbodies (Wohl 2017). Despite their ecological importance, such streams are often overlooked with regard to the management of potential impacts of human activity. Crossings over streams and associated culverts, in particular, may have a negative impact on fish by acting as migration hindrances. Studies in Central Norway (Bergan 2015b, Bergan & Nøst 2017, Eloranta et al. 2019), Sweden (Schönfeldt 2017), and Finland (Eloranta & Eloranta 2016) have shown that fish passage may be hindered in as many as 30–50% of cases where a culvert is present. The result of migration hindrances may be that fish lose access to spawning and rearing habitats. Additionally, dams, culverts and natural migration barriers can change hydrological conditions and act as size-selective bottlenecks preventing fish of certain size classes from passing the structure and migrating upstream. Finally, old dams and an inappropriate culvert type and/or an incorrect installation may also lead to increased flood risk and erosion damage to riverbanks (Eloranta 2017, Eloranta et al. 2019), which may damage fish habitat and reduce water quality.

Diadromous fish populations in some regions in Norway have been shown to experience problems associated with crossing artificial obstacles (see Bækken & Bergan 2012a, Bækken & Bergan 2012b, Bækken & Bergan 2012c, Haugland & Vågnes Hjelle 2015). Dams and culverts that are constructed without strong regard to fish migration (see for example ***Figure 1***) may be one of the reasons why so many populations of sea trout (anadromous brown trout; *Salmo trutta* L.) in Norway have vulnerable or endangered status (Direktoratet for naturforvaltning 2009), and why there has been sea trout extirpation in some stream reaches within Sør-Trøndelag (Bergan 2013, Bergan & Nøst 2017). In accordance with the "Regional Action Plan for Water Management in the Trøndelag Water Region 2016-2021" (Sør-Trøndelag fylkeskommune 2015), it is now expected that the Norwegian Water Resources and Energy Directorate (Norges vassdrags og energi direktorat, NVE), the Norwegian Public Roads Administration (Statens vegvesen) and the Norwegian National Rail Administration (Jernbaneverket) will intensify their work on upgrading streams, improving spawning grounds, and facilitating migration routes to restore ecological continuity in the current planning period (see for example Haugland & Vågnes Hjelle 2015). However, there is a knowledge gap as to the scale of the problem, both in Norway and in other countries.

In order to conserve or restore sea trout populations within streams, it is necessary to find a cost-effective method for identifying locations where it is most critical to implement mitigation or restoration measures. Although it is known that many dams and culverts cause migration problems, their locations and the extent to which they are obstructive to migration have not been thoroughly mapped and documented. Since it is laborious to map streams manually, we propose a method for identifying migration obstacles, both natural and artificial, in streams using Geographic Information System (GIS) analysis of remote sensing data. The approach has worked well in other countries for mapping artificial migratory hindrances (Januchowski-Hartley et al. 2014), but has not been fully tested in Norway. Such a GIS tool must be tested and adapted to local data in Norway before it can be widely applied. Data from laser scanning (LiDAR) – particularly the high resolution airborne-based survey data that have recently become available in Norway – allow development of this approach within Norway.

Figure 1. *Examples of culverts: an old culvert under Fv 707 Leinstrandvegen over the Lauglobekken stream (left panel), and a culvert under a private road over the Eggbekken stream (right panel). All hotpots for spawning in both streams are located upstream of these culverts. In the case of Eggbekken, all seatrout spawning may collapse in some years due to this migration hindrance.*

1.2 Objectives

The objective of this study was to establish a prototype methodology to map and verify natural and artificial migration hindrances to fish in a cost-effective manner. We used sea trout as the fish species of interest because it is reliant on access to spawning grounds in small streams so is particularly susceptible to migration hindrances in streams. A limited geographical area – part of Trondheim Region, consisting of Trondheim, Melhus, Midre Gauldal and Skaun municipalities – was used as a case-study to verify the method. This region was chosen because this area is now well covered by high-resolution LiDAR data, and relatively detailed mapping of sea trout populations and some culverts exists (Bergan & Nøst 2017). In addition, a working dialogue has been established between the project participants and the local environment administration authorities.

First, we derived a stream network (building on the approach of Jasiewicz & Metz 2011) from a high-resolution (1 m^2 spatial resolution) LiDAR-derived Digital Terrain model (DTM) that contained potential natural and artificial migration hindrances. Secondly, we used site-based information on sea trout to model the relationship between stream network properties and sea trout prevalence as a basis for evaluating the extent to which the estimated migration hindrances constituted real migratory hindrances to sea trout.

The combination of the two steps described above allowed the creation of a map tool showing the likelihood that network properties (including potential migration hindrances) affected sea trout prevalence. Such a map is an important tool that can be used to identify where to prioritize further field investigation and restoration (see for example Maitland et al. 2016), as it will highlight parts of the stream network with the highest probability of a migratory obstacle preventing access to spawning and rearing habitats. By purposefully selecting field investigations, it will be possible to identify areas in need of remediation in a more cost-effective manner, without having to manually survey streams in the field to find migratory obstacles.

2 Methods

The methodology used here is a further development of that in the INVAFISH project (2015-2019). The INVAFISH project (funded by the Research Council of Norway (#243910), NINA and NTNU) developed methodologies for large-scale mapping of natural migration obstacles in rivers based on terrain models. The Norwegian terrain models used in the INVAFISH project were not based on LiDAR data, but the methodology had the potential to be easily applied to the more accurate, higher spatial resolution data that are now available from LiDAR in a large part of the country, and the tools (in GRASS GIS 7) used for hydrological analysis are able to utilize such high-resolution data. In INVAFISH, the goal was to model the potential spread of non-native fish between lakes on a large (national or regional) scale, based on the fish species' ability to pass the natural height variation in the river landscape. Thus, we have not previously tested the potential of using a terrain model for identifying anthropogenic hindrances.

In the following sections, we describe the process for (1) construction of a terrain-based stream network that included information on natural and artificial hindrances pertinent to sea trout, and (2) modelling how such network properties may influence the prevalence of sea trout. All data processing was conducted using free and open source software; GRASS GIS 7 (GRASS Development Team 2019) was used for construction of the stream network, and R (R Development Core Team 2009) was used for modelling effects of migration hindrances on sea trout. Network analysis was done using Python 3 and igraph (Csárdi & Nepusz 2006). QGIS (QGIS Development Team 2019) was used for the preparation of some output maps. The main terminology used in this report is outlined in **Table 1**.

Table 1. *Terminology.*

Abbreviation	Term	Meaning
DTM	Digital Terrain Model	A raster grid where the mean elevation in each grid cell is that of the ground surface. Features on the surface (such as trees or artificial structures) have been removed
DSM	Digital Surface Model	A raster grid where the mean elevation in each grid cell is the sum of ground surface elevation and features on the surface
NVE Elvenett	*Norges vassdrags og energi direktorat* ELVIS elvenett	Map database from The Norwegian Water Resources and Energy Directorate (NVE). Includes information on the nationwide stream/river network
FKB	Felles kartdatabase	Map database from *Kartverket* (Norwegian Mapping Authority). Includes information on selected stream/river networks at greater detail than that of the NVE Elvenett
N50	N50 Kartdata	Map database from *Kartveket*. Includes information on road and rail paths, and road types
NVDB	Nasjonal vegdatabank	Map database from *Statens vegvesen* (Norwegian Public Roads Administration). Includes information on culverts for selected roads
GLMM	Generalized Linear Mixed Model	A form of parametric regression modelling allowing for hierarchical data structures
AIC	Akaike’s Information Criterion	An estimator of the relative quality of statistical models for a given set of data. Used in selection of the optimal GLMM

2.1 Construction of the stream network

The stream network was generated using a Digital Terrain Model (DTM) – *Nasjonal detaljert høydemodell* (NDH) – obtained from the hoydedata.no portal, developed by Geodata for the Norwegian Mapping Authority (*Kartverket*). This model is based on airborne LiDAR data, acquired by TerraTec AS (terratec.no). The model now covers 200 000 km^2 of Norway (230 000 km^2 will be available in 2022). The DTM shows ground surface elevation, with surface features such as buildings and overlying tall vegetation (bushes, trees) having been removed (data pre-removal and showing the height of all remotely sensed features is available in the form of a Digital Surface Model, DSM). The finest resolution data available from this model (used in the current study) has a 1 m^2 spatial resolution. For the current study, an area of Trondheim Region, encompassing all of Trondheim and Melhus municipalities and parts of Midre Gauldal and Skaun municipalities, was selected (**Figure 2**).

Construction of the stream network consisted of four steps:

1) Identifying and extracting artificial barriers
2) Terrain-based derivation of the stream network
3) Multi-scale computation of slope throughout the stream network
4) Integration of the stream network with crossings, culverts and electrofishing sampling sites

The end result of this was to create a stream network that both (i) followed the terrain more accurately (and thus followed the real stream watercourse better) than existing manually digitized networks (e.g. NVE Elvenett), and (ii) contained information on the spatial relationships between properties relevant to migration hindrances potentially affecting sea trout populations. The process for these four steps of data extraction is documented at: https://github.com/NINAnor/culverts_fragmentation. Individual scripts are detailed in **Table 2**.

Table 2. *Scripts for construction of the stream network.*

Processing step	Script source	Author
Identifying and extracting artificial barriers	https://data_maintenance.gitlab.io/r.stream.culvert/ https://data_maintenance.gitlab.io/r.stream.carve/	S. Blumentrath
Terrain-based derivation of the stream network	https://github.com/OSGeo/grass/tree/master/raster/r.stream.extract	R. Blazek, M. Landa, M. Metz
Multi-scale computation of slope throughout the stream network	https://grass.osgeo.org/grass76/manuals/addons/r.slope.direction.html	S. Blumentrath
Integration of stream network with crossings, culverts, electrofishing sites	https://github.com/NINAnor/culverts_fragmentation/blob/master/seatrout_net.py	S. Blumentrath

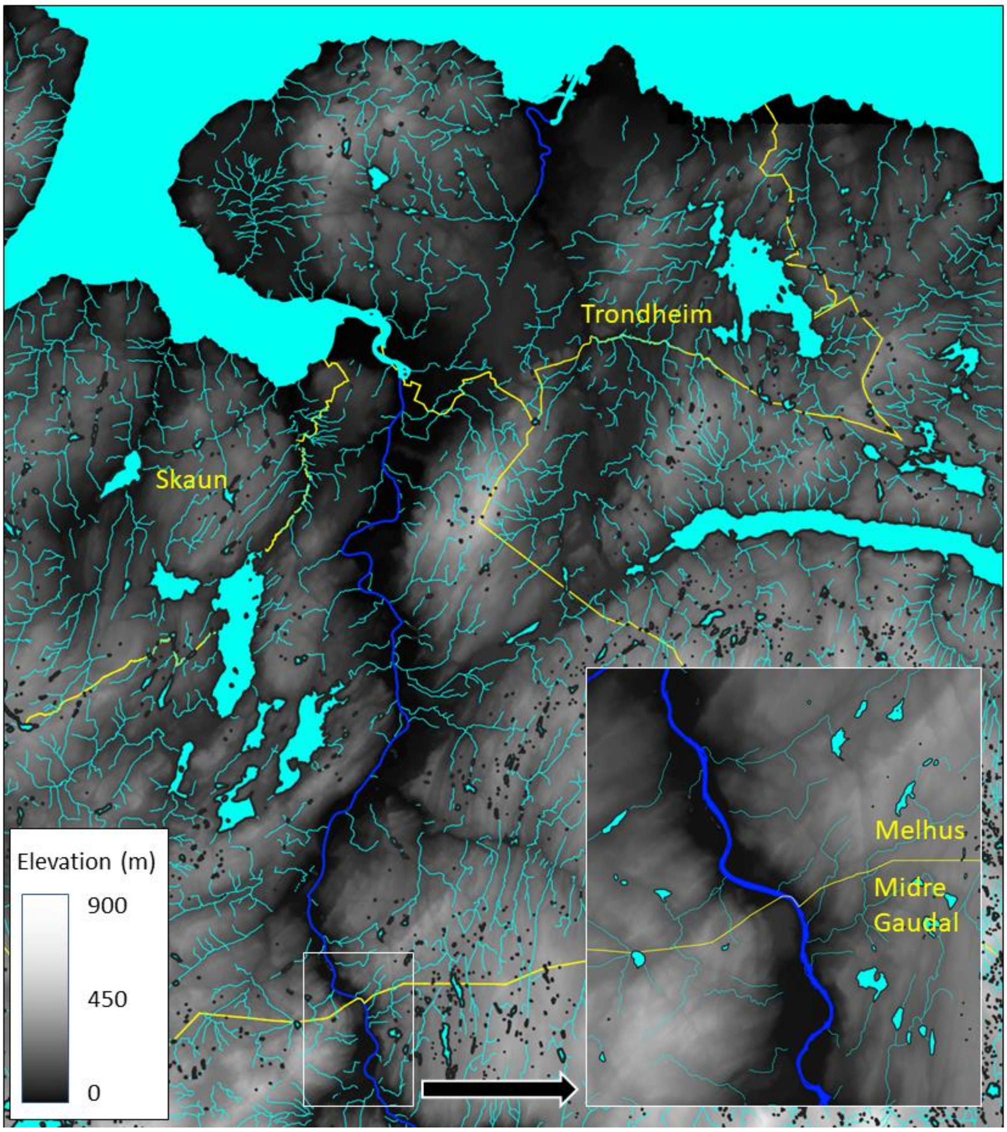

Figure 2. *DTM of study area: municipality boundaries, lakes, Trondheimsfjord, and main watercourse of the rivers Nidelva (anadromous stretch) and Gaula are shown.*

2.1.1 Identifying and extracting artificial barriers

Deriving streams from LiDAR-based DTMs can provide data on stream networks and their physical characteristics with unprecedented precision. However, remote sensing data collection is based on a "line-of-site" acquisition process, so derived maps may contain artefacts when the stream network is covered by artificial structures such as bridges, culverts and pipes. Bridges and culverts appear as "dams" in the drainages networks and thus can significantly influence the topology of stream networks derived from LiDAR-based DTMs (see Mäkinen et al. 2019). Artefacts of up to 25 m in height were found to exist along the stream network for the area selected in the current study.

DTMs were therefore corrected by identifying artificial barriers (which would potentially contain culverts) and extracting (cutting through) these artefacts from the DTM before construction of a new terrain-derived stream network. Different approaches for correction were initially tested:

- RichDEM: High Performance Terrain Analysis (Barnes 2016)
- Automated stream network generation based on culverts (Mäkinen et al. 2019)
- GAT WhiteBox (https://jblindsay.github.io/ghrg/Whitebox/)

However, because of shortcomings in the existing algorithms with regards to computational requirements and applicability to a system in which some of the culverts were long (> 100 m), a new approach was applied in this study: the GRASS GIS addon module *r.stream.culvert*.

The r.stream.culvert module combined information on hydrology, geomorphometrics, and anthropogenic infrastructure to generate lines that crossed artificial barriers longer than a user-specified minimum size. To do this, the module identified potential culverts in areas of the DTM where simulated overland flow was dammed by short-scale increases in elevation (associated with artificial barriers). This module was reliant upon the GRASS module *r.terraflow* (https://grass.osgeo.org/grass78/manuals/r.terraflow.html) for performing flow computation in the DTM. The *r.stream.culvert* module first identified potential culvert inlets, then identified potential culvert outlets, and then joined matching inlets and outlets.

1. Potential culvert inlets were identified differently for long and short obstructions. For long obstructions, associated with larger road constructions, such areas could be subdivided by the road network. These areas were then filtered using size, depth and altitude difference to identify the closest point to the road. For the remaining obstructions, the lowest elevation point upstream of the obstruction was extracted. These points were considered to represent inlets of potential culverts.
2. Culvert outlets were identified using the GRASS module *r.geomorphon* (https://grass.osgeo.org/grass76/manuals/addons/r.geomorphon.html), which identifies geomorphons (terrain forms) and associated geometry. These terrain forms (valleys and depressions) represented the potential drainage network where overland flow could be expected to continue downstream from a culvert.
3. From the culvert inlet points, lines were constructed to all valleys and depressions within a user defined search radius (here 120 m). Statistics on these lines were collected with regard to their slope, their distance to roads, the altitude difference between inlet and outlet, the altitude difference to the closest road at inlet and outlet, and on the individual terrain features (valleys and depressions) they connected. This information was used to filter out the lines that most likely represent culverts using the following criteria: (1) decline in elevation from the inlet point; (2) length and slope of the line; (3) the combination of different terrain structures; and (4) the spatial crossing of, or proximity to, a road (used for small culverts in ditches).

Outputs from *r.stream.culvert* were then used by a further GRASS GIS addon module, *r.stream carve*.

The *r.stream.carve* module altered the DTM elevations to remove artificial structures across the stream network. It worked as follows:

1. Altitude was extracted at the vertices of the input lines (inlet and outlet of a potential culvert) and lines were converted to 3D.
2. Points were interpolated between the start and end points along the lines at positions corresponded to the cells of the DTM.
3. The Z-coordinates of the interpolated points were converted to a raster and the input DTM (elevation) was modified where its altitude exceeded the altitude within this raster.

2.1.2 Terrain-based derivation of the stream network

A terrain-based stream network was derived from the corrected DTM using the GRASS module *r.stream.extract*. The module *r.stream.extract* (main author Radim Blazek; GRASS 7 improvements: Martin Landa, Markus Metz) uses an A^T least-cost search algorithm that minimizes the impact of DTM data errors, providing more accurate results in areas of low slope than alternative approaches. Surface flow is calculated using the Multiple Flow Direction (MFD) algorithm that is known to produce more accurate results compared to Single Flow Direction algorithms. In the MFD algorithm in *r.stream.extract*, water flow is distributed from a cell to all neighboring cells with lower elevation. During flow accumulation, the slope towards neighboring cells is used as a weighting factor for proportional distribution of the surface flow. The A^T least-cost path controls routing of overland flow across depressions and obstacles. The main output of the *r.stream.extract* module is a detailed stream network in both raster and vector format as well as a raster map depicting flow direction.

2.1.3 Multi-scale computation of slope throughout the stream network

Slope was computed across a range of spatial scales using the module *r.slope.direction*. This module computed slope as a gradient angle defined by the difference in altitude between pairs of pixels in a raster map, where the pixel pairs were identified at different spatial distances defined as steps (pixels) following a given map direction. For each focal pixel, the altitude difference to the Nth pixel downstream was computed, divided by the cartesian distance between the two pixels along that path and converted to an inclination in degrees. Thus, input data to this process were the corrected DTM (Section 2.1.1) and the flow direction map (Section 2.1.2).

Because it was not known which slope measure would best capture potential migration barriers for sea trout, stream slope was computed at different spatial scales, namely 1, 5, 11, 21, 31 and 51 raster (DTM) cells, along the network. Here, shorter distances between the pairs of pixels captured local, small-scale inclination (and thus extremes in slope), while larger distances (e.g. 51 pixels) capture the average slope over longer stretches (but could omit short steep sections through averaging).

2.1.4 Integrating the stream network with crossings, culverts, electrofishing sites

In order to be able to estimate the potential impact of culverts on sea trout migration, it was necessary to integrate the stream network produced in the procedure above with GIS map data on road and rail crossings, known culverts, and electrofishing sites.

2.1.4.1 Road and rail crossings, and culverts

Road and rail networks were obtained from the N50 database provided by GeoNorge (geonorge.no). These line data sets were spatially intersected with the stream network to create a point vector map containing the locations of the intersections. The lines of the stream network were then subdivided at the point locations of the intersections. This enabled potential culverts (see Section 2.1.1) to be included as part of a more comprehensive network dataset.

Known culvert positions and characteristics were obtained from the National Road Database (NVDB; https://www.vegvesen.no/fag/teknologi/nasjonal+vegdatabank). This database stores information about all state, municipal and private, county and forest roads, including road-associated infrastructure such as culverts. Additionally, this database includes culvert characteristics (dimensions, shape, construction material) for a subset of culverts of the entire database. These characteristics were spatially joined to the point vector map with the intersections of roads, rail tracks and the stream network.

2.1.4.2 Electrofishing sites

Data on the prevalence (presence or absence) of juvenile sea trout were obtained from a variety of electrofishing surveys reported by the Trondheim Kommune Environmental Unit (Miljøenheten), NINA, and NIVA (**Table 3**). Electrofishing data were obtained from tributaries in three regions, classified according to where they drained: (1) those draining into the Gaula river; (2) those draining into the anadromous part of the Nidelva river and (3) those draining into Trondheimsfjord (**Figure 3; Table 4**). Only data from parts of the streams that had populations of sea trout (as opposed to non-anadromous brown trout) were retained: trout data from tributaries feeding the non-anadromous part of the Nidelva (i.e. upstream of Leirfossen dam) were removed. Most streams (≈ 60%) where sea trout data were obtained were tributaries draining into the Gaula. Only three streams drained into the Nidelva, but those that did were sampled intensively. Sampling intensity increased over the years for the range of years when data were available (**Supplementary figure 1**). Additionally, the exact geolocation of the electrofishing sites varied according to year. The potential limitation of this dataset configuration with regard to analyzing the effects of hindrances on the sea trout distribution is discussed in Section 4.3.

The electrofishing sites locations were snapped to the stream network, correcting for errors resulting from GPS-based positioning of the sites within the field. As with the intersections with roads and rail tracks, the lines of the stream network were further subdivided at the locations of the snapped electrofishing sites to create a fully integrated stream network.

Table 3. *Sources of sea trout data.*

Source	Year	# Streams	# EFS	Reference
Trondheim Kommune	2012	9	34	(Nøst 2013)
	2012	10	26	(Nøst 2014)
	2014	7	21	(Nøst 2015)
	2015	8	30	(Nøst 2016)
	2016	13	40	(Nøst 2017)
	2017	12	108	(Nøst 2018)
NINA	2001-2018	11	19	Unpublished
	2013	12	26	(Solem et al. 2014)
	2014	10	18	(Bergan 2015a)
	2015	10	27	(Bergan & Solem 2015)
	2016	15	32	(Bergan & Solem 2016)
	2017	1	2	(Bergan & Solem 2018)
NIVA	2010	2	2	(Bergan 2011)
	2011	9	34	(Bergan 2012)

Table 4. *Number of electrofishing sites (# EFS) per stream.*

Streams draining to Gaula (N = 17)		Streams draining to Nidelva (N = 3)		Streams draining to fjord (N = 8)	
Stream	# EFS	Stream	# EFS	Stream	# EFS
Bortna	4	Heimdalsbekken	35	Bråbekken	3
Buskleinbekken	36	Leirelva	57	Børselva	4
Eggbekken	43	Uglabekken	13	Elsetbekken	5
Kaldvella	14			Flakkbekken	32
Langbekken	13			Ilabekken	8
Lauglobekken	4			Klefstadbekken	8
Loa	14			Ryebekken	6
Lynga	13			Stordalsbekken	14
Møsta	10				
Ratbekken	8				
Reitanbekken	4				
Sandbekken	8				
Skårvollbekken	7				
Søra	3				
Ustbekken	4				
Varmbubekken	9				
Ørbekken	6				

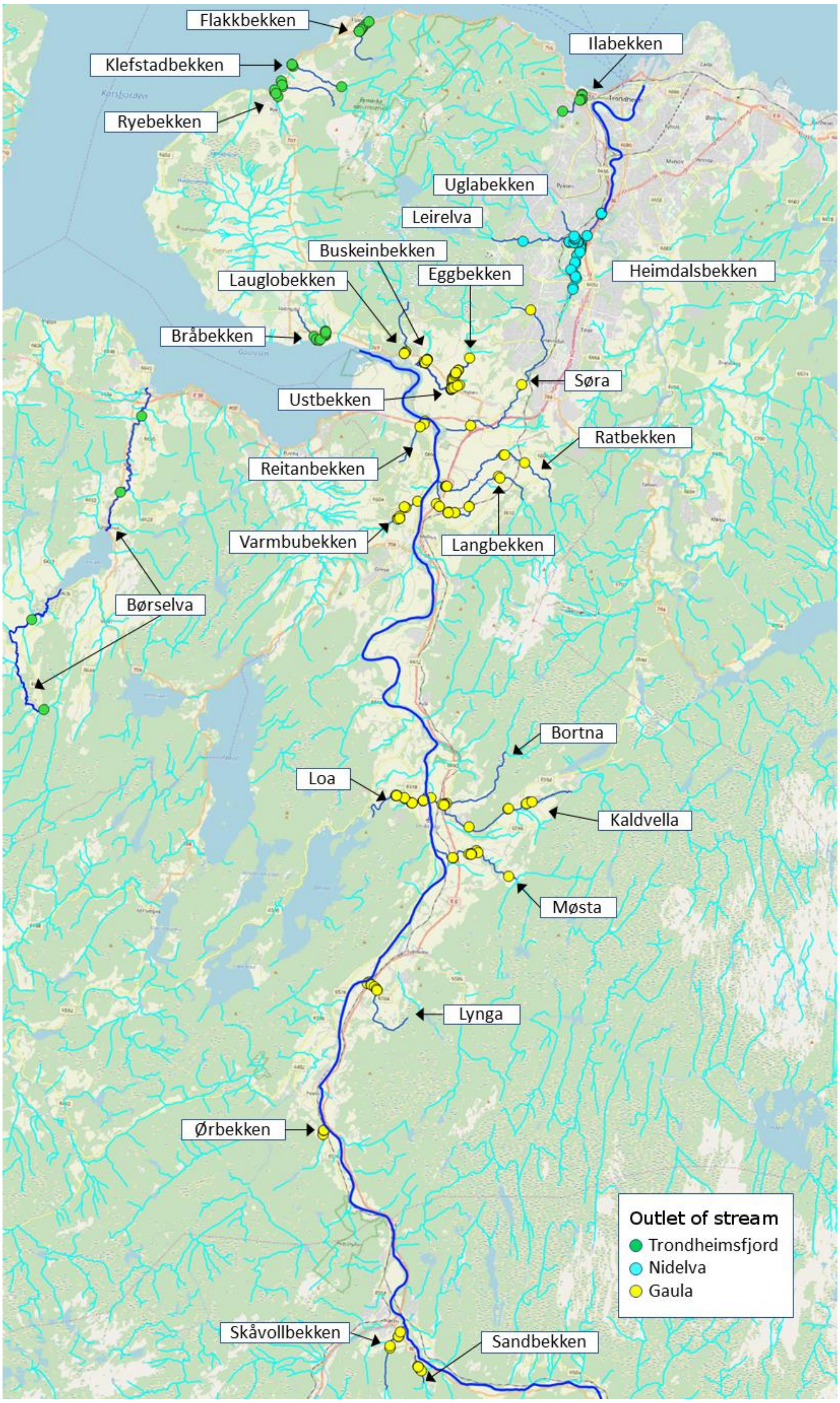

***Figure 3**. Distribution of electrofishing sites (filled circles) for streams discharging into Trondheimsfjord and the Nidelva and Gaula rivers. All streams (NVE Elvenett) are shown in light blue; streams with electrofishing surveys are shown in dark blue; the rivers Nidelva (anadromous stretch) and Gaula are shown by thick dark blue lines.*

2.1.4.3 Data structure of integrated network

The integrated stream network contained information on road and rail intersections, together with the electrofishing sites. Potential predictor variables for modeling migration hindrances were produced using network analysis. In the first step, points ("nodes" in network terminology) for road and rail crossings and electrofishing sites were inserted into the terrain-derived stream network. In the second step, these intersection sites were further described with regards to their position in the network and local conditions of the stream at the respective site. The python program *seatrout_net.py* (**Table 2**) was developed to achieve integration of all data and to conduct network analysis. When integrating culverts to the database, intersections of roads, rail tracks and the terrain-derived stream network were used to "identify" where potential culverts were on the network, and these were matched to road and rail crossings as a second step. The integrated network included information on:

1. Maximum, average and standard deviation of stream slope at different spatial scales (local slope between neighboring 1 m^2 DTM cells) at the positions of the crossings/culverts and electrofishing sites, as well as average slope over distances of 1, 5, 11, 21, 31 and 51 DTM cells) downstream from electrofishing sites.
2. A list of road/rail stream intersections and their number downstream from electrofishing sites. Information on road type (private, municipal, county) and whether a culvert was present in the NVDB database was also registered.
3. A list of electrofishing sites and their number upstream from road/rail stream intersections.

Spatial data were written into a GeoPackage database that contained:

1. the stream network with integrated road/rail intersections and electrofishing sites
2. the point layer with road and rail intersections
3. the point layer with the electrofishing sites
4. a line vector map with modeled potential culverts from *r.stream.culvert*
5. vector maps with different, potentially relevant road construction objects (culverts, bridges etc.) from NVDB

2.2 Modelling effects of migration hindrances on sea trout

The relationship between the spatial distribution of sea trout and potential migration hindrances was determined using generalized linear mixed modelling (GLMM). Sea trout prevalence (presence or absence) was used as the response variable, and models were fitted to the prevalence of each age group separately (0+ or ≥1+), and to pooled age groups. Models were only fitted to streams with at least three electrofishing sites to allow the stream to be used as a random effect – this dataset had 383 observations collected from 28 streams. GLMMs were fitted using the *glmer* function of the *lme4* library, using bobyqa optimization, with predictor variables having been standardized (mean = 0, standard deviation = 1) to help model fitting. Before GLMM fitting, multicollinearity among predictors was examined using Variance Inflation Factors, according to the approach of Zuur et al. (2009). Model predictor variables were (1) the number of artificial hindrances downstream of the electrofishing site (quantified as *either* the number of downstream crossings *or* the number of downstream culverts), (2) the maximum slope downstream of the electrofishing site (calculated at a scale of *either* 5, 11, 21, 31 *or* 51 DTM cells), (3) the distance from the electrofishing site to the sea, and (4) the elevation of the electrofishing site (**Table 5**). Artificial hindrance were characterized in one of two ways – firstly, the number of downstream crossings (the total number of downstream intersections between road/rails and the stream), and secondly, the number of downstream culverts (data from the NVDB database) – because there were potential limitations with either metric (see Section 4.2.4). Given that artificial hindrances were characterized in two ways, and natural hindrances (maximum slope) in five ways, we therefore fitted 10 models for each age group and for pooled groups.

Table 5. *Fixed effects used in the GLMMs. CrossN and CulN were not used in the same model; MaxSlope was estimated over a range of distances.*

Predictor	Model abbreviation
Number of downstream crossings	CrossN
Number of downstream culverts	CulN
Maximum slope between the electrofishing site and the sea	MaxSlope
Distance from the electrofishing site to the sea	Dist
Elevation of the electrofishing site	Elev

Model fits were evaluated using Akaike's Information Criterion (AIC) (R function *AIC()*), and variables were removed using backward selection until the model with lowest AIC was found (the optimal model). The explanatory power of the optimal models was evaluated using a pseudo R-squared for GLMMs (the *squaredGLMM()* function of the *MuMIn()* library). This provides a marginal R^2 (the variance explained by the fixed factors) and a conditional R^2 (the variance explained by the whole model, including both fixed and random factors). Additionally, the optimal models were also evaluated with regard to how accurately they were able to predict the observed prevalence. A prediction of absence was defined as $P < 0.5$ and a prediction of presence was defined as $P \geq 0.5$.

2.3 A map tool for predicting sea trout occurrence

A GRASS module map tool was developed to allow prediction of sea trout prevalence based on characteristics of the stream network (Section 0) and parameters of the sea trout prevalence models (Section 2.2) (https://seatrout.gitlab.io/r.stream.accessibility/). This module predicted prevalence, *p*, from stream characteristics using the coefficients of the GLMM model as follow:

$$LinPred = a + \sum b_i S_i$$
$$p = exp(LinPred)/\left(1 + exp(LinPred)\right)$$

where *a* is the GLMM model intercept and b_i is the GLMM coefficient for standardized variable S_i. Given that the GLMM model was based on standardized variables, the parameters of the standardization were also use by the module to transform the variable measured in the stream network in the same fashion that variables has been standardized for use in the GLMM:

$$S_i = (V_i - Cen_i)/Scale_i$$

where V_i is the original variable extracted from the network, and Cen_i and $Scale_i$ are parameters of the standardization of the variable within the GLMM. Thus for a module predicting prevalence based on the number of downstream culverts (CulN) and distance (Dist), this module used seven input parameters: intercept, coefficient for scaled CulN, coefficient for scaled Dist, center and scale parameters for the standardization of CulN, and center and scale parameters for the standardization of Dist. This module was designed so that parameters could be easily modified to utilize results from different GLMM models.

3 Results

3.1 Construction of the stream network

3.1.1 Identifying and extracting artificial barriers

While the NVDB road database mostly contains information on culverts under major roads, potential culverts could be mapped for smaller roads by applying the *r.stream.culvert* module to the high-resolution DTM (see **Figure 4**). A significant number of culverts in NVDB were not matched by potential culverts identified with *r.stream.culvert*. This is likely due to the fact that *r.stream.culvert* operates only on drainage patterns visible in the terrain, particularly those related to stream networks. NVDB, in contrast, also contains many culverts whose main purpose is to handle peak runoff from rainfall events and which are detached from freshwater drainage networks most of the time.

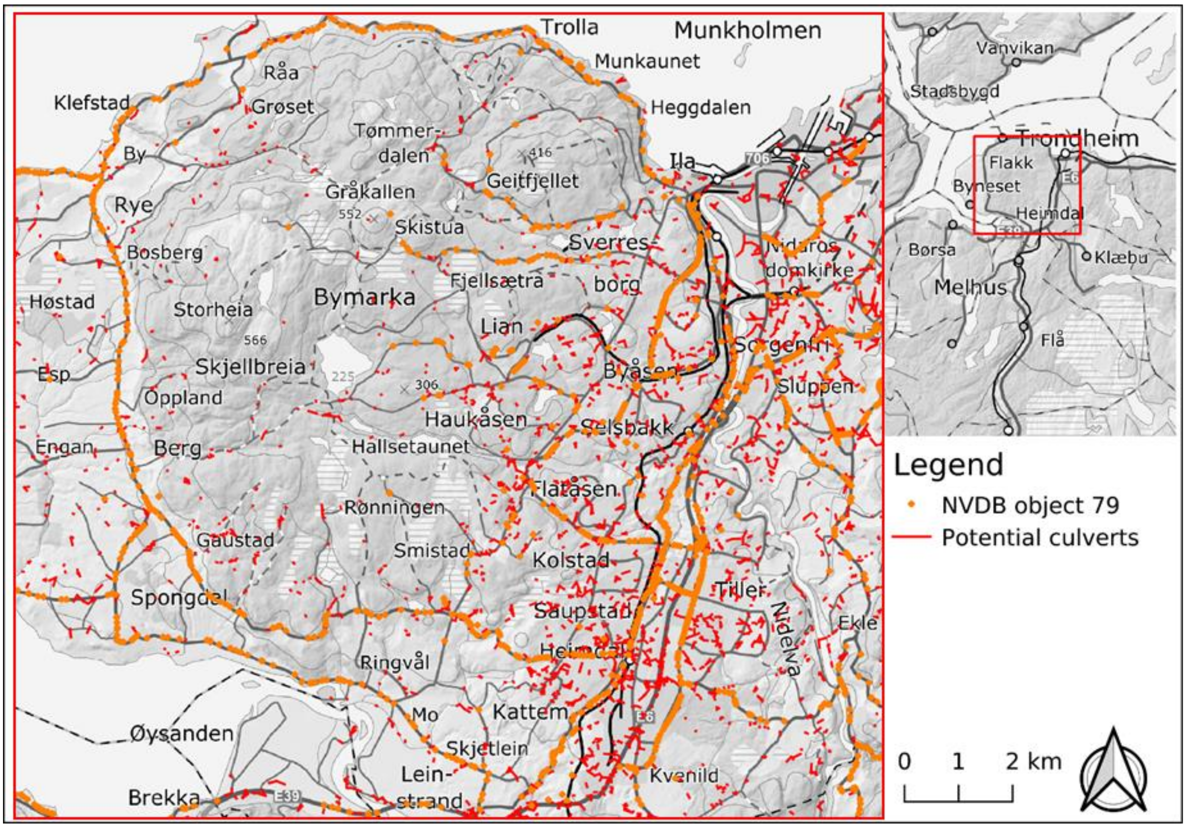

Figure 4. *Potential culverts identified with the development version of r.stream.culvert and culverts present in NVDB.*

There were also occasions when culverts were not detected by the *r.stream.culvert module*, even when there were NVDB culverts present along the streams. For example, along the coastal road Bynesveien, the NVDB culvert that was present was not identified by the module (see **Figure 5**). This is likely due to the lack of drainage structures in the steep and narrow terrain between the road and the sea.

Without the use of the GRASS GIS modules *r.stream.culvert* and *r.stream.carve*, structures crossing the stream resulted in the generation of a discontinuous stream network. For example, in **Figure 6** (left panel), a rail track (≈ 25 m above the stream) completely altered the topology of the terrain-derived stream network compared to the real flow pattern; correcting for this (**Figure 6**; right panel) allowed the creation of a network that was more consistent with the real flow pattern. Furthermore, slope estimates in the streams would have been altered significantly without the application of these modules, because even if the topology and general flow pattern were not altered, the artificial structures would have shown up as “spikes” in the longitudinal profile because the A^T least-cost search algorithm in *r.stream.extract* would have traversed smaller obstacles and routed the overland flow over them.

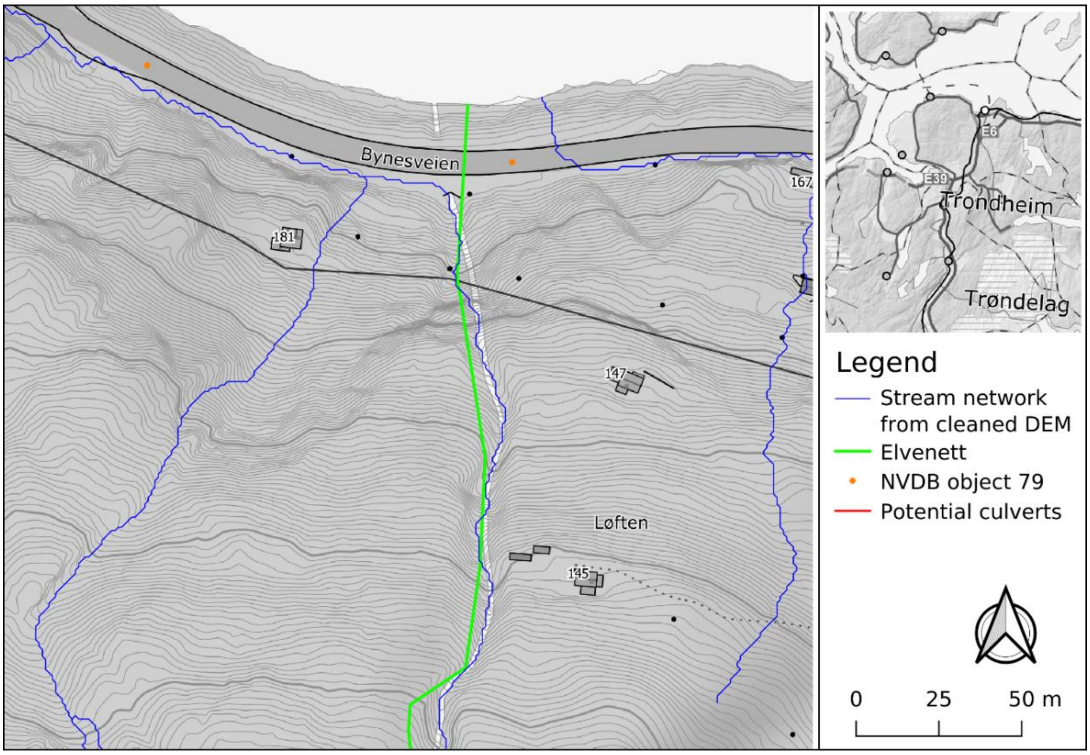

Figure 5. *Example of an omission error (undetected culvert) at Bynesveien.*

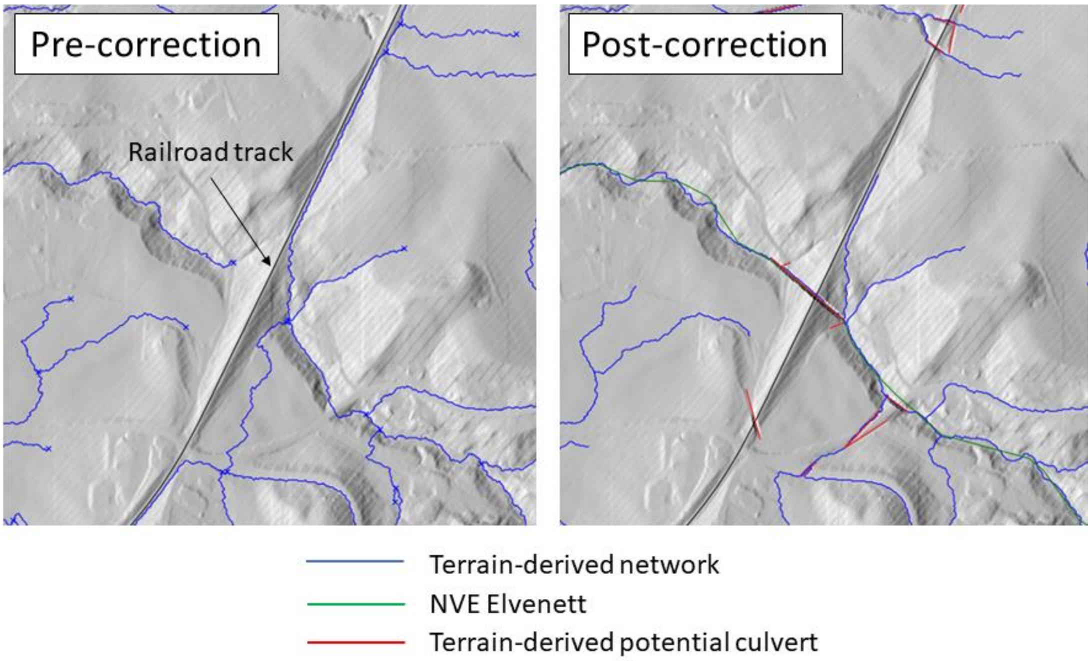

Figure 6. *Effect of terrain correction on terrain-derived stream network: pre-correction (left panel); post-correction (right panel).*

The *stream.culvert* module also created some wrongly located potential culverts (false positives), which indicates that improved filtering should be applied before carving into the DTM. The false positives in the cases in this study did not however affect the results of the modelling in a significant way as they did not affect the flow pattern of the study streams.

It was essential to perform a terrain-correction of the DTM data before using it to create an accurate stream network that was as consistent as possible with that existing in reality. This was particularly the case because we used high resolution (1 m^2) DTM data, where small man-made river-crossing structures were present that would have reduced the accuracy of a stream network generated from uncorrected data. The development versions of the *r.stream.culvert* and *r.stream.carve* addons were able to identify and correct for numerous anthropogenic structures with a length of up to 120 m. Application of the modules *r.stream.culvert* and *r.stream.carve* allowed the generation of a network where the general flow pattern found within the manually digitized stream network NVE Elvenett was maintained, and also eliminated smaller terrain artefacts where roads crossed the stream network.

3.1.2 Terrain-based derivation of the stream network

The terrain-derived stream network showed the most probable drainage network for the topography (**Figure 7**). When deriving the stream network from the DTM, the threshold for stream initialization was deliberately set relatively low so that all minor streams would be captured in the process. Therefore, not all channels in the derived network corresponded to real, existing streams. Such false positives, however, will not have affected the modelling of migration hindrance effects on sea trout because only those parts of the stream network that were downstream from the electrofishing sites (and corresponded to real, existing streams) were included in sea trout models.

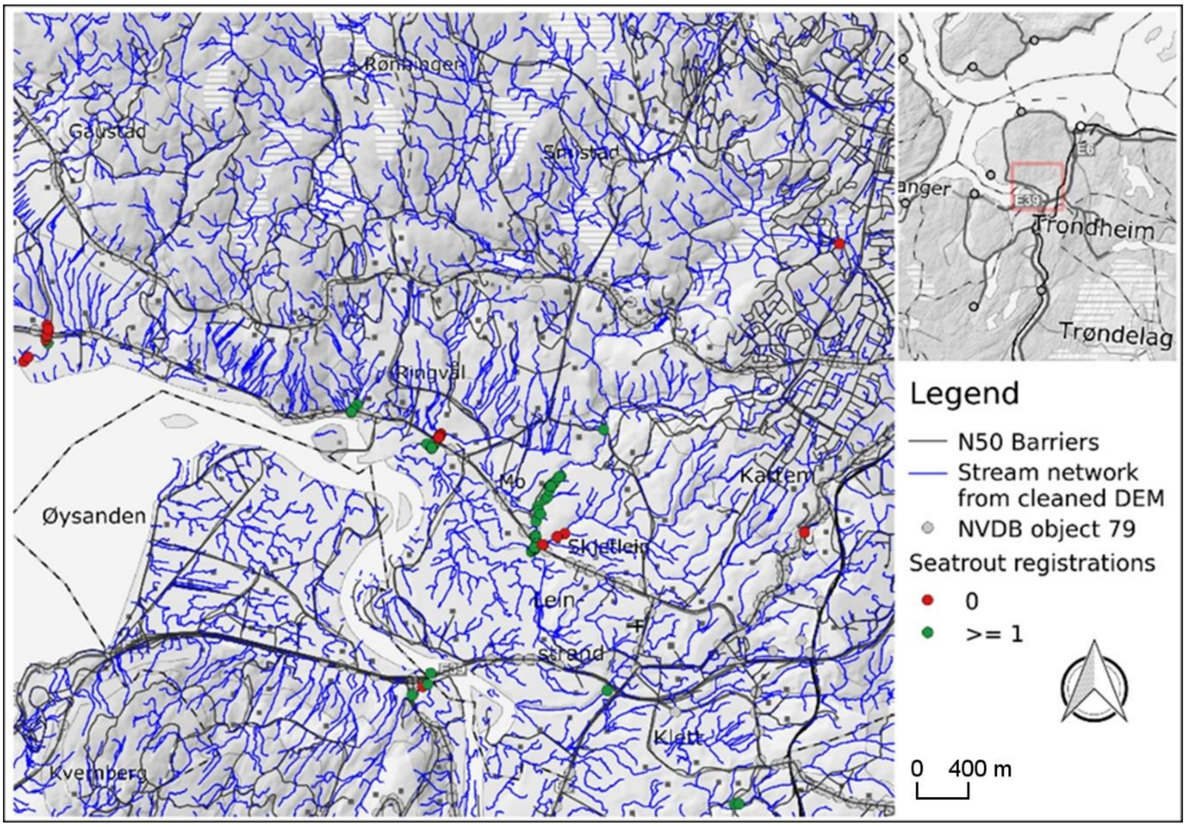

Figure 7. *Terrain-derived stream network.*

In general, the streams present in the NVE Elvenett dataset were captured in the terrain-derived stream network (**Figure 8**). Differences mainly occurred in flat areas (such as lentic waterbodies) where small elevation differences in the very detailed DTM caused winding flow lines in the terrain-derived stream network; in comparison, the NVE Elvenett network is digitized with straight centerlines through the waterbodies so does not suffer from this problem.

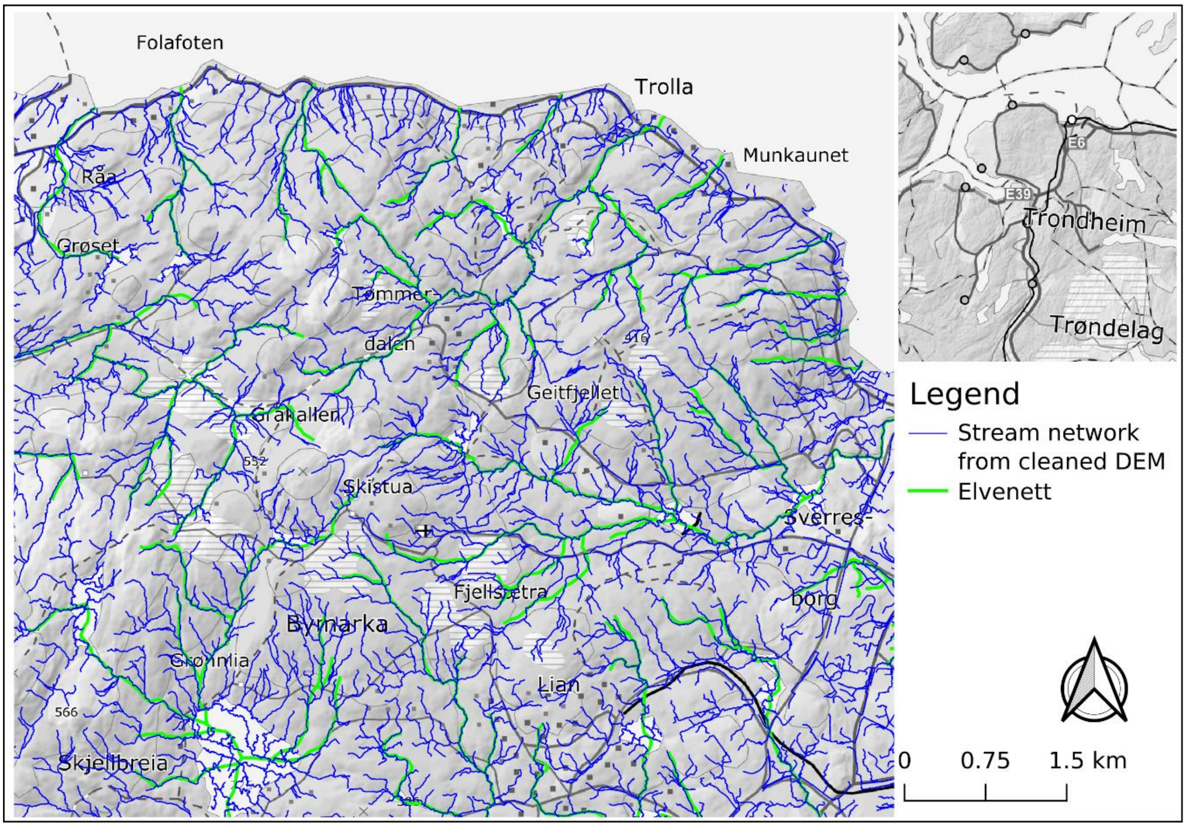

Figure 8*. Stream network derived from the corrected DTM compared to NVE Elvenett.*

The stream network derived from the DTM showed a significantly higher level of detail compared to the NVE Elvenett dataset (see **Figure 9**). In fact, it strongly concorded with the representation of streams in the more detailed FKB dataset (also **Figure 9**). However, in contrast to the lines and polygons in FKB, the terrain-derived stream network represented a coherent, connected and directed dataset that has the potential for use in routing (network analysis).

3.1.3 Multi-scale computation of slope throughout the stream network

An important feature of the terrain-derived stream network was that each pixel within the stream was assigned a flow direction to the next pixel in the stream. This feature was used to compute slope in the streams at different spatial scales using the *r.slope.direction* module in GRASS GIS. Estimated stream slope was scale dependent (see **Figure 10**). There was higher variation in slope values when measured across fewer pixels, while measurements across a larger number of pixels (across a longer section within the stream network) resulted in less variation of slope values, both at local scales and in general across the network.

Negative slope values were occasionally created within the terrain-derived stream network at all scales. The presence of negative slope values indicates that there were some unresolved areas in the corrected DTM where surface runoff was being virtually routed uphill. Negative values tended to be generated in flat areas, or in urban areas where numerous anthropogenic structures were interfering with surface runoff.

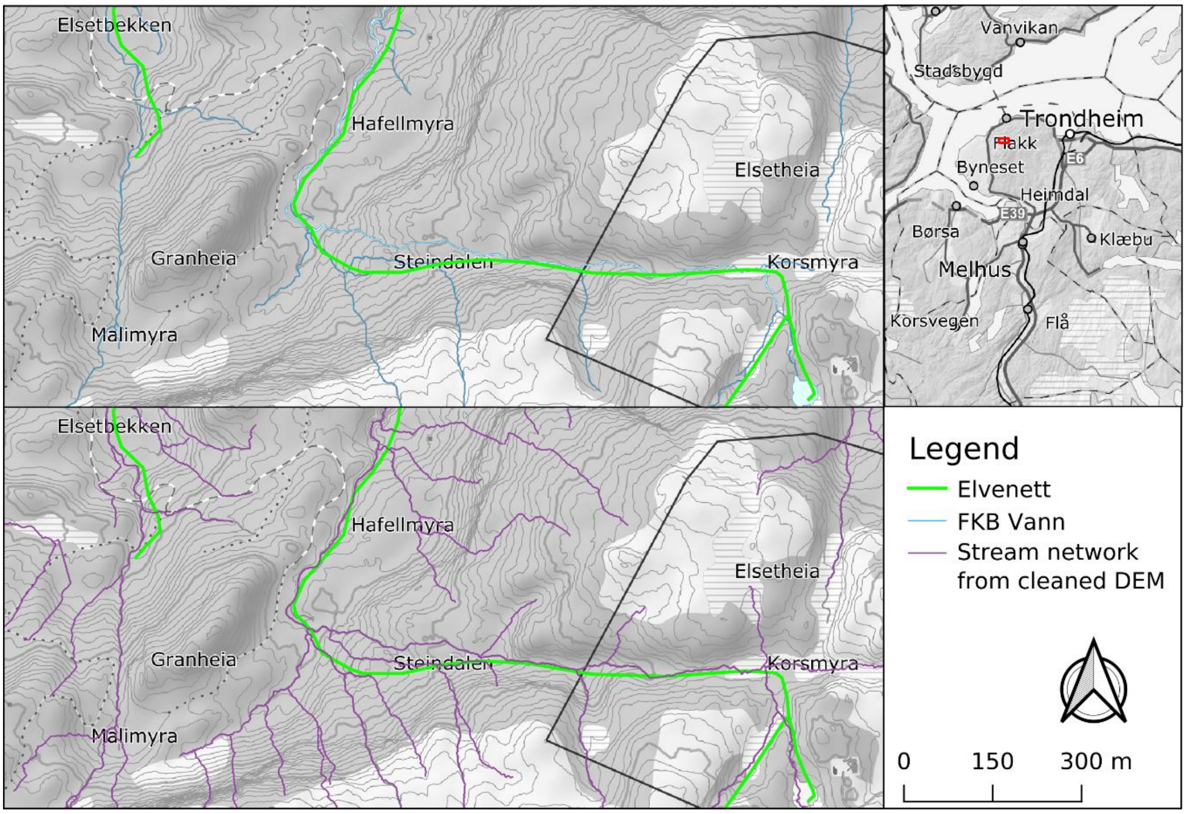

***Figure 9**. Comparison of the level of detail in the FKB dataset (upper panel) and the terrain-derived network (lower panel). The NVE Elvenett has been superimposed on both panels.*

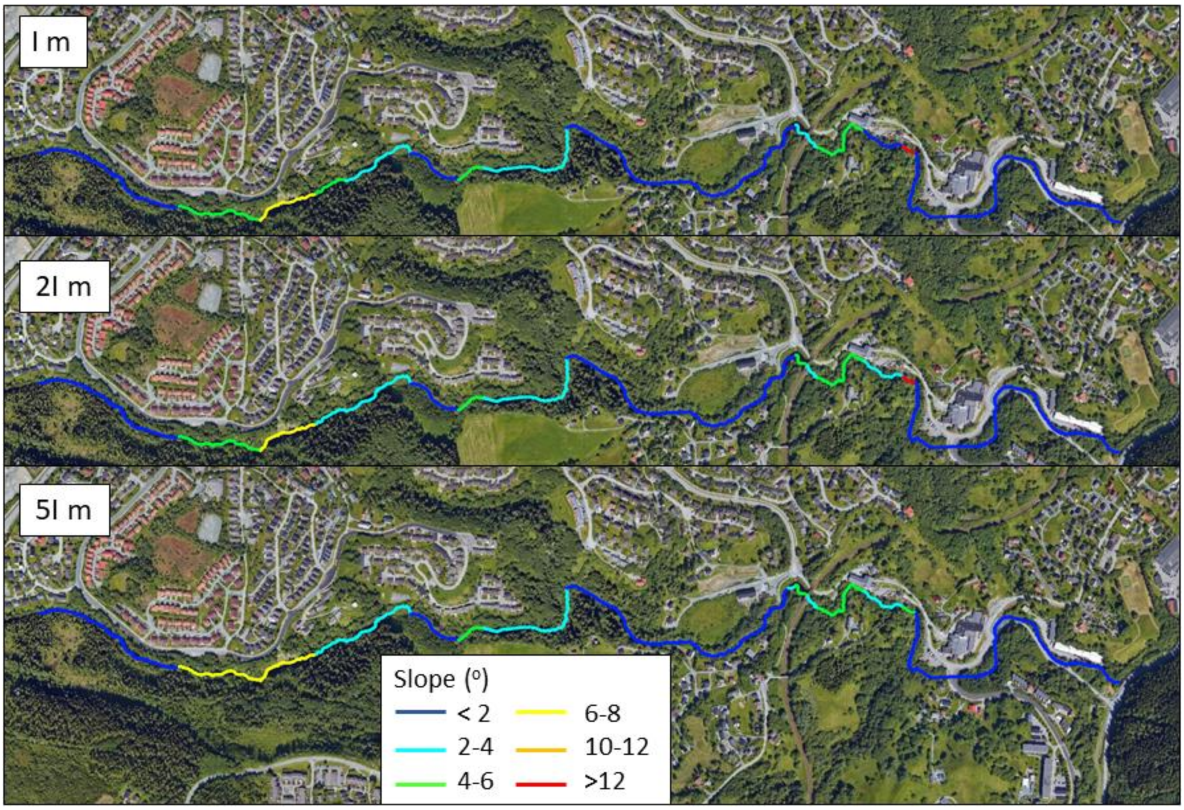

***Figure 10**. Multi-scale measures of slope in Leirelva.*

3.1.4 Integrating the network with crossings, culverts and electrofishing sites

By intersecting the terrain-derived stream network with roads and rail tracks from the N50 database, a total of 169 408 crossings were integrated with the generated stream network across the study area, together with the electrofishing sites. However, the NVDB culvert database was limited in size: only 147 objects from NVDB were registered downstream of sea trout electrofishing sites, and only 90 of these matched with intersections (see also **Figure 4**). An example of an integrated stream network is shown in **Figure 11**. This dataset was used as the basis for computing the predictors for modelling the prevalence of sea trout described in Section 2.2.

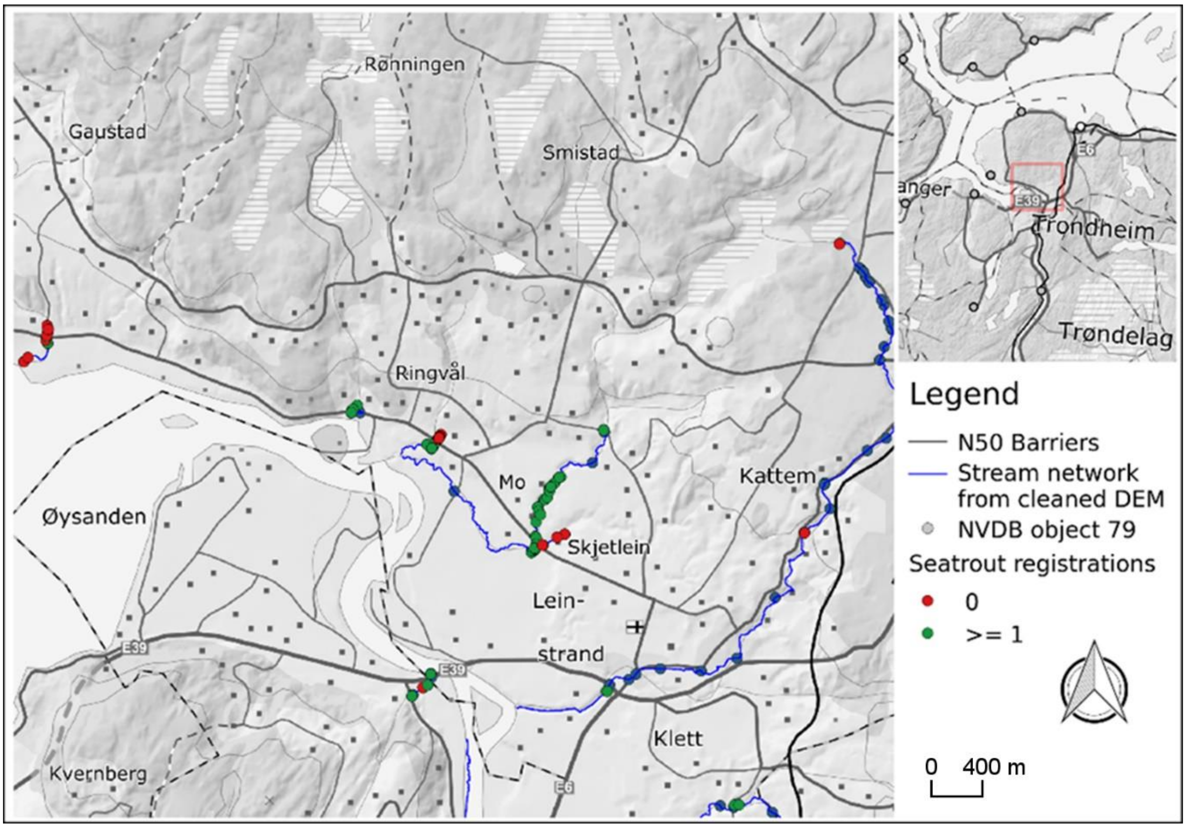

Figure 11. *Terrain-derived stream network integrated with crossings, culverts and electrofishing sites.*

3.2 Modelling effects of migration hindrances on sea trout

3.2.1 Characteristics of sea trout electrofishing survey data

Both age groups (0+ and ≥1+) were not always found together at the same electrofishing site: 17% of sites with ≥1+ sea trout present had no 0+ sea trout present, whereas 10% of sites with 0+ sea trout present had no ≥1+ sea trout present. Sea trout prevalence in the electrofishing sites was high. Only 18% of sites had no sea trout of either age group present, only 35% of sites had no 0+ sea trout present, and only 28% had no ≥1+ sea trout present. Prevalence varied according to stream from zero (for example Bråbekken and Ustbekken) to one (for example Bortna, Børselva, Klefstadbekken and Lauglobekken) (**Figure 12**).

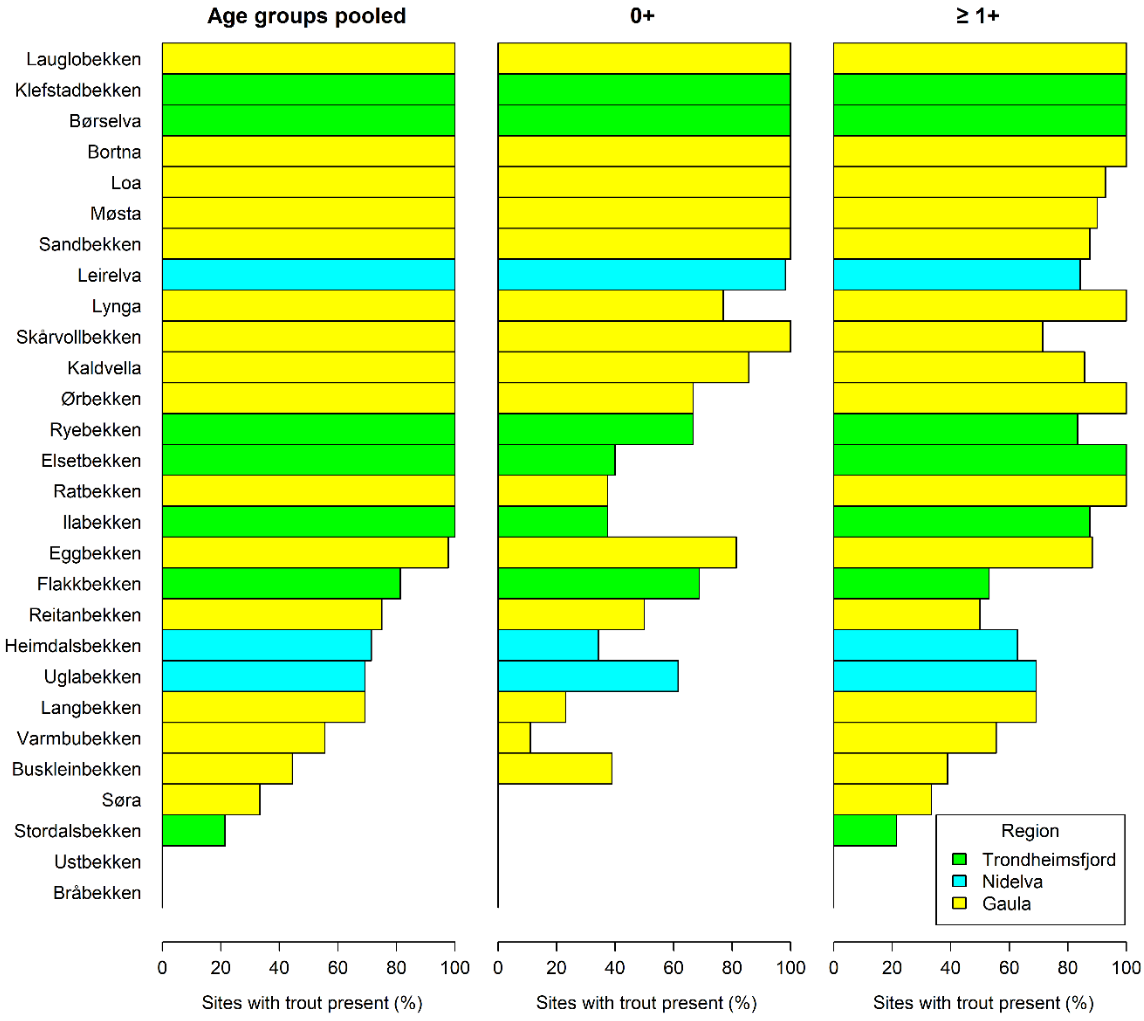

__Figure 12.__ Presence of sea trout in electrofishing sites.

3.2.2 Sea trout prevalence models

Variance inflation factors (VIFs) among predictors were small (always less than < 4) (**Supplementary table 1**). Therefore, the amount of multi-collinearity among predictors was considered acceptable for use within the same GLMM model. Initial models are shown in **Supplementary table 2-4**. Maximum downstream slope (regardless of the scale over which this was estimated) and elevation were removed from all models based on AIC values of fitted prevalence GLMMs.

The optimal models, in terms of AIC, were similar regardless of whether the number of downstream artificial migration hindrances was parameterized from crossings or from NVDB culverts (***Table* 6**). For age groups pooled, prevalence was strongly negatively related to the number of downstream crossings or culverts, and positively related to distance downstream (although the significance of the latter was marginal). Maximum downstream slope and elevation change were excluded from the optimal model. Relationships were different according to which age group was being considered. For the 0+ age group, only distance downstream was retained (a positive relationship with prevalence), and all other variables were omitted. For the ≥1+ age group, the model was similar to that for age groups pooled: decreasing prevalence with an increase in the number of downstream crossings or culverts and increasing prevalence with an increase in distance downstream.

Table 6. *Coefficients of the optimal prevalence GLMMs. Significant model parameters (P < 0.05) are highlighted in bold. CrossN = Number of downstream crossings, CulN = number of downstream culverts, Dist = distance from the electrofishing site to the sea.*

Age group	Model	Parameter	Estimate	Std. Error	z value	Pr(>|z|)
Pooled	Crossings	(Intercept)	7.050	3.362	2.097	**0.036**
		scale(CrossN)	-8.701	2.598	-3.349	**0.001**
		scale(Dist)	13.688	6.898	1.984	**0.047**
	NVDB culverts	(Intercept)	4.454	1.645	2.708	**0.007**
		scale(CulN)	-3.639	0.942	-3.862	**<0.001**
		scale(Dist)	4.816	2.041	2.359	**0.018**
0+	Crossings	(Intercept)	0.632	0.420	1.506	0.132
		scale(Dist)	1.200	0.405	2.962	**0.003**
	NVDB culverts	(Intercept)	0.632	0.420	1.506	0.132
		scale(Dist)	1.200	0.405	2.962	**0.003**
≥1+	Crossings	(Intercept)	1.249	0.308	4.051	**<0.001**
		scale(CrossN)	-1.289	0.451	-2.859	**0.004**
		scale(Dist)	1.722	0.520	3.311	**0.001**
	NVDB culverts	(Intercept)	1.150	0.364	3.157	**0.002**
		scale(CulN)	-0.914	0.376	-2.427	**0.015**
		scale(Dist)	1.061	0.380	2.792	**0.005**

Optimal models had low explanatory power (**Table 7**). The model fitted to pooled age groups, using crossings as a proxy for culverts, had the highest goodness-of-fit (conditional $R^2 = 0.75$), but models fitted to individual age groups had much lower explanatory power. In addition, models had a low classification accuracy. The model for pooled age groups based on crossings correctly predicted trout presence on 89.5% of occasions, but this model was not able to adequately predict the absence of trout (classification accuracy = 12.9%).

Table 7. *Coefficient of determination (R^2) and classification accuracy of the optimal GLMMs.*

Age group	Model	R^2		Classification accuracy (%)	
		Conditional	Marginal	Trout present	Trout absent
Pooled	Crossings	0.75	0.96	89.5	12.9
	NVDB culverts	0.36	0.92	76.0	20.0
0+	Crossings	0.16	0.54	77.0	45.2
	NVDB culverts	0.16	0.54	77.0	45.2
≥ 1+	Crossings	0.17	0.35	99.3	6.5
	NVDB culverts	0.12	0.40	85.1	15.0

4 Discussion

4.1 Main findings

Routines developed in this study were shown to be effective for generating a stream network from high-resolution LiDAR-derived DTM data. This network provided a better representation of that existing in reality than the manually-digitized stream network currently available from NVE's Elvenett. LiDAR data has been previously used to derive the channels of small streams (Roalkvam 2014). However, this is the first study in Norway to apply this approach over an extended area to (1) identify artificial structures crossing the streams with the goal to modifying the DTM so that a valid terrain-based stream network can be generated, and (2) to integrate these data with additional GIS data (road and rail crossings and culverts) so that suitability of these data can be assessed with regard to an ecological application (investigation of migration hindrances affecting sea trout).

With regard to modelling migration hindrances on sea trout, it was found that sea trout prevalence (either ≥1+ age group or age groups pooled) was inversely related to the number of downstream crossings or culverts, suggesting that artificial migration hindrances may reduce the accessibility of a watercourse to sea trout. However, the predictive ability of the fitted models was low, limiting their usefulness within a management context. Additionally, no relationship was found for the effect of downstream slope on trout prevalence, suggesting that natural hindrances from steep slopes were not evident in the study area. Some of the limitations in our models of migration hindrance effects on sea trout prevalence may, however, be related to limitations in the datasets used.

In the following sections, we discuss the approaches used in this study. Issues related to GIS-based derivation of a stream network, consistent with the topography and containing natural and artificial migration hindrances, are discussed in Section 4.2. The implications of using existent datasets for estimating the distribution of sea trout are discussed in Section 4.3. The limitations associated with both establishing network properties and estimating the effect of migration hindrances on sea trout distribution are discussed in Section 4.4. We then identify areas where there is potential for improvement in approaches in Section 4.5.

4.2 Use of a GIS-based approach to determine migration hindrances

This study has shown that a GIS-based approach, reliant on processing high-resolution LiDAR DTM data, alongside integration with GIS datasets on road and rail infrastructure, can be used to construct a more accurate representation of stream networks at an unprecedented level of detail. In addition, potential migration hindrances for sea trout populations could be mapped that were not present in any other existing data sources (e.g. NVDB). However, in this first pilot application, several areas of improvement of the underlying methodology may be identified, and further processing of corrected DTMs may be required.

4.2.1 Identifying and extracting artificial barriers

Based on visual assessment, the development version of the *r.stream.culvert* module was able to identify most of the cases where artefacts in the DTM resulted from road or rail crossings. Even situations where the stream was below the surface for distances of up to 120 m were registered. However, both false positive and false negative potential culverts were registered: the former could occur in narrow streams where anthropogenic structures alongside the river banks might cause a localized increase in elevation within the DTM; the latter could occur if the structure overlying the river was low relative to the longitudinal stream gradient.

The produced outcome in the form of vector lines with potential culverts could be used for improving the DTM for stream extraction using the *r.stream.extract* module, and could serve as a basis for further manual inspection and correction. A more thorough testing, over a wider range of streams than that found in the study area, and further improvement of these tools can be recommended. In particular, (1) existing data on streams could be used to aid the process of identifying relevant sinks in the terrain as well as filtering out false positive potential culverts; and (2) the *r.stream.culvert* module could be modified to utilize data on waterbodies (including the ocean and potentially mires), in addition to channels in the topography, to determine possible outlet points of potential culverts.

4.2.2 Terrain-based derivation of the stream network

The available stream network databases suffer from weaknesses with regard to providing accurate mapping of small streams. The N50 Elvenett provides a nationwide coverage of a connected flow-directed stream network, but it is limited by gaps in the network and poor spatial resolution. Gaps in the network result from areas where streams become submerged (e.g. in marshland areas) or where streams flow through pipes/culverts in densely populated or agricultural areas, and from errors in the underlying data. These gaps are filled to ensure a continuous network but the correct watercourses may deviate from the real watercourses in some cases. The resolution of the N50 Elvenett is also too coarse (median distance of digitized sections ≈ 30 m) for accurate representation of highly meandering streams, and can result in errors in extracted stream profiles when integrating the network with a high-resolution DTM. The FKB database offers higher accuracy, with stream watercourses being derived from photogrammetric analysis of aerial photographs. However, photogrammetry is less effective in areas with poor visibility, such as in dense forests or areas with anthropogenic infrastructure, and is ineffective where streams flow through pipes/culverts or gutters. As a result, there may be poor locational accuracy and incomplete coverage in some areas. These limitations in the N50 Elvenett and FKB databases may be partially overcome using the terrain-based approach, based on high resolution DTM data, that was developed in this study.

The 1 m^2 spatial resolution of the DTM was sufficient for derivation of a stream network that followed the terrain better than the NVE Elvenett (**Figure 13**). In particular, the fact that this was a DTM (with surface features removed) rather than a DSM allowed terrain-based stream extraction even in tree-covered valleys – a typical surface feature present for most streams examined in this study. With regard to correctly mapping the stream network watercourses, this terrain-based approach provided several advantages and disadvantages when compared with manual derivation (**Table 8**).

Two main limitations with the terrain-based derivation approach were identified in this study. Firstly, the terrain-based derivation approach did not deliver accurate results in areas where infrastructure was so dense that the stream was covered for an extended distance (for instance, for a > 300 m long stretch of Heimsdalbekken which ran under a built-up area). The procedure is therefore less reliable for use in heavily modified ("piped") waterbodies (such as those sometimes found in urban areas), and it would be necessary to rely on alternate GIS data sources in such circumstances. If spatial line vector data on channelized sections of the stream network from inlet to outlet were available (preferable in 3D), these could be used by *r.stream.carve* to correctly route the surface runoff flow through the channels. Secondly, the terrain-based derivation approach generated many false positives; it identified the most likely drainage routes through the topography, but not all of these corresponded to the real stream network. In **Figure 14**, the terrain-derived network, for example, has generated channels that match the topography better than the NVE Elvenett channels, but also has false positive channels alongside the road as well as in other low-lying areas. It is therefore necessary to use ancillary data (FKB, N50, NVE Elvenett) to select parts of the constructed stream network corresponding to those existing in reality, and/or fine tuning the parameters of the stream extraction modules to reduce the number of false positives. These false positives did not affect the modelling results on effects of migration hindrances on sea trout prevalence because stream reaches included in the modelling coincided with those existing in reality, but they could affect other potential applications of this stream extraction method (depending on the application in question). Conversely, it should also be noted that some of the terrain-derived channels that are not present in ancillary data may actually be real channels: for instance, ephemeral or potential channels that have not been digitized in existing network datasets (see **Figure 14**). This method therefore has potential for surveying of previously unmapped channels.

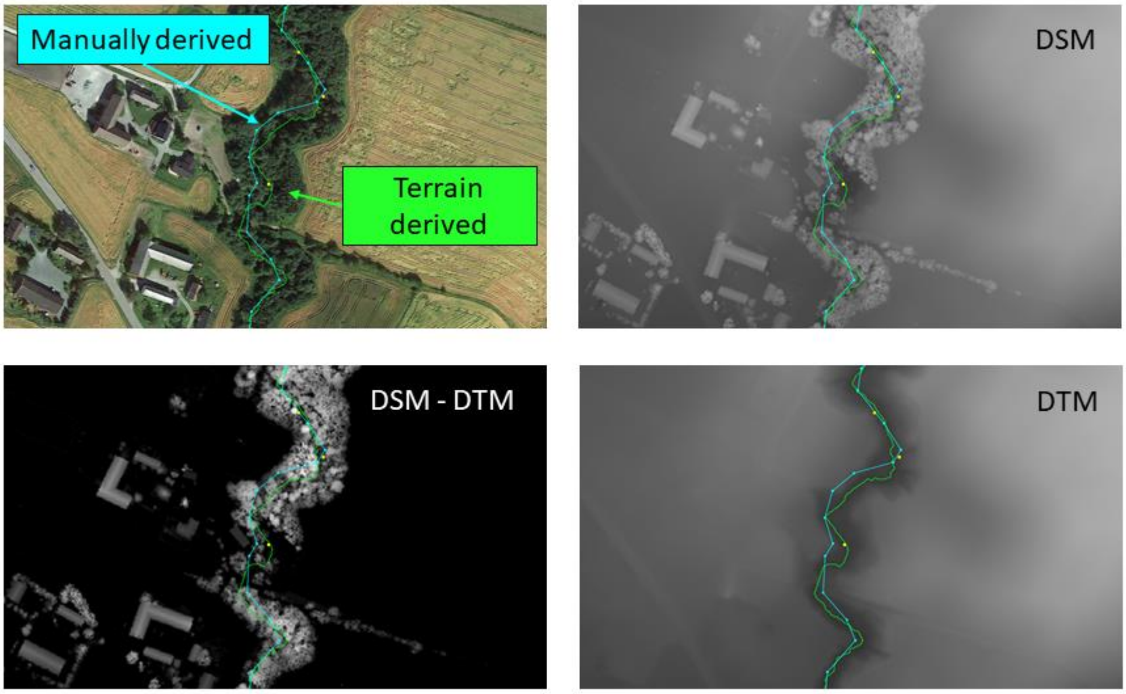

Figure 13*. Manually derived versus terrain-derived stream network superimposed on an aerial photograph composite (upper left panel), DSM (upper right panel), the elevation difference between the DSM and the DTM (lower left panel) and the DTM (lower right panel).*

Table 8. *Terrain-derived versus manually-digitized stream networks.*

	Terrain-derived stream networks	Manually-digitized stream networks
Pros	• Matches the DTM • High local accuracy	• High accuracy of overall topology
Cons	• Dependent on quality of the underlying DTM • Dependent on algorithms (e.g. MFD vs SFD) • Corrected LiDAR DTMs may still contain artefacts • More difficult to capture local climate and hydrology (precipitation, mires, glaciers, and runoff potential) • Computationally intensive when applied to high resolution data over larger areas • Produces false-positives of network presence	• Mis-match with DTM • Labor intensive and prone to human error • May miss necessary details (especially, small tributaries) • May be unusable / incompatible across country borders (countries use different scales and approaches; connectivity of network topology across borders is not guaranteed)

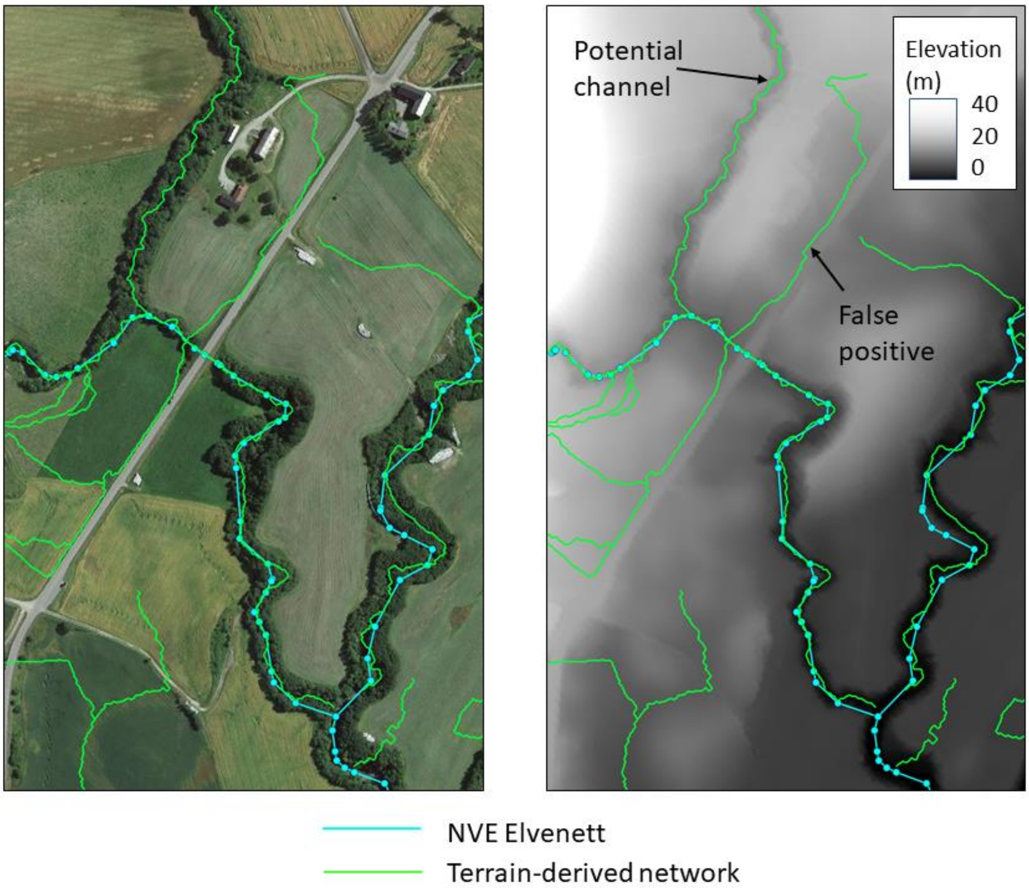

***Figure 14**. Terrain-derived network, showing false positives, superimposed on an aerial photograph (left panel) and DTM (right panel).*

While the study area in this pilot application was entirely within the borders of a single country, it should be noted that deriving stream networks from DTMs can be particularly useful in studies involving catchments that cross country borders. Transnational stream networks that are compatible across country borders are currently only available at a very coarse scale and cover only main streams/rivers (see for example https://www.eea.europa.eu/publications/eea-catchments-and-rivers-network), despite the implementation of the Water Framework Directive. Terrain-based derivation may be a solution to this issue.

4.2.3 Multi-scale computation of slope throughout the stream network

Given that the terrain-derived stream network matched the topography better than the coarser resolution NVE Elvenett, it can be expected that the generated slopes from the terrain-derived network will have been more consistent with reality. However, there were some errors in slope derivation, evident from negative slopes having been predicted in parts of some streams. These locations were mainly not at the core of stream networks and were therefore less relevant in the context of this study. Additionally, slopes downstream from electrofishing sites were consistently above zero so this will not have impacted our findings with regard to modelling sea trout prevalence. However, locations with negative slope should be investigated in future work because they point to possible issues in the cleaning process of the DTM. There is potential for modifying module parameters – for instance using a Minimalistic Sink Filling approach (filling only sinks with a set difference in altitude and of small size) to overcome this problem after an initial correction of the DTM.

4.2.4 Integrating the network with crossings and culverts

DTM data alone could not be used to identify culverts, and it was necessary to use additional GIS data sources. In the current study, crossings from the N50 road and rail network were used to find the potential location of culverts. However, not every crossing necessarily represents a culvert (for instance, the crossing could be a bridge with an unobstructed, unconstrained flow beneath). Integration with NVDB data was therefore necessary for a more accurate determination of culvert locations. A limitation of the NVDB database, however, is that it is incomplete. In particular, culvert characteristics are not available for all culverts. For example, 85.4% of culverts in the NVDB database used in the study area had no information on culvert diameter, 84.4% had no information on culvert shape, and 89.3% had no information on culvert building material. Additionally, it was not guaranteed that all culverts throughout the study area were registered within the database (see also **Figure 4**). Finally, the presence of culverts was not temporally static (with culverts being upgraded or installed with the addition of new anthropogenic infrastructure), which had implications for modelling their effect on sea trout prevalence.

4.3 Use of existent datasets for quantifying sea trout occurrence

Although it was possible to identify a relationship between migration hindrances and sea trout prevalence, modelled relationships were weak and had low explanatory power. For modelling the response in the model (sea trout prevalence), the electrofishing dataset was limited with regard to (1) how well it represented solely sea trout rather than (resident) brown trout, (2) how suitable it was for determining sea trout prevalence and (3) how much survey bias existed.

4.3.1 Anadromous sea trout versus resident brown trout

The objective of this study was to examine the impact of potential migration hindrances on the spatial distribution of sea trout. The *Salmo trutta* data used in this study were only selected from stream stretches defined as being anadromous – that is, where there was no structure (such as a waterfall or a dam) preventing the possibility of migration to and from the sea – so data were used as indication of the presence of sea trout. However, it is possible that some of the trout registered in the electro-fishing datasets originated from non-anadromous, resident brown trout populations, especially for streams where there was an upstream lake. *Salmo trutta* populations can be composed of both anadromous and non-anadromous individuals together (Jonsson & Jonsson 2006), and in fact, migration behavior can change over an individual trout's lifetime (see Ferguson et al. 2019). Differentiating between phenotypically similar anadromous and non-anadromous juveniles during electro-fishing sampling is not practically feasible and therefore no information was available on the presence of the non-anadromous phenotype with the electrofishing samples. However, anadromy in *Salmo trutta* is negatively correlated with altitude and migration distance (Jonsson & Jonsson, 2006; Ruokonen et al., 2018). Electrofishing sites used in this study were at low altitude (median = 25.7 m, max = 165 m) and tended to be sited at a short distance to sea (median = 5.2 km). Sites that were further inland were situated near rivers known to support sea trout. For instance, the most distant sites were situated in Sandbekken, 62.8 km from the sea, but this stream is situated on a part of the Gaula river that is known to contain sea trout (Solem et al., 2014), and the sites were situated only several hundred meters upstream of where Sandbekken met the Gaula. Given the low elevations and short distances to sea (or a river known to contain sea trout), it can be expected that most juvenile trout caught in the electrofishing surveys originated from anadromous sea trout.

4.3.2 Determining sea trout prevalence

Sea trout prevalence (i.e. presence or absence) was used as a metric for describing the sea trout population rather than abundance (number of individuals per unit area) because it was considered to be a more useful metric for modelling controls on accessibility. Two sites could have markedly different abundances but have the same accessibility, with the difference in abundance between the sites being due to a range of other factors, such as overall ecosystem quality. An additional advantage of using prevalence instead of abundance as a metric of trout occupancy is that it will be less prone to biases in measurement resulting from amalgamating electrofishing data from different sources. Electrofishing data are prone to bias, particularly if there are differences in stream characteristics, population characteristics or electrofishing methodologies, all of which can affect capture probability (Hedger et al. 2018). Electrofishing data used in this study were obtained across a range of steams, all with different population characteristics, and from multiple sources (although all researchers complied with NS-EN 14011) leading to the potential for biased measurement estimates. These biases may cause greater errors in abundance estimates than in prevalence estimates: while they might cause differences in estimated abundance, they are unlikely to switch a "presence" to an "absence" unless they are extreme.

The metric prevalence may be used to estimate whether a fish can reach an area but there is the potential for misinterpreting absences. While a prevalence of one indicates a fish definitely can reach an area (so there is 100% certainty of what is occurring for this condition), a prevalence of zero indicates that either the fish either cannot or that it was not detected (so there is less than 100% certainty of what is occurring for this condition). Given that prevalence was high (> 0.85 for both age groups pooled), we can be 100% sure that at least 85% of our observations were showing correct indications of trout existence. Of the remaining observations, a certain (unknown) percentage will have been indicating that part of the watercourse was inaccessible, when it may actually have been accessible. For example, in Buskleinbekken, sea trout were not observed in sites upstream of the road crossing the stream, suggesting the possible occurrence of a migration barrier (**Figure 15**). Sea trout were observed in some sites downstream of the road, but were absent in others. The fact that sea trout were detected in some surveys downstream of the road suggests that the detection absences downstream of the road cannot be used to suggest with 100% confidence that this part of the watercourse was inaccessible.

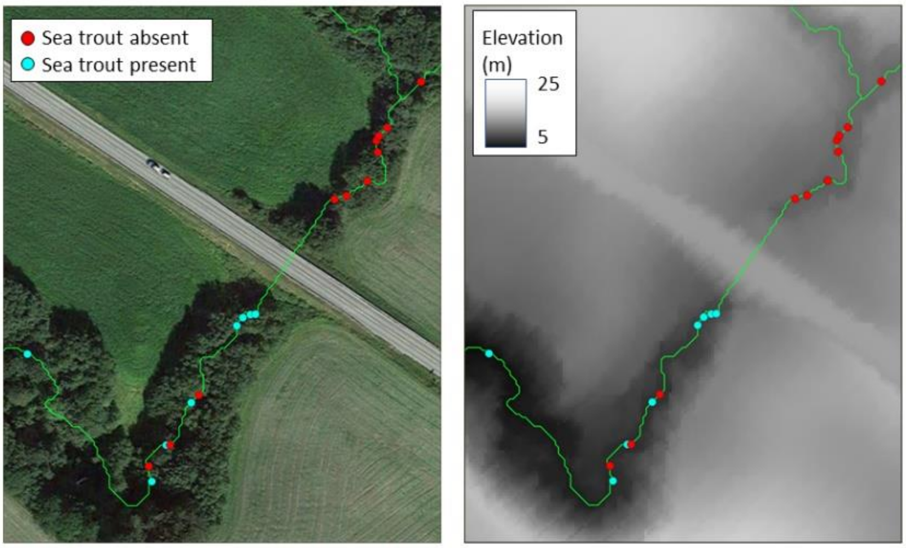

***Figure 15**. Sea trout presence and absence in electrofishing sites in Buskleinbekken, superimposed on an aerial photograph (left panel) and DTM (right panel).*

4.3.3 Survey bias

The electrofishing data available were acquired from surveys that were not conducted with the intention of providing an accurate estimate of the spatial distribution of sea trout prevalence or abundance within streams or across the region. As such, electrofishing data were limited with regard to: (1) a bias to being in sites where sea trout were present; and (2) a sub-optimal spatial coverage of the region. The electrofishing data did not provide a random sample of population characteristics across the region. The data were acquired for the assessment of population characteristics (for example, targeted surveys intended to collect enough fish for determining age distributions) so were biased to sites supporting fish. In fact, the registered prevalence of > 0.85 (age classes pooled) suggests that the surveys were biased to sites where sea trout were present as it is highly unlikely that 85% of the area of all streams considered in this study will have had sea trout present. The electrofishing data provided poor coverage, both within individual streams and across the region. For example, the sample intensity was greatest around Trondheim, and areas further south along the Gaula river were under-sampled. Additionally, survey data were not acquired with the purpose of examining the effect of migration hindrances, so survey sites in any given river were therefore not always positioned both upstream and downstream of migrations hindrances.

4.4 Implications for modelling

The numerous data limitations (see **Table 9**) posed problems for modelling the effect of migration hindrances on sea trout. Models were based on road/rail crossing or culvert data that only partially resolved the true distribution of culverts. Models were also based on sea trout survey data that involved multiple biases, and which has a poor coverage with regard to assessing regional patterns. Finally, to ensure a sufficient sample size, data were acquired from multiple years. During this time, there will have been variation in some of the properties related to migration hindrances (number of culverts or conditions of culverts) and other conditions affecting sea trout (such as ecological conditions). Additionally, there will have been interannual variation in discharge regime which will have affected the ease of passage through culverts. Thus, the fitted models were based on data that included temporal biases but for which was a lack of information available to account for such biases.

Table 9. *Limitations of data used in modelling effect of hindrances on sea trout prevalence.*

Variable type	Limitation
Response	Electrofishing providing a biased estimate of real fish prevalence Sub-optimal spatial distribution of trout presence and absence data among rivers and in relation to the presence of hindrances Low sample size, both within rivers and across the region Temporal bias in sample size
Predictor	Incomplete registration of culverts Temporal bias in culvert registration data Temporal changes in ecological conditions Multiple confounding factors not included in models

Despite these limitations, it was possible to find a relationship between prevalence and migration hindrances in the form of number of downstream crossings or culverts. However, given that observed prevalence across the electrofishing sites was greater than that which probably occurred in nature, it is likely that our models will over-predict prevalence. Predicted prevalence values can therefore be used to show a relative prevalence (i.e. whether one part of the river is more likely to have sea trout than another part of the river) but not the absolute prevalence likely to exist in reality.

4.5 Future development

Although this study identified that the prevalence of sea trout was negatively related to migration hindrances, fitted models had low predictive power. It is therefore suggested that to achieve a better determination of the effect of migration hindrances on sea trout, datasets and modelling approaches need to be further developed.

Datasets need to be improved in terms of size and quality. For further improvement of the methodology for detecting migration hindrances, the potential culverts along the streams identified by the GIS approach in this study could be inventoried in the field. This would provide a significantly improved basis for assessing the accuracy of the approach, as well as assessing the potential permeability of those correctly identified. Another potential solution for field surveys may be reliance on voluntary efforts from local interests (for instance from “citizen science”), but this requires the development of user-friendly map tools for reporting (for example, see the AMBER “Barrier Tracker” application; https://portal.amber.international/).

Models applied in the current study were preliminary as part of a pilot study for assessing how auto-generated maps of migration hindrances could be used in an ecological application (prevalence of sea trout). There is scope for improvement through the addition of other factors that could influence prevalence. It may be relevant to include further information on water quality, and there is potential to predict this through analyses of precipitation and field drainage (Dervo et al. 2017). Additionally, maps of sea trout habitat suitability could be incorporated. Such maps could also be used for assessing the potential impact of a culvert on the fragmentation and accessibility of potential habitat for sea trout. In addition, other predictors than the ones tested in this pilot study should be explored, such as the slope in culverts downstream from electrofishing sites (instead of the maximum slope in the entire downstream watercourse) or slope in interaction with a proxy for discharge (such as the Stream Power Index, SPI) as well as culvert length. Also, alternative modelling approaches could be applied. Instead of using a model looking in the downstream direction (starting from electrofishing sites and modeling the prevalence of sea trout as a function of variables downstream) it is also possible to model the barrier effect on prevalence of sea trout upstream of a culvert as a function of the characteristics of that particular culvert. However, hierarchical correlation structures would need to be taken into account in that case.

The approach outlined in this study offers the opportunity to create maps for prioritizing field surveys. In order to prioritize field mapping efforts, culverts could be ranked with regard to the length of the stream network upstream of the structure as a proxy for the potential amount of upstream habitat affected (see **Figure 16**). Additional parameters such as habitat quality or interdependence with other dams or culverts upstream could be included in such a prioritization map.

The methodology developed in this study has the potential to be extended to a number of applied issues: for example, developing and testing the method for other species or regions, and using this for the implementation of restoration measures. Depending on the availability of high-resolution terrain data, this approach could also be used to produce detailed stream networks in areas without coverage by the more detailed FKB data. The method and aggregated data can also be combined with results and knowledge from another ongoing project ("Restoration measures in connection with old ponds"; Norwegian Environment Agency (# 2018/1551)), as well as with other projects done in other parts of the country (Bækken & Bergan 2012a, Bækken & Bergan 2012b, Bækken & Bergan 2012c, Eloranta et al. 2019, Pedersen et al. 2017).

Extending the procedure used in this study across a larger area of Norway is viable. DTM data are available from the Norwegian Mapping Authority for over 80% of Norway’s land surface area. Although there is potential to use alternative DTM data sources for areas outside that covered, it is unlikely that the available spatial resolution of these sources would be sufficient for achieving a comparable level of detail, especially with regard to identifying potential culverts, because DTMs that are interpolated from contour lines usually do not represent this kind of structure, and alternative sources of satellite-derived LiDAR data are only available at a lower spatial resolution. The potential for terrain data based on photogrammetric acquisition to yield comparable results has not yet been evaluated. Since photogrammetry has been or will be used in the new detailed National Terrain datasets of the Norwegian Mapping Authority, it may be recommended to evaluate the applicability of this data source for hydrological analysis as was done for airborne LiDAR data in this study. The tools for pre-processing the terrain data and the scripts developed for network analysis in the current study may be capable of handling larger amounts of data and have the potential to be applied for other catchments and other types of input data.

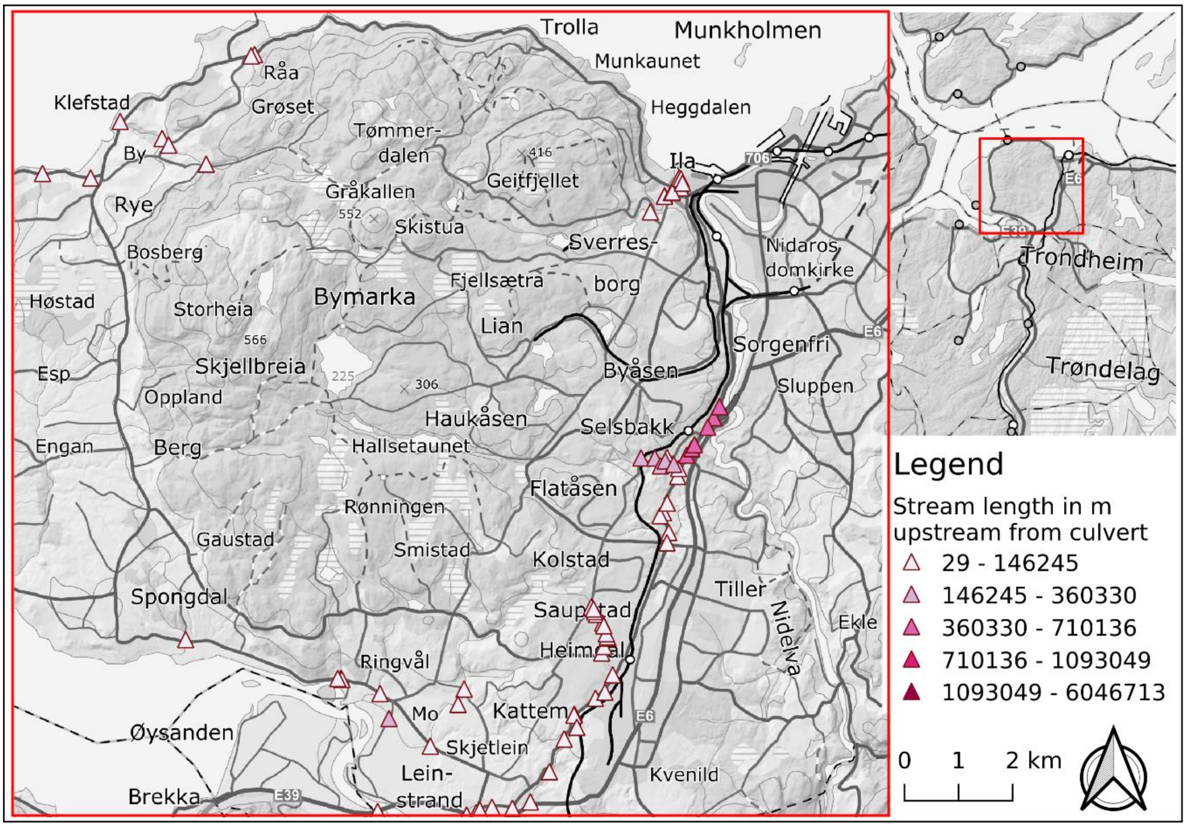

***Figure 16**. Example of the type of map that can be used to assist prioritization of targeted field surveys.*

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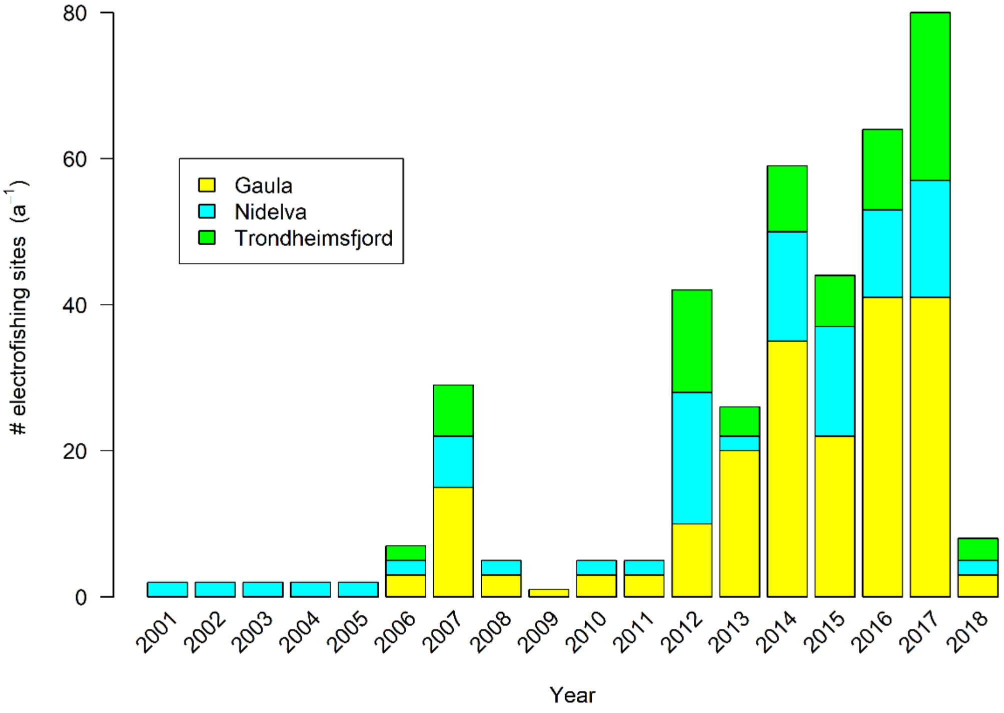
6 Appendix

6.1 Details on electrofishing sites



Supplementary figure 1*. Number of electrofishing sites in each year.*

6.2 GLMM models

Supplementary table 1. *Variance inflation factors among predictors used in the GLMM models: CrossN = Number of downstream crossings; CulN = number of downstream culverts; MaxSlope = maximum downstream slope; Dist = distance from the electrofishing site to the sea, Elev = elevation of the electrofishing site.*

Model	Parameter	Variance inflation factor
Crossings	CrossN	3.27
	MaxSlope*	1.44
	Dist	2.28
	Elev	2.61
NVDB Culverts	CulN	2.85
	MaxSlope*	1.87
	Dist	1.46
	Elev	3.89

** The maximum downstream slope (MaxSlope) presented here was that estimated over 51 DTM cells. VIF factors using slope maxima estimated over 5, 11, 21, and 31 units were similar.*

Supplementary table 2. *Coefficients of the initial prevalence GLMMs (age groups pooled); CrossN = Number of downstream crossings, CulN = number of downstream culverts, MaxSlope = maximum downstream slope, Dist = distance from the electrofishing site to the sea, Elev = elevation of the electrofishing site.*

Model	Parameter	Estimate	Std. Error	z value	Pr(>|z|)
Crossings	(Intercept)	7.330	3.701	1.980	0.048
	scale(CrossN)	-7.989	2.908	-2.747	0.006
	scale(MaxSlope)	0.108	0.496	0.219	0.827
	scale(Dist)	14.066	7.661	1.836	0.066
	scale(Elev)	-0.449	0.873	-0.515	0.607
NVDB culverts	(Intercept)	4.672	1.739	2.687	0.007
	scale(CulN)	-3.069	1.106	-2.775	0.006
	scale(MaxSlope)	0.102	0.476	0.214	0.831
	scale(Dist)	5.545	2.516	2.204	0.028
	scale(Elev)	-0.616	0.797	-0.772	0.440

Supplementary table 3. *Coefficients of the initial prevalence GLMMs (0+ age group).*

Model	Parameter	Estimate	Std. Error	z value	Pr(>|z|)
Crossings	(Intercept)	0.604	0.441	1.369	0.171
	scale(CrossN)	-0.683	0.663	-1.031	0.302
	scale(MaxSlope)	-0.074	0.280	-0.265	0.791
	scale(Dist)	1.692	0.593	2.852	0.004
	scale(Elev)	0.085	0.425	0.201	0.841
NVDB culverts	(Intercept)	0.619	0.434	1.426	0.154
	scale(CulN)	0.057	0.496	0.115	0.909
	scale(MaxSlope)	0.039	0.269	0.146	0.884
	scale(Dist)	1.335	0.491	2.717	0.007
	scale(Elev)	-0.239	0.389	-0.615	0.538

Supplementary table 4. *Coefficients of the initial prevalence GLMMs (≥1+ age group).*

Model	Parameter	Estimate	Std. Error	z value	Pr(>|z|)
Crossings	(Intercept)	1.235	0.312	3.954	<0.001
	scale(CrossN)	-1.236	0.515	-2.399	0.016
	scale(MaxSlope)	0.073	0.24	0.305	0.761
	scale(Dist)	1.714	0.526	3.258	0.001
	scale(Elev)	-0.094	0.326	-0.287	0.774
NVDB culverts	(Intercept)	1.147	0.36	3.182	0.001
	scale(CulN)	-0.76	0.466	-1.63	0.103
	scale(MaxSlope)	0.102	0.253	0.401	0.688
	scale(Dist)	1.076	0.379	2.835	0.005
	scale(Elev)	-0.196	0.344	-0.568	0.570

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NINA Report

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